THE VALUE AND LIMITATIONS OF REMOTE SENSING FOR THE INTERPRETATION OF TROPICAL FORESTS WITH PARTICULAR REFERENCE TO SOUTHWESTERN NIGERIA

BY

FEIOLA BISOYE LARIN-ALABI
B.Sc.,Cert.For.Photoint.

DOCTOR OF PHILOSOPHY

DEPARTMENT OF FORESTRY AND NATURAL RESOURCES
EDINBURGH UNIVERSITY, SCOTLAND, UNITED KINGDOM

1979

ABSTRACT

This work aims to show the values and limitations of aerial photographs, Landsat and side-looking airborne radar (SLAR) images for forest-type recognition, tree-species identification, timber-volume estimation and area estimation of the Southeast Asian, the Amazonian and the African tropical forests.

The studies comprise an investigation by a review of literature on the applications of the three remote sensing systems in the three tropical forest regions and an experimental investigation of the tropical African forests using Southwestern Nigeria as a typical example. The findings on the technical capabilities of the three systems and the economics of their use were interrelated for the evaluation.

The investigations show that remote sensing techniques are easier, quicker and cheaper than ground techniques for tropical forest surveys. Only aerial photography can be successfully used for species-identification and volume estimation. Despite the similar cost of SLAR imagery and the cheaper cost of Landsat imagery, they cannot compete successfully with aerial photography for forest-type recognition and area estimation. In a combined use, they none-the-less add extra value to photo-information.

The lack of funds and the unfavourable weather conditions as well as the complex forest structure and floristic composition are the main factors constraining the use of remote sensing in tropical forest surveys. Options for an economic use of remote sensing are recommended and suggestions for further investigation are made.

FRONTISPIECE: AN EARLY REMOTE SENSING PLATFORM
The pigeon camera and its carrier-pigeon

"Just at the moment when men transform themselves into birds, the birds become photographers."

L'illustration (1908) No. 3429 p.322 quoted by ASP (1975). Photograph reproduced from Photogram. Eng. & Rem. Sensing 53(7)

This thesis is dedicated to my wife for her
ability to cope without ever complaining
and to our children for their forebearance.

DECLARATION OF ORIGINALITY

[redacted]

This thesis has been composed by me from the results of my own investigations.

Help from other people and reference to other investigations have been duly acknowledged in the thesis.

Part of the material included in the thesis has been published before its presentation.

The thesis has not been submitted elsewhere for the award of any qualification whatsoever.

[redacted]

(F. B. Larin-Alabi).

31st July, 1979

ACKNOWLEDGEMENTS

I wish to express my sincere thanks to my supervisor, Dr. Ian Langdale-Brown for his guidance and support over the last three years. I also wish to thank Dr. Roger Kirby of the Department of Geography of Edinburgh University for access to his equipment and his helpful assistance. I am grateful to Dr. Robert Muetzelfeldt for his advice on the statistical aspects of the work.

I wish to thank my friend and colleague, Akin Akinsanmi of the Forest Resources Management Department of the University of Ibadan, Nigeria, for providing the aerial photographs used in this investigation. But for his kindness, the photointerpretation would not have been possible.

I am also indebted to William Trevett and David Parry of Hunting Technical Surveys Limited in the United Kingdom, for supplying materials and information on the Nirad Project. Thanks are also due to Peter Allen, Remote Sensing and Cartographic Advisor to the Nigerian Government, for his helpful discussions.

Another colleague of mine, Sue Hutton translated the French and other literature into English. I am particularly grateful to her and her husband Len, for their kind gestures to me.

This work was sponsored by the Federal Government of Nigeria and I am grateful for their financial support.

I wish to thank Robin and Susan Mackenzie for reading the draft and for their friendship.

Finally, I wish to thank my wife, Caroline, for her steadfast support throughout the period of this study and also for typing innumerable drafts. Without her help the work would not have been finished.

F. B. Larin-Alabi.

Department of Forestry and
Natural Resources,
Edinburgh University,
Scotland, U.K.

31st July, 1979

LIST OF CONTENTS

CHAPTER 5 THE USE OF REMOTE SENSING FOR AREA ESTIMATION

CHAPTER 6 ECONOMICS OF THE USE OF REMOTE SENSING IN FOREST SURVEYS

PART II EXPERIMENTAL INVESTIGATION

CHAPTER 7 VEGETATION AND REMOTE SENSING IMAGERY OF SOUTHWESTERN NIGERIA

CHAPTER 8 PHOTOINTERPRETATION

CHAPTER 9 INTERPRETATION OF LANDSAT IMAGERY

CHAPTER 10 INTERPRETATION OF SLAR IMAGERY

CHAPTER 11 APPRAISAL OF REMOTE SENSING IN NIGERIA

PART III FINDINGS OF THE INVESTIGATIONS

CHAPTER 12 THE VALUE AND LIMITATIONS OF REMOTE SENSING FOR THE INTERPRETATION OF TROPICAL FORESTS

APPENDIXES

LIST OF ILLUSTRATIONS

LIST OF TABLES

INTRODUCTION

The efficiency of any system of resource management depends on the quality of its data base for both prescription and implementation. There is a shortage of data with regard to forest management in many tropical countries such as Nigeria and this hinders management. This shortage is mainly due to the problems associated with the existing survey methods.

Remote sensing supplemented by ground information is acknowledged to be a satisfactory method of gathering information for resource management. Foresters were among the first people to appreciate the value of remote sensing (Harper, 1976) and they pioneered the use of aerial photography in resource management (Latham & McCarty, 1972). The amount of information currently available from remote sensing is so large that foresters are uncertain what precise use to make of it.

Most of the evidence for these views comes from the temperate forest environment. The possibilities of using remote sensing techniques to gather information on tropical forests have not been adequately tested. Moreover, most of the work that has been done on tropical forests relates to Amazonian and the Southeast Asian regions. It is therefore not known how valuable remote sensing techniques are for the survey of tropical forests generally and in particular those in the African region.

This investigation aims to show how the various imaging remote sensing systems could be used at an economic cost to gather information on tropical forests. The acquisition of the following categories of information which constitute a resource data base was considered: resource recognition:

(a) resource location, distinguishing forests and separating them into a number of general types (forest-type recognition).

(b) resource composition, identifying the economic tree-species within each general type (species identification).

resource assessment:

(c) resource quantity (and also quality), estimating the volumes of the growing stock and the yield of each general type (volume estimation).

(d) resource distribution, estimating the areas of each general type (area estimation) to relate the resource quantity and quality to the area of each general type.

The potential of the three main imaging remote sensing systems - aerial photography, Landsat multispectral scanner (MSS) and side-looking air-borne radar (SLAR) - for providing these categories of information was evaluated on a comparative and integrated basis.

The studies consist of a review of the literature on applications of remote sensing to forest surveys in the tropics and an experimental investigation of the tropical African forests using Southwestern Nigeria as a typical example. The economics of remote sensing were considered in both investigations. The studies were limited to visual interpretation of the photographic products of these remote sensing systems because these products are readily available and convenient to use in conjunction with field observations.

The report of the studies is presented in three parts. Part I comprises the investigation by literature review while Part II comprises the experimental investigation. Part III integrates the findings on the technical capabilities of the three remote sensing systems and the economics of their use in tropical forest surveys.

PART I

INVESTIGATION BY
LITERATURE REVIEW

"... whilst remote sensing is presently viewed as a new technology, it may also be providing new philosophical concepts and a challenge to the exact sciences of our environment ... Remote sensing has ... served well in bridging the gaps between scientific disciplines and this in turn emphasises the importance of multi-disciplinary studies ... Let us not forget that the application of remote sensing ... has weakness and strength in being both a science and an art."

J. A. Howard (1974).

Introduction to Part I

The main objectives of the literature review are:-

(a) to assess the extent to which remote sensing has been used in surveys of tropical forests

(b) to identify the technical and economic problems associated with the applications of remote sensing to forest management in the tropics.

(c) to suggest probable solutions to these problems.

The review is presented in six chapters:-

Chapter 1 is an introductory chapter which gives:

- a comparative description of the characteristics of three remote sensing systems.
- a general description of the characteristics of tropical forests
- an explanation on the ways in which environmental factors influence remote sensing in the tropics.

This chapter provides a background for the next four chapters which review the use of all three types of imagery to gather the four different categories of information:

(a)	forest-type recognition	(Chapter 2)
(b)	tree-species identification	(Chapter 3)
(c)	volume estimation	(Chapter 4)
(d)	area estimation	(Chapter 5)

Each of these chapters covers:-

(i) the purpose of the review and the approach to it

(ii) the applications of the three remote sensing systems in each of the three main tropical forest regions

(iii) inferences and conclusions of the review

Chapter 6 covers the economics of the use of the three remote sensing systems in relation to their technical capabilities.

CHAPTER 1

REMOTE SENSING SYSTEMS AND TROPICAL FORESTS

1 Remote sensing concept

The scope of remote sensing varies according to the various definitions of the term 'remote sensing'. Barrett and Curtis (1976) defined remote sensing as 'the observation of a target by a device separated from it by some distance'. This definition has been adopted for this thesis. At present forest remote sensing is restricted to methods that employ electromagnetic energy as the means of detecting and measuring target characteristics.

This concept can be viewed from two basic standpoints: the technical and the philosophical. Technically, remote sensing systems are not specifically designed for a particular application, they are either established or experimental programmes intended for many applications. Philosophically, users have been led to expect an excessively high success ratio from remote sensing technology. In order to obtain an optimum success ratio for a particular application, the interpretation of remote sensing imagery should be based on well-understood principles:

- the technical limitations of individual systems for providing the information being sought.
- the various methods of image enhancement to provide more options for the extraction of the information.

In this respect the characteristics of the three main remote sensing systems - aerial photographic, Landsat MSS and SLAR systems are compared in Section 1-1 and the image enhancement techniques used for these studies are described in Section 7-2.1

1-1 Comparison of the main remote sensing systems

The characteristics of aerial photographic, Landsat and SLAR imaging systems are compared in Table 1.1. The table is designed to provide the basic principles on which the concepts of remote sensing

Table 1.1 Comparison of photographic, Landsat and radar imaging remote sensing systems

Characteristics	Photographic system	Landsat system	Radar system
A General			
1 Typical system	aerial photography	Landsat I & II	SLAR
2 Typical sensor	aerial photographic camera (frame or panoramic)	multispectral scanner	side-looking airborne radar (real or synthetic aperture)
3 Platform	numerous, mainly aircraft (and also spacecraft)	spacecraft - satellite (unmanned)	mainly aircraft (seldom spacecraft)
4 Altitude	any altitude	918km. altitude	restricted to aircraft operations
5 Commercial availability	system commercially available and user-controlled	system neither available commercially nor user-controlled	system commercially available and user-controlled
6 Security restrictions	image acquisition under political and security restrictions	image acquisition not under any political or security restrictions	image acquisition under political and security restrictions
B Coverage			
1 Acquisition scale	wide range, from very small to very large can be enlarged with consequent loss of image definition	fixed, fundamentally small, 1:3 369 000 but also generated at 1:1 000 000 scale without loss of definition	limited range, economic scales vary between 1:250 000 and 1:500 000 can be enlarged with consequent loss of definition
2 Regional coverage	each photograph covers limited area which varies with scale	each image covers a fixed area, 185km. x 185km.	typical image covers an area tens of km. wide and hundreds of km. long
3 Coverage extension	the limited coverage can be extended by mosaics	the broad synoptic coverage can be extended further by mosaics	the coverage can be extended by mosaics
4 Multidate coverage	coverage not repetitive, multidate images are expensive to acquire	coverage repetitive, multidate images are available at economic cost	coverage not repetitive multidate images are expensive to acquire
5 Image cost	moderate cost per sq.km., but higher if only a small area is covered in a single mission	very low cost per sq.km. irrespective of area covered	high cost per sq.km. but competitive with aerial photographic costs if a very large area is covered in a single mission
C Operation			
1 Operating mode	passive, depends on natural illumination of the scene	passive, depends on natural illumination of the scene	active, depends on natural illumination of the scene

Characteristics	Photographic system	Landsat system	Radar system
2 Operating conditions	requires daylight and good weather conditions	requires daylight and good weather conditions	can be operated round the clock (day or night) under most weather conditions
3 Imaging limitations	imaging affected by haze in the shorter wavelengths and cloud cover	imaging affected by haze in the shorter wavelengths and cloud cover	atmospheric effects are minimal and none in the X band except during rainstorms
4 Oblique illumination	sun elevation varies across photographs of the same flight and even of the same strip according to the local sun time during exposure. Illumination may not be uniform on individual photographs	sun elevation is constant, platform is geostationary and sun synchronous, individual scenes are imaged at approximately the same local sun time, image illumination is constant but varies with season	radar depression angle varies from near range to far range across the image, time delay device is used to adjust the echo-time differences that are due to the variation in the depression angle across the image
D Imaging			
1 Sensing wavelengths	micrometre wavelengths (0.3μm. - 0.9μm.)	micrometre wavelengths (0.5μm. - 1.1μm.)	centimetre wavelengths (0.86cm. - 25cm.)
2 Sensing bands	photographic ultraviolet band (0.3μm - 0.4μm.), visible band (6.4μm. - 0.7μm), photographic infrared band (0.7μm. - 0.9μm.)	visible band (0.5μm. -0.7μm.), reflective infrared band (0.7μm. - 1.1μm.)	radar bands, most commonly used are :- Ka (0.8cm - 1.1cm.) *0.86cm. X (2.4cm. - 3.8cm.) *3 & 3.2cm. L (15cm. - 30cm.) *20cm.
3 Spectral range	usually one broad band using various film/filter combinations, multiband photography with multispectral camera	fundamentally multispectral using four bands: band 4 (0.5μm. - 0.6μm.) band 5 (0.6μm. - 0.7μm.) band 6 (0.7μm. - 0.8μm.) band 7 (0.8μm. - 1.1μm.)	individual systems restricted to specific wavelengths indicated above, no multispectral content in individual SLAR systems
4 Property sensed	reflectance differences between fine surface patterns	reflectance differences between gross surface patterns	surface-roughness differences between surface or geological patterns
5 Signal reception	signals travel through camera lens, sensing occurs in the selected view in 'mirror image' form	signals travel through oscillating scanning mirror, sensing occurs during east-bond oscillation in array scanning system	signals travel through radar antenna, sensing occurs in the look direction in line-scan form
6 Recording mode	angular distances are recorded in uncalibrated form on photographic film by optical methods	angular distances are recorded in digital form on magnetic tapes by electro-optical methods	echo-time intervals (two way travel time of radar energy) are recorded in uncalibrated form as scanlines on cathode ray tube by electro-mechanical methods

Characteristics	Photographic system	Landsat system	Radar system
7 Photographic products	direct recording on photographic film	magnetic tapes are played back on electron beam film recorders	scanlines are recorded by strip film recorder of the cathode tube
E Resolution			
1 Pixel size (PS)	of micrometre dimensions, depends on the resolving power of film/filter combination and camera lens	79m. x 79m.	10m. x 10m.
2 Ground resolution (GR)	very high spatial resolution varies between a fraction of a metre to a few metres according to scale	very low spatial resolution varies between 200m. and 250m.	high spatial resolution, fairly constant at the economic scales, generally 10m.
3 PS/GR ratio	PS/GR ratio is low because angular distances are difficult to measure precisely	PS/GR ratio is very low, because angular distances are difficult to measure precisely	PS/GR is very high because echo-time intervals are more precisely measured than angular distances
4 Information content	very high information content due to very high spatial resolution and small pixel size	lower information content due to large pixel size and low spatial resolution	moderate information content due to fairly small pixel size, very high subsurface information due to high PS/GR ratio
5 Atmospheric effects	atmospheric scattering (haze) reduces contrast ratio and the resolving power of photographs, the effects are reduced by using suitable film/filter combinations	atmospheric scattering (haze) reduces contrast ratio and the resolving power of imagery, the effects are reduced by digital reprocessing of imagery	atmospheric effects are minimal in the microwaves, hence the contrast ratio and the resolving power of imagery are both high
F Image characteristics			
1 Image rendition	familiar pictorial rendition in tone, colour or false colour of objects by direct recording on photographic films	unfamiliar tonal rendition derived from calibrated object-reflectance recorded on magnetic tapes	familiar pictorial rendition of surface roughness derived from echo-time intervals transformed into scanlines
2 Photographic enhancement	rendition in multiband photography is improved by colour composite generation	rendition in multispectral imagery is improved by colour composite generation	there is no multispectral content, imaging is presently limited to individual radar bands
3 Digital image-enhancement	information is not calibrated but can be digitized for computer analysis	information is available in digital form (computer-compatible tapes) suitable for computer analysis	information is not calibrated but can be digitized for computer analysis

Characteristics	Photographic system	Landsat system	Radar system
4 Effect of pixel size	small pixel size enhances finer surface features which are filtered off by the larger pixels of Landsat and SLAR, consequently individual objects such as trees and surface relief are emphasized and subsurface patterns are obscured	very large pixel size filters off finer details that cause reflectance differences with aerial photography and enhances gross features which do not cause surface-roughness differences in the microwaves, consequently gross surface features such as general forest types are emphasized	moderate pixel size filters off finer details that cause reflectance differences with photography and emphasises features that cause surface-roughness differences in the microwaves but do not cause reflectance differences with Landsat, consequently surface roughness and geological features are emphasized
5 Effect of sun angle	low sun angle (10° or less) enhances subtle differences in relief, texture and pattern with loss in tonal contrast, high sun angle results in sharp tonal contrast with loss in relief, texture and pattern definition, in vertical aerial photography lineaments are obscured	low to intermediate sun angle enhances geological signals	low radar depression angle enhances geological signals
6 Effect of illumination differences	photo-mosaics are usually marred by illumination differences on the component photographs, quality can be improved to some extent by photographic methods; matched edges are noticeable but readily distinguished from lineaments	Landsat mosaics are of high quality due to uniform illumination of the scenes whose images compose the mosaic, quality can be improved by digital methods in which matched edges are virtually eliminated	radar mosaics are usually marred by matched edges of the component images, these matched edges are not readily distinguished from lineaments; also the effects of the variation in the transmitted radar energy are often noticeable between adjacent strips to give the impression of change in terrain pattern
7 Image defects	individual photographs are marred by very long shadows due to poor illumination and by solar reflection point (hot spot or no-shadow point) due to high sun elevation	individual images are marred by sixth line banding, sixth line dropout and scanline offset which can be corrected digitally by reprocessing	individual images are marred by sidelobe banding (restricted to near range) foreshortening, layover and radar shadows
8 Geometric distortions	nadir viewing angle varies between narrow and wide angles geometric distortions increase with angle of view, distortions are corrected photographically or photogrammetrically during plotting	scan angle is narrow (11.56°), geometric distortions are minimal,consequently images are inherently orthographic, distortions are corrected by digital methods	viewing angle varies between 10° and 50°, time-delay device is used to normalise the effect of range on the echo-time, geometric distortions increase with scan angle and they are corrected partially by radargrammetric methods during plotting

Characteristics	Photographic system	Landsat system	Radar system
9 Image analysis	wide range of highly developed photogrammetric equipment	digital processing methods are highly developed	narrow range of radargrammetric equipment (still under development)
G Stereo-image			
1 Stereo coverage	fundamentally stereoscopic coverage	limited stereoscopic coverage	stereoscopic coverage at an additional cost
2 Overlap	forward overlap varies with exposure interval and lateral overlap varies with flight line spacing	forward overlap is constant at 10%, lateral overlap varies with altitude (14 - 21.4% in the tropics)	there is no forward overlap in strip imaging, lateral overlap varies with flight line spacing
3 Stereo-geometry	stereoscopic observation is based on point - perspective geometry	stereoscopic observation is based on point perspective geometry	stereoscopic observation is based on line perspective geometry
4 Stereoscopic properties	optimum base/height ratio and vertical exaggeration (typically four) hence parallax is suitably measured	inadequate base/height ratio (0.174 - 0.163 in the tropics) and vertical exaggeration (under 1.3 and varies with latitude, 1.12 - 1.22 in the tropics) hence parallax difficult to measure	adequate base/height ratio and vertical exaggeration but parallax difficult to measure due to datum swarp in line perspective geometry
5 Image displacement	objects are displaced radially away from nadir, radial displacement increases away from nadir and most pronounced at photo corners	near-orthography, image displacement is minimal and it increases away from nadir	objects are displaced towards the nadir (near range), displacement decreases from near range to far range
6 Stereo observation	stereoscopic observation is better along flight line (forward overlap) but also easy with lateral overlap	stereoscopic observation is better along orbit-perths (lateral overlap), forward overlap is insufficient	stereoscopic observation is limited to range (look) direction, it is not possible in azimuth (flight) direction due to continuous strip imaging
7 Stereoplotting	ground control points are readily plotted because vertical illumination can be simulated in the stereomodel	there is no reliable methods of establishing ground controls, images are registered unto base maps compiled with Lambert projection	ground control points are difficult to plot due to datum swarp and the difficulty in simulating side-look illumination in the stereomodel
8 Stereoplotting obstacles	photostereo is usually affected by radially increasing topographic displacement and tilt (very noticeable on photo corners).	difficulty in obtaining stereo-images suitable for optimum stereo-perception	radar stereo is usually affected by radar shadows, foreshortening, and layover

Source: [illegible] literature survey ([illegible], 1976).

technology and applications are based. The table shows that while certain features can be resolved on the imagery of one type of system they may not be resolved on another type. Also, several different materials may have the same signature and be indistinguishable on one type of imagery. This is a primary argument for acquiring imagery in more than one spectral band, but few of the remote sensing systems can be used simultaneously and still acquire optimum imagery. For instance, the high altitude and sidelook geometry of radar acquisition are incompatible with other systems.

Moreover, the expense of multiple flights with different aircraft and imaging systems is excessive for certain surveys, say reconnaissance surveys, which should be relatively inexpensive to be cost-effective. These count against the multiple-sensor concept and favour the strategy of selecting the remote sensing system that provides, at an economic cost, the maximum amount of information for a particular survey.

In either the multiple-sensor concept or the optimum-sensor strategy, both technical and philosophical precautions should be taken in respect of:

- the extent to which the survey objectives can be fulfilled through the currently available remote sensing methods.
- the extent to which the available financial and other resources can be economically used to fulfil the survey objectives through remote sensing methods, and
- the feasibility of acquiring the necessary remote sensing imagery at an economic cost.

These precautions are considered in the sections of this thesis that deal with the interpretation of the various categories of forest management information on remote sensing imagery.

1-2 Characteristics of tropical forests

Tropical forests consist of woody vegetation types ranging from open savanna woodland to closed high forest. Tropical forests cover a total area of approximately 19 million sq.km. or 14% of the world's land area and slightly less than half of the world's forested area. They are nearly all located in the developing countries where they represent an important resource for production and conservation. In Nigeria, the closed high forest which produces practically all of Nigeria's industrial round wood and occupies about one tenth of Nigeria's 924 000sq.km. land area, is found in the south. The savanna which occupies about 800 000sq.km. in the north contributes only poles and fuelwood as does the small coastal stretch of mangrove in the south.

To understand the application of remote sensing to the survey of tropical forests, some knowledge of these forest communities and the forest environment is essential. Therefore, the most important forest community - the tropical rainforest, which is the vegetation of the test area in Southwestern Nigeria - and the environmental factors influencing the remote sensing of these forests are described.

The tropical rainforest is important for its high quality timber which is in high demand in the world market. Three main tropical rainforest regions are generally recognised. These are:-

(a) the Amazonian region dominated by the Amazon basin and other parts of the east coast of Brazil, but also including a coastal stretch from Ecuador to Mexico and the Caribbean Islands.

(b) the southeast Asian region consisting of Indonesia, Malaysia, Burma, Thailand (Siam)Kampuchea (Cambodia) Sri Lanka (Ceylon), the Vietnams and the Phillipines.

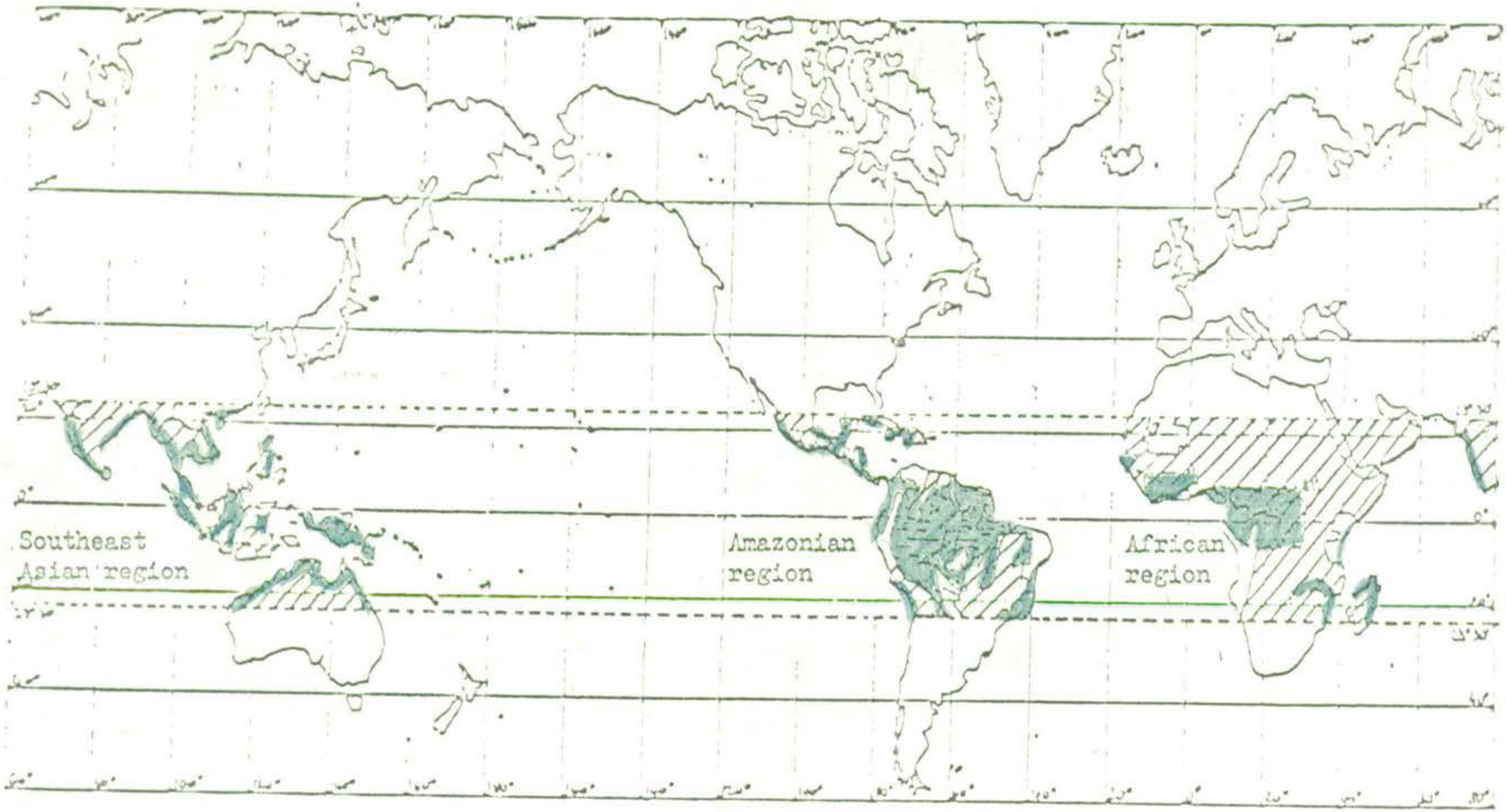
(c) the African region comprising a West African coastal stretch from Gambia to Liberia, Southern Nigeria, Cameroons, a central belt stretching from the Congo basin to the Great Lakes in East Africa and the western slopes of Madagascar.

The geographical locations of these regions are shown in Fig. 1.1.

The tropical rainforest is a climax vegetation which develops under very humid conditions - an annual rainfall of 1500 mm. - 4000 mm. is evenly distributed throughout the year, a less rainy season with as little as 50 mm. - 70 mm. of annual rainfall does not last longer than three months. The temperature is relatively constant varying only between 20°C and 26°C and the light intensity under the trees is approximately 0.004 to 0.033 of that in the open (ASP, 1975a).

In vertical profile, tropical rainforest cannot be stratified into layers: crowns exist at all levels, with discontinuous taller emergents, to give the canopy an almost completely irregular structure. Tropical rainforest contains a very large number of species most of which are of low incidence particularly in the highly mixed forest-types. Nigerian forests contain over 576 tree-species capable of attaining a minimum height of 12m. and a diameter of 19cm. at breast height (Ola-Adams & Iyamabo, 1977). In the closed high forest areas there are about 47 species per hectare of trees with a minimum diameter of 10cm. at breast height (Richards, 1939), the incidence of the commonest species being two in every hundred trees with a minimum mid-stem diameter of 7cm. (Omeoga, 1976). This mixed and varied composition affects the interpretation of the forests.

Except under special climatic and edaphic conditions, no species is of outstanding importance either ecologically or economically. For example, in 1950 only seven of the Nigerian tree species were considered to be of commercial timber value, by 1975 the number of the species



Source: Howard (1976)

Fig. 1.1 Map location and Landsat coverage of the main tropical forest regions

oblique hatching indicates 10% least cloud-cover or less.
green colouring indicates tropical rain-forest areas.
(Note the failure to obtain Landsat coverage of most tropical rain-forest areas).

regarded as commercially acceptable timber species increased to forty seven. This number is expected to increase in the near future. This notwithstanding, the botanical richness of tropical forests may be said to be inversely proportional to their commercial value. Furthermore, the tropical forests do not constitute an inexhaustible source of timber. Regeneration after exploitation is difficult because all representatives of the chosen species are felled.

1-3 Environmental factors influencing the remote sensing of tropical forests

The following environmental factors influence the use of remote sensing techniques to gather information on tropical forests

(a) local climate and weather
(b) landuse and forest nature
(c) topography and terrain conditions

The magnitude of their influence varies from region to region according to the severity of these factors. The ensuing discussion applies to tropical forests in general, with more emphasis on the test area in Southwestern Nigeria.

(a) Local climate and weather

In the tropics, many aspects of remote sensing, particularly the acquisition of imagery, are affected by climatic or weather conditions such as:

- sky cloud-cover and atmospheric haze
- solar radiation in terms of temperature and light intensity
- rainfall and relative humidity

In Nigeria, except for local variations, weather conditions tend to be increasingly limiting from the northwest to the southeast direction and vice versa according to seasons. This is probably due to the influence of the intertropical front where the humid equatorial air mass from the southwest coast meets the dry tropical continental air mass (harmattan) from the northwest desert area.

Both aerial photographic and Landsat systems image in the micrometre wavelengths (visible and reflective infrared bands). They depend on solar illumination of the scene being imaged. Cloud-cover, moisture haze, dust, and smoke haze are responsible for atmospheric absorption and scattering of solar energy, particularly in the shorter wavelengths. Passive imaging in these wavelengths results in low scene contrast ratios. This hinders the detection of objects by the imaging systems and the resolution of objects on the acquired imagery. On the other hand SLAR is an active system producing its own illumination for imaging in the centimetre wavelengths (microwave band).

Passive imaging in the micrometer wavelengths, particularly in the photographic band, demands stringent weather conditions. Suitable photographic weather conditions specify no haze and less than 12.5% sky cloud-cover (Kio, 1974; ASP, 1975a). In the tropics these conditions are only fulfilled on a few isolated days in the year. For instance, the mean annual sky cloud-cover for southern Nigeria is 50% or more with a mean monthly cover of 90% or more in the rainy season and 40% or less in the dry season.

The experience from Landsat system which is not user-controlled, clearly indicates the extent to which cloud-cover affects the acquisition of imagery by passive sensing in the micrometre wavelengths.

The index to Landsat coverage (Eros Data Centre, 1976) records cloudiness by referring to the percentage cloud-cover of the best available imagery of a Landsat scene as the 'least cloud-cover'. The least cloud-cover for southern Nigeria increases in a northwest to the southeast direction and is nowhere less than 20 - 30%.

A repeated geographic computer search conducted for the present investigator by Eros Data Centre shows that, to date, only five Landsat frames with 50% least cloud-cover or less are available for the test area (Southwestern Nigeria which is covered approximately by two Landsat scenes. An examination of the best frame (30% least cloud-cover) showed that the cloud-cover is concentrated along the coast with decreasing intensity inland. Moreover the cloud-free areas are haze-covered in band 4 and 5 imagery.

Furthermore, Landsat frames of tropical areas with less than 10% cloud-cover between August, 1972 and April, 1975 were significantly few (Howard, 1976). For the same period 30% of the tropical land surface and 55% of the tropical high forest areas were not covered (Fig. 1.1).

The annual rainfallin southern Nigeria varies between 2500mm. in the coastal areas and 1200mm. inland (Hopkins, 1974; Hall, 1977) with only three to four less rainy months. Aerial photography which is involved in over 80% of remote sensing activities of the developing countries, is virtually impossible during the rainy season. There is a double peak wet season during which rains are accompanied by line squalls which prevent aircraft flights. The short dry season which usually interrupts the rainy season occurs between July and August. In the absence of perennial clouds, this short dry season is the most suitable photographic season. There is another period of suitable photographic weather shortly after the rainy season when the ground is too damp for burning (which results in smoke haze) and when the atmosphere is free of dust (dust haze) and cloud-cover is reduced.

By carefully studying the occurrence of the short dry season or any other suitable photographic weather, aerial photography can be planned to coincide with it to reduce the effect of cloud-cover and haze. This is not possible with Landsat imaging system which operates on precisely fixed schedules.

The mean daily sunshine in Southern Nigeria is between three to six hours in the coastal areas where it may fall to two hours in the rainy or wet season. Aerial photography is restricted to mid-mornings when sunshine is minimal. The geostationary and sunsynchronous Landsat system images individual scenes at approximately 09.30 hours local time, thus individual scenes are uniformly illuminated. With aerial photography scene illumination may vary between strips of the same photograph or even between photographs of the same strip.

Active imaging in the centimetre wavelengths by SLAR is not limited by weather or scene illumination conditions. SLAR imagery can therefore be acquired round the clock in all weather except during heavy rainstorms. Operations are only limited by human conditions, namely:

- the endurance of the aircrew and the flight time limitations imposed on the aircrew by the civil aviation authorities.

In Southwestern Nigeria, the coastal region has a mean monthly relative humidity of not less than 95% at 06.00 hours local time though this may fall below 60% at 1200 hours during the driest months. These figures decrease inland from the coast. This high relative humidity accounts, in part for moisture haze which reduces the quality of imagery acquired by passive sensing in the micrometre wavelengths. The mean solar radiation is 1.5 to 1.9 joules/sq.cm. per day. Colour aerial photographs tend to fade on long exposure to brilliant sunshine and photographic chemicals rapidly decompose on brief exposures to bright light. The mean daily temperatures vary between 21°C and 31°C and the daily range of temperature increases inland from the coast particularly during severe harmattans. Colour films are damaged by exposure to high temperatures and, under humid conditions, they are liable to fungal attack. In view of these considerations, photographic laboratories have to be airconditioned to preserve these materials.

(b) Landuse and forest nature

Shifting cultivation is the main system of agriculture practised in many tropical forest areas. In the more densely populated and predominantly agricultural areas, shifting cultivation may be both intensive and extensive. Intricate landuse patterns have resulted from repeated shifting cultivation of extensive tracts of forests. For instance, about 180 000sq.km. in Southern Nigeria enjoy a climate suitable for the development of high forest yet little of this land supports forests today. Human activities over a considerable period of time have altered and even obliterated much of the natural vegetation. In Southwestern Nigeria, with a population density of about 100 persons per sq.km. shifting cultivation is very intensive. As a result most of the forest zone now consists of complex mosaics of irregular small blocks of farms and associated fallows, forest regrowths of various grades and secondary forests of different kinds. Such an irregular and intricate landuse pattern affects the interpretative value of the remote sensing imagery of these areas, particularly aerial photography. Also, the intensity of field sampling for ground information has to be increased for a reliable check.

Extensive clearing during cultivation exposes much of the ground surface which under dry conditions results in dust haze. In addition, burning results in smoke haze. Both dust and smoke haze reduce the interpretative value of imagery acquired by passive sensing in the micrometre wavelengths.

In undisturbed forests, the canopy is a continuum which obscures the ground. The interpretative value of large scale imagery of such forests is reduced by the lack of sufficient land marks to locate 'photosamples' on the ground. Even if photosamples can be located on the ground, the screening effect of the canopy also hinders the use of optical instruments for field measurements and observations of the individual trees.

(c) Topography and terrain conditions

With regard to the remote sensing of forested areas topography is viewed in two aspects -

- macrotopography i.e. the gross topography as represented by contours on maps or as viewed on stereomodels from aerial photographs.
- microtopography i.e. the terrain as it appears to any one moving about in the forest. This is usually concealed by contours on maps or by vegetation on aerial photographs.

In mountainous areas, macrotopography may hinder low-altitude flights for very large scale aerial photography or aerial reconnaissance by helicopters and field observations for ground information. Also, macrotopography often causes a wide scale variation on individual photographs of such areas. In flat or nearly flat terrain, macrotopography does not constitute an obstacle to imagery acquisition but the terrain conditions may hinder field work. The terrain may be of difficult access due to the occurrence of swamps, impenetrable forests and stony ground.

Southwestern Nigeria, like most other parts of Nigeria, is predominantly a lowland area whose altitude varies between 200m. and 900m. It is therefore unlikely that macrotopography would pose any serious problem to the acquisition of imagery and the collection of ground information in Southwestern Nigeria except for a few isolated cases of the occurrence of hilly areas. In the pilot survey for the indicative inventory of the tropical high forest in Nigeria, some field plots were either relocated or completely abandoned because they were inaccessible. The inaccessibility was largely due to the microtopography and the difficult terrain conditions rather than the macrotopography (Sutter, 1973).

The foregoing indicate the various ways in which environmental factors could affect remote sensing projects in the tropics. Climatic and weather conditions hinder the acquisition of the necessary imagery, while atmospheric conditions reduce the interpretative value of the acquired imagery. Ground conditions may also hinder field checking of the interpretation made.

CHAPTER 2

THE USE OF REMOTE SENSING FOR FOREST-TYPE RECOGNITION

2 Forest-type recognition

Timber is considered the most significant forest resource, particularly in the tropics. The initial stage in the collection of data on which to base the management of this resource is the separation of the forests containing the resource from other vegetation and landuse types.

The forests can be separated into general types according to the natural conditions under which they develop. The resulting classification implies the ecological status of the forests and it is therefore useful in choosing the most suitable silvicultural system for the management of the forests. Also, the forests can be separated into condition classes according to those characteristics which indicate their resource value or potential. For example, separation into stem-diameter or volume classes and classification by the incidence of timber-species would indicate the relative quantity of timber in the various parts of the forests. Separation of forests into condition classes is therefore useful in the assessment of the growing stock and its yield. Both 'natural' and 'condition' classes are usually obtained by field surveys which are slow and often expensive for extensive tropical forest areas.

This separation can be accomplished by remote sensing methods. The purpose of this review of literature is to assess the value and limitations of the use of remote sensing methods for forest-type recognition in the tropics. The extent to which the visual interpretation of aerial photographs, Landsat and SLAR images have been used to assist the recognition of forest types in the Southeast Asian, the Amazonian and the African tropical forest regions was reviewed in that order to indicate the successes obtained. References were occasionally made to computer-assisted interpretation for illustrations.

To avoid repetition the interpretation procedures, criteria and problems were not recounted in the review (Section 2-1) except where they are illustrative. However, these were summarised in Section 2-3 for drawing inferences and conclusions.

2-1 Review of Literature on forest-type recognition

In Indonesia, Hannibal (1952) separated on aerial photographs several types of natural vegetation and vegetation influenced by man. Of the former, he distinguished mangroves, marshland forests and dry forest. The dry forest was further separated into subtypes by wood density but the boundaries were indistinct. In the latter, old and young secondary forest, logged-over forests and forest plantations were well defined on the aerial photographs. He remarked the similarities among dry agricultural fields, wet rice fields and grass (or grazing) areas on the aerial photographs. Also, in Indonesia, Swellengrebel (1965) used 1:20 000 scale panchromatic aerial photographs for the reconnaissance and exploitation forest surveys and reported that mangroves, swamp forest and dryland forest of Sumatera (Sumatra) were easily recognisable on aerial photographs.

In Sabah (North Borneo) Francis and Wood (1955) distinguished on 1:30 000 and 1:25 000 scale aerial photographs, sixteen vegetation types twelve of which were natural forests. The interpretation was based primarily on topography and average size of photo-visible crowns. They classified the vegetation types by their commercial value and the extent of human interference into six general types:-

salt water swamp forest (three types)
transitional forests (two types)
drained inland forests (four types)
inland forests liable to flood (three types)

cultivation areas (two types)

cleared land (two types)

Though this classification did not correspond exactly with that of Brown (1953), which they adopted for the interpretation, they reported a close relationship between the two classifications. Nyyssonnen(1962) remarked that more forest-types could be delineated on better quality aerial photographs. Howroyd (1954) reported that it was generally simple to separate the various types of 'commercial' dryland forest, mangrove, nipah palm forest and secondary forests of Sabah on aerial photographs, except in partially logged-over forests. In Sarawak, Browne (1958) reported the ease of separation of mangroves, various types of dipterocarp and swamp forest, heath, riparian and mossy forests on small scale aerial photographs.

Taylor and Stewart (1958) interpreted the vegetation of Papua New Guinea on 1:40 000 scale aerial photographs. Paijmans (1970) interpreted the vegetation of central and western Papua New Guinea on 1:36 000 and 1:86.000 scale aerial photographs and obtained similar results. Five general forest-types were recognised by physiographic and edaphic conditions, and several subtypes by wood density. In the southwest of Papua New Guinea, dry evergreen-forest could not be distinguished from evergreen rainforest despite the differences in their floristic composition. It was also not possible to interpret local mosaics of forest-savanna-grassland on the aerial photographs. Similar work was done in the Fiji Islands (Miller, 1957). About 16 200sq.km. were interpreted on 1:40 000 and 1:16 000 scale aerial photographs using canopy density to ascertain the extent of logging and the amount of unworked forest.

Merrit and Ranatunga (1959) and de Rosayro (1959) interpreted the ecological types of Sinharaya rainforest in Sri Lanka (Ceylon) on

1:45 840 scale aerial photographs and obtained similar results. In the wetter parts of the rainforest, eight virgin forest-types, two secondary forest-types and four non-forest types were recognised using a rather complex interpretation procedure; de Rosayro, however adopted a simpler procedure for the interpretation of the drier areas. He separated medium, low and non-productive forests by their crown closure and crown diameter/stem height relations but he made no attempt to distinguish them by their species composition which is vital for commercial assessment.

On 1:48 000 scale aerial photographs of the lowland areas of the north province of Thailand, Loetsch (1957) recognised mixed deciduous, semi-evergreen dipterocarp forests, and permanent flood and non-forest areas. He indicated that teak-bearing and non teak-bearing deciduous forests could be distinguished from each other if photography was flown during the flowering period of teak. Also, the evergreen forests in one province could be subdivided into four strata on 1:15 000 scale aerial photographs by the incidence of young Dipterocarpus alatus trees. He reported that without any previous field experience of the area, forest areas in Thailand were satisfactorily interpreted on poor quality 1:20 000 scale aerial photographs. The interpretation was based mainly on photomensuration. Twelve categories were separated. These included two evergreen forest types, three semi-evergreen forest and woodland types, two shrub-savanna types and four marshland types with several subtypes.

Rollet (1959) and Wheeler (1959) described the forest inventories of Kampuchea (Cambodia). In the inventory of East Mekong, the forest types described in the different classification schemes adopted were easily recognised on aerial photographs. In Guatemala, Mason and Wood (1952) interpreted five forest types on 1:40 000 scale aerial photographs using the criteria of tone, texture, wood density and photomensuration of the dominant trees. Using the same scale of aerial photography, Harrison and Spurr (1955) also separated the same forest into seven general types by the incidence of Mahogany which is the main economic tree-species. Randall (1969) used 1:60 000 scale aerial photographs in conjunction with photomosaics for the interpretation of the forest types in the Dominican Republic. He separated low broadleaved forest, shrub forest, thorn bush, two density classes of pine forest, mangrove and swamp forests.

In Guyana, Swellengrebel (1959) described five different forest types on 1:30 000 scale aerial photographs, while in the neighbouring country of Surinam, Van-Dillenwijn (1957) described thirty different forest types on 1:40 000 scale aerial photographs. Van-Dillenwijn's interpretation key included a brief description of the characteristics and the distribution of each forest type accompanied by stereopairs of aerial and terrestrial photographs. Heinsdijk (1952) described on 1:40 000 scale aerial photographs, ten types of vegetation found in Surinam. Four of these were forest types by Surinamese standards (when majority of bigger trees are not below 10cm. diameter at breast height - DBH). He classified the vegetation by site conditions and floristic composition. He found that individual species were not recognisable on the aerial photographs but they could only be identified by inference, and to some extent, by extrapolation from areas of existing data.

Heinsdijk (1955) described a technical procedure for forest type mapping from aerial photographs. From his experience in the Amazonian region, Heinsdijk (1957, 1958) stressed the importance of ground information in photointerpretation. Francis (1957) and Cahusac (1957) reported their experience in the African region and discussed forest-type interpretation in general terms, Francis (1957) remarked that, in Africa, photomensuration alone was insufficient for the separation of forests into types, and concluded that forest type interpretation should be complemented by field sampling. According to him, forest areas which appear fairly homogeneous on aerial photographs, might contain several forest types which have no distinct boundaries, and which are only defined by their floristic composition. In Tanzania, Howard (1959) delineated on 1:30 000 scale aerial photographs, various grades of woodland by their tonal and textural differences. He recognised, among other vegetation types, riverine forests, permanent swamp and thicket/regeneration areas within the woodland.

The work of the Savanna Investigation Unit in Nigeria was reported by Howard (1964, 1967). Aerial photographs at the scale of 1:40 000 were used to collect information on the indigenous savanna vegetation within the forest reserves (managed forests) for the preparation of 'scientific' management plans. Several forest types were separated by combined photointerpretation and field transversing. In areas where rainfall is not the limiting factor in moulding the vegetation, specific species were found to be associated with specific sites. Consequently, the photointerpretation of these areas was easier than that of the other areas where rainfall is the critical factor in the development of the forests.

Kio (1971) discussed forestry applications of photointerpretation in Nigeria. He referred to the inventory of a group of high-forest reserves in the Cross River State and the landuse survey of Southwestern Nigeria. Both projects relied mainly on photointerpretation for type delineation, and photogrammetry for map compilation. He also reported his interpretation of Olokemeji Forest Reserve on 1:40 000 aerial photographs. He found that by photointerpretation alone, nine distinct vegetation types could be described within the forest reserve. He delineated five semideciduous forest types including high forest, hill forest, derived savanna, farm regrowth and forest plantations by their photophysiognomy and general photoappearance. However, he concluded that photointerpretation should be checked by field sampling, since similar photocommunities might be different in their floristic composition, though such differences might not necessarily imply changes in ecological status.

Cooper (1960) prepared a list of Nigerian forest reserves which were interpreted on aerial photographs for management purposes. The interpretation included stock-mapping, forest type delineation, and soil surveys. Oyelese (1968) indicated that the generalised landuse pattern and the broad forest types in the complex forest zone of Ibadan Division in Southwestern Nigeria could be interpreted on aerial photographs with some degree of accuracy provided that there is adequate ground information.

In parts of Western Cameroon and Uganda, Langdale-Brown (1968, 1968a) interpreted the major physiognomic types of vegetation on 1:40 000 and 1:30 000 scale aerial photographs respectively. In the case of Western Cameroon, information from literature and established maps was used to control the interpretation, while in the case of Uganda photointerpretation was done in conjunction with field transversing. In both studies the importance of ground information is implied.

Lanly (1972) discussed the value of photointerpretation for forest surveys in francophone countries of tropical Africa. He remarked that, in most cases, the forest types easily identifiable on aerial photographs were pure stands of certain species amidst heterogeneous populations. He cited examples of certain Legumes, such as Microlobium (Gilbertiodendron) dewevrei especially in Congo, Zaire and southeastern Cameroon, Monopetalanthus species and Musanga cecropioides which colonise cleared forest areas. He also remarked that edaphic forest types, such as mangrove and swamp forest, were easily recognisable on aerial photographs. Also, on aerial photographs, the transition zone between evergreen and semideciduous forests was easily detected but without any distinct boundaries. Howard (1970) stated that, at the scales of 1:80 000 to 1:20 000, photocommunities may conform to plant formations and at the scales of 1:20 000 to 1:15 000 they may conform to subformations and associations while at the scale of 1:5000 or less they may conform to smaller assemblages of vegetation.

Paijmans (1970) used 1:36 000 and 1:86 000 scale aerial photographs separately to classify the vegetation of Papua New Guinea and obtained similar results. Miller (1957) remarked that vegetation physiognomy was readily recognised on medium scale aerial photographs. This supports the results obtained by Paijmans. There has been little emphasis on the value of various film/filter combinations for forest type separation. According to Howard and Lanly (1975), a plant formation or subformation is not a floristic unit but a structural unit with often distinctive spectral radiance/albedo which results in characteristic photographic relative grey scale value by which it can be identified. They remarked the established value of panchromatic (black/white) films with yellow (minus blue filter) for the interpretation of tropical forests. Garver (1953) also remarked that black/white film has the most popular tonal range familiar to the perception of the human eye because it provides higher resolution, better contrast and definition than other film types, especially when yellow filter is used. He recommended the use of glossy paper for better image reproduction. Francis (1957) found that colour films usually give fairly poor tonal contrast in the important green band. Haller and Bega (1973) preferred colour infrared film. This film type has been successfully used for forest surveys in francophone countries of tropical Africa. (Howard, 1976; Lanly, 1972). Rhody (1965) found that diapositives are of greater value than any other photographic product in the interpretation of the more subtle tonal contrasts which, indeed, express forest composition.

Using Landsat imagery of the Central Afar region of Ethiopia, Parry (1974) found that only riverine forest, desert, very open areas of Cadaba rotundifolia and Acacia seyal bushes, and combined areas of irrigated crops and swamps, could be delineated with confidence on the imagery. Detailed ground information was required for the delineation of the other vegetated areas. He remarked that no unique tonal signatures for vegetation types were identified, and concluded that Landsat imagery was a valuable addition to aerial photography for natural resource evaluation. He recommended the use of Landsat colour composite generated from bands 4, 5 and 7 because of its superiority over the individual spectral images. He also remarked that a combined use of the individual spectral images could also result in a satisfactory separation of the vegetation types.

Lanly (1976) reported two Landsat studies carried out in Nigeria and Colombia. The studies aimed to assess the value of Landsat imagery for classifying and mapping landuse and vegetation in tropical areas. In both studies computer-assisted interpretation was employed because the poor quality of the individual spectral images and colour composites generated from them were unsatisfactory for visual interpretation. The computer-assisted interpretation for the Columbian studies was supervised, while that for Nigeria was unsupervised due to the lack of precisely located training sets. The Macerena region was chosen for the Colombian studies, while a group of adjacent forest reserves within the forest-savanna mosaic zone was interpreted in Nigeria. In the Nigerian studies, the separation of forest, i.e. degraded forest, secondary growth and derived savanna, was satisfactory but the separation of the various grades of vegetation between forest and savanna was less successful. This was due to the irregular shapes and the intermingling of the various vegetation types.

More satisfactory results were obtained in the Colombian studies. Lanly concluded that a lot of research was still necessary before a good correlation between computer classification and ground information could be obtained. He therefore suggested that all possibilities offered by optical methods and visual interpretation should be used to the maximum in order to take the advantages of the broad synoptic view, and the repetitive and the multispectral nature of Landsat images.

In Central Djawa (Java) in Indonesia, Meijerink and Donker (1978) conducted a computer-assisted landuse interpretation of Landsat information. They remarked that, in certain cases, computer-assisted interpretation could give inadequate or misleading results. They therefore suggested the maximum use of visual interpretation techniques. They concluded that the landuse categories could not be separated spectrally, even after the transformation of the Landsat data sets. Though this investigation was yet to be completed, they hoped to obtain maximum landuse information by component analysis in which the spectral data sets would be compressed to two components.

SLAR imagery has been widely used for vegetation surveys, mainly in regions where climatic and weather conditions do not favour aerial photography, particularly in the Amazonian region. The first example of tropical vegetation mapping from SLAR is probably that of the Darian Province in Southeast Panama in 1962, under the Ramp (RAdar Mapping of Panama) project. The project area of about 17,000sq.km. was imaged in the Ka band by SLAR (Viksne et.al., 1970; Veloso et.al., 1973). Viksne and others (1970) stated that Ka band permitted the evaluation of various vegetation types because vegetation is not suppressed by the Ka band SLAR imaging. Evergreen forest, semideciduous forests low and tall tree swamps, palm forests, mangroves, logged-over forest, and built-up areas, were readily separated on the imagery by the characteristics of their radar return signals. Lewis and McDonald (1972) also identified, in addition, three tidal vegetation types.

Sicco-Smith (1974) stated that only very broad physiographic regions could be delineated on the 1:220 000 scale SLAR imagery of Columbia principally by physiographic differences. He separated coastal zone under maritime influence; alluvial plains and low terraces subject to innundation; terraces intersected by low hills; high hills and high plains. By further interpretation on 1:40 000 scale aerial photographs in conjunction with aerial reconnaissance, and his local knowledge of the area, he described two to five vegetation types within each region. In all, he identified seventeen vegetation types.

The ASP (1975a) also reported that the 1:250 000 Ka band SLAR imagery of Nicaragua gave similar results but Pinus caribeae stands, which tend to be darker on the imagery, were separated into three distinct density classes. Martin-Kaye (1974) also separated on SLAR imagery of Nicaragua, 28 vegetation types and landuse categories. These are various combinations and mixtures of the main types and categories he separated - hard wood mountain and hill forests; riparian hard wood forest; upland, mountain, pine and swamp savannas; mangrove swamps, grassland, plantations and cultivated areas.

In Brazil over 4 200 000sq.km. of the Amazon basin were imaged with synthetic aperture SLAR at the scale of 1:400 000 under the Radam (RADar AMazon) multidisciplinary project. The swath width was 37km. with 20 - 50% lateral overlap (FAO, 1974). de Azevedo (1971) reported that useful small scale thematic maps of acceptable planimetric accuracy were compiled from the image interpretation and ground information to select priority areas for more detailed remote sensing and field surveys. SLAR imagery had also been used for forest surveys in Papua New Guinea, Indonesia and Equador (FAO, 1974; ASP, 1975a).

Larin-Alabi (1978) referred to the on-going Mirad Project for the survey of the vegetation of Nigeria. The entire country was imaged in the X band using real aperture SLAR at the scale of 1:250 000. The swath width was 25km. with 60% lateral overlap. Allen (personal communication, July, 1977) remarked that the results of this nation-wide survey exceeded what was ever thought possible, adding that it was the first SLAR survey that covered so many ecological zones.

From available reports (HTS, 1977, 1978), the imagery of Southwestern Nigeria could be used for the separation of only the broad vegetation types. In areas of fairly even terrain, mangrove, various grades of swamp forest, disturbed and undisturbed mature forest (high forest) oil palm forest, rubber forest and farmlands, were easily distinguished. In areas with rough topography vegetation types could not be distinguished without intensive field work. One significant fact which emanated from the deliberations of the International Geographic Union Workshop recently held in Nigeria, was that the SLAR imagery of Nigeria was more useful for soil and landform mapping in forested areas than for forest mapping (F. A. Akinsanmi, personal communication, August, 1978). This is due to stronger suppression of vegetation to favour the expression of topography in the X band than in the Ka band.

From their experience in the Amazon basin, Disperati and Keech (1978) concluded that the combined use of aerial photography, Landsat and SLAR imagery increased the confidence and accuracy of forest surveys. They remarked that in several cases, patterns detected on aerial photographs were also recognised on Landsat and SLAR imagery, but the interpretation of these patterns was less satisfactory at the scale of the SLAR imagery.

2-2 Inferences and conclusions

The foregoing review of literature shows that greater success has been achieved in the Southeast Asian region with aerial photography while the successes in the Amazonian region are virtually limited to SLAR. The former situation is due mainly to the frequent occurrence of 'good photographic weather' while the latter situation can be attributed to the persistent occurrence of unfavourable weather conditions for photography. SLAR can operate under almost all weather conditions. Evidence from literature was not sufficient to give a clear picture of the situation in the African region. None-the-less, it indicates that the relatively little success in this region may be due partly to 'bad photographic weather'. For the three main regions good quality Landsat images are rare and scarce. Consequently the repetitive imaging of Landsat has not been of any real value in tropical forest surveys, Cloud-cover, haze and dispersion are the most important weather factors which hinder aerial photography and Landsat imaging. Infrared photography has been found useful in areas where photography is possible but for haze and dispersion. However, a photographic method which can reduce or eliminate the effect of cloud-cover has not been developed. The inclusion of infrared bands in Landsat system has been found useful in providing haze free images but the problem of cloud-cover still remains.

In spite of the limitations by weather, aerial photography has been used more widely for tropical forest surveys. This can be explained by its superior resolution which permits the recognition of objects and individual trees in particular not only by their photographic tone, texture and pattern, but also by their shapes. Consequently, forest types have been recognised by their photophysiognomy. The units of interpretation for extensive management are forest types while the units of interpretation for intensive management are individual trees. As most tropical forests are usually under extensive management, only a general type of forest information is required. Because of this, a wide range of photographic scales and various film/filter combinations are acceptable for the interpretation of tropical forests without any restriction.

Somewhat surprisingly therefore, small scale aerial photography is not as restrictive as might be expected. It could even be more useful than the larger scale ones for providing general forest information as small scale images tend to bring out, in a broad view, the more subtle similarities between the different variants of a particular forest type. This broad view can be extended by using photomosaics. This is a primary argument for the use of Landsat and SLAR imagery. However, their inferior resolution reduces their value for the interpretation of tropical forest. Nevertheless, they have been used to a certain extent in providing additional information to that obtained by photointerpretation. Small scale Landsat images have been used to group the exclusive 'photocommunities' i.e. forest types interpreted on aerial photographs into more inclusive broad types. Also, topographic emphasis by SLAR has been used to separate forests into physiographic classes which are less noticeable on either aerial photographs or Landsat images. For regions where aerial photography is not feasible SLAR has been used to a considerable extent for the interpretation of forest types.

The successes obtained with each remote sensing system in each forest region corresponds to the extent of the use of the system as well as the nature of the forests in the region. Generally, there is a wide range of variation resulting from varied mixtures of the very large number of species whose individual trees differ in size, shape and form. This variation has resulted into innumerable forest types which differ little from each other. In addition these types intermingle without distinct boundaries and with frequent occurrence of transition zones between types. What obtains in an undisturbed forest area is a continuum of indistinguishable forest types. There is therefore a tendency to underestimate the number of existing forest types. Large scale imagery and aerial photography in particular have been used to overcome this problem.

The complex structure and composition of tropical forests are complicated further by human interference. Shifting cultivation, destructive logging, grazing and burning have resulted in frequent occurrence of complex vegetation mosaics. In the disturbed forests there is therefore the tendency to overestimate the number of existing forest types. In such circumstances small scale imagery have been used to overcome this difficulty. The African region has a wider range of forest variation and a more complicated forest structure and composition than the other two regions. Human interference is also greater in this region. This accounts partly for the comparatively little work that have been done in the African region. Most of the investigations on tropical forests by remote sensing methods have been carried out in Southeast Asia using mainly aerial photography and in the Amazonian region using mainly SLAR because of weather conditions. The little use of remote sensing methods for forest surveys in the African region is due to the limitations of weather on the acquisition of the necessary images as well as the limitations of the complex structure and composition of the forests themselves on their interpretation.

With the wide range of variation within the tropical forests and the little differences between the forest types it has been difficult to establish clearly defining interpretation criteria that can be used in a logical sequence. This shortcoming usually reduces the confidence of the interpretation. The interpretation of tropical forest types on remote sensing images has been based on tonal and textural differences i.e. 'visual spectral signatures'. In addition, photophysiognomy has been used in photointerpretation generally and to some extent in SLAR interpretation of even sloping or flat forest areas. Because of its superior resolution, aerial photography has been used further to separate forest types by the incidence of emergent trees inrrespective of their species and by their physiognomic height differences.

The large number of species and the low incidence of individual species per unit area have not permitted forest type separation by floristic composition in the strongly species-mixed forests e.g. West African forests. In certain cases some forests have been successfully separated by the incidence of the most abundant species e.g. dipterocarp forests in Southeast Asian region. Generally, the occurrence of pure or nearly pure stands of some individual species and mixed stands of very few species is rare and scarce in the tropics.

Such stands occur under extreme ecological conditions. The ecological specialisation of species has been helpful for separating mangroves and palm forest, for example, from other forest types. Furthermore, species are artificially concentrated in plantations which also constitute forest types by themselves. Plantations have been separated by their linear boundaries from natural forest types which normally have sinuous boundaries.

The use of 'photomensuration' for forest type separation is limited to photointerpretation as individual trees are not resolved by Landsat and SLAR. The uneven-age of natural forests has resulted in mixtures of crown sizes, and/or tree heights which restrict the use of photomensuration data for type-separation. Nevertheless, forest types have been separated by their mixture of crown sizes. The canopy which is the only source of direct information of tropical forests on aerial aerial photographs is more often closed than not and so prevents parallax heighting of trees. Furthermore, percentage crown closure has no real value for separating closed forests into types. However, some success has been obtained by estimating percentage crown closure for the emergents where their incidence is high or for the dominant and the codominant species where they can be identified on aerial photographs.

A salient factor in the interpretation of the remote sensing imagery of tropical forests is the lack of uniformity in the classification schemes to which the various interpretations are structurally linked. There is a wide variation in the terminology used for the nomenclature and description of the forests types. As a result, a basis for the comparison of either these schemes or the interpretations which are structurally linked to them, is difficult to establish. This can be explained by the complex nature of the forests themselves. Often, the existing schemes are either too generalised to be satisfactorily applied to specific areas, or too localised (regionalised) to be suitable for other areas. Moreover, they are usually inadequate for forestry purposes, even if they are satisfactory for other disciplines.

Several attempts have been made to evolve standardised classification schemes for both regional and universal application, but none of them could effectively incorporate the wide range of vegetation diversity found within the tropics. For instance, both the Yangambi Classification Scheme (CCTA/CSA, 1956) and the Unesco Classification Scheme (Keay, 1959), were attempts to standardise the classification of African vegetation on a phytogeographical basis for multidisciplinary use. Also, the Unesco International Classification (UNESCO, 1973) is a similar attempt for world vegetation.

As a result of this classification problem, 'photocommunities' seldom conform with those described in the classification schemes adopted for the interpretation. This could be explained by the differences between the classification and interpretation criteria. To avoid this obstacle, Lanly (1973) suggested that efforts should be made, as far as possible, to fit condition classifications obtained by interpretation to the existing and well-accepted classification schemes, so as to allow for comparison of the results obtained by different interpretations. As this is seldom practicable, most interpreters frequently disregard the existing classifications and develop their own classification. If the classification developed is deemed unsatisfactory, Lanly suggested that it should be refined and condensed in order that the classes (or groups of classes) of the new classification are compatible with the classes (or groups of classes) of the existing ones.

At present, it is therefore difficult to obtain a conclusive picture of the interpretation of tropical forests on remote sensing imagery from the experience in the three main regions because the material on which opinions have been advanced varies markedly with respect to the imagery types, survey objectives, the interpretation techniques and the nature of the forests. The experience of individual international organisations such as the French National Geographical Institute (IGN), the FAO/UNDP and the UNESCO might be expected to cast more light on this. They have done good quality work in most tropical forest areas using standardised and uniform survey procedures, but their findings have not differed markedly from those of individual workers whose procedures vary widely and whose areas of coverage are limited to their individual localities. With more experience in the use of remote sensing methods for tropical forest survey, most of the obstacles encountered may be overcome gradually, more so when the forest management trend in the tropics is presently being shifted from natural system of regeneration to plantation forestry.

In view of the foregoing inferences and conclusions it is my opinion that the use of remote sensing methods supplemented by field checking is superior to pure field methods for the recognition of forest types in the tropics. For a typical tropical forest area, the amount of forest information available on aerial photographs, Landsat and SLAR images increases in that order. Consequently aerial photographs would be more useful for separating forest types for intensive management. For rapid reconnaissance surveys of extensive areas, Landsat images can provide sufficient information. SLAR images can be used for separating forest types in areas which have resisted photographic efforts provided the terrain is even sloping or flat.

The relative costs of their acquisition and interpretation for forestry purposes are discussed in Chapter 6 and 11. The extent to which they can provide the required information on forest types is investigated further in Chapters 8 - 10.

CHAPTER 3

THE USE OF REMOTE SENSING FOR TREE-SPECIES IDENTIFICATION

3 Tree-species identification

Trees constitute the ultimate units of forest management. With regard to a particular forest resource, the qualitative and quantitative assessment of the trees are used, in combination with other factors such as site potential and economic evaluation, for the prescription of the most suitable management system and for the subsequent implementation of the management system chosen. Species identification is a fundamental requirement for such assessments for timber resource management. The assessment of the volume of the growing stock and its yield without species identification creates management problems because the growth rates of individual tree species vary according to the site and/or plant community in which they are found. Also, the economic value of the forests varies according to the utilisation potential of their constituent species. It is therefore essential to know the species composition of the management units. In tropical forest surveys species identification is usually accomplished in the field.

The purpose of this review of literature is to assess the value and limitations of remote sensing methods for the identification of tropical tree species. The approach to this review is similar to that of Chapter 2. Section 3-1 reviews the extent of the use of the three remote sensing systems in the three main tropical forest regions. It also reviews the successes obtained and the problems encountered. Section 3-2 summarises the inference and conclusions from the review of literature.

3-1 Review of literature on species identification

The Wallaba forest in Guyana is characterised by three main species - _Mora gonggripii_ (morakukea), _Mora excelsa_ (mora) and _Ocotea_ rodiaei (greenheart) - which have a gregarious growing habit. Swellengrebel (1959) identified these species on 1:10 000 scale aerial photographs by their gregarious nature. He found that they could be identified by their general photoappearance as a group, rather than by individual tree features within the group. The same is true for Shorea curtisii (alan) and Dryobalanops aromatica (camphor) which characterise the hill forests in Malaysia. They are recognised by their cauliflower crown form (Loetsch & Haller, 1973), but they are easily confused with the other species in the same genera. Shorea curtisii, which grows on ridges, was identified by its white crowns on aerial photographs. Dryobalanops aromatica was identified by its feathery crown surface on 1:40 000 scale aerial photographs of Sumateran forests (Nyyssonen, 1962; Hannibal, 1952).

Merrit and Ranatunga (1959) similarly identified Dipterocarpus zeylanicus (hora), Dipterocarpus hispidus (hora), and Doona congestiflora (thiniya) which characterise the Sinharajah forest in Sri Lanka. Dacrydium elatum, Podocarpus nerifolius, and Casuarina equisetifolia, the gregarious species characterising the mixed tropical forests in Sarawak, were identified on 1:20 000 scale and smaller scale aerial photographs when they occur in groups, or as individual trees at larger photoscales (Loetsch & Haller, 1973).

Agathis and Auricaria were identified on aerial photographs at various scales when they occur together in stands or as individuals. In Brazil Auricaria stands were delineated at 1:70 000 photoscale. In West Irian Jaya, stands in which Agathis labillardieri and Auricaria cunninghamii were predominant were delineated at 1:20 000 photoscale (Swellengrebel, 1959). At the scales of 1:15 000 - 1:10 000 Auricaria cunninghamii was recognised on high elevations in West Irian Jaya because of its white photoappearance (probably due to encrustation with lichens), and its pencil shaped crown (Boon, 1956). Loetsch and Haller (1973) similarly identified Pinus merkusii and Pinus khasya on 1:20 000 scale aerial photographs of Thailand by their gregarious growing habit.

Some species simply occur in groups within the forest. On aerial photographs their crowns form conspicuous patches within the canopy. Terminalia superba and Triplochiton scleroxylon are typical examples which have been identified by this characteristic in some francophone countries of tropical Africa (Lanly, 1972). Musanga cecropioides (umbrella tree), which is characteristic of regenerating forest, was similarly identified in Ghana (Francis, 1957) and the Central African Empire (Howard & Lanly, 1975).

From his experience of the Malili forest in Sulawesi, Hannibal (1952) concluded that under Indonesian conditions, species occurring in groups which represent a fair proportion of the emergents could be identified only in exceptional cases. Heinsdijk (1957, 1958) concluded from his Malili Sulawesi investigations that at the scale of 1:40 000, species identification on aerial photographs is highly speculative under Indonesian conditions. In the Amazonian region, Heinsdijk (1957, 1958) found that by intensive photostudy and field work, it was possible in some cases to identify with certainty, a number of tree species. He reported that species identification was fairly easy when a single species dominated the canopy, or formed conspicuous patches within the canopy, as in the case of Goupia globra and Hymenolobium petraeum. He added that some species could be easily identified when a forest type comprises a few, say two or three, species. For example, the coastal swamp forest in Surinam comprises mainly Virola surinamensis (baboen) and Symphonia globulifera (matakki). Baboen was identified on 1:10 000 scale aerial photographs by its light tone and roundish crowns (Stellingwerf, 1966).

Also, a wide range of photographic scales has been used to identify some gregarious species forming pure, or nearly pure, stands. Loetsch and Haller (1973) identified *Dipterocarpus* *utriculus*, the main component of the high open dry dipterocarp forests in Thailand and Kampuchaea, by its light tone on aerial photographs. Lanly (1972) reported that certain leguminous tree species could also be identified on aerial photographs because they occur in natural populations as pure, or nearly pure, stands. Such legumes are *Macrolobium* (*Gilbertiodendron*) *dewevrei* in Congo, Zaire and Southeastern Cameroon, and *Monopetalanthus* *species* in several places.

Under extreme ecological limitations the gregarious nature of some species or groups of related species are often linked with edaphic conditions. Consequently, these species are more or less restricted to specific sites. For instance, on 1:20 000 scale aerial photographs of Sabah, Francis and Wood (1955) identified ten mangrove species and a few marshland species by their occurrence on specific sites. The interpretation was done in conjunction with intensive field work. The species identified included *Rhizophora* (red mangrove), *Nipa* *fructicans* (nipa palm) in the mangrove areas, and *Metroxylon* *sagu* (sago palm or sage) in the marshland areas. Francis (1960) identified *Isoberlinia* *doka*, which grows on lateritic hill caps in Sudan, by its fungi-like patterns on aerial photographs. Howard and Lanly (1975) reported the phototyping of *Campnosperma* *panamensis* littoral stands, and *Guibortia* *demeusei*, *Hura* *crepitans*, *Mora* *excelsa*, *Priora* *copaifera* riparian forests.

Some individual tree species, irrespective of their gregarious nature or edaphic condition have striking characteristics by which they could be identified on aerial photographs. In Thailand *Dipterocarpus* alatus was identified by its characteristic large crown and the brightly shining leaves of its emerging bright-toned crowns. Ceiba pentandra (bottle tree or silk cotton tree) was identified in Ghana by its characteristic crown form on aerial photographs (Francis, 1957). Under Ugandan conditions, Cahusac (1957) stated that it was possible to identify about six tree species by their crown habit and tone on small scale aerial photographs. In Ivory Coast about ten species were similarly identified, but with frequent field checking (Bergeroo-Campagne, 1955), Lanly (1972) also reported that certain plant families genera or species with conspicuously large crowns have been identified on aerial photographs. He referred to the Sapotaceae family in which Baillonella toxisperma and Austranella congolensis were identified on aerial photographs of many francophone countries in tropical Africa. On aerial photographs palms were generally identified as individual trees by their conspicuous crown habit. For example, the stellate crown of Elaeis guineense cannot be mistaken for another species. In Nigeria, Raphia and Borassus palms have also been identified by the photoappearance of their crowns in addition to their gregarious growing habit (Cooper, 1960; Charter, 1969).

Many tropical tree species are also known to exhibit certain characteristic phenology and/or colouration during flushing or flowering. These species could be identified by these characteristics on aerial photographs, but such phenology and colouration rarely last longer than a few weeks. It follows that the acquisition of aerial photographs and the collection of ground information would have to be accomplished within this brief period and this would present serious organizational problems. Francis (1957) referred to the identification of mahogany species, particularly Khaya ivorensis, by the coppery colour of the flush on normal colour and colour infrared aerial photographs. In Ghana, this flush lasts for only two weeks. Loetsch (1957) also reported that Tectona grandis (teak) was better identified on aerial photographs acquired during its brief flowering period of one month. However, teak could be identified with certainty on 1:15 000 scale aerial photographs by its cottony texture.

The ASP (1975a) reported two investigations on the value of colour and infrared photography for the identification of tropical tree species. In the first investigation 1:10 000 - 1:5000 scale, normal colour and colour infrared aerial photographs were used for the identification of commercial tree species in Gabon and Cameroon. The identification of Cynometra hankei, Erythrophleum invorense, Lophira alata (azobe), and Pycnanthus angolensis and, others proved disappointing because of the polymorphic structure of their crowns and the phenological variation within individual species hampered their identification. The intra-species phenological variation in azobe covered a considerable period, In the second investigation 1:10 000 - 1:5000 scale, panchromatic, normal colour, black/white and colour infrared aerial photographs were similarly used in Surinam. As in the first investigation, the phenological variations between the individuals of a species hampered recognition. Only two species, which are of no commercial value, were identified on the colour and colour infrared aerial photographs. In both cases colour and texture were important features for recognition.

Further to the Gabon-Cameroon investigations, Howard and Lanly (1975) reported an error (without biases) of 25% in the identification of individual Terminalia superba (limba) trees. Lanly (1972) also reported an error of about 27% in the identification of Aukoumea klaineana (okoumes) and Lophira alata (azobe). He remarked that the identification of okoumes was more promising. But contrary to the results of the Surinam investigation, de Milde and Sayn-Wittgenstein (1973) reported that they obtained encouraging results by using only panchromatic and normal colour aerial photographs of Surinam for species identification. In Tanzania, Howard (1959) reported that only Acacia tanganyikensis and Brachystegia tamarindus var microphylla could be identified on 1:50 000 and 1:10 000 scale aerial photographs taken during the dry season to identify timber-size trees.

Using good quality aerial photographs at various scales to determine the incidence of the economic tree species in Malili forest in Sulawesi, Paijmans (1951) could identify only Anthocephalus microphyllus in the lowland forest, and Campnospermum species in the hill forest, out of about 100 species in question. He concluded that the identification of tropical tree species on aerial photographs was difficult and highly speculative. He observed that it was difficult to produce a set of objective photocriteria to identify correctly a sufficiently high percentage of the numerous species found in tropical forests. He indicated that greater success could be obtained with spectrophotometry, particularly when only a few species are to be identified. He also indicated that photomethods specially designed for forestry purposes could yield better results in the identification of tropical tree species. Howard and Lanly (1975) reported that species could be identified if the spectral radiance/albedo of the plant community characterised by these species is known.

Several workers (Hannibal, 1952; Swellengrebel, 1959; Nyyssonen, 1962; Miller, 1963) have reported the difficulty in separating tropical tree species spectrally. They reported that broadleaved species (the main component of tropical forests) were more difficult to separate from one another spectrally, or otherwise, than the conifers (the main component of temperate forests). This is because spectrophotometric values vary more widely within the conifers than within the broadleaved species. Further the spectral difference usually observed between broadleaved species and conifers in the temperate region is rarely noticeable in the tropics (Miller, 1963). Miller reported a typical case in the pine savanna in Hunduras. In this case, a pine species associated with broadleaved species could be separated from its associates by qualitative photointerpretation but not by quantitative spectral analysis.

Miller (1963) and Howard (1976) emphasized that the identification of tropical forest species have to rely on colour, since morphological differences alone are not sufficient for species-discrimination, more so when several tropical species show distinctive colour differences at different times, particularly during flushing and flowering. In the opinion of Hindley and Smith (1957), photographic methods other than the conventional panchromatic photography are not likely to provide any significant advantage for the identification of tropical tree species. Francis (1957) found that normal colour aerial photography generally gave poor tonal differences in the important green band and that infrared aerial photography had no significant advantage over panchromatic aerial photography. His findings supported the opinion expressed by Hindley and Smith. Francis also found that panchromatic film with yellow (minus blue) filter provided the greatest overall tonal rendering for most tropical forests, and savanna in particular, while panchromatic film with red filter resulted in poor tonal quality. Normal infrared photography (infrared film with deep red filter) showed more contrast than modified infrared photography (infrared film with yellow filter). This higher contrast accentuates tonal differences within the vegetation, thereby improving species identification. For example, on colour infrared aerial photographs of a forest region in

Ghana, Francis identified a mahogany species by the copper colour of its first flush.

In view of the various obstacles which hinder the qualitative identification of tropical tree species on aerial photographs, further attempts have been made to identify them by quantitative methods. The two most commonly used quantitative methods are microdensitometry and spectrophotometry, neither of which is reliable for establishing tonal (spectral) signatures for tropical tree species. In the laboratory, the wavelength interval normally used for discrimination of spectral signatures is 0.001um. The spectral resolution of photographic systems is restricted by filters to 0.1um. The analysis of a spectral range covering 0.4um would give only four levels (0.4um/0.1um) of discrimination with aerial photography instead of the 400 levels (0.4um/0.001um) which are normally possible in the laboratory. Discrimination of tropical tree species which normally have a very close range of spectral reflectance values becomes increasingly difficult as these values become closer. (The resulting spectral signatures of these species are not often precise for confident discrimination).

3-2 Inferences and conclusions

As a generalisation, species identification by any technique is a far more difficult problem in the tropics than in the temperate region. In the temperate region, forest surveys would rarely involve more than twenty species in one area and more often than not, only about ten species would be all that must be identified. In tropical forests, several hundreds of species are encountered within a few kilometres and thousands of species may occur over a large geographic region. Tropical tree species are not only large in number, but also strongly mixed to the extent that the incidence of individual species is very low for a given forested area. Consequently, each forest type contains varied mixtures of species. Species identification is easily accomplished when a relatively few species with very high incidence are involved. As this condition is seldom fulfilled in most tropical forest areas, the existence of pure stands of a single species and mixed stands of very few species is few and scarce. Such stands exist under extreme ecological conditions as in the case of mangroves. In certain cases, trees of a single species or a group of species with gregarious growing habits occur in patches of substantial sizes within the natural forests. This gregarious growing habit of some species has been employed in the artificial concentration of these species into plantations.

In view of these considerations, identification of tropical tree-species has followed two different approaches. In the first approach which is limited to photointerpretation, species identification relies on the photoappearance of the individual trees in addition to their photographic characteristics of tone and texture (inductive identification). The second approach which extends further to Landsat and SLAR interpretation relies on the photographic characteristics of pure stands of a single species or mixed stands of a very few species. With this approach, species identification is equivalent to forest type recognition in which species are identified by inference (deductive identification). These two approaches which were not distinguished in the review of literature are considered separately in the following inferences and conclusions.

The relative successes obtained in tree-species identification by remote sensing methods in the three main tropical forest regions are similar to those obtained in forest type recognition. The same reasons which were advanced for the relative successes in forest-type recognition also explain the relative successes in tree-species identification. The striking similarities in the physical appearance and the morphological characteristics of several tropical species have not permitted the use of these characteristics to identify these species with confidence, not even in the field. In most cases, the vegetative and reproductive organs which could not be resolved on remote sensing images are important for the field identification of these species. In extreme cases species identification is completed in the laboratory by microscopic examination of the'fine structures' of these organs.

The little success obtained in the identification of tropical tree-species on remote sensing images is due partly to the recognisable crown form and texture as well as tonal appearance (inductive identification) and partly to the gregarious growing habit (deductive identification) of these species. The canopy is the only source of direct information of tropical forests on aerial photographs. Successful discrimination of individual species by the photoappearance of their crowns within the canopy has been hindered by several factors. It is only under exceptional circumstances that individual tree-species have been recognised at the economic scales (mainly 1:20 000 - 1:40 000) at which the aerial photographs were available not even at 1:15 000 - 1:10 000 photoscales. Most of the aerial photographs used for these forestry investigations were usually flown for purposes other than forestry, and they were frequently not at scales suitable for species identification under most tropical conditions. With larger photoscales the recognition of individual species could be improved.

Several workers including Paijmans (1951), Heinsdijk (1957,1958), Paijmans (1959), Nyyssonen (1962), Loetsch and Haller (1973), remarked the lack of distinctive crown features for the recognition of tropical tree-species on aerial photographs. However, some species have been successfully identified by their distinctive crown features. Quite often, the commonly occurring species with such striking crown characteristics have no utilisation potential but they usually characterise forests with high commercial value. For instance, Musanga cecropioides which is a gregarious species without any utilisation potential characterises the productive high forests in West Africa. It has been identified on aerial photographs by its distinctive umbrella shaped crowns. As a result of the very large number of species to be identified, it is not unusual to limit identification to the commercially important and the potentially utilisable species. It would be realistic in such a situation to include 'the indicator species' of the commercially important forest types in the various identification schemes.

It has been observed that, even when species have distinctive crown characteristics, the individual of the same species shows tonal differences in the photoappearance of their crowns within the canopy, as a result of their phenological and/or height differences. On the other hand, the individuals of different species, irrespective of their phenology and heights shows tonal similarities in the photoappearance of their crowns within the canopy (Swellengrebel, 1959). This has hindered the photo-identification of such species. It has also been observed that some species show variable phenology both in space and time. This phenological variation is usually expressed by distinctive colouration. For instance, the copper brown colour of the early flush of mahogany has aided its identification on colour aerial photography, and the white cottony appearance of Tectona grandis (teak) during flowering has aided its identification on panchromatic aerial photography. However, the photo-identification of some species by the distinctive phenology they exhibit during flushing and/or flowering has not been reliable for two main reasons. In the first place, such phenology may not be consistent within certain species because the individual trees may flush and flower at different seasons as a result of age and/or site differences. (Paijmans, 1951; Francis, 1957). Secondly, such distinctive phenology usually persists for only a very brief period, which may not coincide with suitable photographic season. Assuming that distinctive phenology is consistent, aerial photography and field checking of photointerpretation, should be accomplished within the brief period of occurrence of this phenology. It is only under this condition that the species can be identified with confidence. In some cases, it may be necessary to postpone field checking until the following season if the survey area is extensive.

Tropical tree-species usually have polymorphic crowns. A single species may have different crown shapes and forms depending among other factors on their genetic constitution and the environmental variables affecting their growths. Consequently the discrimination of individual species within the canopy by the photoappearance of their crowns is seldom reliable because of the polymorphic structure of these crowns. None-the-less, it has been possible to identify certain species by the peculiarity of their occurrence in the plant community. For instance, some mahogany species or leguminous species which constitute the emergent trees of certain West African forests have been identified by this peculiarity.

Inductive identification of tropical tree-species by visual observations of individual trees on aerial photographs has been successful only in exceptional cases. The use of infrared photography has not yielded a greater success. The use of colour photography has not improved the state of the art as the levels of discrimination in the important green band are too few for an efficient separation of species not even with microdensitometric methods.

The rare occurrence of pure stands of single species and mixed stands of few species has not permitted the use of deductive identification to a large extent. It has been used mainly for the identification of plantation species and the exotics in particular e.g. Gmelina species. It has also been used to some extent for the identification of species which are highly specialised under extreme ecological conditions to form virtually pure stands e.g. Borassus palm stands and Elaeis guineense (oil palm) stands in Nigeria. Even then these palms have distinctive stellate crowns on aerial photographs. Oil palm stands have been recognised on SLAR images of Nigeria by their characteristic 'radar signature' but these stands have not been recognised on Landsat images. The foregoing have shows that species identification by remote sensing methods is not conclusive and therefore requires intensive field checking.

In view of the large number of tropical tree-species without any distinctive photocharacteristics and the low incidence of the individual species, it is my opinion that reliable identification of these species can be accomplished only by field methods. However, it can be concluded that aerial photography yields more information on tree-species which constitute the ultimate units of management. It is therefore suggested that aerial photography should be used to the optimum in forest surveys that include remote sensing methods, but photointerpretation by itself cannot provide all the information required for species identification. Species identification can be improved by extensive photostudy and intensive field checks of the interpretation. In cases where species identification cannot be accomplished by photointerpretation, field methods should be used. This notwithstanding, it is still necessary to explore further the various ways in which aerial photography can assist the identification of tree-species particularly when volume estimation is included in the survey objectives. Further possibilities of the use of aerial photographs to assist species recognition are investigated in Chapter 8 (Section 8-3).

CHAPTER 4

THE USE OF REMOTE SENSING FOR VOLUME ESTIMATION

4 Volume estimation

The two principal goals of forest management are the production (yield) and protection (conservation) of forest resources, in this particular case, timber. In order to reach these goals through management by sustension, which is based on the principle of sustained yield, accurate information is required on the quantity (volume) and the quality of the growing stock and on its growth rate. Often information is also required on forest drain. This information is obtained by forest mensuration. Forest mensuration comprises the measurement of tree characteristics on the individual trees and the measurement of the sizes of the forest classes within a survey area. Tree information is obtained by relating the tree characteristics to the area of the forest e.g. volume per hectare, hence the term area-related tree information. Tree information can be assessed for the individual species or groups of species within each forest class, management unit or survey area provided the area information is available for the computation. The area-related tree information required on the growing stock and its yield is volume. This is used to establish the cutting possibilities within the forest management unit. In the tropics the collection of data for volume estimation is accomplished mainly by field mensuration of the forests. Though field mensuration provides accurate data, it is usually slow and often expensive. Forest mensuration can be accomplished also by remote sensing methods.

The purpose of this review is to assess the value and limitations of remote sensing methods for forest mensuration in the tropics. The review covers the tree information aspect of forest mensuration. The area information aspect is consid^e^red in Chapter 5. As the individual trees on which measurements are made cannot be resolved or recognised by their shapes on Landsat and SLAR images, only the use of aerial photographs for forest mensuration (photomensuration) and consequently for volume estimation (photovolume) is considered in this review. The tree characteristics measured on the individual trees are important not only as volume estimators, but also as forest characteristics by themselves. Consequently, their use for separating forests into condition classes (photostratification) is considered. Section 4-1 reviews the possibilities and limitations of the photomensuration of tree and forest characteristics. It also discusses the quantitative relationships which can be established between photomensuration and field mensuration data. Section 4-2 reviews the relative efficiency of the various photovolume estimation techniques for volume estimation under tropical forest conditions. Section 4-3 reviews the various ways in which photomensuration data can be used to stratify tropical forests into condition classes for a reliable assessment of forest volumes. Section 4-4 summarises the inferences and conclusion of the review of literature.

In this review of literature, established forestry terms are replaced by their conventional symbols where they make for a more precise description and a clearer understanding. For instance, lower case letters are used for parameters measured directly on aerial photographs e.g. crown diameter (cd), while upper case letters are used for parameters measured directly in the field e.g. DBH and CD. In order to differentiate field and photo-regression methods, the dependent variable precedes the independent variable using the appropriate letter case for the symbols, as in cd/DBH for field regression, and DBH/cd for photo regression. CD/DBH indicates a field regression using crown diameter and DBH measured directly in the field. The prefix 'field' or 'photo' is added to a parameter symbol to indicate the regression method used for its derivation. The source of the primary data used for the regression of the parameter is indicated by the letter-case e.g. photo-DBH.

photo-DBH = DBH obtained by photo regression based on
DBH measured in the field.

field-cd = crown diameter obtained by field regression based
on crown diameters measured on aerial photographs.

4-1 Photomensuration

Forest mensuration in the field is mainly concerned with stem dimensions for volume estimation. Except for research and other purposes, crown dimensions are seldom measured. Tree height and stem diameters are measured according to their various definitions listed with other conventional forestry standards in Appendix 1C. Because of the physical contact with the individual trees, which of course is not possible in photomensuration, more parameters are measurable in the field than on aerial photographs. For instance, measurements are often made for bark and defect volume reduction. In addition, several tree and stand indexes, such as taper function, taper and form factors, are obtained as a result of stem diameters measured at various height levels on the individual trees.

However, in photomensuration the only stem dimension measurable is the total tree height. In the tropics photogrammetric tree heighting by parallax method is more or less restricted to the open forests and the savanna in particular. In the closed forests, the ground is obscured by the canopy, and this precludes parallax heighting of the individual trees. Nevertheless, the overall canopy is sufficiently solid to act as a general measure of height, being fairly constant for individual stands.

On aerial photographs, the canopy is the main source of direct information of closed tropical forests. Consequently, photomensuration of tropical forests is mainly concerned with crown measurements. Usually, crown diameter (cd) and occasionally, crown area(ca) are measured directly on aerial photographs for volume estimation. Since the main volume estimator measured in the field (DBH) is not measurable on aerial photographs, statistical relationships are often sought between photomensuration parameters and field mensuration parameters, or the ultimate volume (V) estimated from the field data. Relationships are rarely sought between field and photomensuration data of the same parameter because it is an unnecessary intermediate stage in volume estimation.

It is noteworthy that while volume is mainly estimated on tree basis by field methods, it is mainly estimated on stand basis by photo methods. Field volume estimation on stand basis and photo volume estimation on tree basis are less accurate. Stand volume estimates could be obtained from individual tree volumes but the reverse is not possible. The parameters obtained for individual trees could be averaged for the stand if volume is to be estimated on stand basis, but this would require additional parameters for the entire stand. For example, field volume estimation would require stem count and basal area density (BA), and photo volume estimation would require crown count and canopy density or percentage crown closure (cc), depending on the volume estimation technique being used. It is also possible to derive many of the stand parameters from the measurements on individual trees e.g. basal area and canopy densities from DBH and crown areas respectively. These possibilities are considered in the ensuing literature review under:-

(a) tree heighting
(b) crown measurements
(c) wood density estimations

4-1.1 Tree heighting

Of the three main techniques for tree heighting on aerial photographs, the parallax method is the most satisfactory in terms of precision and accuracy. The shadow method is time consuming and unreliable without establishing appropriate conversion tables. Shadow length is a function of sun's angle which varies with latitude, time of the day, and month of the year according to seasons. As a result, separate height conversion graphs would be required for each degree of latitude of the survey area in respect of each hour of the day and each month of the photographic season. However, this method has been established and used for nearly twenty years in Canada (Spurr, 1948). The displacement method of tree heighting is only suitable for low altitude/wide angle aerial photography of conical trees (Loetsch, 1957a). Tropical trees are rarely conical, and low altitude wide angle photography is seldom acquired for tropical forests.

Spurr (1948) indicated that by using the appropriate formula for height conversion, tree height could be estimated on 1:15 840 scale aerial photographs within an error of ± 5m. for individual trees, and ± 3m. for the average of many trees. Garver and Moessner (1949), using the parallax wedge to measure tree heights on 1:20 000 scale aerial photographs, obtained an error of ± 3m. with a 67% confidence. Trees with apical dominance, particularly the conifers, are reported to be more difficult to measure on aerial photographs than those with rounded crowns particularly the broad-leaved species. The reverse is the case in the field, if total tree height is to be measured.

According to Francis (1957), the height range of the parallax instrument must be of sufficient amplitude to cover the height range in mountainous areas. The height range of the third order plotters is approximately 25% of the flying height for conventional aerial photography (Rhody, 1965). In the tropics the bole height is of greater interest than tree height, which is fairly constant for certain forests e.g. dipterocarp forests (Howroyd, 1954). Bole height cannot be measured on aerial photographs, nor reliably correlated with tree height. Paijmans (1975) proposed that it could be regarded as a constant for trees over 50cm. diameter at breast height (DBH) or above buttress (DAB) for volume estimation.

The tree height/DBH correlation for tropical broad leaved species is lower than that for temperate conifers. Consequently, the use of tree height for volume estimation on stand basis is seldom reliable (Loetsch, 1957), more so when it is fairly constant for a stand which normally comprises a wide range of bole heights. Loetsch and Haller (1973) found that, in most tropical forests, about 10 - 30 trees with photovisible crowns and a minimum of five emergent trees are usually encountered per plot. They suggested the use of circular plots of moderate size in photomensuration because errors in photovolume estimates increase with plot size. Also, McAndrews (1955) suggested the measurement of the three tallest trees per plot for photovolume estimations.

The foregoing shows that photomensuration of individual tree heights is of little value for the volume estimation of closed tropical forest stands. Bole height, which is more related to volume, is not photo-measurable. As a result, investigations should be concentrated on photomensuration of more reliable volume parameters which are the crown dimensions.

4-1.2 Crown measurements

On aerial photographs, crown diameters (cd) are measured stereoscopically using only the movable floating dot of the parallax bar, or using micrometer wedge and crown diameter scales in the form of dot or circle gauges. Crown diameters are also measured on single aerial photographs with crown diameter scales, or any other precise device for measuring horizontal distances. Crown area (ca) is usually obtained from the crown diameter, but it is more reliably estimated by direct measurement with dot grid or other suitable area measuring devices.

In practice, only a fraction of some crowns are photovisible for measurements. The more spreading crown-forming branches of a tree may be obscured by neighbouring canopy trees,or invisible for other reasons. Also, the outline of many crowns may be indistinct due to sparse branching at crown edges. Most tropical broad leaved emergents usually have irregular shapes,and their crown diameters are better obtained by averaging two measurements taken along any two perpendicular axes, preferably along the short and the long axes of the crown. Even then, accurate crown diameters may not be obtained. For instance, the area of a crown with a 13.5m. diameter averaged from 12 x 15m. perpendicular measurements is 143sq.m. whereas the area of a 13.5m. square or a 12 x 15m. rectangle is approximately equal to that of a circle 15m. wide, in which case the crown diameter has been underestimated by 10%.

The accuracy of crown measurements is largely influenced by radial displacement (Paijmans, 1975). Radial displacement increases away from the principal point with scale and elevation of object. Consequently errors in crown diameter measurements would increase with the photo scale, tree height, and the radial distance of the crown image from the principal point. These errors are more pronounced on large scale and long focal length aerial photographs,particularly at photo edges. Crown dimensions are generally more reliably measured in the effective area of the photographs. Swellengrebel (1959) suggested that crown diameters should be measured along a perpendicular axis to the radial line and, if the crown images are unidentical on the stereopair, measurement should be made on the image that is nearer to the principal point. Frequently, shadows are bothersome. In such cases, crown diameter should be measured along a perpendicular axis to the shadow direction. Worley and Meyer (1955) obtained an error of ± 1m. in crown measurements on 1:20 000 scale aerial photographs.

On the main assumption that the amount of foliage determines the amount of plant assimilation, and therefore the amount of wood, crown dimensions are measured as substitutes for DBH or any of its derivatives. Photomensuration data are therefore used principally to establish a dimensional relationship between the crown and the stem. The cd/DBH relationship is the most important dimensional relationship for volume estimation, though ca/BA relationship is also used. The trees in the lowest crown diameter class measured on aerial photographs, seldom belong to the lowest stem-diameter class measured in the field.

The cd/DBH relationship for tropical tree species has not been fully investigated, but reports indicate a definite cd/DBH correlation which in most cases is not as strong as that obtained for temperate tree species (Paijmans, 1951; Loetsch, 1957; Heinsdijk, 1957, 1958; Francis, 1966). Howroyd (1954) found that cd/DBH correlation for a group of species in Sarawak forests was so close that all the species within the group could be represented by a single regression line. Similar correlation was reported (Nyyssonen, 1955) for certain species in the dense lowland and fairly homogenous Waikambas forest of Sukadana area in Indonesia.

A strong cd/DBH correlation was reported for <u>Pentacme contorta</u> in the Phillipines (Macabeo, 1957), <u>Eperua fulcata</u> above 50cm. DBH in Wallaba forests, and <u>Mora exclesa</u> above 70cm. DBH in Mora forests in Guyana (Swellengrebel, 1959). The same is true for a group of

Amazonian species above 25cm. DBH in Surinam (Heinsdijk, 1957), and a group of virgin forest species in Malili-Sulawesi (Paijmans, 1951). Minor (1951) found a strong cd/DBH correlation for the sourthern pines, Pinus alustria and Pinus taeda.

In Central Irian (Java) the cd/DBH correlation for plantation teak trees was very close (r = 0.66) but that for primary (natural) forest trees was loose (r = 0.33) while there was no cd/DBH correlation for overmature trees. (Hollerwoger, 1954). In Kampuchea and Vietnam, Rollet (1960) observed a loose cd/DBH correlation for a group of five dipterocarp species. Loetsch & Haller (1973) reported that,as a generalisation, there was no cd/DBH correlation for trees over 100cm. DBH irrespective of species and that cd/DBH correlations are mostly significant for canopy trees. Spurr (1948) suggested as a rule of thumb that DBH of a tree should be taken as one sixteenth of the crown diameter (cd) while Paijmans (1975) found that crown diameter (cd) of a tree was about 20 to 22 times the DBH for the straight aspect of CD/DBH regression. These two approximations from photo sampling indicate a constant CD/DBH dimensional ratio. Nyyssonen (1955) found that in order to obtain a reliable cd/DBH correlation, the number of observations for each crown diameter class should be fairly large. The larger the number of observations the smaller the standard deviation and the more accurate the extrapolation from the regression.

The foregoing isolated investigations on cd/DBH dimensional association by photomethods and other similar field investigations not reported in this thesis, have not illuminated the actual crown-stem diameter growth ratio trends which occur within the forests. Foresters have long established the existence of a definite CD/DBH dimensional association for forest trees irrespective of site, age and in some cases, silvicultural treatments. The CD/DBH regression lines were often found to be rectilinear, and occasionally curvilinear, with little difference between the two.

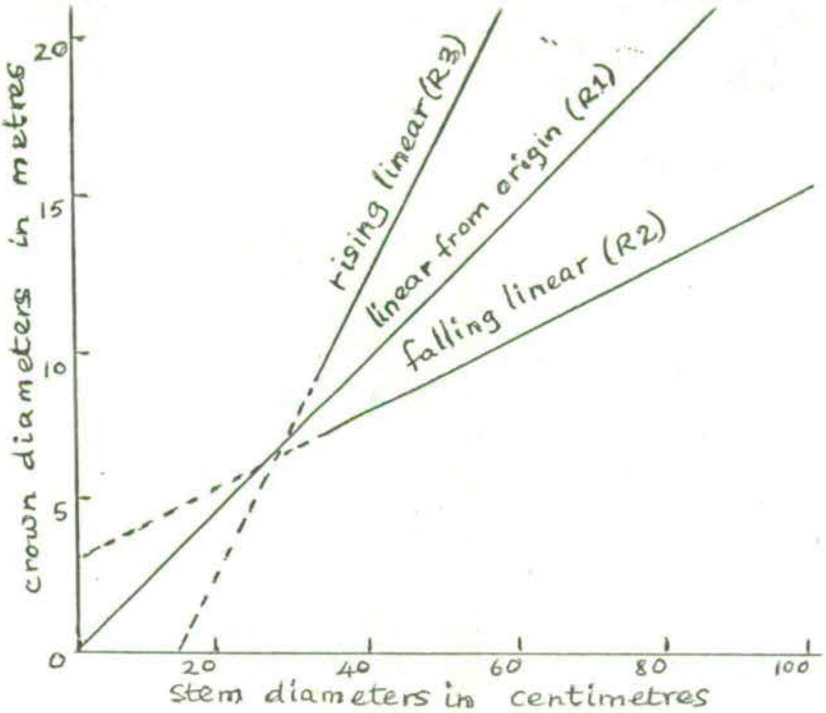
In the light of a field work on 17 economically important tropical tree species, Dawkins (1963) examined six CD/DBH regression trends postulated by earlier workers. He collected samples from 15 species on 19 sites, some of them from both uneven-aged natural forests and forest plantations. His samples included several examples from Southwestern Nigeria, especially *Triplochiton scleroxylon* and *Nauclea diderchii* from natural forests and forest plantations. The six CD/DBH regression trends examined by Dawkins are illustrated with hypothetical diameters in Fig.4.1. These six regression trends are summarised (in sensu Dawkins) as follows:-

Regression trend	Regression line	Regression constant (a)	CD/DBH growth ratio
Rectilineal (R)			
R1	linear from origin	zero	constant
R2	falling linear	positive	decreasing
R3	rising linear	negative	increasing
Curvilineal (C)			
C1	sigmoid	-	constant in the central stretch
C2	falling curved	positive	decreasing
C3	rising curved	negative	increasing

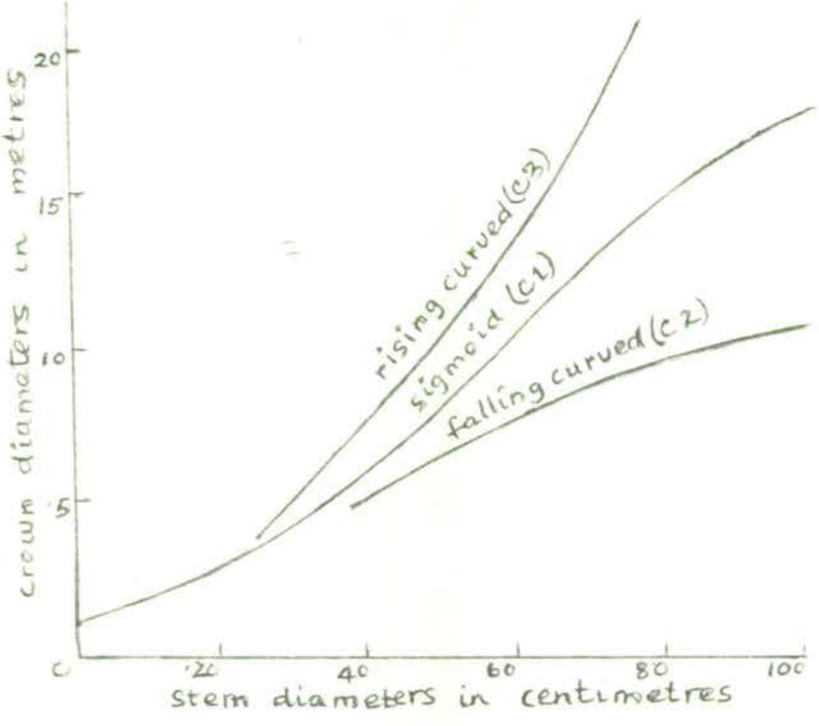
Dawkins proposed that the most practical interpretation of CD/DBH and DBH/CD correlations over the normal range of tree size of the established crop is rectilinear (R1 - R3), but if the juvenile trees in the lower extreme, and the senile trees in the upper extreme were included, the correct interpretation would probably be curvilinear (C1 - C3) in the equations.

Fig: 4.1 Comparative illustration of crown-stem diameter relationships commonly obtained by regression of field mensuration data

(a) Rectilineal regression trends



(b) Curvilineal regression trends



Source: Dawkins (1963)

$CD = a + b.DBH$ and

$DBH = a_1 + b_1.CD$ in which

a & a_1 = regression constants with different values

b & b_1 = regression coefficients with different values

when a height factor is introduced in the regression, the first equation becomes:-

$CD = a + b.DBH - c.H$ in which

c = regression coefficient for height

Dawkins found that the regression constant was related to the species tolerance for other species within the plant community. Tolerant species had low 'a' values which were almost unaffected by silvicultural treatments like thinning and spaced planting. Intolerant species showed a highly variable 'a' value clearly indicative of treatment. High positive 'a' values were associated with excessive crop density. He observed that in even aged tropical crops, the density limit that could be tolerated without crown overlap ranges from 19 to 23cu.m. per ha. Negative 'a' values were associated with photo samples of uneven-aged crops and field samples of recently thinned even-aged crop. Negative 'a' values were also encountered when height factor is introduced to the regression equation. He observed that the regression coefficient for DBH (b) was diagnostic only when 'a' value is low or zero. In other words 'b' is diagnostic for almost any sample of intolerant species or of relatively open-grown tolerant species. Though specific, the magnitude of 'b' value must be assessed relative to 'a' value.

Dawkins observed that the CD/DBH growth ratio trends were seldom affected by site and rarely by age except at the two extremes of the regression. He also found that if the true status of a species was uncertain, the apparent status could be obtained from the scatter diagram of its higher CD/DBH ratios excluding the maximum ratio by assuming a rectilineal regression. The intercept (a) could be fixed accordingly. A low or high 'a' value would then indicate a highly intolerant or tolerant species respectively. Constant CD/DBH growth ratio (R1 & C1) occasionally associated with trees growing in the open and frequently with very limited i.e. biased sampling. This ratio can be obtained by frequent thinning or harvesting at critical time of canopy closure to avoid decelerated stem growth or else widespread crown degrade.

Decelerating CD/DBH growth ratio (R2 & C2) is encountered when height factor is introduced into the regression. Height factor is consistently negative and more often insignificant than not. This CD/DBH growth ratio trend may be regarded as the true trend in nature because taller trees of a given diameter, for mechanical reasons generally have smaller crowns than the shorter ones. However, this is not universal since higher quality sites are not always capable of greater basal area densities for a given mean DBH, though they generally show a greater average height. Nevertheless, if crop basal area is allowed to rise to maturity as generally shown in yield tables a decelerating CD/DBH growth ratio would be obtained.

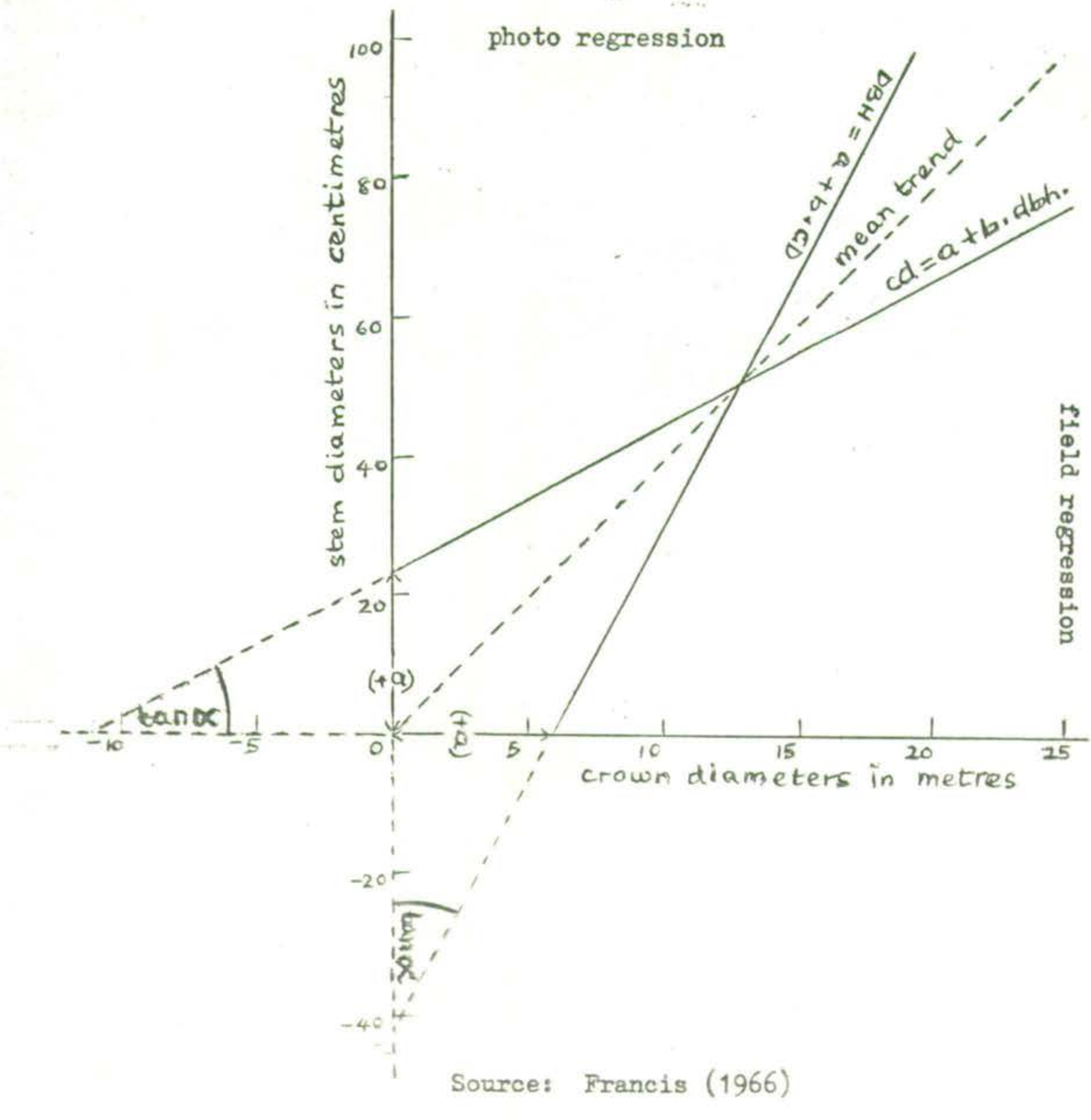
Accelerating CD/DBH growth ratio (R3 & C3) assumes a non-competitive coexistence of plants. As non-competitive coexistence within a plant community is an ecological rarity, this growth ratio is associated with the effect of opening up of previously restricted crown. In practice this is accomplished by thinning. The basal area density could be steadily reduced to maturity by progressively increasing the thinning proportions. This would allow an accelerated crown growth resulting in a CD/DBH growth ratio that increases with age or size of the tree. The opening up of previously restricted crowns can be achieved theoretically in two ways. The first way is by sampling a forest composed mainly of light demanding and 'crowd' tolerant species. In this case the juvenile trees grow very tall with slender conical crowns under restricted and shaded conditions. Their CD/DBH growth ratio is therefore low. They eventually grow above the general canopy as emergents with wide spreading crowns to give the maximum CD/DBH growth ratio possible for their size class. A regression which includes both growth patterns would definitely show an accelerating CD/DBH growth ratio. The second way is by using the criterion of aerial visibility to select the sample trees. As the forest mensuration data are limited to these aerially visible trees, the smallest visible crowns would belong to the tallest trees in their crown diameter class and consequently an exceptional DBH class. Moreover, for mechanical reasons, taller trees of a given diameter usually carry narrower crowns than the shorter ones. The largest visible crowns belong to DBH class whose crowns are entirely visible e.g. emergents. Such diameter class comprises trees with maximum CD/DBH growth ratio possible since they are theoretically competition-free. A regression which includes both conditions would result in an accelerating CD/DBH growth ratio. This accounts for the accelerating CD/DBH growth ratio obtained for photosamples of closed crops and field samples of recently thinned even-aged crops.

Dawkins' investigation was significant because the results explain why CD/DBH or DBH/CD regressions cannot start from graph origin. According to him, if the artificial restriction of measuring stem diameters at breast height is removed in order to include the "below the line" juvenile trees i.e. trees without a measurable DBH, the regression lines would probably start from origin. However, it is a biological fact that the intersection of plant growth graphs and consequently growth ratio regressions progressively depart from origin as germination, seedling and sampling stages are excluded in that order from the regression. Dawkins' investigation also shows that if juvenile and senile trees are introduced into the rectilineal regression trends, the corresponding curvilineal trends would be obtained. He proposed linear(R1) interpretation for the central stretch the sigmoid (C1) trend since the greater part of a tree's life would fall within the central stretch. However, he failed to establish similar relationship between the falling linear (R2) and curved(C2) trends and between the rising linear (R3) and curved (C3) trends. Consequently, the investigation failed to establish the actual trend within the forest. Furthermore, Dawkins' findings imply that both positive and negative 'a' values and consequently incompatible regression trends can be obtained with the same sample trees e.g. photosamples and field samples of an even aged forest crop.

Dawkins' investigation further shows that CD/DBH and DBH/CD regressions are not interchangeable, but does not explain why negative 'a' values were frequently associated with regressions based on photosamples. Francis (1966) explained that the negative 'a' values obtained for photosamples by Dawkins were due to the common and incorrect application of field regression (CD/DBH) technique to photomensuration data. Though Dawkins realised that CD/DBH and DBH/CD regressions were not interchangeable, he did not take into account that the latter was more appropriate for photomensuration data.

The fundamental difference between photo regression (DBH/cd) and field regression (CD/DBH) is that the independent variable in the former is the crown diameter, while in the latter it is the DBH. The effect of interchanging the variables on the 'a' values is graphically illustrated with hypothetical data in Fig. 4.2 which in the normal reading position depicts photo regression and if oriented 90° anticlockwise left depicts field regression. Though the orientation results in the

Fig: 4.2 Comparative illustration of crown-stem diameter relationships obtained by regression of field and photo mensuration data



Source: Francis (1966)

mirror image of the field graph, the origin being on the right instead of the left hand side, the illustration is equally as effective as the actual graph being depicted. If the illustration is considered for photo and field regressions separately, positive 'a' values indicative of a decelerating CD/DBH growth ratio would be obtained in either case. If the intercept of the photo regression is below the origin, a negative 'a' value indicative of an accelerating CD/DBH growth ratio would be obtained. False negative 'a' values would be obtained for photo regression if the illustration is oriented for field regression. This explains why Dawkins obtained negative 'a' values for his photo samples. Similarly negative 'a' values would be obtained for field regression if the illustration is oriented for photo regression. Another important difference between photo and field regressions is the intercept angle (α), which may be higher in one of the regressions to give a higher CD/DBH growth ratio trend or vice versa.

However, Francis did not dispute the legitimate occurrence of an accelerating CD/DBH growth ratio resulting from recent thinning (Dawkins, (1963), or from the inclusion of height factor in the regression (Briegleb, 1952; Curtin, 1964). He found that the interpretation of crown-stem diameter correlations by photo methods follow the same trends observed for field regressions by Dawkins. According to Francis DBH/cd regression could be rectilineal, curvilineal, or sigmondal, depending on several factors which could not be adequately summarised for an appreciation of their practical application without recourse to many true examples. He realised that the natural structure of the forests does not permit a perfect CD/DBH correlation because trees with the same crown diameter do not usually have the same DBH and height, while trees with the same DBH do not usually have the same crown diameter and height. By ignoring height and using crown diameter and DBH, this imperfection can be illustrated as follows: A tree of known crown diamter and DBH is taken as a standard. The DBH of other trees having the same crown diameters as the standard tree are measured. Also, the crown diameters of other trees having the same DBH as the standard tree are measured. By simple comparison, the mean DBH for the other trees would differ from the DBH of the standard tree with which they share the same crown diameter. Similarly the mean crown diameter of the other trees would be different from the crown diameter of the standard tree with which they share the same DBH. It follows that, even if the same mensuration data are used for the two regressions, they would not give the same results when compared for the same tree because there is no perfect correlation between crown diameter and DBH in nature. In the light of these conflicting results, confusion is apt to arise in establishing the CD/DBH growth ratio. This confusion is often aggravated by a biased sample or imprecise mensuration methods.

Francis observed that the differences usually found in the CD/DBH growth ratios established by the two methods were often wrongly attributed to site differences and silvicultural treatments. He indicated that the differences would still exist even if these factors are ignored and if mensuration methods are precise and accurate. Francis accepted the methods used by Spurr (1960) and Dawkins (1963) to be precise enough for obtaining accurate photo and field mensuration data respectively. In his opinion both photo and field regression trends frequently observed are largely due to a peculiarity or a chance product of the statistical methods used for the regression. According to him, either trend does not necessarily represent the actual CD/DBH growth ratio trend, which could be obtained only by repetitive mensuration over a considerable time lapse. He postulated that the mean of both photo and field regressions (see Fig.4.2.) was more representative of the overall CD/DBH growth ratio trend in the forest. But neither crown diameter nor DBH could be reliably estimated from the average, since the underestimations for the bigger trees do not usually cancel the overestimations for the smaller trees in overall accurate totals.

As a generalisation, the trends obtained in photo and field regressions are determined by

- the non-existence of a perfect crown-stem diameter correlation
- artificial restrictions imposed by the conventional breast-height measurement of stem diameters
- limitations imposed by aerial or photo visibility factor

if crown diameters are obtained by photomensuration and

- the graph system relative to the choice of the dependent variable and the grouping of the independent variable.

The effects of these factors on the regressions are mostly pronounced in the upper and lower extremities as depicted in Fig. 4.2.1.

(i) <u>the upper extremity of the regression</u>

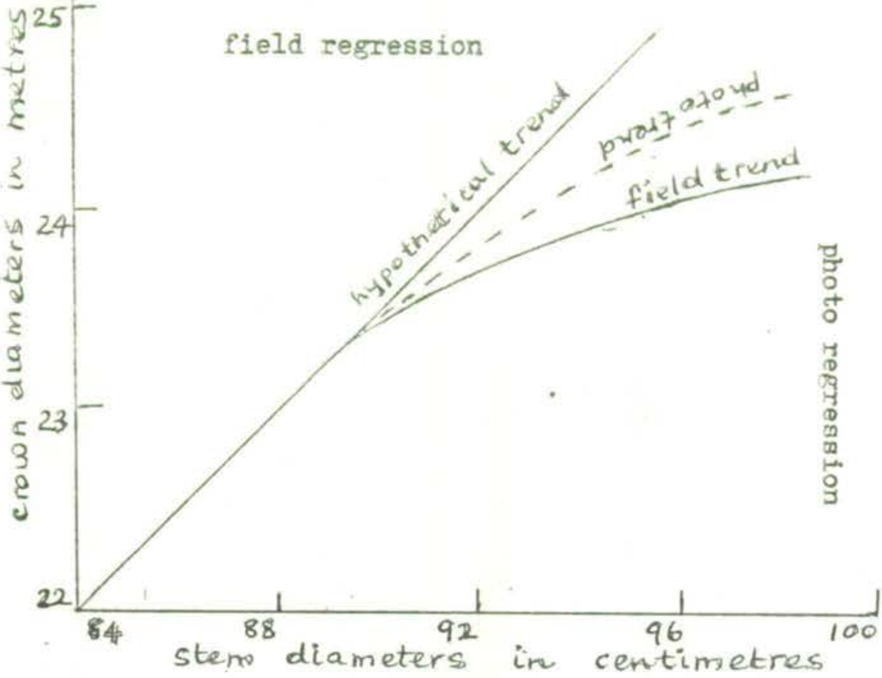
The top-end of the crown-stem diameter regressions is due to the combined effect of the natural structure of the forest and the graph system. The natural structure of the forests results in imperfect CD/DBH correlation,the effect of which increases with the increasing 'a' values. This effect is drastically reduced in young or even-aged stands and in limited samples. Further the largest recorded crown does not usually coincide with the largest recorded stem and vice versa, except by chance in limited samples. Even if they coincide, the other trees in the highest class of the independent variable would still have their crown or stem diameters, as the case may be, smaller than that of the tree with the largest recorded crown and stem diameters. Because of the wide variation in the upper diameter classes, the average of the higher values of the dependent variable would occur proportionately closer to the axis of the independent variable than the highest value. This would result in a falling rectilineal or curvilineal regression controlled by the middle diameter classes (see Fig. 4.2.1a).

(ii) <u>lower extremity of the regression</u>

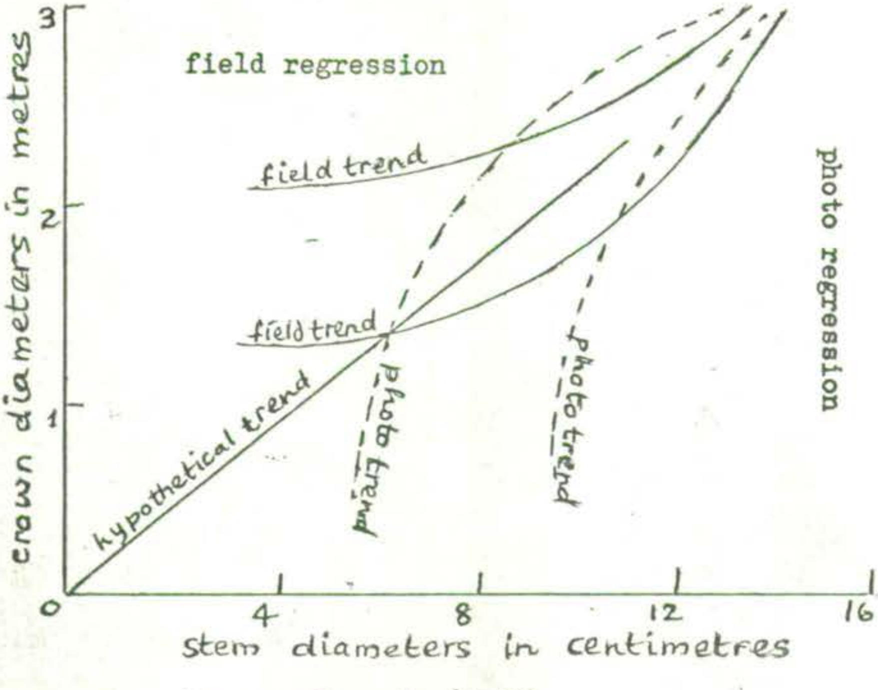
The nature of regression is influenced by the lower limit set for the independent variable, DBH for field method, cd for photomethod. If the normal artificial restriction imposed by measuring stem diameter at breast height is disregarded to include the smallest independent variables in the whole range, both field and photo regression lines would start from origin and diverge immediately thereafter.

Fig: 4.2.1 Comparative illustration of field and photo regression trends for the extreme crown-stem diameter classes

(a) Regression trends in the upper diameter classes



(b) Regression trends in the lower diameter classes



Source: Francis (1966)

The exclusion of these lower values of the independent variables belonging to the "below the line" trees changes the positions of the regression lines, and takes their intersection away from the origin. The higher the lower limit set for the independent variables, the larger the values of 'a', and the farther the intersection from the origin. Also, the exclusion of these "below the line" trees moves the average position of each class of the dependent variable away from the axis of the independent variable, thus creating a curve at the base as depicted in (Fig. 4.2.1b). A curvilineal regression curved at both extremeties in opposite directions results in a sigmoid.

Regression trends may be altered by regrouping the values of the independent variable, or completely reserved by a wrong choice of the independent variable. Regression trends are also affected by data transformation and weighting. Furthermore, different species have different CD/DBH regression trends. It is possible for a group of species to follow similar or the same DBH/cd regression trends. Because tropical tree species are difficult to identify on aerial photographs, it is generally difficult to establish DBH/cd regression trends for the individual species or groups of species. In view of this, a single DBH/cd regression could be established for all the species. In which case, the DBH predictions for individual trees would be inaccurate. This inaccuracy would be reflected in the subsequent volume estimates based on the predicted DBH.

4-1.3 Wood density estimation

The term 'wood density' is often inaccurately used to mean the amount of wood. By definition, wood density refers to any forest characteristic, including volume, which indicates the amount of wood. Such forest characters which can be derived from corresponding tree characteristics are tabulated in Table 4.1 for both field and photo mensuration. As shown in the table, the mean DBH, according to its often distorted forestry definition, is that of the mean basal area. The simple arithmetic average of DBH would result in false mean DBH. In the field, mean basal area is obtained as basal area factor (BAF) by point sampling using the angle gauge method. The most commonly used angle gauge is the relascope. In the angle gauge method the larger trees with the important volume are better represented, and enumeration of an excessive number of small trees is avoided. Since the selection of sample trees is proportional to tree size, the angle count (relascope method) closely approaches optimum allocation, which is very useful in crown-stem diameter regression and volume regressions.

Also, wood density (BAD) can be predicted for a stand of known area (A), and canopy density (CAD) from the CD/DBH growth ratio of the mean tree as follows:

BAD	= A x CAD	÷ $(\text{CD/DBH})^2$
in sq.m. per ha.	in sq.m.	both in the same units

If photo-DBH (DBH obtained from DBH/cd regression) is used for the prediction of basal area density, the DBH/cd regression should include height factor, because crown diameter is more related to the product of basal area and height (DBH^2H), than to basal area $(\text{DBH})^2$ alone. Otherwise, the regression should be based on crown and stem diameter classes obtained by grouping the sample trees into height classes (Ilvessalo, 1950).

In photomensuration, canopy density is obtained as percentage crown closure using crown density scales calibrated in percentages. Stereograms of field plots with known crown closure are also used as interpretation keys for estimating crown closure of photo plots.

Table 4.1. Forest stand-characteristics derived from tree-characteristics

Field mensuration	Photomensuration
Data	Data
1. stand area (A) in sq.m.	stand area (a) in sq.m.
2. total number of stems (N)	total number of crowns (n)
3. total stem diameter (ΣDBH) in sq.m.	total crown diameter (Σcd) in sq.m.
4. total basal area (ΣDBH) in sq.m.	total crown area (Σca) in sq.m.
Characteristics	Characteristics
1. stems per hectare $= N/A \times 10^4$ stems/ha.	crowns per hectare $= n/a \times 10^4$ crowns/ha.
2. mean stem diameter $= \sqrt{\Sigma(DBH)^2/N}$ *	mean crown diameter $= \sqrt{\Sigma(cd)^2/n}$ *
3. basal area factor (BAF)+ or mean basal area $= \Sigma BA/N$	crown area factor (caf) or mean crown area $= \Sigma ca/n$
4. basal area density (BAD) or wood density $= \Sigma BA/A$	crown area density (cad) or canopy density $= \Sigma ca/a$
5. wood density per hectare $= BAD \times 10^4$ sq.m./ha.	canopy density per hectare $= cad \times 10^4$ sq.m./ha.
6. percentage stem closure(BC) $= BAD \times 10^2\%$	percentage crown closure (cc)+ $= cad \times 10^2\%$

* according to forestry definition

\+ also measured directly for the stand

On very large scale aerial photographs crown closure could be reliably estimated with a dot grid. Crown closure could be visually estimated with fair accuracy by following some well defined guidelines.

Pope (1960) described two methods for the visual estimation of crown closure. In the first method, trees normally scattered over the photoplot are imaginarily concentrated on a portion of the plot - 'tree cramming'. The area imaginarily covered by the trees is expressed as a percentage of the plot area to give the percentage crown closure. In the second method, the number of trees with average crown diameter is counted and expressed as a percentage of the number of such trees that would be required to fill the entire plot.

An objective field checking of crown closure obtained by photo mensuration is extremely difficult because the methods used for field estimation of crown closure are difficult and generally too slow. e.g. The moosehorn method (Robinson, 1947) often used in America and the plane table mapping method (ASP, 1975a). Moessner (1949) observed that errors in the photo estimation of crown closure seldom exceeded ten percent. Loose (1953) and Bonner (1968) used 1:17 200 and 1:15 840 scale aerial photographs respectively to estimate crown closures. In either case the estimation error was less than ten percent.

The use of crown closure as a criterion in forest mensuration presupposes a canopy that is not completely closed. This condition is rarely obtained in closed tropical forests. The part of the growing stock to be considered in crown closure estimation in closed forests is open to debate. It is logical to specify the minimum tree size to be considered. Estimation of crown closure could be limited to trees with a specified minimum crown diameter or DBH. Crown closure estimation could be restricted to the economic species or the emergent trees, if they could be reliably separated on aerial photographs.

The difficulty of identifying tropical trees on aerial photographs reduces the accuracy of the crown counts of individual species. For instance, a crown count of Virola surinamensis on 1:10 000 scale aerial photographs contained an error of 30% (Howard and Lanly, 1975). Lanly (1972) reported an error of less than 25% (without biases) for the crown counts of Terminalia superba on 1:50 000 scale aerial photographs of Southern Congo. These levels of accuracy are useful only for a rough estimation of volumes. Sayn-Wittgenstein and Aldred (1967) found that errors in crown count increased with wood density and heterogeneity of the forest stand. Counting accuracy could be improved by high resolution aerial photography. On aerial photographs of tropical forests, it is common for crowns of a group of neighbouring canopy-trees to appear as one large crown. Also, a very big tree may have more than one compact tuft to appear as separate crowns of several trees, but such trees are usually of little timber value (Swellengrebel, 1956).

Since the number of photovisible crowns usually reflects the canopy structure (Nyyssonen, 1962), wood density estimated from photomensuration of the crowns is more valuable for stratifying tropical forests into volume-related classes, than for estimating the actual volumes.

4-2 Photovolume estimation techniques

The techniques used for estimating volume on aerial photographs are fundamentally the same as those used in the field. Photo mensuration data collected from photo samples for volume estimation are usually measurements made on the individual sample trees. These data are used to estimate the stand volume either on tree or on stand basis. In the former case, the volumes of the individual sample trees are computed for the subsequent estimation of the stand volume. In the latter case, the stand characteristics are computed from the corresponding tree characteristics for the direct estimation of the stand volume. Certain stand characteristics, such as percentage crown closure, are also directly measurable on aerial photographs.

Volume estimation on tree or stand basis is accomplished by using volume formulas or volume equations. In the formula technique, geometric formulas for simple solids are used without establishing any quantitative relationship between the measured parameters and volume. Consequently, all components of volume must be provided as required in the formula. Since DBH, the most important volume component, is not measurable on aerial photographs, it must be derived from its quantitative relationship with crown diameter (cd), the most important photo volume parameter (DBH/cd regression).

In the equation technique, regressions for establishing a quantitative relationship between a few measured parameters and volume are used directly for volume estimation. In this case, the main photo volume estimator, crown diameter (cd), is directly related to volume (V) established from field mensuration data (V/cd regression).

In view of the above considerations photovolume estimation techniques can be summarised as follows:

volume estimation on tree basis by

- geometric formulas
- regression equations

volume estimation on stand basis by

- geometric formulas
- regression equations

The ensuing evaluation of these techniques is based on their relative efficiency for estimating forest volume from the limited amount of forest mensuration data that can be obtained from aerial photographs of tropical forests. Volume estimations on tree and stand basis are not considered separately but they are distinguished where both are not covered by the same generalisations.

4-2.1 Photovolume formulas and equations

Of the numerous formulas and equations established for estimating volume on aerial photographs, only the basic types are used in Table 4.2 to illustrate their classification. Most of them are more complex than the examples given. For uniformity and consistence, most of the formulas and equations cited are presented in their simplified forms, occasionally using symbols different from those normally used.

(a) Photovolume formulas

Because more parameters are measured in the field, a larger number of volume formulas is available for estimating volume in the field than on aerial photographs. For example, stem diameters can be measured at any height level using high precision optical instruments. Volume formulas may even dispense with DBH as in the case of Log Concept formulas in which the stem or bole is imaginarily divided into a number of logs. The tree volume is subsequently calculated from the various lengths and diameters of these imaginary logs. This is a primary argument against the use of DBH and DAB in particular for estimating tropical forest volumes as mentioned in Section 4-1.2. Another possibility is the inclusion of taper in volume formulas (and sometimes in equations). Taper is expressed in form concept formulas as form factor - a theoretical volume ratio between a tree and a reference geometric solid (commonly a cylinder) of the same basal diameter and height (see Table 4.2). It is expressed in taper concept formulas as taper factor - a diameter ratio between a given height level

Table 4.2. Examples of photovolume formulas and equations

Volume . . .	Formula	Equation
On tree basis	Form concept formula $v = ba.h.f$	Local volume equation $V = a + b\ (cd)^2$ Standard volume equation $V = a + b\ (cd)^2.h$
On stand basis	$v = \frac{ca.h.f}{(cd/DBH)}$ (after Zieger, 1928)*	$V = a + b.h + c.n$ (after Stellingwerf, 1962)*
In which	v = total stand photovolume ba = photo basal area derived from DBH/cd regression ca = photo crown area derived from photo crown diameter h = photo height f = form factor obtained in the field or from tables cd = photo crown diameter DBH = photo-DBH cd/DBH = a ratio for the mean tree	V = volume established in the field cd = photo crown diameter h = photo height n = photo crown count a = regression constant b = regression coefficient for crown diameter c = regression coefficient for crown count

* quoted by ASP (1975a).

and the breast height level of a tree (a ratio between an upper stem diameter and DBH). Taper factors, being diameter ratios directly estimated on individual trees, are of greater practical value for volume estimation than form factors which are theoretical ratios. However, taper concept formulas are generally more complex than the corresponding form concept formulas because some include taper functions. A taper function, in parametric terms, is a taper factor weighted by the corresponding height. In other words, it is the height-diameter relationship for a tree. The major drawback in the use of volume formulas for estimating photovolumes is the need to establish the value of at least, one parameter by field methods. e.g. form factor, taper factor and taper function. Such parameter cannot be measured directly on aerial photographs.

As a quantitative relationship is not established between volume and volume parameters for the trees within the survey area, volume formulas are generally valid for universal application, provided they are fed with reliable data. For instance, a photo-DBH established by DBH/cd regression with a 30% standard deviation would give a standard deviation of 60% in the volume of individual trees (ASP, 1975a). The height used in photo volume formulas does not conform with the height defined for estimating volumes of tropical forests. In the tropics bole height is more important in volume estimation than tree height, which is fairly constant for many closed stands. Moreover, tree heighting on aerial photographs of closed tropical forests is either difficult or impossible, because the ground is usually obscured by the canopy. It follows that the use of volume formulas for such forests would not give satisfactory estimates of the volumes of the individual trees. Photo volume formulas are of great value only in volume estimation on stand basis. However, this would require field mensuration of a large number of trees for the accurate assessment of the mean form or taper factor. Generally, volume estimation on stand basis by formula technique is very suitable for reconnaissance surveys in which only rough estimates of stand volumes are required, and for surveys which are economically constrained.

(b) Photovolume equations

There are two basic regression equations for estimaing volume:

- Local volume equation: in which volume is quantitatively related to only one independent variable - the main volume parameter - crown diameter (cd) by photomethods and DBH by field methods.
- Standard volume equation: in which volume is quantitatively related to two independent variables - the main volume parameter (cd or DBH) and another parameter - height (h or H).

In addition to these two basic volume equations, combined volume equations are often developed to avoid the measurement of the second parameter (h or H) on every sample tree. More complex volume equations are also developed to improve the accuracy of the volume estimates. The improved accuracy so obtained does not usually balance the additional costs involved.

Volume equations permit, from detailed measurements on a limited number of judiciously selected sample trees, the objective estimation of the volume of a much larger number of trees in the sampling units, and consequently the required total volume. However, volume equations are generally of restricted application outside the sets of conditions under which they were originally constructed. A volume equation is usually valid for a given region, site quality, silvicultural treatment, species (or group of species), and sometimes a given range of tree characteristics. Once established for a given set of conditions, a volume equation is capable of continuous refinements. For this reason, volume equations may be of great value in the tropical forest areas where the forest data are inadequate and forest mensuration is a new research field. The low exploitable potential of some tropical forests seldom provides an economic justification for the use of such expensive volume estimation techniques.

Standard volume equations imply the measurement of the second characteristic on every sample tree, or a proportion of the sample trees. This would involve longer enumeration time and additional costs. Bole height, which is more important than total height in volume estimation of tropical forests, cannot be measured on aerial photographs. In many tropical forests, the average bole height in every diameter class above a certain diameter is fairly constant for a given species or possibly a group of species. This is particularly so in West African tropical high forests (Lanly, 1973). Moreover, the total height measured on aerial photographs was also reported to be constant for some stands in closed forest. The inclusion of bole height, or any other height in volume equations does not appear to be essential for tropical forests, provided the number of trees in each class of the independent variable (cd or DBH) is large enough, and the variability within each class around this constant (h or H) is relatively small in the sampling unit. For tropical forests, the reduction in sampling error by the inclusion of height may be insignificant relative to the total error, bearing in mind the magnitude of the sampling error and measurement errors. In view of these considerations, the most suitable technique for estimating tropical forest volumes at an economic cost would probably be local volume equations. Errors due to exclusion of height may be reduced, possibly by using height classes to group the independent variable for the volume regression. This possibility has not been tested for tropical forests. However, Ilvessalo (1950) reported that strong DBH/cd correlations were usually obtained when trees are grouped into height classes.

Several workers have tested different kinds of variables to determine the most suitable components for tree volume equations. Sayn-Wittgeinstein and Aldred (1967) found that the combined variable height multiplied by the logarithm of crown area (h.log.ca) was the most powerful volume estimator. Francis (1966) suggested that if crown diameter was to be correlated directly with volume (V), the volume should be established from both DBH and height. But if the volume (v) is established from only photo-DBH, Bonner (1964) suggested that the crown diameter and height, being the strongest volume variables, should be used for the photo-DBH prediction. Such photo-DBH predictions made by Paijmans (1951) for Malili-Sulawesi forest trees had a standard error of 30%. This would result in 60% standard deviation for the volume estimates of individual trees. The combined variable crown diameter and crown diameter squared was also reported to be a strong DBH estimator. The construction and techniques of stand volume equations vary to some extent according to species. Moessner and others (1951) found that the combined variable of crown closure (cc), crown diameter (cd), and height (h), worked best in the estimation of stand volumes. Paelinck (1958) used crown closure alone to estimate the volume of a tropical forest stand. His estimates had a standard error of 30%. The combined variable of crown diameter and crown diameter squared $(cd)^2$ is reported to be a satisfactory volume estimator. Pope (1962) found that height squared times crown closure (h^2cc) increased the value of stand volume equations accounting for over 88% of the total variation. Moessner (1963) found that crown diameter, height, and the square of their products $(cd.h)^2$, gave the best estimates of stand volume. The combined variable - crown diameter and crown diameter squared $(cd)^2$ - was reported to be a satisfactory estimator of stand volume.

The ASP (1975a) referred to two stand volume equations which the present author thinks would be of interest to tropical forest surveys. The first equation was developed by Stellingwerf in 1962 for Scots pine in the Netherlands, volume per hectare (V) is estimated from crown count (n) and mean height (h) of the dominant trees in the regression.—

$$V = a + b.h^3 + c.n$$

The second equation was developed by Bogyay in 1970 for 10 - 16 year-old pine stands in Hungary. Volume per hectare (V) is estimated from the stand age (y) and the average stand height (h) in the regression.

$$\log V = a - b.\log y + c.h$$

In these equations a, b & c are different regression constants. The application of these equations to tropical forests has not been reported in literature. The second equation would be of value for the estimation of tropical forest plantation yield. So far, direct photomethods for estimating yield of the forest growing stock have not been described in literature.

4-2.2 Photovolume tables and other photovolume summaries

In the same way as maps are used to summarise survey results, volume tables, graphs, and alignment charts, are used to summarise volume estimates obtained by the various volume estimation techniques. There are two basic types of volume tables corresponding to the two basic types of volume equations, but they are not necessarily derived from them.

- Local (one-entry) volume tables, in which volumes are tabulated against the corresponding values of the main volume estimator (usually cd or DBH). Table-entry requires only one known parameter.

Local volume tables correspond to local volume equations.

- Standard (two-entry) volume tables, in which volumes are tabulated against the corresponding values of the main volume estimator and another parameter usually height (h or H). Table entry requires two known parameters. Standard volume tables correspond with standard volume equations.

Volume tables can be derived from volume formulas, but such tables are generally less accurate than those derived from equations. This is because volume formulas lack the quantitative relationship established in volume equations between volume and the volume parameters.

Generally, graphical summary of volumes is usually less objective than the corresponding volume table, because graphs provide only approximate solutions to the formulas or equations they represent. The exact quantitative solutions are provided by the corresponding volume tables. Also, graphical procedures usually require large amounts of data, but minimum knowledge of mathematics and statistics. The construction of alignment charts requires special techniques because their multi-entry nature requires the inclusion of all the variables in the formula or equation in a single alignment. Like formulas, they only provide approximate solutions to the equations they represent without actually solving them. Volume regression graphs are also graphical summaries of volume equations. They are mainly used to determine the regression constants and coefficients rather than the individual tree volumes, which are normally computed from the regression equation. Once the volume regression is established, the corresponding volume tables can be constructed.

Photo volume tables and field volume tables cannot be used interchangeably because of the imperfect correlation between crown and stem diameters. Moreover, corresponding 'heights' used differ by definition and therefore in value. While total height is used in photo volume tables, other stem heights (such as bole height for tropical trees) are used. Furthermore a DBH class in field volume regression is confined to a compact unit of trees with clear bole height and taper alone affecting volume. On the other hand, a crown diameter class (cd) in photo volume regression is a loose group of different sized trees varying both in DBH, height and taper. Greatest heights are not confined to the highest DBH class. Consequently, different volumes are obtained when the two regressions are compared for the same tree. Similarly, corresponding photo volume and field volume tables cannot be used interchangeably because field mensuration data are more accurate than photomensuration data.

The standard error of stand photo volume tables is likely to vary between 15 - 30% while that of the tree volume tables may be higher because stand characteristics are more accurately estimated on aerial photographs than tree characteristics (Howard, 1976). Photo volume tables are more efficient when photomensuration data used for table entry are correlated with ground information to correct systematic errors in photomensuration (Nyyssonen, 1962). Without such correlations, only the approximate volumes could be predicted. The predicted volumes, being relative volumes, are useful for stratifying the forest area ahead of field inventory as part of the subsampling technique in the preliminary surveys (Loetsch & Haller, 1973).

4-2.3 Photovolume estimation methods

Volumes can be estimated on aerial photographs by direct and indirect methods, using photo volume tables in both cases. The direct method relies entirely on photosampling without field sampling. The indirect method relies on field sampling to correct systematic errors in the photomensuration. The disadvantage of the direct method is the inability to estimate the magnitude of bias from the use of photo volume tables. Literature is scarce on the comparison of direct volume estimates and field volume alone. Rogers (1958) observed a difference greater than 10% in only a few cases of the comparisons he made. He found that these would require adjustment after a field check. The other cases were almost evenly balanced between negative and positive differences. Moessner (1964) showed that the direct photo volumes estimated by experienced forest photointerpreters were within 15% of the field volume estimates 90% of the time. Direct photo volume estimation is of great value where forests are not readily accessible.

Bickford (1961) listed three basic requirements for efficient sampling:

- condition classes should be defined independently of samples to obtain class averages.
- class averages should show real differences.
- observations should be properly distributed by classes.

It follows that in the indirect methods, the forest area should be stratified by volume related-characteristics into homogeneous classes before field sampling. The variation within individual classes should be less than the variation between the classes. Photomensuration data for predicting volume from volume tables should be obtained by sample plots, systematically distributed over the entire survey area on aerial photographs. Several workers have described various multistage sampling designs for both the direct, and the indirect, volume estimations on aerial photographs. The [illegible] unique designs were described by Westby and others (1968) for direct estimation, and

Langley (1969) for indirect estimation.

The design by Westby and others involved the division of the forest area into equal rectangular blocks, and each block into strips. Sample strips were selected from each block for photography. Equal number of photoplots were randomly distributed in the individual sample strips. The DBH and volume of each tree in the photoplots was estimated using functions of height, crown area, number of trees growing in a circular surrounding of the subject tree, and the number of trees taller than the subject tree among six nearest neighbouring trees. These functions were derived from only 100 trees measured in the field.

In the first phase of Langley's design, the forest area was divided into equal blocks on very small scale space photographs using a square grid templet. By photointerpretation, the forest area in each unit was related to volume by prediction (probability proportional to prediction (3P) sampling technique of Grosenbough (1965). Two strata were selected from each block using variable probability theory. The second phase included four subsampling stages, two of which were accomplished on aerial photographs. Each stratum was covered by small scale aerial photography. Also, each stratum was subdivided into equal strips on the small scale aerial photographs using strip grid templet. Two strips were selected from each stratum with probability proportional to the predicted volume. Each strip was simultaneously photographed at a medium scale for an entire coverage, and at a large scale for an interval coverage. Each exposure of the interval coverage comprised a cluster of stereo-triplets of aerial photographs. The centre photograph of each stereo-triplet was divided into equal photoplots for stereoscopic photomensuration. The volume of each photoplot was predicted from the photomensuration data. One photoplot was finally selected in each sample strip for field sampling, using the 3P technique (probability proportional to the predicted volumes). The DBH of all trees in the selected photoplot was measured in the field, and the volume of each tree was estimated from volume tables. These volume estimates were used to select four to six trees, which were accurately measured for DBH and height to compute the exact volume of each tree.

According to Langley, in order to obtain volume estimates for the whole survey area, the computed tree volumes were expanded back through the sampling formula, using the probabilities and area expansion factors computed at each sampling stage. The large scale photo cluster area was related to the medium scale strip area to provide an expansion factor for the scale photo volumes. By using a multistage design based on the 3P technique, Langley sampled a 24 686sq.km. survey area from only ten field plots totalling 2.43ha. He obtained a total volume of 63 million cubic metres with a sampling error of 13%.

Photointerpretation keys have also been used for volume estimation. A typical example is the use of stereograms constructed for areas of known conditions e.g. field volumes (Moessner, 1956; Avery, 1967; Aldrich, 1967). Construction of stereograms is fundamentally based on statistical stratification into volume or volume related classes. Their use involves visual comparisons mainly, though some measurements are occasionally made for the comparison. Generally, volumes estimated from interpretation keys such as stereograms are subjective and often inaccurate. They are useful, however, as first level information for extensive surveys, such as exploratory or reconnaissance surveys.

The foregoing are a few of the various schemes used for volume estimation. These schemes vary according to the prevailing conditions in the forest area. Different forest types, site qualities, silvicultural treatments, species composition, stand sizes, and other conditions, may require different schemes. Moessner (1963a) found that volume classes obtained by photomensuration, and aerial volume tables, were best of the eighteen schemes tested. He also found that the use of volume classes could reduce the field-survey time by about 60%.

4-2.4 Reliability of photovolume estimates

The accuracy of volume estimated on aerial photographs is determined by several factors, including the precision and accuracy of the photomensuration. Other factors mainly affect the statistical procedures directly or indirectly, the most important being:

- species identification and species distribution
- field location of photoplots and field recognition of photosample trees.
- photo visibility factor

The difficulty in identifying tropical tree species, particularly on aerial photographs, hinders the assessment of the forest growing stock for management purposes. Consequently, it is seldom possible to assess separate volume equations for the individual species of mixed tropical forests, but three possibilities can be considered for such forests:-

(i) separate volume equations for the most important (economic) species and a common volume equation for the remaining species.

(ii) separate volume equations for the most important species and each of the remaining species grouped with one of these possibly according to their taper curves.

(iii) separate volume equations for homogeneous volume-related classes derived from volume-DBH scattergrams of different species or from any other suitable analysis e.g. multivariate analysis.

In situations where volume equations have not been established, several equations have to be tested in search of a suitable equation. For instance, Barley and others (1972) tested nine equations on *Pinus caribaea* var *caribaea* in Cajalbana forest in Cuba. The construction of a new equation and the testing of the existing ones are time consuming and expensive. Francis (1966) described a method for photo recognition of species where identification is difficult or impossible, provided good quality aerial photographs are availabel at suitable scales. The method relies on photoreading of photocharacteristics identified with a species or a group of species for the recognition of the particular species or group of species elsewhere on aerial photographs. Such photo descriptions, though non-informative, are useful for grouping unidentified species for volume regressions, because species with the same photocharacteristics are likely to have common tree characteristics. The degree of identification error could be greatly reduced by matching these photocharacteristics with height, crown size, and site in the photoreading.

It is still generally difficult to estimate the proportion of trees which belong to a particular species or a group of species within a forested area, or even within a stand. As a result, it is often difficult to estimate the volumes of these trees from the total forest or stand volume. For instance, the volume of the economic species is of greater value than the total volume in the production aspect of forest management. If the proportion of the economic species is known, it is possible, without the need for species identification, to estimate the volume of the economic species from the total volume. However, the incidence of economic species varies widely, even within a forest stand.

Heinsdijk (1957, 1958) found that only 20 of about 125 species occurring in a study area within the lowland forest in Surinam were of timber value. Also, Ola-Adams and Iyamabo (1977) Larin-Alabi (1978), reported that only 47 of over 560 Nigeria tree species were being harvested. It is generally difficult, if not impossible, to establish a mathematical relationship between the number of trees belonging to the economic species, and the total number of trees in a large forested area. The probable solution would be to establish this relationship for separate parts of the forested areas. For example, Heinsdijk (1957, 1958) established a definite relationship ($r = 0.855$) between the volume of the economic trees and the total volume of a fairly homogeneous stand of dense lowland forest in Warkambas in Sukadana area (Surinam). Similarly, Swellengrebel (1961) found that the volume of green heart (Ocotea radiaei) in green heart bearing mixed rainforests of Guyana was fairly constant for individual units he delineated on 1:30 000 scale aerial photographs. His volume estimates had an error of 1.5%.

In volume regression, different species would follow different trends (Sayn-Wittgenstein & Aldred, 1967), but if species identification is not feasible, the only possibilityis to establish a mean regression for all the species in a particular forested area. This would result in inaccurate volume predictions for individual trees of the different species. Furthermore, if the species composition varies in different parts of the forest, the extrapolation of the regression for one part to the other parts would result in over estimation of the less abundant species and under estimation of the more abundant species in these other parts.

Another problem is the difficulty in locating photoplots and photosample trees in the field. In most tropical forests, the general absence of clear landmarks on aerial photographs to aid the precise location of photoplots and photosample trees in the field, often results in wrong correlations and inaccurate volume estimates. Aerial photographs flown for purposes other than forestry, are often used in tropical forest surveys. These photographs are seldom recent or available at suitable scales. These problems compound the difficulty generally encountered in the precise location of photoplots and sample trees in the field.

Probably the most significant factor affecting the reliability of photovolume estimates, is the photo visibility criterion. It sets the limit for volume parameters measured for volume formulas and the limit for the lowest class of crown diameter measured for volume equations. However, several workers, including Paijmans (1951, 1975), Heinsdijk (1957, 1958), Nyyssonen (1955, 1962), and Swellengrebel (1959) indicated that the trees whose crowns are not photo-visible do not generally contribute significantly to the total volume. These workers also indicated that the largest photo-visible crowns belong to trees which generally contribute only a small percentage of the overall volume. Such trees are also reported to carry the largest amount of defects. It is common for economic trees whose crowns are not photo-visible, to occur in exploitable sizes below the canopy. Above all, parts of the crowns of the trees which contribute significantly to the overall volume, may be obscured by neighbouring canopy-trees. Francis (1966), Lanly (1973), and other workers, suggested that correction factors could be applied on the overall estimate to account for exploitable trees whose crowns are not visible entirely, or whose crowns are obscured in parts. A correction factor would be needed also in respect of defective trees carrying very large crowns. The problem is by no means solved by applying correction factors, for the simple reason that the distribution of the trees in question varies in different parts of a forested area.

The statistical implications of photo-visibility factor on volume-related (DBH/cd) and volume (V/cd) regressions were considered in Sections 4-1.2 and 4-2.1 respectively. Photo-visibility criterion permits the mensuration of canopy trees only. It was also suggested that if the proportion of the canopy trees, or more specifically the emergents which belong to the economic species is known it is possible to estimate, by multiple proportion or ratio estimates, the volume of economic trees from the total volume. Again, this would be unrealistic for a large survey area, because the proportion would vary in different parts of the survey area.

Finally, much that could be observed by photointerpretation is difficult to translate into statistical data. Since quantitative interpretation cannot be separated entirely from qualitative interpretation, statistical assessment of the quantitative information alone would not give the most satisfactory overall appraisal of the whole situation. This explains why the accuracy of quantitative photo surveys is generally low,relative to quantitative field surveys. The reverse is almost the case for qualitative surveys. Empirical data are usually obtained when qualitative photo-information is quantified. Such secondary data may not be suitable for the statistical tests designed to solve the problem at hand. Consequently, misleading statistical procedures are followed only to obtain wrong values for the degree of reliability of the photo survey.

Since the reliability of survey results is usually determined in statistical terms, it is necessary for the forester to consult a statistician. However, the statistician may not fully understand the forestry implications of the photointerpretation data being handled. For the simple reason that some observations on remote sensing imagery cannot be adequately quantified for statistical analysis, Francis (1966) indicated that the use of simple graphical methods of averaging, and least square method to obtain data sets for regression, were preferable for forestry purposes. He added that the use of grouped data would reduce handling and computation to a minimum. Instead of following sophisticated procedures involved in regressions, which include variables for defects and rejects, simple correction factors could be applied to the overall volume estimated by simpler regression equations. Confidence limits are then determined to give the probability of reliability of the results. It is often reported that the reliable minimum estimate increases with reduced scatter obtained by additional measurement. This is seldom true for regressions based on truly representative samples, because a sufficient number of trees would have been considered in each class of variable to determine the class average. Additional measurements would still give the same average, otherwise the regression sample would not be regarded as representative of the population.

4-3 Photostratification

Stratification of forests into condition classes is more rapidly accomplished on aerial photographs than in the field. Generally, stratification based on photo or field mensuration data could be regarded as statistical classification, because the stratification criteria are quantified. For this reason, the individual strata would have a standard error of the parameter being assessed lower than that of the unstratified forest in respect of the characteristics used for the stratification. Consequently, the sampling error of the estimates of these characteristics, or of other dependent characteristics would be greatly reduced. Photostratification of tropical forests ahead of field inventory, helps to establish a survey approach similar to that for temperate forest surveys, in which stratification is principally used to improve sampling efficiency. Photostratification helps to establish a sampling frame from which sampling units can be drawn objectively. Sampling efficiency is improved either by reducing the sampling error for an equal sampling intensity, or by reducing the sampling intensity for the same level of accuracy (sampling error) relative to a corresponding unstratified sampling, (Howard & Lanly, 1975; Larin-Alabi, 1978). In the latter case, the amount of field work could be reduced by up to 60% (Spurr, 1948; Luender, 1959; & Kio, 1971). Such reduction would save money, time and effort, over unstratified sampling. Moreover, a large number of photosamples could be examined rapidly with only a few plots checked in the field for necessary correlations with ground information (Miller, 1963 & Langley, 1969).

In addition to their importance in volume estimation, stem and crown dimensions are important forest characteristics by themselves for their individual or combined use in stratifying forests into 'condition classes', with or without subsequent volume estimation. The stratification ahead of inventory (a priori-stratification) is directly based on photomensuration data, and it is different from stratification following inventory (a posteriori-stratification)which is based on volume - the outcome of the inventory.

The main characteristics frequently used for photostratification of forests are percentage crown closure, crown count, crown area, or diameter and height. These characteristics could be used individually or in various combinations. Stratification based on these characteristics is important to forest management, because the characteristics are parameters of volume on which management is ultimately based. Photostratification based on other characteristics which could be appraised on aerial photographs without quantification, is also useful. Such stratification is less realistic in a statistical sense than that based on characteristics that can be quantified on aerial photographs. For instance, accessibility, merchantability, cover types, and physiognomy, are fundamentally qualitative characteristics frequently used for photostratification. Occasionally, condition classes obtained by photostratification may correspond with those of existing classification systems, particularly when the same criteria are used.

In view of the foregoing considerations, Landsat data are suitable for statistical stratification of forests to some extent. Experience with aerial photographs indicates that photostratification of forests into volume or timber density classes, could be based on stereoscopic profiling (Smith, 1969; Howard 1970a, 1970b). Also, non-stereoscopic measurements of crown diameter and crown closure are more efficient than the corresponding stereoscopic measurements for photostratification of forests into volume classes. This is mainly due to the general stereoscopic effect under magnification which makes precise measurements of horizontal distances on a three dimensional crown image very difficult (Francis, 1966). Furthermore, using circular plots is of greater value for photostratification than the conventional line sampling or any other sampling technique (Boon, 1961). Finally, simple statistical tests, such as the chi-squared test, are adequate for testing the reliability of photostratification. Complex statistical tests may not be justified because some important observations are not easily translated into suitable statistical forms (Francis, 1966).

Because of the heterogeneity of tropical forests relative to several characteristics and factors, a single criterion is not efficient on its own to provide a very satisfactory photostratification of these forests. Pooling several characteristics and factors as a set of stratification criteria, could provide the most satisfactory stratification. Statistical evaluation of such stratification would be very difficult. Moreover, some of the criteria may not be quantifiable for statistical analysis. Probably the most objective stratification, would be one based on quantifiable characteristics as obtained by photomensuration. Again, the statistical tests may not produce significant differences as observed between the classes. As long as the main objective of the stratification is achieved - to improve sampling efficiency or to save costs - any stratification method could be used in the photostratification of tropical forests.

4-4 Inferences and conclusions

Most of the obstacles which hinder photomensuration of tropical forests are mainly due to the nature of the forests, rather than the technical limitations of the aerial photographs themselves. The only technical limitation which is apparent is the general lack of aerial photographs at scales suitable for photomensuration. The economic scales at which aerial photography of tropical forest areas are flown have not been adequate for reliable data collection by photomensuration techniques. Most of these photographs have been acquired for purposes other than forestry. This notwithstanding, only a few parameters can be measured on aerial photographs of tropical forests. The canopy which is the only source of direct information of closed forests on aerial photographs obscures the ground and this has prevented parallax heighting of trees. Also, percentage crown closure has not been of any interpretative value because the canopy of the productive forests is closed and continuous. However, it has been possible to determine percentage crown closure for a group trees above a specified minimum crown diameter or a given species or group of species. Photomensuration of tropical forests is therefore concentrated on crown measurements. The irregular shapes and the polymorphic structure of the crowns of tropical trees have hindered the precise and accurate measurements of these crowns.

As the principal objective of photomensuration is to estimate volume at a speed which is superior to that of field methods alone and with the same precision and accuracy, it is essential that photomensuration data (or photovolumes) are correlated strongly with field mensuration data and/or field volumes. The difficulties in locating sample plots and sample trees in the field have hindered the collection of the necessary field data for such correlations. The closed and continuous canopy over extensive areas usually obscured the landmarks that could have been used in orientation. The striking similarities between the crowns of different species, the polymorphic structure of the crowns of individual species have not permitted the recognition of the individual trees in the field. Furthermore, the indistinctive crown characteristics of individual species hinder the accurate species identification which is important in correlating photo and field mensuration data as well as in volume estimation.

Crown diameter, being the most important photo parameter of volume is usually related to the most important field parameter of volume which is DBH or DAB. There is a stronger and a more consistent DBH/cd correlation for temperate tree species than for tropical tree species. Though a perfect DBH/cd correlation does not exist in nature, it is not certain whether the weaker correlation frequently observed for tropical species is primarily due to the tree shape and form or to the conventional use of DBH or DAB for the correlation. In the former case most tropical species do not have distinctive crown shape or form and several species usually have plank buttresses. These irregularities of shape and form of boles and crowns may account, in part, for the weak DBH/cd correlation usually observed for tropical tree species. In the latter case the use of DBH or DAB was originally established for temperate tree with definite shape and form. Buttresses of tropical trees are usually large and high in comparison with those of the temperate trees. These differences between temperate and tropical trees have caused differences in the strengths of their DBH/cd correlations.

In view of these considerations, the use of DBH or DAB for tropical trees raises some questions. Volumes of tropical trees estimated by judicious application of log formulas without using DBH or DAB have been found to be more reliable than those estimated by taper formulas using DBH or DAB(Banyard, 1973; Lanly, 1973). With taper formulas, some volume is lost relative to breast height or buttress height. This lost volume is not compensated in the volume of the reference cylinder used in the taper formulas. Further research is needed to determine a more usable bole diameter, other than DBH and DAB in particular, for estimating wood volume of tropical trees. However, such diameter may not permit bark measurements which is possible with DBH. In spite of the various problems associated with photomensuration, various workers have used photo methods to some extent for estimating volumes of tropical forests.

The difficulty of parallax heighting has restricted the use of the formula technique for photo estimation of tree volume in closed tropical forests. The main option is therefore the use of the equation technique which is also hampered by the difficulty of identifying tropical tree species on aerial photographs. For this reason, volume estimation by photo methods in the tropics would therefore be on stand basis. In this case the volume of individual trees is not and cannot be estimated from the stand volume. Whichever approach is used to estimate tropical forest volumes by photo methods, volume estimates would still be unreliable for management purposes. Such volume estimates have been used mainly for assessing the relative timber content of the various parts of the forest and have provided a basis for forest stratification ahead of field inventory. More reliable volume estimates have been obtained with stratification than without.

The use of volume equations for tropical forests is still a new procedure for estimating volume by field methods. Until there is an established use, volume formulas would remain the main technique for estimating the timber volume of tropical forests. As volume equations and volume tables become established for several species or groups of species in different parts of the tropical forests, photo volume equations would be of greater value than they are at present. It would then be possible to use photomensuration data directly with photo volume tables. At present, some investigators use photomensuration data with field volume tables only to obtain unreliable volume estimates. Photo volumes and field volumes differ markedly because they are obtained by different procedures, using different estimators of volume and different independent variable in the statistical regressions.

It is my opinion that photomensuration is more valuable for stratifying tropical forests ahead of field inventory than for estimating the volumes of these forests and that accurate volume estimates of tropical forests can be obtained only by field sampling. Photomethods supplemented by field sampling, in comparison with purely field methods, have the advantage of improving the sampling efficiency either by reducing the sampling error for an equal sampling intensity or by reducing the sampling intensity, and therefore the costs, required for the same level of sampling error. The realisation of this advantage would depend on the usage of photo methods which is still limited by several factors including economic constraints. Moreover, as plantation forestry is gradually replacing the natural regeneration silvicultural system in the tropics, so would the use of photo methods for volume estimation be of increased value for the estimation of tropical forest volumes. The technical capabilities of aerial photographs for forest mensuration were not investigated as explained in the "Introduction to Part II". However, the possibilities for forest mensuration on the aerial photographs were considered along with the interpretation of forest types and tree species in Chapter 8.

CHAPTER 5

THE USE OF REMOTE SENSING FOR AREA ESTIMATION

5 Area estimation

The primary aim of forest mensuration is to collect tree information within a forested area and to relate this information to the area of the forest. For this purpose, information is required on the total area of individual forest classes within a forest management unit. These classes are defined by some classification or stratification e.g. forest types and condition classes such as diameter, height, and volume classes. Area information is principally used for estimating the total values of the forest characteristics (tree-information) being assessed for individual forest classes and consequently for the management unit. It follows that the reliability of the estimates of the forest characteristics depends on the accuracy of the area estimates. When extensive forest tracts constitute a unit of management as in the tropics, information is required mainly on the distribution of the forest classes within the management unit. For a more intensive management in which the management units are comparatively smaller, information is also required on the distribution of the sample plots from which the forest characteristics are assessed within the management unit. Generally, the distribution of sample plots in comparison with that of forest classes, is of relatively minor importance in an extensive management unit.

Map compilation is essential when spatial distribution of forest classes and sample plots are required. In this case, area estimation can be accomplished on these maps. Compilation of new maps is unnecessary if there is an efficient data base, as new information collected during forest surveys is used to revise the existing maps and to update the existing data. The position is different in many tropical forest areas for which there is a general lack of accurate forest maps and efficient data bases. Areas are usually estimated on forest maps compiled from the results of inefficient forest mensuration data. As new and superior techniques are being used for collecting tree information, the data on the existing forest maps become outdated. Consequently, there is a need in the tropics to compile new forest maps from which accurate area estimates can be obtained. Area estimation and mapping can be accomplished by ground methods which are usually slow and often very expensive for large parts of forests and tropical forests in particular. For extensive forest region area estimation and mapping can be accomplished at a superior speed and at an economic cost by remote sensing methods.

In assessing the value and limitations of remote sensing methods for estimating forest areas in the tropics, it is not sufficient to consider cartometry in isolation from the characteristics of the remote sensing images being used and those of the forests being investigated. Irrespective of the area estimation method employed, these characteristics affect the overall accuracy of the area estimates. In addition, only these characteristics provide the background to explain such cartometric discrepancies which may occur in the area estimates and their implications.

In view of these considerations the ensuing review of literature covers:-

(a) interpretative value of remote sensing imagery.

(b) the use of remote sensing imagery as map substitutes.

(c) the use of remote sensing imagery as a source of information for mapping.

(d) area estimation methods.

These are considered in terms of relative efficiency and acceptable accuracy for forestry purposes as follows:

5-1 Interpretative value of aerial photographs, Landsat and SLAR imagery

As areas of forest classes which have been interpreted on remote sensing imagery are to be estimated, the accuracy of the estimates depends largely on the interpretability of forest characteristics on remote sensing imagery. This in turn depends largely on the extent to which the forests can be detected and resolved by the imaging system, and the extent to which the forests can be recognised on the images being interpreted. These conditions are determined by the characteristics of the imaging systems and their resulting imagery as outlined in Table 1.1.

The detection of the presence or absence of information by a remote sensing system is determined by the wavelength of the recording band. Also, the resolution of the information on the resulting imagery is determined by the size of the resolution cell (picture element or pixel) of the remote sensing system. Generally, objects shorter than half the recording wavelength are not detected and those smaller than the pixel are not resolved. During imaging, the relatively low frequencies of the recording wavelength suppress the higher spatial frequencies of objects shorter than half the recording wavelength while the pixel acts as a filter for small objects. It follows that the size of the objects that can be detected and resolved by an imaging system increases with recording wavelength and the pixel fineness. Consequently smaller objects are resolved better on images acquired in the shorter wavelengths and with fine pixels. As resolution is better represented at larger imaging scales object recognition on remote sensing images increases with the acquisition scale of the imagery.

The foregoing accounts for the recognition of objects by their shape on aerial photographs. It also explains the recognition of surface features by their reflectance on Landsat images and by their surface roughness on SLAR images. However, it should be noted that radar energy does not penetrate the vegetation canopy as frequently reported in literature. Instead, it interacts with vegetation and tends to be reflected rather than transmitted by vegetation (Sabins,1978). This is clearly shown by the SLAR expression of physiognomic differences in the vegetation of areas where topographic height differences are virtually absent i.e. in flat or even sloping terrain. Answering his own question on how far and how fine remote sensing is, Hempenius (1979) applied the pixel concept to the scale (how far) and the resolution (how fine) of different types of aerial photography, satellite and radar imagery. The table below which compares in relative terms the resolution of typical examples of these imaging systems is based on the findings of Hempenius.

Characteristics	Panchromatic aerial photography	Landsat MSS system	SLAR imaging system
imaging band	visible and near infrared	visible and near infrared	microwaves
wavelength	short (micrometres)	short (micrometres)	long (centimetres)
frequency	high	high	very low
pixel size	very small	very large	large
pixel fineness	very fine	coarse	medium
scale	very large	very small	small
resolution	very high	very low	low
resolved objects	small objects	extensive features	large objects and extensive features
main recognition criterion	shape differences	surface reflectance differences	surface roughness differences

The characteristics listed above are quantified in Table 5.1

Table 5.1 Comparison of the resolution of aerial photographs Landsat and SLAR imagery

	Source of imagery	Printing scale	Ground resolution			
			linear (m)	area ha.	linear (m)	area ha.
1	Aerial photography (after Sabins, 1978)	(line pairs per cm.)	(40)	(40)	(100)	(100)
	6100m. altitude	1:40 000	0.50	$0.0^{5}25$	0.20	$0.0^{6}40$
	4575m. altitude	1:30 000	0.37	$0.0^{5}14$	0.15	$0.0^{6}23$
	3050m. altitude	1:20 000	0.25	$0.0^{6}63$	0.10	$0.0^{6}10$
	1525m. altitude	1:10 000	0.15	$0.0^{6}23$	0.05	$0.0^{7}25$
2	Landsat MSS (after ASP, 1975a)	(scene contrast)	(low)	(low)	(high)	(high)
	Scene corrected (bulk) Band 4 images					
	archival films	1:3 369 000	126	1.588	54	0.292
	3rd generation film positives	1:3 369 000	118	1.392	53	0.281
	3rd generation film positives	1:1 000 000	136	1.850	57	0.325
	computer compatible tapes	-	97	0.941	44	0.194
	Precision processed Band 4 images					
	5th generation film positives	1:1 000 000	184	3.386	79	0.624
	computer compatible tapes	-	193	3.725	80	0.640
3	SLAR imagery (after ASP, 1975a)	(depression angle)	(overall)	(overall)	(16°-29°)	(16°-29°)
	Motorola 94 (depression angle 10°-29°)	computed averages	57.7	0.345	52.4	0.275
	Westinghouse 97 (depression angle 16°-50°)		17.3	0.030	18.2	0.033
	Goodyear 102 (depression angle 14°-45°)		16.7	0.028	16.6	0.028
4	Small scale imagery (after Howard, 1976)	(resolution)	linear (m)		area (ha.)	
	aerial photography	1: 50 000	3		$0.0^{4}9$	
	stratospheric photography	1:120 000	3		$0.0^{4}9$	
	1:40 000 scale SLAR imagery	1:250 000	10 - 20		0.010 - 0.040	
	1:50 000 scale SLAR imagery	1:250 000	40 - 60		0.160 - 0.360	
	Landsat colour composite images	1:250 000	224 - 316		5.018 - 9.986	
	Landsat computer print-out	1.250 000	100 - 187		1.002 - 3.497	

Sources noted above.

which also compares the ground resolution of the three types of imagery acquired at various scales.

In view of these considerations, aerial photography can provide a greater amount of forest information than Landsat and SLAR imaging systems because of its superior resolution. Consequently, aerial photographs are more widely used for forest surveys than Landsat and SLAR images. However, each system has its own application. For instance, because of its broad synoptic view Landsat imagery can be used for grouping the exclusive forest types separated by photointerpretation into more inclusive general types. Also, because of its emphasis on surface roughness, SLAR imagery can be used for mapping the terrain of forested areas.

The extent of the use of the three types of imagery as map substitutes or as sources of information for mapping is determined by the size of the minimum unit of delineation possible on the imagery and consequently by the ground resolution of the imagery (see Table 5.1).

The theoretical image resolution is not usually achieved in practice. Boon (1960) reported the minimum unit of delineation on 1:50 000 scale aerial photographs to be 0.25ha. while Howard (1976) reported 4ha. for Landsat. Sabins (1978) stated that Landsat ground resolution varied between 4 - 6.25ha. though some investigators claimed that objects of about 0.64ha. in size and lineaments only 15m. wide could be resolved. The resolution achieved in practice is generally worse than the corresponding theoretical resolution. Howard (1976) suggested that the "best identification of units of similarity" (optimum unit of delineation) for Landsat imagery should be about 1 - 3.5ha. generally, and about 5 - 10ha. for colour composites. Aerial photography provides the best resolution for interpretation. SLAR resolution is moderate while that of Landsat is poor.

Image characteristics constitute an important factor in the interpretation of forest characteristics on remote sensing imagery. Shadows and highlights which are characteristics of aerial photographs and SLAR are virtually absent in Landsat due to its small scale. Shadows aid interpretation as a means of orientation. In some cases, tree heights are measured from tree shadows, but in other cases shadows may obscure objects and so hinder interpretation. With aerial photography, shadows and highlights usually cause false tonal variation which may lead to wrong interpretation. However, some objects have characteristic shadows and highlights which aid their recognition. Topographic relief which is determined by relief features such as mountains, hills, valleys and canyons is expressed as highlights and shadows. The side-look geometry of SLAR system causes topographic features to create shadows towards the look-direction, the hill top being represented by highlights. Radar shadows and highlights are more pronounced where lineaments are oriented normal to the look-direction. They are longer in the far range than in the near range. These enhance the interpretation of lineaments on SLAR mosaics compiled from near-range images but hinder the interpretation of forests.

Surface roughness of the terrain strongly influences the strength of radar returns. Surface roughness, which is quite distinct from topographic relief, is determined by surface textural features such as canopy structure in vegetated areas and microtopography in non-vegetated areas. A smooth surface reflects all the incident radar energy without any backscattered component. Consequently the smooth surface produces a dark signature on the image. A rough surface scatters most of the incident energy causing a relatively strong backscattered component which produces a bright signature on the image. A surface of intermediate roughness reflects a portion of the incident energy and diffusely scatters a portion. This causes some backscattered component which produces an intermediate signature on the image. As a result of this, topographic height differences can be mistaken for physiognomic height differences within a forested area.

In addition to surface roughness, bright radar returns are produced by metallic targets such as the aluminium corner reflectors used as ground controls for the Nirad Project in Nigeria. Also bright radar returns are produced by corner reflectors that are formed by three planar surfaces intersecting at right angles. Regardless of the incidence angle at which a radar wave enters the cavity of a corner reflector, it is reflected directly back to the antenna. Outcrops of regularly jointed and layered volcanic and sedimentary rocks may form natural reflectors. The spacing geometry of plantation trees also creates corner reflectors within the canopy to aid their identification on SLAR imagery. For instance, the spacing geometry of _Elaeis guineense_ (oil palm) plantation and the leaf geometry of this palm tree create sufficiently compact corner reflectors to make the species a very strong radar target. Oil palm plantations were quite distinct on the SLAR imagery of Nigeria but the interpreters of the imagery did not mention the corner reflector effect in their report (HTS, 1977, 1978). Man-made features such as buildings and bridges also form corner reflectors. In forested areas roads which are not obscured by the canopy also form corner reflectors. Abrupt changes in the physiognomy usually create corner reflectors by which the physiognomic height differences can be recognised on SLAR images.

Cloud-cover which affects both photographic and Landsat systems is penetrated by radar energy. In the tropics, rain causes Ka-band energy to be backscattered and returned to the antenna without reaching the ground. This results in strong returns. The longer X-band energy is backscattered only by the heaviest rainstorms.. L-band energy is virtually unaffected. As SLAR images in the X-band, it offers the advantage of producing cloud free images.

Side-lobe banding is characteristic of SLAR imagery. These are patterns of light bands parallel with light direction and concentrated in the near range. Side-lobe banding is due to subsidiary pulses (side-lobes) transmitted in addition to the main pulse. The terrain returns from these side-lobes reinforce the main return signals to cause brighter bands on the image. The lower energy of the side-lobes is largely attenuated by the longer echo-time of the far-range. A similar banding which is represented by brighter or darker than others may occur in every sixth Landsat scan line due to the higher or lower sensitivity of one of the six detectors. Sixth line drop out is a Landsat image defect in which no data is recorded for every sixth scan line which is black on the image. On some Landsat images, the scan lines are offset horizontally in either a random or periodic fashion. These bandings and line offsets cause serious defects on enlarged images and so hinder interpretation.

All the image irregularities outlined above hinder forest interpretation on remote sensing imagery. However, imagery can be reprocessed for image restoration or enhancement. As Landsat information is primarily recorded in digital form, all the image irregularities and geometric distortions can be corrected by digital image restoration before they are commercially available. This adds to the interpretative value of Landsat images.

The commercial products of the three types of imaging systems can also be reprocessed by the user to enhance the extraction of information. These enhancement procedures include contrast enhancement by electronic photographic processing, density slicing and edge enhancement. Colour composite generation from black/white multispectral images provides an additional option of colour for interpretation. This is possible with Landsat images and multispectral aerial photographs as none of the currently available SLAR systems produces multispectral images. Multispectral aerial photography is rarely used in the tropics for forest surveys. Consequently, Landsat images are the only option for creating colour composite images for the interpretation of tropical forests. This is another advantage of Landsat interpretation.

The use of different film/filter combinations in the single channel (broad band) aerial photography also provides several options of image representation e.g. infrared and colour images. Infrared aerial photography is of great advantage where atmospheric haze hinders panchromatic aerial photography. Also colour photography and colour infrared in particular are of great advantage where forest types cannot be separated by tonal differences on black/white photographs.

As Landsat information is available in multispectral and digital forms, ratio images of a scene can be synthesised from different spectral bands (inter-spectral ratio images) or from different frames (inter-temporal ratio images). Corresponding tonal values, of the spectral or temporal images being synthesised into ratio images, are combined in various ways by simple arithmetic operations to produce a single tonal value for a set of corresponding tonal value. By digitizing the tones on multispectral aerial photographs, synthesised ratio images can be produced, but on such images objects cannot be recognised by their shapes. The suitability of Landsat information for synthesising ratio images provides an additional option for interpretation. Multispectral photography is seldom used in tropical forest surveys. The single channel imaging of SLAR precludes the synthesis of ratio images from SLAR imagery.

In conclusion, SLAR interpretation is hindered by the large amount of image irregularities which are difficult to rectify and the narrow range of enhancement possibilities. Image irregularities of Landsat though insignificant at the acquisition scale can be eliminated completely by image restoration and by reprocessing. Also, several methods are available for enhancing the extraction of Landsat information. In spite of these, the low resolution of Landsat hinders detail interpretation which is required in forest management surveys. For its superior resolution aerial photography can provide the required forest information. Aerial photographs can be acquired in colour and false colour without the need to enhance them before information can be extracted. Image irregularities are minimal. Moreover, interpretation aids and instruments are available not only to facilitate their interpretation but also to increase the confidence of the interpretation. In view of the foregoing, it is therefore my opinion that aerial photographs are superior to Landsat and SLAR images for the interpretation of tropical forests.

5-2 The use of remote sensing imagery as map substitutes

A map, being an orthogonal projection, differs from a remote sensing imagery which is fundamentally a central projection. (Paul Sam p 120) Consequently, there is uniformity in the scale at which terrain objects are represented on a map while there is variation in the scale at which they are represented on remote sensing imagery. This variation in the scale of remote sensing imagery is expressed as image displacement. It follows that if remote sensing imagery is used in place of a map for estimating forest areas, the planimetric errors due to image displacement would reduce the accuracy of the estimates. In aerial photography image displacement is largely due to surface relief and camera tilt. In the former, elevation differences between terrain objects cause the photo images of these objects to be displaced outwards from the nadir (relief or topographic displacement). In the latter the inclination of the camera causes photo images of terrain objects to be displaced outwards from the isocentre.

On the truly vertical aerial photograph, relief displacement increases radially outwards while tilt displacement is absent. In tilted aerial photography, a truly vertical condition obtains only along the isoline. Using the isoline as a reference, the photoscale increases radially outwards on the 'depression' side and decreases outwards on the 'elevation' side. In aerial photography, it is unnecessary to restore geometric fidelity before aerial photographs are used for the estimation of areas because of the availability of photogrammetric instruments designed for reconstructing geometrically accurate stereomodels from overlapping photographs. Nevertheless, rectified prints can be produced from these stereomodels. Only tilt displacement can be eliminated by rectification leaving relief displacement uncorrected.

Additional image displacements are caused by distortions resulting from small optical and mechanical defects in the camera and film. However, the major planimetric errors in the truly vertical photography are caused by relief displacement. Added to this, in the near-vertical aerial photography is tilt displacement. The effects of these errors on the planimetry of space photography are minimal relative to photo-scale. These errors indicate the positional mapping accuracy of the photographs at various scales. For 23cm. x 23cm. aerial photographs taken with Wild RC5, RC8 or Zeiss 15/23 camera and 152.4mm. lens whose distortion does not exceed ten micrometres, the following mapping accuracy was given in the Meridian Data Sheet annexed to an undated advertising publication by Meridian Airmaps Limited, Sussex, United Kingdom:-

Photo Scale	Planimetric Accuracy ($\pm$m)	Altimetric Accuracy ($\pm$m)	Contour Interval (m)
1:20 000	1.01	0.61	3.05
1:15 000	0.76	0.46	2.29
1:10 000	0.51	0.30	1.52
1: 5 000	0.25	0.15	0.61
1: 1 000	0.06	0.03	0.30

The actual accuracy obtained in practice can be worse than that stated above, depending on the efficiency of the methods used for the estimation. There is a wide range of photogrammetric instruments for correcting planimetric errors on aerial photographs.

Landsat imagery is normally corrected for geometric distortions before it is commercially available to the user. The standard commercial Landsat products are also capable of continuous refinement. Geometric errors which are corrected during image restoration processes are:

(a) Systematic distortions: which are not predictable and they must be evaluated from the Landsat tracking data or ground control information. Systematic distortions due to earth rotation and spacecraft velocity are evaluated from the tracking data. Those due to the altitude and attitude (pitch, roll and yaw) of the aircraft are evaluated from the ground control information.

(b) Systematic distortions: which can be predicted in advance are normally evaluated from pre-launching tests. These distortions are principally due to scanner distortion, mirror velocity variations and scan skew.

The planimetric accuracy of the restored Landsat imagery is expressed as positional mapping accuracy and registration accuracy, both of which are higher in precision processed images than in scene-corrected images as indicated below:

	Accuracy in metres	
	Scene corrected (bulk) images	Precision processed images
Positional mapping accuracy		
film products	776	743
paper products	780	757
Registration accuracy		
all products	336	159

Positional accuracy is a measure of the ability to locate a point in an image by its geocentric latitude and longitude. Registration accuracy refers to the ability to superimpose any point in one image with that same point on a different image (ASP, 1975a).

The central projection in Landsat imaging system applies to individual pixels (79m. x 79m.). It does not apply to an entire scene (185km. x 185km.) as in the case of area photography where it applies to the entire area covered by each photograph. It follows that the radial component of the errors resulting from perspective geometry are relatively small. As each scene is covered by millions of pixels (5.48×10^6) the radial magnitude of geometric errors is minimal. At the very small scale of Landsat images (1:3 369 000) the geometric errors and consequently the planimetric errors on each image are insignificant. Therefore Landsat images are virtually orthographic.

The planimetric errors which are due to image geometry can be minimised by using rectified prints or mosaics as map substitutes to estimate forest areas. Rectified aerial photographs are normally obtained from photographic reproduction of stereomodels which have been corrected for geometric errors. However, relief displacement is not eliminated on rectified prints. For economy, radargrammetric procedures are rarely used for forest surveys consequently 'rectified'

SLAR images are not common. Precision processed Landsat images can be regarded as rectified images for their superior planimetry although they are not generated from bulk (scene corrected) images. These are normally generated from the primary acquisition digital data.

The use of a time delay in the plotting circuit in SLAR system normally eliminates the effect of radial distance on the planimetry of SLAR images. Nevertheless, the side-look geometry of SLAR results in large geometric errors which can be corrected only to a limited extent. SLAR images are presented either as slant-range display which is typical of the real aperture SLAR systems or as ground-range display which is typical of synthetic aperture SLAR systems. In the slant-range display, the scale in the range (look) direction is compressed in the near-range portion of the image because targets are plotted on echo-time basis. The change in the depression angle from near range to far range causes the image display to be distorted relative to corresponding images on aerial photographs.

To produce undistorted ground range images SLAR systems employ a time delay in the plotting circuit to compensate for the echo-time differences. This compensation results in approximately orthogonal geometry in which the image scales are equal in the range and azimuth (flight) directions. The curvature of the transmitted SLAR pulse causes the top of a tall vertical target to reflect energy in advance of its base. This results in the displacement (layover) of the top of the target towards the near range direction (i.e. towards the nadir). In aerial photography, objects are displaced radially relative to the nadir. Other geometric errors in SLAR are distortions due to the altitude and the attitude (pitch, roll and yaw) of the aircraft. For economy, radargrammetric procedures are rarely used in the interpretation of SLAR for forestry purposes. Instead SLAR mosaics are interpreted and these are not sufficiently accurate for area estimation for management purposes.

As planimetric errors 'contract' with scale reduction, the use of mosaics tends to minimise the estimation errors which are due to the image geometry. This is because mosaics are usually compiled at the image scale and reproduced at reduced scale. Mosaics can be compiled with or without common orientation controls for the component images. The efficiency of mosaics for area estimation increases with the amount of control employed for their construction. Consequently, the relative efficiency of uncontrolled, semicontrolled, fully controlled mosaics increases in that order.

With aerial photography, orthophotomosaics (fully controlled mosaic of rectified prints) and photomaps (orthophotomosaic with superimposed contours) provide the best substitutes for maps. Landsat system provides several options for mosaic compilation. Mosaics can be constructed directly with scene corrected or precision processed images or from colour composites generated from them. Mosaics can be constructed from synthetic ratio images and synthetic stereo images. With SLAR system, mosaic compilation requires conditions which are more stringent than those of aerial photography and Landsat system. SLAR mosaics are more commonly used than individual SLAR strips either for interpretation or aerial estimation because of the high cost of radargrammetric instruments. In addition to their usefulness for minimising planimetric errors, mosaics provide a broader view than individual prints and so enhance regional interpretation.

A major drawback in the use of mosaics for interpretation is their general lack of tonal uniformity between adjacent prints. Contrast stretching by electronic photographic processes circumvents this drawback. Contrast stretching of Landsat tonal range is digitally accomplished by directional (linear) or spatial filtering. SLAR imagery has tonal uniformity across individual strips but matched edges in SLAR mosaics often simulate lineaments, particularly at enlarged scales.

5-3 The use of remote sensing imagery as a source of information for mapping

Results of forest interpretation are normally summarised on maps when spatial distribution (location) is required in addition to the numerical distribution (sizes) of the interpreted themes. The results can be presented on photogrammetric or thematic maps. In both procedures accurate interpretation and precise delineation of the themes are assumed. Forest maps are compiled mainly from aerial photographs because they contain more forest information than Landsat and SLAR imagery. The following account is based mainly on the compilation of maps from aerial photographs. Photogrammetric mapping implies an accurate mapping of natural and cultural features mainly from aerial photographs without any delibrate preconception of a particular theme as is the case in thematic mapping. Both planimetric and altimetric accuracy are essential for photogrammetric mapping. In thematic mapping, planimetric accuracy is of greater importance because area-related information is being compiled into maps. Because of the higher costs of establishing ground controls to meet the accuracy requirements, photogrammetric mapping is more expensive than thematic mapping. Thematic mapping requires only the transfer of the interpreted themes into the base maps which are mainly used to minimise mapping errors. This explains why thematic mapping is preferred by foresters.

Minimum acceptable accuracy is usually specified for any survey. The minimum acceptable accuracy in forest mapping relates to the planimetric error because planimetric themes are usually mapped. Minimum acceptable accuracy is expressed as point tolerance or ground error. Point tolerance is the maximum acceptable error in the location of any of the ground control points on the compiled map. Ground error is the maximum acceptable error in the location of a specified percentage of the ground control points on the compiled map. For extensive resource surveys (exploratory and reconnaissance) maps are compiled at small scales with a wide tolerance so that the resource could be accurately located. For intensive resource surveys (management and exploitation) maps are compiled at large scales with a close tolerance so as to obtain a reliable estimate of the resource (Moreno, 1970).

Stellingwerf (1973) indicated that a point tolerance of 100m. was suitable for extensive forest surveys as in the tropics and 10 - 20m. for more intensive survey. He added that high-value temperate forests were usually mapped with 2m - 20m. tolerance. For instance, point tolerance of forest maps in Europe is generally 5 - 8m. though some forest maps have been compiled at the scales of 1:2 000 and 1:1 000 with point tolerance of 2.5m. and 1.3m. respectively. In Switzerland topographic and cadastral maps are usually compiled at the scale of 1:10 000 with 1.5m. tolerance while forest maps are compiled at 1:40 000 scale with 5m. tolerance. The 1:50 000 and 1:25 000 scale Swiss National maps have 2m. and 1.5m. point tolerance respectively.

Rhody (1965) suggested that mapping accuracy should be determined according to the problem being investigated and the required results, adding that accuracy specifications should not be too rigid. The upper limit of planimetric accuracy in forest mapping is usually restricted by the ground resolution of the remote sensing imagery being used. According to Stellingwerf (1973) the maximum attainable planimetric accuracy for forest mapping from aerial photographs is restricted to 5m. tolerance. A minimum accuracy of 85% was suggested for forest type mapping from 1:80 000 - 1: 3 000 000 scale remote sensing imagery (ASP, 1975a) Howard (1976) suggested that a generally acceptable point tolerance should not be more than the ground equivalent of 0.5mm. on the map irrespective of the mapping scale. The extent to which the maximum attainable mapping accuracy can be reconciled with the minimum acceptable accuracy depends not only on the planimetric accuracy of the remote sensing imagery being used (see Section 5-2) but also on:

(a) the scale at which the thematic maps are compiled.

(b) the method for transferring thematic information from imagery into base maps.

(c) the amount of control for the thematic mapping.

The following discussion considers these factors in the light of the requirements for forest mapping.

5-3.1 Mapping scale

The scales of thematic mapping are determined by the scales of the base map and the remote sensing imagery being used. Thematic mapping requires good topographic or planimetric base maps for the transfer of the interpreted themes. Base maps should be available at suitable scales relative to the size of the survey area to be mapped and the intensity of the interpretation and field work. According to Maling (1971) maps should be compiled at a scale large enough to represent the information being mapped without unnecessary generalisation or exaggeration. The scale of the base map is usually selected in relation to the size of the smallest unit of delineation on the imagery. The larger the size of the smallest unit of delineation the smaller the scale of the base maps that would be required for the mapping. Also, the remote sensing imagery should be available at suitable scales because most of the transfer methods currently used for forest mapping permit scale enlargements up to 2.5 times and reductions down to 5 times (Loetsch & Haller, 1973). The minimum mappable area (smallest unit of delineation) should be reconciled with the minimum mapping area (smallest unit for which separate area estimate is required) in relation to the working scale. Base maps, by definition, should be of acceptable accuracy relative to the minimum accuracy specified for the individual surveys. Allowance is usually given for interpretation and mapping errors while assessing the acceptability of the accuracy of a base map. This makes it possible to determine the extent to which the maximum attainable accuracy could be reconciled with the minimum acceptable accuracy.

In view of the above consideration, any of the following could be used as a base map:-

(a) an existing topographic or planimetric map enlarged or reduced to the working scale.

(b) photo-map or an orthophotomosaic.

(c) a controlled or semi-controlled mosaic.

(d) a Landsat or any other satellite imagery for being inherently orthographic at the acquisition scale.

(e) a specially prepared sketch or skeletal planimetric map.

If none of these is available, and the survey area is relatively small, base map can be constructed from topographic field survey data.
If the survey is neither a reconnaissance type nor one that covers a small area that can be topographically surveyed, photogrammetric mapping should be considered.

For many tropical forest areas, there is a general lack of accurate base maps at suitable scales. According to Oyelese (1968) this hinders thematic mapping from remote sensing imagery because some features recorded on aerial photographs may be absent on the base map and vice versa. This is usually due to the considerable time lapse between the two recordings. Miller (1957) also remarked the general shortage of topographic and other reliable maps at a scale larger than 1:250 000 in tropical commonwealth countries. He added that in these countries, generalised forest maps were usually compiled at the scale of 1:50 000 while emptier territories were mapped at various scales between 1:125 000 to 1:100 000. In Nigeria, national maps are usually produced at 1:3 000 000 scale. Topographic maps are produced at various scales between 1:100 000 and 1:25 000. Virtually all recent maps including natural resource maps are compiled by photogrammetric methods.

Moreno (1970) suggested various scales for forest mapping in relation to the type of survey being conducted as follows:-

Type of survey	Mapping scale
exploratory	1:50 000 and lower
reconnaissance	1:50 000 - 1:40 000
management	1:40 000 - 1:25 000
research	1:15 000 and higher

Generalised and management maps are usually compiled at the scales of 1:50 000 and 1:10 000 respectively. For areas smaller than 100ha. these scales are usually increased to 1:25 000 and 1:5000 respectively. Loetsch and Haller (1973) stated that in Europe 1:50 000 scale base maps are commonly used for compiling stand and management maps at scales varying between 1:20 000 and 1:10 000. They also indicated that base maps whose scales vary between 1:20 000 and 1:10 000 could be used for compiling maps for less intensive forest management. Lanly (1972), Loetsch and Haller (1973) stated that scales between 1:100 000 and 1:50 000 were acceptable for forest type mapping in the tropics.

According to Lanly (1973), while the operation scales for forest mapping vary between 1:10 000 and 1:5000, a scale of 1:50 000 was generally sufficient for a feasibility study to some extent in the tropics.

5-3.2 Information transfer methods

The transfer of thematic information from remote sensing imagery to a base map involves a geometric transformation from a perspective image into an orthogonal representation. If the geometric errors and image distortions of the imagery are not eliminated, they would be copied on the map. It follows that information cannot be transferred from imagery to a map by direct (overlay) tracing. In view of these considerations various instruments have been designed in relation to the different methods which are used for the transfer of information from imagery to maps. Of these, photogrammetric instruments and methods are more commonly used for forest mapping.

Maling (1971) grouped the existing photogrammetric instruments into two broad categories according to the two basic methods of information transfer:

- approximate or semigraphical methods in which simple transfer instruments are used.
- geometrically rigorous instrumental methods or analogue methods in which photogrammetric plotting instruments are used.

For the present investigation, these categories of instruments and methods have been redesignated as follows:

- transfer instruments and methods.
- plotting instruments and methods.

Not only does this redesignation distinguish between thematic and photogrammetric mapping as defined for the present studies, it also makes Maling's terminology less restrictive to cartography and more applicable to forestry.

The use of transfer instruments for thematic mapping is based on the assumptions that the terrain is flat and that the aerial photographs are truly vertical. With these assumptions, a perspective congruence (linear cross ratios or anharmonic ratios) of projective geometry is preserved between the terrain, photograph and map. This assumption of perspective congruence between a central projection and an orthogonal projection means that angles measured at the principal point of an aerial photograph are equivalent to those which might be measured at the corresponding points either on the map or on the terrain. The principle of perspective congruence (cross ratios or anharmonic ratios) is employed for designing these transfer instruments. Transfer instruments are primarily designed for tracing planimetric details with a provision for the approximate rectification of tilt displacement. They employ various projection principles and methods for superimposing photo images on the corresponding maps.

The sketchmaster and stereosketch utilise the camera lucida principle. The sketchmaster which is designed for monoscopic transfer is unsuitable for the transfer of intricate delineations. The stereosketch is designed for stereoscopic transfer. Another camera lucida type instrument is the new Bausch and Lomb Stereo Zoom Transfer Scope which is designed for both monoscopic and stereoscopic transfer. The optical pantographs constitute another category of transfer instruments to which the epidiascope and the reflecting projectors belong. Optical pantographs are optical projector instruments designed for monoscopic transfer. As camera lucida type instruments and the optical pantographs have no mechanical tracing devices, transfer is done manually. Though the perspective congruence provides a geometric connection between the plane of the photograph and that of the map irrespective of the amount of camera tilt, the method cannot correct for relief displacement. Consequently, it is restricted to aerial photographs of flat or uniformly sloping terrain. The method requires a minimum of four control points for the relative orientation of each photograph with the map.

The principle of perspective congruence is also used for designing another category of transfer instruments. These instruments have mechanical tracing devices. As the principle of perspective congruence also implies that corresponding angular distances on the photograph and the map would represent the same ground distance, the map position of a terrain point can be determined by the intersection of mutual radial lines which connect the principal point with the terrain point on the individual photographs. This principle of radial line intersection is used in the design of radial line plotters. With a radial line plotter, the position of a terrain point is determined by the intersection of only two radial lines from the centres of adjacent photographs. These radial lines are represented by two moving cursor arms which provide continuous intersection along any boundary. The movement of the cursor arms are connected to a mechanical tracing device. Because it is primarily designed for planimetric sketching from vertical aerial photographs, it cannot be used satisfactorily for aerial photographs with more than 3° tilt. Three control points are required for the relative orientation of the photographs in the radial line methods.

In addition to the perspective congruence principle, some transfer instruments utilise parallax differences for the relative orientation of the photographs. The parallax differences are measured with parallax bar and converted into heights by parallax formulas. These are stereometer-type instruments. This category includes the tracing stereometer which, like the other transfer instruments, has no correction device. The tracing stereometer is a simple device used in conjunction with a mirror stereoscope to determine elevation differences and to trace form lines and planimetry from stereopairs of vertical aerial photographs by direct measurement of parallax differences.

In the use of all transfer instruments described above, stereoscopic delineation is assumed. However, with stereoscopic transfer instruments both the interpretation and the transfer can be accomplished simultaneously. If delineations have been made prior to mapping, the interpretation can be checked and corrected during transfer. This is not possible with monoscopic transfer instruments. All the transfer instruments are easy to operate and most of them have devices for varying the mapping scale. However, as the laborious and time-consuming semigraphical method is the only means of establishing map control for simple transfers of this nature, the pace of work is usually slow. Also, the use of semigraphical method in the mapping procedure restricts the working scale to the photo-scale. If maps are required at scales larger than the working scale, the relatively small scale maps produced initially have to be enlarged. Interpretation errors in locating points and in delineating areas together with transfer errors would be magnified by excessive scale enlargement.

The terrain of some tropical forest areas do not justify the assumption that the ground is a plane surface. Also the radial line principle assumes a surface relief that is less than one tenth of the flying height. For some mountainous tropical forest areas, aerial photographs have to be acquired at a scale which is unsuitable for forest interpretation in order to fulfil this assumption. Granted that this assumption is fulfilled, the use of the principal point instead of the nadir as the radial centre for the semigraphical methods is correct only for the truly vertical aerial photography which is difficult to achieve in practice. In oblique aerial photography the nadir does not coincide with the principal point. Their separation increases with camera tilt. With the photogrammetric methods which are currently available for civilian use, it is still not possible to determine the exact position of the nadir, even in relation to the principal point or otherwise. This causes a systematic error in the semigraphical method particularly when large scale aerial photographs are used. This error is reflected in the planimetric accuracy of the final map.

Despite the obvious limitations narrated above, transfer instruments are commonly used for forest map compilation not only because they satisfy the required planimetric accuracy but also because they are available at an economic cost and can be operated without any special training. In a situation where accurate base maps at suitable scales are lacking, instruments of higher precision and accuracy are required for mapping. For instance, in the tropics most of the existing forest maps are either outdated or inaccurate while only few are reliable and available at suitable scales. This situation makes map revision difficult if not impossible. The most realistic option is to compile new forest maps.

As these instruments are designed primarily for the transfer of planimetric details, they cannot, with confidence, be used to obtain reliable altimetric information for the planning of some forest operations such as the extraction of timber and the construction of forest roads. Nevertheless, other important forest information delineated during interpretation are easily mapped with these transfer instruments. If the new maps would be used as base maps for future surveys, they must contain some altimetric information. As simple transfer instruments cannot provide reliable altimetric information in form of contours, only photogrammetric plotting instruments can be used to draw contours as a continuous process. These instruments are generally classified by their relative efficiencies into three orders, but they are more distinctly categorised by the type of solution they provide for geometric errors. In the former case, the three orders reflect the relative costs. Of these instruments, the universal first order plotters are the most expensive and the most precise. In the latter case, plotting instruments which provide approximate solution to geometric errors are classified as approximate instruments. This group corresponds to the third order plotters. Plotting instruments which provide exact solution to geometric errors are classified as precision instruments. This group corresponds to the second order and the universal first order plotters.

The approximate instruments (third order plotters) include the Zeiss stereotope and the Galileo-Santoni stereomicrometer. As camera tilt cannot be introduced into the stereomodel, approximate instruments cannot create a small scale analogue of the geometrical conditions which occurred at the time of photography. However, they make partial correction for relief displacement and for stereomodel deformation. With these instruments maps can be compiled at scales different from the photoscale. They can be used to plot at scales larger than the photoscale because their operation does not depend on preliminary semigraphical work. However, excessive enlargements are not desirable since the geometric solution is only approximate. Topographic plotting with approximate instruments requires a minimum of four control points situated near the corners of the stereomodel. Only three of these points are required for planimetric transfer.

When accuracy cannot be sacrificed for economy, maps have to be compiled with precision instruments. These precision instruments which are designed for optical and/or mechanical projection are used for instrumental triangulation in which visual optical or visual mechanical stereomodels are developed without extensive mathematical computations. In mechanical projection, the optical paths provided do not affect the perspective projection geometry. They are only a means of viewing the photographs. With precision instruments, camera tilt can be introduced into the stereomodel in order to create a geometrically exact analogue of the conditions of photography by optical or mechanical restitution of the bundles of light rays which entered the camera during photography. For a complete restitution, correction must be made for subtle image distortions which are too small to be considered in semigraphical methods. In view of the very stringent requirements for a complete restitution, many precision instruments are designed to be used with a particular kind of photography in respect of format size, emulsion type, camera design and lens system. Consequently, a series of photographs can be processed in exactly the same way and used for plotting with virtually no variation in certain setting of the instruments used. For example, most of the second order instruments such as Multiplex, Kelsh plotter, and other anaglyph plotters are designed for use with 23cm. x 23cm. wide angle photography taken by a particular camera design so that lens distortion can be removed in the projection. These instruments operate at a fixed scale-ratio between photograph and stereomodel but plotting is normally done at the scale of the stereomodel. In spite of this fixed scale ratio in the second order plotters an external reference or a mathematical adjustment is required to maintain a consistent scale and a continuous datum for the successive stereomodels.

Though the precision of the second order instruments balances their costs, there is a need for a greater versatility than that provided by these instruments, not only for scientific purposes as indicated by Maling (1971) but also for economy. Only the universal first order plotters are able to provide this versatility but at a considerable cost. The universal first order plotters accept vertical, oblique and horizontal 23cm. x 23cm. photography in contrast to the most precise second order instruments which cannot accept camera tilts greater than 10°. Furthermore, the universal first order plotters provide direct connection relative to scale and datum between successive stereomodels without any external reference or a mathematical adjustment.

Not even all the universal first order plotters can accommodate a sufficiently wide range of focal lengths to cover all the categories of 23cm. x 23cm. superwide and wide angle photography. When consideration is given to the 70mm. photography which is being widely used for forestry investigations, the limitations of these analogue precision instruments become more apparent. The only instruments with sufficient flexibility to accept all sizes and kinds of photography are the analytical plotters. They are also universal first order plotters in the sense that they provide direct connection between successive stereomodels but they are distinguished as a different category of instruments not only by their flexibility to accept any photography but also by their unique projection method. In these instruments, mathematical stereomodels are created by analytical projection in contrast to the visual optical or visual mechanical stereomodels of the analogue universal first order plotters.

The cost-benefit of universal first order plotters for forest mapping is considerably lower than those of other plotters which can provide the required level of accuracy. Experience has shown that simple transfer instruments are adequate for forest mapping where accurate base maps are available at suitable scale. If satisfactory base maps are lacking new maps can be satisfactorily compiled with second order plotters or else third order plotters.

Monoscopic transfer devices can be used for thematic map compilation from Landsat and SLAR imagery. However, since Landsat information is primarily acquired in digital form, mapping from Landsat data by automated (computer) methods appears to be more promising than by transfer methods. Also, when semigraphical methods are applied to SLAR imagery, the 'side-look' projection makes the geometric connection between image and map less rigorous. Consequently radargrammetric methods cannot provide accurate maps. In view of the foregoing it is my opinion that simple transfer instruments are efficient for forest mapping from aerial photographs. As small scale imagery such as Landsat and SLAR are used in forestry mainly to map the location of forest resources, direct tracing of the delineations on the images is sufficient to meet this requirement.

5-3.3 Map control methods

Any form of mapping from remote sensing imagery requires some control for orientation in order to minimise the mapping error. According to Maling (1971), whatever mapping methods are used, a considerable control would be required. The use of ground methods for controlling map compilation from remote sensing imagery is very costly in terms of time, money and effort. For economy, information from remote sensing imagery which is also shown on established maps can be used instead. Such information includes boundaries of natural features, intersection of lineaments, road junctions and river confluences. The positions of some of these features are liable to change with time as a result of human interference e.g. forest boundaries. However, in built up areas, there are sufficiently well defined and permanent structural features which could be used as planimetric control. In extensive tropical forests and the closed high forest in particular these structural features (hard details: in sensu Maling) are virtually absent and prominent landmarks are rare to control planimetry. This is particularly true when small scale remote sensing imagery such as that of the Landsat is used. For instance, forest and other boundaries on a computer print-out of automated interpretation of Landsat information are only approximate. These boundaries are satisfactory for regional mapping but at scales which are suitable for forest management they become less meaningful, though Landsat imagery is inherently orthographic at the acquisition scale.

As controls may be difficult to establish for map revision, it may be desirable to compile new maps. However, when altimetry is considered, map compilation from non-photographic small scale imagery is hindered by the general lack of reliable methods for establishing ground controls. The small scale of Landsat images, and the side-look geometry of SLAR do not favour the use of conventional aerial control methods. In addition, the high cost of radargrammetric methods prevents their use for routine forest mapping. Nevertheless, photogrammetric methods provide several options of map control by aerial triangulation. The purpose of aerial triangulation is to locate in each photograph of stereomodel a regular pattern of minor control points (photo control points or pass points) whose positions and heights may be adjusted to the ground control which is available. Aerial triangulation permits not only the use of fewer ground control points without any significant loss in accuracy, but also the use of some control points which by ground methods may be difficult to locate. Four photo-control points situated at the corners of each stereomodel normally provide an effective planimetric control. According to

Maling (1971), it is the number of photographs or stereomodels which is significant in aerial triangulation but not the size of the area being mapped.

There are two main categories of aerial triangulation methods which correspond with the two main mapping methods. Semigraphical methods are used for controlling map compilation with transfer instruments. Because they are based on the principle of radial line intersection, semigraphical control methods are also called radial triangulation. Aerial control of map compilation with plotting instruments is accomplished by spatial triangulation.

Ligterink (1968) described three radial triangulation methods. Though the three methods are semigraphical, he characterised them by the method used to adjust closing errors in the templet assembly as follows:-

graphical - the English (Arundel) method
- the American (Hand-templet) method
mechanical - the slotted templet method

The Arundel method assumes that all air bases of a flight line form a perfectly continuous straight line. In practice however, variation in the aircraft velocity results in unequal air bases while variation in the aircraft attitude (roll, pitch and yaw) results in a zig zag flight line. Also variation in the altitude of the aircraft results in scale variation. As a result of all these, the plotting of a flight line from aerial photographs results in a broken zig zag line. In the strip templet, the radial centres (air or camera stations) which are represented by the principal points of the photographs are plotted on a straight line which represents the flight line. The mutual radial lines constructed from the overlapping photographs intersect before the templet assembly. It follows that the position of a photo control cannot be determined by resection. Instead it is determined by the superimposition of a pair of corresponding intersections during the templet assembly.

As the air bases within the individual strips are brought to the same scale by the 'base in - base out' triangulation procedure, it is also necessary to bring all the strip templets to the same scale during the templet assembly. This is also accomplished by the radial line intersection method. By using two common tie points at the ends of the sidelap the position of the ground control point in one strip is adjusted relative to that of the ground control point in the succeeding strip. This is done in such a way that the adjustment is relayed from the first to the last strip.

When the ground control points are adjusted the superimposed intersections become separated. The closing error resulting from this separation increases with the amount of adjustment, as the air bases and the radial line intersections are rigidly fixed before the templet assembly, the closing errors cannot be distributed between the photo control points by adjusting the air bases to become shorter or larger. Instead, personal judgment is used to fix each photo control point within the confines of its two separate intersections. Nevertheless, with the Arundel method, there is no theoretical limit for scale reduction or enlargement during mapping. With the other two methods, scale reduction and enlargement are restricted by the photo scale. The Arundel method, though simple,is inaccurate. It is only suitable for a survey area covered by a very few flight lines or a very few rows of laterally overlapping aerial photographs. The radial triangulation of a survey area covered by a large number of aerial photographs belonging to many flight lines, would contain large errors.

In the hand templet and slotted templet methods the radial lines of individual photographs are constructed on separate templets unlike in the Arundel method where the radial lines of all photographs of a flight line are constructed on a strip templet. As the radial line intersections are not rigidly fixed before the templet assembly is fixed to the control sheet, closing errors can be distributed among the photo control points as ground control points are encountered. This is accomplished in the hand held templet by relaying the templets to shorter or larger air bases giving small amount of swing to the templets. The procedure being graphical is time consuming and it involves a great deal of personal judgment. In the slotted templet method, the distribution of closing errors among the photo control points is easier, being accomplished mechanically. In each templet, holes and slots replace the radial centres and radial lines respectively. Corresponding radial centres and radial lines are held together mechanically with a stud. Once the ground control points are fixed by studs onto the control sheet, the whole templet assembly is self adjusting for closing errors. The hand templet and the slotted templet can be constructed only at or close to the photo scale. Being more accurate than the Arundel and hand templet methods, the slotted templet method is commonly used on forest mapping but it is expensive and time consuming. Nevertheless, it is more suitable for survey areas covered by a large number of aerial photographs or flight strips.

Ligterink (1968) reported that the accuracy of maps aerially controlled by the slotted templet method increases with the number and the spread of the ground control points over the survey area. He mentioned that analytical radial triangulation provided a more satisfactory aerial control for thematic mapping but this method is seldom used in forest mapping. Maling (1971) also mentioned the use of stereotemplets which is a logical development of the slotted templet.

A stereotemplet is constructed for each stereomodel which has been partly oriented in a plotter. The stereotemplet method has the advantage of not being dependent on the assumption that aerial photographs are truly vertical. Also, the stereotemplets can be constructed at scales suitable for subsequent plotting rather than the photo scale.

For the aerial control of map compilation with plotting instruments, Maling (1971) discussed three methods of spatial triangulation. These are strip triangulation, independent model triangulation and analytical triangulation. In strip triangulation successive stereomodels along a strip are tied by sequential bridging in a suitable plotter such as the universal first order plotters with 'Full Zeiss Parallelogram'. This device permits the tilts in one stereomodel to be carried forward to the next by alternately setting the stereomodels in 'base in - base out' fashion, similar bridging is accomplished in analogue form with Multiplex and other analyph plotters. The use of the independent and the analytical triangulation methods for aerial control involves complex mathematical computations which require computer assistance. This is not essential in routine forest mapping. As the control requirements for thematic mapping and forest mapping in particular are less stringent than those for cartographic mapping, the use of radial triangulation methods provides effective map control to achieve the acceptable mapping accuracy. More so when altimetric information is rarely required and accurate base maps are available. It would be uneconomical to use the more expensive spatial triangulation method and precision instruments in such a situation where these do not offer any significant advantage over the use of the less expensive radial triangulation methods and transfer instruments.

An entirely different approach is followed in the compilation of maps from non-stereoscopic and very small-scale remote sensing imagery. According to Loetsch and Haller (1973), areas less than 500sq.km. can be mapped in orthogonal projection which disregards the curvature of the earth and shows geocentric longitudes and latitudes as straight lines normal to each other. Maps of larger areas are compiled in a system of planimetric coordinates which accounts for the curvature of the earth. Maling (1965, 1966) stated that further errors are due to factors other than projection and scale deformations, in the use of a projection method whose principle does not illustrate the geographical relationships being sought. According to him (Maling 1966a) the choice of the most suitable map projection which would provide the best representation of a given country depends on the location or distribution of the points to be mapped and on the purpose of the map. He added that the location of these points influences the choice of the aspect or of the projection, while their distribution influences the class of projection and the intended purpose of mapping determines the choice of the special property of the projection.

In view of the fact that most forest maps are thematic, radial line triangulation method can provide adequate aerial control for forest maps compiled from aerial photographs, more so when simple transfer instruments are used. For small scale Landsat and SLAR mapping the relatively small forest information available may not justify any rigorous map control. Furthermore, such maps are used for locating forest resources rather than for estimating areas. Consequently,direct tracing can be adequate in such cases.

5-4 Area estimation methods and techniques

The conventional methods and techniques which are used for area estimation can be classified according to their forestry applications as follows:-

A Methods used for undelineated areas

  1 Systematic sampling methods

    1. point sampling method

    2. plot sampling method

B Methods used for delineated areas

  1 Grid sampling methods

    1. dot grid method (points)

    2. rectangular grid method (squares or rectangles)

    3. strip (linear) grid method (transects)

  2 Instrumental methods

    1. planimeter method

For clarity, the systematic sampling methods (A.1) and the grid sampling methods (B.1) are designated as 'sampling techniques' in the ensuing discussion while the planimeter method (B.2) is designated as 'complete census technique'. The total area of each class of forest characteristic e.g. a forest-type and a volume-class can be estimated by applying any of these methods, to the entire survey area (total coverage) or to a representative part of it (partial coverage). As the choice of area estimation method depends on the interpretation procedure, complete coverage is not applicable to an interpretation which is accomplished by partial delineation or by multistage sampling. However, complete census is applicable to an interpretation which is accomplished by partial coverage or a supervised computer interpretation. The value and limitations of the methods listed above are viewed on three different but inter-related considerations:

1. statistical considerations
2. cartometric considerations
3. forest mensuration considerations

5-4.1 Statistical considerations

The area estimation methods listed in A.1 and B.1 are based on the same principle of sampling theory but they differ in technique. Area estimation by the methods in A.1 is accomplished in conjunction with interpretation during which the sample points or plots are tallied for the classes of forest characteristics being interpreted. These methods are therefore regarded as 'systematic sampling methods'. The sample points/plots can be distributed with the interpretation aids used in B.1 methods, but the measurements are not made with the interpretation aids as in B.1. Area estimation by the methods in B.1 is accomplished after interpretation. The interpretation aids being grid templets are used as overlays on maps or delineated imagery. These methods can therefore be regarded as 'grid sampling methods'.

In the systematic sampling (A.1.1 and A.1.2) and the dot grid (B.1.1) methods, the sampling intensities are determined statistically before the estimation of areas. In the point and plot sampling techniques, the predetermined sampling intensity can be achieved with one sample as sample distribution does not rely on any interpretation aid. In the dot grid method however, sample distribution depends on the density of the dots. Consequently, several samples may be required to obtain the predetermined sampling intensity. This is accomplished by relaying the dot grid in different positions for a number of times which is determined from the dot density and the predetermined sampling intensity. Though it is possible in practice to use a predetermined sampling intensity in the rectangular grid (B.1.2) or strip grid (B.1.3) method, this is rarely necessary as several samples can be drawn to increase the confidence of the estimation. In a partial coverage by multistage sampling, each stage requires an area expansion factor for the estimation of the total areas from the estimates obtained from the ultimate sampling stage. This notwithstanding, both partial and complete coverage procedures require area extension factors to compute the area estimates from the measurements on the maps or imagery.

In systematic sampling methods the area extension factor is determined directly from the spacing of the sample points or plots and the scale of the imagery or map. As the plot count which is a non-dimensional quantitative attribute is used for the estimation, the area extension factor does not depend on the plot size which is only important for the interpretation. Moreover, approximately equal sized plots (circular or rectangular) are normally used since variation in image scale does not permit the use of exactly equal sized plots which is only possible with maps.

In the grid sampling methods however, the area extension factor (relative grid factor) is determined from the absolute grid factor which is normally stated on the grid templet e.g. 4 dots/sq.cm. for a dot grid, 1 rectangle/10sq.cm. for a rectangular grids and 1cm./8sq.cm. for a strip grid. The absolute grid factors of dot grid and rectangular grid relate to the densities of dots and rectangles respectively. As transect measurement is a dimensional quantitative attribute, the absolute grid factor of strip grid is determined from the spacing (density) and the total length of all the transects. The relative grid factor relates the absolute grid factor to ground area hence the term 'area extension factor'. In total coverage only the area extension factor is required. However, in the partial coverage an area expansion factor is required to expand the sample estimates back the entire survey area. For instance, each stage of a multistage sampling requires its own area expansion factor for the successive expansion of the area estimates from the last stage back to the first stage and finally to the entire survey area.

In sampling methods, the samples are represented by a density of points, plots dots etc. which can be counted or by a density of transects which can be measured. Also, different samples can be drawn by redistributing the sample points or plots without altering their systematic relationships or by relaying the grid templets in different positions. As a result, a sampling method is characterised by a sampling intensity which can be determined before or after the estimation of areas. An area estimate obtained by a sampling method is therefore subject to sampling error in addition to the standard error. Sample points etc. do not exist in complete census method and different samples cannot be drawn either. Repeated planimetering of the same delineations does not imply sampling. Consequently, a complete census method is not characterised by a sampling intensity. It follows that an area estimate obtained by a complete census method can be evaluated by only its standard error as it is not subject to sampling error.

For the reasons above, area estimates obtained by sampling methods are more potent for statistical evaluation than those obtained by complete census methods. The former is less consistent than the latter due to the use of sampling procedures, but the inconsistence can be minimised by increasing the sampling intensity or drawing several samples. Because instrumental procedures are employed, area estimates obtained by complete census methods are liable to subjective biases which cannot be determined precisely. The procedures of area estimation by sampling are easier to follow than those of complete census. For instance, drawing several samples by relaying the grid templet in different position is easier than the preliminary instrument calibration of the complete census method. Also, the computation in sampling method is easier than that in complete census method. According to Lanly (1973) foresters tend to over look the statistical aspects of forest mensuration which includes area estimation. A rigorous statistical evaluation is essential for a meaningful and useful interpretation of the estimates obtained from forest mensuration data.

5-4.2 Cartometic considerations

Maling (1968) remarked that the inadequate professional and linguistic communication between research workers had led to a considerable duplication of efforts in developing area estimation technique and evaluating the relative efficiency of these techniques. He drew inferences from forestry, geographical, surveying and cartographic literature. His investigation on cartometric measurement of intricately sinuous lines is of direct relevance to forest mensuration because the boundaries of the forests whose areas are to be estimated are more often sinuous than not. According to him, discrepancies in the measurement of sinuous lines constitute a cartometric problem which many workers often consider trivial but which is none-the-less important. He indicated that investigations should establish not only the sources and the magnitudes of the different components of measurement errors but also the various ways in which these errors can be compensated or corrected to make the measurements meaningful to the intended use. For this reason, he emphasised the need for rigorous statistical evaluation of the precision and accuracy of the various measuring instruments and methods.

Measurement errors can be grouped into three categories - cartographic, instrumental and operating errors. Cartographic errors are due to map projection, cartographic generalisation and paper deformation. The magnitude of errors which are due to map projection is determined by the efficiency of the projection method. This type of error depends largely on the size of the survey area and to a lesser extent on the mapping scale. Cartographic errors increase with the amount of cartographic generalisations made in the symbolic representation, say of boundaries, on the map. Irrespective of map scale, the measurements of an area with a sinuous boundary should give the same ground area estimates. This is rarely the case in practice. For instance, when maps are compiled at a large scale, sinuous boundaries are well represented. With successive reduction in the mapping scale the representation of the sinuous boundaries become simpler. This progressive simplification in cartographic representation (cartographic generalisation) usually result in estimation errors whose magnitude increases with the reduction in mapping scale.

Also, when maps are compiled at a small scale, sinuous boundaries are simplified, with progressive enlargement of the small scale map, the representation of the sinuous boundary progressively departs from the actual representation that could have been used if the maps were compiled at these enlargement scales. Consequently, measurement errors increase with scale-enlargement of the original map. This type of error usually occurs when base maps are not available at suitable scales. Errors which are due to paper deformation decreases with the stability of the paper used for mapping. This type of error has been classified as a cartographic error because only the cartographers can provide the best advice on the grade of paper quality to be used for mapping.

Instrumental errors are directly related to the precision of instruments e.g. planimeter or the stability of materials e.g. dot grid templet and they decrease with increase in these attributes (Allen, 1975). Also, some errors, though not truly instrumental are related to the suitability of the estimation method for the shape and the map size of the survey area. Between 1973 and 1976 the ITC (International Institute for Aerial Survey and Earth Sciences, Enschede, Netherlands) Sub-Department of Forestry and the Edinburgh University, Department of Forestry separately conducted series of tests on the relative efficiency of the various methods for estimating forests with small and large map-areas. The ITC test was carried out by the N7/8 students (including the present investigator) with at least six months postgraduate training and experience in photointerpretation. The Edinburgh University tests were carried out by second year Ecological Science undergraduates with photogrammetric experience (I. Langdale-Brown, R. Muetzelfeldt; personal communication June, 1979).

For the ITC test measurements were made directly on 1:20 000 scale forest stand map of the Schneegattern forest district in Austria. The forest stand which was measured comprises of four forest ranges with sinuous boundaries. The entire forest stand represented 'large map-area' while each forest range represented 'small map-area'. The areas of the entire stand and the individual ranges were estimated separately by each student with a compensating polar planimeter and the ITC dot grid (4 dots/sq.cm.). For uniformity and consistence, the operating and computation procedures in the ITC laboratory instruction book for N7/8 courses were followed. The relative efficiency of the two methods was determined from the tally of the results obtained by the individual students without further statistical evaluation.

The measurements for the Edinburgh University tests were made on cyclostyled reproductions from 1:25 000 scale Ordnance Survey Map of Edinburgh area. An area with sinuous boundary was used as 'large map-area' while a triangular area within it was used as 'small map-area'. However, the large map area for the Edinburgh University test was smaller than any of the small map-areas of the ITC test. The measurements were made with compensating planimeter, dot grids of various dot separations and by geometric methods. Unlike the ITC test, the areas were estimated from group data comprising the individual measurements made by the students. The results were valuated statistically. The results of the two series of tests are summarised in Table 5.2.

These results apparently show that the planimeter is more efficient for estimating large areas while the dot grid is more efficient for estimating small areas irrespective of the nature of the boundaries. The fact that the small map-area in the ITC test is larger than the large map-area of the Edinburgh University tests raises the question of what map-area should be regarded as the maximum for the dot grid method or as maximum for the planimeter method. By comparing the precision of the planimeter and the dot grid methods with that of the geometric method for estimating small areas, it can be inferred that the dot grid method is more efficient than the planimeter for estimating areas with definite geometric shapes. This is supported by the fact that the coefficient of variation for the dot grid method is closer to that of geometric method than that of the planimeter method.

Furthermore, the results showed that the precision of the dot grid method increases with the separation of dots. This agrees with the assumptions of Maling (1968) that but higher precision does not necessarily imply higher accuracy. According to Banyard (1973) precision (e.g. sampling error) indicates the agreement in a series of measurements while accuracy (e.g. standard error) indicates the closeness of a measured value to the true value. In view of these considerations,

Table 5.2 Comparison of geometric, dot grid and planimeter methods for area estimation

Summary of the results of the ITC test

Map-size		Relative efficiency in decreasing order		
		precision and accuracy	ease of operation and computation	ease of measurement
Small area	1	planimeter	dot grid	planimeter
	2	dot grid	transect	dot grid
	3	transect	planimeter	transect
Large area	1	planimeter	dot grid	planimeter
	2	dot grid	planimeter	transect
	3	transect	transect	dot grid

Summary of the results of the Edinburgh University tests

		Precision in decreasing order (coefficient of variation)		
		1973 Test	1975 Test	1976 Test
Small area	1	geometric method (5.9)	25 dots/cm^2 grid (7.6)	geometric method (4.4)
	2	10 dots/cm^2 grid (7.4)	geometric method (9.1)	25 dots/cm^2 grid (7.0)
	3	4 dots/cm^2 grid (8.6)	4 dots/cm^2 grid (16.0)	planimeter method (9.1)
	4	planimeter method (9.1)	planimeter method (13.1)	4 dots/cm^2 grid (9.5)
Large area	1	planimeter method (1.4)	planimeter method (6.6)	4 dots/cm^2 grid (3.0)
	2	4 dots/cm^2 grid (2.3)	4 dots/cm^2 grid (7.1)	planimeter method (4.2)

it is my opinion that irrespective of 'map size' the planimeter is more efficient for areas with sinuous outline while the dot grid is more efficient for areas with fairly regular outline that closely approximates to a definite geometric shape. My opinion is supported by the integrator-mechanism in the instrumentation of planimeters and the geometric regularity of dot distribution on dot grids.

As several methods are available for area estimation, the choice of method would depend on economy. If for relative efficiency, the dot grid is preferred, it is suggested that dots separation on the grid being used should match the map size of the area being estimated i.e. the smaller the map size the higher the dot density. This suggestion is supported by the findings of Maling (1968) that the higher the dot density the lower the precision of the measurements but the higher the accuracy of the estimates. It follows that by using high density dot grid for small map-areas and low density dot grid for large map-areas precision would balance accuracy. Not only does the use of low density dot grid for large areas save time and effort it also minimises counting errors.

In addition to instrumental errors which are due to differences in the relative precision of the various measuring devices, operating errors also exist between different operators. It is usually difficult to assess the magnitude of the personal equation involved in operating these devices.

Generally, it is usually difficult to separate the measurement errors into their various components particularly when various factors come into play. Granted that the relative efficiency of the individual methods or devices can be established and that all errors can be compensated or corrected it would be necessary also to establish the interpretative value of the final estimates for the intended purpose in relation to the amount of time and effort involved. According to Maling (1968) this can be done by reducing the results into homogeneous data and relating them to meaningful dimensions on the ground. In forestry practices, only the overall accuracy of the area estimates obtained from measurements is significant to forest management. As long as the maximum accuracy which can be achieved with a particular area estimation technique or method does not fall below the minimum accuracy acceptable for forest management, foresters tend to overlook or completely ignore the cartometric implications of the methods being used for area estimation. However, the dot grid and planimeter methods are commonly used for estimating forest areas.

5-4.3 Forest mensuration considerations

The choice of area estimation method is restricted by the interpretation procedure. In an interpretation without delineation area estimation is done by sampling in conjunction with the interpretation. In such a situation, an efficient key is a fundamental requirement for the interpretation and consequently the area-estimation. The interpretation key should be based on a set of precise criteria and definitions to provide uniformity and consistence over time and between interpreters. Also, interpretation keys should be constructed in such a way that they can be appraised in the field because those which are too refined usually increase interpretation errors and therefore increase the risk of errors in area estimation.

Area estimation without delineation circumvents the laborious intermediate stages of delineation and mapping. However, only the numerical distribution can be obtained by this procedure but where spatial distribution of the different forest classes is also required, interpretation should be done by delineation. This would allow the estimation of areas by complete census. The major drawback in interpretation by delineation is the biases which are due to subjective delineation if the boundaries are indistinct or if there is a transition zone between two adjoining classes of forest. These subjective biases reduce the accuracy of the estimations. Even if boundaries are clearly defined and transition zones are virtually absent, the forest may be highly mixed for the forest characteristic thus resulting in intricate delineations. The intricacy of the delineations may be compounded by wide variations of the characteristic within a small area. These are the typical conditions which obtain for most tropical forests and of shifting cultivation areas in particular.

In area estimation accomplished on map or delineated imagery, the areas of small patches of forests delineated with non-forests do not usually compensate those of small patches of non-forests delineated with forests. This imbalance results in a biased estimate of the area-related forest information being assessed. According to Moessner (1957) the proportion of forested parts of a given area increases with decreasing size of the minimum unit of delineation. Consequently, the resulting biases in the area estimates would also increase with the imagery or map scale. For this reason, it is often useful to specify the size of minimum unit of delineation to allow the comparison of different surveys. In cases where spatial distribution is required in addition to numerical distribution, maps are normally compiled. Very small units delineated on the remote sensing imagery are not usually mapped. This is another type of cartographic generalisation for an easy interpretation of the compiled maps. When areas are estimated on such maps there is usually an underestimation of the areas of the forest classes to which these very small patches belong. Area estimation by partial coverage as in partial delineation is unsuitable for tropical forests. Under tropical conditions, the precise location of a representative part of any given survey area is often difficult if not impossible. Such representative part may not even exist owing to the wide range of variation within very small areas of tropical forest. The procedure may be satisfactory for reconnaissance surveys in the tropics as this type of survey is rapidly accomplished by multistage sampling.

In view of the above considerations, the complete coverage procedure of area estimation preferably using the dot grid or planimeter appears to be the only way by which meaningful and useful estimates of tropical forest areas can be obtained. As forest characteristics are normally related to area, the partial coverage procedure by any method or technique is not likely to yield area estimates that would be of value in the interpretation of these forest characteristics for management purposes.

5-5 Inferences and conclusions

Remote sensing images can be used in two ways for estimating forest areas depending on the interpretation techniques and methods. Areas can be estimated directly on the images or from maps compiled from them. In the latter case, interpretation of the entire survey area (complete coverage) by delineation i.e. complete delineation is necessary. In the former case, there are several options of interpretation. Interpretation can be done by partial coverage of the survey area. This procedure is unsatisfactory for tropical forest areas due to the wide range of variation which does not permit a precise location of a small area that is sufficiently representative of the extensive tracts of forests. This precludes interpretation by partial delineation of the survey area. It follows therefore that the entire survey area should be interpreted.

The interpretation can be done by sampling or by delineation. In view of the difficulty in constructing and applying an interpretation key which could effectively cover the large number of forest types resulting from the wide range of forest cover, it is my opinion that interpretation by sampling is not suitable for tropical forest conditions. Consequently tropical forest areas cannot be estimated with confidence by sampling interpretation. It follows that delineations should be made during interpretation. The whole argument culminates in the total coverage of the survey area by complete delineation. In effect, complete delineation of the survey area on remote sensing images is the most effective interpretation procedure for estimating tropical forest areas.

This has not answered the question of whether to estimate forest areas directly on remote sensing images or on maps compiled from them. In the former case the accuracy of the area estimates would depend, among other factors, on the geometric fidelity of the remote sensing imagery being used. The literature review shows that Landsat images are inherently orthographic. Consequently, delineations and area estimations can be made directly on them, but the amount of detail available on them may not meet the requirements of the survey. Image displacements on aerial photographs and SLAR images in particular result in geometric errors which affect their planimetry. As the accuracy of area estimates also depends on the accuracy of the interpretation and delineation, accurate delineations can be made on aerial photographs with precise simple transfer instruments. Furthermore, rectified photographs can be reproduced from stereomodels that have been reconstructed from overlapping photographs. All image displacements except relief displacement are eliminated on rectified aerial photographs. Consequently, they can be used to obtain a more accurate area estimate.

The image distortions on SLAR images often hinder the accurate delineation of areas with rugged topography, thus reducing the value of these images for area estimation. In view of these considerations it is my opinion that both aerial photographs and Landsat images are superior to SLAR images in providing area information on tropical forest types. As many surveys cover extensive areas Landsat mosaics, orthophotomosaics and SLAR mosaics can be used at a greater speed than individual prints which are more difficult to handle. Moreover, mosaics provides direct connection between individual prints and reduces the errors in the estimation of a forest area that is not completely covered by a single print.

The fact that forest areas can be estimated on remote sensing images at an accuracy which is acceptable for forestry purposes raises the question of the need to compile maps. The general lack of accurate forest maps at suitable scales in the tropics is a primary argument for map compilation. Once compiled, maps can be reproduced at economic costs for various uses but remote sensing images are more expensive to reproduce. Moreover, the storage conditions of remote sensing images are more stringent than those of maps. Maps are also easier to handle. If the option is to compile maps, aerial photography, because of its photogrammetric properties is superior to Landsat and SLAR images for forest map compilation. Radargrammetric methods have not been widely used for forest mapping. Aerial photography provides more forest information.

If forest maps are to be compiled from aerial photographs, simple transfer instruments are adequate to achieve the required planimetric accuracy provided that accurate base maps are available at suitable scale and the mapping is adequately controlled preferably by the radial triangulation using slotted templets. Nevertheless, direct tracing of delineations on Landsat and SLAR images have been found to be satisfactory for exploratory and reconnaissance surveys as they are basically used for resource location. The major drawback in the use of maps for area estimation of forests is the inability to assess the accuracy of the interpretation from which the maps have been compiled once they are in circulation. With remote sensing images wrong interpretations can be corrected before the area estimation is accomplished. Moreover, the extent of cartographic generalisations cannot be evaluated for the necessary adjustments in the final estimates.

Assuming that both remote sensing images and maps are equally effective for estimating forest areas, the question of which method to be used for the estimation becomes significant in the final accuracy of the estimates. As interpretation without delineation has been ruled out, area estimation by sampling without delineation is not considered further. The four methods by which delineated areas can be estimated are:-

(a) geometric methods.

(b) direct systematic sampling methods i.e. point or plot sampling.

(c) grid sampling methods i.e. dot, rectangular and strip grids.

(d) complete census method i.e. planimetering.

Geometric methods are efficient for estimation of areas with definite geometric shapes e.g. triangular or rectangular plantation blocks. Most forest boundaries are sinuous and this precludes the use of geometric methods for forest area estimation. Direct systematic sampling requires statistical computations for the numerical distribution of the sample points or plots. Inaccuracy may arise during the spatial distribution of these sample points or plots on the images or maps. The sample points or their equivalents have been distributed spatially on the grids. Consequently the grid sampling methods are easier to apply than the direct sampling methods. Linear measurement in the strip grid method is slower and less accurate than dot or rectangle count in the other two grid methods. Moreover, area computation from counts of dot or rectangles is easier to accomplish than that from linear measurements. In addition areas estimated by the strip method are less accurate. These eliminate the use of strip grid method for estimating forest areas. As points are qualitative attributes without dimensions, the number of points within a delineated area can be precisely determined on the dot grid. But with rectangular grids, this is very difficult, because the rectangles being counted are qualitative attributes with dimensions. This makes it difficult to determine the proportion of a rectangle to be included in the delineated area when such rectangle extends beyond the delineations. In view of this consideration it is my opinion that the dot grid method is more efficient than the strip or rectangular grid methods.

It follows therefore that tropical forest areas can be estimated more satisfactorily by dot grid sampling method or planimeter complete census method. The instrumentation of the planimeter supports its use for estimating areas with sinuous outline but it is more difficult to operate than the dot grid. Rigid mathematical formulas are used for the area computation in the planimeter method. The final estimates are not subject to sampling errors. Consequently, the amount of bias cannot be estimated neither can it be compensated. Simpler computation procedures are followed in the use of the dot grid sampling method. The final estimates are subject to sampling error.

Consequently the amount of bias can be estimated and compensated.

It is often reported that the dot grid is more efficient for estimating small areas while the planimeter is more efficient for estimating large areas on map or on remote sensing images. Evidence from the review of literature shows that such conclusions were made as a result of using inappropriate dot grids. Provided that the dot density on the grids matches the map size of the area being estimated, accurate area estimates can be obtained with dot grids irrespective of the map size. Foresters tend to be very rigid about consistence of their methodology without realising that the use of different density dot grids to estimate areas of different sizes on maps or remote sensing images does not imply inconsistence. By considering costs, ease of operation especially in the field, and the duration of operation and computation, it is my opinion that the dot grid method can provide reliable area estimates for forestry purposes. In view of this its relative efficiency is higher than that of the planimeter method.

In conclusion, remote sensing images can be used as map substitutes for the estimation of tropical forest areas provided that complete delineation of the entire survey area is made on these images. In situations where the geometric errors on the images are excessive, the maximum attainable accuracy may fall below the minimum acceptable accuracy. This problem can be overcome by compiling accurate maps from the delineated images. In either case accurate interpretation is a fundamental requirement for a reliable area estimation. Forest areas can be estimated more accurately by the dot grid or planimeter than by other methods but area estimates obtained with the dot grid method are more potent for statistical evaluation.

CHAPTER 6

THE ECONOMICS OF THE USE OF REMOTE SENSING IN FOREST SURVEYS

6 Economics of the use of remote sensing for forest surveys

The most important consideration in any remote sensing programme is the economic aspect which is often neglected by individual investigators who are basically more interested in their resource survey results than in the economic implications of their choice of technique and methods. The use of remote sensing especially over large areas, is generally thought to have the advantage of saving money, time and effort. Any form of remote sensing is basically expensive. Therefore a rational approach to an economic evaluation must be to make comparisons between surveys which include remote sensing and those based entirely on ground methods. The cost of any remote sensing surveys in terms of money and time is determined by a number of variables for which it is difficult, if not impossible, to establish generally acceptable standards because they vary both in space and time. Furthermore, as the different types of remote sensing imagery are not ordinarily acquired for the same area or interpreted for the same purpose, this review is limited to the discussion of the factors which tend to increase the costs of using remote sensing methods for forest surveys in the tropics. These factors were considered under two categories as follows:-

1 Environmental factors
    (a) local climate and weather
    (b) characteristics of the survey area
2 Technical factors
    (a) choice of remote sensing techniques
    (b) specifications of imagery and survey objectives
    (c) instrumentation, technology and expertise

The extent to which these factors can increase the cost and duration of remote sensing programmes and the various ways in which their effects can be minimised were discussed. The actual cost to the user is also of more practical value than diverse quotations from various contractors for the same amount of work. Relative costs are of more practical value to this investigation than absolute costs which are, of course, important. Costs are quoted in United States (US) dollars or relative values and are averages of data which vary widely but serve as a rough guide to remote sensing.

6-1 Environmental factors influencing the cost and duration of remote sensing surveys

The influence of environmental factors on the costs is greater in the tropical forests than in the temperate forests. In the tropical rainforest, the influence of these factors is highly divergent even within the same geographical region for the same survey. These factors are discussed below.

6-1.1 Local climate and weather

Most tropical forest and especially the high forest areas often have persistent or near-permanent cloud which hinders acquisition flights for user-controlled remote sensing systems. In addition to cloud cover, haze cover restricts or at least reduces the quality of photography or imagery. Of the remote sensing systems considered in this investigation only Landsat is not user-controlled. As a result the user is not involved in any financial risk in imagery acquisition with Landsat. The Landsat programme is a free access, global venture sponsored by the United States of America. Landsat is a geostationary sun-synchronous passive remote sensing system which images in the visible and near infrared portions of the electromagnetic spectrum. The quality of Landsat imagery is therefore affected by cloud and haze cover. Nevertheless the few good quality Landsat images of tropical areas can be purchased cheaply from agencies of the United States Department of Interior Geological Survey. Table 6.1 shows the price list of Standard Remote Sensing data available from the Eros Data Centre.

The only active system considered in this investigation is SLAR which provides its own energy source for imaging. It senses in the microwaves or centimetre wavelengths which penetrate cloud and haze.

Table 6.1 Costs of standard Landsat photographic products

Image size	Nominal scale	Product format	Product code	Price* ($)
Black/White				
5.6 cm.	1:3 369 000	Film positive	11	8.00
5.6 cm.	1:3 369 000	Film negative	01	10.00
18.5 cm.	1:1 000 000	Film positive	13	10.00
18.5 cm.	1:1 000 000	Film negative	03	10.00
18.5 cm.	1:1 000 000	Paper	23	8.00
37 cm.	1:500 000	Paper	24	12.00
75 cm.	1:250 000	Paper	26	20.00
Color Composites				
Master printer	-	-	59	50.00
18.5 cm.	1:1 000 000	Film positive	53	15.00
18.5 cm.	1:1 000 000	Paper	63	12.00
37 cm.	1:500 000	Paper	64	25.00
75 cm.	1:250 000	Paper	66	50.00

* These prices were current in late 1978 but are subject to change.

Source: Sabins (1978)

SLAR is therefore capable of being operated round the clock and in all weather if ground conditions permit flight. The advantage of its near all-weather day and night capabilities without cloud limitations permits SLAR imagery to be acquired at fairly fixed prices. The only limitations to SLAR imaging besides heavy rain storms (Lanly, 1976a) are the endurance of the air-crews and the restrictions on flight by civil aviation authorities. If weather conditions are unsuitable in some parts of extensive areas to be covered by SLAR, operations can be shifted to other parts of the survey area where theweather is suitable in order to reduce the waiting time. This was the case with the Nirad Project which took advantage of the large size of Nigeria and the diverse climatic conditions to cover the entire country (924 000sq.km.) at the scale of 1:250 000 within a period of six months by a series of disjointed flights. This would not have been possible with aerial photography. By such careful planning of any user-controlled remote sensing project, programmes can be executed at a precise schedule and exactly predetermined cost. Dependent operations can all be integrated to save more money, time and effort. In Panama the 17 000sq.km. Ramp Project area was covered by SLAR at the scale of 1:250 000 in only four hours (Howard, 1976). Similarly in Brazil the SLAR coverage of the 4 200 000sq.km. Radam project area at the scale of 1:400 000 took a relatively short period of about six months (FAO, 1974). Most of these areas covered by SLAR have for long frustrated all photographic efforts.

In aerial photography both the flight and imaging are affected by weather conditions. Good photographic weather conditions specify no haze and less than 12.5% cloud cover (ASP, 1975a) but these are difficult to come by in the tropical high forest areas, where the weather is unreliable and unpredictable. Crews are compelled to standby for considerable periods awaiting good flight or photographic weather. It is not unusual for survey programmes to be frustrated over successive seasons without any guarantee possible on the time they would be completed and at what cost and quality. Some contracting firms therefore avoid fixed price contracts (Morris & Martin-Kaye, 1973) and insist on daily rates (Avery & Mayer, 1962). The consequence of such frustration is not only loss of money and time but also inefficient interim operations, incomplete utilization of equipment and personnel, forgotten purpose and in extreme cases eventual abandonment of the entire programme. Even when such programmes are not abandoned dependent projects have to wait in sympathy for an indefinite time. Costs are reduced if contractors are given the option of flying an area at a convenient time rather than at a fixed specified date. Contractors can then handle many contracts, each executed under suitable local weather conditions. By this method, Howard (1970) indicated that a cost saving of up to 50% was possible. Cost can also be saved, according to Howard (1976), by carefully studying the occurrence of short dry seasons in cloud-prone tropical areas to coincide with photographic mission and also by the use of high flight aircraft (Avery & Mayer, 1962; Howard 1976). In high rainfall tropical areas flying time is often restricted to mornings at certain periods of the year due to thunder storms (Howard, 1970). In Nigeria there is a greater amount of flying time in the savanna region than in the forest region which seldom enjoys good photographic weather. This is a sharp contrast to Australian conditions which, according to Howard (1970), allow photographic flights for most of the year.

Assuming that weather permits flight and imaging, Howard (1970) stated that a good air-crew could photograph 1900 - 2300sq.km. at the scale of 1:15 840 in five hours flight and that much more can be achieved by high altitude photography using long focal length cameras. In addition it is also possible to photograph from 4000m. altitude on a greater number of days than at 8000m. altitude, a vantage point for the use of super-wide angle cameras. He also estimated that at the scales of 1:10 560, 1:15 840 and 1:21 000 using 23 x 23cm. format with 33% overlap, approximately 414 622 and 892sq.km. would be covered in each hour by an aircraft travelling at 273km. per hour. Howard (1976) has also estimated that a fleet of 20 high-flight aircraft would be needed to cover the world's tropical forest areas every 18 days which is the coverage frequency of Landsat I and II which image at 920km. altitude. Martin-Kaye (1974) stated that SLAR can image large areas in continuous strips of up to 200km. wide from fast moving jet aircraft.

Another aspect of remote sensing the cost of which is influenced by weather, is the collection of ground information against which imagery interpretation is checked. Under favourable conditions the cost may be negligible and the time and effort involved may be minimal. Under unfavourable conditions such as rainy seasons, field work is often at a standstill and many areas are flooded making access difficult. These conditions increase the cost of data collection. Sometimes data collection must be postponed till more favourable weather. In the indicative inventory phase of Nigerian High Forest Development Project, the inventory of certain forests was postponed for two seasons because of inaccessibility while motor boats had to be used to reach some deltaic swamp forests.

6-1.2 Characteristics of the survey area

The cost of remote sensing survey per unit area decreases sharply with increase in size of the survey area to a certain point beyond which cost decreases insignificantly with increase in area size (Loetsch & Haller, 1973). From this point cost per unit area becomes progressively more dependent on scale than area size. If this relationship is graphically expressed, the area size depicted by this point indicates the minimum survey area by which the remote sensing survey has a cost benefit over similar ground survey. Lanly (1976a) suggested that at least 250 000sq.km. should be contracted out at a time for a SLAR programme because of its high cost. Howard (1970) reported that the minimum cost for a very small area covered by a single stereopair of aerial photographs tends to be equal to the positioning fees which are fixed for a particular flight. Besides area size, the shape and continuity of survey area affect costs. According to Loetsch & Haller (1973) discontinuous and isolated forest patches of irregular shapes scattered over a survey area have been shown to increase photographic costs by 30 - 50% of what they should have normally cost for continuous rectangular forest blocks of the same size. In India, Tomar (1976) estimated the cost of aerial photography at 1:30 000 to be $0.97 per sq.km. of forest area and $0.28 per sq.km. of the geographical area containing the 1128sq.km. of forest compartments scattered in isolated patches.

Further, the positioning fee of any airbone imaging system depends on the flying distance from the maintenance and operation base to the survey area. A project area close to the base costs less to cover than a distant one requiring the setting-up of temporary bases. In Australia (Howard, 1970) the positioning fees for an area 160km. from the base (in Melbourne or Sydney) are twice as much as those for areas a few miles away. For the Nirad Project in Nigeria, Lagos and Kano were the main operation bases and equally effective territory. Above all, tropical countries are usually far from regions of advanced remote sensing technology and from centres of commercial hire of the more unusual and latest types of equipment. This often results in higher costs to these countries than those close to centres of commercial hire of equipment. This condition favours the use of conventional aircraft and standard panchromatic photography (Howard, 1970) and even then the positioning fee is still high. According to Howard (1970) the tropical forest zone in Australia has a flight positioning distance of about 3500km. from commercial hire in Melbourne or Sydney and if high-flight (8000m. altitude) survey is required the aircraft had to be hired from the United States. Both the aircraft and SLAR equipment used for SLAR survey of Nigeria belong to the United States contracting firm - Motorola Aerial Remote Sensing.

The characteristic of the survey area also affects cost of collecting ground data. In creek or mountainous areas where the terrain is rough and in dense forests which are inpenetrable, accessibility is a major limitation to the collection of ground information. The more difficult the access the more money, time and effort are involved in the field work. The complexity of the forest itself may not lend the area to rapid sampling. Under unfavourable ground conditions, the cost of field sampling to provide adequate control for an interpretation sometimes exceeds one third of the total survey cost. In the Niger-dams Multipurpose development project in Nigeria the cost of establishing ground control was more than twice the cost of mapping (Balfour et.al., 1968). Also the collection of ground information for the Nirad Project was fairly rapid in the savanna region but became increasingly difficult as the more complex tropical forest areas with difficult terrain was approached. Howard (1970) suggested that costs could be considerably reduced by aerial reconnaissance and by using the same aircraft to convey field crews in areas of difficult access.

Assuming satisfactory ground conditions, an intimate knowledge of the local environment and forest conditions in the survey area facilitates both the interpretation and field sampling and thereby saves the money, effort and time that could have been wasted in familiarisation programmes.

6-2 Technical factors influencing the cost and duration of remote sensing surveys

The choice of remote sensing method is determined by the survey objectives as the information being sought must be appraisable on the remote sensing images. Also, the extraction of information from the imagery requires adequate equipment and sufficiently trained personnel. The extent to which these factors influence the cost of remote sensing of tropical forests is discussed below.

6-2.1 Choice of remote sensing technique

No exact cost comparisons of the various remote sensing techniques can be given because they are not ordinarily acquired for the same area or for the same purpose. Even if they are, the specifications for their acquisition may not provide a definite basis for their comparison. Nevertheless it will suffice to give costs of acquisition of the different imagery in various places under diverse conditions.

Of the three systems concerned, only Landsat imagery is available to the user at precisely fixed prices because the Landsat system is operated on a global basis and centrally controlled. For a Landsat scene (approximately 34 225sq.km.), the cost of a set of four spectral photographic imagery varies between $32 and $80 and that of the corresponding colour composite varies between $62 and $100 (including the cost of generating its master-printer). These prices vary according to the required product format (i.e. paper print film negative or film positive) among other factors. Computer Compatible tape (CCT) set for a scene costs $200. These prices shown in Table 6.1 are for scene corrected (bulk) imagery; precision processed imagery is usually more expensive. In the tropics, aerial photographic coverage of an area equivalent to a Landsat scene, according to Howard (1976) would cost over $100 000 at medium scale and under favourable conditions. SLAR coverage of an equivalent area at the economic scales of 1:250 000 and 1:400 000 was likely to cost between $100 000 and $150 000 excluding the cost of additional flights for stereoscopy. This amounts to about $3 - $5 per sq.km. over large areas.

From the above quotations Landsat imagery is comparatively inexpensive (at least to date). Economically the cost of the acquisition of SLAR imagery is competitive with aerial photography provided that large areas (at least 250 000sq.km.) are covered at a time, more so when there is cost variation among the photographic films. As a generalisation, black/white photography is less expensive than colour photography. Based on the provision of acceptable sets, Howard (1970) stated that the cost ratio of black/white and colour photography varied between 1:5 and 1:3 while Smith (1963) quoted a 5:6 cost ratio that included all fixed costs. For large areas having known favourable weather conditions and easily accessible to contractors, this cost ratio, according to Howard and Lanly (1975) would probably exceed 4:5. Furthermore, panchromatic photography is less expensive than infrared photography either black/white or colour. Francis quoted a cost ratio of 10:11:13 for black/white, normal colour and colour infrared photography. Despite the differences in cost, the extra cost of one type of photography is usually balanced by the additional dimension of extracting information provided by the type of photography. Howard (1976) indicated that with wide usage, these cost ratios were likely to decrease with consequent increase in the cost benefit of colour over black/white aerial photography and infrared over panchromatic aerial photography. This is highly speculative in the tropics because colour films are more susceptible than black/white films to damage by high relative humidity and high temperature while colour prints are, in addition, more susceptible to fading (especially under too bright sunlight) and fungal attack. Consequently processing and storage would require air conditioned laboratories to prevent wastage. The extra cost of colour photography would therefore include cost of installation and maintenance of the air conditioners or the cost of wastage. To appreciate this further, the cost ratio of black/white and colour films according to Howard (1970) was 1:4 while that of processing varied between 1:3 and 1:6. His most recent cost ratios (Howard, 1976) were 10:11 for these films and 3:4 for their processing.

The ultimate photographic products to some extent influence the cost of acquisition of the remote sensing imagery. As a generalisation, transparencies are more expensive than paper prints whose cost in turn depends on the quality of the paper. Colour prints are more expensive than black/white prints from their complementary negatives while prints from diapositives (film positives) are more expensive than prints from negatives and sometimes twice as expensive (Kummer, 1964). Howard (1970) qoutes $0.04 per copy of copycat prints in the United Kingdom or Dalcopy prints in Australia, $0.78 per copy of oxalid print of photomosaic at 3.5 times enlargement and $3.90 per copy of contact prints from the oxalid master-printer in the Western United States of America.

Because of the high cost of photographic processing it is worthwhile setting up a processing and storage laboratory provided that the negative-processed film is retained by the user and, he has rights to reprint. In certain countries and especially in Nigeria, remote sensing imagery acquisition is vested on central authorities which control user-acquisition of imagery or make imagery commercially available to the users. According to Howard (1970) such central authorities usually charged a government royalty on each reprint as a means of recovering the initial acquisition cost. With the establishment of a central Remote Sensing Unit in the Federal Department of Forestry in Nigeria, the production of national resource maps has been vested on this Department while the Federal Survey Department still holds the overall control of remote sensing imagery acquisition and national maps production.

Another aspect of remote sensing which involves considerable cost is the interpretation and field checking. Nevertheless various workers have shown that forest surveys incorporating remote sensing are less expensive than those that rely entirely on ground methods provided that a large area is involved. As a basis for comparison, a 100% survey of selected valuable tropical forest areas in Ghana using entirely ground methods cost between ₵1.75 and ₵2.60 per hectare in 1956 according to Francis (1957) while a cost-saving of 20 - 25% was made by aerial survey. In similar surveys in India (Tomar, 1976) and Sri-Lanka (Mott, 1976) a cost saving of about 70% was made by the use of remote sensing techniques. Stellingwerf (1963) reported a cost saving of 11% per hectare in a survey of a 10 000ha. forest area in Holland using 1:20 000 scale aerial photographs while under extremely favourable ground conditions as in the Southeastern United States cost savings could reach 99.9% (US. Forest Service, 1959).

An investigation reported by Lyons (1964) showed that for the same efficiency, cost saving by photo-survey was 86% and for the same cost the sampling error was reduced by 13% through photo-survey. The same report showed that a cost reduction of 25% could be achieved for a specified survey objective. Carver & Moessner (1949) concluded from their investigations in Missouri that the use of aerial photography reduces the number of expensive field plots needed. Of the 100 000 photo plots involved in the survey only 25 000 were stereoscopically examined to determine the forest-types, while the ground information on volume was collected from only 2000 of these plots.

Finally, generalisation could not be made on interpretation costs because they vary widely in different parts of the tropical forest zone and many of the factors that influence costs are of divergent magnitudes even within a geographical region or a particular survey.

The choice of technique also influences the time involved in imagery interpretation. At the most economic scale of each remote sensing system, the coverage of a given extensive area would require a larger number of aerial photographs than SLAR strips or Landsat imagery. Interpretation time depends among other things on the number of images to be handled for the survey areas. Larin-Alabi (1978) estimated that about 5 200 aerial photographs would be required to cover the tropical lowland rain forest (mainly high forests) in Nigeria at the scale of 1:40 000 using 23 x 23cm. format with 70% overlap and 30% sidelap and that these aerial photographs could be replaced by only five Landsat frames or four SLAR imagery strips. Similarly Kio (1974) estimated that a single space photograph could replace 3200 conventional aerial photographs of one region and that at the scale of 1:40 000 (without further specification) aerial photographic coverage of Nigeria would require 81 000 photographs. The comparatively small number of Landsat images to be handled for a very large area is an advantage of saving interpretation time over aerial photography in particular but the reprocessing (e.g. additive colour viewing and photographic reproductions) of Landsat imagery is usually time-consuming. Computer-assisted interpretation of Landsat information on CCT is acknowledged to be more rapid and objective but the computer programming involved is time-consuming. In addition, computer facilities are neither cheap nor generally available in many tropical forest areas.

Tomar (1976) reported that by using 1:60 000 scale aerial photographs for stock mapping of the 1128sq.km. forest area in Vidisha in India the pace of work was 1.6 times faster than by ground methods (37.5% time-saving). Also in India, Maslekar (1977) reported that the assessment of success in a 330ha. of young teak plantation took only 10.5 man-hours using 1:10 000 panchromatic aerial photographs whereas corresponding assessment by ground methods would have lasted longer with less accurate results. Stellingwerf (1963) reported that in one man-day an interpreter was able to examine 5000 photoplots on 1:20 000 scale aerial photographs in conjunction with stereograms. Dodge & Bryant (1976) using computerised satellite information estimated that the development of spectral signatures for forest types in one county in the USA required 250 man-hours or 30 computer minutes. The ensuing statistics and computations required 50 man-hours or five computer minutes if given the appropriate soft-ware. Unfortunately the available hardware in most tropical countries is low-capacity type not suitable for handling Landsat data.

6-2.2 Specification of imagery and survey objectives

Of the specifications for the acquisition of remote sensing imagery, scale is the overriding cost-determinant especially in aerial photography of an extensive area such as a geographical region. For a fixed large area size cost of photography increases with nominal scale. According to Harrison & Spurr (1955) doubling the nominal scale more than doubles the cost of the photography. Howard (1970) reported that the cost of acquisition of aerial photographs under Sweedish conditions increased threefold by doubling the nominal scale. By doubling the scale and using the same flight lines and exposure intervals, Avery & Mayer

(1962) stated that the effective (stereoscopic) area is reduced to a quarter. In order to have equally effective areas using the same format at different scales, the flight lines and exposure intervals should be closer relative to the scale. This would result in a greater number of flight lines and exposures for a fixed area and a consequent increase in both the flying time and photographic costs.

However, for a fixed area size the gross cost of photographic processing of a film negative, contact or enlargement print and reprint decreases with increase in the number of exposures and therefore with increase in scale (ASP, 1975a). At the same time the overall photographic cost per unit area increases with scale. Under the diverse tropical conditions, cost of photography per unit area using the same scale, differs according to the prevailing local conditions. In India medium scale aerial photography for an extensive geographical region according to Tomar (1976) costs between $0.28 and $0.97 per sq.km. Howard (1970) estimated the cost of small-medium scale aerial photographs per sq.km. to be between $0.29 and $0.89 in Australia $0.54 and $0.78 in the United States, $1.71 in New Zealand, $0.73 in the United Kingdom and $0.49 in Eastern Canada.

The survey objective is usually the first indicator of the survey cost. In surveys which incorporate remote sensing, the amount of information needed to achieve the objectives dictates the scale of imagery, the levels of interpretation, photogrammetry and cartography which would be involved in the survey. In forest surveys the amount of information required for exploratory, reconnaissance, management (exploitation) and research surveys increases in that order, so also does the cost of every aspect of remote sensing involved.

Since the results of forest surveys are summarised mostly in thematic maps, planimetric accuracy is more essential and basic to forest map-compilation than topographic accuracy. Additional costs are involved in the planimetric control of maps compiled from remote sensing imagery. In many tropical areas planimetric base maps at suitable scale and of acceptable accuracy are seldom available; as a result new maps are photogrammetrically compiled at additional cost. In order to have an overall view of the forests which have not been previously mapped, photomosaics are usually required. The cost of uncontrolled, semi-controlled, fully controlled and ortho-photomosaics increase in that order according to the amount of control involved and the scale at which they are prepared. Mosaics are also useful as interpretation guide. For their broad view ortho-photomaps are useful map substitutes but expensive to produce. Where direct planimetric measurements on aerial photographs are desirable ratioed and rectified prints can be acquired for this purpose at additional cost.

As a generalisation the amount of photogrammetric and cartographic work involved in planimetric mapping from remote sensing imagery is considerably less than that involved in topographic mapping, consequently planimetric mapping costs less. This low cost favours the use of remote sensing techniques for forest surveys because forest maps are basically planimetric. An examination of a typical tropical survey cost data quoted by ASP (1975a) indicates that the cost of topographic mapping (all aspects from photographic flight to cartography but excluding ground information) is twice that of planimetric mapping from aerial photographs whose scale is about 2.5 times that of the maps compiled from them. From the same survey data the cost of photogrammetry and cartography for topographic mapping is thrice that of planimetric mapping. The cost ratio of cartography for planimetric mapping and topographic mapping at any scale is somewhat constant at 1:2 while that of photogrammetry decreases with increase in scale - 1:20

for small scale, 1:10 for medium scale and 1:5 (projected) for large scale. Table 6.2 abridged from the data of ASP (1975a) depicts the above trends.

In New Zealand topographic mapping costs between $0.57 and $1.97 per ha. at 1:24 000 scale with 1.5m. contours and at 1:12 000 scale with 0.5m. contours (Howard, 1970) while in Victoria (Australia) planimetric mapping costs $0.01 per ha. at 1:17 920 scale using 1:5 840 scale aerial photographs. According to Balfour and others (1968) the cost of planimetric mapping, for the Nigeria Nigerdams multipurpose project at the scale of 1:50 000 from 1:40 000 scale aerial photographs was $2.79 per sq.km. for an area of 842sq.km. while that of topographic mapping was $10.45 per sq.km. In Ghana, under similar ground conditions as in Nigeria, topographic mapping by ground methods, according to Francis (1957) cost between $220 - $270 per sq.km. in 1956. This shows that the use of remote sensing for surveys, however expensive, is still cheaper than the use of entirely ground methods, provided the survey area is large.

6-2.3 Instrumentation technology and personnel

The cost of acquisition and interpretation of remote sensing imagery usually reflects the type of equipment and personnel employed. The use of new equipment in conjunction with highly trained personnel costs more than the use of second-hand and less sophisticated equipment. Costs would be considerably reduced if both equipment and personnel were locally available. Only a few tropical countries have adequate equipment and indigenous personnel. Those countries which lack equipment and personnel but could afford the cost, have to contract their remote sensing projects to expatriate firms. Alternatively, they have to hire equipment from centres of commercial

Table 6.2 **Relative costs of typical tropical surveys using various scales of aerial photography**

Photoscale	1: 70 000		1: 40 000		1:20 000		1:10 000	
Mapscale	1:150 000		1:100 000		1:50 000		1:25 000	
Planimetric (P)	P		P		P		P	
Topographic (T)		T		T		T		T
Photographic flight	1.00	1.00	2.75	2.75	6.75	6.75	15.13	15.13
Photography	0.06	0.13	0.19	0.38	0.75	1.50	3.00	6.00
Interpretation	0.09	0.09	0.25	0.25	1.06	1.06	4.28	4.28
Aerial control	0.08	0.75	0.25	2.25	1.00	9.25	3.90	37.50
Photogrammetry	0.08	2.25	0.25	2.75	0.83	8.00	6.75	25.83
Cartography	1.13	1.75	1.13	1.75	2.50	4.50	6.25	12.00
Total	2.44	5.97	4.82	10.13	12.89	31.06	39.31	100.74
Ground information	5.00	5.00	5.00	5.00	125.00	125.00	125.00	125.00
Grand total	7.44	10.97	9.82	15.13	137.89	156.06	164.31	225.74

Source: American Society of Photogrammetry (1975a)

The relative figures in this table are averages of many data which diverge widely. Only areas greater than 500 sq.km. were considered. Relative costs for smaller areas would be higher. The cost of photographic flight per 100 sq.km. is taken as unit for comparison. Diapositives were needed for topographic plotting in addition to paper prints needed for interpretation.

Aerial control was by radial triangulation with slotted template for planimetric mapping and aerial triangulation with adjustment for topographic mapping. Ground information for the 1:70 000 and 1:40 000 scale photointerpretation was obtained by 0.005 - 0.01% field reconnaissance survey while that for the 1:20 000 and 1:10 000 scale photointerpretation was by 2% exploitation field survey.

hire and recruit personnel from regions of advanced remote sensing technology. Consequently the cost of remote sensing projects in these countries is much higher than the temperate countries, more so when considerable distances are involved in the mobilisation of equipment and personnel. Those countries which cannot afford the cost of their remote sensing projects, have to rely on international agencies for assistance. In these circumstances, the valuable field experience is gained by the expatriates who man these projects and the advantage to the country is lost when they leave at the conclusion of the projects.

For relatively low-cost remote sensing surveys in tropical areas, Lanly (1976a) and Larin-Alabi (1978) suggested that thought should be given in planning - whether countries of comparatively small areas should be combined with those of a larger area as in the case of Radam Project in the Amazon region and Ramp Project in the Panama region. This could also be considered along the West African Coast but Hutton (1977) from her experience in Botswana indicated that such a venture would be hindered, among other constraints, by the difficulty in establishing an effective communication system for data transmission.

The cost of remote sensing surveys tends to decrease with increase in usage of a particular technique both in space and time and with technological advancements in the remote sensing systems and associated techniques. Sisam (1947) illustrated the trend of cost reduction for aerial photography with data for the United States where, between 1936 and 1942, approximately 1 036 000sq.km. were photographed annually for the United States Department of Agriculture at the standard scale of 1:20 000. By the end of the sixth year the cost of aerial photography decreased by 47% per sq.km. despite the general war-time inflation. Another example of cost reduction by increased usage was cited by Latham and McCarty (1972). They stated that normal colour photography formerly costing about twice or thrice black/white photography cost only one and a half times and indicated that the relative cost of colour photography would decrease with increased usage. Another major advantage of increased and wide usage is the availability of remote sensing imagery over many areas. The coverage may be sufficiently adequate so that new coverages may not be necessary for some particular surveys as is the case in Canada and the United States of America. Consequently, the cost of acquisition is saved.

Security restrictions by the military of countries and advanced remote sensing technology encourage industrial monopoly which in turn renders the hardware (and sometimes the software) too expensive for developing countries to afford. If costs are to be kept favourable, according to Kio (1974), there should be a free market in which competing contractors could tender for work. He added that government policies often favoured the development of monopoly either by deliberately using military aircraft, or contracting work to its own civil aviation authority, or by intentionally creating an unstable market by contracting out work at irregular intervals.

In a rapidly evolving technology such as remote sensing, existing systems are usually outdated by inventions and current knowledge rendered obsolete by innovations before they are fully utilised. Consequently the cost of purchase of new equipment to replace the outdated ones and of repeated personnel training to keep abreast of new knowledge becomes excessively high (Larin-Alabi, 1978; Kio, 1971).

6-3 Inferences and conclusions

Evidence from literature was not sufficient to make definite conclusionson the economics of the use of the three remote sensing systems for tropical forest surveys. However, it permitted some generalisations to be made on the costs in terms of money, time and effort. The most significant finding of the review of literature is that forest surveys which include remote sensing techniquesare cheaper and quicker than those which rely entirely on ground techniques.

Any form of remote sensing is expensive. Imagery acquisition accounts for a substantial proportion of the total costs of forest surveys employing remote sensing techniques. Many tropical foresters often base their disapproval of remote sensing techniques on the high cost of image acquisition without considering the high cost of the camp and field survey equipment as well as the cost of mobilising the field crews. If it can be argued that both the camp and field survey equipment were not primarily purchased for a particular survey, the same argument should hold for imagery acquisition. In this consideration, remote sensing surveys are more economical. Imagery can be acquired for interdisciplinary and multipurpose use. Consequently, acquisition cost can be shared by the various users. If suitable imagery which has been acquired for purposes other than forestry are available they can be reproduced also cheaply. The advantage of reproducing remote sensing images for simultaneous use avoids the uneconomical delays associated with sharing of equipment and materials in ground surveys.

In addition, tropical foresters do not usually realise that several overheads in the cost of ground surveys of large areas may be greater than the cost of imagery acquisition in remote sensing surveys. For instance, unfavourable weather and ground conditions which do not permit the optional use of manpower and other resources in the field usually results in substantial increase in the total cost of ground surveys. Above all, the superior speed of remote sensing surveys more than balances the additional cost which is due to image acquisition.

Assuming favourable weather and ground conditions for the survey technique being used, all evidences indicate that Landsat survey is cheaper than ground survey, photo and SLAR surveys. This is primarily because the user is not involved financially in the acquisition of Landsat imagery. For small areas, both photo and SLAR surveys may be more expensive than ground survey as the flight positioning fee is fairly constant for any coverage. This means that the imagery acquisition cost per unit area would decrease with increase in the size of the survey area. The flight positioning fee of SLAR is higher than that of aerial photography. Consequently, SLAR images cost more for the same area.

The magnitude of the difference in costs could not be established for the present studies because the material from which evidence is drawn shows that both aerial photography and SLAR were not usually acquired over the same area or for the same purpose. The effect factors which influence the absolute acquisition costs of the images would therefore vary. It is certain that there is usually an optimum size of survey area for which one of ground, photo and SLAR techniques is cheaper. But these optimum areas cannot be determined with confidence as a result of the varied interactions of the factors influencing the costs of the different surveys. Because aerial photography can be acquired over a wide range of scales, cost is determined mainly by the size of the survey area, in the first place, until a maximum size is reached when the cost is then determined mainly by the photoscale. This trend is less noticeable with SLAR because of its restricted range of acquisition scale (1:250 000 - 1:500 000) while it is virtually absent with Landsat because of its constant acquisition scale (1:3 369 000).

For very large survey areas, photo and SLAR surveys are cheaper than ground surveys. At the restricted scales of SLAR (1:250 000 - 1:500 000), aerial photography is cheaper than SLAR imagery. However, when scale factor is introduced, aerial photography becomes increasingly expensive with increasing scale until a point is reached where SLAR becomes cheaper.

The foregoing shows that while Landsat surveys are generally cheaper than SLAR and photo surveys, their costs may be similar for a particular survey. For a realistic economic evaluation of using the different remote sensing systems for forestry purposes, their monetary costs have to be weighted by the amount of forest information which they can provide. The amount of forest information available with Landsat, though of a general type, balances the cost of its imagery. Despite its similar cost, SLAR cannot compete successfully with aerial photography because of its low information content. For instance, individual trees are usually resolved by aerial photography and if the aerial photographs are acquired at suitable scales, both species identification and forest mensuration can be carried out stereoscopically. Since individual trees are not normally resolved on Landsat and SLAR images, their identification and measurements are not possible even when stereoscopic observation is possible. Landsat images may be useful for grouping photointerpreted forest types into more inclusive general types. SLAR imagery may be more useful than other types of imagery for mapping terrain features obscured by vegetation in forested areas. Also, it has the advantage of being acquired for areas where environmental factors frequently frustrate photographic efforts and Landsat imaging. The technical capabilities of the three types of imagery are investigated further in Chapters 8 - 10.

On technical considerations, any remote sensing programme designed for forest surveys should therefore include aerial photography in order to be cost-effective for the particular survey. It is not economically advisable, particularly for developing tropical countries, to acquire different types of remote sensing imagery simply to obtain maximum information. If this is the only practical solution to the problem at hand it is suggested that such multi-sensor imagery acquisition should be an interdisciplinary programme so that the acquisition costs could be shared by the various disciplines involved in the programme. This would reduce considerably the cost to individual users. The acquisition cost could be reduced further if in a multi-sensor imagery programme only one type of imagery is acquired and used in conjunction with other types of imagery recently acquired for other purposes. In such circumstances, it may even be unnecessary to acquire new imagery if the available ones are very recent. If new imagery is to be acquired, it is economical to cover a very large area at a time. For example, neighbouring countries intending to carry out, say, forest surveys, can pool their financial resources to acquire the necessary imagery, but such efforts are frequently frustrated by political undertones, even in an interdisciplinary remote sensing programme within a country.

Further, most tropical countries do not possess adequate remote sensing equipment and sufficient trained personnel to man their remote sensing programmes. As a result the nominal costs of these programmes are increased by various overheads including those involved in contracting these projects to expatriate firms. Since it may not be the same firm that usually wins the award of these contracts, different firms have to start each project from the initial stages. With established personnel, future projects could utilise previous experience and thereby save these additional initial costs. It is suggested, therefore, that these countries should embark on personnel training programmes and establishment of remote sensing units either independently or jointly to save costs. For example, the Economic Commission for Africa has already established a training centre for aerial surveys in Ile-Ife, Nigeria. An international remote sensing centre has been established in Ouagadougou, Upper Volta and another in Nairobi, Kenya (E. E. Arubayi, personal communication, October, 1978). In Nigeria, plans are going ahead to establish a national remote sensing centre with a data bank in Kaduna in addition to the remote sensing unit at the Federal Department of Forestry in Ibadan. This centre would concern itself mainly with research on remote sensing applications and training of personnel.

It is only when the use of remote sensing is well established for tropical resource surveys that its economic advantages could be evaluated with confidence. Presently there is little experience. The little experience shows clearly that remote sensing methods are quicker than ground survey methods, and indicates that they are likely to be cheaper with wider usage. It may be too early to conclude from the state of the art in most tropical countries that remote sensing methods are cheaper than ground methods for forest surveys. More so when private forestry is rare in the tropics. Forestry being a government venture in most tropical countries, may be affected considerably by administrative and policy constraints. These in turn, will affect any remote sensing project for forest surveys. The economics of the use of remote sensing in such government forestry services is investigated further in Chapter 11.

PART II

EXPERIMENTAL INVESTIGATION

" The tendency in the past has been to seek information which tells <u>how to do</u> what decision makers <u>have already decided to do</u>. Current scientific approach is to gather information that will help to <u>anticipate problems</u> and to suggest <u>what to do</u> to solve them."

P. R. O. Kio (1974).

" Using satellite photography, (side-looking) air-borne radar and ground control, the Federal Department of Forestry is surveying the natural vegetation of Nigeria - a major step in increasing the prosperity of all our people."

Federal Department of Forestry, Nigeria (1976).

Introduction to Part II

The main objectives of the experimental investigation are:-

(a) to verify and augment in a test area representative of the African tropical forests (Southwestern Nigeria) the findings from the review of literature on the applications of remote sensing to forest management in the tropics.

(b) to appraise remote sensing in Nigeria ahd Nigerian forestry services in particular and to identify the problems associated with routine use of remote sensing in Nigeria.

(c) to suggest practical solutions to overcome the problems associated with the use of remote sensing for gathering information for forest management purposes in the tropics.

The report of the experimental investigation is presented in five chapters:-

Chapter 7 is introductory to the interpretation work and it describes:

(a) the classification of the vegetation of the test area.

(b) the sources and specifications of the remote sensing imagery used.

This chapter provides a background for the next three chapters which report the interpretation of the three types of imagery of the test area for all four categories of information:

Chapter 8 Photointerpretation

Chapter 9 Interpretation of Landsat imagery

Chapter 10 Interpretation of SLAR imagery

Each of these reports covers:-

(i) purpose and objectives of the interpretation.

(ii) materials and methods including image enhancement procedures.

(iii) the results and discussion.

(iv) findings of the interpretation

Chapter 11 reports a survey conducted by postal questionnaire to appraise remote sensing in Nigeria with regard to:

(i) the status of remote sensing in resource surveys in Nigeria

(ii) the current use of remote sensing by Nigerian forestry services.

(iii) the problems associated with routine use of remote sensing for resource surveys in Nigeria.

This chapter also relates the present investigator's previous experience in forest surveys to the results of the survey.

The experimental investigation reported in Chapters 8 - 10 was limited mainly to the interpretation of forest-types because it is the only category of information that provides a base line for comparing the relative efficiency of the three types of images for tropical forest surveys. Tree species identification was limited to photointerpretation. As the individual trees are not resolved on Landsat and SLAR images, species identification on these images is an equivalent of forest type recognition.

Photomensuration was not conducted to estimate forest volumes as this investigation did not include a field work by which photomensuration data could be correlated with field data. The relative efficiency of the three types of imagery as map substitutes for area estimation was not investigated because maps showing the spatial distribution of the numerical distribution of the forests being investigated were not available for the necessary correlations.

CHAPTER 7

VEGETATION AND REMOTE SENSING IMAGERY OF SOUTHWESTERN NIGERIA

7 The geographic location of the test area and test sites

A test area of about 58 000sq.km. in Southwestern Nigeria (see Fig. 7.1) was chosen for regional interpretation using small scale Landsat and SLAR imagery. The approximate geographic corner-coordinates of the test area are:-

Northwest - 7°30'N 2°50'E
Southwest - 6°20'N 2°45'E
Southeast - 5°40'N 5°00'E
Northeast - 7°50'N 5°00'E

Within the test area five different test sites (see Fig. 7.1) were selected for photointerpretation at larger scales. Their approximate geographic locations are:-

Test Site	Approximate location	
Olokemeji Forest Reserve	7°25'N	3°30'E
Ijaiye Forest Reserve	7°35'N	3°40'E
Ibadan Fuel Plantation	7°23'N	3°52'E
Ibadan University Teak Plantation	7°27'N	3°54'E
Omo Forest Reserve	6°50'N	4°15'E

The vegetation of Southwestern Nigeria is predominantly tropical rain-forest and consists of a wide range of ecological types. This makes it a suitable test area. Moreover, the present investigator, in his official duties had earlier carried out routine field surveys of test sites and other productive forests within the test area. He was therefore familiar with the local forest conditions. This facilitated the interpretation work.

7-1 The vegetation of Southwestern Nigeria

The wide range of variation within the tropical forest zone has resulted in local and regional classifications of the tropical forests. These classification schemes are seldom of universal application. They lack uniformity in terminology and nomenclature. This hinders their comparison even within a single geographic region. The best known and the most widely used classification of Nigerian vegetation is that of Keay (1959a). He classifies the vegetation into ten broad zones which

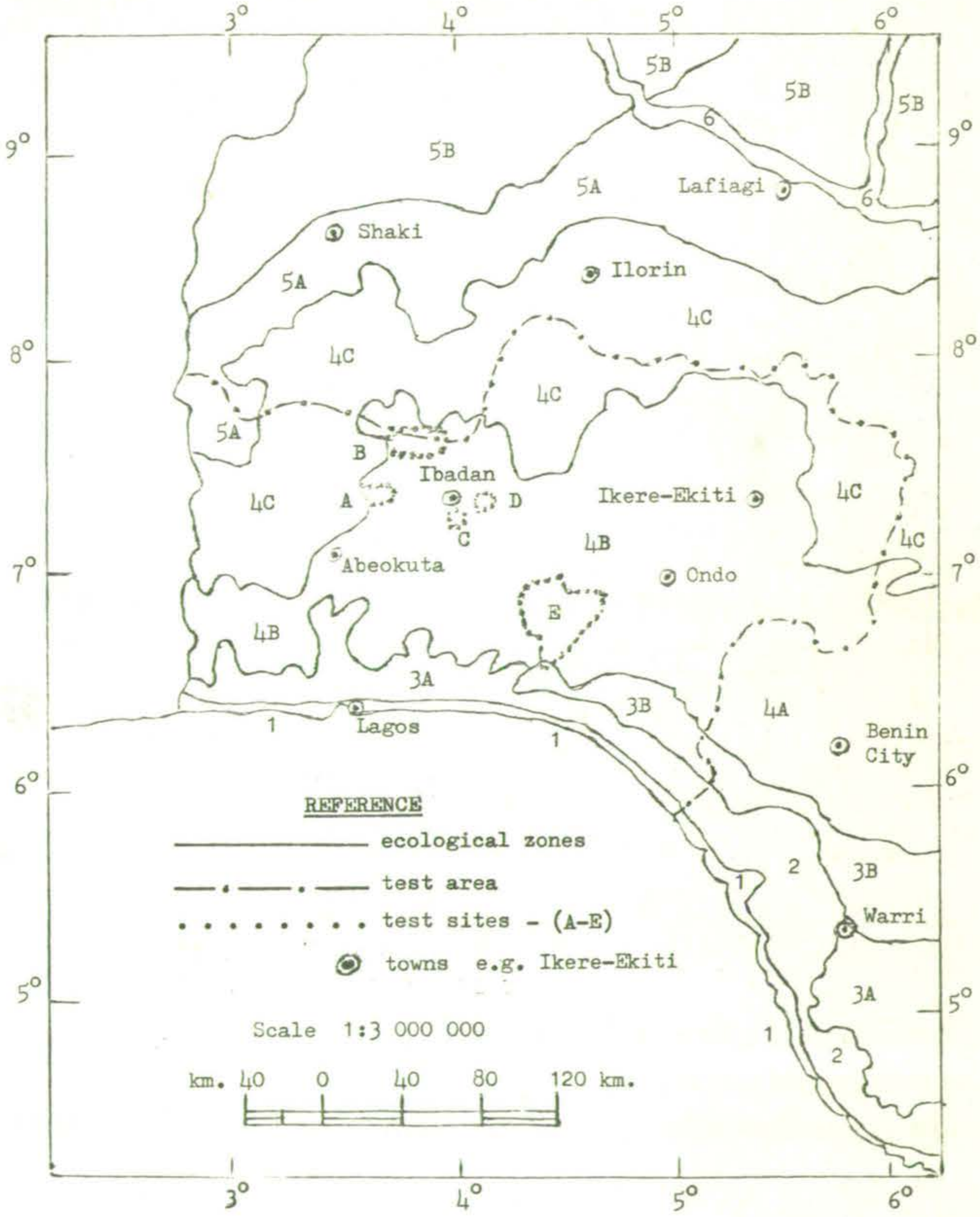


Fig. 7.1 Map of ecological zones of Southwestern Nigeria showing the test area and test sites

Source: Charter (1970)

Key to Fig. 7.1 (left)

	Ecological zones
	COASTAL VEGETATION (1)
1	Strand vegetation, thicket & forest
	MANGROVE (2)
2	Mangrove (Rhizophira racemosa)
	SWAMP FOREST/RIPARIAN FOREST (3)
3A	Deltaic swamp complex
3B	Seasonal swamp forest
	MOIST LOWLAND FOREST (4)
4A	Moist semideciduous forest (Leguminosae - Meliaceae)
4B	Moist semideciduous forest (Sterculiaceae - Moraceae - Ulmaceae)
4C	Forest-savanna mosaic
*	Moist evergreen forest
	DRY FORESTS/WOODED SAVANNA (5)
5A	Mixed leguminous wooded savanna (Afzelia africana & Khaya senegalensis)
5B	Mixed leguminous wooded savanna (Isoberlinia spp.)
*	Dry semideciduous forest
*	Dry deciduous forest
	EDAPHIC/BIOTIC SAVANNA (6)
	Flood plain complex

Test sites

A	Olokemeji Forest Reserve
B	Ijaiye Forest Reserve
C	Ibadan Fuel Plantation
D	Ibadan University Teak Plantation
E	Omo Forest Reserve

* Not mapped owing to its limited distribution and restricted occurrence in Southwestern Nigeria.

correspond to the main climatic zones. He also describes the variations within each zone without further classification into types. A more detailed schme is that which Charter (1969) prepared for the National Atlas of Nigeria which has yet to be published. In his scheme, based on more recent information and photointerpretation, Charter describes over fifty vegetation types in about twenty ecological zones. Charter's nomenclature and terminology make it possible to compare precisely the vegetation of Nigeria with those of other parts of Africa.

Charter's classification was adopted for the interpretation of the test area. The equivalents of the vegetation types found in the test area are given in Table 7.1.

The following description of the vegetation of Southwestern Nigeria is based on Charter's classification scheme. The ecological zones of vegetation found in the test area, inland from the coast (Fig.7.1) are:-

(a) coastal vegetation
(b) mangrove
(c) swamp forest
(d) riparian forest
(e) moist lowland forest

These ecological zones do not indicate homogenous blocks of vegetation. Rather, each zone represents a mixture of types and is characterised by the most extensive type found within it.

The vegetation types found in these ecological zones are described below:-

(a) Coastal vegetation

The coastal vegetation comprises halophyllous strand vegetation, coastal thicket and forest, all intermingled on sandy beaches, coastal creeks and lagoons within the tidal range:

(i) herbaceous strand vegetation with Ipomoea pes-caprae

Table 7.1 Equivalents of the main vegetation types found in southwestern Nigeria

CHARTER (1969)	KEAY (1959)	HALL (1977)	CCTA/CSA (1956)	BURTT-DAVY (1938)	UNESCO (1973)
Ecological zones of Nigerian vegetation	Outline of Nigerian vegetation	Forest-types in Nigeria	Yangambi Classification of African vegetation	Classification of Tropical Woody vegetation	International Classification of vegetation
1 COASTAL VEGETATION (3 types)	Mangrove and coastal vegetation	-	-	Tropical littoral woodland	-
2 MANGROVE (2 types)			Mangrove	Littoral mangrove woodland	Mangrove forest
3 SWAMP FOREST Deltaic swamp complex (comprises 8 distinct swamp forest types	Fresh water swamp communities	-	Swamp forest	Tropical fresh water swamps	Tropical ombrophilous alluvial forest (seasonally water-logged)
SWAMP FOREST seasonal swamp forest (undifferentiated)			Periodic swamp forest		Tropical ombrophilous swamp forest
4 RIPARIAN FOREST (6 types)	Riparian forest	-	Riparian forest	Tropical riparian woodland	Tropical ombrophilous alluvial forest (riparian)
5 MOIST LOWLAND FOREST evergreen	Lowland rain-forest	Forests on ferralitic soils (3 types) & Forests on ferruginous tropical soils (2 types)	Moist evergreen forest	Tropical lowland evergreen rain-forest	Tropical ombrophilous lowland forest
MOIST LOWLAND FOREST semideciduous (2 types)			Moist deciduous forest	Tropical semi-evergreen forest	Tropical evergreen seasonal lowland forest
MOIST LOWLAND FOREST forest-savanna mosaic	Derived savanna with relict forest	-	-	Tropical moist deciduous forest	Tropical semideciduous lowland forest

Sources noted above.

occurs on sandy and gravelly seashore not subject to immersion but under constant maritime influence.

(ii) coastal thicket with Chrysobalanus orbicularis, Hibiscus tiliaceous and Thepseria populnea is shrubby, evergreen or deciduous (due to physiological drought). It is usually more or less impenetrable. It often occurs in clumps with grass substratum absent or discontinuous.

(iii) undifferentiated coastal forest.

(b) Mangrove

The mangrove is a closed stand established on saline sods within the tidal range. Mangrove may occur as forest, thicket or bush, depending on the extent to which it has been degraded by human activities. In vertical profile, mangrove has only one layer of trees. The trees are stilt-rooted or bear pneumatophores and the leaves are sclerophyllous.

(i) red mangrove (Rhizophoraceae). The drier areas of this type are dominated by Rhizophora mangle while the swamp edges are dominated by R. racemosa. The middle areas are dominated by R. harrisoni.

(ii) white mangrove (Verbenaceceae). This type is mainly dominated by Avicennia africana.

(c) Swamp forest

Swamp forest is a closed stand of irregular structure with two discontinuous layers of trees which bear stilt-roots or pneumatophores. Many genera have buttresses. The canopy is continuous but not uniform. As a rule, swamp forest is poor in undergrowth except in the more open space where dense tangle of shrubs and lianes form an almost impenetrable undergrowth with an ill-defined shrub and herb layer. Aquatic grassland within the swamp forest is actually a stage in the hydrosere leading to the development of swamp forest. It is different from herbaceous swamp which is a distinct life-form dominated by *Cyperus papyrus* (sedge) and *Phragmites communis* (grass). The soil in swamp forest areas is either permanently flooded or at least saturated for most of the year. Swamp forest types are usually differentiated by the most abundant species present:-

(i) *deltaic swamp complex*. This type occurs along lower river-courses within the tidal range. The water table is therefore much affected by sea tides. Deltaic swamp complex comprises *Alchornea floribunda* thicket, palm swamp with *Elaeis guineensis* (oil palm) on sandy levees, isolated areas of moribund *Rhizophora racemosa* and types (ii - vi).

(ii) *Oxystigma mannii* swamp

(iii) *Rhaphia hookerii* swamp - a form of degraded swamp forest

(iv) *Pandanus candelabra* swamp - Pandanus is a climbing palm with hooked spine, more often found in association with large aroids.

(v) *Mitragyna ciliata* swamp - abundant on ancient ridges within mangrove areas.

(vi) *Cynometra megalophylla* swamp

(vii) *undifferentiated seasonal swamp forest*. This type is similar to the deltaic swamp complex but poorer in species. It is found on edaphically wet habitats supplied with brackish or fresh water, not necessarily along river courses. The water table fluctuates according to seasons.

(d) *Riparian forest*

This is a closed stand of irregular structure varying between those of the moist forest in the south and riparian woodland in the more northerly savanna areas of Nigeria. Lianes are abundant. It is found not only along present, but also along former river courses.

The soil is neither innundated nor saturated, even periodically, but it is maintained at a higher moisture content owing to the nearness of water courses. Riparian forest-types are distinguished by the most abundant species present. The following types are recognised:-

(i) *Cleistopholis patens*

(ii) *Mitragyna stipulosa* and *Berlinia grandiflora*

(iii) *Irvingia smithii* and *Manilkara oborata*

(iv) *Khaya senegatensis* and *Syzygium guineensis*

(v) *Mitragyna inermis Diospyros mesipiliformis* and *Celtis integrifolia*

(vi) undifferentiated submontane riparian forest

(e) *Moist lowland forest*

This is a closed stand of several layers of trees which are generally tall. In vertical profile, these layers are not apparent because crowns occur at all levels. The canopy is continuous but uneven due to the irregular occurence of taller emergents. Some of the tree genera have buttresses. There is sparse undergrowth of shrubs and herbs which are mainly tree reproductions. Grasses are uncommon and, if present, they are of specialised forest genera. Three types are recognised:-

(i) *Moist evergreen forest*. This type is found in the wetter areas of the moist lowland forest zone. Lianes are virtually absent. Vascular epiphytes are only abundant under extremely humid conditions. The vegetation is evergreen except for some sporadically occuring deciduous species. Some of the emergent species may be deciduous but foliage reduction is not noticeable. *Lophira alata*, *Baillonella toxisperma* and *Nauclea diderrichii* are abundant.

(ii) *Moist semideciduous forest*. This type is found in the relatively drier areas of the moist lowland forest zone. Lianes occur occasionally while epiphytes are rare or absent. Forb and graminoid stratum is scarce or sparse when present. Some of the canopy trees are deciduous and foliage reduction is noticeable in the dry season. Understorey trees and shrubs are evergreen. Two varieties of this forest-type are recognised by the families of trees present.

- Moist semideciduous forest with abundant
  Leguminosae (*Gossweillerodendron*, *Cyclodiscus* and *Brachystegia*)and
  Meliaceae (*Khaya ivorensis* *Entandophragma*, *Lovoa* and *Guiarea*)
- Moist semideciduous forest with abundant
  Sterculiaceae (*Triplochiton*, *Sterculia*, *Cola* *Pterygota* and *Mansonia*)
  Moraceae (*Antiaris*, *Chlorophora* and *Ficus*) and
  Ulmaceae (*Celtis* and *Holoptela*)

(iii) *Forest-savanna mosaic*. This is a degraded moist forest comprising moist semideciduous forest on high level sites, well-developed riparian forests in the valleys and wooded savanna with Daniellia oliveri and oil palms.

The relict patches of moist forest or forest trees with oil palm and climbers growing on relatively dry soil are supported only by rainfall. The wooded savanna (derived savanna) has been induced by traditional shifting cultivation which admits a grassy ground layer during fallowing. This grassy layer encourages fire in the dry season dry season.

> Wooded savanna is a mixed formation of trees, shrubs and grasses. The grasses are at least 1.2m. tall. They are perennial forming a continuous layer dominating a lower stratum. They are usually burnt annually. The commonest grasses are Andropogon tinctorum and Loudetia arundinacea. The woody plants usually present are of variable density.

Except for inaccessible stony hill-top areas, areas unsuitable for cultivation and the strict forest reserves with inviolate plots, most of the moist forest has been degraded through human activities. The typical forests today are mature secondary forests and fully regrown cur-over forests with multidominants. In most cases, the moist forest zone now consists of intricate mosaics of farms and associated fallows and immature secondary forest.

The oil palm is characteristic of moist forest and may form almost pure stands in some areas. The more northerly parts of the moist forest have been replaced by wooded savanna, oil palm being an indicator of its derivation from the moist forest.

The term 'tropical high forest' is applied to all climatic edaphic and biotic forests sharing the same physiognomy with the tropical rain-forest. The tropical high forest in Nigeria is neither a vegetation zone nor an ecological zone. It is concentrated in but not confined to the moist lowland forest zone. It is also found as isolated forest blocks within savanna areas that enjoy a microclimate suitable for the development of high forest. Also, the term 'thicket' is applied to both ecologically specialised communities and forest regrowths which are similar to the 'physiognomic' thicket in the Yangambi classification scheme (CCTA/CSA, 1956).

7-2 Remote sensing imagery of the test area

The test area was covered by aerial photography, Landsat MSS and SLAR at various dates. The following were the most recent and the best available imagery of the test area at the time of this investigation.

(a) Aerial photographic coverage

Within the test area for regional interpretation, some sites were selected for detailed interpretation. These are forest reserves (managed forests) including forest plantation sites that have been previously covered by panchromatic aerial photography as follows:-

Test site	date of photography	acquisition scale	number of photographic	
			prints	stereomodels
Ijaiye Forest Reserve	March, 1975	1:20 000	4	2
Olokemeji Forest Reserve	Dec. 1962	1:40 000	4	2
Omo Forest Reserve	March, 1975	1:20 000	4	3
Ibadan Fuel Plantation	Dec. 1961	1:40 000	4	2
Ibadan University Teak Plantation	Aug. 1968	1: 6000	4	3

The photographs used for the investigations were commercially reproduced from paper prints by HTS except those of Ibadan Fuel Plantation flown by them. This was due to difficulties in obtaining reprints from the original negatives.

(b) Regional coverage by Landsat MSS and SLAR

The test area is approximately covered by two Landsat scenes - path-row 204-055 and path-row 205-055. The best available frames of these scenes are:

Frame number	Date of exposure	Least cloud-cover	* Quality rating of band 4	5	6	7
E1107-09273	7/11/72	30%	5	8	8	8
E1036-09323	28/8/72	30%	8	8	8	8
E1108-09332	8/11/72	30%	5	5	5	5

* Quality rating ranges from very poor (0) to excellent (9)

The 1:3 369 000 scale multispectral 70mm. film negatives and positives and also 1:1 000 000 scale spectral film negatives of bands 5 and 7 of each frame were purchased from Eros Data Centre.

Between October, 1976 and March, 1977 the test area was covered at the scale of 1:250 000 by Motorola AN/APS - 94D real-aperture SLAR system, as part of the Nirad (NIgeria RADar) project - nationwide vegetation survey. The imagery was acquired in the X-band (3cm.) wavelength. The swath width was 25km. with 60% swath lateral overlap. The following SLAR mosaics, covering the test area, were purchased from Hunting Technical Services Limited (HTS), who were responsible for the interpretation phase of the Nirad Project:

Mosaic sheet NB31-3N (north look)
Mosaic sheet NB31-4S (south look)
Mosaic sheet NB31-7S (south look)
Mosaic sheet NB31-8S (south look)

Neither the original film strips nor paper prints were available for this investigation.

7-2.1 Enhancement of the imagery of the test area

The imagery of the test area was enhanced to improve its interpretative quality. Because of the limited resources, facilities and time available for this investigation, the enhancement of aerial photographs and SLAR was limited to enlargement printing. This was to create bigger images of the objects being investigated. The

Landsat imagery was enhanced further by generating colour composites by colour additive processing of the black/white spectral images. These colour composites were also printed at enlarged scales (see Section 9-1).

The following enlargement printing was made:

The 1:40 000 scale aerial photographs of Ibadan Fuel Plantation and environments were enlarged to 1:20 000 by Hunting Technical Services Limited.

Contact prints of the 1:1 000 000 scale Landsat spectral imagery were made by Fairey Surveys Limited. Images of the areas of interest were reproduced at larger scales from these contact prints by 35mm. microphotography.

The original plan to print the generated colour composites to the same scale with the SLAR mosaics was abandoned because of technical problems. The geographic co-ordinate markings at the edges of the Landsat 70mm. film transparencies which are the only direct means of scale calibration during printing, were obscured by the 70mm. Antinewton diaslides holding the transparencies. As a result, the composites were not printed to scale. However the approximate printing scales were extrapolated from the contact prints of the 1:1 000 000 scale spectral imagery.

The images of test sites were reproduced from the 1:250 000 scale SLAR mosaics at the scales of 1:100 000 and 1:50 000 by Hunting Technical Services Limited.

CHAPTER 8

PHOTOINTERPRETATION

8 Photointerpretation

The main purpose of this investigation is to verify and augment the findings of the review of literature on the use of aerial photographs for gathering forest information for management purposes in the tropics. The investigation was also designed to:

(a) verify the extent to which the variations in the forest-cover within a single ecological zone can influence the choice of interpretation techniques.

(b) verify the extent to which the variability of photointerpretation can affect the total estimates of area-related forest information.

In order to fulfil the purpose and objectives of the investigation, five test sites representing different ranges of vegetation within the Nigerian moist low-land forest zone were interpreted on panchromatic aerial photographs specified in Section 7-2 and repeated below:

	Test site	Photo scale	Date
(a)	Olokemeji Forest Reserve	1:40 000	December,1962
(b)	Ijaiye Forest Reserve	1:20 000	March, 1975
(c)	Ibadan Fuel Plantation	1:40 000	December,1962
(d)	Ibadan University (UI) Teak Plantation	1: 6 000	August, 1968
(e)	Omo Forest Reserve	1:20 000	March, 1975

The types of filters used for the photography were not known. The five sets of aerial photographs differ in object-magnification, quality and tonal range because they were acquired at difference seasons and at different scales. The 1:40 000 scale aerial photographs were enlarged to 1:20 000 to provide a uniform working scale. The individual sets of photographs were interpreted separately because of the differences in their quality and tonal range.

The interpretation is reported in three parts:

(a) forest type recognition

(b) forest cover variation and photointerpretation variability

(c) tree-species identification

8-1 Forest type recognition

Information from relevant literature on the forest types of the test sites was first collated and evaluated. The present investigator's previous survey of these sites and his knowledge of the local forest conditions facilitated the evaluation. The evaluated information provided the ground information for the control of the photointerpretation as a field work was not conducted. Several workers including Langdale-Brown (1968), Mason and Wood (1952) have shown that, in the absence of primary data, secondary data can provide a satisfactory and effective control for photointerpretation. Further correlations between photoevidence and the ground information on the forest types were established after comparing the interpretation with the information on published vegetation and forest maps.

8-1.1 Materials and methods

A preliminary examination of the aerial photographs was conducted to establish a set of criteria for the interpretation of the forest types. They were examined visually with the aid of a hand held magnifier and stereoscopically under lowmagnification. The following sets of criteria were derived for the interpretation.

(a) Photoappearance

(i) Photographic tone: Because a relative grey scale was not printed on the individual photographs, the

Kodak relative grey scale was used as an interpretation aid for the tonal separation of the forest types. The relative grey scale values were classified into qualitative tonal grades as follows:

relative grey scale value	tonal qualitative grade
0.00	white
0.10 - 0.25	light
0.40 - 0.55	medium
0.75 - 1.10	dark
1.25 - 1.90	black

The use of a relative grey scale which is not printed directly on the individual aerial photographs has a major drawback. When such a scale is used to assist the interpretation of a series of photographs united by a common grey scale during printing, cross references can be made from one photograph to another. However, in a situation such as this investigation where a disparate collection of individual photographs or sets of prints is being handled, the scale can only be used to assist the interpretation of one photograph at a time and cross references to other prints cannot be made.

(ii) Photographic texture: the following grades of texture were used in the interpretation: smooth, fine, medium, coarse and rough. For this investigation rough texture includes stippled, mottled or specular appearance.

(iii) Photographic pattern: rectangular, concentric, radial and other systematic patterns are described as regular patterns while those without any systematic arrangement are described as irregular patterns.

(b) Stereoscopic appearance

This relates mainly to the gross characteristics of the canopy which is the only source of direct information of most tropical forests on aerial photographs. The characteristics of the canopy could not be quantified precisely because the small scale and poor quality of the aerial photographs limited precise measurements. Moreover, the variations within individual forest types obscured the variation between the forest types. Stand-heights were not measured because the closed canopy of the forests obscured the ground and so prevented parallax measurements. However, the canopy layer is sufficiently compact to act as a general measure of the relative heights of the forest types. Also, percentage crown closure was not used as a criterion because it has no interpretative value for closed forests. For these reasons, it was considered more realistic to describe the characteristics of the canopy in relative qualitative terms as defined and coded in Table 8.1. These characteristics are botanical attributes which were appraised on the aerial photographs stereoscopically. The botanical attributes were listed in alphabetic codes. The observed variations of each attributes (variants) were listed in a hierarchical order reflecting the gradation in canopy development. For each attribute, the first variant represents the highest level of its development while the last represents the lowest level. These variants are not mutually exclusive and the number of variants is not constant for the individual attributes. The variants of

Table 8.1 List of the botanical attributes of the forest canopy

A Presence or absence of canopy

1. present
2. absent

B Continuity of canopy

1. continuous, without gaps
2. continuous, with small gaps
3. broken, with large gaps
4. patched, occurs as small patches
5. patched and dotted
6. dotted, occurs as small groups of crowns
7. not applicable

C Relative density of canopy

1. dense, crowns interlock
2. closed, crowns do not interlock
3. light, crowns just touching
4. open, crowns separated and herb layer visible
5. not applicable

D Relative height level of canopy

1. high
2. moderate
3. low
4. very low
5. not applicable

E Mixture of crown sizes

1. large
2. large and medium mixed
3. large, medium and small mixed
4. medium and small mixed
5. medium
6. small
7. not applicable

F Arrangement of crowns

1. irregular, with high incidence of emergents
2. mixture of regular and irregular arrangements
3. regular with low incidence of emergents
4. regular without emergents
5. not applicable

each attribute were coded numerically starting with unity (1) for the first variant. The last code number is recorded for an attribute which is "not applicable" due to the absence of canopy. For assessing the level of canopy development, the total number of attributes which is six in the present investigation was used as a reference. Consequently, only one variant of each attribute was scored for each unit of delineation. Because the variants of each attribute were not mutually exclusive, the variant which was most frequently encountered was scored for the unit of delineation being examined. Furthermore, as several units were examined, the same set of attributes was considered because the number of variants was not constant for the individual attributes. The closeness of the sum of the code numbers to the reference indicates how well-developed the canopy is. It follows that the nature of the forests within several units of delineation can be assessed by this method. Also, the method can be used to establish the differences and similarities between two or more forest types (see Section 8-1.2). However, this does not necessarily imply the establishment of an interpretation key for forest type separation.

(c) Ecological sites

These were considered in situations where a forest type is associated with specific sites e.g. riparian forest along river courses and hill forest on hill crests.

The criteria were used in combination for distinguishing different areas on the aerial photographs. These areas were delineated stereoscopically. Similar areas were grouped into units of similarity. Each unit of similarity was further examined stereoscopically under x8 magnification for more subtle differences. The grouping was adjusted accordingly. The forest type equivalents of the units of similarity were extrapolated from the information collated from literature and established maps. The accuracy of the interpretation was not assessed because the 'ground information' was not sufficiently precise for an accurate checking of the interpretation. For instance, forest type maps of the test area are rare or scarce if they exist. Furthermore, the information available on the existing maps is less detailed than that on the aerial photographs which were interpreted. Before the test sites were interpreted separately, a general interpretation was done following a modified procedure (see Section 8-2.1) in order to verify the forest-cover variation within the test area.

8-1.2 Results and discussion

Sixteen forest types (1-16) including eleven natural types (1-8 and 14-16) were separated on aerial photographs by their photoappearance and the stereoscopic appearance of their canopies. The results of the photointerpretation are presented in Table 8.1.1. The forest types (1-16) are illustrated in Figs 8.1 to 8.5 by the numbers in brackets after the names of the forest types in Table 8.1 and in the ensuing discussion. On the right hand side of this table, the numerical codes of the variants of these attributes which are scored for each forest type are recorded in the appropriate columns (A-F). The sum of the numerical codes for each forest type is recorded in the last column. The minimum possible sum is equal to the number of attributes i.e. the sum of all the codes of the first variants of the individual attributes. This sum indicates the forests with the most

Table 8.1.1 Photographic description of the forest types

xxx Forest types		** Photo appearance			* Botanical attributes of the canopy						
		tone	texture	pattern (shape)	A	B	C	D	E	F	SUM
(a)	Olokemeji Forest Reserve										
I	Dry semideciduous										
	i hill forest (1)	light/medium	medium/coarse	regular	1	2	2	3	3	2	13
	ii high forest (2)	medium	medium	regular	1	1	1	1	3	1	8
	iii low forest (3)	medium	medium	regular	1	1	1	2	4	3	12
II	Wet semideciduous										
	i high forest (4)	medium	medium	regular	1	1	1	1	2	1	7
	ii low forest (5)	medium	medium	regular	1	1	1	2	3	3	11
	iii open forest (6)	medium/dark	coarse	irregular	1	2	2	2	3	2	12
III	Forest savanna transition (7)	light	medium	regular	1	3	2	2	4	2	14
IV	Wooded savanna (8)	dark (mottled)	smooth	irregular	2	7	5	5	4	5	28
V	Thicket/forest regrowth (9)	dark/medium	fine	irregular (patches)	1	1	1	4	6	4	17
VI	Forest plantation (10)	medium	fine/medium	regular (rectangular) (blocks)	1	2	2	x	x	4	-
VII	Cultivation areas (11)	mixed	smooth	irregular (patches)	2	7	5	5	7	5	31
(b)	Ijaiye Forest Reserve										
I	Wet semideciduous										
	i open forest (6)	dark	coarse	irregular	1	2	2	2	3	2	12
II	Forest savanna transition (7)	light	medium	regular	1	3	2	2	4	2	14
III	Wooded savanna (8)	dark (mottled)	smooth	irregular (patches)	2	6	5	5	4	5	26
IV	Thicket/forest regrowth (9)	dark/medium	fine	irregular (rectangular) (patches)	1	1	1	4	6	4	17
V	Cultivation areas (11)	mixed	smooth	irregular (patches)	2	7	5	5	7	5	31

	xxx Forest types	** Photo appearance			* Botanical attributes of the canopy						
		tone	texture	pattern (shape)	A	B	C	D	E	F	SUM
(c)	<u>Ibadan Fuel Plantation</u>										
I	Wet semideciduous										
	i open forest (6)	dark	coarse	irregular	1	2	2	2	3	2	12
II	Thicket/forest regrowth (9)	dark/medium	fine	irregular (patches)	1	1	1	4	6	4	17
III	Forest plantation (10)	medium/dark	medium/fine	regular (rectangular) (blocks)	1	1	2	x	x	4	-
IV	Cultivation areas (11)	mixed	smooth/fine	irregular (patches)	2	7	5	5	7	5	31
V	Complex vegetation mosaic (12)	mixed	smooth/fine	irregular (patches)	+	+	+	+	+	+	-
(d)	<u>Ibadan University Teak plantation</u>										
I	Forest plantations (10)	light/dark	fine/medium	regular (blocks)	1	1	2	x	x	3	-
II	Cultivation areas (11)	mixed	smooth	irregular (patches)	2	7	5	5	7	5	31
III	Complex vegetation mosaic (12)	mixed	smooth	irregular (patches)	+	+	+	+	+	+	-
(e)	<u>Omo Forest Reserve</u>										
I	Thicket/forest regrowth (9)	dark	fine	irregular (patches)	1	1	1	4	6	4	17
II	Forest plantation (10)	light	medium	regular (continuum)	1	1	2	x	x	3	-
III	Cultivation areas (11)	mixed	smooth	irregular (patches)	2	7	5	5	7	5	31
IV	Taungya farms (13)	medium	fine	regular (blocks)	2	7	5	5	7	5	31
V	Evergreen										
	i riparian forest (14)	medium/dark	coarse	irregular	1	2	3	1	3	1	11
	ii mature high forest (15)	medium	medium/coarse	regular (continuum)	1	1	1	1	2	1	7
	iii immature high forest (16)	medium	medium	regular (continuum)	1	1	1	2	3	3	11

Table 8.1.1 Photographic description of the forest types (continued)

***	The numbers in brackets are used in the illustrations (Figs. 8.1 - 8.5) to designate the forest types.
**	These relate to the actual prints which were interpreted
*	The definition of the alphabetic and numeric codes are given on Table 8.1.
+	This characteristic is not consistent for the forest type
x	Characteristics depend on the age of the forest type

developed canopy e.g. mature closed high forest. The maximum possible score is equal to the number of attributes plus the number of their variants i.e. the sum of the last codes of the individual attributes. This sum indicates vegetation without canopy e.g. grassland.

In the present investigation the minimum and the maximum sums are six and thirty one respectively. The differences and similarities between forest types can be assessed by comparing their scores in the sum column first, and then their scores in the attribute columns. For example, the three high forest types (2, 4 & 15) are similar in all respects except that the dry semideciduous type (2) has a mixture of large medium crown sizes while the wet semideciduous (4) and the evergreen (15) both have a mixture of only large and medium crown sizes. As the comparison is based on canopy attributes, only the forest types with canopies can be differentiated. The differences between types which have no canopies cannot be established e.g. cultivation areas(11) and taungya farms (13). However, they can be distinguished from the other types by the absence of canopy.

In the five test sites, sixteen forest types(1-16) including eleven natural types (1-8 and 14-16) were separated on aerial photographs by their photoappearance and the stereoscopic appearance of their canopies. During the interpretation it was observed that the boundaries between reserved and unreserved (free) forests were very distinct on the aerial photographs despite their poor quality (Figs. 8.1 & 8.2). Where a reserve boundary cuts across a forest type or two adjoining forest types, the reserved parts of these forests were observed to be more densely vegetated than the unreserved parts. Also, the boundary between the two forest types were observed to be more distinct in the free areas than in the reserved areas. Both conditions are illustrated in Fig. 8.2 by the wet semideciduous open forest (6) and the forest savanna transition (7).

Forest types or subtypes belonging to a more general type were difficult to separate and delineate when they occur as immediate neighbours. For example, there are no distinct boundaries between the six moist semideciduous forest types (1-6) found at Olokemeji, nor even between the wet (1-3) and the dry (4-6) types. Also, the three moist evergreen types (14-16) merge and intermingle without distinct boundaries. The delineation of these types was based on personal judgment.

The five forest types induced by man (9-13) were easy to separate from the natural forest types. Forest plantations (10) and taungya farms (13) were encountered only in the reserved forests. Thicket/forest regrowth (9), cultivation areas (11) and complex vegetation mosaic (12) were encountered only in the free forests. The induced forest types in the reserved forest (10 & 13) differ markedly from those in the free area (9, 11 & 12). The former have uniform tone texture and pattern. They were seen on aerial photographs as rectangular blocks. These rectangular blocks are usually in parallel alignment when they adjoin each other. The latter have inconsistent photographic tone, texture and pattern. However, they were recognised by patches of small rectangular blocks which occur in groups without any definite arrangement. These rectangular blocks are either recent farms and farm-fallows in the cultivation areas or bush-fallows (abandoned farm-fallows) in the thicket/forest regrowth. For this investigation, a fallow is defined as an abandoned farmland, a farm-fallow being more recent than a bush-fallow. An advanced bush-fallow is regarded as a forest regrowth. Because of their development on abandoned farm sites, forest regrowths are usually interpreted as farm-regrowths by many workers e.g. Kio (1971). In this interpretation, thickets and forest refrowths are regarded as a single type - thicket/forest regrowth (9) because naturally occuring thickets could not be distinguished from advanced bush-fallows.

Cultivation areas (11) comprise varied mixtures of farms, farm-fallows and the natural forest type within an area. Also, varied mixtures of cultivation areas, forest regrowths thickets and the natural forest type within an area were interpreted as complex vegetation mosaic (12). In either case, the varied mixtures intermingle to form an intricate patchwork of vegetal cover. Where cultivation areas (11), complex vegetation mosaic (12) and thicket/forest regrowth (9) adjoin, the first two types were separated by the density of the light toned rectangular blocks which were virtually absent in the third type. The density of these light toned rectangular blocks was higher in the first type (11) than in the second type (12). The third type (9) was separated from the other types (11 & 12) by its similarity to natural forest types from which it was also separated by its finer texture.

The interpretation shows a definite gradation in the forest cover variation in the ecological zone represented by the study area. Starting from Omo in the south to Ibadan, Olokemeji and Ijaiye, the number of forest types and the natural forest types in particular increases in that order northwards (see Tables 8.2 and 8.2.1 respectively). In the drier parts represented by Olokemeji, nine natural forest types (1-9) were recognised by photointerpretation. Three (6-8) were recognised in Ijaiye, another site in the drier parts. In the wetter part of the zone (Omo) only three types (14-16) were recognised. Of the several types present in the middle parts of the zone, only one type (6) was recognised. Because of their nearness to the densely populated city of Ibadan, the forests in the two test sites in this middle part have been subjected to excessive human interference. The fuel plantation is 4.5km. west of Ibadan while the University Teak Plantation is 8.5km. north. For this reason, the two Ibadan sites were not sufficiently representative of the middle parts of the zone. Gambari Forest Reserve (26.5km. south of Ibadan City) which is more representative of this part was previously chosen but the aerial photographs of the forest reserve were not available for the present investigation. Nevertheless, the representation of this part by the two Ibadan sites did not alter the gradation in the forest-cover variation of the test area.

The observed gradation is mainly due to the combined effect of climatic, biotic and edaphic factors. In the drier northern parts of the test area, where there is low rainfall, availability of water becomes a limiting factor in the development of forests. In a situation where the development of forests is controlled by factors other than rainfall, edaphically wet habitats would have better developed forests and forest-regrowths than drier habitats. Small differences in other ecological factors e.g. site quality would be reflected as large differences in the rates of forest development. In the more extreme cases, plant species become linked to specific edaphic conditions by ecological specialisation. All these possible conditions usually result in a wide range of forest-cover variation. However, in the wetter parts of the zone, where the rainfall is high, the effect of biotic, edaphic and climatic factors other than rainfall on forest development is usually obscured by the generally luxuriant forest growth resulting from large amount of available water. This accounts for the occurrence of fewer forest types which can only be distinguished by their floristic composition. An extensive tract of forest which appears fairly homogeneous on aerial photographs usually comprises several forest types which merge into each other or intermingle without distinct boundaries.

The following examples of the interpretation of the five test sites are given in a sequence which demonstrates the observed gradation of the forest-cover variation across the test area in a radial direction from Olokemeji.

(a) Olokemeji Forest Reserve and environments

Approximate geographic location: 7°25'N 3°30'E

Ecological type: Moist semideciduous lowland forest. The test site lies in the drier part of the ecological zone close to the neighbouring forest-savanna mosaic zone. It could be regarded as a transition between forest and savanna.

Remote sensing imagery: 1:40 000 scale panchromatic aerial photographs acquired in December, 1962 (Fig.8.1) and 1:20 000 scale enlargement prints. The aerial photographs are poor in quality due to haze and dispersion.

Total area interpreted: 11 000ha. comprising parts of the reserved and free forests.

Number of types separated: eleven forest types (1-11) including eight natural types (1-8) (see Table 8.1a).

Interpretation: The photoappearances of the six moist semideciduous forest types (1-6) are similar. The wetter types (4-6) were distinguished from the dry types (1-3) by the mixture of crown sizes. The former has more large crowns and fewer small crowns. In both, the compact canopies of the low forests (3 & 5) occur at a relatively lower height level than those of the high forests (2 & 4). The hill forest (1) is restricted to the hill top and crests. At the hill top the canopy is broken while at the hill crests it is more compact. The site derived its name from these hills. 'Olokemeji' means a place with two facing hills which are locally designated as 'male and female'. The

Fig. 8.1. A delineated aerial photograph of Olokemeji Forest Reserve showing forest types (1:40 000 scale panchromatic, December, 1962).

The numeric representation of the forest types is explained in Table 8.1.1.

open forest (6) is distinguished from the other semideciduous forests (1-5) by its characteristic coarse texture. It is also distinguished from the forest savanna transition (7) by the smaller gaps which are found in its canopy. The ground or herb layer was occasionally visible through the canopy of the forest-savanna transition. The wooded savanna (8) in this site is found in areas with trellis drainage pattern (not illustrated). A conspicuous strand of forest is usually found along the individual river courses which form the trellis pattern. These strands of forests are light toned and they resemble the open forest in photophysiognomy, but they are too narrow to be delineated.

The three forest types influenced by man (9-11) were different from the natural types. The forest plantations (10) comprise pure stands of Tectona grandis (teak). The individual stands have uniform tone and texture but the texture becomes increasingly coarse with stand age. Cultivation areas (11) are more conspicuous than thickets/ forest regrowths (9) which are fewer due to repeated cultivation of the farm-fallows. The boundary between the reserved and free forests were very distinct.

(b) Ijaiye Forest Reserve and environments

Approximate geographic location: 7°35'N 3°40'E

Ecological type: Moist semideciduous lowland forest. The test area lies in the drier parts of the ecological zone close to the neighbouring forest savanna mosaic. It contains more forest-savanna mosaic than moist semideciduous forest.

Remote sensing imagery: 1:20 000 scale panchromatic aerial photographs acquired in March, 1975 (Fig.8.2). The aerial photographs are of satisfactory quality.

Total area interpreted: 2750ha. comprising parts of the reserved

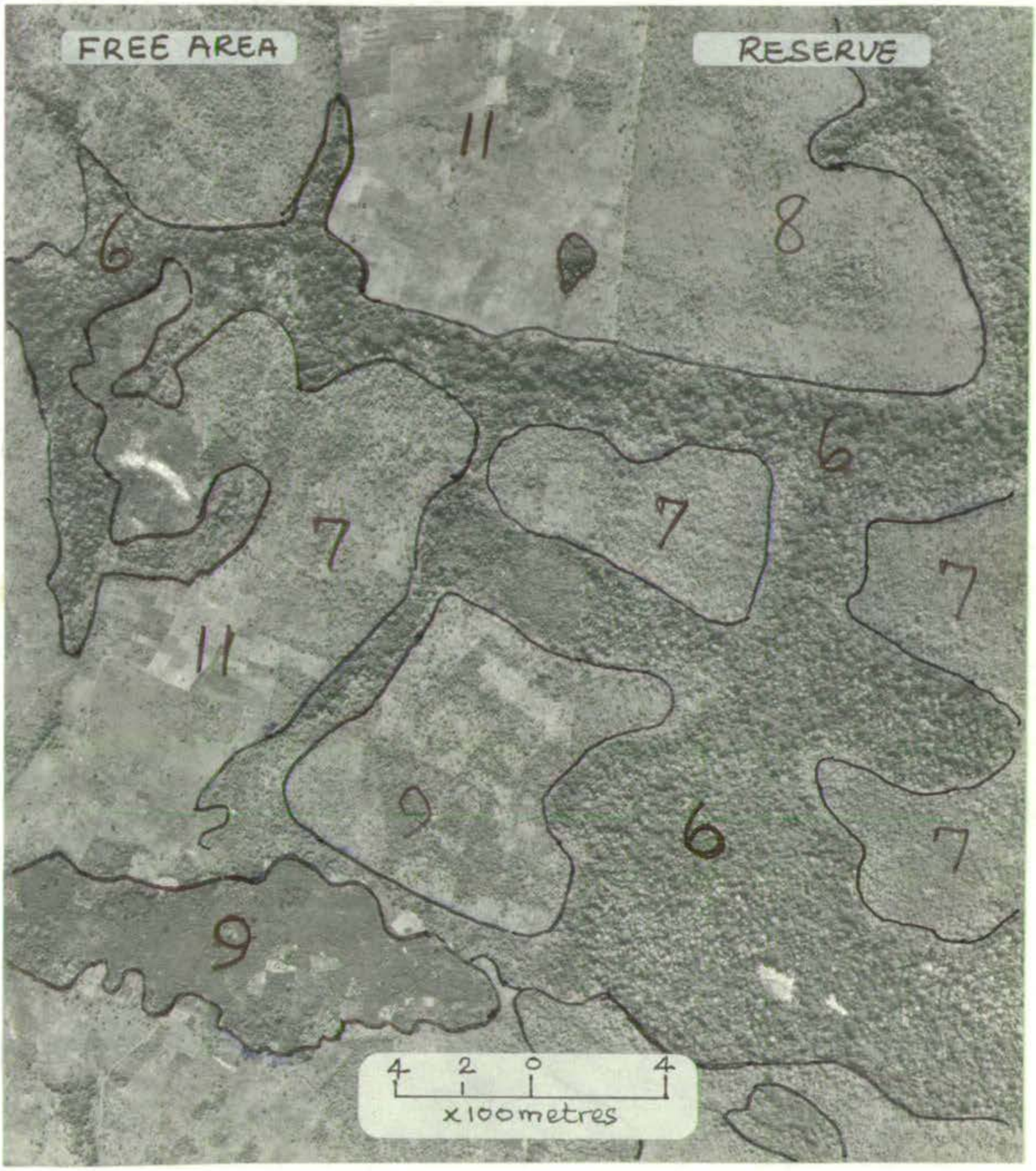


Fig. 8.2. A delineated aerial photograph of Ijaiye Forest Reserve showing forest types (1:20 000 scale panchromatic, March, 1975).
The numeric representation of the forest types is explained in Table 8.1.1.

and unreserved forests.

Number of forest types separated: five forest (6-9 & 11) types including three natural types (6-8)(see Table 8.1a).

Interpretation: The open forest (6) on this site was more distinct on the aerial photographs than that at Olokemeji. This is primarily because it occurs as fringing forests along the old river courses which are wet. The forest-savanna transition (7) in the relatively drier areas is lighter toned. Between these two forest types there is a very light toned strip of an intermediate type which is more pronounced in the reserved forests due to the absence of human interference. The photophysiognomy of this intermediate type is similar to that of the forest strands along the trellis drainage in the wooded savanna at Olokemeji. The wooded savanna (8) in this site is not associated with trellis drainage. In other respects it is similar to that at Olokemeji. The boundary between the reserved and free forests was also distinct. Within the free forest there were more cultivation areas in the forest savanna transition (7) than in the wet open forest (6). Furthermore, thickets/forest regrowths (9) in the open forest are darker toned than those in the forest-savanna transition. It is possible that these dark toned areas are plantations of agricultural crops such as *Theobroma cacao* (cocoa), *Cola acuminata* and *Cola nitida* (kolanuts).

(c) Ibadan Fuel Plantation and environments

Approximate geographic location: $7^{\circ}23'$N $3^{\circ}52'$E

Ecological type: Moist semideciduous lowland forest. The test site is 4.5km. west of Ibadan City which has a population of about two million. The vegetation outside the plantation is typically a derived savanna type resulting from the degradation of the original forests by constant human interference.

Remote sensing imagery: 1:40 000 scale panchromatic aerial photographs acquired in December, 1962 (Fig.8.3) and 1:20 000 scale enlargement prints. The aerial photographs are poor in quality due to haze and dispersion.

Total area interpreted: 11 000ha. including the 285ha. fuel plantation.
Number of forest types separated: three forest types (6 & 9-12) including one natural type (6) (see Table 8.1).

Interpretation: Most of the natural forests have been degraded by shifting cultivation. What remains of the wet semideciduous forests normally found in the wetter parts were recognised only as patches of open forest (6) within the complex mosaic of vegetation (12). Cultivation areas were difficult to separate from complex vegetation mosaic as defined for this investigation. Thicket/forest regrowth (9) was rarely encountered Fig.8.3 illustrates the wetter areas of this site. The fuel plantation (not illustrated) comprises mixed stands of fuelwood species. The research plantation (10) which adjoins the fuel plantation in the west is partly shown in the illustration. The research plantation comprises both pure and mixed stands of timber species. Neither plantation could be separated further into smaller units according to species because of the poor quality of the aerial photographs. The two plantations lie 3.5km. south of the Eleiyele Waterdam (centre of photograph).

The dry semideciduous forests normally found in the drier parts (not illustrated) have also been degraded in some areas to complex vegetation mosaic and in other areas to wooded savanna with distinct cultivation areas. The extreme conditions which obtain for this site are due to the high intensity and the high frequency of shifting cultivation.

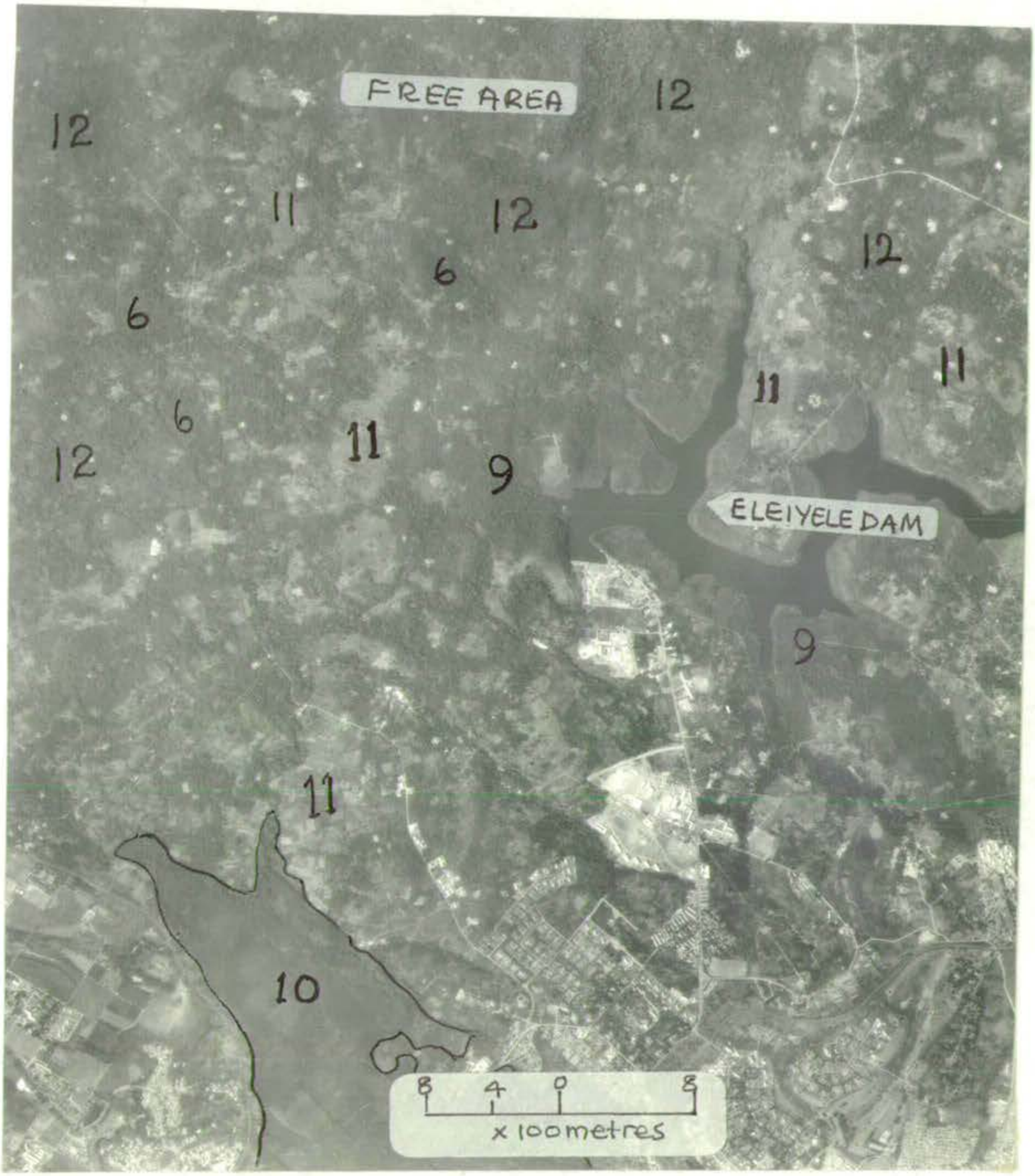


Fig. 8.3. An illustrated aerial photograph of Ibadan showing the Fuel Plantation and forest types (1:40 000 scale panchromatic, December, 1961).

The numeric representation of the forest types is explained in Table 8.1.1.

(d) Ibadan University Teak Plantation

Approximate geographic location: 7°27'N 3°54'E

Ecological type: Moist semideciduous lowland forest. The site also lies in the outskirts of Ibadan City (8.5km. to the north).

Remote sensing imagery: 1:6000 scale panchromatic aerial photographs acquired in August, 1968 (Fig. 8.4). The aerial photographs are of good quality.

Total area interpreted: 215ha. including 40ha. plantation.

Number of types separated: three forest types (10-12) without any natural forest type (see Table 8.1.1).

Interpretation: Only forest types influenced by man were encountered in this site. Cultivation areas (11) and complex vegetation mosaic (not illustrated) are similar to those interpreted in other test sites except that they were better defined in this site. Most of the area interpreted is cultivation areas(11) and recreation areas with amenity planting. The forest plantation (10) comprises pure stands of Tectona grandis (teak) Coffea species (coffee) and Cassia species (cassia). Coffee (10A) and cassia (10B) stands are both dark toned but the former has finer texture. The tone and texture of the teak stands vary according to stand age and silvicultural treatment. The younger crops (10C) are lighter toned than the older crops (10D). The tone of Teak coppice (10E) is more consistent than that of Teak coppice with standards (10F). There is uniformity in the crown sizes within each stand except in the Teak coppice with standards (10F) where there is a mixture of large and medium crown sizes. Younger stands have finer texture than older stands.

(e) Omo Forest Reserve and environments

Approximate geographic location: 6°50'N 4°15'E

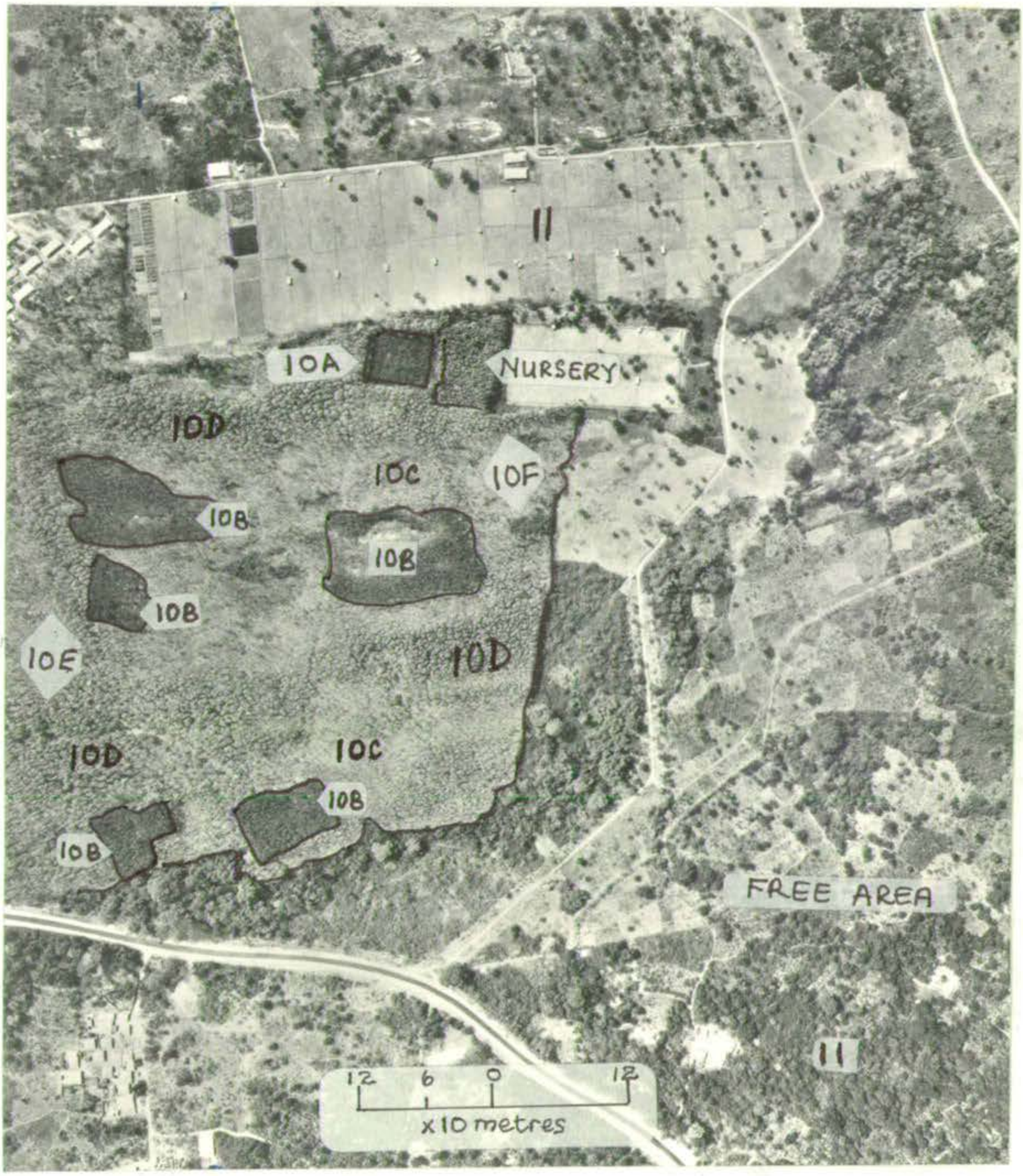


Fig. 8.4. A delineated aerial photograph of Ibadan University showing the Teak Plantation and forest types (1:6000 scale panchromatic, August, 1968).

The numeric representation of the forest types is explained in Table 8.1.1.

Ecological type: Moist semideciduous lowland forest. The test site lies in the wetter parts of this zone. This site consists mainly of tropical high forests.

Remote sensing imagery: 1:20 000 scale panchromatic aerial photographs acquired in March, 1975 (Fig. 8.5).

Total area interpreted: 2400ha. comprising parts of the reserved and unreserved forests.

Number of forest types separated: six forest types (9-11 & 13-16) including three natural types (14-16) (See Table 8.1).

Interpretation: The three natural types are moist evergreen forests which have been disturbed by destructive logging activities. As a result of this disturbance, the continuous canopy is interrupted by gaps in logged-over areas. In extreme cases, the photoappearance of the disturbed forests is similar to that of the wet open semideciduous forest (6); riparian forest (14) is found along the main river course. Though a riparian forest is more or less open, its open nature in this site is largely due to logging disturbance. However, it was possible to characterise it by its location and the mixture of crown sizes within the canopy. Two types of wet evergreen high forest were recognised. The mature high forest (15) has a recognisably higher canopy level than the immature type (16). In the former, the canopy comprises a mixture of large and medium sized crown with a high incidence of emergents. In the latter, the canopy comprises a mixture of medium and small sized crown with few or no emergents. The immature high forest has a more uniform canopy and a finer texture than the mature high forest. The forest plantation (10) comprises pure stands of Gmelina species with a consistent light tone. The canopy is a continuum which is indistinctly interrupted by differences in the height of the component stands of different ages. Younger stands have finer tones than older

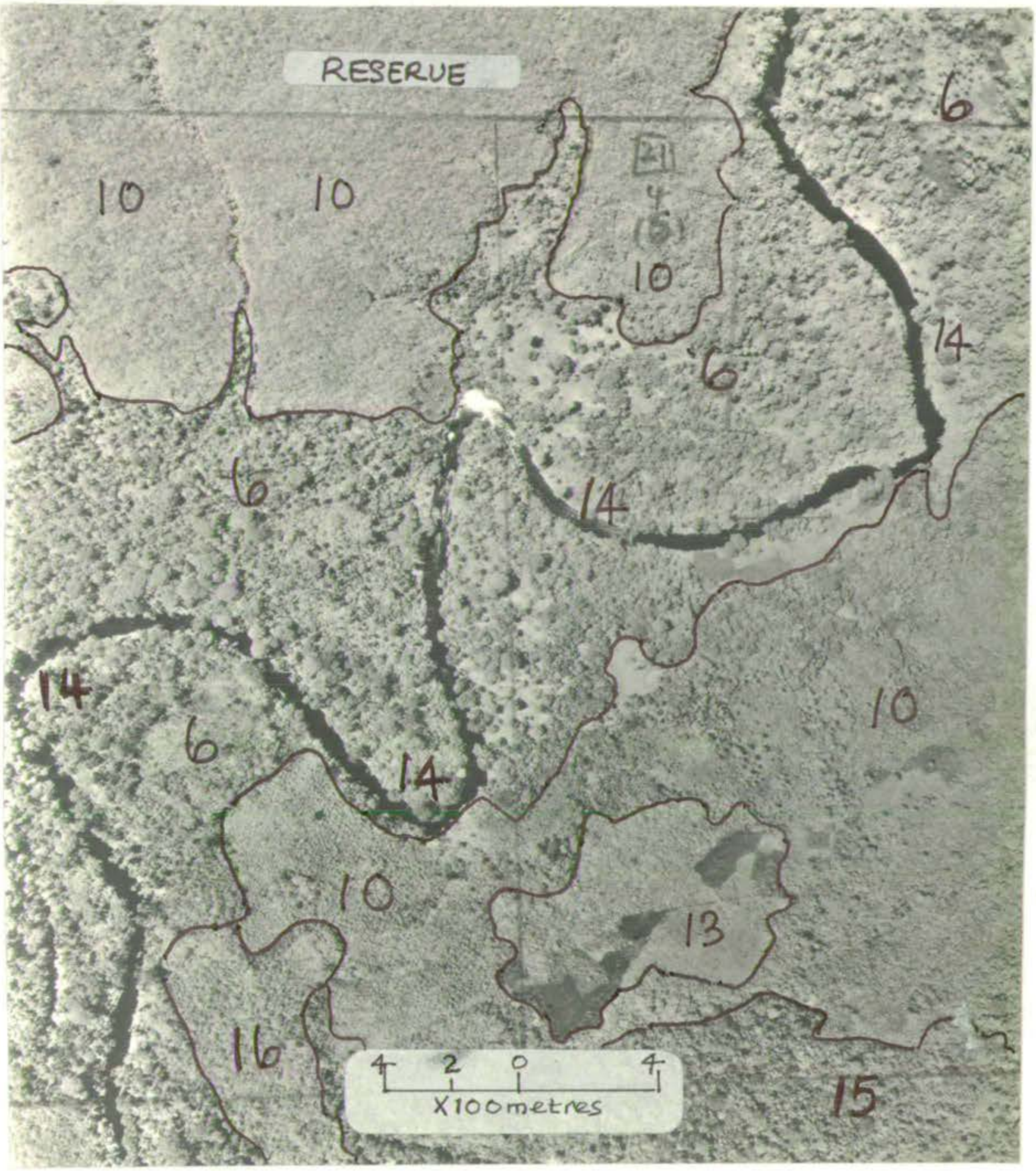


Fig. 8.5. A delineated aerial photograph of Omo Forest Reserve showing forest types (1:20 000 scale panchromatic, March, 1975).

The numeric representation of the forest types is explained in Table 8.1.1.

stands. Taungya farms (13) have smooth texture but they vary in tone depending on the age of the forest crop being nursed among agricultural crops. Taungya farms were normally encountered in the reserved forest areas. Thicket/forest regrowth (9) and cultivation areas (11) are few as most of the areas interpreted are not within the free forest.

The entire interpretation was hindered by the poor quality of the aerial photographs. As the aerial photographs are panchromatic, their quality was largely affected by the season of photography. The aerial photographs of the UI Teak Plantation were acquired during the short dry season (August) between the two peaks of the rainy season. During this period the ground is too damp to favour burning and the atmosphere is relatively free of dust haze, smoke haze and cloud-cover. In Nigeria, this is the most favourable season for aerial photography. This accounts for the superior quality of the aerial photographs of the UI Teak Plantation. The aerial photographs of Omo and Ijaiye were acquired in March i.e. immediately after the harmattan (November - February). During this period atmospheric haze is minimal, aerial photography is only affected by smoke and dust haze which may be virtually absent depending on the ground conditions. The Omo aerial photographs are superior to those of Ijaiye because the relatively wetter ground conditions at Omo are less favourable for smoke and dust haze than the dry ground conditions at Ijaiye. The end of the rainy season just before the onset of the dry season (November - May) should have been another 'good photographic season' but for the line squalls which often prevent photographic flights.

During the dry season, moisture haze is minimal, but other weather conditions usually hinder the acquisition of good quality aerial photographs. The aerial photographs of Olokemeji Forest Reserve and Ibadan Fuel Plantation were acquired during the harmattan at the onset of the dry season. As a result of the harmattan and the relatively dry ground conditions, aerial photography is considerably affected by atmospheric haze, smoke haze, dust haze and dispersion. The aerial photographs of Ibadan Fuel Plantation had more haze and dispersion than those of Olokemeji. The aerial photographs of the UI Teak Plantation were more satisfactory than others for forest interpretation because of their quality and scale (1:6000). This is followed by those of Omo (1:20 000), Ijaiye 1:20 000 and Olokemeji (1:40 000) in that order. The quality of the 1:40 000 scale aerial photographs of Ibadan Fuel Plantation was not satisfactory for interpretation. The interpretative value of the 1:40 000 scale aerial photographs of Olokemeji Forest Reserve and Ibadan Fuel Plantation was reduced further by blurring on enlargement to 1:20 000 scale.

Though the aerial photographs of the UI Teak Plantation were suitable for forest mensuration, they covered only forest plantations. The natural forest types on which the investigation is focussed were not covered by this set of photographs, but they were covered by the other four sets. In most cases the canopies of these natural forest types obscured the ground and so prevented parallax measurements. The small-scale of these photographs did not provide sufficiently large images for a precise measurement of the crowns. Also, the low contrast and poor definition hindered an accurate measurement of the crowns.

8-2 Forest-cover variation and photointerpretation variability

In order to verify the range of forest-cover variation within the ecological zone represented by the test area (Southwestern Nigeria) an interpretation was made by extrapolation before the independent interpretation of each set of aerial photographs. A previous photo interpretation (Kio, 1971) of one of the test sites and the present photointerpretation of the same area were compared in order to establish the reliability in the interpretation of the area. The Olokemeji site was used as a training set to interpret the other four test sites by extrapolation. The site was also used for the photointerpretation variability test. It has a wider range of forest types and a more detailed ground information than the other test sites. This makes it more suitable for both tests.

8-2.1 Materials and methods

(a) Extrapolation test

The detailed interpretation of one part of Olokemeji Forest Reserve was used as a training set for the interpretation of the other part. The number of types successfully extrapolated was checked by an independent interpretation in which all the forest types present were separated. Following the same procedure, the overall interpretation of the Olokemeji Forest Reserve was used as a training set for the interpretation of the remaining four test sites. For each extrapolation, the number of forest types successfully extrapolated was expressed as a percentage of the number of types in the training set. This percentage measures the success of the extrapolation.

(b) Forest-cover variation analysis

For each extrapolation, the number of forest types successfully extrapolated was expressed as a percentage of the number of different forest types in the training set and the extrapolated area combined. This percentage measures the forest cover variation relative to the training set (relative forest cover variation). Also, the difference between the number of forest types in the training set and the extrapolated area was expressed as a percentage of the number of different forest types in the training set and the extrapolated area combined. This percentage measures the forest cover covariation between the training set and the extrapolated area.

(c) Photointerpretation variability

The Olokemeji Forest Reserve and environments were interpreted by Kio (1971). He used the same set of aerial photographs which was used for the present investigation. This provided a basis for an objective comparison of the present interpretation of the area with the one previously made by a different interpreter. The area covered by the stereomodel from the first stereopair of area photographs (see Fig. 8.1) was chosen for the interpretation. The area includes six semideciduous forest types which are so similar in photoappearance that only very subtle differences could be used to separate them on aerial photographs. From the present interpretation, an overlay tracing of the photo-delineation of the six forest types was made. By using a Grant projector, Kio's delineation of these forest types was traced at the photo scale (1:40 000) from his published map. The scaling was accomplished by controlling the projection in such a way that corresponding distances have equal lengths on the aerial photographs and the projected map-image. Distances between pairs of prominent features which were shown on both the photographs and the map were used as the scaling reference.

A sample of 264 points systematically distributed with the ITC Sub-Department of Forestry dot grid was used for the test. Though the sample size was not statistically determined, it was sufficiently large to fulfil the statistical requirements for a simple comparison of this nature. The sample size was arbitrarily chosen for reason of convenience. The sample points were easier to distribute by selecting alternate dots on the dot-grid than by constructing a sampling frame from the results of laborious and time consuming statistical computations. Four dots on the grid represents one square centimetre. By selecting alternate dots as sample points, four sample points on the grid represent four square centimetres. By overlaying the dot grid on the 1:40 000 scale tracing of Kio's map, each sample point represents one square centimetre on the map. This is equivalent to a ground distance of 16ha.

Kio's interpretation was used as ground information though he did not indicate that it was field-checked. The sample points were distributed on the tracing of the ground information map (Kio's map) from the dot grid templet overlay. By overlaying the tracing from the present interpretation on the ground information map, the positions of the sample points were fixed on the latter. The number of points falling within each of the six forest types considered was counted separately for both interpretations. The differences were expressed as percentages. These percentages measure the degree of variability between the two interpretations.

(d) Tests of the statistical significance of the results

The probability levels at which the results of the foregoing verifications are statistically significant were determined by using the Chi squared (X^2) test. Yates' correction for continuity was applied to obtain corrected X^2 values for each data set from the formula.

$$X^2 = (IO-EI-0.5)^2/E \qquad (|O-E|-0.5)^2/E$$

O = observed value

E = expected value

0.5 = Yates' correction factor for continuity

In the extrapolation test

O = number of forest types successfully extrapolated

E = the number of types comprising the training set

In the forest cover variance analysis

O = the difference between the number of forest types in the training set and the extrapolated area

E = number of different forest types in the training set and the extrapolated area

In the photointerpretation variability test

O = number of sample points counted for the present interpretation

E = number of sample points counted for the ground information map (Kio's interpretation).

8-2.2 Results and discussion

The results of the extrapolation test, forest cover variation analysis and photointerpretation variability tests are presented in Table 8.2. These results show that the percentage success of the extrapolation and the relative forest cover variation decreases with increasing radial distance from the training set. The forest cover covariation between the training set and the extrapolation area increases in a similar fashion. The percentage success of the extrapolation indicates the extent to which the training set and an extrapolated area are similar while the forest-cover covariation indicates the extent to which they differ. The relative forest cover variation indicates the degree of variation within an extrapolated area relative to that of the training set.

These observations become more significant statistically as the radial distance from the training set becomes longer. For instance, the observations on the more northerly part of Olokemeji site (Olokemeji II) do not differ significantly from the training set. This is primarily because two areas are contiguous. In the case of Ijaiye, 30km. to the north of the training set, these observations become more significant. Also, as the radial distance from the training set increases southwards to Ibadan Fuel Plantation (45km.), Ibadan University Teak Plantation (49km.) and Omo Forest Reserve (105km.), these observations become increasingly significant in that order.

It may be argued that the observed trends are due to the smaller size of the extrapolated areas relative to the training set. This argument is reduced to an absurdity by considering the large differences

Table 8.2 Analysis of the photointerpretation results: extrapolation, forest cover variation and photointerpretation variability

Sites	expected (E)	observed (O)	O - E	$\frac{(\lvert O-E\rvert-0.5)^2}{E}$	Index
(a) Extrapolation					
(i) All forest types					
Olokemeji II	11	6(55)	5	1.841	08
Ijaiye	11	5(45)	6	2.750	07
Ibadan Fuel	11	4(36)	7	3.841	06
Ibadan University	11	3(27)	8	5.114	04*
Omo	11	3(27)	8	5.114	04*
Overall	-	-	X^2	18.660	01*
Total	55	21(38)	34	20.405	01*
Average	11	4.2(38)	6.8	3.608	06
(ii) Natural forest types					
Olokemeji II	8	3(38)	5	2.531	08
Ijaiye	8	3(38)	5	2.531	08
Ibadan Fuel	8	1(13)	7	5.281	04*
Ibadan University	8	0(0)	8	7.031	03*
Omo	8	0(0)	8	7.031	03*
Overall	-	-	X^2	24.405	01*
Total	40	7(18)	33	26.406	01*
Average	8	1.4(18)	6.6	4.651	05*
(b) Forest cover variation					
(i) All forest types					
Olokemeji II	11	6(55)	5(45)	2.750	07
Ijaiye	11	5(45)	6(55)	1.841	08
Ibadan Fuel	12	4(33)	8(67)	4.688	05*
Ibadan University	12	3(25)	9(75)	6.021	05*
Omo	16	3(19)	13(81)	9.766	02*
Overall	-	-	X^2	25.066	01*
Total	62	21(39)	41(66)	26.457	01*
Average	12.4	4.2(34)	8.2(66)	4.781	05*

Sites	expected (E)	observed (O)	O - E	$\frac{(IO-EI-0.5)^2}{E}$	Index+
(ii) Natural forest types					
Olokemeji II	8	3(37)	5(63)	2.531	08
Ijaiye	8	3(37)	5(63)	2.531	08
Ibadan Fuel	8	1(12)	7(88)	5.281	04*
Ibadan University	8	0(0)	8(100)	7.031	03*
Omo	11	0(0)	11(100)	10.023	02*
Overall	-	-	X^2	27.397	01*
Total	43	7(16)	36(84)	29.308	01*
Average	8.6	1.4(16)	7.2(84)	5.220	04*
(c) <u>Photointerpretation variability</u>					
Dry hill forest	12	11	1(8)	0.021	11
Dry high forest	36	40	4(11)	0.340	10
Dry low forest	10	9	1(10)	0.025	11
Wet high forest	94	85	9(10)	0.769	09
Wet low forest	11	10	1(9)	0.023	11
Wet open forest	41	38	3(7)	0.152	10
Overall	-	-	X^2	1.330	13
All six combined	204	193	11(5)	0.540	09
Total	204	-	19(9)	1.678	08
Average	204	-	3.2(9)	0.214	10

\+ Probability equivalents of the index numbers are given in Table 8.2.1.

* Significant at 0.05 probability level

<u>NOTES</u>:

1. The X^2 distribution table (see Table 8.2.1) is entered with:
   - one degree of freedom for each row in a, b and c above.
   - four degrees of freedom for the relevant column in a and b above.
   - five degrees of freedom for the relevant column in c above.
2. Figures in brackets indicate the percentage:
   - extrapolation success in a
   - forest cover variance in (O) column of b
   - forest cover covariance in (O - E) column of b
   - photointerpretation variability in c

Table 8.2.1 Analysis of the photointerpretation results
Range of Chi squared values for various levels of significance

Level of significance		Range of X^2 values		
Index	Probability (p)	1° of freedom	4° of freedom	5° of freedom
01	below 0.001	above 10.828	above 18.467	above 20.515
02	0.001 - 0.005	10.828 - 7.879	18.467 - 14.860	20.515 - 16.750
03	0.005 - 0.010	7.879 - 6.635	14.860 - 13.277	16.750 - 15.086
04	0.010 - 0.025	6.635 - 5.024	13.277 - 11.143	15.086 - 12.833
05	0.025 - 0.050	5.024 - 3.841	11.143 - 9.488	12.833 - 11.071
06	0.050 - 0.075	3.841 - 3.170	9.488 - 8.496	11.071 - 10.010
07	0.075 - 0.100	3.170 - 2.706	8.496 - 7.779	10.010 - 9.236
08	0.100 - 0.250	2.706 - 1.323	7.779 - 5.385	9.236 - 6.626
09	0.250 - 0.500	1.323 - 0.455	5.385 - 3.357	6.626 - 4.351
10	0.500 - 0.750	0.455 - 0.102	3.357 - 1.923	4.351 - 2.675
11	0.750 - 0.900	0.102 - 0.016	1.923 - 1.064	2.675 - 1.610
12	0.900 - 0.925	0.016 - $0.0^{2}89$	1.064 - 0.897	1.610 - 1.394
13	0.925 - 0.950	$0.0^{2}89$ - $0.0^{2}39$	0.897 - 0.711	1.394 - 1.145
14	0.950 - 0.975	$0.0^{2}39$ - $0.0^{3}98$	0.711 - 0.484	1.145 - 0.831
15	0.975 - 0.990	$0.0^{3}98$ - $0.0^{3}16$	0.484 - 0.297	0.831 - 0.554
16	0.990 - 0.995	$0.0^{3}16$ - $0.0^{4}39$	0.297 - 0.207	0.554 - 0.412
17	0.995 - 0.999	$0.0^{4}39$ - $0.0^{5}16$	0.207 - 0.091	0.412 - 0.210
18	above 0.999	below $0.0^{5}16$	below 0.091	below 0.210

Sources: White, Yeats & Skipworth (1977), Neave (1978).

observed between Olokemeji II and the training set which are contiguous areas of the same size. The argument becomes more absurd on the logical reasoning that with such a large number of forest types in the training set the differences between the training set and other areas interpreted by extrapolation should be relatively small in respect of the number of forest types extrapolated. In other words the training set being a larger area must have included all possible types of forests that could be found in the smaller areas being extrapolated. Moreover, if the size of the smallest test site - Ibadan University Teak Plantation (215ha.)-was the size of the training set and that of the individual extrapolated areas, similar results showing the same trends would have been obtained.

In view of the above considerations, only an ecological explanation could satisfactorily account for the differences observed between the different areas and the increasing statistical significance of these differences. Though these differences increase radially from the area selected as the training set, it is also apparent from the interpretation that the differences increase to the north and to the south of the training set.

In the drier part of the ecological zone rainfall tends to limit forest development. The Olokemeji,which represents this drier part of the moist lowland forest zone,lies very close to the adjoining forest savanna mosaic. As a result of its position, the Olokemeji test site combines the characteristics of both ecological zones. This explains the occurrence of several forest types within the site which gives it a large forest cover variance. The Ijaiye Forest Reserve which is more northerly towards the forest savanna mosaic has more of the characteristics of this zone. It therefore, has relatively smaller forest cover variance than the Olokemeji Forest Reserve. Towards the middle of the ecological zone which is moderately wet, there is smaller variation in the forest cover. Consequently the two Ibadan sites representing this middle part have smaller forest cover variation than the Olokemeji site in the drier areas. The forest types found in the wetter parts of the ecological zone represented by the Omo Forest Reserve, are almost invariably evergreen and less frequently semideciduous. This is mainly due to the generally large amount of rainfall. As rainfall which is the most important factor in forest development is not limiting in this area, there is a relatively little variation in the forest cover in comparison with the relatively drier areas. This explains the small relative cover variation obtained for this site. It can be reasonably concluded that as one moves from the more northerly parts where low rainfall tends to limit forest development to the more southerly parts where factors other than rainfall limit forest development, the variation in the forest cover decreases. In the same fashion, the forest cover covariation between the training set and the extrapolated areas increases from north to south.

The large forest cover variation observed within the ecological zone indicates that the interpretation of forest types in this zone and similar tropical forest areas could not be accomplished with confidence by extrapolation. It therefore follows that irrespective of the interpretation methods used, complete interpretation technique is more reliable than partial interpretation technique or multistage sampling. A complete interpretation would adequately cater for the wide range of variation usually encountered within tropical forests even within very small areas. On the other hand, partial interpretation and interpretation by extrapolation or by multistage sampling would not efficiently account for most of the variations which are seldom repeated even within an extensive forest tract. At best, such an interpretation technique could only account for the gross variations which are less significant to forest management than the more subtle differences. Nevertheless, this appears to be a primary argument for estimating forest areas by point sampling but these subtle variations would be difficult to pool into an efficient interpretation key which can be readily applied.

During the interpretation, it was observed that the quantifiable variations within the forest types obscured those between them. This is illustrated in Table 8.2 by the higher significant levels of the variations within the forest types (indicated in the 'overall' and the 'total' rows) and the lower significant levels of the variation between forest types (indicated in the 'average' rows). It was also observed that the forest types merge and intermingle without distinct boundaries. These observations also constitute a primary argument for estimating forest areas by point sampling. In order to cater for all the subtle variations within the survey area, a very high sampling intensity would be required in addition to an efficient interpretation key that could be easy to apply. These possibilities are difficult to fulfil in practice. As a result both the interpretation and the area estimation of tropical forests would have to rely on delineation of forest types or forest characteristics on aerial photographs.

In view of the above considerations,the variability in photointerpretation accomplished by complete delineation was investigated to indicate the extent to which such variability could affect the estimates of area-related forest information. The results (Table 8.2c) show that the variability in the interpretation of the six similar semideciduous forest types ranges between 7% and 11% giving an average of 9% for each forest type. If the six types are combined as a unit of delineation this gives a variability of only 5%. As variation between forest types increases with decrease in interpretation variability, the 4% difference measures the extent to which the variation within the semideciduous forests (average for the six types) obscured the variation between it (six types combined as a unit) and the adjoining forests.

The levels of significance obtained by Chi squared (X^2) test for the variability in the interpretation of the forest types as individual units or a combined unit of delineation are low. None of the observations is significant at 0.5 probability level (95% confidence level). This indicates that the variations within the moist semideciduous forest and those between it and the adjoining forests are equally small. Variability in the interpretation of a given forest results in either an over estimation or an underestimation of the forest area. Though the variability may not be statistically significant, it results in errors which may affect the estimate of a forest information within the area to a highly significant level. For instance, if the interpretation variability for a 20ha. forest and the standard error for its 15cu.m/ha. volume are both 10% at 0.5 probability level, the two extreme total volume estimates for the forest would be 243cu.m. and 363cu.m. Their extreme values represent a total volume of 300cu.m. ± 120cu.m. or 15±6cu.m./ha., thus increasing the standard error of the volume estimates to 20% which is highly significant in terms of forest management. However, in as much as the overall accuracy of the estimates of a forest information falls within that specified for the survey, the effect of interpretation variability becomes insignificant.

8-3 Tree species identification

The silvicultural practice of artificial concentration of species by plantation methods is based on the gregarious nature of the tree. It follows that if these gregarious species could be characterised on aerial photographs when they occur in plantations or in amenity plantings, this photo-characterisation could be used to assist their recognition on the aerial photographs of the forests containing their natural populations of their 'artificial concentrations'. The primary aim of this interpretation therefore, is to verify the extent to which the gregarious growing habit of tree species can aid their identification on aerial photographs.

8-3.1 Materials and methods

As field work was not conducted to check the interpretation, only the natural populations and the plantations or amenity plantings of known species were considered. In the first place, the aerial photographs were stereoscopically examined to verify the range of crown shapes within the test sites so as to minimise characterising known tree species which would not be encountered outside the areas of their known occurrence. The common range of shapes observed are:-

stereoscopic view: oval, round, ovate, obovate, disc, umbrella, dome and compound.

apex shape: rounded, dome, flat and compound.

non-stereoscopic view: stellate, sinuate, rosette (layered stellate), dentate, crenate, serrate, round and clumped.

The natural populations, plantations and amenity plantings of known species were located on the aerial photographs which were interpreted for forest types. The amenity plantings were either individual trees or groups of trees in recreation areas.

The photographic tone and texture of each area of occurrence of the known species were described using the qualitative tonal grades in Section 8-1.1 as reference. The non-stereoscopic characteristics of the crowns of the known species were described by visual observation with the aid of hand-held magnifiers. The stereoscopic characteristics of these crowns were described under x8 magnification. The photo-description of the known species (see Table 8.3) was used as a training set to locate in other areas, trees or groups of trees with similar crown characteristics. This was accomplished by examining the aerial photographs under x3 magnification. The similarities between the located trees or group of trees and the training set were established by a further examination under x8 objective.

This procedure for species recognition by photo reading sets of characteristics established for known species is similar to an unsupervised computer classification which normally contains some discrepancies. Nevertheless, it was considered the most objective and most realistic procedure in the present circumstances for species recognition on aerial photographs.

8-3.2 Results and discussion

The species which were recognised by photo-reading are indicated in Table 8.3. It was observed that individual species varied in their photographic tone in different areas of their known occurrence e.g. Tectona grandis in Ibadan University Teak Plantation differ in tone from that in forest plantations within Olokemeji Forest Reserve. This may be due to the use of a disparate collection of individual photographs which are not united by a common relative grey scale during photography. In this circumstance, the use of tone for the recognition of species by photo-reading was restricted to individual

Table 8.3 Characteristics of tree-species recognised on aerial photographs

	Tree-species	Ecological status	Photo description	Characterised on aerial photographs of	Recognisable on aerial photographs of
1	*Annogeisus leiocarpus*	single trees in amenity planting	dark toned spreading crowns with irregular outline	UI Teak Plantation	-
2	*Cassia spp.*	gregarious indigenuous species plantation	medium dark toned oval crowns with circular outline	Ibadan Fuel Plantation	UI Teak Plantation
3	*Casuarina spp.*	rows of trees in amenity planting	dark toned compact crowns with oval shape	UI Teak Plantation	-
4	*Coffea spp.* (coffee)	very dark toned crowns	very dark toned crowns with distinct outline	UI Teak Plantation	-
5	*Elaeis guineense* (oil-palm)	single trees occuring with high frequency	bright light toned stellate crowns with elongated radial arms	Omo Forest Reserve	Ibadan Fuel and UI Teak Plantations
6	*Eucalyptus spp.*	exotic species in plantations	medium toned oblong crowns with irregular outline	Ibadan Fuel Plantation (Research plots)	-
7	*Gmelina spp.*	exotic species in plantations	light toned oval crowns with distinct outline	Ibadan Fuel Plantation (Research plots)	Omo Forest Reserve
8	*Khaya ivorensis*	indigenous species occuring with high frequency	dark toned crowns with irregular shape and outline	Ibadan Fuel Plantation (Research plots)	-
9	*Musanga cecropioides*	gregarious species in regenerating forests	medium toned, dome shaped crowns with irregular outline	Omo Forest Reserve	-
10	*Raphia spp.* (raphia-palm)	gregarious species occuring in edaphicals wet habitats	dark toned rossette crowns with short radial arms	Omo Forest Reserve	-
11	*Tectona grandis* (teak)	exotic species in plantations	light-medium toned oval crowns	Olokemeji Forest Reserve	UI Teak Plantation
12	*Terminalia spp.*	indigenous species in plantations	medium-dark toned crowns with circular outline	UI Teak Plantation	-
13	*Triplochiton scleroxylon*	indigenous species in plantations (gregarious)	light-medium toned oval crowns distinct outline	Omo Forest Reserve	-

prints or individual sets of prints. The tonal variation of an individual species may also be due to the effect of their occurrence in different plant communities. According to Howard and Lanly (1975) individual plant communities have characteristic spectral radiance/ albedo by which they could be recognised.

Furthermore, the tonal contrast and image definition on the aerial photographs particularly those of Ibadan Fuel Plantation and Olokemeji Forest Reserve were poor due to haze and dispersion. The tonal contrast and image definition were reduced further by blurring on the enlargement prints. Because of the small scale and poor quality of the contact prints and because of the blurring on the enlargement prints, the aerial photographs did not yield sufficient information for an accurate characterisation of the known species. Above all, the prints were printed from third generation negatives (at least) with a consequent reduction in contrast and definition. It was observed that trees of the same species occurring singly in amenity plantings and in plant communities,such as plantations and natural populations,differed in crown shape. As this difference was also observed between trees of the same species found in plantations and natural populations, a species with spreading crowns when growing singly tendsto have more elongated crowns in a plant community e.g. Annogeissus leiocarpus and Terminalia ivorensis. Also species tend to have more consistent crown shapes within plantations than within their natural populations e.g. Triplochiton scleroxylon.

To explain these differences, it is known from field experience that differences exist between the growing habit of a species occurring as single individual trees, and its growing habit in a plant community. Also differences exist between the growing habit of a species in plantations and its growing habit in natural populations. These differences could be expressed in the shape, form, and height, of the trees and in their crown features. These account for the difficulty in locating the characterised species in areas other than plantations on the aerial photographs. It is interesting that Cordia species (locally called Omo) could be neither characterised nor located in Omo Forest Reserve (so named for its high incidence of Cordia trees).

Despite these shortcomings, a few species were readily characterised and located with certainty. For example, Elaeis guineense (oil-palm) has stellate crown with elongated radial arms arranged in definite alignment. It is quite distinct from Raphia species (raphia palm) whose crowns tend to be rossette shaped and Musa sapientum (banana) whose stellate crowns have broad radiating arms. Some species that were similarly recognised with certainty are of little economic value, e.g. Musanga cecropioides (umbrella tree) has characteristic spreading crowns which are dome shaped or umbrella shaped with speckled appearance. The other species recognised are exotics e.g. Tectona grandis and Gmelina species. The indigenous plantation species were difficult to characterise or locate mainly because of the small scale and poor quality of the photographs rather than the irregularity in their crown shapes.

In conclusion, species recognition on aerial photographs by this procedure would require good quality aerial photographs at very large scale for an adequate characterisation of the species. The identification of the species recognised would also require a field-check in view of the results of this investigation.

8-4 Findings of the photointerpretation

The poor quality of aerial photographs which were acquired during the harmattan shows that seasonal variation in weather conditions affects not only the acquisition of aerial photographs but also their quality. The aerial photographs which were acquired during the short dry season between the two peaks of the rainy season were better in quality as atmospheric haze was minimal during this period. The inability to obtain recent photographs may imply that weather conditions have not permitted their acquisition, more so when aerial photographs of the cloud-prone coastal areas were not available for the present studies. If this is the case, the use of infrared photography may provide haze and dispersion free but not cloud free images of a survey area with similar weather conditions. The inability to obtain recent aerial photographs may also imply that aerial photography is not frequently used for resource surveys in the test area because of factors other than weather conditions.

The acquisition scales of the aerial photographs used for this investigation were mainly 1:20 000 and 1:40 000. This indicates that large scale aerial photography which is more suitable for intensive forest surveys is not frequently acquired for resources surveys in the test area. Only the aerial photographs of Ibadan University Teak Plantation were available at a scale suitable for intensive forest survey. However, the economic scales at which most of the aerial photographs were available provided sufficient information on the forest types but less information on the individual tree-species. The enlargement prints did not offer any significant advantage as boundaries of the forest types and the outlines of the individual crowns were blurred. Measurements could be made easily but with low precision. Also, stereoscopic observation was not possible with the enlargement prints. The use of aerial photographs acquired at scales larger than the economic scales would increase the confidence of surveys that require information on the individual trees. Though photomensuration was not done due to the lack of adequate ground information, observations made during the interpretation indicate that forest mensuration of the test area and therefore of similar forest areas on aerial photographs would rarely provide the forest management data at the required level of accuracy. But the accuracy of photomensuration data could be improved by using good quality aerial photographs acquired at suitably large scales.

Despite the inability to conduct field work, the information obtained on the vegetal cover of the test area from aerial photographs was more detailed than that published in maps and literature. This indicates that usefulness of aerial photography for gathering forest information which may be difficult to obtain by other methods. For example, it was possible to separate eleven forest-types including eight natural types on the aerial photographs of Olokemeji Forest Reserve. This area is usually mapped as semideciduous forest. Also, the extent of human interference on the forests and the tropical high forest in particular was easy to determine on aerial photographs in some cases when the high forest could be separated into distrubed and undisturbed subtypes according to the severity of human interference. These subtypes are not usually mapped. By photointerpretation alone it was possible to distinguish a main forest type into several subtypes according to their photographic appearance with little recourse to field work. However, such distinction does not necessarily imply changes in the ecological status of the main forest type.

The forest cover variation test shows that there is a wide range of variation in the forest cover of the test area which may not permit interpretation by extrapolation or by multistage sampling. With such a wide range of variation, a sufficiently representative part of a survey area would be difficult to obtain for an extrapolation. Also, multistage sampling would not provide reliable results. Only 'total coverage' interpretation would probably give the most satisfactory results. Even then the wide variation would not permit interpretation without delineation as the construction of an 'all-embracing' interpretation key for a survey area would be difficult if not impossible to achieve. It follows that interpretation has to be done by delineation as it was done in the present studies. This would permit not only the reliable estimation of the areas of the individual forest types but also their location by spatial distribution.

The photointerpretation variability test shows that the absence of indistinct forest boundaries usually results in varied delineations by different operators. Such variations may be apparently insignificant, but they often affect the estimates of area-related information substantially. This notwithstanding, it is my opinion that interpretation should be accomplished by delineation in as much as interpretation without delineation is frequently hampered by the difficulties in constructing effective interpretation keys.

Evidence from literature shows that tropical forests were usually interpreted without a clearly defined set of objective interpretation criteria or an ordered use of these criteria. For this reason, a comprehensive procedure was developed by which a set of attributes constituting the interpretation criteria was applied to each unit of delineation in an ordered fashion. The procedure was not necessarily designed for forest type recognition, rather, it was designed to determine the type of vegetal cover found within delineated units of similarity which could be a forest type. Numerical codes were used for each attribute in such a way that the lowest code numbers represent the attributes of mature closed high forest while the highest code numbers represent the attributes of grassland. By adding the code numbers for individual units the lowest values are obtained for units closer to mature high forest while the highest values are obtained for units closer to grassland. For the comparison of forest types, the coding should be completed for individual units of delineation or else discrepancies would arise.

The results of the interpretation show that this procedure was efficient for grading the vegetal cover types in the test area but it can be greatly improved by expanding the list of attributes and by including quantitative data. However, the procedure needs to be tested on other tropical forest. A procedure for the remote sensing of Scottish coastal habitats in which attributes were used in a similar way was reported by Kirby (1977). The application of the procedure was tested by student interpreters (Remote sensing option class of Edinburgh University, Geography Department). Though the results of the test (in which the present investigator took part) was not statistically analysed, it showed that the procedure was efficient for its purpose.

The results show that species identification by photointerpretation alone is difficult. Despite the fact that only a few known species were interpreted by photoreading, it was still difficult to separate them from other species due to the striking similarities in their photoappearance, Tropical tree species usually have polymorphic crowns. Also, single species show variable phenology both in space and time. This usually hinders their identification on aerial photographs. The gregarious growing habit by which some tropical tree species have been identified on aerial photographs has been of limited value for the identification of the species in the test area. This is mainly due to the rarity of such species and the mixture. Even the ecologically specialised species show gregarious growing habits are linked to edaphic conditions were still difficult to recognise in different areas on aerial photographs. The few species which were easily recognisable are of little economic importance, though some of them characterise the highly productive forests e.g. Musanga cecropioides. Species identification which is a requirement for the assessment of the quantity and quality of timber resource cannot be accomplished with confidence from small scale panchromatic aerial photographs in the tropics. The most probable solution would have been the use of large scale normal colour aerial photography but the discrimination levels in the important green band are relatively few. Consequently, the use of colour infrared aerial photography may be desirable. The low precision of photomensuration accomplished on colour aerial photographs may not justify the acquisition of colour aerial photography. Moreover, the recognition of forest types which constitute the major units of forest management in the tropics can be accomplished on good quality aerial photographs irrespective of film/filter combination and scale.

In view of the foregoing, it is my opinion that species identification should be accomplished in the field. What is important is the recognition of field sample trees on aerial photographs or the location of photo sample trees in the field. Both would require large scale aerial photographs for an intensive photostudy in conjunction with frequent field checking.

The findings of the interpretation support those of the review of literature presented in Chapters 2-5. The extent to which forest types can be separated by photointerpretation is compared with that of Landsat interpretation in Chapter 9 and with that of SLAR interpretation in Chapter 10. The findings on the technical capabilities and the economics of the use of the three systems in tropical forest surveys are interrelated in Chapter 12.

CHAPTER 9

INTERPRETATION OF LANDSAT IMAGERY

9 Interpretation of Landsat imagery

The main purpose of this investigation is to verify and augment the findings from literature review on the use of Landsat images for gathering forest information for management purposes in the tropics. The investigation is also designed to verify the extent to which the additive colour process and microphotography could be used to enhance the interpretation of tropical forests on Landsat images.

The first task was to establish the general level of information which can be obtained from Landsat images by visual interpretation. This was accomplished by interpreting the black/white prints of both negative and positive spectral images of the test area first and comparing the interpretation with map information for the necessary correlations. The second task was to determine the spectral images and filters that could be combined (band/filter combinations) to generate satisfactory colour-enhanced images (colour composite images) of the test area. This was accomplished by additive colour processing reported in Section 9-1.1. The third task was to determine the 'goodness of fit' of the colour composites for discriminating the interpreted forest types. This was accomplished by comparing the sharpness of the forest type boundaries on the colour composites. The fourth task was to determine the capability of the colour composites for the separation of the forest types. This was accomplished by comparing the extent to which the forest types can be recognised on the 'best fit' colour composites. The final task was to delineate the forest types and compare the Landsat interpretation with map information and photointerpretation respectively.

9-1 Materials and method

The following 1:3 369 000 scale film negative and positive images of the test area from the four spectral bands were used for the additive colour processing (Section 9-1.1).

Landsat scene	Frame number	Date of imaging	Band 4 quality	Percentage cloud cover
204-055	E1107 - 09273	7/11/72	5	30%
205-055	E1036 - 09323	28/8/72	8	30%
205-055	E1108 - 09332	8/11/72	5	30%

Quality ranges from very poor (0) to excellent (9)

Colour composite images were generated from the spectral images of the test area to provide colour enhanced images for the interpretation. The colour composite images were reproduced by microphotography to provide enlarged images for the interpretation without loss of image definition. Both procedures are described in Section 9-1.1. Contact black/white prints of the 1:1 000 000 scale film negatives and positives of Landsat frames E1107 - 09273 and E1108 - 09332 were interpreted to establish the general level of forest information available on Landsat images (Section 9-1.2). The colour composite images generated from the 1:3 369 000 scale spectral images were investigated further in Section 9-1.2.

9-1.1 Additive colour processing of the Landsat imagery

The Fairey additive colour viewer (FACV) shown in Fig. 9.1 was used for the additive colour viewing. The FACV is a four channel fixed magnification (x4 ± 12.5% lens tolerance) projector instrument suitable for colour viewing of Landsat 70mm. film transparencies. The horizontal viewing screen is built into a table top for easy photography and tracing of the projected image. Each channel has horizontal (X), vertical (Y) and rotation registration controls. The two position lamp-brightness switch, four-position filter selection switch and push-button iris diaphragm illumination controls for each channel are recessed into the table top to permit simultaneous operation and viewing.

Since all Landsat frames of a particular scene are approximately at the same scale and geographic location, up to four spectral images of the same scene can be optically combined on FACV into a single colour composite image. Colour composite images can be generated from

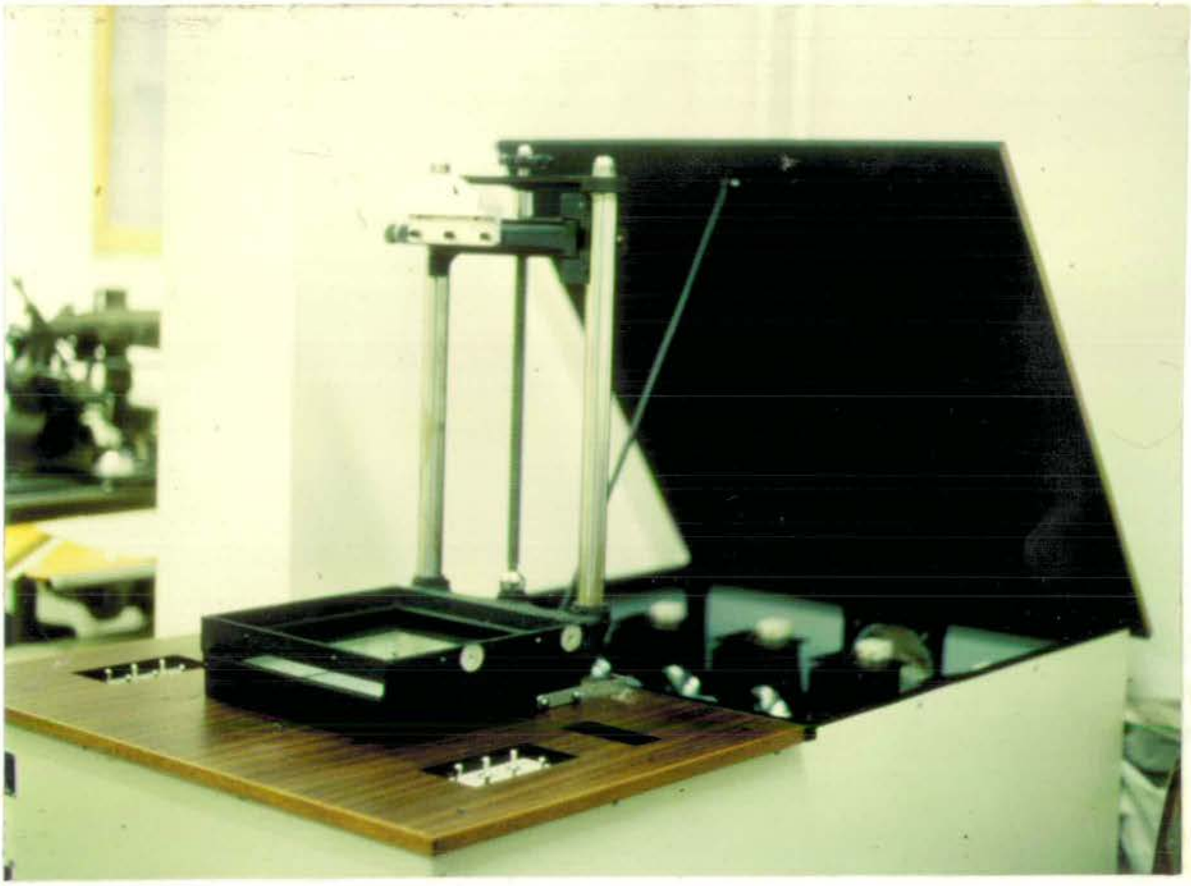


Fig. 9.1. Fairey additive colour viewer.

negative and/or positive spectral images of the same frame(interspectral composite) or of different frames of the same scene (intertemporal composite) using any band/filter combination for their projection.

FACV, therefore, offers a wide range of options for displaying the information content of Landsat 70mm. film transparencies through an overall flexibility in frame/film source/band/filter combinations for colour composite generation. The procedures followed to generate colour composite image using FACV are:-

(a) instrument calibration
(b) composite generation tests
(c) image registration
(d) photographic reproduction

(a) Instrument calibration

Instrument calibration consists of filter selection for the individual projection channels and determination of optimum light intensity for projection with the individual filters selected, magnification scaling to provide equidimensional images from the four channels and image distortion correction for optimum registration of superimposed images.

The projector channels were designated by the colour of the filters assigned to them - blue, green, orange and red. The filter which provided the most satisfactory image from frame E1107-09273 band 7 spectral transparencies (the best imagery of the test areas) was selected for each channel. Also, the light intensity required to provide satisfactory definition on superimposed images was determined for each channel. This was done by projecting frame E1107-09273 spectral transparencies using band/filter combination B (see Section 9.1b) with high lamp brightness. Prominent features on the superimposed images were purposely set out of registration to observe their degree of definition at different illuminations on the individual channels. The most suitable filter/light intensity combination for the individual channels are:-

Projector channel	FACV specifications			
	Filter colour	Chance number	Transmittance visible	Illumination level required
blue	blue	OB 10	1.70%	9
green	green	OG 1	18.00%	7
orange	deep orange	OY 1	40.00%	5
red	ruby	OR 1	6.00%	10

These filter/light intensity combinations were used for projecting the spectral images.

Specially designed grids provided by FACV manufacturers were used for magnification scaling and image distortion correction. The grid image from the blue channel was set central and square on the viewing screen using the X, Y and rotation controls. By alternately moving the projector along its optical bench and measuring the dimensions of the image, the scale was set at approximately four times magnification (x 4). The diagonals of the grid image were measured and necessary image distortions were corrected by turning the appropriate control knobs. The focus was adjusted to achieve an even-focussed perfect square. In the same way, the other channels were individually scaled to this magnification and corrected for image distortion. The blue channel grid image was used as a master-image for scaling the other individual bands to the same magnification and for correcting image distortion. The grid images were superimposed and their registration differences evened out relative to the master-image.

The magnification scale calculated from the dimensions of the composite grid image is x 3.94. The precision of the instrument calculated from the manufacturer's specification is 99.4%, an instrument error of 0.06% resulting in registration accuracy of ± 20m. for the Landsat 70mm. film transparencies.

(b) Composite generation tests

These tests were used to establish the most satisfactory colour composite images for the test area with regard to the type of composite film source, spectral composition and band/filter combinations.

The Landsat 70mm. film transparencies were fixed into 70mm. Antinewton diaslides. The frame number, film source and spectral band of each transparency were labelled on its slide e.g. E1107-09273 + 5 and E1107-09273 - 7 mean band 5 film positive and band 7 film negative of Landsat frame E1107-09273. The frames and film sources were coded for subsequent use as follows:-

Code	Meaning
1	frame E1107-09273
2	frame E1036-09323
3	frame E1108-09332
N	film negative
P	film positive
S	combined film negative and positive

Spectral images of frame E1107-09273 were superimposed using each of the 24 possible band/filter combinations. This was to determine the band/filter combinations which provide the most satisfactory colour composite views. While some of the resulting composites were repetitions of others, many did not provide satisfactory composites. Satisfactory composites were provided by the following band/filter combinations:

Code for band/filter	Spectral bands of images projected on			
	blue channel	green channel	orange channel	red channel
A	4	5	6	7
B	7	4	5	6
C	6	7	4	5
D	5	6	4	7
E	7	6	4	5
F	4	5	7	6

The most suitable spectral compositions for generating satisfactory interspectral composites from a single film source were also determined with frame E1107-09273 spectral images. These spectral compositions are:-

band/filter combination code	Spectral composition of	
	3 band composites	2 band composites
A	4560) 0567)	0560
B	0567	4060
C	0567	0067
D	0567	0560
E	0567	0067
F	4507) 0567)	0507

Four-band composites in this category were unsatisfactory because they contained too much detail. The above spectral compositions were also suitable for generating satisfactory interspectral composites from combined film sources preferably using bands 4 and 5 film positives and band 6 and 7 film negatives. In this category, the only satisfactory four-band composite was generated with band/filter combination F.

Because of the generally poor quality of band 4 imagery (due to haze and dispersion) and the striking qualitative similarities between bands 6 and 7 imagery, (due to acquisition in the infrared band), only bands 5 and 7 spectral transparencies of frames E1036-09327 and E1108-09332 which cover the same scene were used for intertemporal composite generation. Of the numerous intertemporal composites examined only three were satisfactory. These are:-

	Spectral composition			
Projector channel*	Blue	Green	Orange	Red
frame code*	2	3	2	3
Band 7 composite	-7	+7	+7	-7
band 5 composite	-5	+5	+5	-7
bands 5/7 composite	+7	+5	-5	-7

* band/filter combination does not apply
- indicates film positive
+ indicates film negative

(c) Image registration

Since the FACV was already calibrated, only X, Y and rotation controls were used for image registration which was performed in conjunction with composite generation tests. For each colour composite, the constituent spectral images were superimposed using band 7 image, or else band 6 image as master-image. Prominent features such as coastlines, inland water-bodies, rivers and roads were used as registration references. Optimum registration was achieved by evening out the registration difference.

The observed registration difference was largely due to the registration error of the Landsat product used (159m.) and partly due to the FACV instrument error (ca 20m.). To some extent, it is also due to the differences in spectral responses of the registration references.

Specific areas, film positive composites and interspectral composites were better registered than entire scenes, film negative composites and intertemporal composites respectively. In the first case, an overall registration of an entire scene could not be achieved due to the combined effect of the errors stated above. By registering part of a scene at a time the effect of these errors is minimised.

In the second case the 70mm. film positive (3rd generation products) have higher positional mapping accuracy (±53m. to ±118m.) than the 70mm. film negatives-archival films (±54m. to ±126m.). Moreover, film positives provided better definition of linear structures and thus enhanced registration. In the third case, the spectral response of individual registration references in a particular band varies according to season. This seasonal inter-band variation increased the registration difference for a particular feature in intertemporal composite generation. Furthermore, cloud and haze cover were not consistent on the multidate imagery of a scene. As a result, some features used as registration references were obscured in some spectral bands thus making their registration difficult and inaccurate. For instance, band 4 imagery of the three frames examined was of limited value for composite generation due to too much haze cover. Haze cover was less in band 5 imagery and virtually absent in band 7 imagery.

Interspectral composites generated from combined film sources provided better representation of forested areas than any other type of composite. Despite their better definition of linear features, composites generated from positive film sources provided a poorer representation of forested areas than the corresponding composites generated from film negatives.

For easy identification of their photographic reproductions, the interspectral composites were coded. This was not necessary for the intertemporal composites because they were relatively few. Each interspectral composite consists of several alphanumeric digits. The first three digits, separated from others by a stop, represent the Landsat frame, film source and band/filter combination respectively (see Section 9-1b). The remaining four digits represent the spectral composition. They are numeric when the spectral composition is from a single film source. The component spectral images are represented by their band numbers in order, zero (0) representing bands which were not used. The four digits are alphabetic when the spectral composition is from a combined film source. In this case the film source codes of the component images replace the band numbers in order, X representing bands which were not used.

Examples:

1NA. 4560 = colour composite image generated from frame E1107-09273 by projecting spectral images of bands 4, 5 and 6 film positives through blue, green and orange filters respectively.

2PB. 0567 = colour composite image generated from frame E1036-09327 by projecting spectral images of bands 5, 6 and 7 film positives through green, orange and red filters respectively.

3SF XNXP = colour composite image generated from frame E1108-09332 by projecting spectral images of band 5 film negative and band 7 film positive through green and orange filters respectively.

(d) Photographic reproduction

Photographic reproduction of the most satisfactory colour composite views was made. The photography was done with Asahi SMC Pentax 50mm./f1.4 standard lens for composite views of the entire scenes and with Asahi SMC Pentax-M-Macro 100mm./f4 lens for selected areas of interest. The colour composite views were exposed on various types of colour slide films taking the necessary technical precautions in synchronising speed/aperture with film sensitivity to obtain optimum results for each film-type. This was to test the suitability of the various films for the reproduction. The films tested are:-

Film speed	Commercial name of film	ASA/DIN rating
Fast	Kodak Ektachrome 200 (ED 135)	200/24
	Kodak Ektachrome 160 Tungsten (ET 160)	160/23
	Kodak High Speed Ektachrome 160 (ET 160)	160/23
	Agfa colour CT.21. 135	100/21
Slow	Kodak Ektachrome X (EX 135)	64/19
	Kodak Ektachrome 64 (ER 135)	64/19
	Kodachrome 64 (ER 135)	64/19
	Agfa colour CT.18 135	50/18
	Techrome H 135	50/18

The record of film type and exposure number used for reproducing individual colour composite images was kept for subsequent identification of the slides. Thirteen rolls of various film-types were exposed (about 350 exposures). The films were processed by commercial photographic laboratories.

Of over 300 slides examined by projection, only nine were finally selected for printing. Their selection was based on overall colour balance, image definition and contrast. Because the commercial photographic laboratories do not usually undertake calibrated printing, the composites were ordinarily printed on 25.5 x 20cm. format without scaling. Semi-matt paper, which combines the characteristics of glossy and matt papers, was used for the printing. The printing scales were subsequently extrapolated from contact prints of the 1:1 000 000 scale spectral imagery. The colour composites which were finally selected for printing were:-

Composite Code	Calculated Printing scale	Area coverage
* 1NE. 0567	1: 200 000	Part of scene including Omo
* 1NE. 0067	1: 333 000	Part of scene including Ibadan
* 1NF. 4507	1: 333 000	Ijaiye and Olokemeji
* 1SA. XPNN	1:1 000 000	Entire scene
+ 1SF. NNXP	1:1 000 000	Entire scene
+ 3NA. 0567	1: 200 000	Part of scene including Ibadan
+ 3NF. 0567	1: 200 000	Ijaiye and Olokemeji
* 3SA. XPNN	1: 667 000	Entire scene excluding coastal areas
* 3SF. PPNN	1:1 000 000	Entire scene

* Kodak Ektachrome 64 (ER 135)

\+ Kodak Ektachrome 200 (ED 135)

Kodak Ektachrome 64 and 200 film types were more suitable than the other film-types tested for reproducing colour composite views from FACV by commercial processing. Possibly different results could be obtained by controlling the photographic processing.

Colour composites which included any of the spectral images of frame E1036-09327 were unsatisfactory because of the poor quality of this frame. As a result, the prints made did not include any interspectral composites of this frame or any intertemporal composites.

The foregoing describes how simple optical and photographic techniques were used to enhance Landsat black/white multispectral imagery. The optical technique is based on additive colour theory. Landsat black/white spectral images were optically combined in colour using complementary filters to generate colour composite images. The additive colour views of these colour composites were reproduced by 35mm. microphotography which is known to enhance image contrast (Best & Smith, 1978; Brothers & Fish, 1978; Eyton & Knether, 1978).

9-1.2 Interpretation procedure

Most of the coastal half of the test area could not be interpreted on the Landsat images due to excessive cloud cover. Only the inland half including parts of the neighbouring forest-savanna mosaic zone was interpreted as these areas are relatively cloud free on the images.

The fifteen tonal levels on the relative grey scale of Landsat images were grouped into five qualitative grades relative to their definition on each of the 1:1 000 000 contact prints of frame E1107-09273 -7 and E1107-09327 +7. Starting with number 1 on the left and ending with number 15 on the right, the following qualitative tones were derived for the interpretation~~:~~ of black/white paper prints,

	positive print	negative print
black	1- 2	10-15
dark	3- 4	8-9
medium	5- 7	10-11
light	8-10	12-13
white	11-15	14-15

These qualitative tones were used as criteria for delineating different areas on the 1:1 000 000 paper prints. Similar areas were grouped into units. The corresponding ecological zones or forest types for these units of similarity were extrapolated from information collated from literature. The interpretation was compared with map information and the photointerpretation reported in Chapter 8. By this first level interpretation, the amount of forest information that could be obtained generally from Landsat spectral images was established. This provided a background for the assessment of the technical capabilities of the Landsat colour composite images for forest type separation.

The second level interpretation was accomplished by a visual examination of the paper prints of the colour composites in conjunction with slide projection. The colour composite images were compared for the discrimination of the forest types. From the first level interpretation one delineated unit of each forest type which is obvious on the colour composite images being examined was selected for the comparison. The degree of discrimination was determined by the sharpness of the boundary between each unit and its neighbours i.e. the colour contrast at the boundary. The tonal contrasts in the first level interpretation provided a control for the determination of the degree of colour contrast. For each forest type three colour composite images which provided the best discrimination were scored in the order of their 'goodness of fit'. As the two Landsat scenes of the test area may not contain the same forest types, one colour composite image with the highest 'goodness of fit' score was selected for each scene. This selection permitted the examination of the two Landsat scenes of the test area in the third level interpretation (extent of recognition) of the forest types. The two colour composite images were compared for the recognition of each forest type in different areas. The extent of recognition was determined and scored as follows:-

1. always recognised or separated
2. frequently recognised or separated
3. occasionally recognised or separated
4. rarely recognised or separated

The first level interpretation provided a control for recognition of the forest types on the colour composite images.

The final interpretation was accomplished by delineating the forest types on the colour composite images. The possibility of delineating more forest types was investigated by a further examination of the colour composites. The first level and final interpretations were compared to determine the advantage of colour enhancement in forest interpretation on Landsat images. The overall interpretation was further compared with map information and photointerpretation respectively.

9-2 Results and discussion

The following forest types were separated by their tone on the black/white prints during the first level interpretation (amount of forest information):

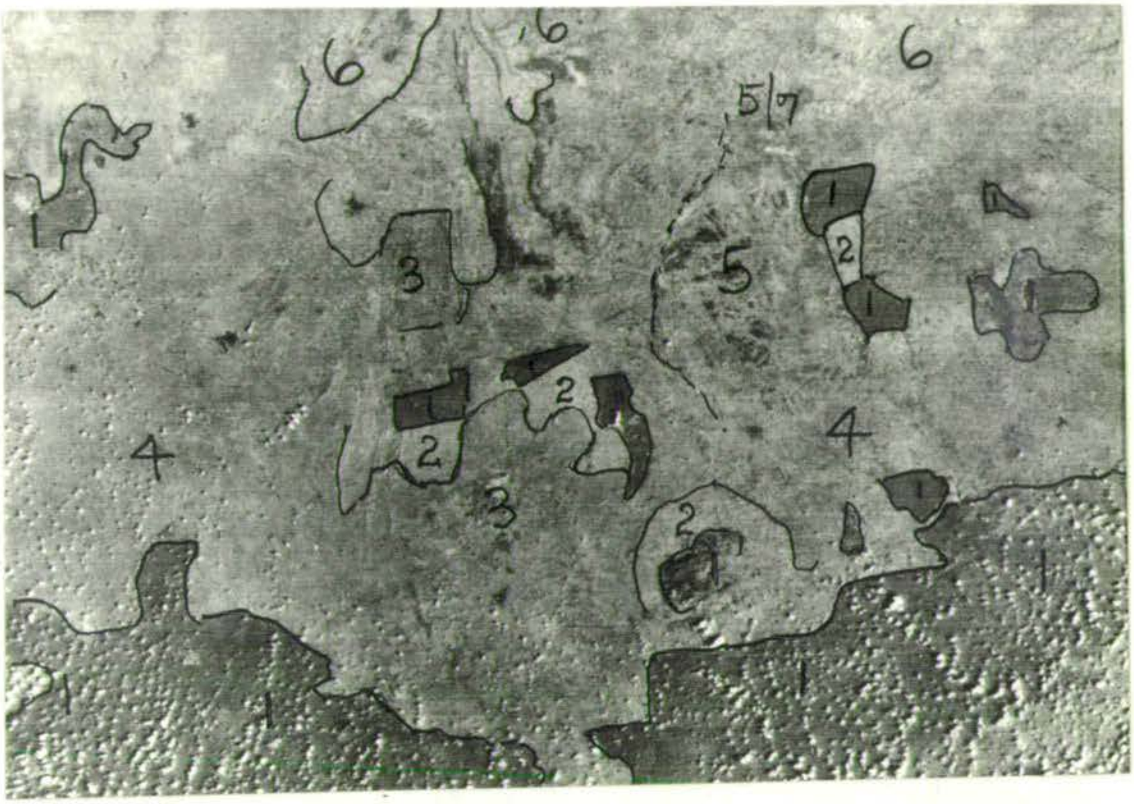
Forest types	Positive spectral image	Negative spectral image
1. evergreen high forest	very dark	very light
2. evergreen low forest	dark	light
3. moist semideciduous forest	dark-medium	medium-light
4. dry semideciduous forest	light-medium	medium-dark
5. forest-savanna mosaic	mixed medium and light	mixed light and medium
6. wooded savanna with riparian forest	medium with dark striations	medium with light striations
7. cultivation areas	smooth light	smooth dark

These forest types are illustrated in Figs. 9.2, 9.2.1, 9.3 and 9.3.1 by their numbers shown in the table above. The evergreen high forest (1) was always recognisable by its distinctive tone even under cloud cover (see Figs. 9.2 & 9.2.1). This type is concentrated but not restricted to the southern part of the test area. The evergreen low forest (2) is more frequently associated with the evergreen high forest than not. It is occasionally found as isolated blocks within the other forest types. The difference between the moist (3) and the dry (4) semideciduous forest types was not distinct where they are

Scale: 1:1 000 000

Fig. 9.2. An illustrated Landsat spectral image of Southwestern Nigeria showing forest types. (E1107-09273 -7 of November 7, 1972 at 1:1 000 000 scale).

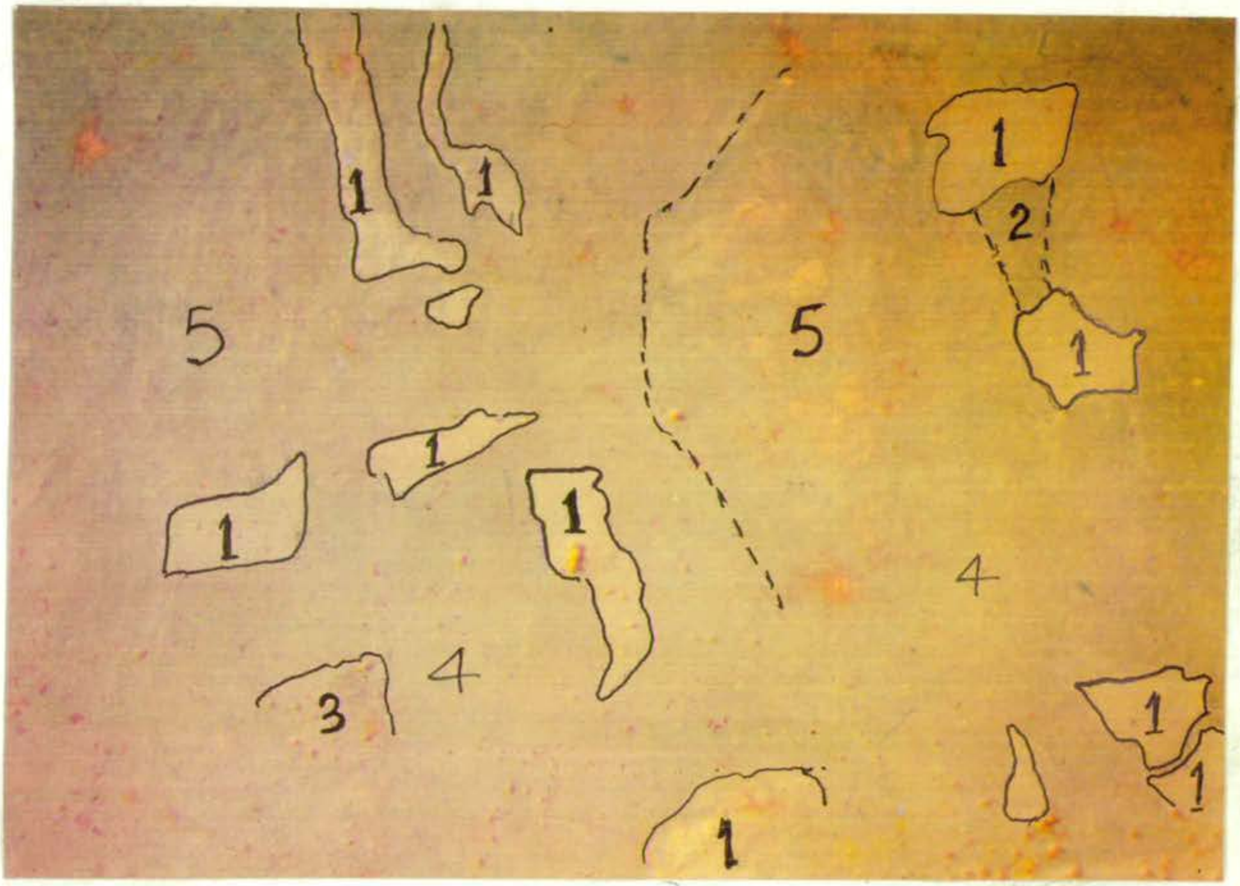
The numeric representation of the forest types is explained at the beginning of Section 9-2 and in Table 9.1.



Scale: 1:1 000 000

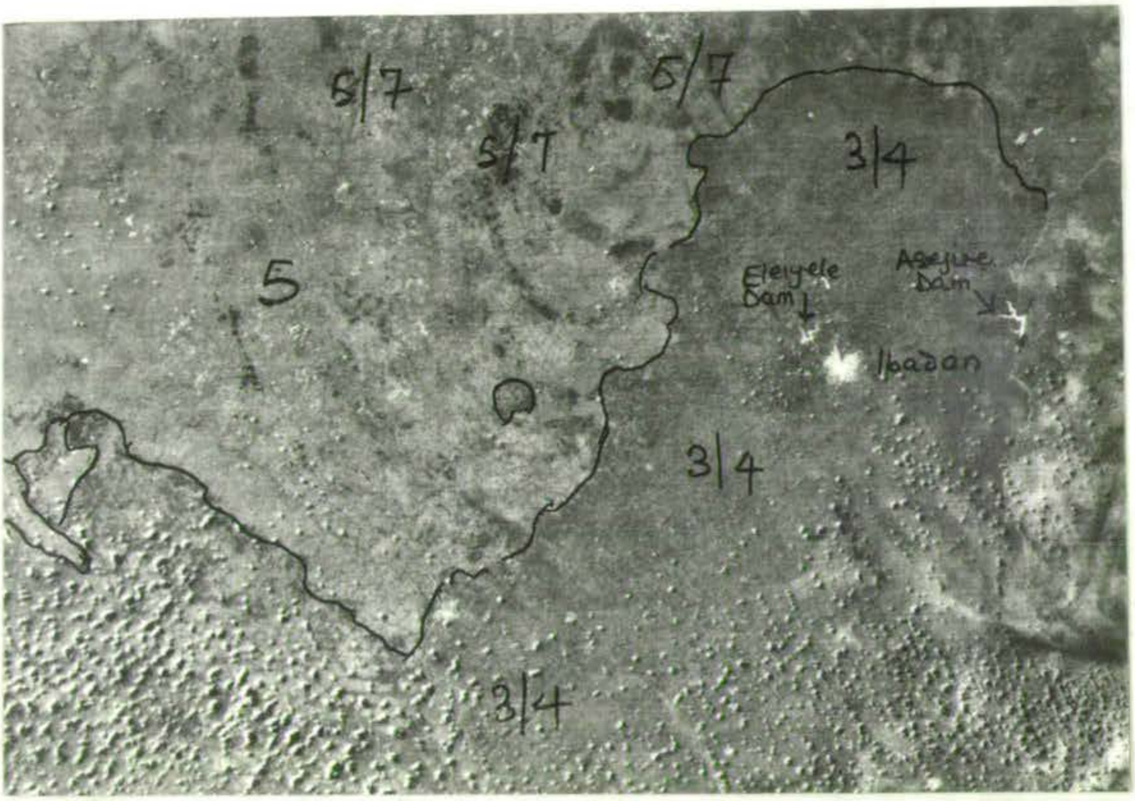
Fig. 9.2.1. An illustrated Landsat spectral image of Southwestern Nigeria showing forest types. (E1107-09273 +7 of November 7, 1972 at 1:1 000 000 scale).

The numeric representation of the forest types is explained at the beginning of Section 9-2 and in Table 9.1.



Scale: 1:200 000

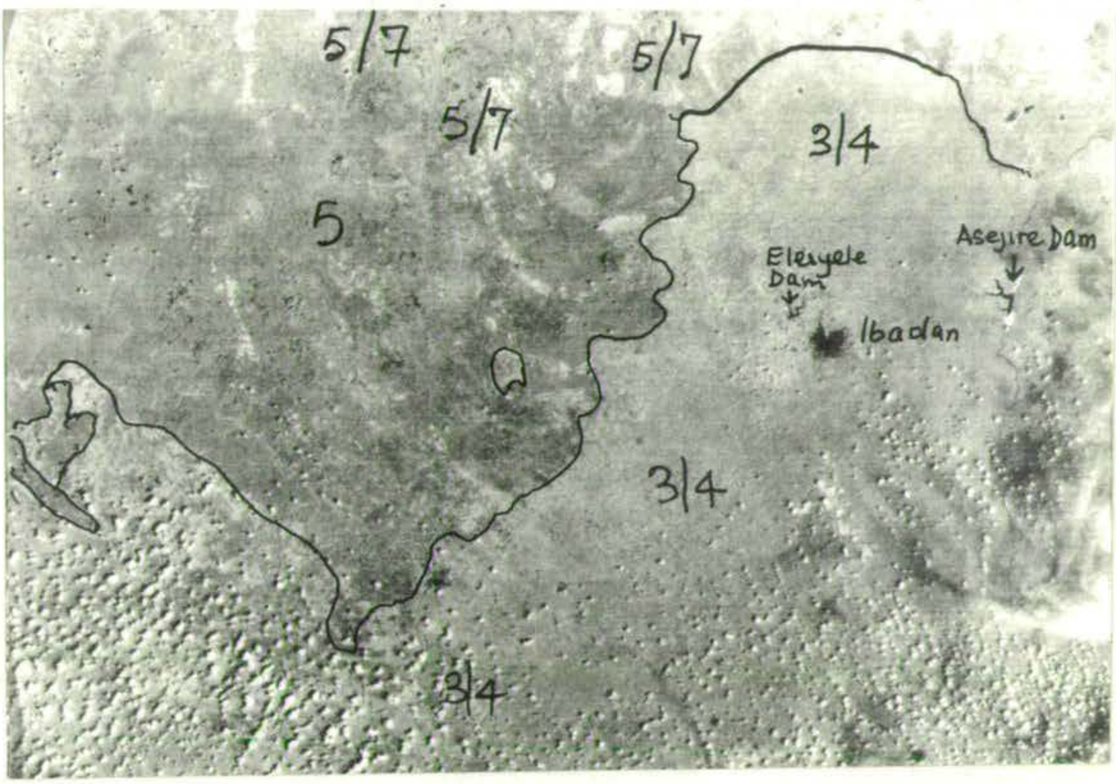
Fig. 9.2.2. An illustrated Landsat colour composite image of Southwestern Nigeria showing forest types. (1:200 000 scale Colour composite 1NE. 0567 generated from 1:3 369 000 scale spectral images of E1107-09273 of November 7, 1972). The numeric representation of the forest types is explained at the beginning of Section 9-2 and in Table 9.1.



Scale: 1:1 000 000

Fig. 9.3. An illustrated Landsat spectral image of Southwestern Nigeria showing forest types. (E1108-09332 -7 of November 8, 1972 at 1:1 000 000 scale).

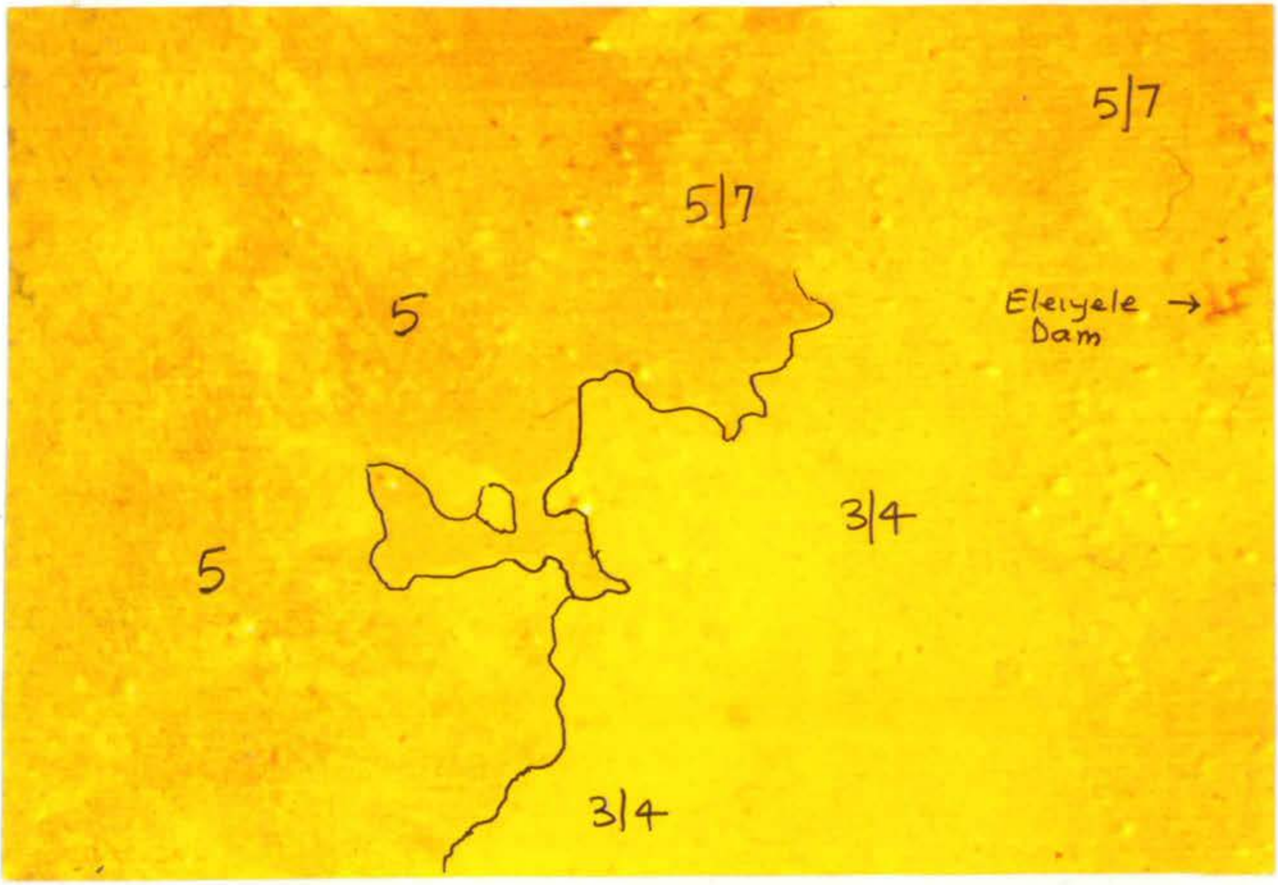
The numeric representation of the forest types is explained at the beginning of Section 9-2 and in Table 9.1.



Scale: 1:1 000 000

Fig. 9.3.1. An illustrated Landsat spectral image of Southwestern Nigeria showing forest types. (E1108-09332 +7 of November 8, 1972 at 1:1 000 000 scale).

The numeric representation of the forest types is explained at the beginning of Section 9-2 and in Table 9.1.



Scale: 1:200 000

Fig. 9.3.2. An illustrated Landsat colour composite image of Southwestern Nigeria showing forest types. (1:200 000 scale Colour composite 3NA.0567 generated from 1:3 369 000 scale spectral images of E1108-09332 of November 8, 1972).

The numeric representation of the forest types is explained at the beginning of Section 9-2 and in Table 9.1.

neighbours. Generally the former type is concentrated to the south while the latter is concentrated to the north of the test area. Mixed forest-savanna mosaic (5) was recognised by its 'mottled' texture comprising of varied mixtures of tones. It is rare in the southern part of the test area. The forest-savanna mosaic was often confused with semideciduous types which have been subjected to intensive shifting cultivation. Wooded savanna with riparian forest (6) was recognised by the striations of wet vegetal cover along river courses. These were frequently associated with various drainage patterns. Cultivation areas (7) were only recognisable where forest regrowth is less than bush and farm fallows as well as recent farm sites.

The 'best fit' colour composites for the discrimination of each forest type in the second level interpretation (degree of discrimination) are tabulated below:-

	Forest type	Best fit colour composite		
		1st	2nd	3rd
1.	evergreen high forest	1NE. 0567	1NE. 0067	1SA. XPNN
2.	evergreen low forest	1NE. 0067	1NF. 4507	1NE. 0567
3.	moist semideciduous	1NE. 0067	1NF. 4507	1NE. 0567
4.	dry semideciduous	1NF. 4507	1NE. 0067	-
5.	mixed forest/savanna	3NA. 0567	3NF. 0567	3SA. XPNN
6.	wooded savanna with riparian forest	3NA. 0567	3NF. 0567	-
7.	cultivation areas	3NA. 0567	3SA. XPNN	-

During the second level interpretation it was observed that colour composite image 1NE. 0567 is similar to 1NE. 4507 except that features expressed in blue on the former were expressed in purple in the latter. Moreover, the former has better overall image contrast. Also, colour composite image 3NA. 0567 is similar to 3NF. 0567 except that the former has less cloud cover. In addition cultivation areas were discriminated best on 3NA. 0567. For these reasons, colour composite images 1NE. 0567 and 3NA. 0567 were chosen as the best fit images.

It would be recalled that colour composite image 1NE. 0567 was generated from bands 5, 6 & 7 spectral images of Landsat frame E1107-09273 using red, green and blue filters respectively. Colour composite image 3NA. 0567 was generated from bands 5, 6 & 7 spectral images of Landsat frame E1108-09332 using green, orange and red filters respectively. Both colour composite images were generated from film negatives of three bands excluding band 4. (For the interpretation of the codes for other colour composite images, see Section 9-1.1c). The failure to obtain a 'best fit' colour composite which includes band 4 showed that band 4 images are of little value for generating colour composite images of the test area. This is mainly due to haze and dispersion since cloud cover is common to all four spectral images. Sections 7-2(b) and 9-1 show that the quality of band 4 images which were obtained in August, during the short dry season between the two peaks of the rainy season was better than that of the band 4 images which were obtained in November at the onset of the harmattan. Weather conditions were more favourable for imaging in the visible spectral band during the short dry season than during harmattan when there are dispersion and haze. Table 9.1 shows the scores which were obtained for the third level interpretation (extent of recognition) of the forest types on the colour composite images as well as the black/white prints. The total scores show that forest types and other features were easier to recognise on the colour composite images than on single spectral images. The scores also show that recognition was easier on positive images than on negative images. Despite these generalisations, the extent of the recognition of the individual forest types and features vary from print to print.

Table 9.1 Comparison of the recognition of forest types and other features on Landsat single spectral and colour composite images

	1:1 000 000 black/white spectral images		1:200 000 colour composite images	
	negative	positive	1NE.0567	3NA.0567
A Forest types (total scores)	(13)	(12)	(10)	(10)
1. evergreen high forest	1	1	1	1
2. evergreen low forest	2	1	1	1
3. moist semideciduous forest	2	2	1	1
4. dry semideciduous forest	2	2	1	1
5. forest savanna mosaic	2	2	1	1
6. wooded savanna/riparian forest	2	1	3	3
7. cultivation areas	2	3	2	2
B Other features (total scores)	(6)	(6)	(5)	(5)
Settlements/inland water bodies	1	2	1	1
roads/rivers	2	1	2	2
wet/dry land	2	2	1	1
forest/non-forest	1	1	1	1
Combined scores	(19)	(18)	(15)	(15)

* 1. always recognised or separated

2. frequently recognised or separated

3. occasionally recognised or separated

4. rarely recognised or separated

Black/white spectral images at 1:1 000 000

Colour composite images at 1:200 000

The forest types are illustrated in Figs. 9.2. - 9.2.1 by the numbers (1-7) which are designated to them in this table.

In the final level of interpretation each of the seven forest types which were previously separated on the black/white prints could not be separated further into subtypes on the colour composite images despite their relatively larger scales. The delineations of the forest types on the colour composite images are illustrated in Figs. 9.2.2 and 9.3.2. The evidence obtained from Landsat interpretation correlates with map information except for some cartographic generalisations in the latter e.g. simple representation of forest type boundaries and exclusion of small patches of a different forest type within a commonly occurring type on the maps. The comparison of Landsat and photointerpretation shows that the more exclusive forest types which were delineated on aerial photographs could be delineated into more inclusive general types on Landsat images. For instance, all the dry semideciduous forest types which were easily recognised by photointerpretation could be recognised as a general type by Landsat interpretation. Also, the extent of the degradation of each type which was recognised by photointerpretation could not be recognised by Landsat interpretation. Such degradation often results in subtypes within the main forest type.

Only seven forest types could be separated on Landsat images despite their colour-enhancement. Somewhat surprisingly, the images acquired in November at the onset of the harmattan, when weather conditions were unfavourable for Landsat images, were more interpretable than those acquired during the short dry season between the two peaks of the rainy season. This may be due to the use of spectral images (bands 5, 6 & 7) whose quality does not appear to depend on seasonal variation in weather conditions as shown in Section 7-2(b). However, the quality of band 4 images appears to depend on seasonal variation in weather conditions as shown in Sections 7-2(b) and 9-1.

The quality of band 4 images acquired in November at the onset of harmattan was poorer than those acquired in August during the short dry season between the rainy seasons. The overall results of the interpretation of the colour composite images do not balance the amount of work involved in generating the colour composites. However, colour permitted an easy separation of different areas represented by the same tone on the black/white prints. For example, the forest savanna and cultivation areas within the forest-savanna which were difficult to separate on the black/white prints are very distinct on colour composite 3NA. 0567. The chroma and hues of the additive colours were difficult to name precisely. However, they were visually distinguishable (see Figs. 9.2.2 & 9.3.2).

It was observed that features which were very distinct on the FACV were blurred in the photographic products of the additive colour views. This is true of linear features and rivers in particular. As a result of this blurring, riparian forests which were very distinct on the 1:1 000 000 prints under magnification were not apparent on the colour composites printed at larger scales. The blurring was mainly due to inaccurate superimposition of the images on the FACV. For the same reason, the forest type boundaries were not as well-defined on the colour composites as they were on the black/white prints. The blurring could be partly due to the general reduction in image definition and contrast on the colour composites relative to the black/white prints.

Microphotographic method was used for the reproduction of the colour composite images in order to improve the image contrast and to maintain the image definition. However, negative results were obtained. The poor Landsat image contrast has been reported to be improved by using relatively simple photographic methods to reprocess the images. Best and Smith (1978) obtained improved image contrast by reprocessing Landsat images using relatively varied film type, exposure, developer chemistry and duration of development. Also, Brothers and Fish (1978) developed a photographic enhancement-overlay processing method by which objects of interest could be isolated by a specific optical density range. The technique primarily developed for detecting changes in vegetation pattern is largely affected by the scale of the imagery being enhanced and the size of the area being analysed. This could also explain the general reduction in image definition observed during the interpretation of the colour-enhanced Landsat images.

Eyton and Knether (1978) found that microphotographic enlargement of satellite images such as Landsat imagery, on high definition/high contrast films could enhance details and so aid interpretation. The limit of enlargement of such continuous tone photography is determined by the resolution of the standard film product and the final resolution of the enlargement acceptable to the viewer. The resolution of enlarged photographs suitable for interpretation or viewing (8 line pairs per mm.) is slightly better than that of the human eye (5-6 line pairs per mm.). In this respect the maximum photographic enlargement should therefore be the ratio of the standard film product resolution to the acceptable viewing resolution.

The resolution of electro-optical Landsat MSS imagery is difficult to assess but this could be approximated to 34, 10 and 5 line pairs per mm. for the 1:3 369 000, 1:1 000 000 and 1:500 000 scale standard Landsat products respectively (Eyton & Knether, 1978). These values would result in 4.25, 1.25 or 0.63 enlargement (or reduction) respectively. For the present studies, the additive colour viewing was at x3.94 magnification which is close to the acceptable x4.25 viewing magnification. Also, the colour composites were printed at different scales varying between 1:200 000 and 1:1 000 000 including the acceptable viewing magnification (ca. 1:800 000).

Images could be enhanced beyond the limits of normal viewing resolution using a conventional 35mm. single lens reflex (SLR) camera with macrolens and conventional or special copying films. For general copying, most conventional colour films, such as those used in the present studies, would yield useful results. According to Eyton and Knether (1978), it is usually unnecessary to use special copying films for contrast control since conventional films also increase contrast. However, they have usually found special films desirable for enhancing subtle tonal differences on satellite. The processing of these special films requires more stringent conditions than that of the conventional films due to their narrow exposure latitudes. Conventional films were used to reproduce the colour composites for the present studies because of the difficulty in obtaining and processing the special copying films locally. The reproduction of the colour composite images on conventional films instead of special films may partly account for the relatively poor results obtained.

By Eros Data Centre Standards, the test area comprises low contrast scenes which normally have poor definition and contrast on Landsat images. Also, bulk (scene corrected) images which have lower registration accuracy and resolution than precision processed images, were used for the investigation. Furthermore, Landsat information is primarily acquired in digital form which is more suited to computer analysis than for visual interpretation. The bulk images used are third generation products of the digital data. If the colour composite views of these images on FACV are regarded as the 4th generation products, it follows that the photographic reproduction of these views would be the 5th generation. There is normally a consequent reduction in the image definition and loss in the information content of the original Landsat products as the number of generations increases.

Finally the limitations of the small scale and the low resolution of Landsat images do not normally permit detailed interpretation. All these considerations contribute to the poor quality of the results obtained.

The investigation is significant in that a comprehensive procedure for additive colour processing of Landsat spectral images was developed. This procedure can be applied to multispectral images from other remote sensing systems. In conclusion, additive colour processing and microphotography enhance the extraction of information from multispectral images. It does not necessarily follow, as often reported, that these procedures improve image definition and contrast, rather the combined procedures provide composite images in additive colours which are easier to handle and interpret than the black/white spectral images.

9-3 Findings of the Landsat interpretation

The visual interpretation of the single spectral images shows that the amount of forest information which is available on Landsat images is generally low. Only the broad forest types could be separated on these images. These broad types could not be separated further into subtypes on the colour composite images generated from these spectral images. The correspondence between the Landsat interpretation and map information shows that the broad forest types depicted on maps can be mapped directly from Landsat images. Despite their small scale, Landsat images provided more forest information than the maps of the test area. For example, small patches of different vegetal cover types found within a broad type on Landsat images were not mapped as a result of cartographic generalisation. Also, the forest boundaries observed on Landsat images were simplified in their cartographic representation on the maps.

The comparison of Landsat and photointerpretation shows that the exclusive forest types obtained by photointerpretation can be grouped into more inclusive general types by Landsat interpretation. For example, the moist semideciduous forest which was separated into dry and wet types as well as high, low and hill types on aerial photographs was recognised as a single unit on Landsat images. By photointerpretation alone, it may be difficult to notice the similarities between these semideciduous types. Furthermore, human interference on tropical forests usually result in sub-types within a main forest type. These subtypes which are generally recognisable on aerial photographs are not recognisable as such on Landsat images which show only the main forest type. It follows that both aerial photographs and Landsat images can be used for the interpretation of complex tropical forests in a complementary fashion. In view of the foregoing, Landsat imagery is of limited value for detail interpretation of tropical forest types. It can be of greater value for rapid exploration and reconnaissance surveys of extensive tropical forest areas. As forests were easily distinguished from non-forests and at the same time separated into broad types on Landsat images, an accurate location of the resource is possible by using Landsat imagery.

The major drawback in the use of Landsat is the inability to obtain good quality images of the productive tropical forests. Cloud free images of these forests are rare and scarce as shown in the present studies. The best images of the test area had 30% cloud cover which was concentrated in the coastal half. This part could not be interpreted on the images. Only three Landsat frames of the two

Landsat scenes covering the test area were available since the inception of Landsat system. This implies that the advantages of the repetition of Landsat images has no real value for cloud prone tropical areas. The band 4 images and to some extent the band 5 images of the test area were poor in quality due to haze and dispersion. The colour composite images which included band 4 images were found to be unsuitable for the interpretation of the test area. As a result of this, the multispectral content of Landsat imagery is of reduced value for the interpretation of tropical forests whose weather conditions are similar to those of the test area.

Because of the wide range of environmental factors affecting the quality of the Landsat images of tropical forests areas, it is suggested that colour composite images should be generated by individual Landsat users in the tropics. This would permit the selection of the most suitable band/filter combinations. In the present studies a comprehensive procedure of generating colour composite images by [illegible] additive colour processing of Landsat spectral images was developed and it was found to be satifactory for the investigation. By this procedure suitable substitutes of the standard Landsat colour composites, which are not often useful for tropical forest interpretation, can be produced at an economic cost. The procedure will be more useful for forestry and other establishments or investigators who have photographic processing facilities. The photographic processing of the colour composite images used for the present studies was done by commercial laboratories. Better results could have been obtained if the processing was controlled by the investigator.

The interpretation of the colour composite images shows that colour enhancement of Landsat imagery does not increase their content. Instead it improves the discrimination of this information and the extent to which it can be extracted. The findings on the technical capabilities of Landsat imagery for forest type recognition are compared with those of SLAR imagery in Chapter 10. The findings of the interpretation support those of the review of literature presented in Chapters 2-5. The usefulness of Landsat imagery for the interpretation of tropical forests cannot be assessed by its low information content alone without cost consideration. This is treated in Chapter 12 which interrelates the findings on the technical capability and the economics of the use of Landsat images for tropical forest interpretation.

CHAPTER 10

INTERPRETATION OF SLAR IMAGERY

10 Interpretation of SLAR imagery

The main purpose of this investigation is to verify and augment the findings of the review of literature on the use of SLAR imagery for gathering forest information for management purposes in the tropics. As SLAR emphasises surface roughness and consequently topography more than aerial photographic and Landsat imaging systems the investigation is also designed to verify the interpretative value of this topographic emphasis for forest type recognition.

As SLAR normally records surface roughness and thereby emphasising topography, the test area was separated into broad physiographic zones on the SLAR mosaics by differences in relief and topography. The forest types in each physiographic zone were separated mainly by physiographic features. Special features in the coastal areas as well as physiognomic height differences in areas with fairly even terrain were also used. In the absence of recognisable landmarks, 'hard details' such as man-made features were used for orientation during the interpretation. The interpretation was compared with map information, Landsat interpretation and photointerpretation and necessary correlations were made.

10-1 Materials and method

The test area was covered by motorola 94 real aperture SLAR between October, 1976 and March, 1977. The 1:250 000 SLAR mosaics of this coverage were used for the investigation. These mosaics are:-

Mosaic number	Look direction	Description of area coverage
NB31-3N	North	area of high relief with moderately broken topography

Mosaic number	Look direction	Description of area coverage
NB31-4S	South	area of high relief with rugged topography
NB31-7S	South	lowland coastal areas
NB31-8S	South	areas of low relief with fairly even topography

Joint Operations Graphic (JOG) maps are normally used for orientation in SLAR interpretation due to the unfamiliar rendition of terrain objects. As these JOG maps were not available, it was necessary to establish an orientation control network. In the first place each mosaic sheet was gridded at 0°15' intervals of longitude and latitude, using their geographic corner coordinate markings as a reference. By examining the SLAR images in conjunction with map information the locations of hard details such as settlements, inland water bodies and roads which are strong radar targets were established.

The test area was separated into four main physiographic zones by using altimetric information from topographic maps and topographic expressions on the SLAR images. The areas covered by the mosaic sheets correspond to the broad physiographic zones. Consequently the mosaic sheets were interpreted separately. The forest types were separated by physiographic features such as landforms and drainage patterns, special features such as those resulting from maritime influences and by physiognomic height differences which were recognised as corner reflections on the images. These criteria were used arbitrarily depending on their applicability to the areas being interpreted.

'Photographic' tone on SLAR images is determined by the slope of the terrain and the radar beam angle rather than surface brightness as in the case with aerial photography. Consequently, photographic tone is of limited value for forest interpretation on SLAR images. For this reason, photographic tone and texture were used only for separating the main forest types into subtypes or grouping them into more inclusive types. The relative grey scale wedge on the SLAR mosaics were grouped into five quality grades starting from the lightest as follows:-

Relative grey scale steps	Tonal quality grade
lightest 1 - 4	white
5 - 7	light
8 - 9	medium
10 - 11	dark
darkest 12 - 15	black

These tonal quality grades were used to establish the tonal differences and similarities between types where appropriate. The textural differences between types were described as smooth, fine, medium, coarse or rough. Rough texture includes mottled texture on radar is determined by the canopy in forested areas and by terrain roughness in open areas.

Delineations were more made during the interpretation. Instead the forest-types were separated in different areas by an intensive 'photostudy' of the SLAR images in conjunction with map information, Landsat and photointerpretation. Several workers including Allen (1975a) have found that without the aid of ground information - primary or secondary forest-types are difficult to separate on SLAR images. Allen (1975a) also found that certain requirements which are basic to SLAR interpretation can be fulfilled only by stereoscopic examination. These include a knowledge of the aspect of the individual SLAR strips - the far range and the near range; the linking up of drainage channels and the 'deadening' i.e. neutralising shadows. The use of SLAR mosaics for the present interpretation created further problems as these essential requirements which also aid the recognition of forest types could not be fulfilled.

The 1:100 000 and 1:5000 enlargement prints which were made from the mosaics for Olokemeji-Ijaiye Forest Reserves, Ibadan Fuel - UI Teak Plantations and Omo Forest Reserves were examined to determine whether enlargement printing could improve SLAR interpretation.

The results of the interpretation are presented in Section 10-2. A summary of the characteristics of the forest types recognised on the SLAR mosaics is given in Table 10.1. In this table each forest type is assigned a number (shown in brackets) by which it is illustrated in Figs. 10.1 - 10.4. Only a few examples of each forest type are shown and they are indicated by broad labels bearing the number assigned to the forest type. Some of the 'hard details' for controlling the interpretation are also shown but they are indicated by strip labels bearing their names. A few examples of the forest types and hard details were illustrated in order to permit an assessment of the interpretability of the SLAR mosaics.

10-3 Results and discussion

The following four physiographic zones were recognised on the SLAR mosaics of the test area.

	Physiographic zone	Location
A	high relief with moderately broken topography	all areas on Mosaic NB31-3N
B	high relief with rugged topography	all areas on Mosaic NB31-4S
C	lowland coastal area	all areas on Mosaic NB31-7S coastal areas on Mosaic NB31-8S

Table 10.1 Characteristics of the forest types interpreted on SLAR images

Forest type		Description	Tone and texture
I	Undifferentiated wooded savanna (1)	restricted to the northern parts of the test area; often associated with conspicuous cultivation areas	light tone and smooth - fine texture
II	Undifferentiated hill vegetation (2)	found on hill crests; often associated with prominent radar shadows	tone depends mainly on slope fine - medium texture
III	Forest savanna mosaic (3)	widespread in the northern parts of the test area. Five physiographic subtypes were recognised by drainage patterns. undifferentiated forest savanna (3A) and forest savanna on: - trellis drainage (3B) - dendrilic drainage (3C) - angular-rectangular(3D) - radial annular drainage (3F)	mottled tone and texture. Savanna is light toned, forests fringing the drainage channels are lighter toned than other forests which have medium to dark toner. Texture of savanna is finer than that of the forests.
IV	Undifferentiated moist forests (4)	undifferentiated moists are widespread in the southern part of the test area. Three physiognomic subtypes were recognised by vegetation height differences. - undifferentiated moist forests (4A) in areas with uneven terrain and - mature forest (4B) ie. high forest - immature forest (4C) i.e. secondary forest in areas with fairly even terrain	generally medium tone, wetter forests may be darker. Texture is medium to dark in the scan direction, abrupt changes from high to low physiognomy have dark boundaries, abrupt changes from low to high have light boundaries.
V	Riparian forest (5)	found along recent and/or old river courses in the lowland areas	medium tone, fine or medium texture
VI	Fresh water swamp forest/ vegetation (6)	restricted to edaphically wet habitats or seasonally flooded areas along lower river courses. Found mainly in the southern parts of the test area	variable tone resulting from seasonal changes in the water table, medium, fine or smooth texture
VII	Deltaic swamp complex (7)	restricted to the coastal parts of the test area. Found on river deltas.	variable tone resulting from variations infloristic composition. Smooth, fine, medium texture.
VIII	Mangrove (8)	found as low physiognomic type in brackish water swamp and as typical mature forest along distributaries in undifferentiated deltaic complex.	light tone and coarse texture resulting from tidal influence which results in striated terrain pattern.
IX	Undifferentiated coastal vegetation (9)	strand vegetation are found mainly on raised beaches along the coast. It comprises herbaceous strand vegetation, thicket and low physiognomic forest.	distinct light tone and smooth texture.

Forest type	Description	Tone and texture
X Forest plantations (10)	these are characterised by their definite geometric shapes which is mainly rectangular. Three physiognomic types were recognised by vegetation height differences - undifferentiated forest plantations (10A) in areas with uneven terrain old forest plantations (10B) and young forest plantation (10C) in areas with fairly even terrain.	light or dark toned depending on site, age and species composition of the plantations
XI Cultivation areas (11)	widespread, but only recognisable in the forest-savanna mosaic and in the wooded savanna.	mottled tone and texture recent cultivation areas have darker tone and finer texture than older cultivation areas.

<u>NOTE</u>: The forest types are illustrated in Figs 10.1 - 10.4 by the numbers shown in brackets.

	Physiographic zone	Location
D	low relief with fairly even topography	all areas on Mosaic NB31-8S except the coastal areas

As each SLAR mosaic covers only one main physiographic zone, the interpretation of the individual SLAR mosaics is discussed separately. The results of the interpretation are illustrated in Figs. 10.1 - 10.4. Areas which belong to a physiographic zone other than the main occuring zone are indicated in the illustrations (Figs. 10.1 - 10.4).

Eleven main forest types were distinguished on the SLAR mosaic images (see Table 10.1). These separation of the forest types are described in the following discussion on the interpretation of the SLAR mosaics.

(a) Interpretation of Mosaic NB31-3N (Fig. 10.1)

This mosaic covers a total land area of 15 770sq.km. comprising the Northwestern parts of the test area. The area has low relief but with moderately broken topography. The moist semideciduous forest and the forest-savanna mosaic are the main ecological zones in this area (Charter, 1970) but their distinction is not apparent on the SLAR mosaic mainly because of the topographic emphasis of SLAR. The forest types in this area were distinguished mainly by physiographic features and drainage patterns in particular. The following seven forest types were recognised.

(a) undifferentiated wooded savanna (1)
(b) undifferentiated hill vegetation (2)
(c) undifferentiated forest-savanna mosaic (3A)
(d) forest savanna on trellis drainage (3B)
(e) forest savanna on dendritic drainage (3C)
(f) undifferentiated moist forest (4A)
(g) cultivation areas (11)

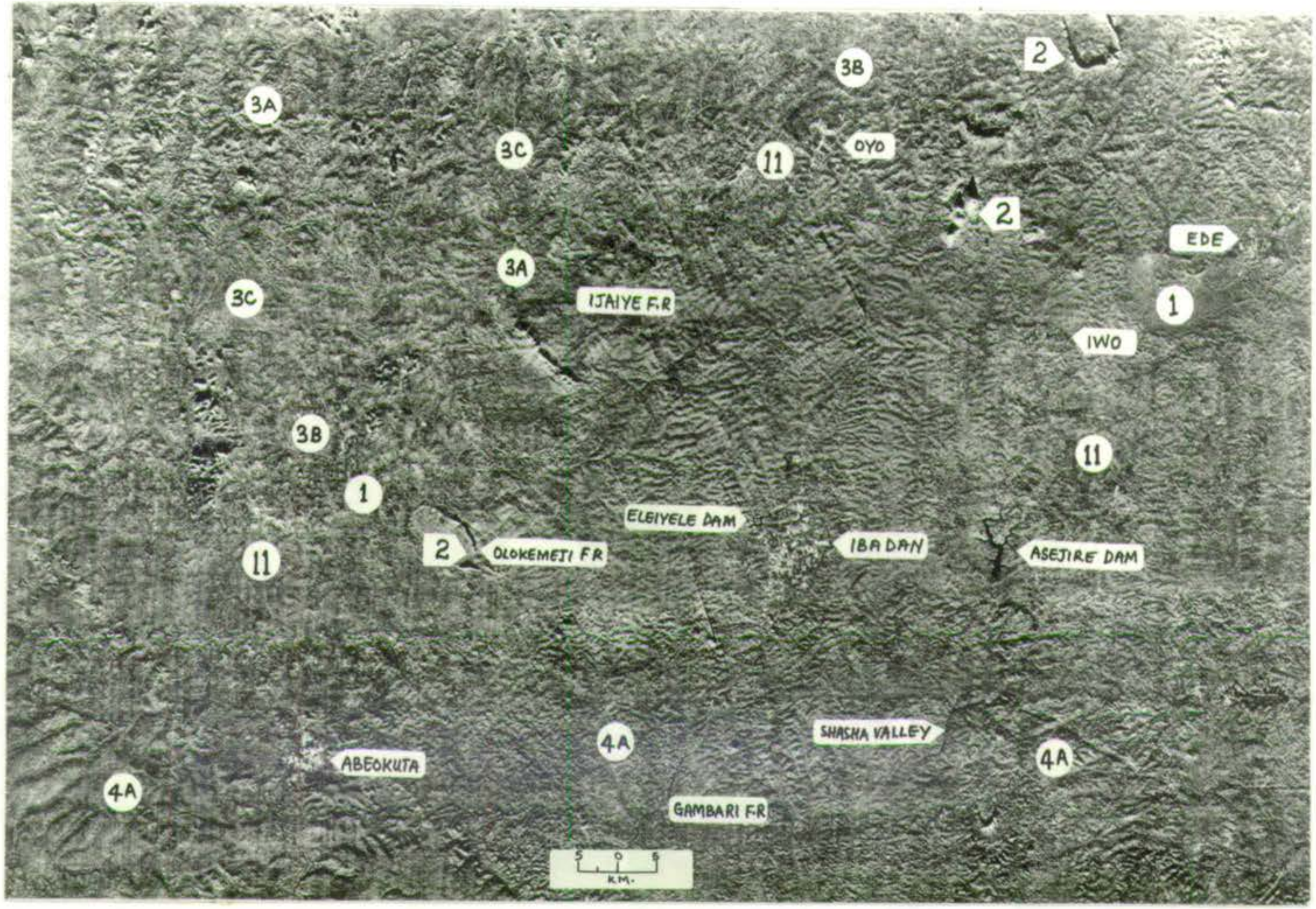


Fig. 10.1 An illustrated SLAR mosaic of Southwestern Nigeria showing forest types in areas of high relief with moderately broken topography (North-look Mosaic NB31-3N at 1:250 000 scale, October 1976 - March 1977).

The numeric representation of the forest types is explained in Table 10.1.

The undifferentiated wooded savanna (1) lies in the moist northerly part of this physiographic zone. It is characterised by the cultivation areas (11) which are more pronounced than they are in the forest savanna mosaic (3). This may be due to the high tonal and textural contrast between the cultivation areas and the wooded savanna as well as the low contrast between them and the forest savanna.

The nature of the vegetation in the hill crests cannot be determined due to the effect of slope on SLAR tone. They could be forest or grassland. They were therefore designated as undifferentiated hill vegetation (2).

The forest-savanna mosaic (3) is a very complex type comprising varied mixtures of forest and savanna. This hindered its interpretation. The best that could be achieved was its separation into physiographic types by the drainage patterns (see Table 10.1) where drainage pattern could not be appraised on the images the mosaic is designated as undifferentiated forest savanna (3A). In the physiographic types of the forest savanna (3B & 3C) which are found in this area, the dendritic drainage patterns are less conspicuous and fewer than the trellis drainage patterns probably due to the nature of the terrain. More often than not the forest component of the forest savanna mosaic was darker toned than the savanna component. It is not certain if this tonal difference is a reflection of the physiognomic heights differences or soil moisture which limits forest development in this relatively dry area. This is complicated further by the lighter tones of the forests bringing the drellis or dedrilic drainage channels and the absence of tonal difference between the components of the undifferentiated forest savanna mosaic (3A) in the wetter areas.

The moist forests in this physiographic zone cannot be separated into ecological types. They were therefore described as undifferentiated moist forests (4A). Furthermore, the physiognomic types could not be separated due to topographic emphasis by SLAR. Nevertheless, where mature forests adjoin savanna, the forests tend to be darker toned e.g. Ijaiye Forest Reserve area. However, this distinction is unreliable as it may also be a reflection of soil moisture or other differences.

The cultivation areas (11) are more conspicuous within the forest savanna on trellis drainage e.g. near Abeokuta than that on dendritic drainage e.g. near Oyo. It is not certain if this is due to topographic height or soil moisture differences rather than the age and type of crops being cultivated or the intensity of cultivation. The cultivation areas are less noticeable in the other forest types in this physiographic zone.

In addition to the forest types, urban settlements were recognised on the SLAR images by their mottled tone and their coarse texture which contrast very sharply to the general background e.g. Ibadan. Roads were recognised as dark or medium tone lineaments. They were quite distinct from river courses which were lighter toned due to the occurrence of fringing forests along them. Also, the river courses form part of the drainage patterns. Inland water bodies e.g. Eleiyele waterdam were recognised by their black images. Shadows of hills were very dark in tone but their locations differentiate them from inland water bodies. These shadows are always associated with highlights. Edaphically wet habitats are also very dark but terrain features can be recognised within them. This is not possible in shadow areas and inland water bodies.

(b) Interpretation of Mosaic NB31-4S (Fig. 10.2)

The mosaic covers a total land area of 15 770sq.km. comprising the northeastern part of the test area. Most of this area has high relief with rugged topography. Part of the central area has a fairly even topography. The main ecological zones found in this area are the moist semideciduous forests and the forest-savanna mosaic (Charter, 1970). Because of the topographic emphasis by SLAR these ecological zones could not be distinguished on the images..

The following seven forest types were recognised in this area.

(a) undifferentiated wooded savanna (1)
(b) undifferentiated hill vegetation (2)
(c) undifferentiated forest savanna (3A)
(d) forest-savanna in angular-rectangular drainage areas (3D)
(e) forest-savanna in radial-annular drainage areas (3E)
(f) undifferentiated moist forests (4A, 4B & 4C)
(g) cultivation area (11)

The interpretation of these forest types except the forest savanna types (3D & 3E) have been described in Mosaic NB31-3S

The forest types in this physiographic zone were more difficult to interpret due to excessive radar shadows and highlights of the rugged topography. These obscure the expression of forest types. For example, the apparent tonal and textural differences between the wooded savanna (1) and the undifferentiated forest-savanna (3A) were less noticeable on this SLAR mosaic. In spite of this, forest-savanna in angular-rectangular drainage areas (3D) and that in radial-annular drainage areas (3E) were very conspicuous as the drainage channels were very prominent within the rugged topography. The undifferentiated hill forests (2) were less noticeable on this SLAR mosaic than on Mosaic NB31-3N. This may be due to the different look-directions of the images or due to the absence of outstanding hills in spite of the

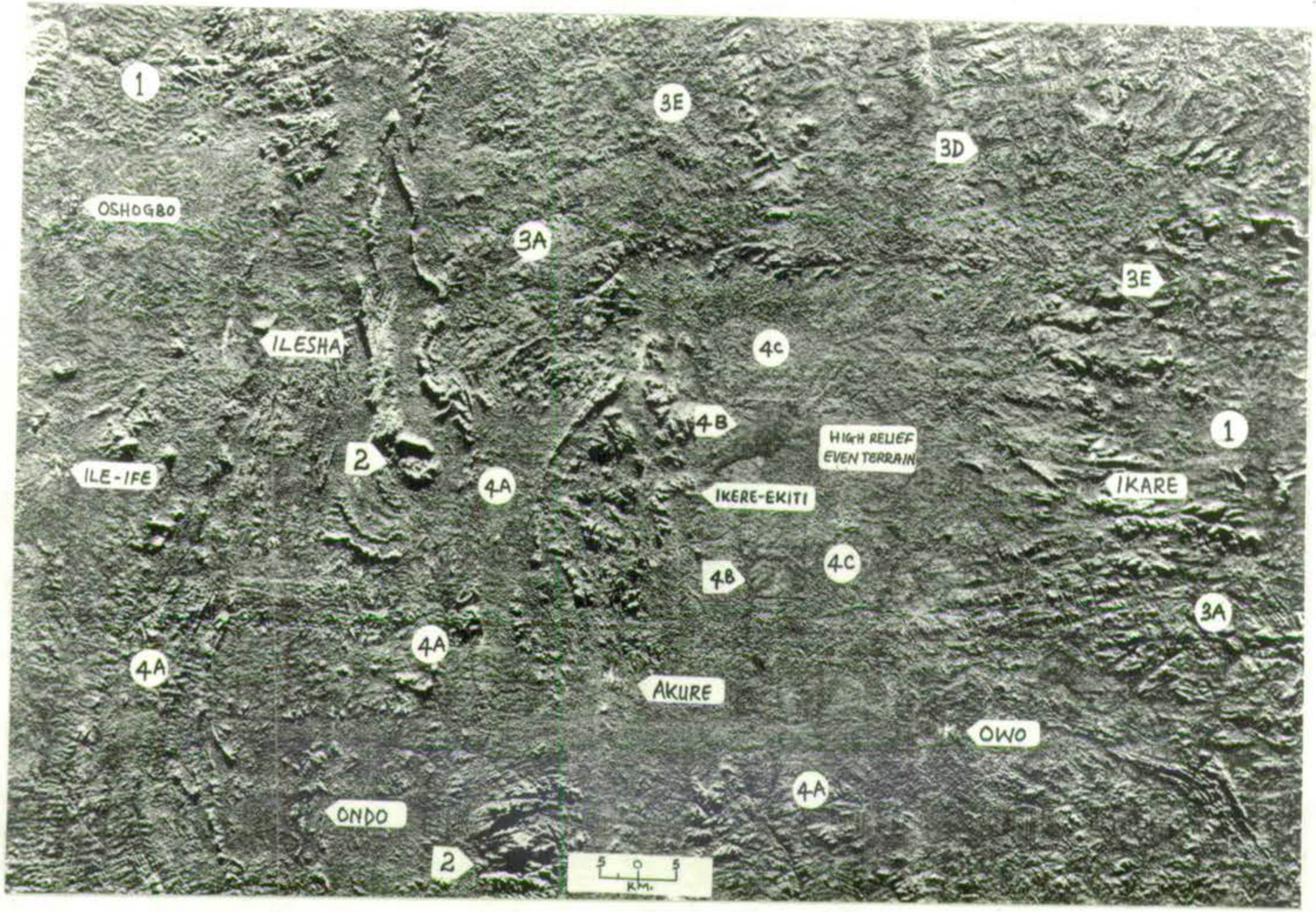


Fig.10.2 An illustrated SLAR mosaic of Southwestern Nigeria showing forest types in areas of high relief with rugged topography (South-look Mosaic NB31-4S at 1:250 000 scale, October 1976 - March 1977). **The numeric representation of the forest types is explained in Table 10.1**

very rugged topography. Nevertheless the undifferentiated moist forests in the central area close to Ikere-Ekiti could be separated into two main physiognomic types - the mature forest (4B) i.e. high forest with high vegetation and immature forest (4C) i.e. secondary forest with lower vegetation. The abrupt changes in the physiognomic types were distinct on the images. In the scan direction, abrupt changes in vegetation height from low to high are recorded by SLAR as light thin lines indicating high reflectance due to corner reflection along the boundary. Abrupt changes from high to low are registered as dark thin lines (radar shadows) indicating low reflection due to 'reversed' corner reflection. The registration of these changes would be reserved on images of the same area scanned from an opposite look-direction.

Hard details particularly the urban settlements and roads were difficult to locate in areas of highlights and shadows.

(c) Interpretation of Mosaic NB31-7S (Fig. 10.3)

This SLAR mosaic covers a land area of about 8 000sq.km. accounting for the coastal Southwestern part of the test area. The relief is low and topography is fairly even. The area contains coastal vegetation and mangrove, swamp and riparian forest as well as moist evergreen and semideciduous forest zones (Charter, 1970). As a result of the fairly even terrain, these ecological zones were readily recognisable on the SLAR mosaic but their boundaries were indistinct. The forest types lying towards the coast were distinguished mainly by special features resulting from tidal influences. Those lying inlands were distinguished mainly by drainage patterns and physiognomic height differences. The forest types in this physiographic zone were easier to separate than those in areas of high relief and broken or rugged topography (see Figs. 10.1 & 10.2).

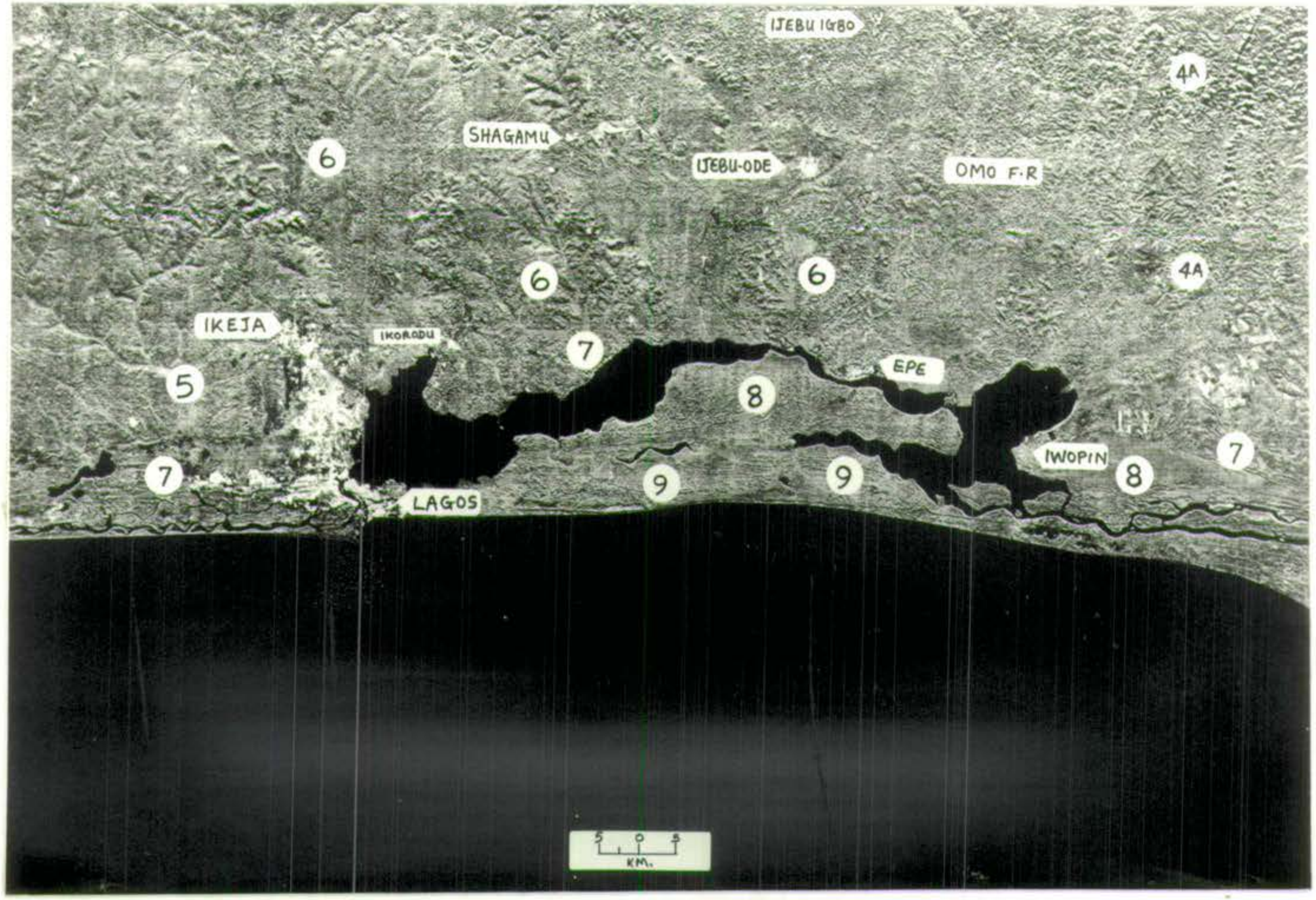


Fig. 10.3 An illustrated SLAR mosaic of Southwestern Nigeria showing forest types in lowland coastal areas (South-look Mosaic NB31-7S at 1:250 000 scale, October 1976 - March 1977). The numeric representation of the forest types is explained in Table 10.1.

The following forest types were recognised:-

(a) undifferentiated moist forest (4A)
(b) riparian forests (5)
(c) forest water swamp forest/vegetation (6)
(d) deltaic swamp complex (7)
(e) mangrove (8)
(f) undifferentiated coastal vegetation (9)

The interpretation of the undifferentiated moist forests has been described for Mosaic NB31-4S. Most of the undifferentiated moist forest (4A) is a mixture of 'mature and immature forests' i.e. tropical high forest and secondary forest. Though these are physiognomic types, their height difference was not noticeable on the images because both types intermingle with very diffuse boundaries. Moreover, the terrain is not flat. The riparian forests (5) are lighter toned than the fresh water swamp forests (6) occuring along river courses. Fresh water swamp forests (6) found outside river courses were coarser in texture probably due to the irregular depressions in which the swamps are normally found or to a mixture of different physiognomic types. The observed variable tone of the fresh water swamp (6) may be due to the varied seasonal changes of the water level at the imagery was acquired. These swamp forests are usually found in permanently or seasonally flooded areas. This condition could not be appraised on the images without ground information.

The variable tone of the deltaic swamp complex (7) may be due to the type of vegetation growing within it. The very dark tones due to herbaceous formation rooting in shallow brackish water. The lighter tones represent either woody vegetation with uniform canopy where the texture is smooth or patches of physiognomic types where the texture is coarse. The mangrove (8) has light/medium tone and coarse texture. They were recognised as low growing physiognomic types in brackish water swamps except in the deltaic swamp complex where they grow as typical forest along the distributary channels of the delta. The coarse texture is largely due to tidal effects. Where tidal effects are severe they result in striations which are parallel to the coast. In other areas the striations form a network without a definite alignment.

The coastal vegetation (9) comprises of hallophyllous strand vegetation, coastal thicket and forest. The herbaceous strand vegetation, the thicket and the forest components could not be separated, hence the term 'undifferentiated coastal vegetation'. The coastal vegetation was often recognised on raised beaches by its distinct light tone and smooth texture. Occasionally the texture was fine or medium depending on the presence of thicket or forest respectively. The undifferentiated coastal vegetation (9) is distinguished from mangrove (8) by the absence of striations which were associated with the latter. Cultivation areas (11) though abundant were not recognisable on this SLAR mosaic.

(d) <u>Interpretation of Mosaic NB31-8S</u> (Fig. 10.4)

The mosaic covers a land area of about 15 000sq.km. accounting for the coastal Southwestern part of the test area including inland areas of low relief with a virtually even terrain excepting small hills and depressions. Similar to Mosaic NB31-7S, the area contains coastal vegetation and mangrove, swamp and riparian forest, as well as moist evergreen and semideciduous forest zones (Charter, 1970). The forest types in this physiographic zone were distinguished mainly by drainage patterns, special features resulting from maritime influences and by physiognomic height differences in the inland areas which are virtually flat. The following forest types were recognised:-

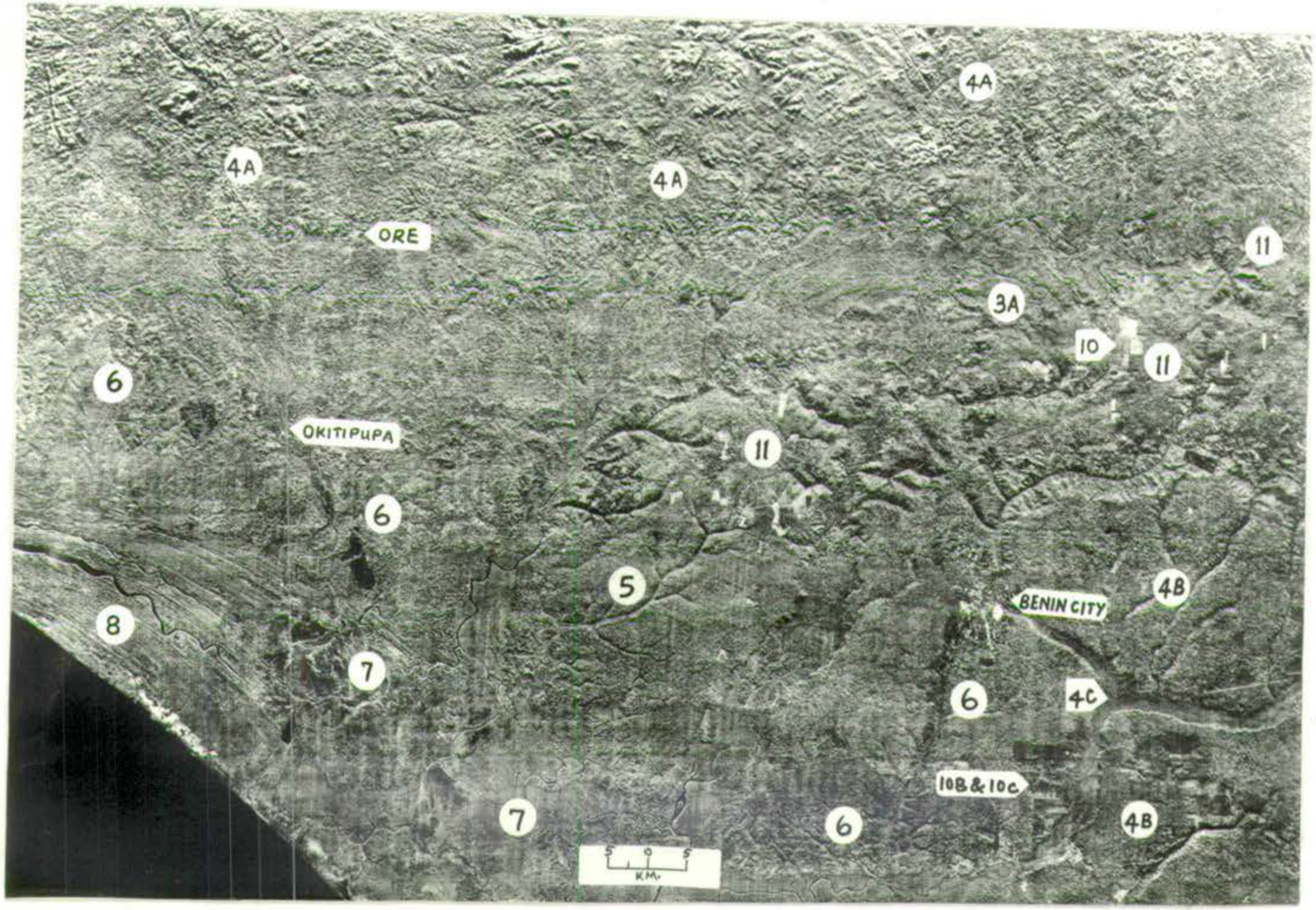


Fig. 10.4. An illustrated SLAR mosaic of Southwestern Nigeria showing forest types in areas of low relief with fairly even topography (South-look Mosaic NB31-8S at 1:250 000 scale, October 1976 - March 1977).

The numeric representation of the forest types is explained in Table 10.1.

(a) undifferentiated moist forests (4A, 4B & 4C)
(b) riparian forest (5)
(c) fresh water swamp forest/vegetation (6)
(d) deltaic swamp complex (7)
(e) mangrove (8)
(f) undifferentiated coastal vegetation (9)
(g) forest plantations (10A, 10B & 10C)
(h) cultivation areas (11)

The interpretation of types 4-9 has been described for Mosaic NB31-7S.

The undifferentiated moist forests could be separated into several physiognomic types by vegetation height differences due to the evenness of the terrain. However, with monoscopic examination only two physiognomic types could be separated by corner reflection effect. These are the mature (4B)and immature forests (4C) both having medium tone but the latter has finer texture. This separation could not be made in the almost uneven northern parts of the physiographic zone where the undifferentiated subtype (4A) is found.

The forest plantations (10) were recognised by their geometric shapes which were mainly rectangular. The boundaries were very distinct due to corner reflection effect, being of a higher or lower physiognomic height than the surrounding vegetation. In areas with uneven terrain the forest plantations could not be differentiated into physiognomic types due to topographic emphasis by SLAR. They were recognised as undifferentiated forest plantations (10A). However, in areas with almost flat terrain the forest plantations, as the undifferentiated moist forests, were separated into old (10B) and young (10C) plantations by physiognomic height differences. The vegetation height of the young plantations (10B) is lower than the older ones (10C).

Cultivation areas(11) though widespread were recognised only in the undifferentiated moist forests occuring in areas with uneven terrain in the northern parts of this physiographic zone.

In the mangrove areas, the striations along the coastlines were more prominent and longer than those on Mosaic NB31-7S. Their alignment conforms to the coastline, irregularly aligned short striations being virtually absent. As a result of the evenness of the terrain's hard details, roads and urban settlements in particular were more prominent and better defined than those in the other physiographic zones.

The interpretations described above were accomplished on the 1:250 000 SLAR mosaics. The 1:100 000 and 1:50 000 scale enlargement prints of the test sites i.e. Olokemeji-Ijaiye sites; Ibadan sites and Omo sites were not interpretable due to difficulties which are often associated with enlargement prints of SLAR imagery and mosaics in particular. According to Francis (1977) filtering of detail increases with wavelength and appreciable enlargement reduces the interpretative value of SLAR. However, he indicated that SLAR images could be enlarged ten times without any significant loss of detail, adding that a general enlargement of 2.5 times and a ten times enlargement of selected areas were usually sufficient for forest interpretation. Despite the fact that the scales of the enlargement prints being interpreted conform to those which were suggested by Francis, extra information on the forest-types could not be obtained. Consequently, the primary aim of separating the main forest types which were interpreted on the 1:250 000 scale mosaics into more inclusive types on the enlargement prints was not achieved.

The use of SLAR mosaics instead of the individual strips hindered the SLAR interpretation. Matched edges of the component SLAR strips often simulated forest boundaries and other lineaments particularly on the enlarged mosaics. Highlights and shadows, speckles of black/white dots became enlarged. This resulted in image-blurring which made visual interpretation difficult. Also, forest boundaries became more diffuse. Certain features which could be recognised on SLAR images only by their range characteristics were difficult to interpret because it was difficult to distinguish the far-range and the near-range of the individual component SLAR strips of the mosaics. Also, the extent of each strip could not be determined precisely. For these reasons, Allen (1975a) suggested that SLAR interpretation should include stereoscopic examination of overlapping SLAR strips.

Furthermore, tonal variation between the component SLAR strips of each mosaic image created problem in determining the extent of each unit of interpretation. For example, a forest type which extends over several strips were often mistaken for several units due to the tonal variation between individual SLAR strips of the mosaic. For this reason, delineations were not made. In order to permit an assessment of the interpretability of the SLAR mosaics, only a few examples of each unit of delineation were illustrated. It was also difficult to correlate SLAR information with photo-information due to these drawbacks in the use of SLAR mosaic for forest interpretation.

The comparison of the SLAR information with map information shows that SLAR images can provide forest information additional to that which is available on the existing maps. The existing maps show only the broad vegetation zones and the main forest types with little information on the more inclusive forest-types which are of greater value to forest management. For example, the vegetation of the lowland coastal areas and that of the inland areas with even terrain were better represented on SLAR images than on map. In spite of this, the moist forests could not be separated into types by SLAR interpretation alone. SLAR interpretation of these forests would require both intensive and extensive fieldwork for type delineation which is often hindered by topographic emphasis on SLAR images.

The correlation between map and SLAR information was weak. The ecological zones which were shown on the maps did not correspond to the physiographic zones obtained by the SLAR interpretation. Nevertheless, the correlation between map and SLAR information on the main forest types becomes stronger as one moves from the more northerly parts of the test area southwards to the coast. This is due to the physiography changing progressively from a rugged topography in the north to a virtually flat terrain in the southern coastal area. For instance, the undifferentiated coastal vegetation and the mangrove, the deltaic swamp complex, the fresh water and the riparian forests which were shown on the existing maps were readily recognisable on the SLAR mosaics of the lowland coastal areas. (Compare Figs. 7.1 and 10.3). In contrast, the moist evergreen and the moist semideciduous forests the forest-savanna mosaic and the wooded savanna which were shown in the maps could not be separated precisely on the SLAR images. This is mainly due to the lack of definite criteria for an objective interpretation and delineation.

The comparison of the photointerpretation and SLAR interpretation shows that only broad forest types can be interpreted on SLAR images. The more inclusive types which were interpreted on aerial photographs could not be interpreted on SLAR images due to the restricted range of scales and the limited enlargement possibilities with SLAR systems. Photographic tone and texture which are important criteria for photointerpretation were of limited value for the SLAR interpretation. The high resolution of aerial photography usually permits object recognition by shape and form in addition to tone and texture. The low resolution of SLAR however, precludes this possibility in SLAR interpretation. Tone and texture obtained with SLAR systems are due to complex interactions of radar energy with targets (terrain objects) and they are determined by the surface geometry of the targets.

It is not certain whether the photographic characteristics on SLAR present the real differences in vegetation or the artefacts resulting from the side-look image geometry, which do not usually reflect the tonal signatures of vegetation. This uncertainty arises from the variability of tonal signatures from the same class of targets in different places on the same SLAR images and from the similarity of the tonal signatures of different classes of targets on SLAR images which are acquired at different seasons. This is complicated further by slope and moisture content being the determinants of tone more often than vegetation. Textural differences are invariably due to differences in surface roughness which may be small or absent between different grades of vegetation. Tonal signatures of targets cannot be predicted with confidence by visual interpretation of SLAR images. Consequently, tone was of very limited value for the visual interpretation of forests of the test area. For the same reason, Stanley (1978) proposed that digital analysis on SLAR imagery could provide the human interpreter with a means of quantifying tonal and textural relationships for generating a reliable forest inventory and for providing a baseline for the management of forest resources.

In spite of these, visual interpretation of SLAR is still less objective than that of aerial photographs. Francis (1977) indicated that a previous experience in the interpretation of unconventional aerial photographs e.g. infrared could be of considerable value for SLAR interpretation. This notwithstanding, precise location of the forest boundaries was still difficult.

The comparison of SLAR and Landsat information shows that the SLAR images of areas of fairly even or uniformly sloping terrain provided more forest information than the corresponding Landsat images. The results are reserved for areas of broken or rugged topography. Despite the higher resolution and the larger scales of the SLAR images as well as their superior quality, the forest information obtained by photointerpretation correlates more with that obtained by Landsat interpretation than with that obtained by SLAR interpretation. This is due to complications introduced into the tonal and textural characteristics by the side-look image geometry of SLAR; the slope and surface roughness of the terrain.

Photographic and Landsat tones are determined by the same factor of surface brightness and they therefore present the same characteristic surface reflectance of the terrain objects and features on corresponding images. For instance, the more exclusive forest types which were separated on aerial photographs e.g. the moist semideciduous forest types could be easily grouped into a more inclusive general type on Landsat images e.g. moist semideciduous type. Probably a strong correlation could have been obtained between the photo information and SLAR information on the forest types in the lowland coastal areas which have a fairly even terrain, if the aerial photographs of these areas were available for the present studies.

According to HTS (1977, 1978) deductive interpretation of SLAR is normally based on a previous field experience and knowledge of the local forest conditions in the area being interpreted. Despite the present author's previous field experience and previous knowledge of the forest conditions in the test area, the SLAR interpretation of the area was still difficult to accomplish. This explains why excessive field checking was required for the SLAR interpretation of Southern Nigeria by HTS. Considering the general level of accuracy of forest interpretation on SLAR images and the amount of effort, time and money involved in the field checking, it is my opinion that the survey of the Nigerian moist lowland forest zone can be accomplished with a higher accuracy and at a lower cost by survey techniques other than SLAR. By no means would the ground survey of this forest zone cost more than its recent SLAR survey within the frame-work of the Nirad Project.

For their similarity to shaded relief maps, SLAR images, according to Allen (1975a), could provide a basis for delineating microtexture i.e. 'radarmorphic' regions, inasmuch as SLAR images provide more information on terrain details than other types of images. However, this was of limited value for the present forest interpretation.

The foregoing indicates that visual interpretation of SLAR images is of limited value and therefore of restrictive use in tropical forest survey.

10-3 Findings of the SLAR interpretation

The results of the interpretation show that only a general type of forest information can be obtained from SLAR images. This is indicated by the fact that the more inclusive forest types which were obtained by photointerpretation could not be separated on the SLAR images. Only the broad forest types could be interpreted to a limited extent on the SLAR images. More often than not these broad types do not usually correspond to groups of related types as often obtained by Landsat interpretation except for areas of even or uniformly sloping terrain.

The major set back in SLAR interpretation is the association of the important visual interpretation criterion of tone with characteristics other than the surface brightness of terrain objects and features. In areas of broken or rugged topography, tonal differences are more often associated with differences in slope and surface roughness than with differences in surface brightness. For this reason, SLAR interpretation would probably be of greater value for terrain analysis of forested areas than for forest type recognition. This is indicated by the weak correlation between SLAR information and map information as well as between SLAR information and photo information. This is particularly true for the interpretation of the areas of broken or rugged topography.

Physiography is the most important criteria for SLAR interpretation because SLAR records only surface roughness and so emphasises topographic height differences of the terrain or physiognomic height differences in the vegetation of even or uniformly sloping terrain. Physiographic and physiognomic height differences seldom reflect ecological differences in the vegetation. Consequently forest types cannot be separated with confidence by SLAR interpretation alone. It is usually difficult to establish a definite set of reliable criteria for SLAR interpretation due to the unusual characteristics of SLAR images. It follows that an extensive as well as an intensive field checking would be required to establish the reliability of forest type separation on SLAR images. This would normally increase the cost of the survey.

Forest type boundaries cannot be determined precisely on SLAR images. These boundaries are usually diffuse on the images not only because the forest types intermingle without distinct boundaries but also because the characteristics recorded by SLAR do not often reflect the ecological characteristics which normally define the forest types. Boundary definition on SLAR is often complicated by the use of SLAR mosaics. Tone varies from strip to strip on SLAR mosaics. Only physiographic features can be linked with high accuracy by their texture on SLAR mosaics. The continuity of forest types on adjacent SLAR strips are often difficult to link on SLAR mosaics. The different parts of the same forest type represented on different strips appear as belonging to different types due to tonal variation between the SLAR strips. This is more apparent on enlarged SLAR mosaics.

Despite the superior speed on SLAR coverage and its superior image quality, restricted scales and inferior resolution as well as its image geometry do not permit SLAR to compete successfully with aerial photography and Landsat imagery in providing information on tropical forests. Variable tonal signatures from the same class of targets, topographic emphasis, large scale system artefacts resulting from system effects and unconventional rendition of terrain objects and features were found to constitute the main hinderances to SLAR interpretation of tropical forests. Being a single channel imaging system, only a few of the various enhancement techniques which are possible with aerial photographs and Landsat images can be applied to SLAR images. For instance, colour images and multispectral or multiband imagery cannot be acquired with the currently available SLAR systems and this prevents the use of colour or colour composite images in SLAR interpretation.

Despite the various limitations of SLAR systems for forest surveys it has the advantage of rapid coverage of tropical forest areas and the provision of good quality images irrespective of weather conditions. However, it is often more expensive than aerial photography for limited coverages. Provided a large area is covered at a time, its cost compares favourably with that of aerial photography.

The relative efficiency of SLAR for tropical forest interpretation is discussed further in Chapter 12 which interrelates the findings on its technical capabilities and the economics of the use of the three remote sensing systems.

CHAPTER 11

APPRAISAL OF
REMOTE SENSING
IN NIGERIA

11 Appraisal of remote sensing in Nigeria

In the literature review, both technical and economic problems were identified in the use of the three remote sensing systems for gathering information for forest management purposes. The economic considerations apply to all four categories of forest management information. The technical problems were usually identified with the collection of specific category of information due to the peculiarities of the remote sensing systems used and the nature of the forests being interpreted. This was confirmed by the interpretation work reported in Chapters 8 - 10.

Remote sensing in Nigeria could not be appraised by literature review due to the scarcity of relevant literature. In view of this, it was considered desirable to conduct a survey by postal questionnaire to verify the state of the art and investigate the associated problems.

Though the survey is primarily for forestry purposes, it was considered more realistic to include other disciplines than to treat forestry in isolation. This would provide a better appreciation of the entire situation in relation to the following objectives of the survey:

(a) to determine the status of remote sensing in Nigeria,
(b) to determine the current use of remote sensing by Nigerian forestry services,
(c) to identify the problems associated with routine use of remote sensing for resource surveys in Nigeria,
(d) to augment the conclusions of the review of literature on remote sensing costs.

Further evidence was obtained from the present investigator's previous experience.

11-1 Survey by postal questionnaire

On 1st May, 1978 a questionnaire (see Appendix IIA) was distributed by post to all Nigerian forestry services and other establishments which, by the nature of their disciplines were likely to include remote sensing methods in their resource surveys in Nigeria. Survey by interviewing, which could have been more suitable in solving the problem at hand, was not feasible due to financial constraints.

(a) Limitations of survey by postal questionnaire

Harper (1977) remarked that postal questionnaire was the least satisfactory method of data collection for the simple reason of poor response. He indicated however, that a response of 15% was satisfactory for certain surveys and this could be improved by reminder notices. Postal questionnaires are of limited value as a sample because they are frequently biased in one direction or the other. For instance, a postal questionnaire relating to a stereoplotter performance might be returned mainly by users with complaints. Satisfied users may not bother to reply. Failure to reply itself does not constitute any bias, but the one-sided nature of the replies does. Conclusions drawn therefrom are valid only in terms of the available evidence. This bias could be considerably reduced if the questionnaire is used as a basis for interviewing, though the respondents may give the interviewer inaccurate or false data.

(b) The design of the questionnaire

In order to satisfactorily establish the status of remote sensing in Nigeria resource surveys and to appraise the state of the art on an economic basis, information was required on the following:-

(i) the type of establishment; Question (Q)1 was used to separate the establishments into groups for the analysis of the questionnaire.

(ii) remote sensing experience and future plans: Q2 to Q7 were used to collect information for establishing the status of remote sensing in resource surveys.

(iii) survey methods and techniques currently used: Q8 to Q11 were used to collect technical information for establishing a basis for the cost comparison of various survey methods.

(iv) cost of surveys by various methods: Q12 to Q15 were used to collect economic information for the evaluation of the relative costs of surveys by various methods.

The questionnaire was not divided into sections according to the information being sought, to avoid repetitions and complications. The questions were arranged in a logical sequence so that the respondents could easily understand the purpose of the questionnaire. This arrangement also permitted the cross-checking of the consistence of the answers given by individual respondents. The questions were presented in simple form, most of them only requiring selection of answers from sets of predetermined answers. By this method the quality of the respondents answers was standardised for individual questions. Moreover, it made the questionnaire easy to handle by the respondents and during the analysis.

(c) <u>Distribution of the questionnaire</u>

The questionnaire was distributed to the following establishments:

Code	Groups
FS	All twenty one Nigerian Federal and State Government forestry professional services (for their direct relevance to the study).
FA	The two Nigerian academic institutions teaching forestry as a discipline (for their direct relevance to the study).

RS Seven Nigerian Federal and State Government non-forestry professional services established before the 1966 creation of new states and whose resource surveys are related to forestry (for having advanced survey units).

RA Six Nigerian academic institutions founded before either the 1976 establishment of new universities or the 1976 creation of more states, and whose disciplines include vegetation studies (for having adequate survey experience).

EC Four expatriate firms and international agencies whose previous Nigerian contracts or projects are related to forest surveys (for their experience in remote sensing surveys and relevant costing).

These establishments were grouped according to their disciplines to indicate the position of forestry in the analysis of the questionnaire.

(d) Return of the Questionnaire

Despite the considerable length of time between the distribution and subsequent analysis of the Questionnaire and despite repeated reminder letters (Appendixes IIB & IIC) the returns (with or without information) and the response (returned with information) were somewhat poor as shown below (percentages in brackets):-

Group	Distribution	Returns	Responses
FS	21(52.5)	11(27.5)	8(20.0)
FA	2(5.0)	2(5.0)	2(5.0)
RS	7(17.5)	4(10.0)	3(7.5)
RA	6(15.0)	3(7.5)	3(7.5)
EC	4(10.0)	1(2.5)	1(2.5)
Total =	40(100.0)	21(52.5)	17(42.5)

The return of 52.5% excludes the three key remote sensing establishments (in FS, RS & RA groups) who did not reply. The response of 42.5%

includes replies from three of the five key forestry states. Kio (1971) reported a response of 71% (including replies from the three key forestry states) to a similar questionnaire he sent out to all the fourteen Nigerian Forestry Services in May, 1970 (a coincidence of date with the present questionnaire). His questionnaire was to determine the use of aerial photographs and the status of forest inventory in the forestry services so as to provide a background for the requirements and proposals for national forest resources inventory (Kio, 1971a).

11-2 Analysis of the questionnaire

The frequencies of the response to the individual questions and of the selection of the individual predetermined answers were tabulated for the four main groups of establishments. Because of the low frequencies obtained, the groups were recombined in two ways each resulting in two categories as follows:-

I. forestry (F+ = FS & FA) and non-forestry (R+ = RS & RA)
II. professional (+S = FS & RS) and academic (+A = FA & RA)

The frequencies were also tabulated for the recombination categories (see Appendix IID). The response frequencies and answers were pooled under two mutually exclusive conditions to provide 2 x 2 contingency data sets suitable for simple statistical analysis. Because the number of establishments in each category is not the same and the number of predetermined answers for each question is not the same, the pooled frequencies were standardised for the primary groups and the recombination categories (see Appendix IIE) as follows:-

$$S = \frac{100 \times F}{Rn \times Qn}$$ in which

S = standardised value
F = frequency value in each cell of the group 2 x 4 or the category 2 x 2 contingency table

Rn = the number of establishments in the group or category

Qn = the number of questions or answers pooled into the same condition.

This standardisation permitted the numerical comparison of the primary data. It was not used for the statistical analysis.

The economic data obtained on the various survey methods were evaluated on a comparative basis without any statistical tests. The remaining aspects of the questionnaire were statistically evaluated.

11-2.1 Methods and procedure of the statistical analysis

Statistical methods were used for the analysis of the questionnaire for two main reasons:-

In the first place, surveys by questionnaire differ markedly from other survey methods because the same results are seldom obtained. If it is repeated under the same conditions, the number of respondents and even the answers by the same respondent would probably vary with each repetition. Also, the respondents would not be the same. By statistical analysis, the likelihood of obtaining the same results by several repetitions can be determined from a single set of observations.

Secondly, statistical methods provide a clearer view and a better judgment of the meaning and the significance of numerical data.

The analysis was restricted to 2 x 2 contingency tests by the small sample size resulting from the restricted distribution and the poor return of the questionnaire. But complex statistical tests were rarely necessary because the data are in frequency form for which many simple but stringent statistical tests are available. The most suitable tests for solving the problem at hand are:-

(i) Phi coefficient test of association ($X\phi$ test)

(ii) Chi squared test of significance (X^2 test)

(iii) Fisher's exact probability test (P test)

The data format for the contingency tests is shown below:-

	category I	category II	condition total
condition I	A	B	A + B
condition II	C	D	C + D
category total	A + C	B + D	N

The various values of the statistics $X\phi$, X^2 and P for data sets were computed from the following formulas using the format above:-

$$X\phi = \phi\sqrt{N} \text{ in which}$$

$$\phi = \frac{AD - BC}{\sqrt{(A + B)\ (C + D)\ (A + C)\ (B + D)}}$$

$$X^2 = \frac{N(\ /AD - BC/ - 0.5N)^2}{(A + B)(C + D)(A + C)(B + D)}$$

$$P = \frac{(A + B)!\ (C + D)!\ (A + C)!\ (B + D)!}{N!\ A!\ B!\ C!\ D!}$$

For convenience of computation of the test statistic P, each contingency table is oriented in such a way that the smallest value occupies the top left hand (i.e. cell A) cell of the data format. The exact probability for each contingency table is the sum of the P values of the observed data and those of the more extreme cases. For a two-tailed test the number of data sets is equal to the smallest marginal total plus one, but in a one-tailed test of this nature it is equal to the value of the smallest cell plus one. In either case, the value of the smallest cell in the most extreme case is 0. The sets are designated by the value of the smallest cell - that is cell A :- sets 0, 1, 2 etc. with attached probabilities P_0, P_1, P_2 etc.

The P values are computed as below:-

$$P_0 = \frac{(A_0 + B_0)!\ (C_0 + D_0)!\ (A_0 + C_0)!\ (B_0 + D_0)!}{N!\ A_0!\ B_0!\ C_0!\ D_0!}$$

Since $A_0 = 0$, the formula cancels down to

$$P_0 = \frac{(C_0 + D_0)!\ (B_0 + D_0)!}{N!\ D_0!}$$

From P_0 value, other P values, say P_1 and P_2, and the value of the test statistic P are computed as follows:-

$$P_1 = \frac{P_0\ B_0\ C_0}{A_1\ D_1}$$

$$P_2 = \frac{P_1\ B_1\ C_1}{A_2\ D_2}$$

$$P = P_0 + P_1 + P_2 \text{ etc.}$$

A Hewlett Packard HP 27 pocket calculator was used for the computations. It has the advantage of an automatic memory four-stack register for storing intermediate results, ten addressable storage registers and preprogrammed scientific mathematical and statistical functions, particularly the factorials of numbers. For small samples of this nature (see Table 11.1)the valuable time that would have been used for drawing computer programmes was saved by using the facilities offered by the calculator.

The computed test statistics Xø, X^2 and P together with their levels of significance are shown in Table 11.1. The X^2 test statistic enters the X^2 distribution table with one degree of freedom for a 2 x 2 contingency test. The three statistics were basically used to test the Null hypothesis which was restated in equivalent form for each set of mutually exclusive conditions. The equivalent forms of the hypothesis were not presented since they are distinctly implied in the discussion of the results (see Section 11-3). It suffices to indicate that in order to determine if a statement is false, the Null hypothesis is made and if a statement is true the alternative hypothesis is made.

A combined use of the three tests was desirable because some of the data sets did not fulfil the requirements of one test or the other, particularly the X^2 test. For instance, the X^2 test is inappropriate for -

(i) contingency tables with more than one degree of freedom if more than one fifth of the cells have an expected value of less than five and/or if any cell has an expected value of less than one as in the case of the group 2 x 4 contingency analysis initially envisaged.

(ii) contingency tables in which the sample total is less than twenty or in which the sample total lies between twenty and forty and the smallest expected is less than five Swinscow (1978).

The X^2 values were corrected for continuity using Yates' correction. Though Phi coefficient (ø) is a logical extension of Chi squared (X^2), Xø values were computed from X^2 for two reasons: Firstly, Yates' correction normally results in the reduction of probability values and frequently overcorrects, so that the corrected X^2 could be almost as far from the true value as the uncorrected X^2 (Norcliffe, 1977). Secondly, ø values computed from corrected X^2 values would not attain their theoretical limits of +1 and -1 due to Yates' correction. Moreover, it is easier to compute uncorrected X^2 values from ø values than the other way round using the following formula:-

$$X^2 = \phi^2N \text{ or } (\phi\sqrt{N})^2 \text{ or } (X\phi)^2$$

It follows that if the X^2 test was based on uncorrected X^2 values the conclusions drawn will be the same as those drawn with the $X\phi$ test. $X\phi$ test has the dual advantage of being a test of correlation as well as of significance (Conover, 1971).

11-3 Discussion of the results of the analysis

The results of the statistical analysis are presented in Table 11.1. In this table, the test statistic ($X\phi$, X^2 and P) values are indexed to show their levels of significance. The indexes of significance range from 01, the most significant, to 17, the least significant level. The probability equivalents of these indexes and the corresponding values of the test statistics with one degree of freedom for table entry are given in Table 11.1.1. The results obtained from the $X\phi$, X^2 and P tests at the commonly used probability level of 0.05, are compared in Table 11.1.2.

As the data sets were of limited analytical value statistically, an outcome was accepted to be significant if it was so proved for one recombination category by at least one test. On the other hand, an outcome was regarded as insignificant if it was proved so for both recombination groups by all the tests. In essence, the ensuing discussion is primarily based on Table 11.1.2.

(a) Response to the questionnaire

The analysis shows that the 'return' and the 'response' were representative samples of the population assumed by the 'distribution' of the questionnaire since the distribution ratio was not significantly different from either the return or the response ratio (Q1 a & b).

Table 11.1 Analysis of the questionnaire:
Summary of the results of the 2 x 2 contingency tests

Mutually exclusive conditions (questionnaire numbers)		Test	Categories			
			F+	R+	+S	+A
Q1	(a) distribution of questionnaire		23	13	28	8
	return of questionnaire		13	7	15	5
		$X\phi$	-0.083 (09)		+0.236 (10)	
		X^2	0.043 (10)		0.009 (12)	
		P	0.585 (10)		0.718 (10)	
	(b) distribution of questionnaire		23	13	28	8
	response to questionnaire		10	6	11	5
		$X\phi$	+0.096 (11)		+0.694 (11)	
		X^2	0.047 (11)		0.120 (10)	
		P	0.837 (11)		0.851 (11)	
	(c) return of questionnaire		13	7	15	5
	response to questionnaire		10	6	11	5
		$X\phi$	+0.135 (10)		+0.416 (10)	
		X^2	0.038 (11)		0.002 (14)	
		P	0.724 (10)		0.786 (11)	
Q2	use ground methods mainly (2.1)		9	2	9	2
	use remote sensing methods mainly (2.2 & 2.3)		1	6	4	3
		$X\phi$	+2.811 (17)		+1.139 (11)	
		X^2	5.403 (04)		0.360 (09)	
		P	0.009 (03)		0.027 (05)	

Mutually exclusive conditions (questionnaire numbers)	Test	Categories			
		F+	R+	+S	+A
Q3 remote sensing imagery used (3.1 – 3.4)		2	11	6	7
remote sensing imagery not used (3.5)		8	1	8	1
	$X\phi$	-3.404 (01)		-2.049 (04)	
	X^2	8.814 (01)		2.554 (08)	
	P	0.001 (02)		0.052 (06)	
Q4 possess photogrammetric equipment (4.1 – 4.7)		9	19	18	10
no photogrammetric equipment (4.8)		4	0	4	0
	$X\phi$	-2.585 (02)		-1.441 (06)	
	X^2	4.164 (05)		0.748 (09)	
	P	0.020 (08)		0.203 (08)	
Q5 possess image enhancement equipment (5.1 – 5.5)		3	0	1	2
no image enhancement equipment (5.6)		7	6	10	3
	$X\phi$	+1.488 (13)		-1.367 (07)	
	X^2	0.684 (09)		0.604 (09)	
	P	0.214 (08)		0.214 (08)	
Q6 use of remote sensing constrained(6.1 – 6.4)		23	10	19	14
ground methods are cheaper (6.5)		2	0	2	0
	$X\phi$	-0.921 (08)		-1.189 (08)	
	X^2	0.013 (12)		0.199 (10)	
	P	0.504 (10)		0.353 (09)	
Q7 remote sensing desirable (7.1 – 7.3)		8	5	8	5
remote sensing not desirable (7.4)		2	0	2	0
	$X\phi$	-1.074 (08)		-1.074 (08)	
	X^2	0.072 (11)		0.072 (11)	
	P	0.429 (09)		0.429 (09)	

Mutually exclusive conditions (questionnaire numbers)	Test	Categories			
		F+	R+	+S	+A
Q8 (a) ground data as main survey data (8.1.1)		2	1	3	0
ground data as ground information for remote sensing survey (8.1.2)		2	2	2	2
	$X\phi$	+0.441	(10)	+0.966	(11)
	X^2	0.109	(10)	0.365	(10)
	P	0.629	(10)	0.286	(09)
Q8 (b) mineral/geological/ soil survey (8.4.1 - 8.4.3)		4	3	6	1
agricultural/forest/ vegetation survey (8.5.1 - 8.5.3)		16	1	12	5
	$X\phi$	+2.209	(15)	+0.778	(11)
	X^2	2.582	(08)	0.067	(11)
	P	0.059	(06)	0.414	(09)
(c) non-vegetation surveys (8.3.1 - 8.3.3 & 8.4.1 - 8.4.3)		4	7	9	2
vegetation surveys (8.5.1 - 8.5.3)		16	1	12	5
	$X\phi$	-3.304	(01)	+0.670	(10)
	X^2	8.269	(02)	0.050	(11)
	P	0.002	(02)	0.419	(09)
Q9 complete census survey frame (9.2)		3	3	6	0
sampling survey frame (9.2)		7	2	5	4
	$X\phi$	-1.118	(08)	+1.907	(14)
	X^2	0.313	(10)	1.717	(08)
	P	0.287	(09)	0.092	(07)

Mutually exclusive conditions (questionnaire numbers)		Test	Categories			
			F+	R+	+S	+A
Q10	simple sampling designs 10.1.1, 10.1.2; 10.2.1 & 10.2.2		6	2	4	4
	complex sampling designs 10.3.1, 10.3.2; 10.4.1 & 10.4.2		2	1	1	2
		Xø	+0.276 (10)		+0.494 (10)	
		X^2	0.234 (10)		0.034 (11)	
		P	0.848 (11)		0.576 (10)	
Q8 to Q15	(a) answers received to Q8 – Q15		42	20	38	24
	Q8 – Q15 unanswered		38	28	50	16
		Xø	+1.187 (11)		−1.765 (05)	
		X^2	1.009 (09)		2.477 (08)	
		P^*	0.072 (06)		0.036 (05)	
	(b) answers received to Q8 – Q11		33	14	31	16
	answers received to Q12 – Q15		9	6	7	8
		Xø	+0.737 (11)		+1.335 (12)	
		X^2	0.176 (10)		0.330 (10)	
		P	0.854 (11)		0.151 (08)	
	(c) answers received to Q12 – Q15 subquestions		34	30	24	40
	Q12 – Q15 unanswered		176	96	207	65
		Xø	−1.722 (05)		−5.995 (01)	
		X^2	2.491 (08)		34.162 (01)	
		P^*	0.026 (05)		$0.0^8 64$(01)	
	(d) answers received to Q12 & Q13 subquestions		18	8	14	12
	answers received to Q14 & Q15 subquestions		16	22	10	28
		Xø	+2.136 (15)		+2.234 (15)	
		X^2	3.537 (06)		3.887 (05)	
		P	0.029 (05)		0.025 (05)	

Mutually exclusive conditions (questionnaire numbers)		Test	Categories			
			F+	R+	+S	+A
Q16	remote sensing facilities available (16.1 - 16.5)		2	9	4	7
	no remote sensing facilities (16.6)		9	1	9	1
		Xø	-3.291 (01)		-2.528 (03)	
		X^2	8.144 (02)		4.318 (05)	
		P	0.002 (02)		0.170 (08)	

* Test statistic was computed for only the observed data sets using logarithm of factorials because the generation of the actual value is laborious as it exceeds the capacity Hewlett Packard HP - 27 pocket calculator

The probability equivalents of the index of significance in brackets after the test statistics are given in Table 11.1.1.

Table 11.1.1 Analysis of the questionnaire:
The values of test statistics $X\phi$, X^2 and P at
various levels of significance (p)

Level of significance		Test statistic	
Index	+ Probability (p)	$X\phi$ range	* X^2 range
01	below 0.001	below -3.090	above 10.828
02	0.001 - 0.005	-3.090 - -2.576	10.828 - 7.879
03	0.005 - 0.010	-2.576 - -2.326	7.879 - 6.635
04	0.010 - 0.025	-2.326 - -1.960	6.635 - 5.024
05	0.025 - 0.050	-1.960 - -1.645	5.024 - 3.841
06	0.050 - 0.075	-1.645 - -1.440	3.841 - 3.170
07	0.075 - 0.100	-1.440 - -1.282	3.170 - 2.706
08	0.100 - 0.250	-1.282 - -0.675	2.706 - 1.323
09	0.250 - 0.500	-0.675 - 0.000	1.323 - 0.455
10	0.500 - 0.750	0.000 - +0.675	0.455 - 0.102
11	0.750 - 0.900	+0.675 - +1.282	0.102 - 0.016
12	0.900 - 0.925	+1.282 - +1.440	0.016 - $0.0^{2}89$
13	0.925 - 0.950	+1.440 - +1.645	$0.0^{2}89$ - $0.0^{2}39$
14	0.950 - 0.975	+1.645 - +1.960	$0.0^{2}39$ - $0.0^{3}98$
15	0.975 - 0.990	+1.960 - +2.326	$0.0^{3}98$ - $0.0^{3}16$
16	0.990 - 0.995	+2.326 - +2.576	$0.0^{3}16$ - $0.0^{4}39$
17	0.995 - 0.999	+2.576 - +3.090	$0.0^{4}39$ - $0.0^{5}16$
18	above 0.999	above +3.090	below $0.0^{5}16$

\+ equivalent of Fisher's exact probability (p)

* corrected X^2 values for a two-tailed test with one degree of freedom for table entry; values corresponding to indexes 01 - 09 are approximates of uncorrected X^2 values or corrected X^2 values compensated for 'Yates' over correction' for continuity in a one-tailed test.

Sources: Conover (1971) White, Yeats & Skipworth (1977),* Neave (1978)*

Table 11.1.2 Analysis of the questionnaire: Comparison of the phi coefficient, chi squared and exact probability tests at 0.05 probability level

		Categories					
	Mutually exclusive conditions considered	F+ & R+			+S & +A		
		X	X^2	P	X	X^2	P
Q1	(a) questionnaire distribution/return	+	+	+	+	+	+
	(b) questionnaire distribution/response	+	+	+	+	+	+
	(c) questionnaire return/response	+	+	+	+	+	+
Q2	ground/remote sensing methods usage	+	*	*	+	+	*
Q3	remote sensing imagery used/not used	*	*	*	*	+	+
Q4	photogrammetric equipment available/none	*	(*)	+	+	+	+
Q5	enhancement equipment available/none	+	+	+	+	+	+
Q6	remote sensing constrained/cheaper methods	+	+	+	+	+	+
Q7	remote sensing desirable/not desirable	+	+	+	+	+	+
Q8	(a) ground data as main/control data	+	+	+	+	+	+
	(b) physical/biological resource surveys	+	+	+	+	+	+
	(c) non-vegetation/vegetation surveys	*	*	*	+	+	+
Q9	complete census/sampling survey frame	+	+	+	+	+	+
Q10	sampling design simple/complex	+	+	+	+	+	+
Q8 to Q15	(a) Q8 - Q15 answered/not answered	+	+	+	*	+	*
	(b) Q8 - Q11 /Q12 - Q15 answers received	+	+	+	+	+	+
	(c) Q12 - Q15 subquestions answered/not	*	+	*	*	*	*
	(d) Q12 & Q13/Q14 & Q15 subanswers received	+	+	*	+	(*)	*
Q16	remote sensing facilities available/none	*	*	*	*	(*)	+

\+ not significant at $p = 0.05$

* significant at $p = 0.05$

(*) significant at $p = 0.10$ in one-tailed test but also significant at $p = 0.05$ if 'Yate's over correction' for continuity is compensated or if uncorrected X^2 is used.

Moreover, the return ratio and response ratio were not significantly different (Q1b). Being a representative sample, inferences and conclusions could be drawn from the response for the population of establishments to whom the questionnaire was sent.

The groups of establishment differ significantly in their disposition to provide either technical or economic information on their survey methods (Q8 - Q15a). Consequently, inferences and conclusions drawn from the observed data might not be valid for the population due to inadequate information. The forestry academic group was better disposed while the non-forestry professional group was less disposed than others. The amount of technical and economic information provided by the respondents were equally low (Q8 - Q15b). The number of answers received to Q12 to Q15 on economic data is significantly lower than those not received (Q8 - Q15c). Also, the number of answers received to Q12 and Q13 was significantly lower than that received to Q14 and Q15 (Q8 - Q15c). The implication of the results of the analysis of Q8 to Q15 is that technical information was insufficient to establish a standard for evaluating the economic data obtained. Consequently, simple comparison of data was the only option, more so when the economic data to be evaluated were also inadequate.

(b) Status of remote sensing in Nigerian resource surveys

The analysis conclusively shows that in Nigeria ground methods are mainly used for resource surveys,and forest surveys in particular (Q2) as reported earlier by Kio (1971). Remote sensing methods were seldom used by the forestry professional group but more frequently used by the forestry academic and non-forestry groups (Q2 & Q3). This is because these groups possess more photogrammetric and image enhancement equipment than the forestry professional group (Q4 & Q5). This difference was statistically significant for photogrammetric equipment

(Q4) but has not been proved so for image enhancement equipment (Q5). Only the academic groups have computer facilities. None of the state forestry services planned to establish any form of remote sensing unit independently, but one of the respondents from the forestry academic group intends to improve on its own set-up and to add more to the existing unit (Q16). The same finding was reported by Kio (1971) in the analysis of his questionnaire.

The limited use of remote sensing methods for resource surveys and for forest surveys in particular, is largely due to economic constraints rather than a cheaper alternative (Q6). The order of importance of the predetermined economic constraints was almost the same for each group or category of establishments, the most important constraint being the lack of appropriate equipment followed by the inadequacy of funds, the insufficiency of trained personnel and inadequate sensor coverage of areas of interest in that order.

Of the respondents, the 12.5% who indicated that ground methods are cheaper and that consequently remote sensing is undesirable in Nigeria, belong to the forestry professional group. This claim, though statistically insignificant, raises an issue of practical significance. The claim could be supported by the possession of an efficient data base, but this is not the case with Nigerian forestry services. Further, it could be reasoned that such establishments were not familiar with remote sensing. But the forestry services were already intimate, before the distribution of the questionnaire, with remote sensing through the on-going Nirad Project and the wide publicity on remote sensing in the news media (e.g. Kio, 1977).

Their reason for indicating that ground methods are cheaper could be that these forestry services make use of only the established staff in all their field surveys. In this case the cost of the acquisition of remote sensing imagery would increase the total survey costs. It must be realised that, for going to the field, this established staff also draws substantial monetary incentives in addition to their salaries. These monetary incentives usually account for a substantial proportion of the total survey costs. In certain circumstances such monetary incentives may be close to the amount that would have been used to acquire the relevant remote sensing imagery. It could also be inferred that these establishments did not consider the time and effort involved in field surveys to guide their choice of economic constraints to remote sensing and their choice of remote sensing set-up.

There was a consensus in favour of a remote sensing set-up in Nigeria as previously shown by the results of Kio's questionnaire. However, opinion differed between the categories on the type of set-up desirable (Q7). The primary data showed that the forestry and the academic categories favoured separate remote sensing units for groups of related disciplines. Probably the establishments concerned might have thought their data needs would not be efficiently handled by a central set-up. The non-forestry category favoured a central unit with dispersed user-facilities for various disciplines. This may be due to the close similarities in their data needs. The professional category favoured a central unit supplying individual disciplines with their data needs. The analysis of Kio's questionnaire shows that forestry services favoured a central set-up. As his questionnaire was limited to the forestry services it was not clear from his results whether the type of central set-up was for forestry services alone or for the entire country irrespective of professional disciplines.

For economic reasons, a central set-up is suggested. For technical reasons, the central unit should have both dispersed user-facilities and data supply facilities for various disciplines.

(c) Technical information on survey methods

The analysis shows that ground surveys were the main source of forest data since remote sensing methods were seldom used for forestry purposes in Nigeria (Q8). Vegetation surveys and forest surveys in particular, tend to be more dependent on ground methods than geological and related surveys or other surveys combined (Q8). The survey frames of the forestry and the non-forestry categories differ significantly, but such a difference could not be established between the professional and the academic establishments. The forestry professional group base their surveys mainly on sampling, while the non-forestry professional group base their surveys on both complete census and sampling (Q9). There was a general tendency within the groups to use the simpler sampling techniques. The more complex techniques are used by the forestry category only (Q10).

(d) Economic information on survey methods

The sampling techniques and survey designs employed by the respondents vary so widely that a basis could not be established for the comparison of ground survey and remote sensing survey costs (Q10). The respondents could not provide definite information either on the size of the sampling units within their sampling frame or on the level of accuracy desired and achieved (Q11). Also, the data provided on the costs and the duration of their surveys were insufficient to make generalisations (Q12 to Q15).

Despite these problems, some salient facts emerged from the questionnaire. As indicated in the replies received to the questionnaire, most of the routine resource surveys in Nigeria are executed by salaried staff who also draw various substantial monetary incentives for going to the field. This makes an accurate estimation of survey costs somewhat difficult as indicated by the respondents. Small, but important, projects are often attached to bigger ones. As a result, cost estimations become more difficult. Surveys executed by international agencies using a specified budget also involve funds extraneous to the budget. For instance, the salaries of the Nigerian established staff who are counterparts or party to these surveys are normally paid from different financial votes.

The duration of these surveys could not be readily assessed because of various complications. For instance, several projects may be handled simultaneously by the same staff. It is not unusual for a project to be preferentially suspended for another depending on convenience and prevailing conditions or urgency. Even when only one project is being handled at a time, various phases in its execution may be disjointed due to some delays, such as shortage of materials or reassignment of staff.

More reliable economic data on resource surveys in Nigeria were expected from the academic institutions. These too, are faced with similar problems. In the first place, they are more interested in the academic aspect than the economic aspect which is usually neglected. The expatriate firms to whom the more important projects are contracted did not reply the questionnaire. Only one international agency replied, but this agency like other respondents, remarked on its inability to provide definite economic data owing to various factors, including those stated earlier. According to this respondent, the field sampling of photovisible graminoid herbaceous vegetation in the savanna areas of Nigeria was limited to about sixty days in the year. Also, the survey costs included the cost of mobilisation of expatriate staff and equipment over considerable distances.

Some of the economic data obtained through the questionnaire are given below:-

Ground surveys

Year	Survey objective	Area (sq.km.)	Duration (man-years)	Cost (US dollars	
				Total	per sq.km.
1975	vegetation survey	352	3.29	7,560	21.48
1977	land resources	800	0.67	-	-
1977	forest survey	139	9.16	16,413	118.08

Remote sensing surveys (aerial photography)

Year	Survey objective	Area (sq.km.)	Duration (man-years)	Cost (US dollars)	
				Total	per sq.km.
+ 1969	land resources	230,000	47.00	-	-
* 1975	landuse	36	0.42	12,600	350.00
* 1976	forest mapping	390	0.58	2,860	7.36

+ 1:50 000 scale aerial photography

* 1:20 000 scale aerial photography

The above data show that the cost and duration of these surveys vary widely even for the same survey objectives. A basis for comparing both the cost and duration of surveys by ground and remote sensing methods could not be established. Consequently, definite conclusions could not be made as to which method is cheaper or quicker.

(e) Practical significance of the results for forestry services

It is significant from the replies to the questionnaire that little or no attention has been given to the technical and economic aspects of forest surveys in Nigeria. In the former case, only sparse information was given on sampling methods and designs. The sampling methods and designs currently used are those that were used when forest resources were more abundant without the need for a very critical assessment of the resource quality and quantity. In other words, volume estimation has not been an important consideration in Nigerian forest survey, particularly those conducted by the state forestry services. In essence, in a situation of plenty, survey accuracy has not been a significant issue. But the position is most likely to change in the immediate future, now that forest resources are becoming less abundant.

At present,only the Forestry Research Institute of Nigeria (FRIN) and the Federal Department of Forestry (FDF) include volume estimation in their forest surveys. FRIN, an older establishment, normally carries out research investigations while FDF, a more recent establishment, carries out forest development surveys, but the forests are actually owned and managed by the state forestry services. This situation may not constitute obstacles to management if there is efficient co-ordination through a central body drawn from all the Nigerian forestry services.

In the latter case, as in the former, information is scarce on the cost of surveys in terms of money and time for the reasons which were advanced earlier (see Section 11.3d) . Less attention is given to the economic aspects of forest surveys mainly because salaried staff carry out the surveys. The government provides the capital funds and if they are inadequate or exhausted, requests may be made for more. The result is that only the capital costs of survey are considered without costing the individual phases of the project execution which are also important. Such circumstances may endanger the execution of such surveys. If funds are released late, the survey may take too long to complete and sometimes the data obtained may be out-dated. On the other hand, if funds are not released the surveys may be suspended or even abandoned. But these dangers are easily avoided by costing the individual phases of the survey to obtain the capital cost instead of the other way round which is normally more difficult.

More attention should be given to both the technical and economic aspects of resource surveys in Nigeria and elsewhere in the tropics in order to provide a basis for the economic evaluation of the various methods being used in resource surveys. This would assist the selection of the method that will provide the required information at an economic cost.

11-3.1 Further evidence from the investigator's previous experience

Further attempts were made to obtain economic data by comparing the routine forest surveys previously conducted by the present investigator in Southwestern Nigeria with the present research studies. It should be appreciated, however, that the two cases differ markedly in their objectives and approach.

A typical example of the former is the pilot survey for the Nigerian high forest indicative inventory in parts of Ife and Shasha forest reserves reported by Sutter (1973). The objectives of the survey were to train field staff in the new forest mensuration techniques and the associated volume calculation procedures, as well as to give the field crews a first hand experience in camp shifting and logistics associated with field surveys. The latter objective directly dealt with the economic aspect of the survey and therefore provided more precise economic data on a typical ground survey than those obtained through the questionnaire.

The survey area of 31 600ha. comprises 'non-exploited' and previously 'exploited' forests, which at the time of survey were either 'undisturbed' or 'disturbed' by recent human interference. The non-exploited forest was divided into 6.44 x 6.44km. blocks to serve as the sampling frame, while the previously exploited forest was divided into 9.66 x 9.66km. blocks. In each block, a 200 x 200m. tract was randomly located to serve as a sampling unit. Plots were located at the corners and half-way between the corners of each tract. This resulted in a cluster of eight satellite plots with an interplot distance of 100m. for each tract. Sampling intensity is not relevant because point sampling by relascope (angle gauge) was used in the survey.

It was envisaged to determine the utilizable volume of timber trees over 60cm. DBH with a maximum standard error of 20% for non-exploited forests and 25% for previously exploited forests at 0.05 probability level. The standard error achieved at this probability level was 16% for non-exploited, 21% for previously exploited and 13% for both forest types 'pooled' as a unit. The entire survey cost ¢2892.96 and was completed in one month by the field crews - a duration of 5.83 man-years. The cost amounts to ¢9.15 per sq.km. The cost of enumeration of a tract was ¢62.16. Four camps were established during the survey, each costing an average of ¢194.88.

It was observed that the field crews were very enthusiastic because the survey was the first routine forest inventory by the forest service using the new techniques. Despite the time devoted to training the field crews and the long distance trekking to the field, the survey was completed within a short time. The lack of motorable forest roads resulted in the excessive cost of camp establishment. Porters were hired to convey tents and other camp equipment to and from the various camp sites.

Remote sensing methods were not used in the investigation described above. However, the duration of the various stages in the investigational aspect of the present studies is given in Table 11.2. The data in this table are averages for forest-type separation for each imagery type, being the only interpretation common to the three imagery types. The duration quoted includes the time spent for advancing technical explanations to the various observations made in each stage, one man-day being a six-hour working day. The table shows that the combined use of the three imagery-types for the 31 600ha. pilot survey area would last only 0.12 man-years, only 2% of the time used for the field survey. The cost of the investigational aspect of the present studies comprises the cost of the remote sensing images which were used

Table 11.2 Duration of the different phases in the use of aerial photographs, Landsat and SLAR imagery for forest-type recognition

Phases	Duration in man-days per		
	Stereomodel (Airphoto)	Landsat frame	SLAR mosaic
Image enhancement	-	(1.25)	-
FACV instrument calibration	-	0.50	-
composite image registration	-	0.25	-
viewing and photography	-	0.25	-
Interpretation	(7.00)	(42.50)	(40.00)
photostudy	3.00	30.00	28.00
forest-type delineation	1.00	6.50	5.25
checking and adjustment	1.50	3.50	3.50
transfer by tracing	1.50	2.50	3.25
Total =	7.00	43.75	40.00
Area coverage (sq.km.)	50.78	34 225	20 160
Duration per sq.km. (man-days)	0.1378	0.0013	0.0020
Duration for 31 600ha. (man-days)	43.56	0.40	0.63
Combined duration for 31 600ha.	44.59 man-days (0.12 man-year)		

and that of the interpretation. The costs of the photographic reproduction of the three imagery-types were computed from the amounts stated on the various receipts obtained from the commercial photographic laboratories who made the reproductions. These costs are:-

Image-type	Area coverage (sq.km.)	Average cost of reproduction ($)	
		Total	per sq.km.
Aerial photographs	84.64	16.31	0.193
Landsat imagery	34 225.00	76.50	0.002
SLAR mosaics	20 160.00	97.00	0.005
		Total =	0.200

The data above are averages of the costs of the various photographic reproductions made for the present studies. Reproduction costs for aerial photographs and SLAR imagery include the costs of generating negative transparencies from the prints being reproduced. The cost of Landsat image reproduction includes the cost of the standard Landsat products (spectral transparencies) and the cost of generating colour composite images.

The photographic reproduction costs clearly indicate that the cost of acquisition of remote sensing imagery could be greatly reduced by covering a very large area at a time. The cost of image reproduction per sq.km. is significantly low for Landsat and SLAR imagery, SLAR costing twice as much. The reproduction cost of $0.19 per sq.km. for aerial photographs is forty times that for SLAR imagery which should normally cost more. This is largely due to the very small area coverage of the aerial photographs. For large area coverages, both costs may be competitive. The cost for Landsat image reproduction is definitely less than that for either aerial photographs or SLAR imagery and often relatively insignificant.

On the basis of the data above, the total cost of reproduction of these image-types for the 31 600ha. pilot survey area would be ₦63.20, those of aerial photographs, Landsat and radar imagery being ₦60.99, ₦0.63 and ₦1.58 respectively.

Definite standards could not be established for the evaluation of the interpretation costs in the present studies. It was difficult to decide whether to base the evaluation on the present investigator's:

- student grant of ₦13.42 per day if he is on a Nigerian postgraduate scholarship to study overseas or
- present salary of ₦23.93 per day excluding the allowances attached to his rank as a forest officer conducting this investigation as part of his official duties or
- 'estacode' rate of ₦25.42 per day normally paid to Nigerian senior civil servants who are on Staff Development in-service training course or
- combined present salary and estacode rate of ₦49.35 per day. This is an exceptional condition or
- average earning of ₦20.92 per day which is the average of student grant, salary and estacode combined. This would be the most ideal condition.

Nevertheless, the five different rates were used separately for the estimation of the interpretation costs. The costs of using aerial photographs, Landsat and SLAR images separately and in combination to interpret 31 600ha, i.e. the size of the pilot survey area, are given in Table 11.3. This table shows that the cost of the combined use of the three remote sensing methods for the pilot survey would vary between ₦661.60 and ₦1196.68 i.e. between ₦2.13 and ₦3.79 per sq.km.

The costs quoted for remote sensing surveys do not include the cost of field checking which was not accomplished for the interpretation. Furthermore, the cost of remote sensing surveys at five different rates given in Table 11.3 show the range of variation that can be expected if tenders were invited for contracting the survey to remote sensing firms. The costs based on the average of student grant, salary and estacode is the most ideal case while that which is based on both salary and estacode (which applies for the present studies) is an exceptional case.

This further evidence from my previous experience shows that remote sensing surveys can be accomplished at a superior speed, saving about 80% of the time that would have been used for a similar survey by ground methods alone. Also, they can be accomplished at an economic cost, saving between 59% and 77%. This agrees with the findings of the literature review. It should be realised that two surveys differ markedly in objectives and approach. While the pilot survey is a routine field investigation, the present studies constitute basic research and are conducted in isolation without field checking which should have normally increased the cost and the duration.

It may be argued that the remote sensing costs do not include image acquisition costs. It should be realised also that the field survey costs did not include overheads such as camp and survey equipment. The comparative costing of remote sensing surveys and field surveys requires a little thought in one aspect and a little faith in the other. For instance, the remote sensing images were not primarily acquired for the present investigation neither were the camp equipment and survey instruments purchased for the pilot survey

Table 11.3 Comparison of the costs of surveying a 31 600ha. forest block in Southwestern Nigeria by remote sensing and ground methods

	Wages	Breakdown of costs	Cost in $			
			Aerial photography	Landsat imagery	SLAR imagery	Combined use
		duration (man-days)^x	(43.56)	(0.40)	(0.63)	(44.59)
(a)	Scholarship	imagery	60.99	0.63	1.58	63.20
	($13.42 per day)	interpretation	584.58	5.37	8.45	598.40
		total$^+$	645.57	6.00	10.03	661.60
		per sq.km.*	2.08	0.02	0.03	2.09
(b)	Estacode	imagery	60.99	0.63	1.58	63.20
	($25.42 per day)	interpretation	1107.30	10.17	16.01	1133.48
		total$^+$	1168.29	10.80	17.59	1196.68
		per sq.km.*	3.70	0.03	0.06	3.79
(c)	Salary	imagery	60.99	0.63	1.58	63.20
	($23.93 per day)	interpretation	1042.39	9.57	15.08	1067.04
		total$^+$	1103.38	10.20	16.66	1130.24
		per sq.km.*	3.49	0.03	0.05	3.58
(d)	Average	imagery	60.99	0.63	1.58	63.20
	($20.92 per day)	interpretation	911.28	8.37	13.18	932.82
	(ideal case)	total$^+$	972.27	9.00	14.76	996.02
		per sq.km.*	3.08	0.03	0.05	3.15
(e)	Estacode/Salary	imagery	60.99	0.63	1.58	63.20
	($49.35 per day)	interpretation	2149.69	19.74	31.09	2200.52
	exceptional case	total$^+$	2210.68	20.37	32.67	2263.72
		per sq.km.*	7.00	0.06	0.10	7.16

x compare with 2127.95 man-days for field surveys
\+ compare with $2892.96 for ground survey
* compare with $9.15 per sq.km. for ground survey

Remote sensing costs are based on the present investigation
Field survey costs are based on the report by Sulter (1973)

under reference. Even if they were, the fundamental objective of economy is to avoid waste as much as possible and this includes improvisation which is the case for the present comparison of costs.

11-4 Findings of the survey

As private forestry is not practised in Nigeria, the generalisations which are made from the findings of the questionnaire relate mainly to government forestry services. For a survey by postal questionnaire, a fifty-two percent return as obtained for this investigation is adequate. The major drawback in the present survey is the few responses from the key forestry and remote sensing establishments who could have provided useful information on the state of the art. It is suggested that future surveys of this nature should be handled at governmental level and preferably by interviewing the respondents. Also, it would be necessary to send the questionnaire in advance so that the respondents can collate the required information from the records in their various branches or sections. More replies and reliable information are likely to be received to a questionnaire conducted at governmental level than to one conducted privately.

The analysis of the questionnaire shows that ground methods are mainly used for surveys in Nigeria. Remote sensing is seldom used. Most of the surveys which included remote sensing are executed by international agencies and expatriate firms. Only the non-forestry establishments whose routine surveys depend mainly on photointerpretation employ remote sensing as a survey tool. The academic disciplines are strong advocates of the use of remote sensing as this would facilitate their research investigations particularly on natural resources.

Most of them have not set up any remote sensing unit, even on a small scale in their academic departments. Forestry services make little use of remote sensing. Most of the state forestry services do not possess photogrammetric equipment of any description and none of them intends to set up a small scale photointerpretation unit as this is beyond their budgetary limits.

Most of the respondents indicated that the use of remote sensing as a survey tool is cheaper than pure ground methods. As each establishment is not financially capable by itself to set up a remote sensing unit, there was a concensus in favour of a central remote sensing unit of one type or the other. A few forestry services indicated that ground methods are cheaper, hence they indicated that remote sensing was unnecessary. The analysis of the questionnaire further shows that the limited use of remote sensing for resource surveys is largely due to economic constraints rather than the availability of a cheaper alternative. These constraints are the lack of appropriate equipment, the inadequacy of funds, the insufficiency of trained personnel and inadequate sensor-coverage in that order of importance as indicated by the analysis of the questionnaire.

As all the respondents are government financed establishments, it is my opinion that the limited use of remote sensing in Nigeria is due to the restriction on budgetary limits for each establishment by the government. The breakdown of the national budget may not favour an independent use of remote sensing for resource surveys by each establishment. Moreover, the policy of the government tends to favour the maximum use of human labour to supplement or even replace machine labour in an effort to solve unemployment problems. This may account for the preference of ground methods to remote sensing methods by some respondents. Probably these respondents did not consider the high cost of labour to the government.

The fact that the resource survey establishments in Nigeria are financed by the government introduces policy and administrative constraints to the use of remote sensing methods as a survey tool. Though advanced proposals are normally made at departmental and ministerial levels for consideration in the national budget some of these proposals may be rejected eventually either for policy reasons or for not being of immediate priority at national level. Remote sensing projects which are included in such proposals have to be abandoned. Even if the proposals are accepted, the funds allocated to such survey projects are either insufficient or unavailable at the required time.

These administrative constraints usually disrupt the execution of important survey projects. Some surveys are either postponed for several reasons or abandoned. Even if the funds are sufficient and are released at the required time administrative delays would still disrupt the continuity of work and hamper its effective coordination. The only way of minimising the effects of these administrative delays is to combine several small projects into a large one which will qualify for an independent fund allocation under the capital expenditure in the national budget. This was the case with the Nigerdams Multipurpose Development Project, the High Forest Development Project and the Nirad Projects in Nigeria. They were completed on schedule.

In the first place, only a technical evaluation of different survey methods can provide a basis for an objective comparison of the economics of the use of these methods. Secondly, only reliable and adequate information on the technical and economic aspects of the surveys can permit an accurate assessment of the relative efficiency of the survey methods being used. These aspects of resource surveys have not been given serious consideration by the establishments who execute these surveys. This is indicated by the few responses to this aspect of the questionnaire. None of the respondents could supply adequate information on the statistical evaluation and the cost of their surveys. The academic departments which were able to provide some information on the statistical evaluation of their surveys, were more interested in achieving their research objectives without considering costing as part of the investigations.

From the foregoing it can be concluded that in Nigeria and similar tropical countries, it is difficult to make a comparison of the economy of the different survey methods employed by government financed establishments and the forestry services in particular. For this reason, it is suggested that both the technical and economic aspects of the resource survey methods employed should form part of the survey objectives. This would provide the link between the technical capabilities and the economics of the use of these survey methods. Economic evaluation on this basis, though valid, might still not permit a general appraisal of the whole situation. A well-known fact is that some government financial regulations aimed at financial prudence generally have loop-holes that encourage economic waste. For instance, in a very large project, the financial instruction may permit hiring additional vehicles at a cost higher than would be required to buy additional vehicles. This is usually true for projects that spread over a considerable period and the discrepancy may not be discovered before the conclusion of the projects. Financial control on discovering such discrepancies is seldom effective. Caution should therefore be exercised in the costing of each phase of project execution within government establishments and the forest services in particular.

The information obtained from the respondents was inadequate for an objective comparison of the cost of the different remote sensing methods to the Nigerian users. Further evidence from the investigator's previous experience shows that the remote sensing methods are cheaper and quicker for the survey of tropical forests. Landsat imagery is cheaper to acquire than aerial photography and SLAR imagery. The costs of the latter two may be similar depending on several factors including the size of the survey area and the acquisition scale of the imagery. Photointerpretation takes a longer time than Landsat and SLAR interpretation due to the higher forest information content of aerial photographs. Despite its lower forest information content, SLAR imagery is more difficult to interpret than Landsat imagery and aerial photographs. This is mainly due to the side-look imaging geometry of SLAR. The present studies of Southwestern Nigeria, show that a significant amount of forest information can be obtained directly from remote sensing imagery, even without conducting a field work. This is an obvious advantage of remote sensing. The superior speed of remote sensing methods indicates that remote sensing methods can save time and effort and therefore money. The use of remote sensing methods in conjunction with field checking would probably be more economical than the use of entirely pure ground methods since the constraints to ground methods are more expensive to overcome than those of remote sensing methods.

However, only the relative efficiency based on the speed and ease of operation, the monetary costs and the technical capabilities of the different survey methods is likely to provide the most reliable evaluation. This is considered in Chapter 12 which interrelates these factors with regard to tropical forest surveys.

PART III

FINDINGS OF THE INVESTIGATIONS

"If we are to have an adequate appraisal of our resources on which to base plans for more ordered use, (and) if we are to be able to foresee incipient problems soon enough to make remedial action worthwhile, ... we must improve our ability to collect information. Remote sensing offers ways to help us."

"... If remote sensing lives up to its potential, there will be few people in this world whose lives will not be affected by it."

R. D. Rudd (1974).

Introduction to Part III

This part summarises, in one chapter, the findings of the literature review and experimental investigation by interrelating the technical capabilities of aerial photography, Landsat and SLAR imagery and the economics of their use in tropical forest surveys.

Chapter 12 This chapter comprises:

- a recount of the approach and procedures of the investigations.
- discussion of the interrelationships of the findings on the technical capabilities of the three systems and the economics of their use in tropical forest surveys.
- recommendations on the possible options of using remote sensing in tropical forest surveys and on the aspects of this application that require further investigations.

CHAPTER 12

THE VALUE AND LIMITATIONS OF REMOTE SENSING FOR THE INTERPRETATION OF TROPICAL FORESTS

12 Overview of the investigations

Part I of this work reported the investigation by a review of literature on the forestry applications of remote sensing in the tropics. Part II reported the experimental investigation on the use of remote sensing for the interpretation of a typical example of tropical forests (Southwestern Nigeria). Part III is designed to integrate the findings of both investigations (Chapter 12).

Chapters 1 and 7 provided the background for the review of literature and the experimental investigation respectively. Chapters 2-5 of the literature review give a comparative account of the use of aerial photography, Landsat and SLAR systems for forest type recognition, tree-species identification and volume estimation in the three main tropical forest regions. These categories of information were considered separately. The success obtained and the problems encountered in applying each system were also evaluated. Chapters 8-10 of the experimental investigation verified the amount of forest information that can be obtained with each remote sensing system. The extent to which the forest information can be discriminated and the extent to which it can be recognised were also verified. In Chapter 6 of the literature review as well as Chapter 11 of the experimental investigation, the economics of the use of the three systems for tropical forest interpretation were compared.

As the experimental investigation was designed to verify and augment the findings of the review of literature there is a general correspondence in the subjects being investigated. In either case, inferences and conclusions were drawn and generalisations made on each subject of investigation but these need to be integrated for an overall appraisal.

This Chapter interrelates the findings on the various aspects of remote sensing which were investigated. As a substantial number of inter-relationships can be established on each aspect the important inter-relationships are discussed in conjunction with the relevant background information. For the discussion, the various aspects of remote sensing have been grouped into the following three broad categories:

(1) Remote sensing technology and instrumentation
(2) Interpretation of remote sensing images
(3) Problems of remote sensing

12-1 Discussion of the findings of the investigations

The three broad categories of inter-relationships are considered separately as follows:-

12-1.1 Remote sensing technology and instrumentation

The inter-relationships established within this category are discussed under the following headings:

(a) acquisition of remote sensing imagery
(b) resolution of remote sensing systems
(c) rendition of information on remote sensing images
(d) variety of images within each system
(e) range of image enhancement techniques

(a) Acquisition of remote sensing imagery

The most limiting factor in assessing the technical capabilities of the three remote sensing systems for tropical forest surveys is the possibility of acquiring the necessary imagery of the areas of interest. In the first place, tropical weather and ground conditions may prevent flight missions for imagery acquisition. Only Landsat is free of flight problems, being an unmanned geostationary and sun-synchronous satellite that operates in a space orbit. It is not user-controlled. Both aerial photographic and SLAR flight missions can be planned to coincide with favourable flight conditions.

Imaging in the photographic bands i.e. visible and near infrared are known to be hindered by weather conditions. Cloud cover hampers imaging in these bands. Atmospheric haze and dispersion hinder imaging in the visible spectral band. This is overcome in aerial photography by using infrared films instead of the conventional panchromatic ones. In Landsat the problem is overcome by the infrared components of the spectral imaging channels. However, the problem of cloud cover still persists. This can be overcome to some extent by planning aerial photographic missions to coincide with the occurrence of good photographic season and weather. As Landsat is neither manned nor user-controlled the problem of obtaining cloud free images of the areas of interest still persists. Only SLAR imaging is virtually free of weather problems as radar penetrates haze and cloud. It can be operated round the clock under any weather condition except under the heaviest rainstorms. Its operation is limited only by human factors-endurance of the aircrew and the restrictions on flight by civil aviation authorities.

The greater success obtained with aerial photographs in the Southeast Asian region can be attributed to the occurrence of 'good photographic' weather while the almost compulsory use of SLAR images in the Amazonian region may be attributed to 'bad photographic' weather. Information from literature could not provide sufficient evidence to attribute the little use of aerial photographs in the African region to unfavourable weather conditions, but the inability to obtain good quality Landsat images of the test area indicates that weather conditions also hamper the use of remote sensing in the African region. To support the foregoing, aerial photographs of the cloud prone coastal areas and cloud free Landsat images of good quality were not available for the studies. The quality of the available aerial photographs and Landsat images was hampered by haze and dispersion to varied extents. The SLAR mosaics used were compiled from SLAR imagery acquired within six months over the entire 924 000sq.km. land area of Nigeria without hinderances of weather. The images were free of dispersion, haze and cloud cover.

The foregoing shows that SLAR is of greater value for imaging areas where weather and ground conditions prevent photographic flights or hamper the quality of aerial photographs and Landsat images. Furthermore, SLAR images can be acquired at a superior speed while aerial photographic flights have to await favourable season and weather in order to obtain good quality images. Though the nominal cost of the acquisition of SLAR imagery is higher than that of aerial photography, the higher positioning fee in aerial photography resulting from unfavourable flight conditions tends to balance the higher cost of SLAR, provided large areas are covered at a time. The cost of obtaining Landsat images for an equivalent area is relatively insignificant.

(b) Resolution of remote sensing systems

Despite its cheaper cost, Landsat cannot compete with either aerial photography or SLAR images in providing the information required on tropical forests. Similarly SLAR cannot compete with aerial photography despite its similar cost. By applying the wavelength filter concept that objects which are smaller than half the recording wavelengths cannot be detected, the size of the smallest object that can be detected by aerial photography, Landsat and SLAR increases in that order. Also, by applying the pixel filter concept that objects smaller than the pixel of the recording system cannot be resolved, the size of the smallest objects that can be resolved by aerial photography, Landsat and SLAR increases in that order.

In practice, objects smaller than the pixel have been resolved by Landsat and SLAR. The only reason often advanced is that such objects are strong targets for the recording wavelengths because of their high reflectance properties or reflectivity. It is my opinion that the width of such an object is equal to or greater than half the recording wavelength and its length is equal to or greater than the width of the pixel. Consequently, they are not filtered either by the recording wavelength or the pixel of the system. In view of this, the following formula is proposed for determining the ground resolution (GS) of a remote sensing system from its recording wavelength (WL) and its pixel width (PS).

$$GS = 0.5\ (WL \times PS)$$

This is true for the images used for the present investigation but this proposal needs to be investigated further for different systems and images management. Landsat and SLAR can only resolve the general forest canopy but cannot resolve the individual crowns forming the canopy. Despite their small scale and relatively poor quality, the aerial photographs used for this investigation provided adequate information on the forest types as well as the individual trees. The SLAR mosaics, despite their good quality did not provide any information on the individual trees. It is apparent from the foregoing that only aerial photography can resolve the individual trees which are the ultimate units of forest management.

(c) Rendition of information on remote sensing images

The extent to which the resolved information can be discriminated on the three types of images is determined by its rendition on the images. On aerial photographs and Landsat images, both tone and texture are photographic representations of surface brightness by which terrain features can be discriminated. Aerial photography is capable of being stereoscopically examined. Consequently the individual trees which are resolved can be recognised by their stereoscopic appearance and shape.

The small scale and the low resolution of Landsat restrict its limited stereoscopy to gross canopy features in forested areas and gross surface features in open areas. On SLAR images, tone is an expression of terrain slope while texture relates to surface roughness by which terrain features can be discriminated. Tonal discrimination is of limited value for SLAR interpretation. The scale and resolution of SLAR do not permit individual trees to be discriminated by their stereoscopic appearance and shape. The side-look geometry makes correlation between SLAR evidence and ground information difficult. The non-conventional stereoscopy resulting from this geometry relates to range (distances) and direction (position) of targets (terrain objects) rather than the shapes of these objects. In the present investigation, aerial photographs were easier to interpret despite the great amount of forest detail that is available on them. SLAR imagery was difficult to interpret as a result of the unfamiliar rendition of information and the lack of objective interpretation criteria.

In view of these considerations,aerial photography is superior to either Landsat or SLAR for discriminating forest information particularly that which is required on individual trees. Depending on the survey objectives, Landsat and SLAR can be used at a superior speed for certain surveys. e.g. exploration and reconnaissance surveys by Landsat and terrain mapping by SLAR.

(d) Variety of images within each system

The extent to which forest information can be extracted on remote sensing images also depends on the variety of images that can be acquired with each system. Aerial photography is primarily a single channel i.e. broad band system by which different film/filter combinations can be used to acquire various types of aerial photographs. Typical examples are panchromatic and normal colour aerial photography, infrared, modified infrared and colour infrared photography. Panchromatic photography is cheaper than infrared while normal colour is cheaper than colour infrared. Black/white photography is cheaper than colour. It is uneconomical to acquire different types of aerial photography for the same survey as their combined interpretation does not often have any significant advantage over the interpretation of a single type. Only panchromatic aerial photographs were interpreted in the present studies and the results were satisfactory. Recent developments in aerial photography have permitted the use of multiband aerial photography. A typical example is the 70mm. multiband photography which has been of great value for forest interpretation, particularly in the temperate regions. Its use is still rare in the tropics.

Landsat system is basically multispectral and repetitive. Consequently, multispectral and multidate images are available. But its repetitivity has no real value for tropical forest surveys as seasonal variation in weather conditions prevents repetitive imaging with the photographic bands. The use of multispectral images in the present studies improved the confidence of SLAR interpretation. Cloud cover prevented the correlation of the same features on multidate spectral images of the test area. The currently available SLAR systems are single channel sensors which image in a particular band. The most widely used SLAR bands are the Ka and X bands. The X-band SLAR mosacis were interpreted for the present studies. The interpretation of three types of images in the present studies shows that each system would add an extra value to forest surveys accomplished by ground methods alone. The combined use of the three systems is uneconomical though it increases the confidence of forest surveys.

(e) <u>Range of image enhancement techniques</u>

It is known that the spectral signature of an object is not the same on different spectral images i.e. on different channels. Also, an object may show seasonal variations in its spectral signature. Furthermore, different objects may have the similar signature on the same spectral image i.e. different spectral bands. Such objects can be easily separated by their'composite' spectral signatures on a set of spectral images. The set of spectral images may comprise:-

(i) images obtained with different bands at the same time (single date multispectral).

(ii) images obtained with the same band at different seasons (multidate single channel spectral images).

(iii) images obtained with different bands at different seasons (multidate-multispectral images).

Landsat images can be used to determine these 'composite' spectral signatures without any additional acquisition cost because it is primarily multispectral and repetitive. Multiband photography is seldom used for tropical forest surveys. Consequently,the use of multiband images would involve extra costs. SLAR is a single channel imaging system which does not provide multispectral information. The cost of acquiring repetitive or multidate aerial photography and SLAR imagery would be excessively high for any type of resource survey. Landsat is therefore of greater value for discriminating information by using multispectral and multidate images. Aerial photography can be used for this purpose to some extent but at an exorbitant cost. SLAR is not technically capable of such discrimination.

The extraction of information can be enhanced further by the use of colour. Colour aerial photographs can be acquired directly as a result of the wide range of film/filter combinations which are possible with aerial photography. Normal colour and colour infrared are often used for tropical forest surveys but they are usually more expensive than the corresponding black/white photography. Generally, panchromatic aerial photography is the cheapest while colour infrared is the most expensive. The multispectral nature of Landsat permits the use of colour. Colour composite images can be generated from the black/white spectral images by additive colour processing, provided the appropriate additive colour viewer is available. The generation of colour composite images is cheap. A comprehensive procedure of generating suitable colour composites from additive colour processing of Landsat spectral images was developed for the present studies. The procedure permits selection of the best additive colour composites by systematic elimination of others, first by visual examination of their views on an additive colour viewer and further, by examination of the photographic reproduction of the selected views.

For the present studies only panchromatic aerial photographs were interpreted and the results were satisfactory. Consequently, it may not be economical to acquire different types of aerial photography without any significant increase in the amount of information that can be obtained with only one type. Landsat multispectral images and X-band SLAR images were used for the Landsat and SLAR interpretation respectively.

Despite all the advantages of Landsat, its very small scale and low resolution restrict its use to reconnaissance and exploratory surveys. For forest management surveys, SLAR cannot successfully compete with aerial photography in providing the relevant information despite its similar cost. The forest information content of SLAR does not often justify the cost in a situation where aerial photography is feasible. As aerial photography and SLAR imagery in particular are expensive, substantial amounts can be saved by acquiring the images over large areas at a time, and preferably for multipurpose and interdisciplinary use in which costs would be shared by the various users. There would not be any economic justification for the Nirad Project if it was commissioned for vegetation surveys only. The Nigerian SLAR has been found to be more useful for purposes other than forestry to which the project was attached.

The foregoing discussions of the inter-relationships established on the technology of the remote sensing systems also correspond with those established for the interpretation of the remote sensing images which are discussed in the following section.

12-1.2 Interpretation of remote sensing images

The inter-relationships established within this category are discussed under two main headings which embrace all four categories of forest information on which the centre investigation was based. These headings are:-

(a) information on resource location and distribution i.e. forest type recognition and area estimation.

(b) information on resource composition and quantity (and also quality) i.e. species identification and volume estimation.

These are discussed separately as follows:-

(a) Information on resource location and distribution

By photointerpretation alone, 16 forest types were separated in an area of about 27sq.km. covered by the five test sites. In the entire 58 000sq.km. test area only seven types were separated by Landsat interpretation and eleven types by SLAR interpretation. A comparison of the interpretation of the three types of images shows that the exclusive forest types which were separated on aerial photographs could be grouped into more inclusive general types on either Landsat or SLAR images. This shows that aerial photography provides more information on tropical forest types than either Landsat or SLAR.

The forest types were recognised on aerial photographs mainly by their photophysiognomy as well as their photographic tone and texture. On Landsat images, the forest types were distinguished primarily by the tonal and textural differences which were accentuated by colour enhancement. On SLAR images the forest types were separated mainly by physiographic features and textural differences. Tone was of limited value for SLAR interpretation. With the wide range of variation within tropical forests, definite sets of interpretation criteria cannot be established not even for small areas. Also, an ordered application of the various interpretation criteria to tropical forests is seldom feasible. Interpretation keys covering the range of forest variation in a given survey area are usually difficult to construct and apply. For the present studies a systematic procedure by which the botanical attributes of the canopy can be used to characterise different forest types was developed.

Further comparison of the results of the three interpretations shows that the photointerpretation correlated more with Landsat interpretation than with SLAR. This was due to the differences in the interpretation criteria that can be applied in each case. The strong correlation between Landsat information and photoevidence shows that Landsat and photointerpretation can be used complementarily for forest type separation. Nevertheless, SLAR can provide additional information to that which is available on either aerial photographs or Landsat images. Despite the greater amount of forest information that can be obtained on aerial photographs, small scale imagery, such as SLAR and Landsat, usually adds extra value to photo-information.

Forest type separation by remote sensing methods is more objective than that by ground methods,as remote sensing images provide a bird's eye view of a large area at a time. Nevertheless, the information which they provide requires field checking for relevant correlations. In the present investigation, the duration of both Landsat and SLAR interpretation was shorter than the duration of photointerpretation. Also, the cost of reproducing both SLAR and Landsat images per sq.km. was less than that of aerial photographs because of the smaller area covered by each photograph. This indicates that it is more economical to image a large area at a time. Also, the comparison of the costs and duration of the combined interpretation of the three types of images in the present studies with a similar field survey shows that remote sensing techniques are easier, quicker and cheaper than pure ground techniques.

It has been established in the course of the present studies that the interpretation of tropical forests admits a wide range of image scales and image enhancement options, but it is hindered by their complex structure and floristic composition. Forest-types, each comprising varied mixtures of species, intermingle without distinct boundaries and transition zones are of frequent occurrence. Only pure stands of single species or mixed stands of a few species,which are rare and scarce in most tropical forest areas,can be delineated with confidence.

The lack of distinct boundaries between the forest types usually resultsin subjective delineations with a consequent variability in the area estimates obtained for each forest type by different operators. This variability usually affects the reliability of the total estimates of any forest information that is being related to area. For the fact that virtually all quantitative forest information is area-related, reliable area estimation is important in forest surveys. Landsat images are inherently orthographic. Consequently,they can be used directly as map substitutes for area estimation.

Both aerial photographs and SLAR images contain geometric errors which limit their use as map substitutes for area estimation. Rectified aerial photographs and mosaics compiled from them can be used to some extent for estimating forest areas. Area estimates obtained directly from SLAR images are less accurate than those obtained from either Landsat or aerial photographs. The general practice is to compile maps from the interpreted images. With aerial photography, both the interpretation and mapping can be accomplished by photogrammetric methods. Radargrammetric methods are usually expensive. Consequently, they are rarely used in routine forest surveys. Tropical forest mapping from Landsat images may not require similar procedures because of their geometric fidelity. For this reason Landsat mapping is cheaper than either photogrammetric and radargrammetric mapping.

With regard to forest type recognition, the foregoing indicates that aerial photography can provide more information on the structure and composition as well as the extent (area) of tropical forests.

(b) Information on resource composition and quantity

The most important aspect of forest surveys is the estimation of the amount of the resource. The estimates are obtained from the measurements made on the individual trees. Of the three remote sensing systems considered, only aerial photography can resolve individual trees. Consequently, it is only on aerial photographs that information on the individual trees (tree information) can be obtained. In as much as the individual trees cannot be resolved by Landsat and SLAR, tree species cannot be identified on either Landsat or SLAR images as often reported. What is normally achieved is the recognition of the natural populations of gregarious species or the plantations (artificial concentrations) of species with gregarious growing habits. This view was held in the present studies. It has permitted grouping tree-species identification by Landsat and SLAR interpretation with forest type recognition and so restricts discussion on tree-species identification to photointerpretation alone. The results of the photointerpretation shows that tree species identification is hindered by the striking similarities between individual trees belonging to different species as a result of their polymorphic crowns,and the differences between crowns of the individual trees of the same species as a result of their variable phenology both in space and time. Both conditions are complicated further by the strongly heterogeneous mixture of species in tropical forests. Evidence from literature indicatesthat species identification is not significantly improved by using varied film/filter combinations for aerial photography, not even infrared or colour photography. It is my opinion that species identification is more satisfactorily accomplished in the field. Nevertheless, photointerpretation has assisted the recognition of field sample trees for photomensuration. The recognition of sample trees on aerial photographs improves with increase in photo-scale.

By ground methods, tree height and stem diameter are the most important volume parameters. Stem diameter is not measurable on aerial photographs. Instead,crown diameter is measured in addition to tree height for photovolume. The same problems which hinder tree species identification also hinder photomensuration of the individual trees. In photomensuration, parallax heighting of the individual trees is prevented by the closed and continuous forest canopy. Also, the irregular shapes of the crowns do not usually permit precise and accurate crown-measurements. As stem diameter is not measurable on aerial photographs photo crown diameter is usually correlated with stem diameter measured at breast height (DBH) in the field for volume estimation. Crown/stem diameter correlation, though imperfect for all known tree species is also weak for most tropical species, Consequently, correlation is often sought between photomensuration data and volume estimated from field mensuration data. Photovolume estimates of tropical forests are seldom accurate but they are useful indicators of the relative amount of wood in different parts of a forest. For this reason, photomensuration data or photovolume are more useful for the 'statistical' stratification of tropical forests ahead of field inventory by which more accurate volume estimates can be obtained.

Photomensuration is easier, quicker and cheaper to accomplish than field mensuration,but its lower accuracy reduces its value for volume estimation. Nevertheless, photostratification of forests ahead of ground inventory usually improves the sampling efficiency and the confidence of forest surveys.

The interrelationships which are based on the interpretation of the three types of images show that remote sensing techniques are easier, quicker and cheaper than ground techniques for forest surveys. They also show that remote sensing techniques, though less accurate are more objective than ground techniques. These technical and economic advantages of remote sensing can be used to increase the sampling efficiency of forest survey,but little use is made of them in the tropics. The ensuing discussion deals with the various constraints which limit the use of remote sensing for tropical forest surveys despite these advantages.

12-1.3 Problems of remote sensing in the tropics

The interrelationships of the various factors which constrain the routine use of remote sensing in tropical forest surveys are discussed under this category as follows:-

The most important factor constraining the use of remote sensing in tropical forest surveys is the lack of sufficient funds which also tends to override other factors. Without funds, the necessary equipment cannot be purchased neither can personeel training be accomplished. Adequate equipment and sufficiently trained personnel which are the primary requirements for an economic use of remote sensing techniques are seldom available in most tropical countries. The remote sensing projects of these countries are often executed by contract and this usually prevents the routine use of remote sensing for resource surveys.

Most tropical countries are far from centres of advanced remote sensing technology and centres of commercial hire of remote sensing equipment. These make the cost of remote sensing surveys in these countries excessive, with the result that only the important surveys employ remote sensing techniques. Most countries which cannot afford this high cost have to be content with ground survey methods. Moreover, human labour may even be cheaper to the government under such circumstances. More often than not, the remote sensing projects in these countries are funded and/or executed by international agencies within the frame-work of one form of technical assistance or the other.

The remote sensing survey firms and international agencies who execute these projects are usually expatriates in the project country. The advantage of the valuable experience and knowledge gained on the applications of remote sensing to the local conditions are not retained in these countries when the expatriates who manned the projects leave at the conclusion of their assignments. Such experience and knowledge which are lost, would have provided a background for subsequent resource surveys which include remote sensing techniques. Also, they could have been of great value in saving the cost of familiarisation programmes if the same firms or agencies are to execute subsequent surveys.

12-2 Conclusions on the value and limitations of remote sensing for tropical forest surveys

The following conclusions can be made from the interrelationships of the findings of the investigations.

Remote sensing techniques are easier, quicker and cheaper than ground techniques for forest surveys in the tropics. Despite these advantages, remote sensing techniques cannot successfully compete with ground techniques in providing the information required on tropical forests. As ground techniques are more accurate, adequate ground information is required for checking remote sensing information.

Aerial photography, Landsat and SLAR imagery provide information on the types and extents of tropical forests to varying degrees. Despite the similar cost of SLAR and the lower cost of Landsat, neither can compete successfully with aerial photography in providing the information required on tropical forest types. Nevertheless, each adds some extra value to photo-information and so increases the confidence of the forest surveys, particularly with a combined use of the remote sensing systems.

Photographic tone and texture are the main criteria for Landsat interpretation. Tonal and textural differences on Landsat images can be accentuated by additive colour processing of the spectral images to generate colour composite images. A comprehensive procedure for the additive colour processing of Landsat images was developed for the present studies.

Beside tone and texture, photophysiognomy is the main photointerpretation criterion. Forest types can be separated on aerial photographs by the stereoscopic examination of their canopy structure. A comprehensive procedure of an ordered use of the botanical attributes of forest canopies was also developed for separating forest types on aerial photographs. Only aerial photographs provide information on the individual trees. Consequently, forest types can be separated on aerial photographs by their floristic composition, particularly when they are dominated by a few species.

Physiographic features are the main criteria for SLAR interpretation of tropical forest types though physiognomic height differences are also useful to a limited extent. Tone has little value for forest interpretation on SLAR images.

The higher resolution and the wider range of acceptable working scales of aerial photography permit a more detailed interpretation and mapping of tropical forests. Both the interpretation and mapping can be accomplished by photogrammetric methods. The low resolution and the small scale of Landsat and SLAR imagery restrict their use to generalised interpretation and mapping of tropical forest. Landsat images are inherently orthographic and therefore usable as map substitutes. SLAR images have large geometric errors which prevent their use as map substitutes and radargrammetric methods are seldom used in forest mapping. A formula has been proposed in the present studies for determining the ground resolution that can be achieved on each type of remote sensing image. Because of its high resolution and the large scales at which it can be acquired, aerial photography is useful for the species identification and photomensuration of the individual trees. The photomensuration data can be used directly to estimate forest volume but in the tropics, they are more useful for the statistical stratification of the forests ahead of ground inventory or field sampling. This notwithstanding, forest yield which is the main objective of forest management cannot be estimated on aerial photographs or on any other remote sensing images.

Despite the obvious advantages of remote sensing for tropical forest surveys, its use is limited by several factors. Cloud cover hinders the acquisition of aerial photographs and Landsat images of tropical forests, while haze and dispersion hamper the quality and therefore the interpretation of these images. The complex structure and floristic composition of tropical forests also hinder their interpretation. Aerial photographs can be planned to coincide with favourable season and weather. The quality of SLAR images are virtually unaffected by weather conditions as SLAR can be operated round the clock under most weather conditions excluding the heaviest rainstorms.

Irrespective of the limitations by weather, the overriding factor which constrains the routine use of remote sensing in tropical forest surveys is the general lack of funds. As forestry practice in the tropics is a government enterprise, this lack of funds may be 'artificial' rather than real as a result of the policy of the country's administration. In situations where government policy favours the use of remote sensing for resource surveys, administrative delays may hamper the timely release of funds for such surveys and so hinder their proper execution.

Other important factors which constrain the routine use of remote sensing in tropical forest surveys include the lack of adequate equipment, the insufficient build-up of indigenous personnel, and the considerable distance of tropical countries from countries of advanced remote sensing technology and centres of commercial hire of remote sensing equipment.

12-3 Recommendations for use and suggestions for further investigations

Of the three systems only aerial photography can provide all four categories of information required in forest management though to limited extents. Its inclusion on forest surveys relying on remote sensing techniques is recommended. The use of SLAR imagery is recommended only for areas where aerial photography is not feasible. The forest information provided by aerial photography or SLAR can be supplemented by Landsat information.

The combined use of the three systems can increase the confidence of forest surveys as each adds extra value to the information obtained from the others. For economy however, the acquisition of both aerial photography and SLAR images for the same survey is not recommended except where images are acquired for multipurpose and/or interdisciplinary use in which costs are shared by the various users. The combined use of the three systems for a particular survey is recommended only when imagery which have been recently acquired for purposes other than forestry are available at suitable scales.

The most often neglected aspect of the use of remote sensing for forest surveys in the tropics is the economics of its use. This has not permitted an adequate assessment of its actual costs to the user. For this purpose, the economics of the use of remote sensing in tropical forest surveys should be included in the survey objectives.

The conventional use of diameter at breast height (DBH) and diameter above buttress (DAB) in particular for tropical forest trees, often creates discrepancies in volume estimation. These parameters were originally established for temperate trees which differ from tropical trees both in shape and form. Also, the use of DBH or DAB for tropical trees results in weak crown-stem diameter correlations. As crown-bole diameter relationships are important for the estimation of tropical forest volumes, further research is required to determine which bole diameter correlates best with crown diameter and which is most usable for estimating tropical forest volumes. This is necessary because the crown is the only volume parameter which is measurable on aerial photographs of tropical forests. Research is also required to determine the most efficient volume equations for tropical forests, particularly those equations that can be used for the assessment of forest yield which has not been possible so far with photo-methods.

APPENDIXES

Appendix 1A Method of numbering sections and illustrations

Parts and chapters are designated by roman and arabic numerals respectively as in Part II and Chapter 2. Sections and subsections are designated first by their chapter numbers and thereafter by arabic numerals. A section number is connected with its chapter number with a hyphen as in Section 6-1. A subsection number is connected to its main section number by a stop as in Section 6-1.2 in which the prefix 'sub' is implied.

Illustrations (Tables and Figures) are designated first by their numbers and thereafter by arabic numerals. An illustration number is connected to a chapter number by a stop as in Table 11.1 and Fig. 8.1. The numbers of a subordinate illustration is joined to the number of the main illustration by a stop as in Table 11.1.2.

Appendixes are designated first by the roman numeral correspond to the Part of the thesis to which they relate and thereafter by alphabetic designation as in Appendix 1A and Appendix IIB.

Appendix IB Measurement standards, monetary conversion and names of countries

1 Measurement standards

(a) Linear measurement	equivalents
kilometre (km) = 10^3m	0.621 miles
metre (m) = 10^0m	3.281 feet (ft)
centimetre (cm) = 10^{-2}m	0.394 inches(in)
millimetre (mm) = 10^{-3}m	0.039 inches(in)
micrometer (um) = 10^{-6}m	micron (u)

(b) Area measurement		equivalents
square kilometer (sq.km.)	= 10^6sq.m	0.386 sq. miles
square metre (sq.m.)	= 10^0sq.m	10.764 sq.ft
hectare (ha)	= 10^4sq.m	2.471 acres

(c) Volume measurement		equivalent
cubic metre (cu.m.)	= 10^0cu.m	35.315 cu.ft

2 Monetary conversion

American (US) dollar ($) = £0.49 British pound sterling
as at December, 1978 ₦0.59 Nigerian naira

3 Names of countries

The names of some countries and places were changed after the publication of the literature cited in this thesis. These are:-

Current names used in this thesis	Original names used in literature cited
(a) African Region	
Benin Republic (different from Benin in Nigeria)	Dahomey
Botswana	Bechuanaland
Central African Empire	Central African Republic
Congo	Congo (Brazzaville)
Ghana	Gold Coast

Current names used in this thesis	Original names used in literature cited
Malawi	Nyasaland
Tanzania	Tanganyika
Zaire	Congo (Kinshasa)
Zambia	Southern Rhodesia
(b) Amazonian Region	
Belize	British Honduras
Guyana	British Guiana
Surinam	Netherland Guiana
The Caribbea	West Indies
(c) Southeast Asian Region	
(i) Indonesia	parts of East Indies
Djawa	Java
Iran Jaya	New Guinea (western part)
Kalimantan	Borneo (major part)
Sulawesi	Celebes
Sumatera	Sumatra
(ii) Malaysia	
Sabah	North Borneo
Sarawak	Borneo (northeastern part)
(iii) Others	
Kampuchea	Cambodia (Khmer Republic)
Papua New Guinea	New Guinea (eastern part)
Sri Lanka	Ceylon
Thailand	Siam

Appendix IC Conventional forest mensuration standards in metric system

1 Stem diameter measurements

Stem diameters are measured in centimetres (cm). For easy computation they are often recorded by classes whose interval, in statistical opinion should not exceed one-quarter of the standard deviation. Class intervals commonly used are 2.0 and 2.5cm. for temperate forests and 5.0 or 10.0cm. for mixed tropical forests, the class limit being a multiple of 2.5cm (Lanly, 1973).

(a) diameter at breast height (DBH):

measured at 1.3m. above ground level.

The minimum DBH is normally specified for individual surveys or otherwise decided by the size of sample trees.

(b) diameter above buttress (DAB):

measured at 30cm. above the termination of buttress.

DAB is measured instead of DBH where the presence of buttress precludes DBH measurement.

(c) upper stem diameters (D):

measured at various height levels along the stem to determine taper functions or volume in certain cases.

(d) lower stem diameters:

measured at various height levels up to breast height or 30cm. above buttress to determine lower stem taper function.

(e) stump diameters:

measured for recovery studies.

Notes

(i) diameter over bark (D o.b)

DBH including bark

(ii) diameter under bark (D u.b)

DBH excluding bark

(iii) bark thickness

measured in millimetres (mm) at breast height or above buttress. Double bark thickness is normally used in volume computations.

(iv) basal area

obtained from DBH or DAB

(v) mean DBH or DAB

obtained from mean basal area and not otherwise.

2 Height measurements

Tree heights are measured in metres (m). For easy computation they are recorded by classes whose interval depends on the range. For example, the class interval could be 3m. for heights ranging from 3m. to 30m, 0.3m. for heights up to 3m.and 10m. for heights above 30m. (Lanly 1973).

(a) total height

from ground level

(b) stem height

from ground level to crown point or a specified minimum upper stem diameter (15cm. by Nigerian forestry standards) whichever comes first.

(c) bole height

from 30cm. above ground level or from the termination of buttress to crown point or a specified minimum.

Notes

(i) other heights

measured in relation to upper stem diameters

(ii) buttress height

measured in relation to lower stem diameters

(iii) stump heights

measured for recovery studies

3 Volume estimation

Volumes are usually estimated in cubic metres (cu.m). The estimates are made primarily from volume parameters measured according to some given definitions.

'Volume' is used without qualification to mean

(a) gross volume:

wood volume without reduction for defects or

(b) net volume:

wood volume with reduction for defects.

Notes

'Volume' is normally qualified in individual surveys. These qualifications must be defined for clarity e.g.

(i) commercial volume
(ii) exploitable volume
(iii) industrial volume
(iv) utilizable volume

5 Ring the appropriate number(s) indicating the image enhancement equipment available in your establishment or for your use.

.1 electronic printer.
.2 density slicer/image enhancer.
.3 colour additive viewer.
.4 microdensitometer.
.5 computer.
.6 none of these.

6 Ring the appropriate number(s) indicating the constraint(s) to your use of remote sensing.

.1 aerial sensor coverage irregular or inadequate.
.2 trained personnel insufficient or lacking.
.3 appropriate equipment lacking.
.4 funds inadequate or lacking.
.5 ground methods are cheaper.

7 Ring the appropriate number indicating the remote sensing set-up desirable in the country.

.1 a central unit with dispersed user-facilities for investigators from various disciplines.
.2 a central unit supplying investigators from various disciplines their required information.
.3 separate units for groups of related disciplines.
.4 remote sensing set up not desirable, ground methods are cheaper.

8 Ring the appropriate number indicating your use of ground survey data.

.1.1 main survey data.
.1.2 ground control or check for aerial survey.

.2.1 routine investigations.
.2.2 academic investigations.

.3.1 environmental monitoring.
.3.2 ordnance survey mapping.
.3.3 thematic mapping.

.4.1 geological surveys.
.4.2 mineral exploration.
.4.3 soil surveys.

.5.1 agricultural surveys.
.5.2 forest resource surveys.
.5.3 vegetation surveys.

9 Ring the appropriate number indicating your survey frame.

- .1 total coverage.
- .2 sampling.

10 If your surveys are based on a sampling frame, ring the appropriate number indicating your sampling design.

- .1.1 line sampling.
- .1.2 strip sampling.

- .2.1 transect sampling.
- .2.2 rectangular plot sampling.

- .3.1 circular plot sampling.
- .3.2 plotless or point (relascope sweep) sampling.

- .4.1 multiple-point sampling (cf: Fed. Dept. of Forestry Design).
- .4.2 cluster sampling (different from .4.1 above)

11 For a typical ground survey (based on section 10) carried out by your establishment, supply the following information:-

- .1 size of a sampling unit (recording unit).
- .2 inter-sampling unit distance
- .3 sampling intensity.
- .4 level of accuracy desired.
- .5 level of accuracy achieved.

12 For the survey in Section 11 please supply the following:-

- .1 year of survey ________________
- .2 total area covered ________________
- .3 total cost of survey ________________
- .4 duration of survey (in man-days/months ________________

13 If total estimates are not available for Section 12 give estimates for:-

- .1 size of a unit of report ________________
- .2 number of field plots in this unit ________________
- .3 survey cost for this unit ________________
- .4 duration of survey for this unit (in man hours/days) ________________

14 For a typical aerial survey carried out in Nigeria or under similar tropical conditions by your establishment, supply the following information:-

.1 year of survey ——————————————————
.2 aerial sensor(s) used ——————————————————
.3 acquisition scale ——————————————————
.4 size of survey area ——————————————————
.5 cost of aerial coverage ——————————————————
.6 flight duration ——————————————————
.7 intended purpose of survey ——————————————————

15 For the survey in Section 14, give approximate estimates for the following operations:-

.1 cost of interpretation ——————————————————
.2 cost of field checking ——————————————————
.3 cost of mapping ——————————————————
.4 duration of interpretation(in man days/months)————
.5 duration of field checking(in man days/months) ————
.6 duration of mapping (in man days/months)————————

16 Ring the appropriate number(s) indicating the remote sensing facilities available in your establishment and underline those that are planned for the future.

.1 survey flight unit.
.2 photographic unit.
.3 interpretation unit.
.4 photogrammetric unit.
.5 Cartographic unit.
.6 none of these.

17 THANK YOU FOR YOUR CO-OPERATION AND THE CONSIDERATION GIVEN TO THIS QUESTIONNAIRE.

Appendix IIB Covering letter for the postal distribution of the questionnaire

Ref. No. FB/RS/170

F. B. Larin-Alabi,
Department of Forestry,
University of Edinburgh,
Edinburgh. EH9 3JU
SCOTLAND. U.K.

1st May, 1978.

....

....

....

....

....

Dear Sir,

Remote Sensing Applications In Nigeria:
Questionnaire for Appraisal

I should be grateful if you could complete the enclosed questionnaire and return as soon as possible for evaluation. Your response would be treated as confidential.

The purpose of the questionnaire is to appraise, for academic purposes, the current status of remote sensing in Nigeria.

I am a Nigerian forester carrying out research studies on remote sensing of tropical forest environments.

Your kind consideration and generous co-operation shall be fully appreciated.

Yours faithfully,

(F. B. LARIN-ALABI).

Encs.

Appendix IIC Reminder letter requesting replies to the questionnaire

Ref. No. FB/RS/290

F. B. Larin-Alabi,
Department of Forestry,
University of Edinburgh,
Edinburgh. EH9 3JU,
SCOTLAND. U. K.

REMINDER

24th August, 1978

....

....

....

....

....

Dear Sir,

Remote Sensing Applications In Nigeria:
Questionnaire for Appraisal

I am writing in connection with my letter No. FB/RS/170 of 1st May, 1978 on the subject noted above to which no response has been given.

I should be grateful if you could complete the questionnaire and return it to me as soon as possible.

Your co-operation in this respect shall be fully appreciated.

Yours faithfully,

(F. B. LARIN-ALABI).

Appendix IID Frequencies of response to the questionnaire by groups and categories

	GROUPS				TOTAL	CATEGORIES			
	FS	FA	RS	RA		F+	R+	+S	+A
Q1	21	2	7	6	36	23	13	28	8
a	11	2	4	3	20	13	7	15	5
b	8	2	3	3	16	10	6	11	5
Q2	8	2	3	3	16	10	6	11	2
.1	8	1	1	1	11	9	2	9	2
.2	-	-	3	1	4	-	4	3	1
.3	-	1	1	1	3	1	2	1	2
Q3	8	2	3	3	16	10	6	11	5
.1	-	1	3	2	6	1	5	3	3
.2	-	-	2	2	4	-	4	2	2
.3	-	-	-	-	-	-	-	-	-
.4	-	1	1	1	3	1	2	1	2
.5	8	-	-	1	9	8	1	8	1
Q4	8	2	3	3	16	10	6	11	5
.1	1	-	3	0	4	1	3	4	-
.2	1	2	3	3	9	3	6	4	5
.3	-	1	3	3	7	1	6	3	4
.4	-	1	-	-	1	1	-	-	1
.5	-	-	1	-	1	-	1	1	-
.6	3	-	1	-	4	3	1	4	-
.7	-	-	2	-	2	-	2	2	-
.8	4	-	-	-	4	4	-	4	-

	GROUPS				TOTAL	CATEGORIES			
	FS	FA	RS	RA		F+	R+	+S	+A
Q5	8	2	3	3	16	10	6	11	5
.1	1	-	-	-	1	1	-	1	-
.2	-	-	-	-	-	-	-	-	-
.3	-	-	-	-	-	-	-	-	-
.4	-	-	-	-	-	-	-	-	-
.5	-	2	-	-	2	2	-	-	2
.6	7	-	3	3	13	7	6	10	3
Q6	8	2	2	3	15	10	5	10	5
.1	1	1	-	1	3	2	1	1	2
.2	5	2	-	1	8	7	1	5	3
.3	7	2	1	3	13	9	4	8	5
.4	4	1	1	3	9	5	4	5	4
.5	2	-	-	-	2	2	-	2	-
Q7	8	2	2	3	15	10	5	10	5
.1	-	-	1	2	3	-	3	1	2
.2	3	-	1	-	4	3	1	4	-
.3	3	2	-	1	6	5	1	3	3
.4	2	-	-	-	2	2	-	3	-
Q8	8	2	3	2	15	10	5	11	4
.1.1	2	-	1	-	3	2	1	3	-
.1.2	1	1	1	1	4	2	2	2	2
.2.1	-	-	-	-	-	-	-	-	-
.2.2	-	1	-	1	2	1	1	-	2
.3.1	-	-	1	1	2	-	2	1	1
.3.2	-	-	2	-	2	-	2	2	-
.3.3	-	-	-	-	-	-	-	-	-
.4.1	-	-	1	-	1	-	1	1	-
.4.2	-	-	1	-	1	-	1	1	-
.4.3	4	-	-	1	5	4	1	4	1

	GROUPS				TOTAL	CATEGORIES			
	FS	FA	RS	RA		F+	R+	+S	+A
.5.1	-	-	-	-	-	-	-	-	-
.5.2	7	2	-	-	9	9	-	7	2
.5.3	5	2	-	1	8	7	1	5	3
Q9	8	2	3	2	15	10	5	11	4
.1	3	-	3	-	6	3	3	6	-
.2	5	2	-	2	9	7	2	5	4
Q10	5	2	-	2	9	7	2	5	4
1.1	-	1	-	-	1	1	-	-	1
1.2	2	-	-	-	2	2	-	2	-
2.1	2	-	-	1	3	2	1	2	1
2.2	-	1	-	1	2	1	1	-	2
3.1	1	-	-	1	2	1	1	1	1
3.2	-	1	-	-	1	1	-	-	1
4.1	-	-	-	-	-	-	-	-	-
4.2	-	-	-	-	-	-	-	-	-
Q11	4	2	-	2	8	6	2	4	4
.1	2	2	-	2	6	4	2	2	4
.2	2	-	-	2	4	2	2	2	2
.3	3	1	-	1	5	4	1	3	2
.4	1	1	-	1	3	2	1	1	2
.5	1	1	-	1	3	2	1	1	2
Q12	4	1	-	2	7	5	2	4	3
.1	4	1	-	2	7	5	2	4	3
.2	4	1	-	2	7	5	2	4	3
.3	2	1	-	2	5	3	2	2	3
.4	2	1	-	2	5	3	2	2	3

	GROUPS				TOTAL	CATEGORIES			
	FS	FA	RS	RA		F+	R+	+S	+A
Q13	1	-	-	-	1	1	-	1	-
.1	1	-	-	-	1	1	-	1	-
.2	1	-	-	-	1	1	-	1	-
.3	-	-	-	-	-	-	-	-	-
.4	-	-	-	-	-	-	-	-	-
Q14	1	1	1	2	5	2	3	2	3
.1	1	1	1	2	5	2	3	2	3
.2	-	1	1	2	4	1	3	1	3
.3	1	1	1	2	5	2	3	2	3
.4	-	1	1	1	3	1	2	1	2
.5	-	1	1	-	2	1	1	1	1
.6	-	1	1	1	3	1	2	1	2
.7	1	1	1	1	4	2	2	2	2
Q15	-	1	-	1	2	1	1	-	2
.1	-	1	-	1	2	1	1	-	2
.2	-	1	-	1	2	1	1	-	2
.3	-	1	-	1	2	1	1	-	2
.4	-	1	-	1	2	1	1	-	2
.5	-	1	-	1	2	1	1	-	2
.6	-	1	-	1	2	1	1	-	2
Q16	8	2	3	3	16	10	6	11	5
.1	-	-	-	-	-	-	-	-	-
.2	-	-	-	-	-	-	-	-	-
.3	-	1	1	3	5	1	4	1	4
.4	-	-	1	-	1	-	1	1	-
.5	-	1	2	2	5	1	4	2	3
.6	8	1	1		10	9	1	9	1

<u>Appendix IIE</u> <u>Analysis of the questionnaire:</u>
<u>The contingency data sets and their comparative values obtained by standardisation</u>

Mutually exclusive conditions considered			Groups				Qn	Categories			
			FS	FA	RS	RA		F+	R+	+S	+A
		Rn	21	2	7	6		23	13	28	8
Q1	(a) questionnaire distribution		21 (100)	2 (100)	7 (100)	6 (100)	1	23 (100)	13 (100)	28 (100)	8 (100)
	questionnaire return		11 (52)	2 (100)	4 (57)	3 (50)	1	13 (57)	7 (54)	15 (54)	5 (63)
	(b) questionnaire distribution		21 (100)	2 (100)	7 (100)	6 (100)	1	23 (100)	13 (100)	28 (100)	8 (100)
	questionnaire response		8 (38)	2 (100)	3 (43)	3 (50)	1	10 (43)	6 (46)	11 (39)	5 (63)
	(c) questionnaire return		11 (52)	2 (100)	4 (57)	3 (50)	1	13 (57)	7 (54)	15 (54)	5 (63)
	questionnaire response		8 (38)	2 (100)	3 (43)	3 (50)	1	10 (43)	6 (46)	11 (39)	5 (63)
		Rn	8	2	3	3		10	6	11	5
Q2	ground methods mainly used		8 (100)	1 (50)	1 (33)	1 (33)	1	9 (90)	2 (33)	9 (82)	2 (40)
	remote sensing methods mainly used		0 (0)	1 (25)	4 (67)	2 (33)	2	1 (5)	6 (50)	4 (18)	3 (30)
Q3	remote sensing imagery not used		8 (100)	0 (0)	0 (0)	1 (33)	1	8 (20)	1 (4)	8 (18)	1 (5)
	remote sensing imagery used		0 (0)	2 (25)	6 (50)	5 (42)	4	2 (5)	11 (46)	6 (14)	7 (35)
Q4	photogrammetric equipment available		5 (9)	4 (29)	13 (62)	6 (29)	7	9 (13)	19 (45)	18 (23)	10 (29)
	not available		4 (50)	0 (0)	0 (0)	0 (0)	1	4 (40)	0 (0)	4 (36)	0 (0)
Q5	enhancement equipment available		1 (3)	2 (20)	0 (0)	0 (0)	5	3 (6)	0 (0)	1 (2)	2 (8)
	not available		7 (88)	0 (0)	3 (100)	3 (100)	1	7 (70)	6 (100)	10 (91)	3 (60)
Q6	remote sensing constrained		17 (53)	6 (75)	2 (17)	8 (67)	4	23 (58)	10 (42)	19 (43)	14 (70)
	ground methods cheaper		2 (25)	0 (0)	0 (0)	0 (0)	1	2 (20)	0 (0)	2 (18)	0 (0)
Q7	remote sensing desirable		6 (25)	2 (33)	2 (22)	3 (33)	3	8 (27)	5 (28)	8 (24)	5 (33)
	remote sensing not desirable		2 (25)	0 (0)	0 (0)	0 (0)	1	2 (20)	0 (0)	2 (18)	0 (0)
Q8	(a) ground data as main data		2 (25)	0 (0)	0 (0)	1 (33)	1	2 (20)	1 (17)	3 (27)	0 (0)
	ground data as control data		1 (13)	1 (50)	1 (33)	1 (33)	1	2 (20)	2 (33)	2 (18)	2 (40)
	(b) physical resource surveys		4 (17)	0 (0)	2 (22)	1 (11)	3	4 (13)	3 (17)	6 (18)	1 (7)
	biological resource surveys		12 (50)	4 (67)	0 (0)	1 (11)	3	16 (53)	1 (6)	12 (36)	5 (33)
	(c) non-vegetation surveys		4 (8)	0 (0)	5 (28)	2 (11)	6	4 (7)	7 (19)	9 (14)	2 (7)
	vegetation surveys		12 (50)	4 (67)	0 (0)	1 (11)	3	16 (53)	1 (6)	12 (36)	5 (33)

Mutually exclusive conditions considered			Groups				Qn	Categories			
			FS	FA	RS	RA		F+	R+	+S	+A
		Rn	8	2	3	3		10	6	11	5
Q9	complete census survey frame		3 (38)	0 (0)	3 (100)	0 (0)	1	3 (30)	3 (50)	6 (55)	0 (0)
	sampling survey frame		5 (63)	2 (100)	0 (33)	2 (67)	1	7 (70)	2 (33)	5 (45)	4 (80)
Q10	simple sampling designs		4 (13)	2 (25)	0 (0)	2 (17)	4	6 (15)	2 (8)	4 (9)	4 (20)
	complex sampling designs		1 (3)	1 (13)	1 (8)	1 (8)	4	2 (5)	1 (4)	1 (2)	2 (10)
Q8 to Q15	(a) answers received to Q8 – Q15		31 (48)	11 (69)	7 (29)	13 (54)	8	42 (53)	20 (42)	38 (43)	24 (60)
	Q8 – Q15 unanswered		33 (52)	5 (31)	17 (71)	11 (46)	8	38 (48)	28 (58)	50 (57)	16 (40)
	(b) answers received to Q8 – Q11		25 (78)	8 (100)	6 (50)	8 (67)	4	33 (83)	14 (58)	31 (70)	16 (80)
	answers received to Q12 – Q15		6 (19)	3 (38)	1 (8)	5 (42)	4	9 (23)	6 (25)	7 (15)	8 (40)
	(c) answers received to Q12 – Q15 subquestions		17 (10)	17 (40)	7 (11)	23 (37)	21	34 (16)	30 (24)	24 (10)	40 (38)
	Q12 – Q15 subquestions unanswered		131 (90)	25 (60)	56 (89)	40 (63)	21	176 (84)	96 (76)	207 (90)	65 (62)
	(d) answers received to Q12 & Q13 subquestions		12 (22)	4 (25)	0 (0)	8 (33)	8	18 (23)	8 (17)	14 (16)	12 (30)
	answers received to Q14 & Q15 subquestions		3 (3)	13 (50)	7 (18)	15 (38)	8	16 (12)	22 (28)	10 (7)	28 (43)
Q16	remote sensing facilities available		0 (0)	2 (20)	4 (27)	5 (33)	5	2 (4)	9 (30)	4 (7)	7 (28)
	remote sensing facilities not available		8 (100)	1 (50)	1 (33)	0 (0)	1	9 (90)	1 (17)	9 (82)	1 (20)

<u>NOTE</u> : The comparative values (S) in brackets are obtained from the frequency values (F) before the brackets using the formula –

$$S = \frac{100F}{Rn.Qn}$$

LITERATURE
CITED

LITERATURE CITED

1. AKINSANMI, F. A. (1978) personal communication

2. ALDRICH, R. C. (1967) Stratifying photo plots into volume classes by crown closure comparator. (Research Note PSW - 151) 2pp. USDA Forest Service, USA.

3. ALLEN, P. E. T. (1975) The effect of instrument errors and stability of materials in area estimation. (FO:MISC/75/7) 10pp. FAO, Rome. Italy.

4. ALLEN, P. E. T. (1975a) The uses of side-looking airborne radar imagery for tropical forest surveys. (FO:MSC/75/10) 60pp. FAO, Rome. Italy.

5. ALLEN, P. E. T. (1977) personal communication.

6. AMERICAN SOCIETY OF PHOTOGRAMMETRY (1975) Manual of Remote Sensing (Reeves, R. G.; Anson, A. & Landen, D. eds).
   Vol. I Instruments and techniques (Janza, F. J.; Blue, H. M. & Johnston, J. E. eds).
   American Society of Photogrammetry, Falls Church, Virginia - USA.

7. AMERICAN SOCIETY OF PHOTOGRAMMETRY (1975a) Manual of Remote Sensing (Reeves, R. G.; Anson, A. & Landen, D. eds)
   Vol. II Interpretation and applications (Bowden, L. W. & Pruitt, E. L. eds).
   American Society of Photogrammetry, Falls Church, Virginia - USA.

8. ARUBAYI, E. E. (1978) personal communication.

9. AVERY, G. & MEYER, M. P. (1962) Contracting for forest aerial photography in the United States. (Lake For. Expt. Station Paper No. 96) 37pp.
   USDA Forest Service, USA.

10. AVERY, T. E. (1967) All sorts of stereograms
    Photogram. Eng. 33: 1397-1401

11. BALFOUR, BEATTY AND CO. LTD. & NEDECCO (1968) The role of aerial survey in the investigation of Nigerdams multipurpose development project. In Proceedings Toulouse Conference

Vol.IV (Aerial surveys and integrated studies) pp. 333-343.
UNESCO, Paris.

12. BANYARD, S. (1973) Forest mensuration: fundamentals
(ITC Course Lecture Notes - M9)
ITC, Enschede. Netherlands.

13. BARRET, E. C. & CURTIS, L. F. (1976). Introduction to
environmnetal remote sensing
Chapman and Hall, London.

14. BERGEROO-CAMPAGNE, B. (1955) Inventaire des forets tropicales par
photographies aeriennes (Forest surveys achieved from the
air).
Bois. For. Trop. 43: 3-7.

15. BEST, R. G. & SMITH, J. R. (1978) Photographic contrast
enhancement of Landsat imagery.
Photogram. Eng. & Rem. Sensing 44(8): 1023-1026

16. BICKFORD, C. A. (1961) Stratification for timber cruising
Journal of Forestry 59(10): 761-763.

17. BOGYAY, J. (1970) Moglichkeiten fur der verwendung von
Luftbildern bei der vorratsaufnahme von ungarischen
kiefern waldern. In Berichte III Int. Symp. fur
Photointerpretation Dresden Vol. I pp. 229-241.

18. BONNOR, G. M. (1964) A volume table for red pine by crown
width and height.
Forestry Chronicle 40(3): 339-346.

19. BONNOR, G. M. (1968) A comparison of photo and ground
measurements of canopy density.
Forestry Chronicle 44(3): 12-16.

20. BOON, D. A. (1956) Recent developments in photointerpretation
of tropical forests.
Photogrammetria 12(3): 382-386.

21. BOON, D. A. (1960) Aerial photography and forestry in
Southeast Asia.
Photogram. Eng. 26: 150-155.

22. BOON, D. A. (1961) The evaluation of grouping tendency of tree species in tropical rain forest.
In *Proceedings Symposium IUFRO S25.5*.
IUFRO Freiburg.

23. BRIEGLEB, P. A. (1952) An approach to density measurement in douglas-fir.
Journal of Forestry 50 (7): 529-536.

24. BROTHERS, G. L. & FISH, E. B. (1978) Image enhancement for vegetation pattern change analysis.
Photogram. Eng. & Rem. Sensing 44(5): 607-616

25. BROWN, S. G. (1953) *Notes of Forestry in the Colony of North Borneo* (type-script).
A supplement to the report prepared for the 8th Pacific Science Congress 1952.

26. BROWNE, F. G. (1958) Study of tropical vegetation: Sarawak.
In *Study of tropical vegetation: Proceedings of Kandy Symposium*. pp. 166-167.
UNESCO, Paris.

27. BURLEY, J.; WRIGHT, H. L. & MATOS, E. (1972) A volume tables for *Pinus caribaea* var. *caribaea*
Comm. For. Review 51 (2): 137-143.

28. BURT-DAUY, J. (1938) *The classification of tropical woody* vegetation types (Inst. Paper No.13).
Imperial For. Institute,Oxford. U.K.

29. CAHUSAC, A. B. (1957) *Forest mapping from aerial photographs in Uganda*. Paper prepared for the 7th Brit. Comm. Forestry Conference.
Uganda Forest Department, Entebbe. Uganda.

30. CCTA/CSA (1956) *Phytogeography : Yangambi specialist meetings* (Publication No.22).
Committe for Technical Cooperation in Africa South of Sahara (CCTA)/Scientific Council for Africa South of Sahara (CSA).

31. CHARTER, J. R. (1969) Nigeria vegetation ecological zones: explanatory notes (typescript).

Forestry Research Institute of Nigeria, Ibadan.

32. CHARTER, J. R. (1970) *Vegetation Ecological Zones* (map prepared for the National Atlas of Nigeria yet to be published). Federal Surveys Department, Lagos. Nigeria.

33. CONOVER, W. J. (1971) *Practical non-parametric statistics*. John Wiley & Sons, Inc. New York.

34. COOPER, L. G. (1960) *The use of aerial photography in forestry work in Nigeria* (Technical Note No. 3). Forestry Research Institute of Nigeria, Ibadan.

35. CURTIN, R. A. (1964) Stand density and the relation of crown width to diameter and height in *Eucalyptus* *obliqua* *Australian Forestry* *28*(2)

36. DAWKINS, H. C. (1963) Crown diameters, their relations to bole diameter in tropical forest trees. *Comm. For. Review* *42*: 318-333.

37. DE-AZEVEDO, L. H. A. (1971) Radar in the Amazon. In Proceeding: *7th International Symposium on Remote sensing of the environment*. Vol.3.

38. DE-MILDE, R. & SAYN-WITTGENSTEIN, I. (1973) An experiment in the identification of tropical tree species on aerial photographs. In *Proceedings Symposium IUFRO S6.05* pp.21-37. IUFRO, Freiburg.

39. DE-ROSAYRO, R. A. (1959) The applications of aerial photographs in stock mapping and inventories on an ecological basis in rainforest in Ceylon. *Emp. For. Review* *38*(2): 141-173.

40. DISPERATI, A. A. & KEECH, M. A. (1978) The value of using SLAR, satellite imagery and aerial photography for a forest survey in the Amazon Basin. In *Remote sensing applications in developing countries*. (Collins, W. G. & van Genderen J. L. eds). pp.49-55. Remote Sensing Society. U.K.

41. DODGE, A. G. & BRYANT, E. S. (1976) Forest type mapping with satellite data. *Journal of Forestry* *74*(8): 526-531.

42. EYTON, J. R. & KUETHER, R. P. (1978) Macrophotography of satellite images.
Photogram. Eng. & Rem. Sensing 44(8):1091-1021

43. FAO (1974) Potential use of remote sensing techniques for the monitoring of tropical forests. (FAO/FDT/74/6) 13pp.
Secretariat note on Third Session of the Committee on Forest Development in the tropics.
FAO, Rome. Italy.

44. FEDERAL DEPARTMENT OF FORESTRY, NIGERIA (1976)
Happy Christmas (greeting card).
Fed. Dept. of Forestry, Ibadan, Nigeria.

45. FRANCIS, D. A. (1957) The use of aerial photographs in tropical forests.
Unasylva 11(3):103-109.

46. FRANCIS, D. A. (1960) Interim report to the government of the Sudan on forest inventory (FAO/59/10/7837, Interim Report No.2)
FAO, Rome. Italy.

47. FRANCIS, D. A. (1976) Possibilities and problems of radar image interpretation for vegetation and forest types with particular reference to the humid tropics. In XVI World Congress, Norway 1976 Vol.IV (General subjects) pp.271-279.
IUFRO. Freiburg.

48. FRANCIS, E. C. (1966) Crowns, boles and timber volumes from aerial photographs and field surveys.
Comm. For. Review 45(1): 32-66.

49. FRANCIS E. C. & WOOD, G. H. S. (1955) Classification of the vegetation of North Borneo from aerial photographs.
Malayan Forester 18(1): 38-44.

50. GARVER, R. D. (1953) Aerial photointerpretation by the forestry service.
Photogram. Eng. 19: 117-120.

51. GARVER, R. D. & MOESSNER, K. E. (1949) Forest service use of aerial photography.
Photogram. Eng. 15: 504-517.

52. GROSENBOUGH, L. R. (1965) Three-Pee sampling theory and program 'Th PPP' for computer generation of selection criteria
(Research Note PSW - 21)
USDA, Forest Service. USA.

53. HALL, J. B. (1977) Forest types in Nigeria: An analysis of pre-exploitation forest enumeration data.
Journal of Ecology 65(1): 187-199.

54. HALLER, R. C. & BEGA, R. V. (1973) Detection of forest diseases by remote sensing.
Journal of Forestry 71(1): 18-21.

55. HANNIBAL, L. W. (1952) Aerial forest photointerpretation in Indonesia (FAO/ASIAN Pacific Forestry Commission Document No.75).
FAO, Rome. Italy.

56. HARPER, D. (1976) Eye in the sky: Introduction to remote sensing 164pp.
Multiscience Publications, Montreal. Canada.

57. HARPER, W. M. (1977) Statistics (3rd Ed.) 354pp.
MacDonald and Evans Ltd. Plymouth U.K.

58. HARRISON, J. D. B. & SPURR, S. H. (1955) Planning a national forest inventory (mimeo)
FAO, Rome. Italy.

59. HEINSDIJK, D. (1952) Forest photointerpretation in Surinam. (Part of Symposium on 'The use of aerial photographs in a tropical country (Surinam)').
Photogram. Eng. 18: 158-162

60. HEINSDIJK, D. (1955) Forest type mapping with the help of aerial photos in the tropics.
Tropical Woods 102: 27-46

61. HEINSDIJK, D. (1957) The upper storey of tropical forests
Tropical Woods 107: 66-84

62. HEINSDIJK, D. (1958) The upper storey of tropical forests
Tropical Woods 108: 31-45

63. HEMPENIUS, S. A. (1979) Remote Sensing: how far and how fine? (Public Lecture summarised by W. G. L. de Haas). ITC Journal 1979(1): 127-133

64. HINDLEY, E. & SMITH J. G. H. (1957) Spectrophotometric analysis of foliage of some British Columbia conifers Photogram. Eng. 23: 894-895 -

65. HOLLERWOGER, F. (1954) Is there a correlation in the teak forests between crown diameter and the height of the trees with regard to the diameter on breast height? Journal of Scientific Research in Indonesia 3: 3-20

66. HOPKINS, B. (1974) Forest and Savanna (2nd Ed.) 154pp. Heinneman, Ibadan, Nigeria.

67. HOWARD, J. A. (1970) Aerial photoecology 325pp. Faber & Faber, London. U.K.

68. HOWARD, J. A. (1970a) Stereoscopic profiling and the photogrammetric description of woody vegetation Australian Geographer 11(3): 359-372

69. HOWARD, J. A. (1970b) Stereoscopic profiling of land units from aerial photographs Australian Geographer 11(3): 259-268

70. HOWARD, J. A. (1974) A critique: applications of non-satellite remote sensing of the earths resources (AGD(RS)2/73) 13pp. Paper presented with 13 slides at 24th International Astronautical Congress in Baku USSR - 1973. FAO, Rome. Italy.

71. HOWARD, J. A. (1976) Remote sensing of tropical forests with special reference to satellite imagery (AGD(RS)3/76) 11pp. FAO, Rome. Italy.

72. HOWARD, J. A. C. (1959) The classification of woodland in Western Tanganyika for type mapping from aerial photographs Emp. For Review 38(4): 348-364

73. HOWARD, J. A. & LANLY, P. J. (1975) Remote sensing for tropical forest surveys Unasylva 29(2): 232-237

74. HOWARD, W. J. (1969) A description of some of the surveys carried out by the Savanna Investigation Unit. In Proceedings: 1st Nigerian For. Conf. Kaduna, Northern Nigeria. pp. 71-80
Forestry Association of Nigeria

75. HOWARD, W. J. (1967) Vegetation surveys of savanna forest reserves in Northern Nigeria based on aerial photographs. Comm. For. Review 46(1) 36-50

76. HOWROYD, C. S. (1954) An investigation into commercial volume estimation from air photographs (typescript).
Comm. For. Institute, Oxford. U.K.

77. HUNTING TECHNICAL SERVICES LTD. (1977) Nirad Project Interpretation Phase (Progress Report Nos. 1-3)
Hunting Technical Services Ltd., Herts. U.K.

78. HUNTING TECHNICAL SERVICES LTD. (1978) Nirad Project Interpretation Phase (Progress Report No.4)
Hunting Technical Services Ltd., Herts. U.K.

79. HUTTON, M. S. (1977) A personal view of some problems raised by the Landsat - 1 Programme in Botswana (typescript) 7pp.
Paper presented at 4th Annual Conference of Remote Sensing Society, Sheffield. U.K. - 1977.

80. ILVESSALO, Y. (1950) On the correlation between crown diameter and the stem of trees.
Comm. Inst. For. Fenniae 38(2): 5-320

81. KEAY, R. W. J. (1953) Nigeria: Provisional map of vegetation zones
Federal Surveys Department, Lagos, Nigeria.

82. KEAY, R. W. J. (1959) Vegetation map of Africa south of the Tropic of Cancer (explanatory notes) 24pp.
Oxford University Press, Oxford. U.K.

83. KEAY, R. W. J. (1959a) An outline of Nigerian vegetation (3rd Ed.) 46pp.
Federal Ministry of Information, Lagos, Nigeria.

84. KIO, P. R. O. (1971) The status of aerial photointerpretation in Nigerian Forestry.
Nigerian Journal of Forestry 1(2): 64-68

85. KIO, P. R. O. (1971a) Requirements and proposals for national forest resources inventory in Nigeria (typescript) 23pp. Paper II of the National Forestry Development Committee presented at the National Agricultural Development Seminar, Ibadan, Nigeria. 1971.

86. KIO, P. R. O. (1974) Developing countries and the new science of remote sensing
Comm. For. Review 53(2): 137-145

87. KIO, P. R. O. (1977) Remote sensing: a treat to peace or a blessing? (newspaper publication). In Daily Times (No. 21440 of 5th January, 1977).
Daily Times of Nigeria Limited, Lagos.

88. KIRBY, R. P. (1977) Remote sensing of Scottish coastal habitats (Research Report No.34) 95pp.
Tourism & Recreation Research Unit University of Edinburgh. U.K.

89. KUMMER, R. H. (1964) A use for small scale photography in forest management.
Photogram. Eng. 30(5): 727-732

90. LANGDALE-BROWN, I. (1968) Methods used to assess the general landuse possibilities of parts of Western Cameroon.
In Proceedings Toulouse Conference: IV (Aerial surveys and integrated studies). pp.403-405.
UNESCO, Paris.

91. LANGDALE-BROWN, I. (1968a) Ugandan vegetation survey.
In Proceedings Toulouse Conference: IV (Aerial surveys and integrated studies). pp. 447-478.
UNESCO, Paris.

92. LANGDALE-BROWN, I. (1979) personal communication.

93. LANGLEY, R. G. (1969) New multistage sampling technique using space and aircraft imagery for forest inventory.
In Proceedings 6th Int. Symp. on Remote sensing of the environment pp.1179-1192.

94. LANLY, P. J. (1972) L'utilisation des photographs pour
l'evaluation des resources forestieres: application
au cas de l'Afrique tropicale francophone (The use of
aerial photographs and maps in forest resource surveys:
with special reference to French-speaking tropical Africa).
(FO:MISC/72/20) 17pp.
Paper presented at 3rd Annual Cartographic Conference for
Africa in Addis Ababa - 1972.
FAO, Rome. Italy.

95. LANLY, P. J. (1973) Manual of forest inventory: with special
reference to mixed tropical forests. 200pp.
FAO, Rome. Italy.

96. LANLY, J. P. (1976) Computer aided interpretation of Landsat
imagery for tropical forestry - two experimental studies in
tropical forest areas (typescript)
Paper prepared for the ITC Jubilee Symposium on Surveys
for Development in Enschede, Netherlands, 1976.
(Workshop "new Developments in Forest Surveys).

97. (LANLY) J. P. (1976a) The uses of side-looking airborne radar
imagery for tropical forest studies based on work by
P. E. T. Allen (a review of FAO Publication FO:MISC/75/10)
Comm. For. Review 55(2):161-162

98. LARIN-ALABI, F. B. (1978) Problems of remote sensing in the tropics:
an appraisal of the Nigerian situation with regard to
forest resources.
In Remote sensing applications in developing countries.
(Collins, W. G. & van Genderen eds) pp. 57-61
Remote Sensing Society, U.K.

99. LATHAM, R. P. & McCARTY, T. M. (1972) Recent developments in
remote sensing for forestry.
Journal of Forestry 70(1): 398-402

100. LEWIS, A. J. & McDONALD, H. C. (1972) Mapping of mangrove and
perpendicular oriented shell reefs in Southern Panama
with side-looking radar.
Photogrammetria 28(6): 187-200

101. LIGTERINK, G. H. (1968) Elementary photogrammetry for the interpretation course. (ITC Course Lecture Notes - GEN. 1)
ITC, Delft. Netherlands.

102. LOETSCH, F. (1957) Report to the government of Thailand on inventory methods for tropical forests Parts I & II
(FAO/ETAP Report No. 545).
FAO, Rome. Italy.

103. LOETSCH, F. (1957a) A forest inventory in Thailand
Unasylva 11(4): 174-180

104. LOETSCH, F. & HALLER, K. E. (1973) Forest Inventory Volume I
(Statistics of forest inventory and information from aerial photographs).
BLV Verlagsgesellschaft Munchen.

105. LOOSE, S. T. B. (1953) Timber estimates from large scale photographs.
Photogram. Eng. 19: 752-762

106. LUEDER, D. R. (1959) Aerial photographic interpretation
McGraw-Hill Book Coy in New York. USA.

107. LYONS, E. H. (1964) Recent developments in 70mm. stereophotography from helicopters.
Photogram. Eng. 30(5): 750-756

108. MACABEO, M.E. (1957) Correlation of crown diameter with stump diameter, merchantable length and volume of white Luana (Rentacme contorta (Vido) Merr. and Rolfe)
In Tagkawayan Forests, Quezon Province.
Phillipine Journ. For. 3(1-2): 99-117

109. MACANDREWS, F. D. (1955) Average height weighted by volume on airphoto interpretation. (Tech. Note No.17)
Dept. of North Affairs & Nat. Resources, For. Res. Div.
Canada.

110. MALING, D. H. (1965) Suitable projections for maps of the visible surface of the moon.
Cartographic Journal 2(2): 95-99

111. MALING, D. H. (1966) Current Research in Cartography at the University of Swansea. (Part of the Proceedings of the Symposium of the British Cartographic Society in Swansea 1965).
Cartographic Journal 3(1): 7-8

112. MALING, D. H. (1966a) Some notes about the Trystan Edwards Projection.
Cartographic Journal 3(2): 94-97

113. MALING, D. H. (1968) How long is a piece of string?
Cartographic Journal 5(2): 147-156

114. MALING, D. H. (1971) Photogrammetric techniques relevant to the Nature Conservancy's use of air photography.
In The application of aerial photography to the work of Nature Conservancy (Goodier R. ed) pp.132-149.
The Nature Conservancy, Edinburgh. U.K.

115. MARTIN-KAYE, P. H. A. (1974) Application of side-looking airborne radar in earth resource surveys.
In Environmental remote sensing: applications and achievements (Barret, E. C. Curtis, L. F. eds) pp.29-47

116. MASLEKAR, A. R. (1977) Aerial assessment of young teak plantations of Allapalli Range Maharashtra.
Indian Forester 103(7): 486-489.

117. MASON, B. Jnr. & WOOD, K. B. (1952) A forest survey in Guatemala
Photogram. Eng. 18:140-143

118. MEIJERINK, A. H. J. & DONKER, N. H. W. (1978). The ITC approach to digital processing applied to Landuse mapping in the Himalayas and Central Java
In Remote sensing applications in developing countries (Collins, W. G. & Van Genderen, J. L. eds)
Remote Sensing Society, U.K.

119. MERIDIAN AIRMAPS LTD.(undated) Meridian Airmaps: vertical air photography for planning and civil engineering
(the "Meridian data sheet" enclosed in this advertising publication).
Meridian Airmaps Ltd., Sussex, U.K.

120. MERRIT, V. G. & RANATUNGA, M. S. (1959) Aerial photographic survey of Sinharaja forest.
Ceylon. For. 4(2): 103-136

121. MILLER, R. G. (1957) The use of aerial photography in forestry in the British colonies (Misc. No. 528) pp.7
Paper presented to the 7th Brit. Comm. For. Conf.
Colonial Office, London, U.K.

122. MILLER, R. G. (1963) Forestry and aerial photographs (typescript)
Paper read at the Technical Meeting of the Photogrammetric Society Feb. 1963.

123. MINOR, C. O. (1951) Stem-crown diameter relations in Southern pine.
Journal of Forestry 49(7): 490-493.

124. MOESSNER, K. E. (1949) A crown density scale for photointerpreters
Journal of Forestry 47(7): 569

125. MOESSNER, K. E. (1956) Combined vertical and horizontal stereograms (Intermtn. For. & Range Expt. Station Research Note No.36) 3pp.
USDA, Forest Service. USA.

126. MOESSNER, K. E. (1957) Relation of minimum area standards to proportions obtained by dot samples of aerial photographs (Intermtn. For. & Range Expt. Station Research No.44) 13pp.
USDA, Forest Service. USA.

127. MOESSNER, K. E. (1963) Composite aerial volume tables for conifer stands in mountain states(For. Service Research Note INT - 6) 4pp.
USDA Forest Service. USA.

128. MOESSNER, K. E. (1963a) A test of aerial photo classifications in forest management - volume inventories (For. Service Note INT - 3) 15 pp.
USDA Forest Service. USA.

129. MOESSNER, K. E. (1964) Learning to estimate stand volume from aerial photos (For. Service Research Note INT - 25) 4pp.
USDA Forest Service. USA.

130. MOESSNER, K. E.; BRUNSON, D. F. & JENSEN C. E. (1951) Aerial volume tables for hardwood stands in the Central States. (Central States For. Expt. Station Technical Paper No.122) 15pp.
USDA Forest Service. USA.

131. MORENO, R. (1970) The value of 35mm. vertical aerial photography for forest surveys. Ph.D. Thesis, Department of Forestry & Natural Resources, Edinburgh University. U.K.

132. MORRIS, D. B. & MARTIN-KAYE, P. H. A. (1973) Remote sensing of the environment.
Endeavour 32:117-121

133. MOTT, P. G. (1956) The contouring of a tropical forest area in Ceylon by the use of aerial photographs.
Emp. For. Review 35(1): 34-41

134. MUETZELFELDT, R. I. (1979) personal communication.

135. NEAVE, H. R. (1978) Statistics tables for mathematicians, economists and the behavioural and management sciences 87pp.
George Allen & Unwin (Publications) Ltd, London, U.K.

136. NORCLIFFE, G. B. (1977) Inferential statistics for geographers 272pp.
Hutchinson & Co. Publishers Ltd., London, U.K.

137. NYYSSONEN, A. (1955) On the estimation of growing stock from aerial photographs.
Comm. Inst. For. Fenniae 46(1): 1-57

138. NYYSSONEN, A. (1962) Aerial photographs of tropical forests.
Unasylva 16(1): 3-12

139. OLA-ADAMS, B. A. & IYAMABO, D. E. (1977) Conservation of natural vegetation of Nigeria
Environmental Conservation 4(3): 217-226

140. OMEOGA, U.N. (1976) Vegetation and soil survey of Olokemeji Forest Reserve. Student Project Report, Federal School of Forestry, Ibadan, Nigeria.

141. OYELESE, J. O. (1968) The mapping of landuse patterns from aerial photographs in the forest zone of Ibadan Division.
Nigerian Geographical Journal 11(1): 27-37

142. PAELINCK, P. (1958) Note sur l'estimation du volume des penplements a lumba (Terminalia superba)au Muyinbe a l'aide des photos aeriennes (Note on the estimation of the volume of limba (Terminalia superba) in Muyinbe on aerial photographs).
Bull. Agric. Congo Belge 49(4): 1045-1054

143. PAIJMANS, K. (1951) Een voorbeeld van interpretatie van luchfotos van oerwound in het Malili complex op celebes. (Interpretation of aerial photographs in a virgin forest complex Malili, Celebes).
Tectona 41(2): 111-136

144. PAIJMANS,K. (1970) Land evaluation by airphoto interpretation and field samppling in Australian New Guinea.
Photogrammetria 26(2-3): 77-100

145. PAIJMANS, K. (1975) Lecture notes on air photointerpretation (typescript) 4pp.

146. PARRY, D. E. (1974) A natural resource evaluation of ERTS - 1 imagery of the Central Region of Ethiopia.
Photogram. Record 8(43): 65-80

147. POPE, R. B. (1960) Ocular estimation of crown density on aerial photographs.
Forestry Chronicle 36(1): 89-90

148. POPE, R. B. (1962) Constructing aerial photovolume tables (Pacific Northwest Forest and Range Expt. Station Research Paper No. 214) 25pp.
USDA Forest Service. USA.

149. RANDALL, A. C. (1969) Forest surveys for economic development. In Tropical Resource investigations for economic development. pp.183-229.
Gen. Secretariat, Organisation of American States, Washington. D.C.

150. RHODY, B. (1965) Photointerpretation and mapping for forestry purposes with particular reference to the Wild B8 Aviograph stereoplotter.
Unasylva 19(2): 55-60

151. RICHARDS, P. W. (1939) Ecological studies on the rainforests of Southern Nigeria 1: structure and floristic composition of the primary forest.
Journal of Ecology 27(1): 1-61

152. ROBINSON, M. W. (1947) An instrument to measure forest crown cover.
Forestry Chronicle 13(3): 222-225

153. ROGERS E. J. (1958) Report of Working Group 4 (Foresters) Commission VIII, International Society of Photogrammetry
Photogram. Eng. 24: 603-616

154. ROLLET, B. (1960) Emplois des photographies aeriennes au 1:40 000 pour l'interpretation de la vegetation et les inventoieres forestiers au Cambodge et au Vietnam (Utilisation of 1:40 000 scale aerial photographs for the interpretation of vegetation and forest inventory in Cambodia and Vietnam).
Bois. For. Trop. 74: 16-24

155. RUDD, R. D. (1974) Remote sensing: a better view 132pp.
Duxbury Press, North Scituate. Massachussetts.

156. SABINS, F. F. (1978) Remote sensing: principles and interpretation 426pp.
W. H. Freeman & Co. San Francisco

157. SAYN-WITTGENSTEIN, L. & ALDRED, H. A. (1967) Tree volumes for large-scale photos.
Photogram. Eng. 33: 69-73

158. SICCO-SMITH, G. (1974) Practical applications of radar imagery to tropical rainforest mapping in Colombia.
In Contributions to forest inventory methodology
Bundesforschungsanstalt fur Forst - und Holzwirtschaft, Reinbek. FGR.

159. SICCO-SMITH, G. (1978) SLAR for forest-type classification in a semideciduous tropical region.
ITC Journal 1978(3): 385-401.

160. SISAM, J. W. B. (1947) *The use of aerial survey in forestry and agriculture*. (Imperial Agric. Bureaux Joint Publication No.9) 32pp.
Imperial For. Bureau, Oxford & Imperial Bureau of Pastures and Field Crops. Aberystwyth. U.K.

161. SMITH, D. U. (1969) Timber volume with a kelsh plotter
Photogram. Eng. *34*(4): 363-365

162. SMITH, J. T. (1963) Colour - a new dimension in photogrammetry
Photogram. Eng. *29*(6): 999-1011

163. SPURR, S. H. (1948) Aerial photography.
Unasylva *2*(4): 183-194

164. SPURR, S. H. (1960) *Photogrammetry and photointerpretation*
(2nd ed.) 472pp.
Ronald Press Company, New York. USA.

165. STANLEY, D. J. (1978) Digital analysis of radar imagery for vegetation detection in Nigeria.
In *Remote sensing applications in developing countries*
(Collins, W. G. & van Genderen, J. L. Eds) pp.63-74
Remote Sensing Society, U.K.

166. STELLINGWERF, D. A. (1962) Holzmassen - bestimmung von *Pinus silvestris* auf luftbildern in den Niederlanden.
Allg. Forstz. *1*(2): 29-30

167. STELLINGWERF, D. A. (1963) *Volume estimation on aerial photographs*
(ITC Publication B18)
ITC, Enschede, Netherlands.

168. STELLINGWERF, D. A. (1966) *Practical applications of aerial photographs in forestry and other vegetation studies*
(ITC Publication B 36-38)
ITC, Enschede, Netherlands.

169. STELLINGWERF, D. A. (1976) *Mapping for forestry purposes*
(ITC Course Lecture Notes)
ITC, Enschede, Netherlands.

170. SUTTER, H. (1973) *Trial of indicative forest inventory in Ife Shasha Forest Reserves* (UNDP/FAO Report) 13pp.
Federal Dept. of Forestry, Ibadan, Nigeria.

171. SWELLENGREBEL, E. J. G. (1959) On the value of large scale
aerial photographs in British Guiana forestry.
Emp. For. Review 38(1): 54-64.

172. SWELLENGREBEL, E. J. G. (1961) Estimation of greenheart volume
from small scale aerial photographs.
Emp. For. Review 40(2): 162-171

173. SWELLENGREBEL, E. J. G. (1965) Reconnaissance of tropical forests
with aerial photographs.
Comm. For. Review 44(2): 142-150.

174. SWINSCOW, T. D. V. (1978) Statistics at square one (3rd Ed.) 86pp.
Macmillan Press Ltd., London, U.K.

175. TAYLOR, B. W. & STEWART, G. A. (1958) Vegetation mapping in the
territories of Papua and New Guinea conducted by the CISRO.
In Study of Tropical Vegetation Proceedings of Kandy
Symposium. pp. 127-136.
UNESCO, Paris.

176. TOMAR, M. S. (1976) Use of aerial photographs in working plans
Indian Forester 102(2): 98-108

177. UNESCO (1973) International classification and mapping of
vegetation. 37pp.
UNESCO, Paris.

178. US FOREST SERVICE (1959) Third Progress Report on the status of
aerial survey and techniques in Research (Forest Economics &
Marketing Memorandum) 14pp.
USDA Forest Service. USA

179. VAN-DILLENWIJN, F. J. (1957) Sieutel voor der interpretatie van
be groei-ingswormen met lucht fotos 1:40 000 van het
noordelijk deel van suriname. (Key for the interpretation of
vegetation types on 1:40 000 scale aerial photographs of
Northern Surinam). 45pp.
Dienst's Landsbosbeheer Suriname, Paramaribo.

180. VELOSO, H. P.; JAPIASSU, A. M. S. & FILHO, L. G. (1963) SLAR and
aerial photographs for vegetation surveys.
In The Inventory of Natural Resources Vol.I pp.1-67
Projecto Radam, Brazil.

181. VIKSNE, A.; LISTON, T. C. & SAPP, C. D. (1970)
SLR reconnaissance of Panama.
Photogram. Eng. 36(3) 253-259

182. WESTBY, R. L.; ALDRED, A. H. & SAYN-WITTGEINSTEIN, L. (1968)
The potential of large scale air photographs and radar altimetry in land evaluation.
In Land evaluation 8pp.
Macmillan Press, Australia.

183. WHEELER, P. R. (1959) Preliminary Plan: Forest Survey of Cambodia.
USAID, Cambodia.

184. WHITE, J.; YEATS, A. & SKIPWORTH, G. (1977) Tables for Statisticians (2nd Ed.) 61pp.
Stanley Thornes Publishers Ltd., Cheltenham. U.K.

185. WORLEY, D. P. & MEYER, H. A. (1955) Measurement of crown diameter and crown cover and their accuracy on 1:12 000 scale photographs.
Photogram. Eng. 21: 372-375.

186. ZIEGER, E. (1928) Ermittlung von bestandesmassen aus flugbildern mit hilfe des Hungersholf-Heydeschen Autokartographen. (Determination of stand volumes from aerial photographs with the help of Hugersholf-Hyde Autocartograph).
In Mitteilungen aus der sachsischen forstlichen versuchsanstalt zu Tharandt Vol. 3 pp.97-127.

RELEVANT
PUBLICATION

RELEVANT PUBLICATION

<u>An article published from the material included in this thesis</u>

REFERENCE

LARIN-ALABI, F. B. (1978) Problems of remote sensing in the tropics: an appraisal of the Nigerian situation with regard to forest resources.
In <u>Remote sensing applications in developing countries</u> (Collins, W. G. & van Genderen eds.) pp. 57-61.

The publication contins the papers which were presented at the 4th Annual Conference of the Remote Sensing Society held at the University of Sheffield, U.K. in December, 1977.

THE REMOTE SENSING SOCIETY

REMOTE SENSING APPLICATIONS IN DEVELOPING COUNTRIES

Edited by W.G. COLLINS and J.L. van GENDEREN

Published for the Remote Sensing Society

1978

PROBLEMS OF REMOTE SENSING IN THE TROPICS: AN APPRAISAL OF THE NIGERIAN SITUATION WITH REGARD TO FOREST RESOURCES

F. B. Larin-Alabi
Department of Forestry and Natural Resources
Edinburgh University
Edinburgh

ABSTRACT

The claims about the value of remote sensing for forest surveys have not been realised in the tropics. Persistent cloud-cover over most tropical countries has frustrated photographic efforts and rendered satellite sequential sensing less meaningful. Environmental conditions have imposed some limitations on the choice of techniques and the interpretation of remote sensing imagery.

Operational remote sensing is hindered, in many tropical countries by the lack of adequate equipment and trained personnel. Consequently, their remote sensing projects are often executed by expatriates. The valuable experience of the local forest conditions is gained by these expatriates and the advantage to the country is lost when they leave at the conclusion of their assignments.

If tropical developing countries are to benefit more from the advantages of remote sensing technology, radar, because of its near-all-weather capability, should be improved. Also, the establishment of adequately equipped central and multidisciplinary remote sensing units and personnel training programmes are most desirable in these countries.

Inferences are drawn on the state of the art in Nigeria with particular reference to the tropical high forest system.

CONTENTS

1. INTRODUCTION

Foresters were among the first people to appreciate the value of remote sensing (Harper, 1976) and they pioneered the use of aerial photographs in resource management (Latham & McCarty, 1972). For extensive forest surveys, remote sensing is acknowledged to be a more rapid and easier method of collecting timely information than by expensive ground surveys.

Recent advancements in remote sensing technology and current achievements in its applications to forestry, show that this rapidly evolving technology can assist the solution of many forestry problems. Forestry applications of remote sensing have not been fully explored and its technical capabilities have, as yet, not been adequately tested in the tropical forest environment to justify the generalised claims based mainly on successes obtained in the relatively less complex temperate forest environment.

This paper considers the various problems associated with the use of remote sensing techniques in forest surveys in Nigeria, with particular reference to the tropical high forest as an example of a very complex tropical forest system, and to suggest possible solutions that can serve as a basis for deriving optimum benefit from the advantages of this valuable tool, despite the attendant problems.

2. THE NIGERIAN TROPICAL HIGH FOREST SYSTEM

Nigeria has a total land area of approximately 924,000 sq. km. and most of the country is below 1,500 metres. The tropical high forest, which produces practically all the country's industrial round-wood, lies in the lowland area within the coastal quarter of the country and occupies about one-tenth of the total land area. It is a very dense evergreen closed forest and the difficult terrain in places makes it almost impenetrable without cutting access routes. There is no single-canopy layer. Crowns exist at all levels, with discontinuous emergents to give it an almost completely irregular structure, or very poor vertical layering. The disturbed parts of the forest are degraded (by destructive logging and repeated shifting cultivation) into mosaics of different logging intensities, regrowths of various forms, and farms with irregular patterns. Nigerian forests contain over 560 species of trees capable of attaining a height of at least 12 metres and a diameter of 19 cm. at breast height (Ola-Adams and Iyamabo, 1977). In the tropical high forest zone there is a distribution frequency of about 47 species per hectare, with a minimum diameter of 10 cm. at breast height (Richards, 1939).

3. PROBLEMS OF REMOTE SENSING

The large size of Nigeria, with an extensive area of highly productive forest of difficult access, calls for a rapid method of collecting information for forest management purposes. The essential data requirements are the identification of forest-types, estimation of their areas, the identification of tree-species, and estimation of timber-volumes. Currently this information is obtained mainly by ground survey methods, which despite their obvious advantages, are very slow and often hazardous. For extensive surveys, the information they provide is not always timely, and in many cases the method is very expensive. These problems have been overcome in a number of particular cases by the use of remote sensing.

The more readily available remote sensing techniques in Nigeria are aerial photography, satellite (Landsat) data and radar imagery. Both the acquisition and interpretation of these types of imagery are constrained by several factors.

3.1 Forest-type identification and area estimation

For its photogrammetric properties, high resolution, and familiar pictorial rendition, aerial photography has a higher forest information content than both Landsat and Side-looking Airborne Radar (SLAR) imagery. For extensive surveys, many photographs have to be handled at a time for consistent interpretation of the forest-types, hence aerial photography does not provide a broad synoptic view, as is the case with Landsat and SLAR. At a scale of 1:40,000 using 23 cm. by 23 cm. format, about 57,000 aerial photographs would be required to cover the Nigerian tropical high forest as against only five Landsat scenes or several SLAR strips. The uppermost trees, which are the only source of direct information of tropical high forests on aerial photographs, usually have closed and continuous canopy, hence percentage crown-closure has no interpretation value.

For forest-type delineation satellite sensing has the advantage of providing a very broad synoptic view, which is enhanced by the multispectral content and the capability for automatic (computer-aided) objective interpretation, but its value is reduced by the limitations of scale and resolution. SLAR also provides a broad synoptic view by continuous-strip imaging and sometimes extremely sensitive to changes in vegetal structure (Howard, 1976) but topography tends to be emphasised. This emphasis on topography and limitations of scale and resolution reduces the value of SLAR imagery for forest type delineation. Interpretation of forest-types on SLAR imagery could be enhanced by increasing the scale and improving the resolution of the existing radar systems.

The undisturbed tropical forest is a continuum with very few sharp boundaries, so that on remote sensor-imagery, the forest-types are very difficult to delineate. There is always a tendency to underestimate the number of existing types. Also, area estimations based on such delineations are only approximate. In the disturbed forest, there is a greater variety of types owing to the existence of farm-regrowth-forest mosaics created by human activities. Type-identification is, therefore, also very difficult and the number of types that actually exist is often over-estimated. Some success has been obtained by distinguishing forest areas according to the mixture of crown-sizes present (Langdalelaims before they are outdated by new evelopments. This makes rather difficult the choice f which technique to use. Also, the cost of repeated ersonnel training to keep abreast of new ideas and the purchase of equipment to replace outmoded ones becomes quite high. Similarly, the distance from commercially available hire of the latest equipment significantly increases the mobilization fees.

4. STATE OF THE ART IN NIGERIA

espite all these obstacles, remote sensing has been sed to some extent in various forestry projects in igeria. The survey procedures of the land use survey f Western Nigeria and the inventory of a group of orest reserves in Cross River State were based on hoto-interpretation for forest-type delineation and hotogrammetry for forest-map compilation (Kio, 971). The indicative inventory phase of the High orest Development Project took a long time to omplete (about four years) partly, but not mainly, ecause the sampling procedures were not based on emote sensing.

Probably for this reason, and the lack of adequate, p-to-date data on the various forest systems, on hich to base a planning framework to indicate the management alternatives available and the actions required to sustain the management system chosen, the Federal Government of Nigeria commissioned, in 1976, the NIRAD PROJECT (NIgeria RADar PROJECT) for the survey of the vegetation of the whole country. The entire country was covered by SLAR at a scale of 1:250,000. The results of this nation-wide survey to date appear promising.

There is a growing interest in the formation of a proper remote sensing unit which would have facilities for photographic reproduction of satellite information, as well as a data bank of all information available on the various forms of remote sensing that already exist or are planned for the future. The unit will be central and multidisciplinary.

5. CONCLUSIONS

espite the obstacles which hinder the use of emote sensing in the tropics, there are many alancing advantages. In order to derive optimum enefit from the well-known advantages of this aluable tool, further research should be conducted o improve the resolution and scale of the existing adar system, because of its suitability for sensing loud-prone tropical environments. Such a research rogramme should include the development of a equential and multispectral radar system capable of utomation and the development of reliable echniques of establishing ground control for small-cale satellite imagery.

Also, it is suggested that individual tropical ountries or groups of smaller countries should set p central remote sensing units to supply the nformation required by the various disciplines ccording to the need of each country. In addition, hey should embark on training programmes to provide the personnel to man these units and expand them. Such a central and multidisciplinary establishment will reduce cost which tends to override other factors that hinder the operational use of remote sensing. As radar can be operated under most weather conditions, a general coverage by radar is desirable. This can be supplemented, in a multistage sampling, by occasionally available satellite information and conventional aerial photography flown for the purpose of the intended survey. Such a framework will provide a basis for evolving economical and viable methodologies of co-ordinated use of the more readily available remote sensing techniques.

N.B. Opinions expressed or reflected in this paper are strictly personal and they do not necessarily reflect the opinions or the aspirations of the Federal Government of Nigeria or any government whatsoever.

6. REFERENCES

llen, P. E. T., (1977) personal communication.

arper, D., (1976): Eye in the Sky. Multiscience Publications Limited, Montreal, Canada.

oward, J. A., (1976): Remote Sensing of Tropical Forests with Special Reference to Satellite Imagery, F.A.O. Publications, AGD(RS)3/76.

oward, J. A. and Lanly, J. P., (1975): Remote Sensing for Tropical Forest Surveys. Unasylva, 27(2), 32-37.

io, P. R. O., (1971): The Status of Aerial Photo-interpretation in Nigerian Forestry, Nigerian Journal of Forestry, 1(2), 64-68.

Langdale-Brown, I., (1977) personal communication.

Latham, R. P. and McCarty, T. M., (1972): Recent Developments in Remote Sensing for Forestry. Journal of Forestry, 70(7), 398-402.

Ola-Adams, B. A. and Iyamabo, D. E., (1977): Conservation of Natural Vegetation of Nigeria. Environmental Conservation, 4(3), 217-226.

Richards, P. W., (1939): Ecological Studies on the Rain Forest of Southern Nigeria. 1: The Structure and Floristic Composition of the Primary Forest. Journal of Ecology, 27, 1-61.