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Remote Sensing
and Ecosystem Management

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Abstract

The application of remote sensing techniques to ecological studies has increased in recent years. Nevertheless, the potential contribution of remote sensing to the study of ecology in general, and to wildlife and ecosystem management specifically, has yet to be realized. It would appear that many of the aims and objectives of major international programmes concerned with the conservation of nature and natural resources can be met with the judicious use of remote sensing techniques, if these are suitably integrated with on-going programmes. It is misleading, however, to consider remote sensing as a replacement for existing programmes, as traditional field work and ground verification will always be required.

In the present paper operational remote sensing techniques with direct application to the management and conservation of wildlife and ecosystems are described and evaluated with particular emphasis on northern areas. The use of the eye as an electromagnetic sensor and as a system for providing data from visual surveys is examined and found to be less effective than aerial survey techniques, especially photographic surveys, which extend the human observation system and provide a permanent record of the subject under study.

Remote sensing from satellites yields a regional overview of the area under consideration and provides a basis for monitoring the dynamics of environmental change over time. Such data may also be used to design suitable sampling strategies when more detailed information about a particular area or aspect of the study is required. Such samples may then be obtained from aerial surveys conducted from aircraft, or by ground parties operating in the field. Remote sensing from aircraft also has an important role to play in the assessment of certain wildlife populations, providing a means for conducting an objective census of the population.

In conclusion, remote sensing can add a new dimension to many ecological studies, a dimension which is totally compatible and easily integrated with current programmes. Remote sensing data already available from LANDSAT and from aircraft surveys represent a major data source for ecologists and wildlife managers, administrators and legislators, who are involved in the on-going evaluation and decision-making process which will ultimately determine the future of the world ecosystem.

Introduction

Since 1950 there has been an increase in national and international recognition of the need for careful management of natural resources. The virtual extinction of some of the great whale species and the subsequent legislation and international agreements controlling whaling (McHugh 1974; Myers 1975) drew attention to the plight of animals hunted by man. Similar developments have occurred for other species. Notable amongst these are the native African fauna, many of which now survive only in National Parks because of over-exploitation and/or the destruction of their previous rangelands by man. The number of mammalian species threatened and/or in need of careful management has become the subject of international concern (I.U C.N. 1972). Migratory animals such as the Canada goose *Branta canadensis*, Finnish Reindeer *Rangifer tarandus*, and Polar bear *Ursus maritimus* pose particularly difficult management problems because their annual movements take them into several political jurisdictions and thus international agreements are required if effective conservation measures are to be implemented. The establishment of the Marine Mammal Commission in the United States, and international concern about the seal hunt in the Western Atlantic are further examples of the heightened consciousness towards the conservation of wildlife.

Not all management problems, however, stem from direct exploitation of animals or destruction of habitat by man. The events of recent years have provided examples of the inadvertent effects of technology on wildlife. The establishment of major industrial plants which produce noxious effluents, or the development of supertankers capable of discharging one quarter of a million tonnes of crude oil if they break up after an accident, now provide a continuous threat to both wildlife and wildlands. Such events, subsumed under the general public perception of pollution, imply an immediate need for action to protect and conserve wildlife. For these reasons governments increasingly require detailed knowledge of wildlife in order to protect it either in emergency situations or in the formulation of plans where adequate prior knowledge can prevent difficult consequences. The latter includes not only the establishment of reasonable hunting limits or quotas for wildlife populations, but also the intelligent planning of future land use. Similarly, the decision to introduce exotic species into an established community without careful consideration can create ecological imbalances which are difficult or impossible to correct.

Many of these difficulties are directly related to human population pressures which, in total, underline the need for man to improve the efficiency with which he manages the earth. Because of increasing population pressures it is no longer valid to assume that wilderness exists beyond the populated areas. Refugia previously used by wildlife are increasingly being disturbed by mineral prospecting, recreation complexes, and the greater freedom to travel into regions where travel was previously difficult. These refugia must nevertheless be protected if they are to continue their function as wildlife support areas. National and international awareness of these issues has resulted in crash programmes to delimit and document known refugia and record wildlife activity and distribution over large areas. For example, the Canadian Wildlife Service commissioned the preparation of an Arctic Ecology Map Series to identify and map critical wildlife areas in the Canadian Arctic (ANON. 1972). The principle objectives were to bring together as much data as possible on the habitats utilized by a number of important wildlife species, and to provide a planning tool for both government and industry to help preserve these wildlife areas. A similar concept was adopted by the International Biological Program (Conservation of Terrestrial Communities, IBP-CT) in Canada. They attempted to identify and protect a series of areas across the country, including the Arctic regions, as designated ecological sites (NETTLESHIP and SMITH (Eds.) 1975). Their mandate was "To identify and preserve samples of . . . biological communities for . . . basic and applied research on natural ecosystems", to protect and maintain "ecological and genetic diversity", and to provide baselines "for assessing human impact on the world" (McLAREN and PETERSON 1975). In another study the Canadian Arctic Resources Committee's working group report on the terrestrial environment concluded that national aims should be defined with special attention to seven objectives. These seven objectives included the further development of remote sensing techniques, and emphasized the role of remote sensing in monitoring seasonal, and other temporal changes in the environment. In addition they recommended a comprehensive land use plan built on an inventory of biophysical characteristics and other resources (PIMLOTT et al. (Eds.) 1972). More recently the UNESCO Program on Man and the Biosphere (MAB) has embarked on a Biosphere Reserve Program. These biosphere reserves will include examples of characteristic biomes identified by the International Union for the Conservation of Nature (I.U.C.N.) and integrated on a world-wide basis as conservation management units (Environment Canada 1975).

These programs have all emphasized the need for baseline surveys over extensive areas, including the world's oceans, the polar ice caps, and the northern areas of North America and Eurasia. They have also revealed that the available data for these remote areas are sporadic. This is a direct consequence of being poorly suited to human habitation. Their common characteristic is annual change of great magnitude in either temperature or surface characteristics or both. The change involved is so great that it can be regarded as an on-going process and the dynamics of change are difficult to monitor. This is particularly true of Arctic and sub-Arctic regions where the harshness of winter

makes the area unattractive and inhospitable for field work, and the summer makes travel through muskeg and tundra difficult. Collection of information throughout this extensive area is therefore strongly biased towards the summer season and the monitoring of seasonal conditions is very restricted.

Advances in our knowledge of such regions require a data source, regional in scale and temporal in nature providing information primarily about vegetation, water availability and about other abiotic components of the ecosystem which appear to be key factors in the regulation of animal populations.

Resources management has conventionally been conducted at the local level and data pertinent to this are assembled by specialists working in a defined area or on a specific topic. Often, the international or global context of their work is not established and the lack of coordination between such projects result in reports which feature exotic conditions and neglect the significant events which control the "natural" cycles of the regions being studied. Biologists at this level provide observations which enable managers to make extrapolations to larger areas where conditions appear similar, but where there are no active biological observers. Often such extrapolations are made with the aid of air photos. The expansion of this expertise to national or international scale requires the acquisition of regional scale data and a change in emphasis in the design and direction of existing programs.

This change can be effectively achieved by the judicious use of remote sensing techniques. These techniques provide a precisely controlled extension of the basic process of field observation. Integration of established field programs with the remote sensing data base appears to offer a most efficient approach to international programmes of wildlife management. The integration provides both qualitative and quantitative data for a region and permits inference which can subsequently be checked by field observers to determine its validity. Viewed in this way remote sensing extends the results of existing techniques rather than replacing them or reducing the need for them. In this paper the application of this integrated approach is considered for specific northern regions where conventional methods have proved to be costly, limited in extent and ineffective in providing the data base required by governments attempting to deal with the problems of wildlife management.

At the present time the earth resources satellite programme conducted by NASA has two operational satellites in orbit providing regional scale data with a repeat time of 18 days. Thus, data from this system are available every nine days because the two satellites are in the same orbit nine days apart. These regional scale data may be further amplified by lower altitude aircraft operations. These operations enable users to gather data at any desired scale and by appropriate choice of sensors, the data can have the spectral characteristics most suited to the purpose of the study. Therefore remote sensing instruments with appropriate characteristics can be flown at any desired altitude and thus may assist in the gathering of field observations from ground level to upper atmosphere and outer space (Fig. 3). This extension of the human observation system allows investigators to look at information in the visible spectrum and beyond the visible spectrum. Observations from remote sensing instruments are

quantified and can also be reproduced in their most efficient form as visual images.

Results of LANDSAT data analyses published by NASA indicate that satellites provide reliable information about vegetation and hydrology. Applications of this in several disciplines are well documented and some work on biological applications for habitat mapping, estimation of environmental conditions, and analysis of wildlands and wildlife conditions, indicates the utility of these data for regional observations. These studies exemplify the value of satellite imagery as a holistic view of the earth's surface and from this the extraction of appropriate data is a relatively simple procedure. Some applications of this approach to the study of wildlife populations are described below.

Concern for management of wildlife populations has also created the need for knowledge of animal numbers. The response to this need has often involved the construction of theoretical models incorporating available information about population size, birthrate, survival and the factors which affect these parameters. Success of these models in population management depends upon the accuracy of the parameter estimates and modifications must be made continually to update the model as more information becomes available. Recent studies indicate that remote sensing has an important role to play in monitoring populations of large mammals and in taking a direct census of certain animals under ideal conditions. The work reported below, together with theoretical and practical considerations, suggests that remote sensing can make a significant contribution to the field of wildlife management if properly used.

Remote sensing applications considered in this work are limited to techniques readily available and operational. These include sensing in the visible portion of the electromagnetic spectrum, using both human observers and photographic equipment, and photographic sensing beyond the visible spectrum including ultraviolet, and near infrared (false colour) wavelengths. In addition, the use of scanning systems which record thermal infrared or heat radiation so that it may be reproduced in photographic form, will also be discussed.

The incorporation of remote sensing as an integral tool in ecological studies is a recent phenomenon. For example, the first North American Workshop dealing strictly with Remote Sensing of Wildlife was held in November 1975 (Gouvernement du Quebéc 1975). It appears that in the future remote sensing will play an increasingly important role in monitoring environmental changes whether natural or man-made, and become an integral component of environmental impact studies, land-use planning and wildlife management programs.

The purpose of the present paper is to outline some of the theoretical and practical considerations related to the use of remote sensing techniques in ecological studies. For more detailed information and an encyclopaedic overview of remote sensing we refer the reader to the Manual of Remote Sensing, Volumes 1 and 2, recently published by the American Society of Photogrammetry (1975).

Electromagnetic Radiation

All remote sensing techniques involve the detection of electromagnetic radiation. Electromagnetic radiation exists as a continuum of wavelengths or frequencies from short wavelength — high frequency gamma rays to long wavelength –– low frequency microwaves and beyond (Table 1). Remote sensing capabilities have been developed which utilize much of this radiation, especially that part of the electromagnetic spectrum which continually enters the earth's atmosphere from the sun. Solar radiation which reaches the surface of the earth after being filtered, absorbed, scattered and reflected by the atmosphere, comprises wavelengths primarily from about 290 nm to about 3000 nm, and includes the near ultraviolet, visible, and near infrared regions of the electromagnetic spectrum. Several segments of the solar spectrum beyond 3000 nm do reach the earth's surface, but their contribution to the total amount of solar radiation received is almost negligible (GATES 1962), and of no significance to our present discussion. Ultraviolet wavelengths shorter than 290 nm are filtered out by the ozone layer surrounding the earth. Most wavelengths longer than 3000 nm are also filtered out by the atmosphere before reaching the earth's surface.

Table 1

The Electromagnetic Spectrum *

Region			Approximate Wavelength Range	
Gamma Rays			0.0006–	0.1 nm **
X Rays			0.01–	10 nm
Ultraviolet Radiation			10–	400 nm
Far UV	2.5–	200 nm		
Middle UV	200–	290 nm		
Near UV	290–	400 nm		
Visible light			400–	700 nm
Infrared Radiation			700–	1,000,000 nm
Near IR	700–	1,500 nm		
Middle IR	1,500–	2,500 nm		
Far IR	2,500–	1,000,000 nm		
Radio, TV, and microwaves (including radar)			$1,000,000 - 17 \times 10^{12}$ nm	
Very long electromagnetic waves			$> 17 \times 10^{12}$ nm	

* From various sources including GATES (1962), PARKER and WOLFF (1965), GRAY and COUTTS (1966) and CRONIN et al. (1968).

** 1 nanometre (nm) = 10 Angstroms = 10^{-9} metres.

Note: The electromagnetic spectrum is a continuum of wavelengths. Dividing the spectrum into bands for descriptive purposes is convenient but somewhat arbitrary. Variations on the limits shown here may be found in the literature. When viewed on a logarithmic scale, these differences are not significant.

Regions of the electromagnetic spectrum outside the solar spectrum at the earth's surface which have been utilized in remote sensing include parts of the middle and far infrared radiations (thermal infrared) and microwaves including radar.

This paper will limit its discussion to sensors which are readily available for use in wildlife management and which have particular relevance to ecological problems. These sensors include photographic systems recording information based on detection of reflected solar radiation. In addition, the use of optical-mechanical scanners in detection of thermal infrared radiation emitted as heat from warm surfaces has a variety of uses including detection of homeotherms (CROON et al. 1968; McCULLOUGH et al. 1969; GRAVES et al. 1972; ØRITSLAND and LAVIGNE 1976), thermal pollution (TAYLOR and STINGELIN 1969), forest fires (THACKERY 1968; HIRSCH et al. 1971) and surface water temperatures (TAYLOR and STINGELIN 1969). In fact, infrared thermal scanners are potentially useful in any ecological study where a slight difference in temperature exists between the object under study, and the background.

Observations made by biologists in the field are based on, and limited to, detection of reflected radiation by the eye and are thus confined to the visible spectrum only. Modern remote sensing techniques are thus capable of extending our vision beyond the limits of the visible spectrum (Fig. 1), providing new and more detailed information about our surroundings.

Sensors

In the field of remote sensing the general term "sensor" is used to include all systems which record reflected or radiated electromagnetic energy. Thus the term sensor typically includes camera systems, scanners, radar systems and any similar device which detects electromagnetic radiation from a distance. For convenience, the sensors commonly available can be considered to comprise two main groups, camera systems, and other imaging systems. The ultimate sensor in any remote sensing study is, of course, the human eye. Since visual observations have historically formed the basis of biological studies in the field, and will continue to do so, the role of human vision as a sensor in wildlife investigations cannot be overlooked.

Wildlife management requires information about animal species behaviour, habitat requirements and related factors. For remote sensing to have a valid input into wildlife management it must contribute pertinent data. These data must therefore provide information about animal species, behaviour, habitat, and similar factors. Remote sensing is conventionally used in this manner to provide illustrations in taxonomic studies and such illustrations take the form of photographs using information from the visible spectrum recorded on black and white or colour film. By judicious use of films and filters the resulting image is usually enhanced by the photographer to reveal the important features of the subject. The value of such an image in species identification is underlined by the fact that many biologists use standard photographic images as the criterion by
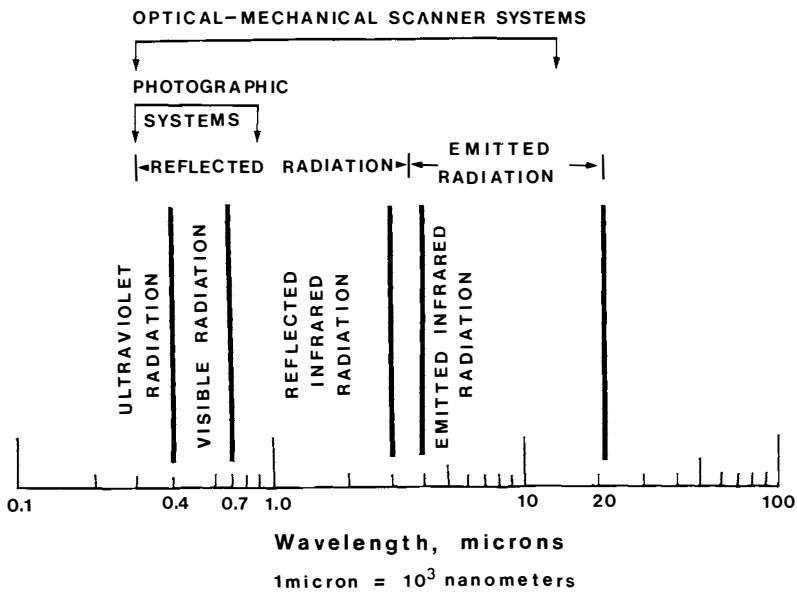
Fig. 1. *The electromagnetic spectrum, showing the regions generally pertinent to remote sensing, and the types of sensors which are used in these regions. (Redrawn from numerous sources).*

which they assign species names to animals they observe in the field or laboratory.

In a complete discussion of sensors there is a place for detailed consideration of cameras, films and lens systems used in animal observation from blinds. Telephoto lenses used to record animal behaviour from remote locations are also a portion of this discussion. However, these topics are adequately covered in the literature on photography and form a conventional and readily accepted part of the theses, papers and reports of scientists studying wildlife. These techniques are valid only for species which, in the visible portion of the spectrum, display their distinguishing features clearly in contrast to the background. Animal camouflage is an effective method of natural simulation of signatures in the visible spectrum and makes the animal difficult to distinguish from its background. This technique has been adopted by man particularly in military activity and the effectiveness of military camouflage is well understood as an extension of the principles of animal camouflage.

Sophistication of military techniques in camouflage detection led to the development of camouflage detection film, now a well-known and understood material which is sensitive to energy at wavelengths greater than those of visible light. At these wavelengths healthy plants can be distinguished from plants suffering stress because of the differences in their reflection of solar radiation. Because such wavelengths are just greater than those of red light in the visible spectrum they are referred to as infrared wavelengths but in the range for which camouflage detection film is effective (450–1.200 nm) this is solely reflected solar energy; it is not heat energy radiating from a thermal source within the subject.

Detection of heat energy by remote sensors is now commonly undertaken in the field using radiation thermometers (e.g. Barnes Engineering Co., Standford Conn., PRT-5). But the results obtained are instantaneous and only for a point (ØRITSLAND and LAVIGNE 1976). Refinements of this concept have been in use as survey devices in aircraft for several years. These devices, known as scanners, survey a scene in a manner similar to a television camera and record thermal radiation. The product of this system can be an image displayed in grey levels which is effectively a heat map, each grey level being equated with a specific temperature range. More sophisticated devices record energy reflected or radiated in other portions of the electromagnetic spectrum in the same manner. The more complex of these may record information in several spectral regions simultaneously and these are known as multi-spectral scanners.

The value of these devices is in the area of contrast enhancement and by careful use of this characteristic the appropriate sensors can yield very detailed information of value to the wildlife managers. Aspects of this are considered in greater detail below. The products of these devices may also be displayed in grey levels or in colour. Information once collected may be arbitrarily blended to give colour balances which are readily interpreted by the human observer which emphasizes again the critical importance of the human visual system in remote sensing studies.

The Eye

The ultimate aim of wildlife studies is to introduce pertinent information into the brain of the wildlife biologist. The most efficient method of achieving this is through the human visual system. This is of course, the basic reason for the photographic, computer printer, or cathode ray tube (CRT) display of all remote sensing data products. In addition, visual search is obviously the most common method of initially detecting animals in the field, and making observations of habitat features.

Despite the importance of the eye as a sensor, its capabilities are limited and must be recognized. The human eye is sensitive to a very restricted part of the electromagnetic spectrum lying between about 400–700 nm (Table 1). By definition, this narrow band of electromagnetic radiation is known as "light". In addition, the eye is not equally sensitive to all wavelengths or colours of light. Under daylight (light-adapted or photopic) conditions, the eye is maximally sensitive to the yellow-green part of the spectrum between 550–560 nm. Spectral sensitivity drops off towards either end of the visible spectrum. Sensitivity also changes in response to the background illumination. Thus under the dim light conditions of early morning and at dusk, not only is the spectral composition of sunlight changed, but so is the sensitivity of the eye.

Despite these sensitivity limitations, unaided human vision is quite satisfactory for detecting many animals, either from the ground, or from aircraft. Well camouflaged animals emphasize the limitations of the eye as a sensor. For example, it is not easy to detect a white polar bear, or a white-coated seal pup against a white background of ice and snow.

Two other problems influence the usefulness of the eye in remote sensing studies. Firstly, the eye provides no permanent record of observations for future study and further detailed analysis. Secondly, visual observations are open to subjective assessments, biased by the experience and motivation of the observer, and his preconceptions about the direction and purpose of his research.

Modern remote sensing technology extends man's vision by retrieving data from beyond the visible spectrum and reformating these data to maximize contrast and thus perception and interpretation, within the confines of the visible spectrum.

The fundamentals of this extension of our vision by remote sensing devices can perhaps best be appreciated by considering an example, the television set. Long wave television waves (invisible to the human eye) are displayed on the television CRT (picture tube). The signals, which are received, and then projected on a screen, may be adjusted in terms of colour, contrast, and brightness, to provide an image which the eye can detect and interpret. Acceptable pictures are therefore images consistent with the viewer's perception of the world. The television set is thus a typical remote sensing receiver, displaying TV microwaves received from a distance in a form which can be seen, and interpreted by the human eye and brain.

Having accepted the ultimate position of the human eye and brain in remote sensing studies, it is important to note the secondary sensors available to the biologist involved in wildlife management.

Camera Systems

Camera systems are quite well understood and in general are accepted devices used in earth survey work. The great variety of camera systems which are available and their versatility are less well understood and appreciated. It is pertinent to consider several types of camera systems.

Wildlife study and management can, and often does benefit from the use of photographic images of both animals and their habitat. These are commonly used by field biologists in the preparation of reports and scientific publications. These photographs are usually oblique views using 35 mm cameras with various lens, filter, and film combinations. Such practice is consistent with the old cliché — a picture is worth a thousand words. This is perhaps the most important generalization which can be made in support of the use of remote sensing devices in the study of nature and natural resources. Detailed aerial surveys using vertical photography typically utilize panchromatic (black and white) film with a characteristic spectral response to a range of electromagnetic radiation slightly greater than the visible spectrum (Fig. 2). This type of photography frequently uses $9'' \times 9''$ (22.9 cm $\times$ 22.9 cm) format, but increasing use is being made of lower cost 35 mm and 70 mm systems for rapid surveys of vegetation, or for other earth resources information.

Examples of photography outside the visible spectrum include the use of infrared false colour film with an appropriate filter (e.g., Wratten 12, Eastman Kodak, Rochester), and ultraviolet photography, made possible by means of a lens which will transmit sufficient amounts of near ultraviolet radiation, e.g. a
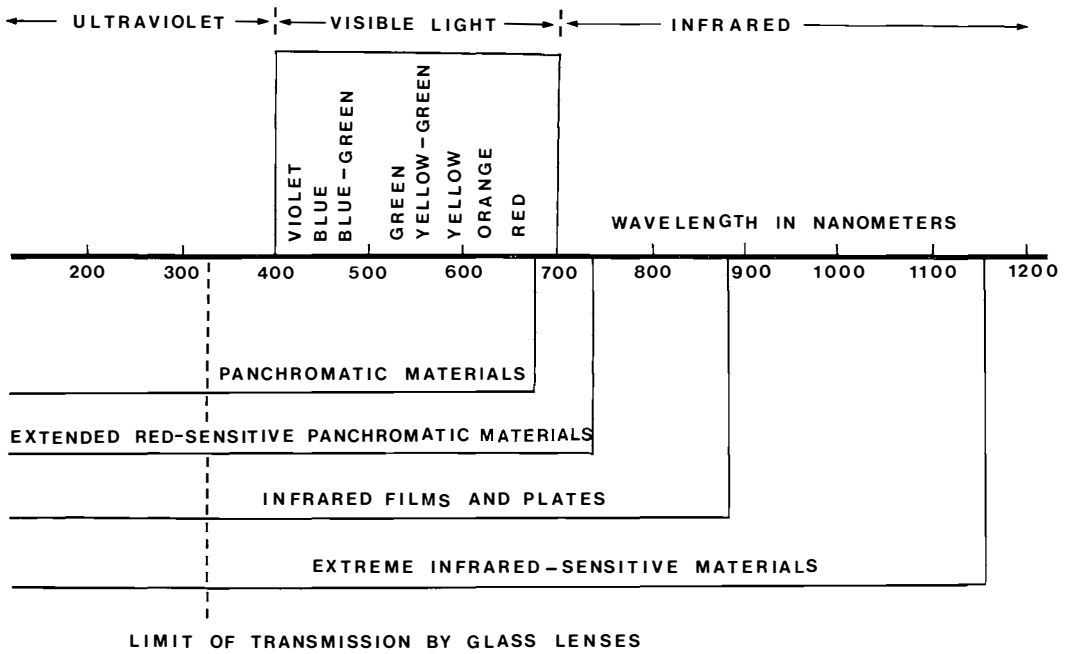
Fig. 2. *The region of the electromagnetic spectrum typically detected by photographic means, and the photographic materials which are used for specific wavelength ranges. (Redrawn from numerous sources).*

quartz lens, and an ultraviolet transmitting filter which is opaque to the visible spectrum, e.g. Wratten 18A (Eastman Kodak, Rochester) (LAVIGNE and ØRITSLAND 1974a, b).

If two or more cameras are trained at the same scene and each records a different portion of the electromagnetic energy the system is described as a multi-spectral camera system and each camera yields a black and white image of a given portion of the spectrum. This technique is particularly effective because each image provides different levels of detail about the target area. The camera filtered to record the near infrared portion of the spectrum between 700–900 nm provides good data about vegetation health and vigour. The portion of the spectrum between 600 and 700 nm is particularly good for recording detail of urban areas. If three or more such cameras are employed, combinations of three images of the same scene can be used to create a composite colour image. This approach is particularly useful for enhancing contrast of specific subjects, and should not be confused with colour imagery which is generated directly on film with a multilayer emulsion to produce a colour image.

Colour photography using survey cameras can take a similar form. Natural colour photography recording light in the visible spectrum is a very useful extension of the conventional black and white photography. Additional information from coloured images can be of considerable value. By appropriate use of filters the range of recorded wavelengths can be restricted so that atmospheric scattering of light in the blue-green portion of the spectrum can be omitted from the image and thus produce a clearer photograph. Similarly false

colour film (also called colour-infrared or camouflage detection film) which is sensitive to the near infrared energy but not to the blue-violet portion of the spectrum produces a compound image. In this film the near infrared information is recorded by a magenta dye. This produces a rich magenta tone for healthy vegetation and purple-blue tones for unhealthy or less vigorous vegetation. This colouration is regarded as conventional for false colour images.

Camera systems are those which create photographs by instantaneous exposure of a photographic emulsion to a whole scene. The product is a "hard copy" photographic image in either positive or negative form from which copies can be made. No copy can ever completely reproduce the original although the loss of information in first or even second generation copies is negligible. For maximum detail it has been suggested that the original negative or positive should be used for image interpretation (HEYLAND pers. comm.). Transparencies viewed on a light table also seem to offer advantages over conventional photographs for many types of studies.

Developments in photographic sensors during this century have refined camera systems to a very high degree. The difficulties with photographic information include image deterioration during processing and storage, and the slow retrieval of data for detailed analysis. Data processing is now increasingly based upon digital systems and the data available from electromagnetic scanners can be readily converted into digital form for manipulation by the large and sophisticated systems now available. Such sensors operate equally well in the visible portion of the spectrum and development of these has been rapid during the last decade. As a result there is a growing tendency for these sensors to dominate the literature on current remote sensing techniques. Whilst this is a feature of sensor marketing it is important to note that visual display of the data, often in photographic form is essential for effective communication to the modern ecologist.

Scanner Systems

Electromagnetic energy can also be detected by electronic systems and, as with television systems, this detection may include visible light, audio frequencies, or other selected portions of the electromagnetic spectrum. Such remote sensing devices, including television cameras, gather data by electronic means and are usually scanning systems. Scanner systems have detectors which move across an aperture and record the received energy at a very rapid rate; each record forms a brightness level for a discrete portion of that scan line. The detector then returns to its starting position and scans another line in the same manner. If the device is moved forward at an appropriate rate, the sequence of scan lines can be reassembled to produce an image. The resulting data record is somewhat comparable to a television signal and as with television the record may be stored on magnetic tape or transmitted directly to an appropriate receiver.

The energy recorded or transmitted can be constrained to selected ranges of electromagnetic energy by judicious choice of detectors, and the ways in which the signal from the detector is analysed. The number of discrete portions of the

spectrum into which the detected signal may be divided defines the type of scanner. Thus a detector producing a signal which is divided into two portions, e.g. visible light and near infrared, is defined as a 2 channel scanner. Scanners are very versatile and are currently available in 4, 8, 12 and 24 channel models. Such scanners are flown in aircraft and spacecraft and are used in recording information at ground level also. This principle is extended into various portions of the spectrum including ultraviolet and infrared and scanners which detect radiated (emitted) heat are used in a variety of applications. Scanners which detect thermal energy are a specialized version of a radiation thermometer and have numerous applications in wildlife studies as noted previously and discussed below. Thermal energy is radiated in a range from 2000–100,000 nm for bodies with temperatures at or near 27°C. Only for bodies with temperatures greater than 527°C can we see colour in the visible spectrum which relates to heat and gives us an optical thermometer, "red hot", "white hot", etc. Thus, emitted thermal energy which we can feel as heat is in the range from 2000 nm to 100,000 nm and this is frequently referred to as thermal infrared (thermal IR) or middle and far infrared wavelengths. Near IR refers to wavelengths close to those of visible red light in the range 700 nm–1500 nm and specifically excludes radiated (emitted) heat (Table 1).

Remote sensing using scanners has two important applications. The use of radiation thermometers in studies of animals to determine the thermal characteristics of their skin or coat under various conditions is legitimately a part of remote sensing which is of particular value to environmental physiologists (ØRITSLAND et al. 1974; ØRITSLAND and LAVIGNE 1976). These studies utilize the same type of information as thermal scanners operating in aircraft and experiments have also been conducted to attempt animal censuses using thermal scanner data gathered by aircraft. False-colour (near infrared) scanner data are also valuable to the ecologist. These data reveal the relative abundance and health of green vegetation very clearly and studies of crop disease, infestation or damage by weather have been successively conducted using scanner data. The results of such studies include the ability to locate and describe the extent of habitat destruction, record anomalous environmental conditions, or permit biomass estimates of vegetation for use in bioenergetics studies. Thus scanner data can provide valuable information about vegetation and habitat conditions in the near infrared region of the spectrum. The radiometric fidelity of a scanner is more constant than that of conventional camera systems in the infrared thereby providing better quantitative data than could be obtained by photography.

As with all sensors, scale is determined by the altitude of the sensor platform. Thus regional data are produced by sensors carried on spacecraft and the most notable of these is the first of the Earth Resources Technology Satellites, launched as ERTS-1 but renamed LANDSAT-1 when the second satellite in the series was launched and named LANDSAT-2. These two satellites produce imagery from 4-band multispectral scanners. Each satellite is in similar orbit taking 18 days to view all of the earth between 82°N and 82°S. LANDSAT-2 is nine days behind LANDSAT-1 in this orbit pattern and each orbit is timed so

that it passes over each point at 0942 h local sun time at an altitude of 900–950 km. The field of view of the scanner is 185 km wide at the surface of the earth with a minimum resolution of 79 m × 56 m. Each scene thus covers 33,000 km² of the earth's surface. The continuous swath viewed by the scanner is 185 km wide and the data, transmitted to receiving stations around the world, are recorded in 185 km units to give a square format image similar to a conventional air photograph. In the 18.5 × 18.5 cm format, these images are at a 1 : 1,000,000 scale.

At this scale the images provide a reasonable overview and this view is in four regions of the electromagnetic spectrum identified as band 4, 500–600 nm; band 5, 600–700 nm; band 6, 7–800 nm; and band 7, 800–1100 nm. Bands 4 and 5 thus include the green, yellow, and red portion of the visible spectrum. Bands 6 and 7 include the near infrared region which is reflected by green vegetation. Band 7 is also a portion of the spectrum which is strongly absorbed by water. The images therefore provide a good record of vegetation and water distribution as well as the record of the information in the visible spectrum.

Other Systems

Remote sensing devices also include sensors which detect other wavelengths of energy reflected or emitted by the earth. Microwave systems including radar imaging systems do exist and have provided useful biological information (e.g. BLOKPOEL 1975) but are not in general use. Passive microwave systems are also in experimental use. In general, sensors of this type including laser sensors should at the present time be regarded as experimental and not commonly available for routine use in wildlife studies. Those which are available are scanning systems and operate in the manner described above but record information in other regions of the electromagnetic spectrum.

Scale

In any application of remote sensing it is necessary to define the scale of the imagery which is gathered. The basic principles of this are simple. The greater the distance between the sensor and the scene the larger the area of view and, the larger the area of view the greater the amount of information which is provided to each element of the image. This latter point is the important control on resolution in an image because each type of image has a unit which cannot be subdivided; this is the grain size of the emulsion in photographs or the picture element (pixel) in scenes recorded electronically. In images created at a 1 : 1 scale the minimum element of the photographic emulsion defines the minimum size of object which can appear on the photograph. This simplified view can easily be extended so that images created at a scale of 1 : 20 may have the same minimum element in the photographic emulsion. But the photograph will record no object, which in reality is smaller than the theoretical limit of resolution, which may appear in the image.

A further complication is that the reflected electromagnetic energy which is focused on the emulsion in the photographic process comprises the reflected energy of each individual item within the field of view. In the same way that a poor focus results in a very generalized picture which gives only the average colour or grey level of the whole scene, each minimum element of photographic emulsion or electronic picture record produces a single colour or grey level from the portion of the scene it is recording. When scale becomes very small this effect becomes important. Equally, to reduce this effect, close-up photography and very fine grained photographic emulsions can be used.

The question of scale thus becomes a question of how much information is required in each image and at what level of detail. Wildlife biologists intent on recording species will require detailed photographs of the animals, but a close-up of an entire big-game animal will not be so finely detailed as a close-up of a small bird. Considerations of this type are automatically included in the decisions of biologists on a day-to-day basis. Some wildlife managers have extended this principle to the management of large areas by use of light aircraft for survey and census work and for monitoring environmental conditions. There are numerous examples of this practice in the scientific literature (e.g. SWANK et al. (Eds.) 1969). The question of scale in these instances resolves into a question of aircraft altitude. Thus, locating and surveying white rhinoceros *Ceratotherium sinum* in the grassland area of a wildlife park can be undertaken at a much greater altitude than surveys intended to locate poaching parties intent on concealment (WHEATER 1969; Ross 1969).

In general, low altitude flights provide the most detailed view and high altitude flights provide the most extensive view (Fig. 3). Consequently remote sensing activities are constrained in the same manner. An aircraft flying at an altitude of 305 m using a camera with a 152.5 mm lens and 229 mm aerial film gathers images at a scale of 1 : 2000 so that an object 2 m in length on the ground appears 1 mm in length on the image. The same aircraft and camera at 3050 m gathers images at 1 : 20,000 so that an object 2 m in length on the ground appears 100 μ (10,000 nm) long in the image and at 30,500 m the system produces an image at 1 : 200,000 which would provide a unit length of 10 μ (1000 nm) for the 2 m object if the emulsion of the film were capable of recording this coherently.

With this in mind it becomes clear that different scales of imagery must be used for different purposes and, as an image of a mouse from an altitude of 305 m shows little detail of the mouse, the converse is equally true, an image of a mouse from 1 m provides little information about its habitat, social behaviour or regional context. This point is extremely well made in a study of beluga whales *Delphinapterus leucas* by HEYLAND (1974) where the detail of film type, altitude and subject definition are clearly presented. Film selection was not a serious problem since the white whales were well contrasted against the blue water.

HEYLAND obtained images at scales of 1 : 24,000, 1 : 18,000, 1 : 12,000, 1 : 8000 and 1 : 2000. Representative images, of the Cunningham Inlet area, Northwest Territories, Canada, at scales of 1 : 24,000, 1 : 8000, and 1 : 2000
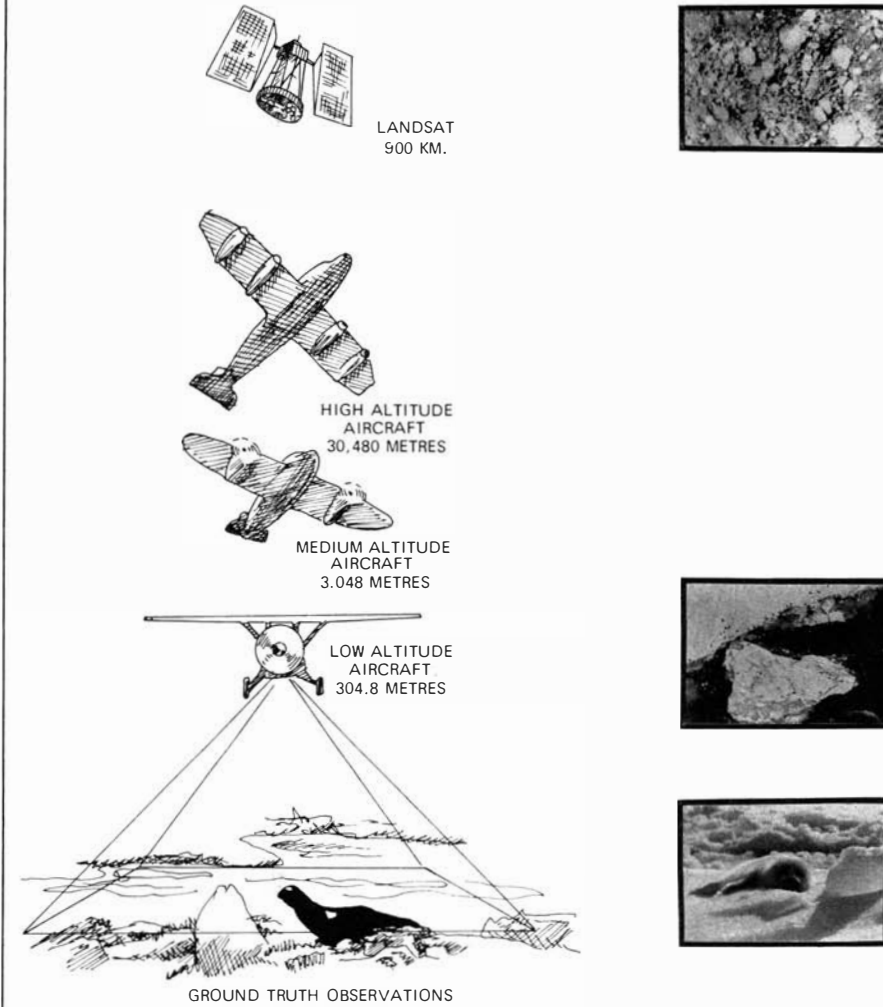
REMOTE SENSING - LEVELS OF OBSERVATION

LANDSAT
900 KM.

HIGH ALTITUDE
AIRCRAFT
30,480 METRES

MEDIUM ALTITUDE
AIRCRAFT
3.048 METRES

LOW ALTITUDE
AIRCRAFT
304.8 METRES

GROUND TRUTH OBSERVATIONS

Fig. 3. *Levels of observation commonly utilized in remote sensing work.*

Fig. 4. *Vertical photograph of the head of Cunningham Inlet, Somerset Island N.W.T., 30 July, 1973. Beluga whales*, Delphinapterus leucas, *are concentrated in the creek mouths. Scale 1 : 24,000. (Courtesy* J. D. HEYLAND).

- 21 -

Fig. 5. *The same scene shown in Fig. 4, at a scale of 1 : 8000. (Courtesy* J. D. HEYLAND).
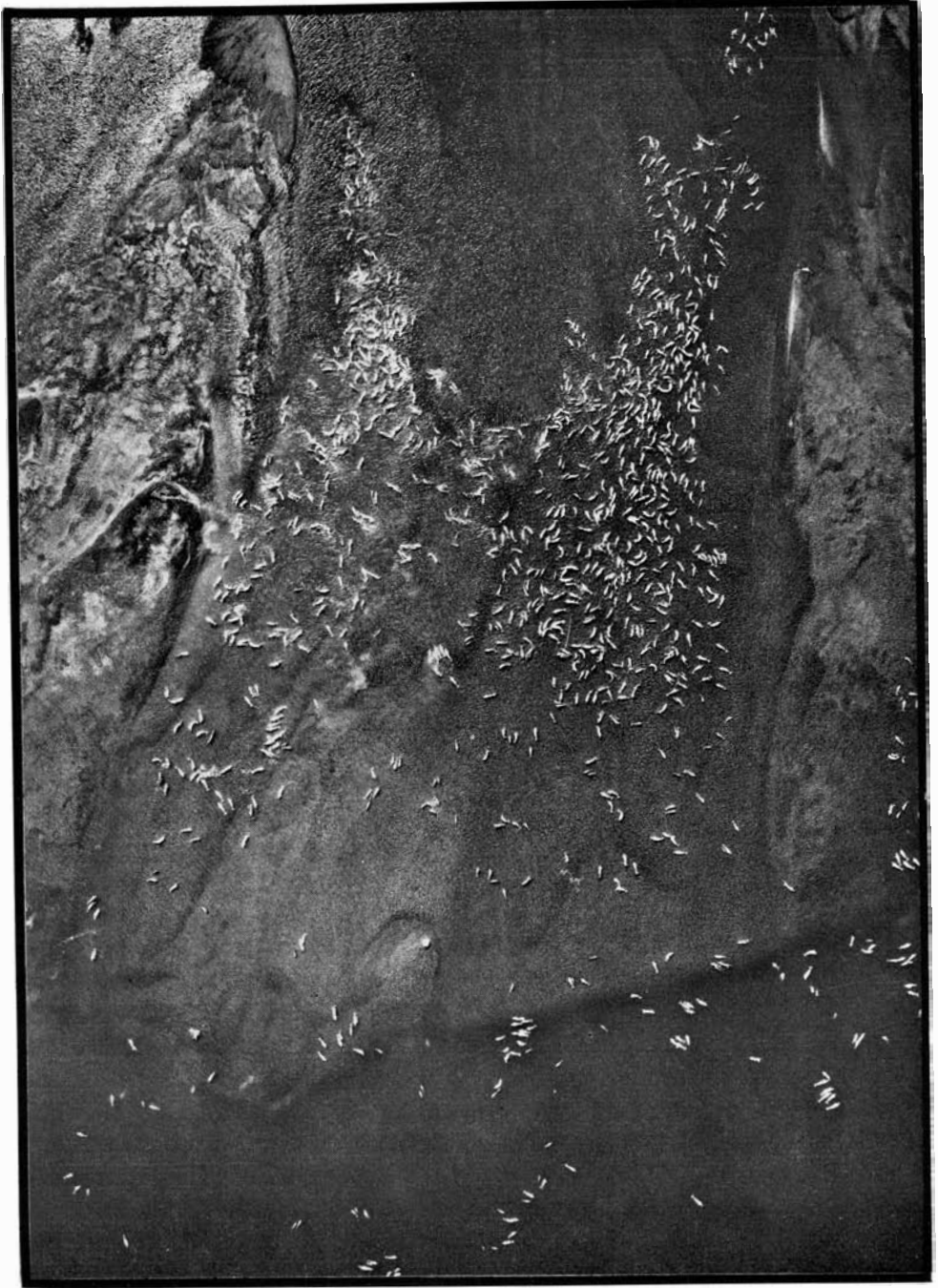
Fig. 6. *Some of the whales in Figs. 4 and 5, at a scale of 1 : 2000. (Courtesy* J. D. HEYLAND).

are reproduced in Figs. 4, 5, and 6, respectively. At scales of 1 : 2000 (Fig. 6), linear measurements of individual whales can be taken and by using pairs of stereoscopic photographs, some inferences about their depth and attitude may also be recorded. HEYLAND (1974) summarized the value of using different scales of imagery in the following statement.

> "White whales can be recorded on a variety of panchromatic films at a number of scales but not all photographs can be used to measure the same parameters. For example, although it is possible to detect large concentrations of whales on photographs at a scale of 1:60,000 it would be very difficult to count them. Linear measurements of whales can be obtained on photos at 1:2,000 but because of the narrow coverage per exposure it is difficult to obtain an appreciation of the distribution of the herd."

The extent and location of the whale herd can be clearly understood at a scale of 1 : 24,000 (Fig. 4). At scales of 1 : 8000 (Fig. 5) and 1 : 2000 (Fig. 6) individual animals may be seen more clearly and the possibility of obtaining accurate counts is greatly enhanced, but the locational perspective of the 1 : 24,000 scale image is lost. A satellite image of the same area at a scale of 1 : 1,000,000 provides the full regional context of Cunningham Inlet (FALCONER and LAVIGNE 1975) where the whales were photographed.

Photographic records of beluga whales at even lower altitudes provide additional information about the animals' behaviour. LAURIN (pers. comm.) has used 35 mm photography with a 200 mm lens from an altitude of 280 m to observe and record beluga whale behaviour in the St. Lawrence estuary. From his imagery it is easy to observe the size and organization of a school of whales, and to plot their movements through time (Fig. 7).

The question of scale therefore centres around the degree of detail desired and the size of the subject to be imaged. These components define the required elevation of the sensors to produce the necessary detail of the subject in question. This, however, fails to adequately cover situations which are frequently encountered where animals cannot easily be viewed. This is particularly the case with animals which are camouflaged or with animals which live in habitats which provide extensive cover. Camouflage detection, as described in this paper can aid greatly in imaging such animals directly, and the problem of scale must again be resolved with reference to the animal. Animals which live with extensive cover provide a more difficult problem.

Forest animals or animals living beneath a canopy of herbaceous plants are not easily detected by remote sensing techniques. This does not, however, imply that remote sensing techniques are of no value in the management of such species. If the animal cannot be detected it may be possible to study the region in which the animal lives and map the habitat zones. If this is done for the pertinent components of habitat, the extent of the habitat type, its quality, and its accessability can be efficiently mapped from photographic imagery. This application is well documented in the scientific literature (e.g. SWANK et al. (Eds.) 1969; American Society of Photogrammetry 1975; FALCONER and LAVIGNE 1975).
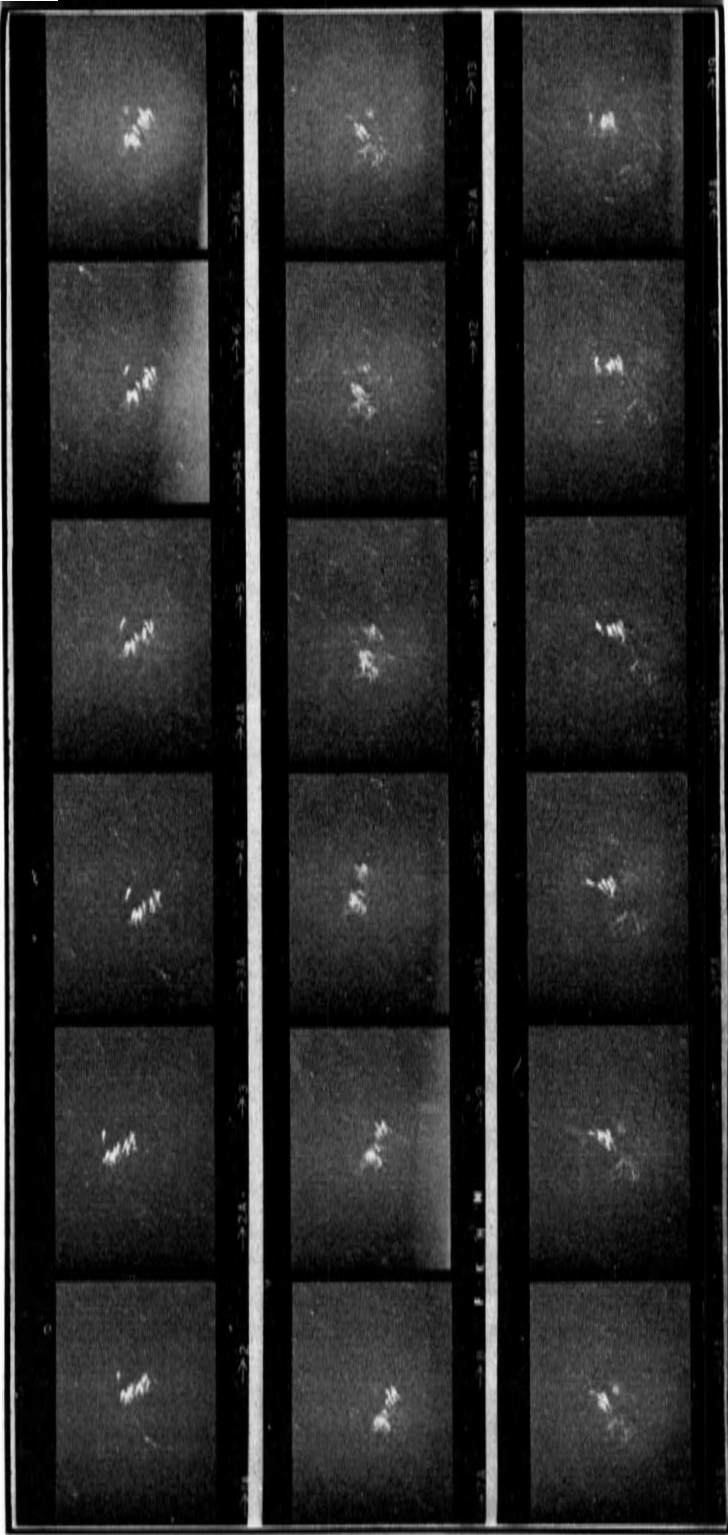
Fig. 7. *Low altitude remote sensing with a hand-held 35 mm camera can be used to study animals in the field.* LAURIN *(pers. comm.) has used this approach to study beluga whales* Delphinapterus leucas. *From a helicopter, hovering at 280 m, and with a 200 mm lens, he photographed a school of whales in the St. Laurence estuary at 2 sec intervals. In frame 1, the animals can be seen swimming near the surface. They begin to dive at frame 7, resurfacing at frame 15, and diving again at frame 18. Such imagery provides a permanent record of the whales which may be carefully studied and analysed to gain further insights into their behaviour. (Courtesy J. LAURIN).*

Remote Sensing Animal Populations

A variety of remote sensing techniques have been used to obtain a quantitative assessment or census of wildlife populations. Such surveys are usually restricted to certain large mammals and birds, and are often conducted from low flying aircraft. In order to obtain meaningful results from an aerial census it is imperative that the biology of the species in question is well known. A knowledge of the temporal and spatial distribution and behaviour of the animal, on a diurnal basis with respect to the particular time of year the survey is conducted, is a prerequisite to embarking on any aerial survey. Assuming that the biology of the animal is well known, selection of an appropriate sensor, the optimum time for conducting the survey, and the survey design are further obstacles to a successful census.

Three types of remote sensing techniques predominate in animal census work to date. These include visual estimates made by human observers, a variety of photographic surveys, and the use of thermal infrared scanners which detect temperature differences between an animal and its background.

Visual Estimation

Estimates of wildlife population numbers are often made visually by observers in low flying aircraft. These censuses are conducted in a variety of ways. Individual animals may be observed, counted, and tallied, and the total count serves as an estimate of population numbers. When large areas must be covered and a direct count is not possible, visual sensing may also be used to obtain samples, from which population estimates may be derived (SINIFF and SKOG 1964). Animals which have been censused in this manner include moose, *Alces alces* (LERESCHE and RAUSCH 1974), deer *Odocoileus hemionus* (GILBERT and GRIEB 1957), ringed seals *Phoca (Pusa) hispida* (SMITH 1973), foxes *Vulpes vulpes* (SARGEANT et al. 1975), and brown bears *Ursus arctos* (ERICKSON and SINIFF 1963). Such surveys inevitably underestimate the actual number of animals in a given area because of a variety of visibility problems (BERGERUD 1968; CAUGHLEY 1972; 1974). Thus they provide only "rough" estimates of population numbers (CAUGHLEY 1974), relative estimates or trend indicators of abundance (LERESCHE and RAUSCH 1974), rather than accurate estimates of population size.

A far more nebulous type of aerial census involves visual estimation of large numbers of animals in a group or aggregation, where it is impossible to count individual animals. Estimates of this type have been made for a variety of avian species, especially waterfowl, where the number of birds in a flock are estimated by eye (e.g. STEVEN 1967; KERBES 1975). Visual surveys of this type are also commonly used to census marine mammal populations (WARTZOK and RAY 1975) including concentrations of harp seals *Pagophilus groenlandicus* on whelping patches in the western Atlantic (MUIR 1975). In this type of survey numbers of animals are "eye-balled" or estimated, not by counting, but by "guestimating", occasionally with reference to standards, such as photographs of

known numbers of birds in a flock (STEVEN 1967). Such surveys often appear to be analogous to estimating the number of beans in a jar, or the number of dots on a page (Figs. 9 and 10).

A few experiments have been conducted to test the precision and accuracy of human observers in estimating the numbers of objects in a defined area. The results of these experiments emphasize the problems associated with obtaining meaningful estimates of animal numbers in the field.

In one preliminary experiment (LAVIGNE unpublished), a group of under-graduate zoology students (n = 134) was presented with three transparencies (Figs. 8, 9, and 10) projected into a large screen for about 10 sec. This was to approximate the viewing time from a helicopter flying at speeds greater than 160 km h^{-1} and is comparable to the times used in other similar experiments (BROWN 1971; WARTZOK and RAY 1975). The first transparency showed adult harp seals on ice off the east coast of Canada (Fig. 8). The other two trans-parencies presented a random distribution of dots on a plain background (Figs. 9 and 10). The students were asked to estimate the number of seals, or dots on each transparency. The results are given in Table 2. In all three cases, the observers as a group were inaccurate and grossly overestimated the number of seals and dots on the transparencies. The lack of precision in the estimates of the group is also obvious from the large standard errors (Table 2). At higher densities (Figs. 9 and 10) it is interesting to note that the 95 per cent confidence limits about the mean do not even include the actual number of dots on the slide.

The tendency for observers to overestimate the number of objects in an

Fig. 8. *A dense aggregation of harp seals* Pagophilus groenlandicus, *probably adult males, photo-graphed in March 1975 on ice off the east coast of Newfoundland, Canada. This was the first trans-parency shown to observers for 10 sec. They were asked to estimate the number of animals seen.*

Table 2

Results of a preliminary experiment to test the accuracy and precision of untrained observers in estimating numbers of objects within a defined area. Transparencies 1, 2 and 3 are shown in Figs. 7, 8, and 9 respectively.

Transparency	No. of Observers	Actual Number	Estimated Number ± 2 S.E.
1	134	161	569± 456
2	134	900	7,564±4,232
3	134	1,200	12,247±6,225

aggregation is not, however, a general phenomenum. The Canadian Wildlife Service, in a similar experiment, found that their observers consistently underestimated the total number of objects present. Their experiment tested the accuracy of observers in estimating sago grains and/or gun shot in varying numbers and proportions, and at different densities on photographs (Brown 1971). Observers were allowed 15 sec to estimate the number of objects present. Variation was again evident among individuals. The suggestion was made that such testing could be used to calibrate individual observers, and to train observers and thus improve estimates in the field (Brown 1971).

Heyland (1972) compared the results of a photographic census with simultaneous visual estimates of numbers of greater snow geese *Anser caerulescens atlantica*. He also found that his observers underestimated the numbers of geese present.

In a more detailed and extensive experiment Wartzok and Ray (1975) conducted simulated census using experienced whale and walrus observers, pilots and inexperienced observers as subjects. Their one hour simulated flight involved the presentation of 80 transparencies.

Thus, they introduced the additional variable of observer fatigue into their study. They also required the observers to identify and estimate numbers of three species of marine mammals, walrus *Odobenus rosmarus*, beluga whales, and bowhead whales *Balaena mysticetus*, although no two species occurred on an individual slide. Many of the transparencies were of habitat only, and contained no animals, as would occur on an actual aerial survey flight.

Briefly, Wartzok and Ray's (1975) conclusions were as follows. For bowhead and beluga whales all observer groups showed significant differences from the correct values. Surprisingly, experienced whale observers did better at counting walrus than experienced walrus observers regardless of the size of the walrus group. Interestingly, for the largest groups of walrus, inexperienced observers appeared "to be at least as good or better than experienced walrus observers" (Wartzok and Ray, 1975). However, no observer group was very accurate, and all groups, except pilots, overestimated the number of animals The precision of the observers was also tested, by comparing estimates from two or more presentations of the same slide. Differences in precision between the observer groups were significant for small numbers of walrus but not for large groups, and pilots provided the most precise estimates.
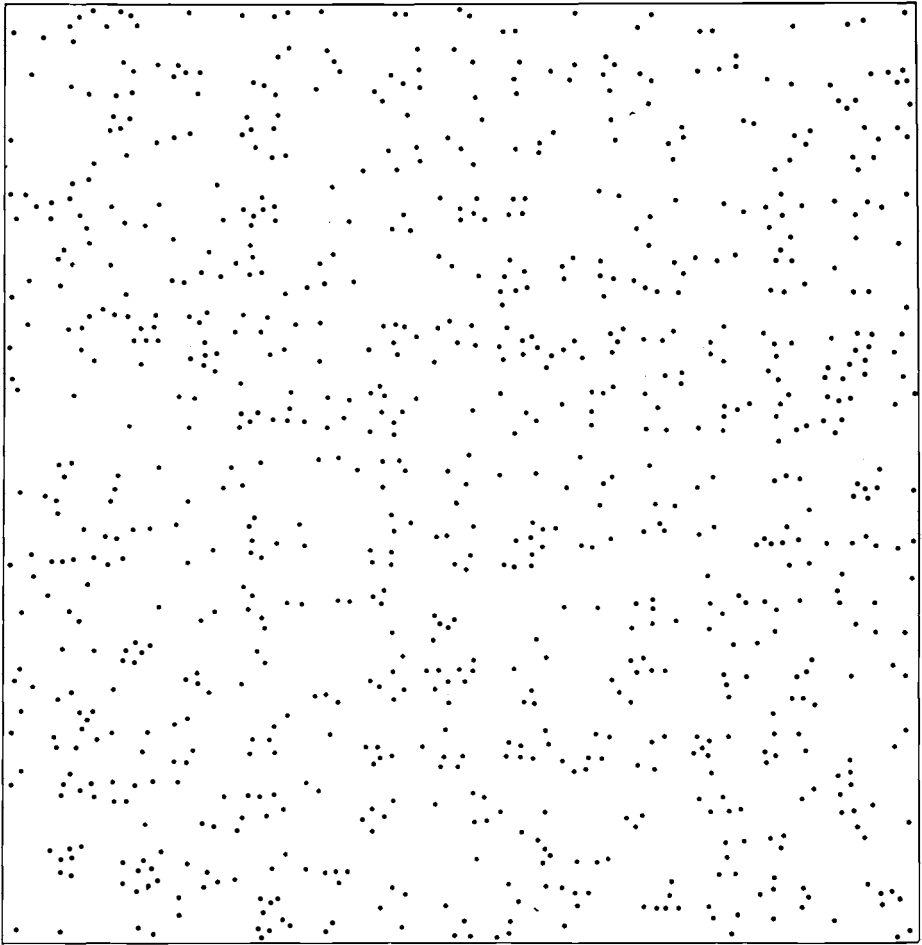
Fig. 9 *The second transparency shown to observers for 10 sec. Individual dots are randomly distributed.*

In conclusion, there are obvious problems related to obtaining population estimates by visual estimation. Many factors affect the accuracy and precision of visual estimates. These factors are well documented in situations where attempts are made to count individual animals (LeResche and Rausch, 1974). They are less well understood, but even more critical when extensive aggregations of animals are "eye-balled" (Wartzok and Ray 1975). These factors thus include variables related to the observer's experience, motivation, and fatigue, the problem of individual variation within, and among observers. They also include variables related to the diurnal behavioural patterns and density of the animals being counted, the physiography of the environment, such things as terrain and vegetation, and the ambient weather conditions, including the presence or absence of clouds, turbulence, and snow cover. The results of visual surveys are also affected by the type of aircraft used, the visibility afforded the observer through windows, and even the abilities of the pilot may influence the results (Bergerud 1968). All these factors are interrelated, and
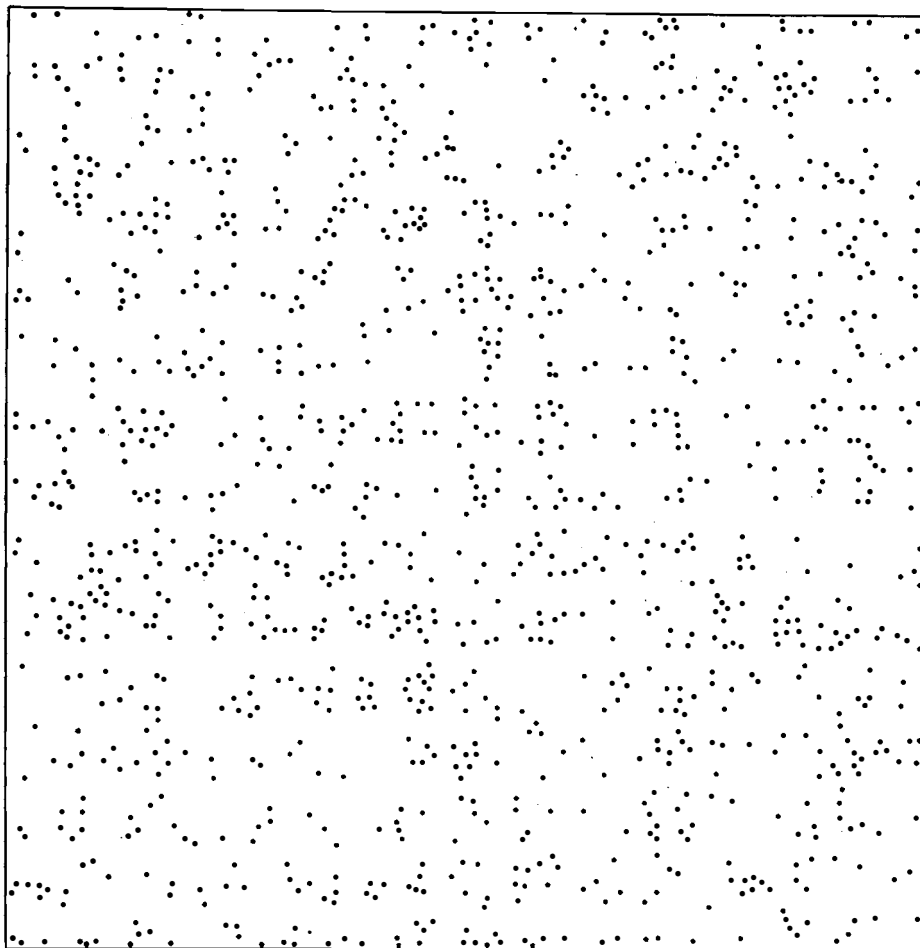
Fig. 10. *The third transparency shown to observers for 10 sec. Individual dots are again randomly distributed.*

any statement concerning the validity of aerial counts must consider them all.

Several attempts have been made to rectify some of the problems associated with obtaining accurate visual estimates of animals. Although there appears to be no technical solution to eliminating the bias, CAUGHLEY (1974) suggested that it may be possible to recognize and estimate the bias during an aerial census and correct the estimates of animal numbers accordingly. Recognizing that visual counts of individual animals will underestimate the number of animals in an area, CAUGHLEY and GODDARD (1972) devised a method for estimating the number of animals in an area from several counts, each of which underestimates the true total. When "eye-balling" the number of birds in distinct flocks, use of standardized photographs of flocks of various sizes (STEVEN 1967) is obviously a conscious attempt to improve upon visual estimates, although there is no way of testing the effectiveness of this modification unless each flock is also photographed in its entirety at the time of the survey (HEY-LAND 1972).

Further complications arise when all the animals in an aggregation cannot be viewed at once. Consider a whelping patch of harp seals lying on ice off the east coast of Canada. The seals may be distributed over an area as large as 1000 km², some animals are visible on the surface of the ice, others are in the water and the proportions on the ice and the water vary throughout the day, and throughout the season. The animals on the ice are distributed in a contagious manner, clumped in groups, with large areas of ice with few or no seals. It is not possible to sex the animals from the air so there is no means of knowing whether the animals being counted are males or females. In addition, the newborn seals are also on the ice and with their white neonatal pelts are poorly contrasted against the background of ice and snow. Considering the previous discussion and these additional complications, it is difficult to accept any visual estimate of seal numbers. To estimate any single parameter, e.g. number of adult females, adult males, or pup production, in this manner would not seem feasible. Despite this, visual estimates of harp seal and production in the western Atlantic are reported each year, and are considered in the decision making process by management personnel.

The variability, and inconsistent and inconclusive results of "simulated" censuses, the inability to verify the results of actual field estimates, and the impossibility of relating observer performance in the laboratory to performance in the field, stress the dubious nature of visual surveys for providing accurate and useful estimates of aggregations of animals in the field. With respect to marine mammals RAY and WARTZOK (1975) noted that "Visual surveys are currently the most widely used method of censusing marine mammals populations, but are generally recognized as unsatisfactory."

This review of the recent literature on visual estimation of animal numbers suggests that it is unwise to place much faith in any visual estimate as an accurate and realistic estimate of absolute numbers of animals in the field. This is especially true when other techniques are available, or could be developed, to provide objective estimates, whose limitations and counting errors may at least be recognized, quantified and considered, prior to making important management decisions based on the assumption that the estimates in question are reasonably accurate. Obtaining a permanent record of animals being censused, for example seals present on the ice at any one instant, is the only way to minimize these problems. A permanent record may be re-examined many times, and animal counts completed and checked, and the only practical method of achieving this is by aerial survey. By definition this will involve the use of remote sensing techniques, at least the use of a camera system, and, as indicated above the choice of scale and spectral region must be appropriate to the situation. Details of this are considered below in the discussion of aerial censusing techniques.

Photographic Surveys

Photographic aerial surveys have numerous advantages over visual estimates of animal numbers. They provide an objective and permanent record of observations which can be counted, checked, analyzed, and reanalyzed if

necessary, at some later date in the laboratory. Ideally, counts of animals obtained from photographs can be compared with simultaneous ground surveys in specific and defined areas to test the precision and accuracy of the sensors being used. Photographic surveys may also be conducted utilizing portions of the electromagnetic spectrum outside the range of human vision, thus providing a very different view of the subject than would normally be obtained. In this way visibility problems associated with the detection of certain camouflaged animals may be easily overcome (LAVIGNE and ØRITSLAND 1974a, b). Selection of appropriate film and filter combinations should be based on a knowledge of the reflectance characteristics of the animal and its background in order to maximize the signal/noise ratio, i.e. to maximize the contrast of the animal against its background and thus the probability of detecting the animal under study. Photographic surveys, like any other census technique, are only suitable for certain types of animals under certain conditions and are not particularly useful if overhead cover or the behaviour of the animal makes it possible to obtain a direct image of the animal.

Photographic surveys have been evaluated for a variety of wildlife species (HEYLAND 1972) but are commonly used in the assessment of few wildlife populations. The advantages of vertical photography over visual census methods have been demonstrated for several species by HEYLAND (1972). For example, photographic surveys of the greater snow goose made it possible not only to census the birds in the region under study, but to distinguish young from adults, separate family units, determine brood sizes, and to obtain information regarding age ratios in the population (HEYLAND 1972). Similarly, photographic surveys are ideally suited for studying and counting beluga whales (HEYLAND 1974) as noted previously in the discussion of scale.

Aerial surveys have also been used for a number of years in the assessment of several pinniped populations. Many pinniped populations, if not all, are presently under some form of scientific scrutiny, either because the animals in question are of some economic, aesthetic or cultural value, or because they are considered pests in the local environment. Accurate estimates of population numbers are required in order to determine annual quotas or allotments for seal hunters or a sealing industry, to establish the numbers and types (age, sex, species) of individuals to be removed by controlled culling programs, or to ensure the protection and conservation of threatened species.

Pinnipeds tend to concentrate in large groups at certain times of the year, usually in conjunction with annual whelping and breeding seasons, or the moult. Such congregations often occur in remote areas, or islands, rocky coastal rookeries, sand beaches, or in the case of pagophilic seals, on ice some distance from land, areas which are generally devoid of overhead cover such as dense vegetation. For these reasons, aerial photographic sensing techniques would seem ideally suited for population assessment of seals, perhaps more than for any other group of mammals.

The use of photographic surveys to assess harp seal populations began more than fifty years ago (SERGEANT 1975). Many of the problems related to conducting a photographic census of any wildlife population may be demon-

strated using the harp seal example. However, recent developments in remote sensing technology now suggest that many of these problems can be overcome. For these reasons the use of photographic surveys to improve estimates of seal populations will be discussed in some detail.

Prior to 1974 ordinary black and white photography, often with a minus blue (yellow) filter was used as the primary sensor in harp seal surveys. These surveys were often conducted over the whelping patches and the sensor detected the adult seals lying on the ice at the time of the flight. The newborn white-coated pups were not detected in large numbers being well camouflaged against the white snow/ice background (SERGEANT 1975). When the imagery was analyzed, the assumption was often made that all adults on the ice were breeding females which each had given birth to a single pup. Thus the number of adults counted could be used to estimate pup production. In reality, however, adult males have been observed on the ice at the time of parturition and during the nursing period. In addition, the number of adult seals on the ice varies with the time of day and it is difficult to estimate the number of animals in the water at any given time. Thus, any extrapolation from the number of adults counted, to an estimate of pup production is subject to numerous sources of error, and is of little value in terms of obtaining an absolute estimate of annual production or population size. Aerial surveys of moulting patches are plagued by similar problems because it is impossible to separate adult seals from immature seals, male seals from female seals. Thus, although it is relatively easy to get photographs of large concentrations of seals, it is extremely difficult to know what, in fact, these animals represent. Despite these problems, harp seals still seem ideally suited as animals which lend themselves to censusing using aerial survey techniques. The entire population of breeding females presents itself to be counted at a specific time every year, in four rather well defined areas in the world (LAVIGNE 1976a). Each female then produces a single pup. These white-coated pups appear to represent the one factor that does remain constant for some time during the whelping season. They remain on the ice for the first two or three weeks of life and tend not to enter the water in significant numbers. Consequently, once pupping is completed there is a brief period when virtually all young of the year are on the the ice together.

Recognizing this, the problem then becomes one of how to improve the contrast of the white seal pup against its white background. The solution to the problem only becomes apparent when the diffuse reflectance characteristics of the seal are compared with those of the background (Fig. 11). Although the white coat of a harp seal pup reflects all wavelengths in the visible spectrum, and thus appears white to the human eye, it does absorb much of the ultraviolet component in solar radiation. Snow, however, not only reflects visible light and appears white to the eye, but also reflects much of the invisible (to the human eye) ultraviolet radiation (Fig. 11). Thus an ultraviolet photograph of a harp seal pup on snow results in a black image of the animal against its white background (LAVIGNE and ØRITSLAND 1974a).

This example emphasizes the need to select specific sensors for specific tasks in order to maximize the contrast of the subject under study. With a knowledge
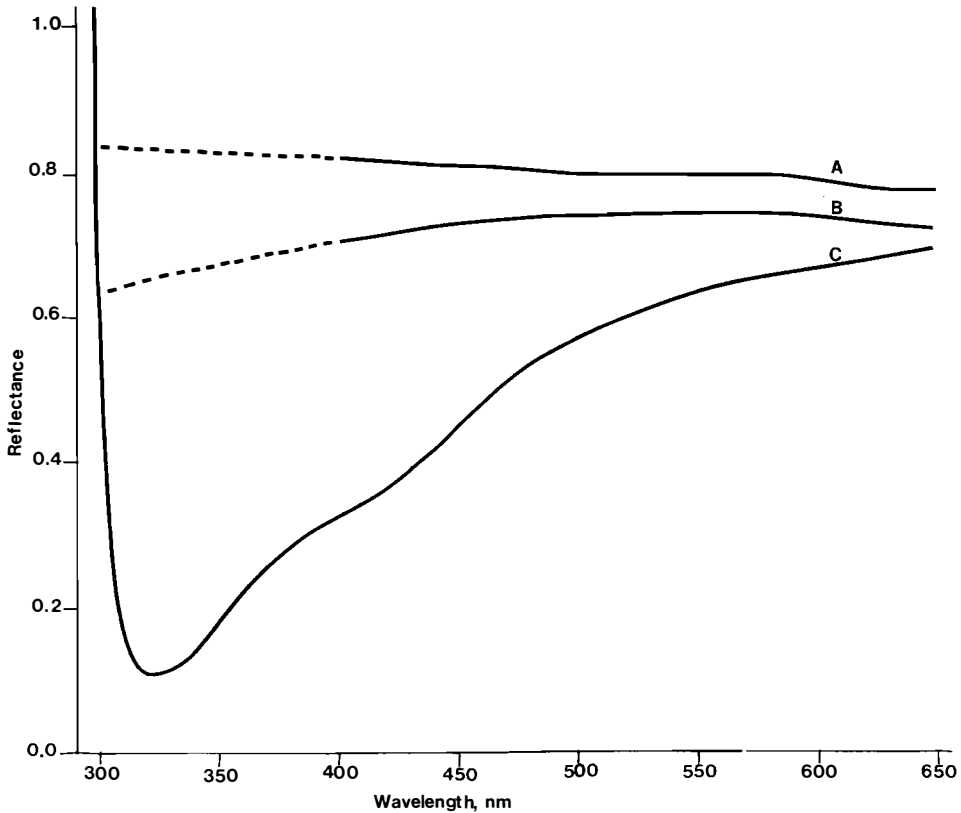
Fig. 11. *Diffuse reflectance curves for fresh snow (A), snow with an ice covering (B), and a white-coated harp seal pup (C). The greatest contrast between the seal and its environment occurs between 300 and 400 nm. (The reflectance curves for snow were compiled from various sources, and extrapolated where specific data were lacking).*

of the reflectance characteristics of the subject and its background, the choice of sensors becomes rather obvious. By selecting that part of the electromagnetic spectrum where the subject and its background differ most, the remaining problem becomes one of locating a suitable sensor e.g. a film and filter combination, which will be sensitive to that particular and restricted band of electromagnetic radiation.

The ability of ultraviolet photography to detect certain white animals on a snow background has only recently been noted (LAVIGNE and ØRITSLAND 1974a, b). Ultraviolet photography may be easily incorporated into existing photographic systems presently used in remote sensing. Since conventional camera lenses made of glass may restrict the transmission of ultraviolet radiation, we have used a quartz lens such as a Hasselblad UV — Sonnar 105 mm lens (C. Zeiss, W. Germany), in conjunction with an ultraviolet transmitting filter, e.g. Kodak 18A (Eastman Kodak, Rochester) to prevent visible wavelengths from reaching the film. Some lenses with glass optics will, however, transmit sufficient ultraviolet radiation for use in ultraviolet photography (LAVIGNE and ØRITSLAND 1974a). This fact will significantly reduce the cost of adding an ultraviolet capability to existing remote sensing equipment. Since all

normal photographic emulsions are sensitive to ultraviolet radiation (Fig. 2), film selection is not a problem. For example, using Kodak Tri-X pan professional film, and Kodak 2402 and 2405 aerial film (Eastman Kodak, Rochester) it is possible to obtain suitable apertures (f/4.3–f/8.0) and fast shutter speeds (1/500 s) for aerial photography.

The introduction of ultraviolet photography as a new method for remote sensing animals (LAVIGNE and ØRITSLAND 1974a) now permits accurate counts of white-coated seal pups at the end of the pupping period thus providing a direct estimate of annual production. This will simultaneously provide an estimate of the number of breeding females in the population, since each gives birth to a single pup.

Since 1974, a variety of remote sensing techniques including ultraviolet photography (LAVIGNE and ØRITSLAND 1974a, b) have been tested for their capability of detecting harp seals and their white-coated offspring on ice, off the east coast of Canada.

Ultraviolet photography has been found to detect adult harp seals with equal accuracy ($p < 0.05$) to any of the photographic sensors tested (LAVIGNE and RONALD 1975). In addition, it also provided the best contrast between white-coated harp seal pups and the ice and snow background (Fig. 12b). At an altitude of 305 m ultraviolet photography detected the same number, or more seals than the ground count made by two experienced observers in a low flying helicopter over the designated area. It also detected significantly more white-coated seals than any other sensor tested. For example, on one experimental flight, the sensor used previously to survey the harp seal in the western Atlantic, black and white photography, with a yellow (minus blue) filter (Fig. 12a), detected only 21% of the pups which were visible on the ultraviolet imagery. Similarly, ordinary black and white photography in the absence of filters, detected 52%, and colour photography, 35%, of the pups which were counted with ultraviolet photography (LAVIGNE and RONALD 1975).

The selection of an appropriate sensor is only the first step in obtaining a successful photographic census. Subsequently, it is necessary to develop a survey technique suitable for sampling the population being studied. This requires a detailed knowledge of the distribution of animals in the environment, and their behaviour patterns during the day at that particular season of the year. Harp seals, for example, are distributed in an aggregated or contagious manner on the whelping ice and this must be taken into account when designing a suitable sampling program. Preliminary results to indicate, however, that most of these problems can be overcome, and that photographic surveys will probably provide the best direct estimates of annual production, and ultimately population size, which can be obtained for such populations (LAVIGNE 1976b).

Aerial photography has also been used to monitor grey seal *Halichoerus grypus* populations on whelping grounds. Off the east coast of Britain the white-coated pups are well contrasted against the dark background of the whelping areas and the animals may be easily detected using photography in the visible portion of the electromagnetic spectrum (BOYD 1957; VAUGHAN 1971; BONNER
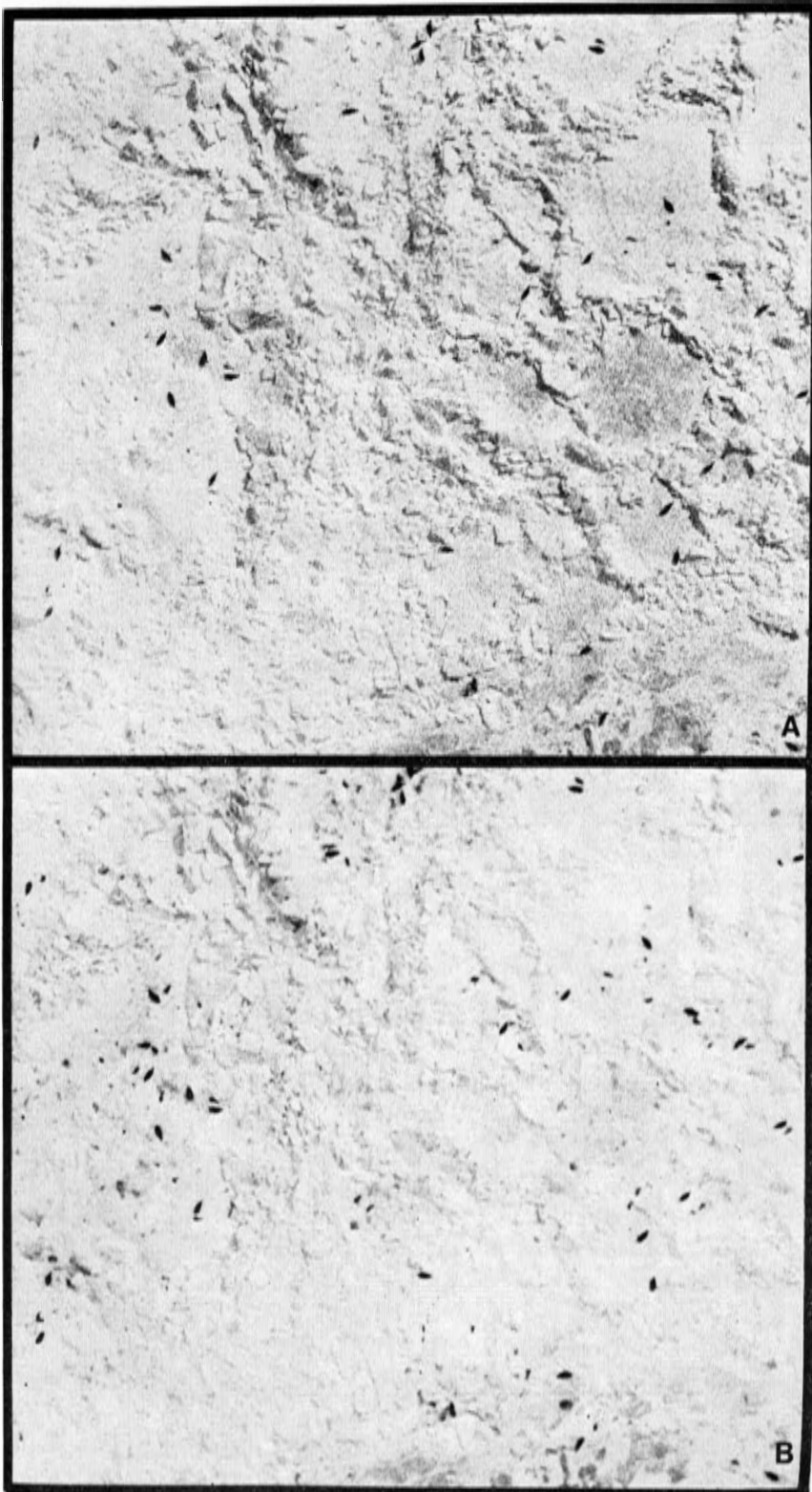
Fig. 12. *Photographs of harp seals* Pagophilus groenlandicus *on ice in the Gulf of St. Lawrence.*
A. Ordinary black and white photography results in the detection of adult seals on the ice.
B. Ultraviolet photography of the same scene detects not only the adult seals, but also their white-coated off-spring.

Fig. 13. *Caribou* Rangifer tarandus *south of Churchill, Manitoba. The large black and white photograph is an enlargement from a 9 × 9 vertical photograph taken from 450 m. The animals and their shadows are seen clearly. The insert shows an ultraviolet photograph of the same animals. Note that the shadows and details of the background have been lost, leaving only the dark shapes of the animals. Since shadows tend to mask individual animals (e.g. note the lower animal in the leading group of three), it would appear that ultraviolet photography might be useful when censusing a dense herd of caribou against a white background of snow. Elimination of shadows eases the counting of individual animals.*

and HICKLING 1974). Adults may also be detected (VAUGHAN 1971) although their dark colouration tends to blend in with the background. In parts of the western Atlantic, grey seals whelp on ice and/or snow. In this case, ultraviolet photography may be used to distinguish the white-coated pups as in the case of the harp seal (LAVIGNE and ØRITSLAND 1974a). In addition to the counts of grey seals which may be obtained from aerial imagery, other pertinent information may be extracted. At low altitudes (150–305 m) it is not difficult to distinguish between adult males and females on the basis of the sexual dimorphism which is found in this species (KING 1964). Thus, the density and distribution of bulls, and cows, and pups in the whelping herd, and the territorial nature of these animals during the whelping season can be observed from the aerial imagery (LAVIGNE et al. 1974) without disturbing these timid animals (CAMERON 1971) by making first hand visual observations.

A variety of other avian and mammalian species may potentially be censused using aerial photographic surveys. Caribou, *Rangifer tarandus* rest in clearings during the winter with the long axis of of the body exposed to the sun (HEY-LAND 1975b), presumably to maximize utilization of solar radiation as an external source of heat energy. This behaviour results in a stationary group of animals, most of them will be exposed to sunlight and away from areas of overhead cover which would otherwise hinder their detection. These conditions appear ideal for aerial survey work. Caribou moving across barren regions may also be counted from aerial imagery (Fig. 13). Using black and white photography the animals and their shadows are clearly seen. In dense herds, these shadows tend to mask individual animals, making counting more difficult. One solution to this problem may involve the use of ultraviolet photography (Fig. 13). The shadows are significantly reduced because of the reflection and scatter of ultraviolet wavelengths (LAVIGNE and ØRITSLAND 1974a), leaving only the dark shapes of the animals to be counted.

Other examples where aerial photography may prove useful in obtaining counts of animals include white-tailed deer *Odocoileus virginianus* wintering in deciduous forest areas such as Rondeau Park, Ontario, Canada (LAVIGNE unpublished data), numerous other mammalian species (SWANK et al. (Eds.) 1969), and a variety of additional avian species (HEYLAND 1972; 1975). By eliminating many of the problems associated with visual estimation of animal numbers, carefully designed photographic aerial surveys should make a significant contribution to the assessment and management of many wildlife species in the near future.

Thermal Scanner Surveys

Thermal infrared radiation emitted by homeotherms is an important avenue of heat loss which may also be utilized for remote detection of individual animals using a thermal infrared line scanner. Thermal infrared imagery has been tested with limited success on a number of animals including white-tailed deer *Odocoileus virgianinus* (see CROON et al. 1968; McCULLOUGH et al. 1969; GRAVES et al. 1972), mule deer *O. hemionus* (see DRISCOLL and PARKER 1973), polar bears *Ursus maritimus* (see BROOKS 1970), and harp seals (LAVIGNE and RONALD 1975).

Thermal infrared radiation is emitted from all surfaces in proportion to the surface emittance (e) and the forth power of the surface temperature (T). A general form of Stefan's law gives the rate of total radiation emitted:

$$W = e \, \sigma T^4$$

where T = degrees Kelvin ($^\circ$K = $^\circ$C+273.15)

σ = a universal constant 5.672×10^{-8} W/m^2 K^4

e = the emittance, here assumed to be the same for all wavelengths involved.

The total radiation is distributed over wavelengths according to Planck's Law and it appears that the wavelength increases with decreasing surface

temperature. Biological surfaces have temperatures largely between —50 and +50°C and emit wavelengths between 2500 and 40,000 nm.

In the context of the present discussion "wildlife" may be considered in terms of a heat generating core covered by an insulating layer of hairs or feathers of varying thickness. HAMMEL et al. (1962) formulated the situation for mammals as follows:

> "Due to the open strukture of the fur, there is no sharply defined geometric surface, so that the surface exchanging radiant energy with the environment may be nearer to the skin surface and therefore somewhat warmer than the surface exchanging energy by conduction and convection. The more closely the fur fibres are packed of course the less the surface temperatures will differ."

We may add that the temperature differences, or the radiation temperature, will decrease with increasing wind because wind "bites" into the fur and cools it.

The thermal infrared radiation detectable by a remote sensor is only that radiation emitted from parts of hairs on an uninterrupted straight line to the sensor. No thermal infrared will be reflected from hair to hair and finally towards the detector. We do not yet have any information on the significance of "grid-type" scattering of infrared radiation between the hairs and may assume it to be insignificant. Hair density (no. per area unit), morphology, and posture (pilo-erection) will be of significance to the amount of thermal-infrared radiation reaching the detector both because of the criterion of the direct line and because the temperature of the emitting hair-surface depends on the underlying insulation which also is a function of the same pelt characteristics. For most species we lack sufficient data on the relations between insulation and avenues of nonevaporative heat loss, meteorological conditions and radiative temperatures to be able to calculate actual radiation temperatures of wildlife. However, some direct measurements of radiative temperatures under a variety of environmental conditions have been made and the results of several thermal remote sensing experiments have been reported in the literature.

Initially it is important to recognize that the radiative surface temperature of any homeotherm will vary depending on the ambient environmental conditions. Such variables as the intensity of solar radiation, windspeed, ambient air temperature, the walking speed of the animal, and for many species, whether the animal has a summer pelt or a winter pelt, all influence the rate of heat loss from the body and thus the radiative surface temperature at any given point in time. Radiative temperatures in the order of 5 to 10C° higher than ambient air temperature have been reported for a variety of species under various environmental conditions. These species include the polar bear (ØRITSLAND et al. 1974; ØRITSLAND and LAVIGNE 1976), reindeer *Rangifer tarandus* (see HAMMEL et al. 1962), white-tailed deer (CROON et al. 1968; MOEN 1968; 1973), harp seal pups and adults resting in air (ØRITSLAND et al. unpublished data) and hooded seal *Cystophora cristata* pups (ØRITSLAND unpublished data). Under certain environmental conditions, however, there will be little temperature difference between a well-insulated homeotherm and its environment. For example, the radiation temperature of adult harp seals

lying on ice may drop to less than 0.2°C above air temperature when it is raining (ØRITSLAND unpublished data). Similarly in high winds, and very cold ambient air temperatures, there will be little temperature difference between a well insulated homeotherm and its environment. Under these conditions, detection of an animal with a thermal scanner becomes unlikely and any counts of animals obtained under these conditions will not be representative of the number of animals present at the time of the survey.

Recently, it has been noted that through preliminary laboratory experimentation it is possible to derive an equation to predict suitable environmental conditions for detecting specific animals with a thermal infrared scanner of known specifications (ØRITSLAND and LAVIGNE 1976).

This approach saves considerable time and money by allowing the investigator to maximize the probability of obtaining usable data on an aerial survey, and thus reduce the number of flights where no usable data would be obtained. In addition, considerable understanding of the dynamics of heat loss by the species being studied is also obtained. Briefly, this approach involves the measurement of heat loss through a pelt sample under a variety of controlled environmental conditions including a range of air temperatures, wind speeds, and the presence or absence of additional radiation within the solar spectrum (ØRITSLAND and LAVIGNE 1976). Additional information may be obtained under known and measurable environmental conditions using captive animals if these are available (ØRITSLAND et al. 1974; CENA and CLARK 1974; ØRITSLAND and LAVIGNE 1976). For polar bears the following predictive equation for radiative temperature was derived (ØRITSLAND and LAVIGNE 1976)

$$Tr = -1.25 + 0.443\ Ta + 0.01\ Va - 0.23 Vw$$

where Tr is radiative temperature (°C); Ta, ambient air temperature (°C), Va, wind speed (m/s); and Vw, walking speed (m/s) of the bear. Similar types of equations have been derived for adult harp seals *Pagophilus groenlandicus* and their white-coated pups (ØRITSLAND et al. unpublished data). It should be noted that ambient air temperature appears to be single most important variable determining the radiative surface temperature of homeotherms studied to date.

A few attempts have been made to carry out controlled experiments involving the use of a thermal scanner in census work. CROON et al. (1968) performed a thermal infrared survey of free ranging white-tailed deer from an altitude of 305 m. On the ground they measured radiation temperatures of the deer penned in the area surveyed from the air. The penned deer were about 7°C warmer than their background and the aerial survey revealed 98 of 101 deer in the area. The authors correctly noted that the radiation temperature will vary depending on weather conditions, surface characteristics, etc. However, in discussing the difficulties of distinguishing between animals of similar size, the authors suggested that "Differences in emissivity between animals of different hair or hide characteristics, and improvement in imagery, may allow finer distinctions" between different species. We must stress here that significant differences in emissivity are unlikely since

all animal surfaces, regardless of colour, have an emissivity of about 1 (HAMMEL 1956). Nevertheless, this study is one of the few involving thermal scanner surveys where adequate ground verification of the survey results was obtained. It demonstrates that under optimum conditions a thermal scanner survey may provide very accurate estimates of animal numbers.

A thermal scanner has also been tested as a possible sensor for detecting and counting harp seals on their whelping grounds in the western Atlantic (LAVIGNE et al. 1974; LAVIGNE et al. 1975; LAVIGNE and RONALD 1975). In general, it is difficult to distinguish between adults and pups on the thermal imagery. There was, however, no significant difference ($p < 0.05$) in counts of total seals on the ice made from the thermal infrared data, and those obtained with ultraviolet photography under the environmental conditions present during flights conducted in 1974. The best imagery was obtained on 6 March 1974 in the Gulf of St. Lawrence when ambient air temperature was 0°C and the wind speed was 8 m/sec. At air temperatures below about —2°C and wind speeds greater than 8 m/sec as occurred during other flights in 1974 and during our flights in March 1975 there is often little difference between the surface temperature of a well insulated seal and its environment. As a result, counts of seals on the thermal infrared imagery underestimated the number of seals present during these flights (LAVIGNE et al. 1975; LAVIGNE and RONALD 1975). Mathematical equations have recently been derived to predict ambient conditions which provide the necessary temperature differences between harp seal adults and pups and their environment to permit detection with a thermal scanner (ØRITSLAND et al. unpublished data).

In conclusion, it would appear that thermal scanners are of very limited use in the detection and counting of wildlife populations. Specifically, for ungulate populations such as deer, thermal scanners must be considered impractical for most routine census activities (CROON et al. 1968; GRAVES et al. 1972). Infrared scanners are unable to penetrate a green leaf canopy (CROON et al. 1968) and are not suitable for surveys of large areas where large differences in topography are present (DRISCOLL and PARKER 1973). The success of a thermal scanner system depends also on the variability of the radiant temperatures of the animal being censused, and its background, and these are influenced greatly by the ambient environmental conditions during the actual flight. Other limitations include problems of distinguishing between species of animals if more than one species is present, and the high cost of the scanning device which may preclude its use in most wildlife studies (CROON et al. 1968).

The most promising use of a thermal scanner may be for detecting and monitoring certain pinniped species such as harp seals and grey seals on ice. The area to be censused is relatively flat, and obviously free of obstructing vegetation. Predictive equations have been derived for harp seals which permit selective use of the scanner to maximize the probability of obtaining good data (ØRITSLAND et al. unpublished data) and under favourable environmental conditions the scanner has been found to accurately detect harp seals on ice (LAVIGNE et al. 1974). However, even in the case of the harp seal, the thermal scanner should probably be considered a back-up sensor for census work to

ultraviolet photography as discussed previously. The use of a thermal infrared sensor to study seals at night does have promise for making observations of the distribution and activity patterns of seals at a time when other sensors are not operational.

Remote Sensing the Physical Environment

Wildlife surveys and ecological studies undertaken on a local scale often have components which are more truly part of the ecology of a larger region. A specific example of this would be a study of kettle lakes in North Dakota (GILMER et al. 1975). The ecology of a typical lake would have, as a major seasonal component, the influx of migrating waterfowl. These birds, on a migration path from their breeding areas in Arctic regions of North America to the southern United States, e.g. the lesser snow goose, use the lakes as feeding and resting areas. An assessment of the conditions along the whole of the migration route requires a regional overview of some 4800–6400 km in length and several hundred km wide. Overviews of this dimension are available only from spacecraft, and mosaics of published maps or aerial photographs which are themselves extracts from material which was gathered many years ago. An overview of conditions along a migration route such as this requires a record of present conditions if it is to be of immediate value to an ecologist. Thus, a daily image from space would be useful. However, such images available on a daily basis are only obtained from weather satellites and they offer poor resolution and therefore little detail of ground conditions. The data from LANDSAT-1 and -2 provide a suitable level of detail for an overview of such a large area but these are only available in a 9 day sequence. For most purposes this time sequence is valuable for ecological work and for monitoring conditions along major migration routes. In the case of birds migrating to the Arctic regions of North America each spring, the snow cover, the progress of the spring thaw, and amounts of open water are all important. Consideration of the conditions in the ocean may also be relevant. This is revealed by Fig. 14 which shows the changing conditions on and around Banks Island in the western Canadian Arctic, in the early summer of 1973.

The utility of LANDSAT imagery for assessing habitat conditions for snow geese has been considered in previous studies (FALCONER and LAVIGNE 1975; KERBES and MOORE 1975). It appears that LANDSAT imagery is superior to traditional map products for recording ecologically sensitive areas.

When LANDSAT imagery is used alongside the maps of the Canadian Ecological Map Series (Anon. 1972) greater detail about habitat conditions is available to the investigator. In their consideration of this, FALCONER and LAVIGNE (1975) noted the need for information about Canada's Arctic so that decisions about the legal limits of disruption of natural vegetation and habitat could be made by an informed government. To meet this need, information is required for a large area. The sparse population plus logistical and economic problems of field studies of Arctic ecology result in the majority of projects being carried out in limited areas exclusively during the brief summer season.
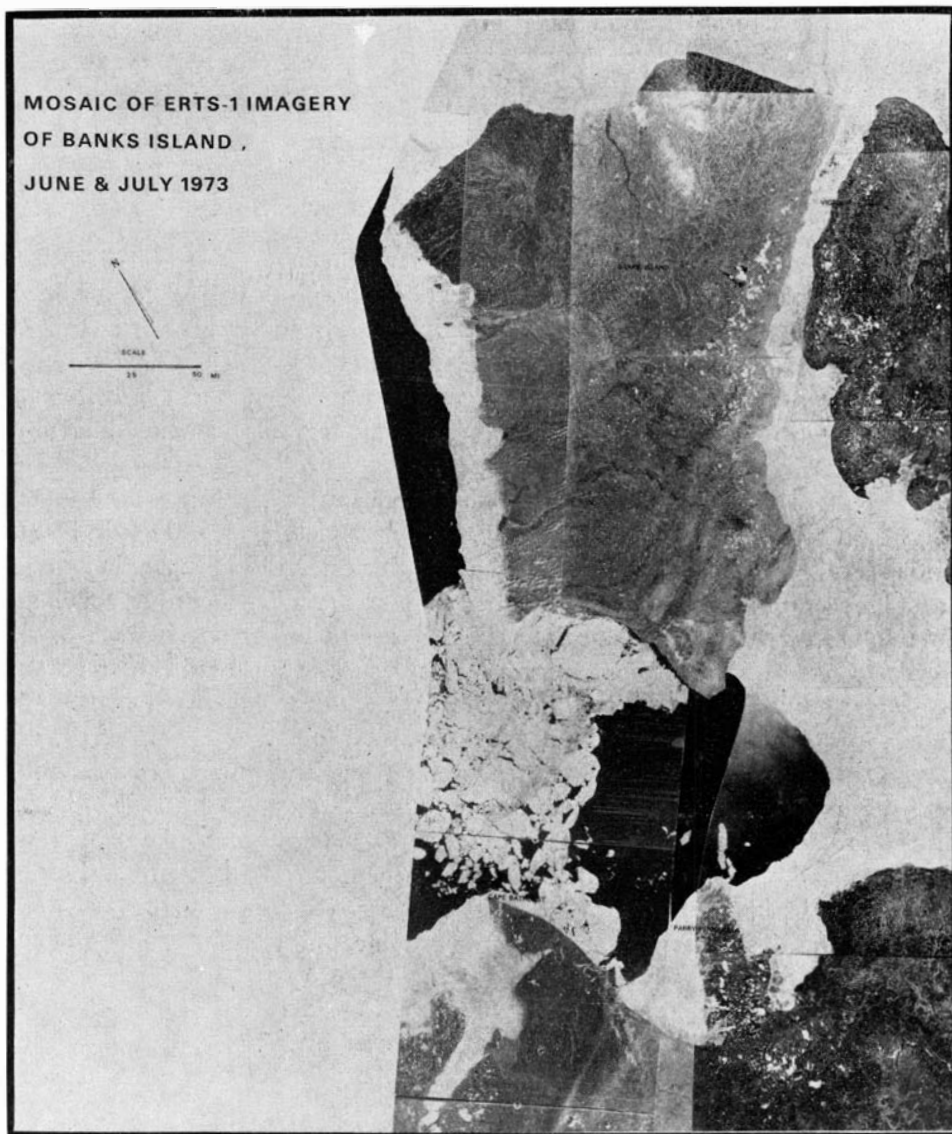
MOSAIC OF ERTS-1 IMAGERY
OF BANKS ISLAND ,
JUNE & JULY 1973

Fig. 14. *A mosaic of LANDSAT-1 (formerly ERTS-1) imagery of Banks Island, June and July, 1973.*

This pattern is revealed by the literature which shows Arctic field studies to be restricted in area and duration, a situation which can be documented for studies of mammals, birds, fish and invertebrates as well as the major plant communities. Existing studies have often been carried out on an opportunistic basis and in consequence they exhibit little or no regional co-ordination.

The need for surveys of wildlife activity in the Arctic appears to be conclusively established. Studies of wildlife activity frequently define important areas in terms of a habitat type or a succession of habitats which an animal visits during seasonal movements or migrations. Thus, the basic need in such

studies is for regional scale data capable of revealing these seasonal patterns and relating the corresponding seasonal changes to the habitat types. This need can be readily met by judicious use of remote sensing data obtained from satellites.

Sensors on LANDSAT, imaging in both the visible and IR portions of the electromagnetic spectrum provide data which can be interpreted for vegetation, hydrology, geological information, ice and snow conditions. Consequently habitats for aquatic species, large mammals, or groups of species associated with a given vegetation type or biophysical region can be delineated at the regional scale. This is apparently true of the regions on Banks Island (Fig. 14) where the LANDSAT imagery reveals the open water of the nesting areas for snow geese and Brant geese, *Branta bernicula* at the mouths of the rivers.

The Arctic Ecology Map sheets which cover Banks Island (Thompson River No. 2034; Horton River No. 2061) and the accompanying descriptive reports establish that this area is regarded as one of the most important wildlife areas in the western Arctic (Anon. 1972). Both the island and the adjacent waters are important for several wildlife species. The map shows an extensive area critical to wildlife along the western shores of Banks Island. Within this area, the Banks Island Migratory Bird Sanctuary, are the major resting areas for the lesser snow goose with colonies along the Egg River, Big River, Sacks River and probably other rivers along the south coast (Anon. 1972). GODFREY (1966) defines lesser snow goose breeding range as covering the whole of Banks Island.

Distribution maps for any species, whether it be plant or animal, denote very generally the limits of a particular species' range. During the breeding season, however, lesser snow geese tend to frequent low hummocky coastal plains, with ponds, shallow lakes or streams, nesting mainly in loose colonies and making nests of mosses and other tundra vegetation lined with down (GODFREY 1966). This description of the snow goose nesting area, typical of wildlife habitat description, is in fact a physiographic description of topography and hydrology with a vegetation inference. Such regions can be identified on the LANDSAT imagery of Banks Island. Furthermore, the LANDSAT images provide information about the progress of the spring thaw and they reveal the dates on which open water is visible, thus permitting a monitoring of the thaw of small lakes. LANDSAT imagery thus bridges the gap between the very generalized species distribution map, and the Arctic Ecology Map (Anon. 1972) which, at the other extreme, outlines sensitive and critical areas for various species based largely on the experience and travels of a few individuals in the vast area of arctic Canada. The scale of a LANDSAT image is such that it is possible to view the area on a regional basis and the resolution is such that natural habitat regions can be outlined.

The ecology map of Banks Island also indicates off-shore movement of polar bears which is extensive from March to June. This movement is reported to involve primarily females and cubs, moving off Banks Island onto broken ice in search of seals. Some insight into the availability of this ice is provided by a temporal sequence of LANDSAT which reveals the changing conditions of the ice off the west coast of Banks Island through the period of ice break up

(FALCONER and LAVIGNE 1975). This dimension of time indicates the point at which the bears are no longer able to use the ice for their off-shore movements. The images also clearly reveal that the nesting areas for geese in the river mouth areas are ice free before the sea ice moves off shore.

Such images are available from the Canadian receiving station within minutes, hours, or days of a satellite pass, depending upon the users' requirements. This means that by the use of these quicklook data, environmental monitoring can be undertaken. One outstanding example of this application involves the use of current satellite imagery to predict the nesting success of lesser snow geese.

From the satellite imagery it is possible to observe the disappearance of snow from breeding colonies and, to use this temporal information to successfully predict subsequent nesting success (KERBES and MOORE 1975). In their study KERBES and MOORE utilized both LANDSAT data and data from the meteorological satellite NOAA. These data were used to establish how much snow cover existed over the nesting area at specific times during the spring. Since the success of nesting at a lesser snow goose colony is closely related to the date at which a significant proportion of the colony is clear of snow, success was predicted as high, intermediate, or low on the basis of the satellite observations. The success of the predictions was confirmed later in the year using a variety of techniques (KERBES and MOORE 1975). Although still in the experimental stages, this approach suggests that the success of the current breeding season may be inferred from satellite imagery and this information can be incorporated into management decisions related to hunting regulations prior to the fall hunting season. It would appear that this approach should be developed and employed on an annual basis for predicting nesting success of numerous species of arctic geese (HEYLAND 1975a; KERBES and MOORE 1975). The utility of this approach to management is clearly important because these birds nest in remote areas where alternate survey methods using ground vehicles or light aircraft are either too costly or impractical.

FALCONER et LAVIGNE (1975) discussed other examples of habitat monitoring using satellite imagery. These examples, including the McKenzie Delta area and the Boothia Peninsula, provided an overview of remote sensing for wildlife studies. The conclusion from this work was that all examples reinforced the value of the greater information content of the LANDSAT image and established its advantages over conventional maps for regional habitat assessment. The Ecology maps produced by the Canadian Wildlife Service at a scale of 1 : 1,000,000 contain significantly less infomation than the satellite images, which are also available at 1 : 1,000,000 scale and FALCONER and LAVIGNE (1975) recommended the use of a satellite image base for such work.

Research indicates that habitat regions can be, and often are, identified on the basis of vegetation, geomorphology, and hydrology. In determining the extent of wildlife range an examination of habitat type is often used for delimiting the location of a given species on a seasonal basis. Therefore maps of animal range will be based on the extent of habitat features such as bare rock, muskeg, lakes or marshes. The occupation of suitable areas by wildlife is also restricted

by climate. For example, the arctic breeding season, is limited by the brevity of the period without snow and ice and most migrant birds must find open water and unfrozen ground in order to feed (IRVING 1972). Thus, much pertinent information can be gathered from LANDSAT data. It is easily possible to monitor the snow-line as it recedes in spring and to locate areas of open water thereby gaining some insight into the dynamics of arctic ecology.

The question of scale is also important in habitat assessment. Detail of nesting sites is not available from satellite imagery. However, wildlife studies which extend over continental areas are not restricted to the use of any single type of remote sensing imagery. The regional (or continental) overview provided by LANDSAT can be used as a first approach to a problem and from this overview, areas of interest can be chosen for further study. This further study may involve sensors of any chosen characteristic being operated from aircraft, balloons, drones or towers at the discretion of the investigator. Thus, imagery of any particular type, given any chosen scale, may be gathered. Referring back to HEYLAND's (1974) study of beluga whales (see above), once the type of estuary where beluga gathered is understood, a search of the coasts of a continent can rapidly be conducted using satellite imagery and the location of every suitable estuary determined. Studies of each could then proceed using aircraft and appropriate sensors to produce data at the required scale.

Similar methods are being used in a current study of the harp seal on its whelping grounds off the coast of Canada. Satellite images are used to produce an overview of the ice conditions (Fig. 15) while lower altitude aircraft operations gather further data concerning the extent of the seal herd and the distribution of adult seals on the ice (LAVIGNE 1976b). Finally, aircraft operating at about 305 m with ultraviolet sensors are used to obtain imagery of adult seals and their white-coated pups on the ice (LAVIGNE and ØRITSLAND 1974a; LAVIGNE 1976a, b). Such a multi-tiered approach provides general information about ice movements and habitat, characterizes the distribution of seals within that habitat, and permits selection of appropriate survey sampling techniques to provide the best possible estimates of pup production for a given year (LAVIGNE 1976b).

Studies of wildlands and wildlife, rangeland and rangeland management, forestry, hydrology and geology are common features of conferences and meetings about remote sensing. The ingredients of all these studies are pertinent to wildlife and ecological studies, a fact clearly revealed by the topics of the papers presented at the workshop on remote sensing of wildlife recently held in Quebec City, Canada under the chairmanship of J. D. HEYLAND. This workshop, an effective contribution to operational uses of remote sensing in wildlife studies, provides clear evidence of the success of remote sensing techniques in the study of wildlife. Digital processing of data undertaken initially for forestry purposes has immediate relevance to wildlife studies (PEET 1975). The monitoring of waterfowl habitat (GILMER et al. 1975) and the use of satellite imagery in the goose management activities of the U.S. Fish and Wildlife Service clearly establish the effectiveness of remote sensing imagery for waterfowl habitat analysis (REEVES et al. 1975).
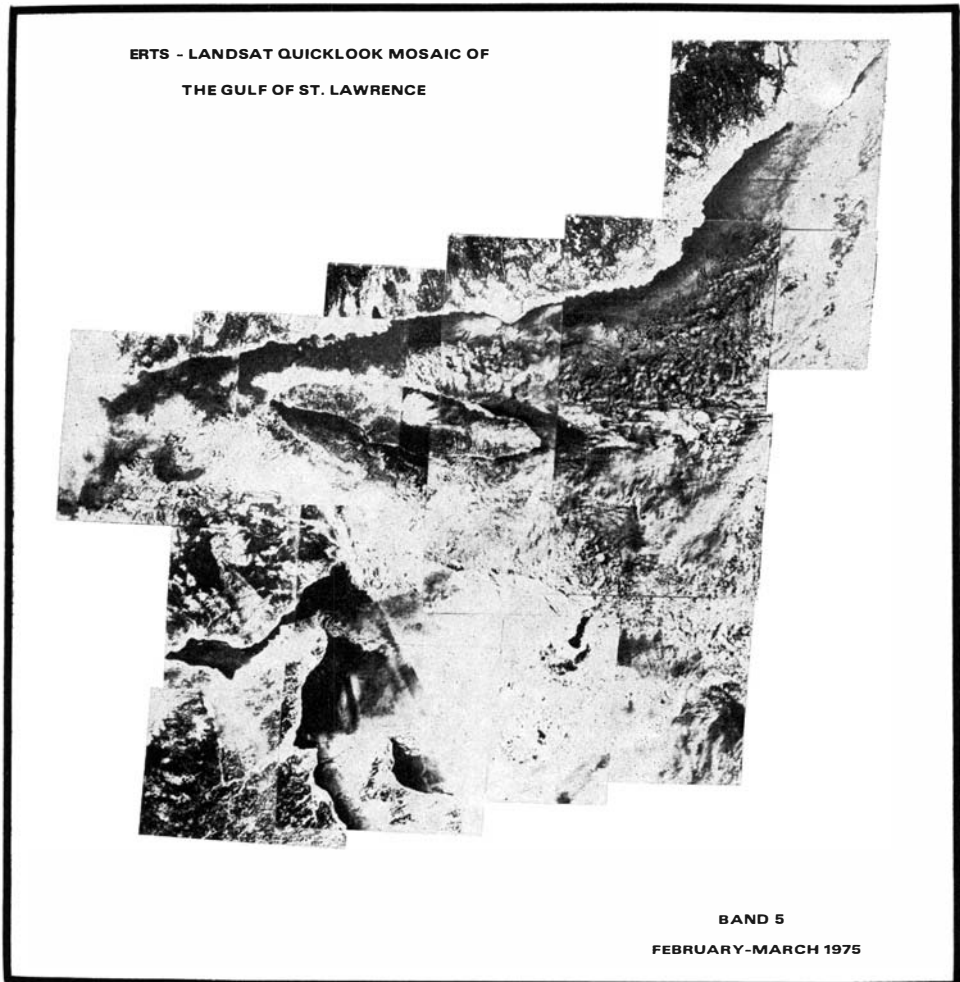
ERTS - LANDSAT QUICKLOOK MOSAIC OF

THE GULF OF ST. LAWRENCE

BAND 5

FEBRUARY-MARCH 1975

Fig. 15. *A mosaic of LANDSAT-1 imagery for the Gulf of St. Lawrence, January to March, 1975.*

At a larger scale remote sensing data generated from 35 mm aerial photography and general remote sensing from light aircraft (MEYER 1975; Williams 1975) are also of great value in ecological study (SWANK et al. (Eds.) 1969; Gouvernment du Quebéc, 1975).

It is impossible to adequately present examples of all the possible applications of remote sensing in monitoring the physical environment. Each and every application of remote sensing to earth resources problems has a potential value to the wildlife ecologist. For example, studies of wetlands can offer very useful information to wildlife management programmes (COWARDIN and MYERS 1974) and refinement of this for detection of edge and its quantitative evaluation (SCHUERHOLZ 1974) indicate the powers of remote sensing data in many aspects of wildlife studies. As with the determination of the appropriate scale and sensor for a given problem, the assessment of all other aspects of remote sensing must be undertaken in the context of a specific problem.

Conclusions

The full documentation of all aspects of remote sensing is an impossible task. It is somewhat akin to a treatise on the uses and applications of a thermometer in its variety and scope. The Manual of Remote Sensing (American Society of Photogrammetry 1975) is a useful source of reference material and the publications of the National Aeronautics and Space Administration (NASA) are equally compendious and useful.

At present, the most important problem related to remote sensing in ecological studies is one of perception, perception of the value of these techniques by field biologists and regional administrators. If the value of remote sensing data is fully recognized and its use is appropriate to the problem, then it should be integrated with the existing management programmes. Only then, for example, does international monitoring of the world ecosystem become possible, providing a basis for effective legislation compatible with the stated aims of international conservation programmes such as IBP and MAB, which demonstrate a scientifically based concern for our natural resources. With appropriate use of remote sensing data, remote areas of the world need not longer remain *terra incognita*. Ignorance of the extent of habitat destruction by man now becomes ignorance by choice. Improved assessments of certain animal populations through the use of remote sensing techniques suggests that a precipitous decline in numbers in these populations may now be based on choice, or inappropriate management decisions and legislation.

Watt (1966) noted that the present bottleneck in ecological research is systems measurement. Application of remote sensing technology to ecological problems will improve the speed and scope of data acquisition in many areas of ecology. These data can also be collected in an appropriate form compatible with modern system analyses using computers (Watt 1966). The potential contribution of remote sensing to ecological studies is obvious, and is totally consistent and easily interfaced with existing approaches. The data now available from LANDSAT and other remote sensing devices provide a major data source, which those concerned with ecosystem management will neglect at their peril.

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