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EARTH RADIATION BUDGET SATELLITE SYSTEM STUDIES

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(ERBSS)

PRELUDE

The ability to predict climate, in particular deviations from historic norms, is becoming of increasing critical importance to the economic well-being of the United States and the world. The importance of the Earth's radiation budget in determining climate has long been recognized. Table I shows an example of the United States activities specifically noting the need for radiation budget measurements. The Earth-orbiting satellite provides a platform, outside the Earth's atmosphere, which is capable of simultaneously monitoring the outgoing reflection of the Sun's energy from the Earth's surface and atmosphere, and the longwave radiation emitted by the Earth and its atmosphere. Equally important, this satellite system is capable of monitoring these fluxes on a daily, monthly, seasonal, even yearly basis for extended periods of time. These capabilities provide the opportunity to conduct detailed studies of the variations in the Earth's radiation budget, the effects of natural and manmade changes in the environment on this budget, and the effects which changes in the energy budget produce on Earth's weather and climate. This document lists the scientific objectives and the associated mission analysis, instrument definition, and data analysis methods to meet those objectives.

TABLE I

U. S. CLIMATE ACTIVITIES SPECIFICALLY NOTING NEED FOR RADIATION BUDGET MEASUREMENTS

• A UNITED STATES CLIMATE PROGRAM DOMESTIC COUNCIL	1974
UNDERSTANDING CLIMATE CHANGE--A PROGRAM FOR ACTION NATIONAL ACADEMY OF SCIENCES--U.S. GARP COMMITTEE	1975
• A REPORT ON THE ELEVENTH SESSION OF THE JOINT ORGANIZING COMMITTEE FOR GARP (INCLUDES POSITION OF U.S. SCIENTISTS)	1975
• H.R. BILL 13736--"NATIONAL CLIMATE PROGRAM ACT OF 1976" (CHARLES MOSHER, R--OHIO)	1975
• U.S. CLIMATE PROGRAM PLAN FEDERAL COUNCIL ON SCIENCE AND TECHNOLOGY/INTERDEPARTMENTAL COMMITTEE ON ATMOSPHERIC SCIENCES	1976
• U.S. ROLE IN GARP CLIMATE PLAN NATIONAL ACADEMY OF SCIENCES--U.S. GARP PANEL ON CLIMATE DYNAMICS	1976
• OUTLOOK FOR SPACE REPORT TO THE NASA ADMINISTRATOR BY THE OUTLOOK FOR SPACE STUDY GROUP	1976
• NASA CLIMATE PLAN REPORT BY GSFC CLIMATE TASK GROUP AND SCIENCE WORKING GROUP 1977 (IN PREPARATION)	

INTRODUCTION

The Earth's population, because of increasing numbers and increasingly demanding habits of consumption, is placing a growing stress upon almost all resources and services necessary to support our civilization. As growing demand closely approaches available supplies, unforeseen deviations in climate from historic norms can produce serious problems or, in some rare instances, benefits. The following is an excerpt from the document entitled "A United States Climate Program":

"• A killing winter freeze followed by a severe summer heat wave and drought produced a 12% shortfall in Russian grain production in 1972. The Soviet decision to offset the losses by purchase abroad reduced world grain reserves and helped drive up food prices.

- Collapse of the Peruvian anchovy harvest in late 1972 and early 1973, related to fluctuations in the Pacific Ocean currents and atmospheric circulation, impacted world supplies of fertilizer, the soybean market, and prices of all other protein feedstocks.

- The anomalously low precipitation in the U. S. Pacific Northwest during the winter of 1972-73 depleted reservoir storage by an amount equivalent to more than 7% of the electric energy requirements for the region.

- A three-week siege of hot, dry weather in the midwest in the summer of 1974, following rain-delayed spring planting, greatly reduced U. S. corn and soybean production at a time of mounting world demand for it.

- Inadequate monsoon rains in some parts of southeast Asia and India in 1974, and floods in other parts, are causing famine and suffering there.

- The Sahel area south of the Sahara Desert has suffered five years of drought, causing famine and death for unknown thousands and the migration of millions.

- Mean temperatures in the higher latitudes of the Northern Hemisphere have dropped significantly since the 1940's. Below normal temperatures for as long as 19 consecutive months have recently been recorded in certain portions of the Artic. This is the longest such period in the last 100 years. As a result of the high-latitude cooling the growing season in Great Britain has shortened by two weeks since 1950, reducing food production and use of certain plant varieties. Nobody knows whether such a trend will continue.

- The sensitive ozone layer of the stratosphere, according to recent studies, is subject to depletion by man-made chemicals such as freon and oxides of nitrogen. The increased ultra-violet radiation passing through this weakened shield could have serious impacts on human health.

Climatic fluctuations are not always bad.

- Consistently favorable growing conditions in the U.S. corn and wheat belts from the late 1950's until this year helped the U.S. maintain its strong position in world food production.

- The mild winter of 1973-74 in the U.S. and Western Europe helped conservation measures to avert catastrophic oil shortages during the Arab oil embargo.

It is clear that climate fluctuations are resulting in major economic, social and political consequences. Our vulnerability has increased: as the world's population and the affluence of part of it have grown, grain reserves have shrunk to the point where they cannot offset the more serious production shortfalls that can be expected due to the ordinary vagaries of climate. The same factors are pressing on other resources, such as water and energy, whose availability and utilization are closely related to climate. Such pressures have thus rapidly amplified the previously experienced impacts of natural climate fluctuations to critical levels.

These concerns are compounded by mounting evidence that man's industrial and agricultural activities may cause changes in climate inadvertently. Some pollutants, or sufficiently large amounts of heat, when released into the atmosphere, may affect regional or global temperature and rainfall patterns. Intensive land clearing, slash burning, or over-grazing also may have adverse effects. Man-induced climatic changes, whose consequences for human health, agricultural productivity, and the economic and political stability of nations may not become evident for a decade or longer, are in urgent need of delineation so that action can be taken to arrest them or ameliorate their consequences. It is equally important to learn which fears of inadvertently shifted climate are unfounded, so that industrial and agricultural growth will not be unnecessarily restrained.

.... our present ability to anticipate and explain either natural fluctuations or man-induced changes of climate falls short of being useful to the planners and policy makers who must face these problems, and short of what science and technology can make possible. There is general agreement among those who have examined the problems, and we concur, that a start can and should be made now on an organized research effort to improve our understanding and prediction* of the natural fluctuations and man-induced changes of climate and their consequences. Furthermore, rapid and significant improvements in the utility of presently available climatic information can also be achieved.

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*By our definition, climate addresses the statistics of weather in time units of at least 2 weeks, and at ranges of weeks, months, years, or longer.

While benefits would derive from a foreknowledge of climate fluctuations on any time scale, the greatest responsiveness of government occurs in the range of a year or so. Hence, predictions and assessments of impacts, to be most useful for decision-making, should aim primarily at the natural year-to-year fluctuations of climate and the cumulative climatic impact of man's activities."

CLIMATE PREDICTION

The foregoing deals with the effect of climate anomalies and implies a need for climate prediction. The following continuing excerpt from "A United States Climate Program" delineates the utility of and justification for a climate predictive capability:

"The most critical climate-related problems are now all too familiar. World shortages in basic food and feed grains cause drastic and erratic shifts in food prices, domestic and foreign demand, food reserves, balance of payments, trade and aid. Energy shortages generate analogous shifts. Because food and energy are at the heart of individual and national survival, it becomes imperative to act to moderate these instabilities.

If the risks of various climatic impacts could be calculated earlier or with greater accuracy, or climatic events anticipated more precisely, the utility of this information in planning, policy formulation, and decision-making would be strikingly enhanced. Even modest gains would assist in:

- More efficient management and planning of domestic and international food supplies and natural resource utilization. A reduction in uncertainties about expected agricultural production allows the maintaining of lower average reserve levels. Storage costs are so high that a reduction in reserve requirements of one percent of U. S. production would result in savings of over $120 million per annum.

- Establishment of agricultural export and food assistance policies which reflect the probabilities of various levels of crop yields.

- Improved predictions of expected energy demands. These would influence allocations of limited crude oil supplies and refinery capacities among competing uses: the manufacture of liquified natural gas, fuel oils, gasoline, jet fuels, fertilizers, and other petro-chemical feed-stocks. Improved scheduling of fuel deliveries to regions expected to encounter abnormally severe winters would also follow.

- Advance preparations for reallocation of water during droughts, and for disaster relief in response to flood or drought.

Early understanding of the climatic consequences of man's activities would permit:

- Readjustment of national and world-wide industrial, commercial, and land management practices to arrest undesirable climate changes.

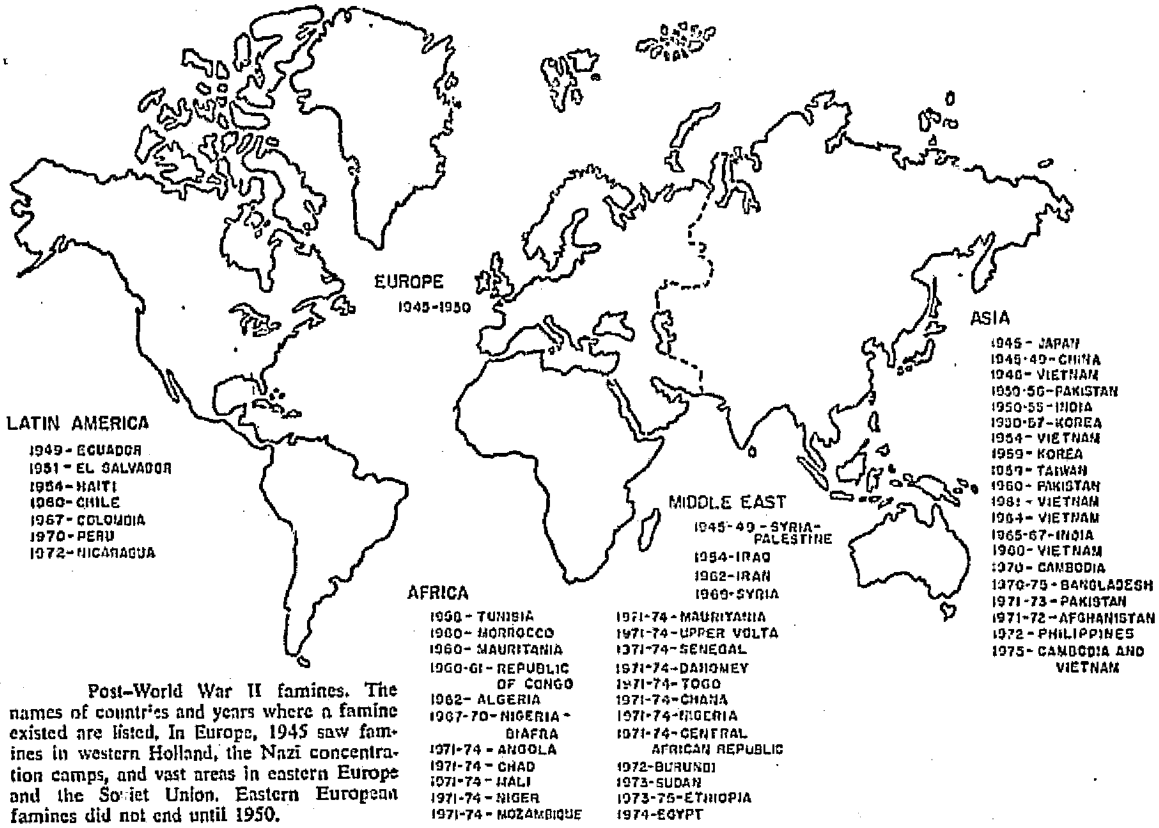
- Initiation of necessary R&D programs--as for example in agriculture--to devise long-term responses to irreversible climate changes.

- Improved long-term investment decisions in water resources and energy."

The goal of climate prediction is to help the nation respond more effectively to climate-induced problems by enabling its Government to be aware of or anticipate climate fluctuations and their domestic and international impacts. For instance, early prediction of the severe winter weather of 1976-1977 would have moderated the effects by allocation of additional fuel oils into the north and east, and would have noted an early need for additional natural gas supplies without which Virginia and many states suffered extreme economic hardship. Early warning of the Buffalo severe winter climate would have allowed better preparedness. Meteorologists and climatologists agree that the spatial distributions of the Earth radiant energy budget and the temporal variations in these distributions are the fundamental physical drivers of climate. The Stockholm meeting of the World Meteorological Organization (1974) identified the importance of energy budget measurements to climate prediction and placed priority emphasis upon satellite measurements. Radiation budget has recently been noted by the NASA Climate Task Group and its Science Working Group as one of the nine "crucial" parameters needed for improved climate prediction.

ECONOMIC VALUE OF CLIMATE PREDICTION

The objective of the ERBSS program is to measure temporal and spatial variations in the Earth radiative energy budget to provide measurements for the advancement of climate prediction methods for both scientific and economic benefit. Earth energy budget (EEB) measurements will provide scientific benefit through their importance to understanding the dynamics of the Earth's atmospheric system and its effect on climate. The importance has been discussed in many individual and group reports (SCEP, SMIC, RMOP, COSPAR, Stockholm Conference on the Physical Basis of Climate Modeling, etc.) over the past several years. On the other hand, the economic benefits of EEB have not been quantified; however, the potential of the measurements is directly related to the benefits of improved climate prediction such as more efficient management and planning of domestic and international food supplies and natural resource utilization. The impact of such capability, for social and humanitarian as well as economic benefit, has been dramatically emphasized by the recent crisis in food supplies in parts of the world, where many have died or suffered from famine and starvation due to climatic fluctuations, as shown in this figure excerpted from Science, vol. 188, May 9, 1975.



Post-World War II famines. The names of countries and years where a famine existed are listed. In Europe, 1945 saw famines in western Holland, the Nazi concentration camps, and vast areas in eastern Europe and the Soviet Union. Eastern European famines did not end until 1950.

As noted in the previous section, improved predictions of expected energy demands would influence allocations of limited crude oil supplies and refinery capacities among competing uses: the manufacture of liquified natural gas, fuel oils, gasoline, jet fuels, fertilizers, and other petrochemical feed-stocks. Improved scheduling of fuel deliveries to regions expected to encounter abnormally severe winters would also follow. Improved prediction of climate would also allow advance preparations for reallocation of water during droughts, and for disaster relief in response to flood or drought.

The future aspect of extending our present day-to-day weather forecasting to climate prediction, that is, to time intervals of 2 weeks and beyond, appears to hold vast opportunities for economic benefits. However, only limited studies have been performed to date analyzing the economic benefits of improved climate prediction.

A report entitled "The Potential Economic Benefits of Improvements in Weather Forecasting," by J. C. Thompson, Department of Meteorology, California State University, San Jose, California, September 1972, indicates that based on a survey of agricultural, industrial, and other activities in the United States, the total annual economic loss due to adverse weather and climate is $12.7 billion per year, and that approximately $5.3 billion per year are protectable losses assuming accurate forecasts and appropriate decision making. The report further indicated that after evaluating the cost of protection and further improvements in forecasting, the total potential gains for our economy as a whole is estimated to be about $740 million per year. The vast majority of this gain ($560 million) would be in agricultural areas. This study also evaluated the potential gains related to the length of the forecast period based on the estimated potential improvement for each forecast period. Results showed maximum gains ($250 million) from improvements in 90-day forecasting with significant, but lesser, gains for lesser periods.

Much has been written in recent years about climate and climate change, particularly as it relates to agricultural production and world food supplies. After almost 20 years of surpluses with stable or declining food prices, a reversal in the world balance of supply and demand occurred with the failure of the Soviet grain crop in 1972. To make up this deficit, the USSR made massive purchases of grain from the U.S. and other major grain exporting countries, which significantly reduced their grain stockpiles. This reduction, followed by the lower than usual yield in 1973-1974 in the U.S., caused grain prices to rise sharply. Since grain production has historically varied from year to year with changes in average monthly and seasonal temperatures and precipitation, improved long-range seasonal climate forecasting will be beneficial to providing more efficient management and planning of domestic and international food supplies. Therefore, a reduction in uncertainties about expected agricultural production will allow not only the moderation of the basic grain and food price fluctuations, but also assist in efficient planning of related transportation and storage costs. As mentioned earlier, one estimate is that a reduction in grain storage requirements by one percent of U.S. production would result in savings of over $120 million per year. In addition to the economic benefits, there are intangible benefits such as the saving of human life associated with better predictability of droughts and famine in specific parts of the world, thereby allowing for timely action to minimize the effects of such climate conditions. Several articles discussing food economics, politics, and social structure relating to our recent and current world food situation are found in Science, vol. 188, May 9, 1975.

Some additional reports which address economic benefits in improvements in weather and climate prediction are:

(1) NAS/NRC Report, "Useful Applications of Earth-Oriented Satellites," 1968 - Summer Study, see vol. I, Forestry-Agricultural-Geography; vol. 3, Hydrology; and vol. 4, Meteorology.

(2) U.S. Department of Commerce Report, "First Five Years of the Environmental Satellite Program - An Assessment," A Report to the Administrator, NOAA, February 1971.

(3) University of Wisconsin Interim Report, "Multidisciplinary Studies of the Social, Economic, and Political Impact Resulting from Recent Advances in Satellite Meteorology," Space Science and Engineering Center, June 1971.

EARTH RADIATION BUDGET DEFINITIONS

In the present discussions of radiation, the following "area" definitions are used:

Regional.- refers specifically to small-scale and medium-scale areas of:

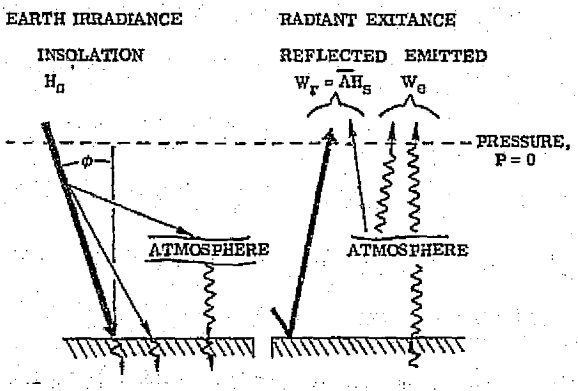
(1) 250 by 250 km grid to 500 by 500 km grid

(2) 1000 by 1000 km grid (10° by 10° grid of great circle arc)

Zonal.- refers to an area band around the Earth whose width is 10° of latitude

Global.- entire Earth

The term "radiation budget" is used synonymously with net radiation and is used to specify radiation loss or gain over any of the above spatial scales. The components of net radiation are: direct solar irradiance, H_s, planetary albedo, $\bar{A}$, and Earth emitted radiant exitance, W_e (see sketch).



The net radiation over a region or zone is

$$Q_{net} = H_s \cos \phi \, (1 - \bar{A}) - W_e$$

and when averaged over the globe,

$$Q_{net} = \frac{H_s}{4} (1 - \bar{A}) - W_e$$

MEASUREMENT REQUIREMENTS

In order to provide radiation budget data for climate studies, different accuracies are required for regional, zonal, and global measurements. Within the last few years, beginning with special study group reports (SCEP, SMIC, RMOP) and followed by group (COSPAR) and individual papers such as those by Vonder Haar (1973), etc., the science requirements for satellite radiation budget data have been thoroughly discussed and debated. For the application of these data to the study of climate, the report of the Stockholm Conference on the Physical Basis of Climate and Climate Modeling (1974) contains a detailed discussion. In the Stockholm GARP conference, three classes of measurements were resolved for designing an observation strategy, including accuracy and resolution requirements. These were:

Class I.- Observations needed to understand the detailed physical and/or chemical processes which are thought to be significant to the climate problem. Class I programs generally need to be very detailed, intensive in space and time, but may be restricted to one or a small number of selected areas of the order of a grid element (100 by 100 km^2) and a limited time period.

Class II.- Global observation of climatic quantities which exhibit a large space and/or time variability, as needed for verifying the fidelity of climate models.

Class III.- Long-term surveillance of slowly varying elements of the climatic system, and the long-term surveillance of environmental parameters and of external "forcing" factors which may in the long run induce climatic trends.

In May 1975, an Earth Energy Budget Workshop was held at the National Center for Atmospheric Research to discuss the application of, and required accuracies for, measurements of incident solar radiation, absorbed or reflected solar radiation, and the Earth's thermal emission. Specialists in many different disciplines including climate modelers, general circulation modelers, satellite meteorologists, and observation specialists took part in the discussions (see table II). Each attendee was asked to list and discuss his requirements for Earth radiation budget data, how the data would be used, and what accuracy and resolution was required. Approximately 20 different problems were presented and discussed. An example is given in table III. The different problems could be divided into (1) measurements of large spatial extent and monthly or longer time scales (similar to Class II and III) for global, zonal, and regional averages of climate model verifications, for climate experiments, and for climate diagnostics, and (2) measurements of small spatial extent and short temporal intervals (similar to Class I) for verification of radiative calculations, parameterizations for climate models, and study of selected small-scale climate features. Approximately two-thirds of the requirements were for large space/time scales.

In September 1975, an ad hoc review panel of the National Academy of Science's Committee on Atmospheric Sciences was convened to review NASA's plans and options in Earth radiation budget. Members of the review panel included:

Dr. John C. Gille, Chairman Dr. Francis P. Bretherton	} NCAR
Dr. Richard S. Lindzen	Harvard Univ.
Dr. J. Murray Mitchell, Jr.	NOAA
Dr. John Strong	Univ. of Massachusetts
Dr. Verner E. Suomi	Univ. of Wisconsin

TABLE II

EARTH ENERGY BUDGET WORKSHOP

MAY 12-14, 1975

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

LIST OF PARTICIPANTS	AFFILIATION
M. TEPPER, CHAIRMAN	NASA
S. SCHNEIDER	NCAR
V. RAMANATHAN	NASA LANGLEY
F. HOUSE	DREXEL U.
J. WINSTON	NOAA NESS
C. LAUGHLIN	NASA GSFC
S. RUTTENBERG	NCAR
H. PRESS	NASA GSFC
R. CURRAN	NASA GSFC
A. LACIS	GISS, NY
W. BANDEEN	NASA GSFC
J. KORNFIELD	GISS, NY
C. RODGERS	NCAR
V. SUOMI	U. OF WISC.
J. MASTERSON	NCAR
M. SCHLESSINGER	RAND
J. COAKLEY	NCAR
W. WASHINGTON	NCAR
R. SOMERVILLE	NCAR
R. BRETHERTON	NCAR
C. LEITH	NCAR
K. HANSON	NOAA
T. SASAMORI	NCAR
J. JOSEPH	NCAR
G. NORTH	WASH. U.
M. WALLACE	U. OF WASH.
T. VONDER HAAR, RAPPORTEUR	CSU

TABLE III - USES OF EARTH RADIATION BUDGET DATA (PARTIAL LIST FROM NCAR WORKSHOP)

	DESCRIPTION OF PROBLEM TO WHICH RADIATION BUDGET DATA ARE APPLIED	S SOLAR-INPUT	A ALBEDO OR REFLECTED POWER	E EARTH EMISSION	DESIRED SCALE, FREQUENCY, AND TOTAL DURATION	PROJECTED RESULTS OF STUDY
J1	VALIDATION OF RADIATIVE ENERGY BALANCE MODELS USED IN CLIMATIC STUDIES	1%	1%	1%	MONTHLY MEAN DATA, ZONALLY AVERAGED	BETTER CLIMATE MODELS
J3	CLOUD CENSUS	1%	1%	1%	LARGE SCALE, LONG TIME PERIOD	SEPARATE AND PRIORITIZE VARIABLES
J4	INDIRECT MEASUREMENT OF OCEAN ENERGY TRANSPORT FROM LATITUDE ZONES	2-3%	2-5%	2-5%	REGION 10-20°; T=MONTHS; FOR 10 YEARS	OCEAN DYNAMICS; CLIMATE FORECASTING (LONG-TERM)
J5	NET RADIATION GRADIENT (POLE TO EQUATOR) FOR INTERANNUAL STUDIES WITH GENERAL CIRCULATION	0.1%	1%** 15-30 W/M^2 60°LAT	2%** 15 W/M^2 60°LAT	ZONE OF 10-20°; T=MONTHS; 5 YRS.	OCEAN-ATMOSPHERE ENERGY TRANSPORT CLIMATE FORECASTING (SHORT-TERM)
L	MONITOR SOLAR INPUT TO EARTH ATMOSPHERE SYSTEM	0.5%	------	-------	TIME: MONTHLY MEAN & VARIANCE LENGTH: FOREVER! SPECTRUM: (1) TOTAL INTEGRAL (2) THREE BROAD BANDS 0.25-0.50μ 0.50-0.70μ 0.70-4.00μ	FUNDAMENTAL ENERGY SOURCE CLIMATE FORECASTING (LONG AND SHORT-TERM)

The final report of the NAS/CAS panel was transmitted to NASA on February 6, 1976. A summary is shown in tables IV, V, and VI. "The initial conclusion was that the strategy for obtaining the necessary measurements for attacking the problem of the Earth's radiation budget (the most crucial external drive for the Earth's climate) required that the measurements be divided into two categories of equal scientific importance; e.g.,

I. Large space and time scales -

(Zonal and global means, time scales of a month or more),

II. Smaller space and time scales -

(Regional means, time scales of hours to days).

The Panel reasons that measurements of Category II are required to develop and test radiation parameterization schemes for synoptic and mesoscale disturbances, for inclusion in dynamic climate models. The Category I measurements are required to monitor long-term changes in the Earth's radiation budget and especially the pole-to-equator gradient of radiative heating and heat transports. These data will also provide data sets against which the outputs of the dynamic models may be checked."

It was this division of radiation budget uses into two categories by the NAS/CAS that prompted our decision to divide the 20 uses depicted under the previous discussion for the workshop into two resolution areas. A more detailed discussion of the scientific requirements for Earth radiation budget measurements for climate prediction can be found in the NASA/GSFC paper, "Review of the Requirements for Satellite Determination of Earth Radiation Budget," by Robert J. Curran, Shu-Hsien Chow, and Myron Nack.

Dr. J. Winston (NOAA) and Dr. G. Hunt (Meteorological Office, United Kingdom) have noted the importance of Earth radiation budget data for climate diagnostics. In particular, they noted that high resolution data on the scale of about 250 km over the entire globe are essential to gain insight into such features as the development of sea-surface temperature anomalies, radiation effects of ice and snow cover on the atmospheric circulation, albedo variation in the desert-vegetation boundaries (e.g., the Charney hypothesis for the self-perpetuation of drought), and major long-period circulation phenomena such as the ITCZ, the monsoon, the jet stream, and blocking anticyclones. Climate diagnostics, through the study of these features, is an important aspect of understanding the interaction of the radiative heating with climatic and synoptic changes in the circulation of the atmosphere and oceans.

In summary, scientific objectives for Earth radiation budget have multiple spatial resolution requirements and temporal resolutions of monthly, seasonal, yearly, and interannual periods. The spatial resolutions and required accuracy include:

Resolution	Accuracy (monthly averages)
10° by 10° regions in tropics	2 - 15 W/m^2
10° latitude zones	2 - 12 W/m^2
equator-pole gradient (net)	4 W/m^2
global (net)	1 W/m^2
250 by 250 km to 500 by 500 km regions	2 - 14 W/m^2

TABLE IV

EARTH RADIATION BUDGET SATELLITE SYSTEM

MISSION OBJECTIVES AND REQUIREMENTS AS REPORTED BY THE NAS/CAS AD HOC PANEL TO REVIEW THE NASA EARTH ENERGY BUDGET PROGRAM

CATEGORY 1 - LARGE SCALE

- MONTHLY NET RADIATION BALANCE 30 KM ALTITUDE, AS A FUNCTION OF LATITUDE, WITH A RESOLUTION APPROACHING 10 DEGREES.
- SIMILAR LONGITUDINAL RESOLUTION IN TROPICS.
- ACCURACY CORRESPONDS TO DIFFERENCES BETWEEN THE NET RADIATION BALANCE IN TROPICS AND POLAR CAPS TO ± 4 W M^{-2}.
- IT APPEARS THAT THE REQUIRED RESOLUTION CAN BE OBTAINED WITH RESTRICTED FIELD-OF-VIEW RADIOMETERS ON POLAR ORBITING AND LOW INCLINATION SATELLITES.
- WIDE ANGLE RADIOMETERS SHOULD BE FLOWN ON THE SAME PLATFORMS.

TABLE V

CATEGORY II

SMALL SCALE OBSERVATION FOR PARAMETERIZATION

- OBSERVATION OF ALBEDOS AND INFRARED FLUXES, AVERAGED OVER LIMITED REGIONS SUCH AS 5 DEGREE GARP SQUARES.
- LARGE NUMBER OF CASES IN A VARIETY OF SYNOPTIC SITUATIONS.
- TIME INTERVAL OF A FEW HOURS.
- RANDOM ERROR OF ± 10 PERCENT.
- MEASUREMENTS OF AVERAGE VISIBLE AND TOTAL INFRARED NEEDED.
- ALSO, HIGH RESOLUTION VISIBLE AND NARROW-BAND INFRARED NEEDED FOR CLOUD TYPE AND CLOUD TOP TEMPERATURE.

TABLE VI

NAS RECOMMENDATIONS:

- DESIGN OF SATELLITE SYSTEM TO ACHIEVE REQUIREMENTS NECESSITATES ATTENTION TO SENSOR ACCURACY AND TO SPATIAL AND TEMPORAL SAMPLING FREQUENCIES. ACCURATE INTEGRATION OVER THE DIURNAL CYCLE IS ESSENTIAL.

- THE PANEL RECOMMENDS THAT HIGH PRIORITY BE GIVEN TO ANALYSIS AND INTERPRETATION OF NIMBUS 6, ERB DATA, AND THAT THE FINDINGS BE USED TO GUIDE THE DEVELOPMENT OF FUTURE SENSORS.

- THE APERTURE OF THE RESTRICTED FIELD-OF-VIEW RADIOMETER NEEDS TO BE DETERMINED BY STUDY.

- MONITOR SOLAR OUTPUT, INTEGRATED OVER WAVELENGTH WITH LONG-TERM PRECISION OF 0.2 PERCENT OR BETTER AND ABSOLUTE ACCURACY OF 0.5 PERCENT OR BETTER.

- ANALYSIS TECHNIQUES FOR IMPROVING SPATIAL RESOLUTION DEVELOPED BY NASA'S LANGLEY RESEARCH CENTER APPEAR TO BE USEFUL. PANEL RECOMMENDS CONTINUED DEVELOPMENT AND TESTING OF THESE TECHNIQUES ON ERB DATA.

PROGRAM DESIGN STUDIES

A team of scientists and engineers from NASA/LaRC, NASA/GSFC, NOAA/NESS, Colorado State University, Drexel University, and University of Wisconsin has been studying the program of measuring the Earth's radiation budget from space. The following sections will review the design/study results of this Earth Radiation Budget Satellite System Working Group. There have been four major areas on which the team has concentrated. The first was Science Definition which was discussed earlier with its detailed discussion in the NASA/GSFC report. The other three major areas deal with the ability to meet the scientific objectives. These study areas were:

1. Orbit Coverage (Sampling), or the capability to sufficiently sample the Earth's radiation budget on all space and time scales.
2. Data Analysis Methods, or the capability to analyze and interpret Earth radiation budget data both at satellite altitude and the "top-of-the-atmosphere."
3. Instrument Definition, or the design of an instrument complement and maintenance of its in-orbit integrity.

The individual study results in these three areas will be discussed along with an overall uncertainty (error) analysis and their relationship in particular to the recommendations of the NAS/CAS and the science working group of the NASA Climate Task Group. However, first of all we will review the background of Earth radiation budget measurements.

BACKGROUND

The current state of knowledge of Earth radiation budget parameters is based on satellite measurements made in the late 1960's.

Beginning with Explorer 7 in October 1959, instruments designed to measure Earth radiation budget have flown or will fly on the missions shown in table VII. All of the missions except the Mariners measured Earth reflected shortwave and emitted longwave radiation. The Mariners 6 and 7 TCFM experiment measured the solar constant. The results of the Earth radiation budget based on satellite measurements were extensively reviewed by Yates and Bandeen (1975), and Allison et al. (1975).

Vonder Haar and Suomi (1971) analyzed a data set largely from low resolution radiometers on many satellites representing 39 months during the 5-year period 1962-1966, and presented the first satellite measurements of planetary albedo and radiation budget for all four seasons and the annual case. They found the Earth-atmosphere system to be warmer and darker (albedo 30 percent) than previously believed, especially in tropical regions. Also, see Winston and Rao, 1963 and Winston, 1967.

Data from the MRIR experiment on NIMBUS 3 provided the first synoptic scale view of the global radiation budget during four seasons (April 1969 to February 1970). The NIMBUS 3 results show a still warmer (255° versus 250°K) and darker (albedo 28-29 percent versus 35 percent) planet than was previously believed, with most of the radiative energy input in excess of those older results in tropical regions, thus requiring higher poleward energy transport (Vonder Haar et al. 1972, Raschke et al. 1973. These results essentially confirm the earlier results of Vonder Haar and Suomi (1971).

Vonder Haar (1972) discussed the natural variation of satellite radiation budget measurements over 17 seasons and the implications with respect to the energetics of the atmosphere and oceans. He concluded that low- and medium-resolution radiometric measurements existing at that time permitted studies at the planetary and synoptic scales, but that new measurements from new sensors were needed to study global climate trends and certain mesoscale phenomena.

Vonder Haar and Raschke (1973) discussed the NIMBUS 3 MRIR results within the framework of the earlier satellite measurements, especially with regard to interannual variations. Ellis (1972) compared 35 months of satellite data on the north-to-south gradient of net radiation with parameters defining the intensity of the general circulation. He found that the interannual variations in the gradient of net radiation and the intensity of the general circulation appeared to be related, with the latter lagging the former by 3 months.

Vonder Haar and Oort (1973) combined measurements of the Earth's radiation budget from satellites with atmospheric energy transport summaries to show the required transport by the oceans between equator and pole. The results showed that the ocean must transport more energy than previously believed; i.e., for the region 0°-70°N the ocean contribution averages 40 percent.

Significant shortcomings of the previous radiation budget measurements can be summarized as follows:

1. Low resolution sensors (those on Explorer 7, TIROS 4, and TIROS 7) used temperature measuring hemispherical sensors which resulted in large thermal contamination by the spacecraft and radiation losses. In addition, the Lambertian assumption was required to utilize the data since the errors resulting from data analysis procedures to correct the measurements from satellite altitude to the top of the atmosphere were poorly understood.

2. Medium resolution sensors (MRIR) suffered from very restricted angular sampling, incomplete spectral coverage, and post-launch deterioration, requiring estimate of correction factors and the Lambertian assumption to utilize the data.

3. The only plane flux sensors were in Sun-synchronous orbits and provided inadequate diurnal sampling.

TABLE VII

RADIATION BUDGET BACKGROUND

EXPLORER 7	HEMISPHERES	1959
TIROS 2	5 CHANNEL SCANNING RADIOMETER	1960
TIROS 3	5 CHANNEL SCANNING RADIOMETER	1961
TIROS 4	5 CHANNEL SCANNING RADIOMETER	1962
TIROS 7	5 CHANNEL SCANNING RADIOMETER	1963
NIMBUS 2	MED. RES. SCANNING RADIOMETER	1966
NIMBUS 3	MED. RES. SCANNING RADIOMETER	1969
OTHER EXPERIMENTAL SATELLITES	FLAT PLATE RADIOMETER	1960's
NOAA OPERATIONAL SATELLITES	FLAT PLATE RADIOMETER	1966-1970
MARINER 6	TEMP. CONTROL FLUX MONITOR	1969
MARINER 7	TEMP. CONTROL FLUX MONITOR	1969
NIMBUS 6	EARTH RADIATION BUDGET EXPERIMENT	1975
(NIMBUS G)	(EARTH RADIATION BUDGET EXPERIMENT)	(1978)

4. Precessional rates required between 65 and 75 days to obtain complete diurnal sampling at the Equator, thus precluding monthly averages.

5. No measurements of the solar output were made thus preventing accurate determination of the net radiative interchange.

6. In the early Explorer and TIROS global heat budget experiments, separation of the radiation into shortwave, longwave, and total was achieved by the use of optical coatings. Past optical coatings had poor spectral characteristics, degraded, and in most cases were not used with inflight calibration methods.

7. The radiation budget data sets were very intermittent, with large time gaps during the 1960's and no data during the early 1970's. For many climate studies, analysis of a long continuous time series is required.

Although no error analysis has been made and no absolute measurement is available for reference, the accuracy of the derived albedo and longwave emission from previous missions has been estimated to be about ±5 percent on the planetary scale (annual average), and ±15 to 20 percent on the regional scale (seasonal average). These past measurements have been adequate for the study of synoptic scale and planetary scale, short-term climate problems. However, it has been recognized that improvement of about an order of magnitude is required to provide adequate observations for monitoring long-term global climatic trends. As a result, efforts have been made, in recent years, to improve measurement technology. One of these efforts is the Earth Radiation Budget (ERB) instrument which flew on NIMBUS 6 (June 1975) and is scheduled to fly on NIMBUS G (1978). It is expected that ERB will measure the solar constant to about 1 percent, the spectral solar irradiance in several broad spectral bands, the albedo, and the emitted longwave radiation. Although no systematic error analysis has been performed for the ERB system, it is felt that because of improved instrument design, the accuracy of the albedo and longwave measurements will be improved over previous measurements. In addition to wide field-of-view sensors, ERB includes high spatial resolution scanning radiometers. Analysis of these measurements will provide a much improved knowledge of the angular distribution of both long- and shortwave radiation.

These two ERB flights may provide valuable data for radiation budget studies of improved accuracies over previous data, but they will not fulfill all of the requirements for a radiation budget system to monitor long-term global climatic trends for the following reasons:

1. They will acquire albedo and emission data only at two local times each day from the NIMBUS Sun-synchronous orbit. Thus, biasing of the mean state of the radiation budget may result from not observing possible diurnal (local-time) variations in these parameters.

2. The albedo measurement from ERB is determined without adequate absolute or relative calibration after launch.

3. The measurement of the solar constant will not achieve the accuracy (<0.5 percent) that many authorities agree is required to investigate possible solar-climatic relationships. Initial results from ERB/NIMBUS 6 (Hickey, et al. 1976) indicate an absolute accuracy of 1.6 percent; however, this may be more indicative of a bias error, since repeatability has been within 0.2 percent).

4. NIMBUS 6 and the remaining NIMBUS experimental satellite (NIMBUS G), separated by 3-1/2 years, do not provide a continuing observing system needed for monitoring long-term global climatic trends.

As a result, a number of proposals for new systems designed to overcome these limitations appeared within recent years. Among these were:

1. Long-term Zonal Earth Energy Budget Experiment (LZEEBE), by NASA Langley Research Center.

2. Earth Radiation Budget Observation System (ERBOS), by the University of Wisconsin, and

3. Radiation Climate Radiometer/Solar and Earth Radiation Monitor (RCR/SERM), by NOAA, Colorado State University, Eppley Laboratories and Ball Brothers Research Corporation.

Phase A studies were completed under contract to the Langley Research Center for each of these proposed systems, each of which suggested that advanced sensor concepts be implemented aboard multiple spacecrafts. Subsequently, the positive features of each of the proposed systems were synthesized into a single system called the Earth Radiation Budget Satellite System (ERBSS). During 1976, a design study for this system was conducted which included analysis of the system errors. The results of that analysis give the best indication of the capability of improved instrumentation included in a system designed to address spatial and temporal sampling and data analysis requirements. The results are summarized in the following sections.

SAMPLING PROBLEM AND REQUIREMENTS

Values of Earth albedo and longwave emission radiation vary significantly with time and geographical location as indicated in figures 1 and 2 (Vonder Haar, 1968). Figure 2 further illustrates that the variation of mean albedo and longwave radiation is a function of season and geographical latitude. Over the globe, albedo is shown to change as much as 300 percent and longwave radiation varies as much as 100 percent. The season of the year is also shown to have an important effect on the radiation at a particular latitude. All of these variations demonstrate the importance of making radiation measurements at all latitudes and times of the year. Even now our knowledge of the diurnal variation is questionable. For instance, the diurnal variations shown in figure 1 are not in agreement with Astling and Horn (1964).

Various numbers of satellites and orbit inclinations have been analyzed to define the satellite combination that provides sufficient coverage of the Earth for spatial and temporal radiation sampling. Illustrations of latitude coverage or sampling as a function of local time are presented in figure 3. These results are for a typical 30-day period, which is consistent with the science requirements.

A nominal altitude of 600 km was selected for the 50° inclination orbit because it provides a 2-to 3-year lifetime and a revisit cycle over Earth of 3 days so as to observe each area from several angles. Sampling coverage for the 98.6° inclination orbits was based on the nominal TIROS-N orbit of 833 km altitude. Although the satellite will have a wide field of view that covers from horizon to horizon, only a 10° great circle of arc on Earth (e.g., 10° latitude and 10° longitude at the equator) was used in defining coverage and sampling capability. The reason for using the 10° angle is twofold: (1) It is commonly employed to provide a reasonable approximation for deconvolution of radiation data from satellite altitudes to the top of the atmosphere (about 30 km); (2) It is approximately the size of the geographical grid proposed for the resolution of the radiation data on a regional scale using the medium field of view sensors.

Figure 3(a) shows hourly latitude coverage provided by two Sun-synchronous ($i = 98.6^\circ$) orbits with equatorial crossings at 0800 and 1500 hours. The variation in density on this figure indicates the number of times a particular latitude band is covered at a given local time (the greater the density, the more times of coverage). The grid density is shown in the figure. Near-polar latitudes are covered during nearly all times of day. However, low and middle latitudes are only covered during the equatorial crossing hours. Thus, there are large gaps in hourly latitude coverage for Sun-synchronous orbits. More complete coverage can be achieved by covering nearly all the low and middle latitudes at each local hour by adding a single satellite at a mid-inclined orbit of about 50° with a faster orbital precession rate (see fig. 3(b)). To cover the low latitudes even more often, a 30° inclined orbit could be used; however, the 30° orbit would not cover the midlatitudes, and neither the 30° nor the 50° orbit would cover the high (polar) latitudes. In other words, to obtain monthly averages over the globe, middle and/or low inclination orbits are desired because of their rapid precessional rates since high inclination orbits, such as 80°, do not precess rapidly enough. High inclination orbits, however, are needed to cover the polar regions--thus, an optimum satellite mix for sampling is a combination of high and middle or low inclinations.

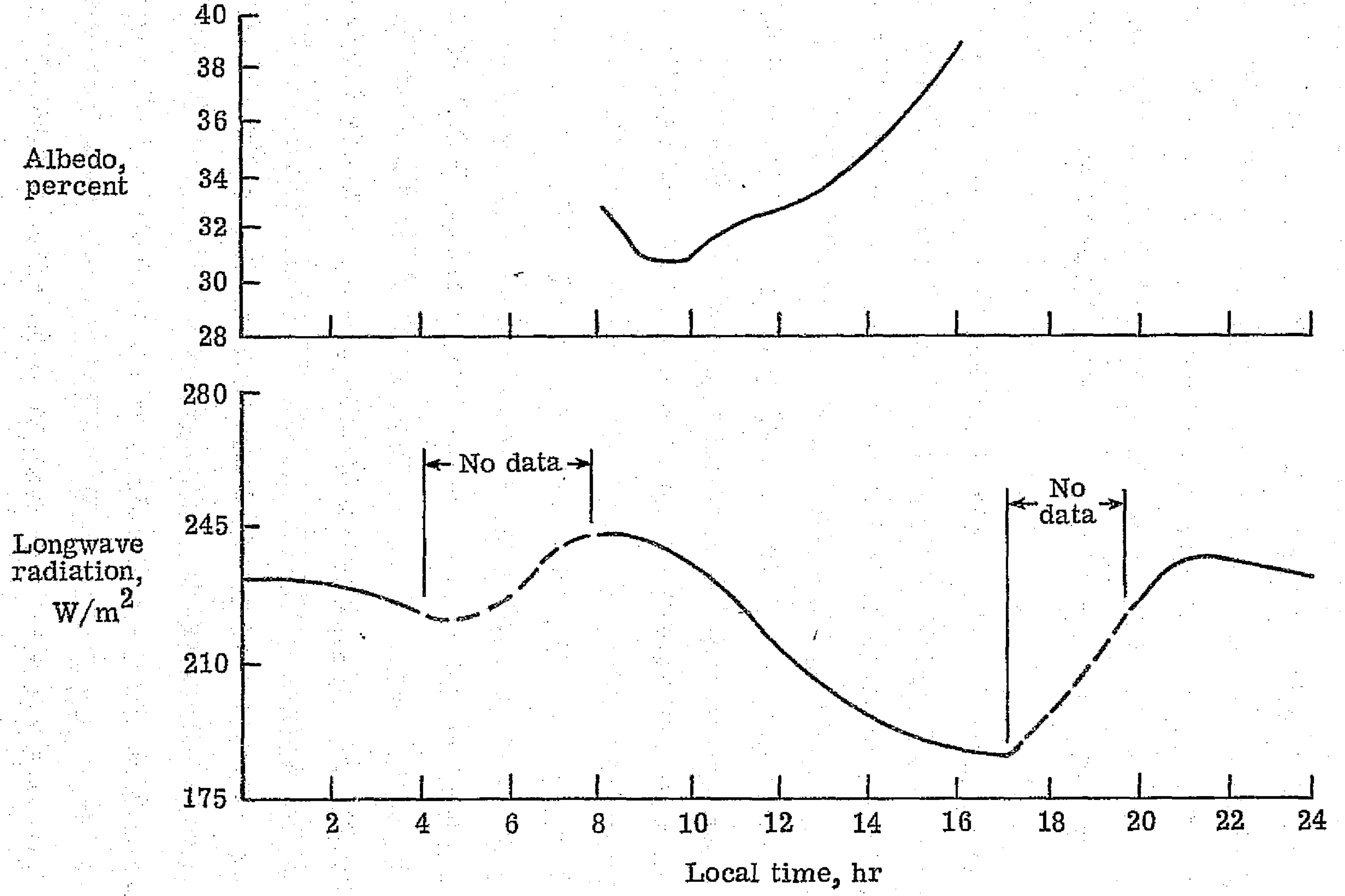


Figure 1.—Typical diurnal variation of Earth albedo and longwave radiation.

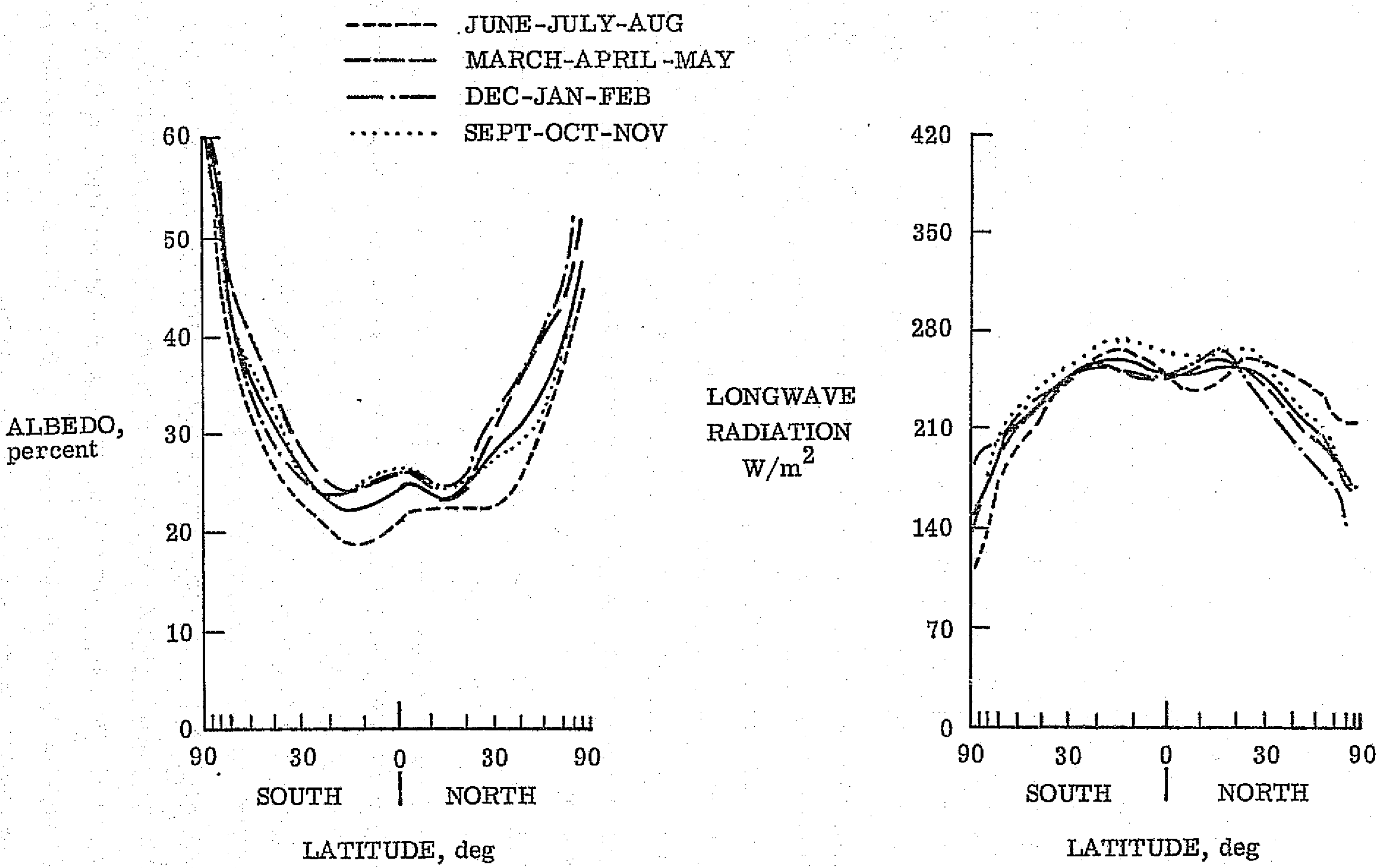


Figure 2 .- Latitude profiles of Earth albedo and longwave radiation for seasons and the annual case (solid line).

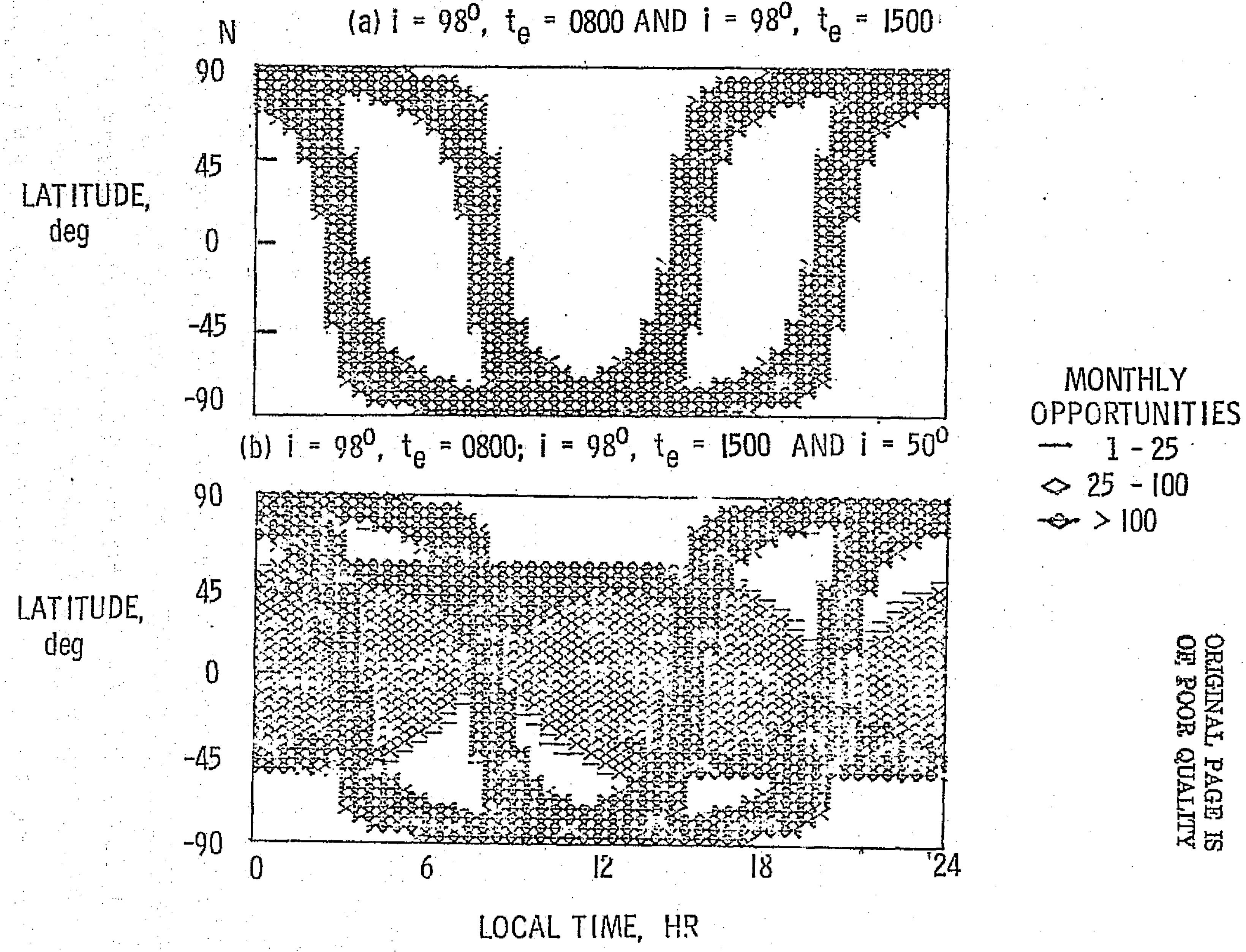


Figure 3.- Temporal-Latitude Zonal Coverage For Multiple Satellites.

To evaluate this thesis, a figure-of-merit parameter which is based on a product of geographical area (not just latitude) and local time coverage, was used to compare the various satellite orbit capabilities. Included in this comparison was the effect on coverage of natural orbit variations (due to natural precession rates of different orbit inclinations). The results are shown in figure 4. As can be seen, two Sun-synchronous satellites together provide an area-local time coverage of less than 30 percent. By combining them with one 80° inclined orbit, the area-local time coverage would be increased to only 60-68 percent. Unfortunately, 3 months are required for the 80° inclined orbit to precess through all local times. Meanwhile the Sun's declination will have changed appreciably thus making separation of diurnal effects from seasonal effects difficult, and will also result in biases in the monthly averages.

The most effective coverage can be obtained by combining the two Sun-synchronous satellites with one 50° inclined satellite; the area-local time coverage would be increased to 85-87 percent. By further adding a 30° inclined satellite, the area-local time coverage would be 88-91 percent. However, figure 4 is based primarily on zonal resolutions which is why the orbit combinations $i = 98^\circ, 98^\circ, 50^\circ$ and $i = 98^\circ, 98^\circ, 50^\circ, 30^\circ$ are comparable — or in other words — three satellites sample zonal resolutions about as well as four satellites. More detailed analysis for periods of time less than 30 days and for improved regional resolution coverage show the advantage of the fourth satellite.

In order to further evaluate the capability of the recommended satellite combination ($i = 98^\circ, 98^\circ, 50^\circ$), a simulation model of the Earth's radiation field, figure 5, developed by Campbell and Vonder Haar (1973), was used to calculate the satellite radiation results shown in figures 6 and 7. Monthly average zonal emitted energy (fig. 6) and reflected energy (fig. 7) as a function of latitude for the three satellite system are shown to compare well with the reference values, which were established by assuming essentially unlimited (i.e., 21) satellites.

Recent sampling studies are refining the expected accuracy of the three satellite system for regional resolution by studying the variability of the scene using cloud-cover statistics. The magnitude of measurements of reflected solar radiation exiting the Earth-atmosphere system is strongly dependent on the amount of cloud cover in the radiometer field of view. Reflected shortwave radiation is directly related to cloud cover since the albedo and angular reflectance characteristics of clouds are usually quite different from that of the underlying surface. Figure 8 presents a summary of the results showing the minimum and maximum accuracy limits (standard deviation of the mean) in equatorial regions for each month. It is apparent from the figure that the regional radiation budget measurements at low latitudes is being performed almost solely by the 50° inclined satellite; however, the two Sun-synchronous satellites complement the system by providing the measurements at mid and high latitudes. The results of figure 8 are

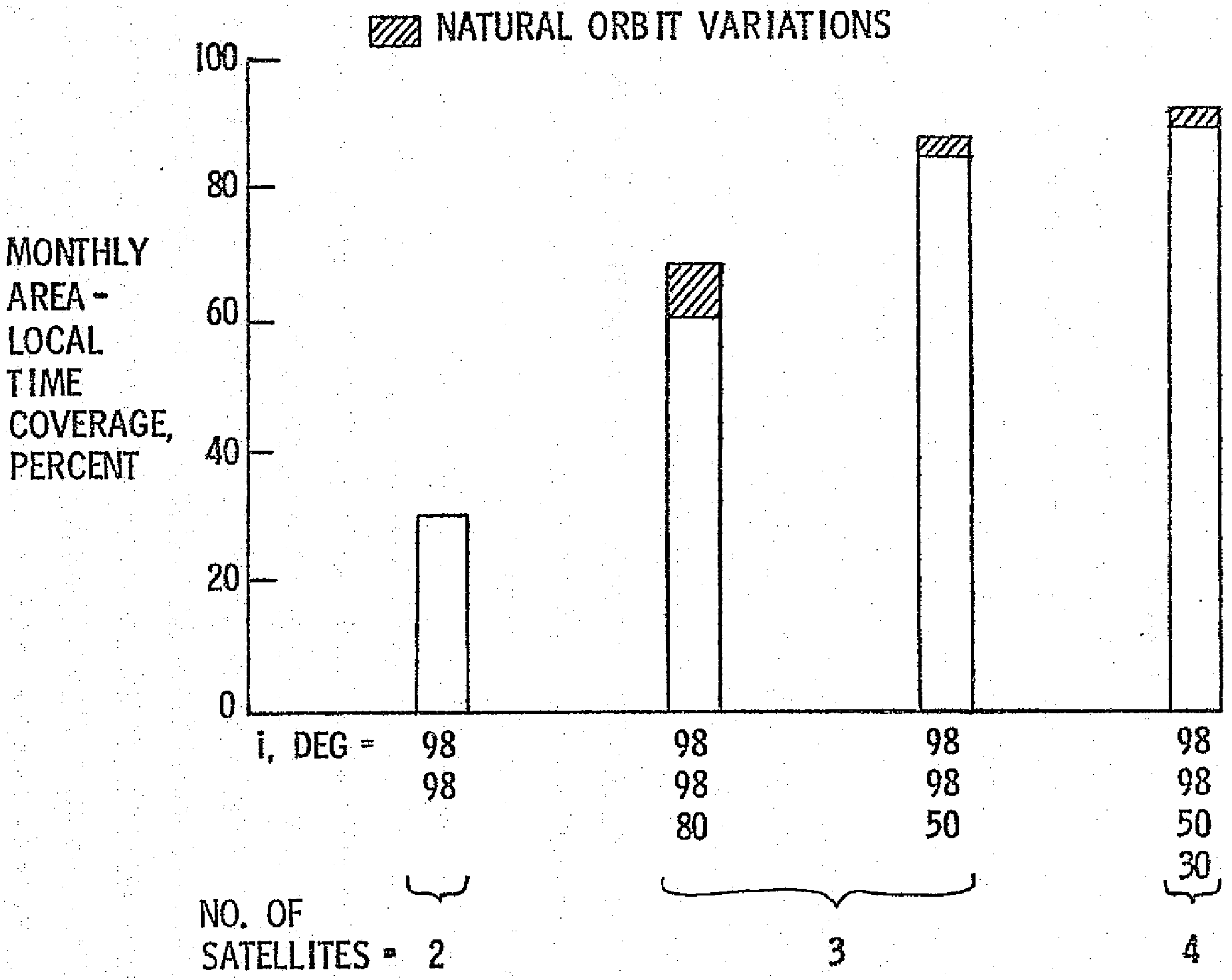


Figure 4.- Comparison of Sampling Capability of Various Satellite Combinations.

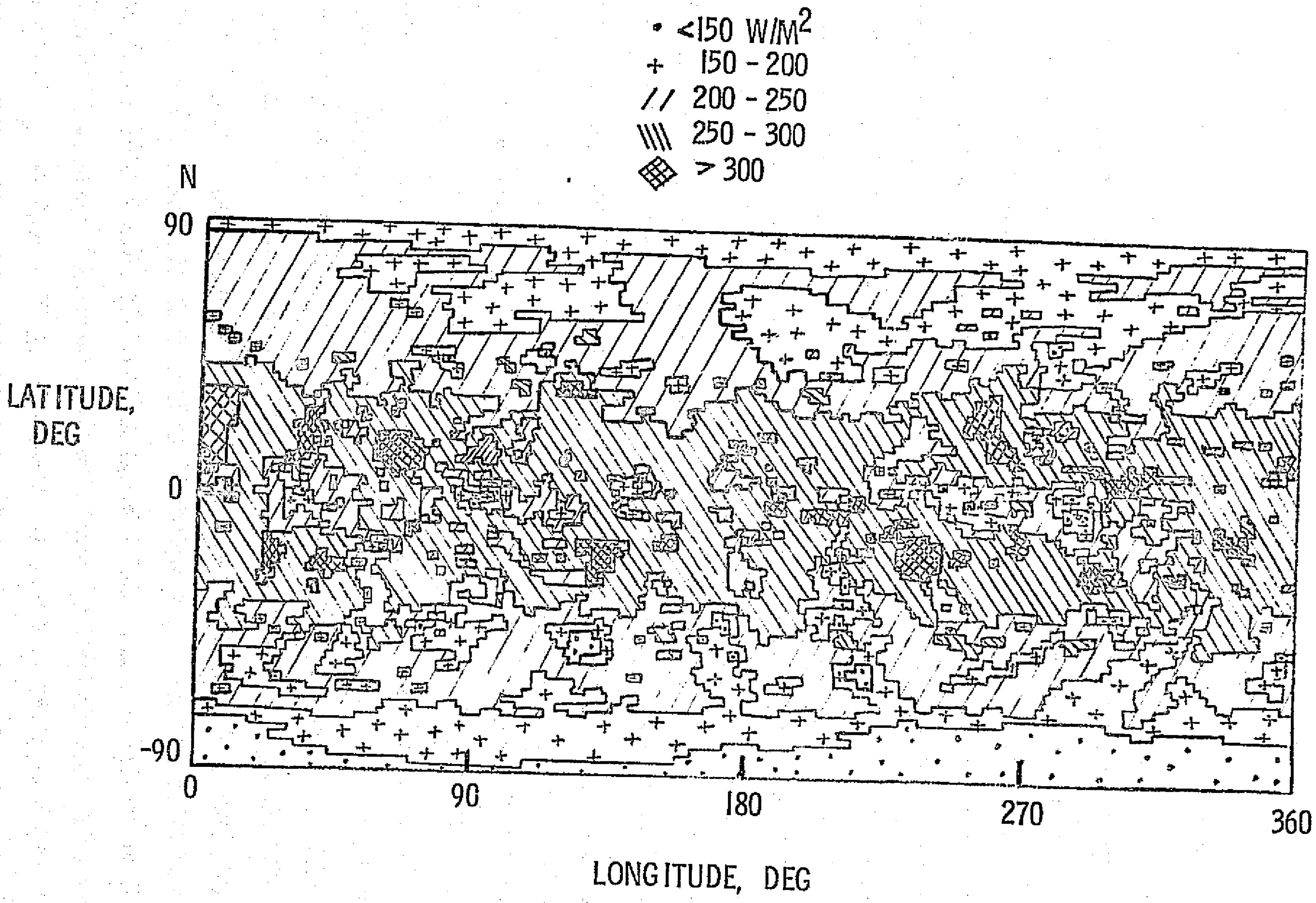


Figure 5.- Earth Emitted Radiation Map.

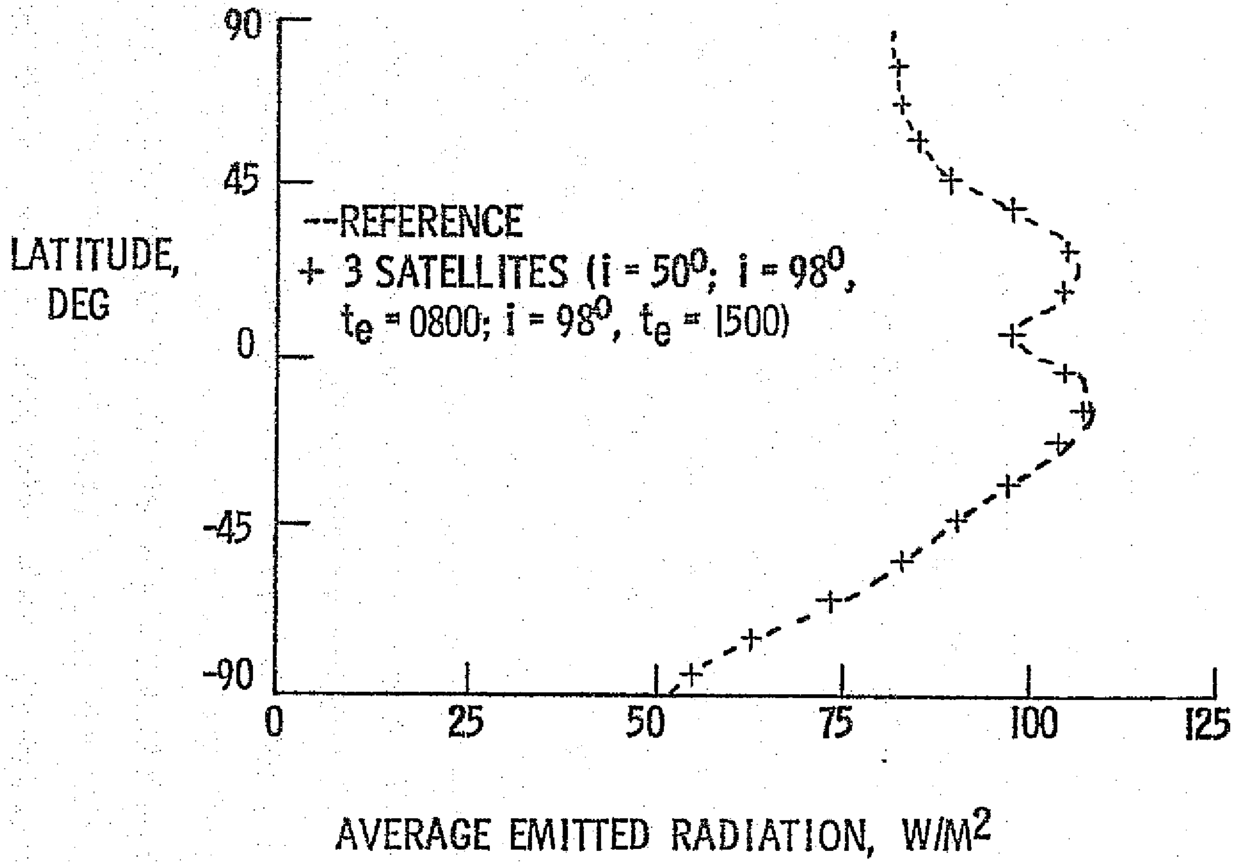


Figure 6.- Simulated Emitted Monthly Zonal Radiation Measurements.

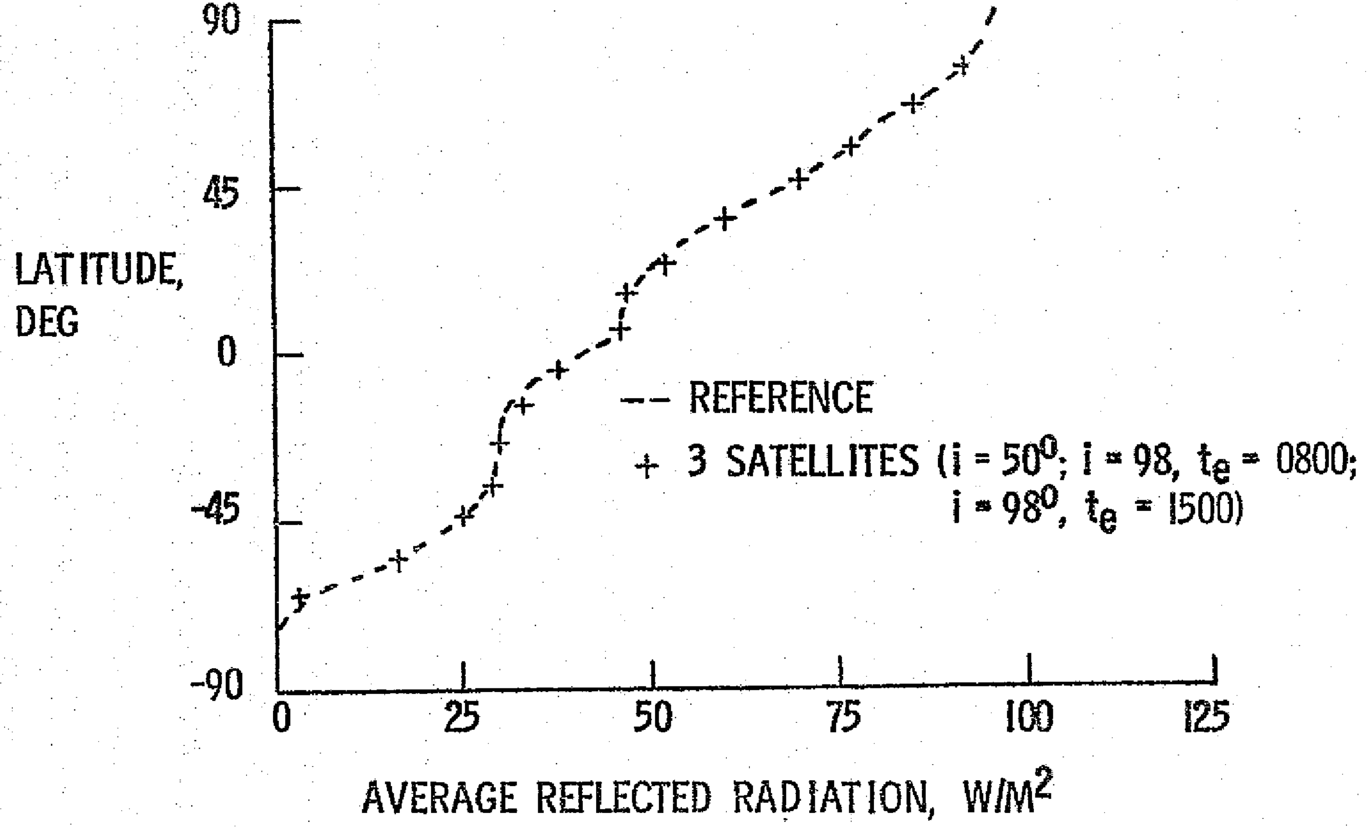


Figure 7.- Simulated Reflected Monthly Zonal Radiation Measurements.

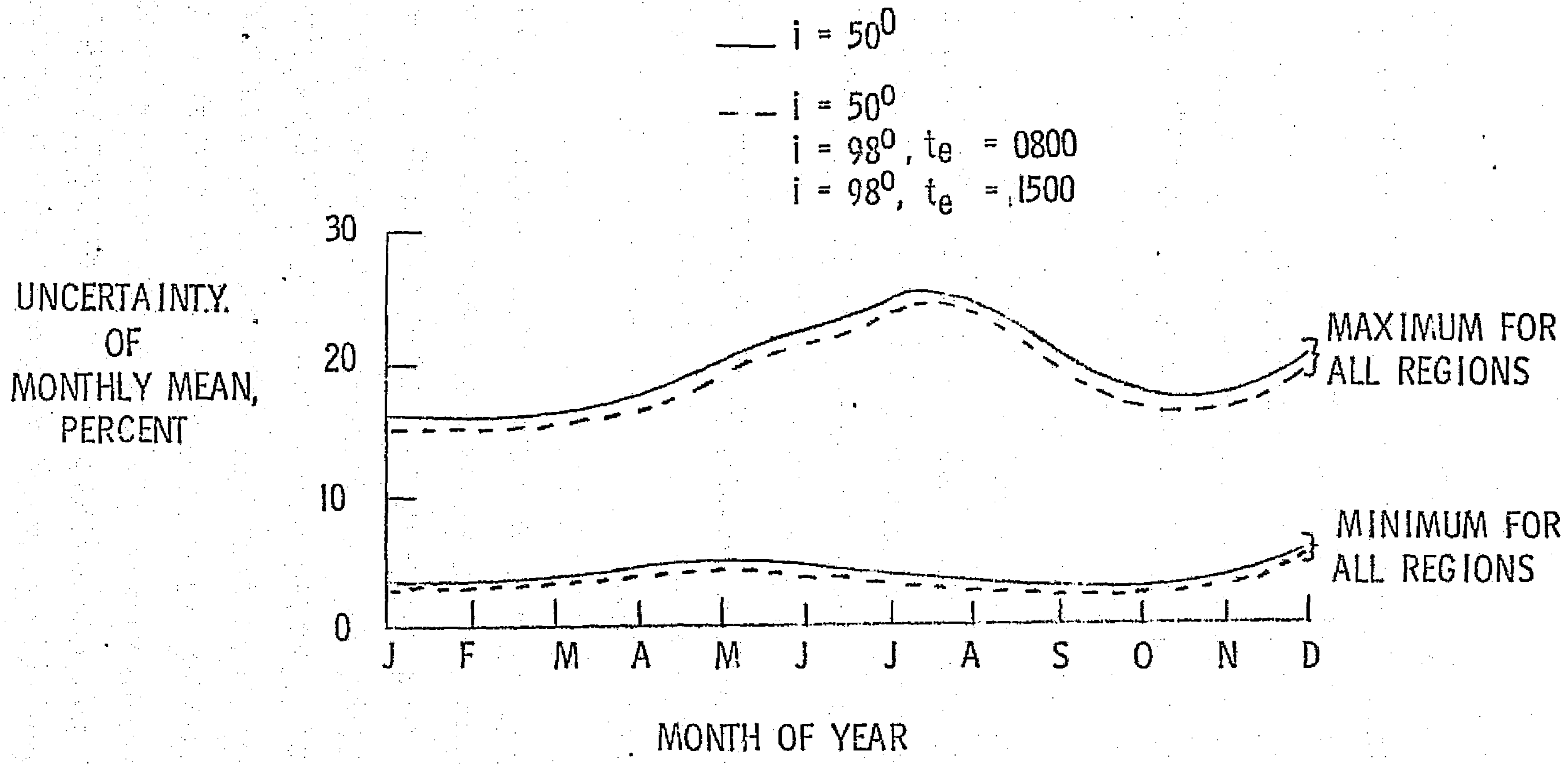


Figure 8.- Reflected Equatorial Regional Radiation Accuracy Based on Sampling of Cloud Statistics (t - 30 Days).

worse-case analysis assuming no a prior knowledge. Persistence of cloud cover, correlation between regions, and refined knowledge of the diurnal cycle which will be established by this mission should allow a determination of regional radiation budget of better than 5 percent, or a reduction of the maximum errors shown in figure 8 by a large factor.

Based on the results of the sampling studies, two 98° inclined orbits coupled with the 50° orbit appear to satisfy the science requirements for regional resolutions, zonal resolutions, equator-to-pole gradient, and global resolutions. The NOAA Sun-synchronous satellites in the TIROS-N series could adequately cover the high latitudes and an ERBSS/AEM (SMMS) satellite having an inclination of 50° could provide sampling in the mid-and low-latitude areas where variations in radiation energetics are most dynamic.

DATA INTERPRETATION AND ANALYSIS

The second major area contributing to the ability to meet the science requirements, besides sampling, is "Data Interpretation and Analysis." Scanner measurements can be summed for small regions or wide field of view (WFOV) and medium field-of-view (MFOV) measurements can be deconvoluted to obtain the radiation budget at the top of the atmosphere for larger regions, latitudinal zones, and the equator-to-pole gradient. The global net radiation budget can be best averaged at satellite altitude. Therefore, even though a MFOV (10°ECA) radiometer can directly view a regional area, two of the most important contributions in the interpretation of ERBSS data are (1) the computation of the Earth radiation budget on a scale smaller than the field of view of the WFOV sensors, and (2) to infer top-of-the-atmosphere radiation budget from satellite measurements.

The essence of the data analysis is shown in figures 9 and 10. Figure 9 shows schematically a satellite sensor over a regional area on the Earth surface. The quantity desired is the total energy leaving the surface; however, only the components directed at the satellite will be measured, and the components directed out the sides will be missed and, thus, must be accounted for by using directional models. Regardless of whether the sensor is WFOV, MFOV, or a scanner, directional models must be used in analyzing the measurements. In addition, the surface elements surrounding the regional or zonal area will also direct radiation to the sensor, and this radiation must be accounted for by subtracting it out of the sensor measurement--except for the scanner. The analysis is further compounded since directional models are not simple, particularly shortwave or solar reflected energy. As can be seen in figure 10, the directional models are a function of the solar flux angle of incidence and the Earth surface type, i.e., clouds, snow, ocean, desert, etc. The directional models shown in figure 10 are characteristic of clouds.

The first step in data analysis is to assign the measured components of the radiation, reflected and emitted, to the correct region and then compute these radiation as they leave the top of the atmosphere. Existing techniques for making these computations have been investigated at Langley Research Center, Drexel University, Goddard Space Flight Center, and Colorado State University.

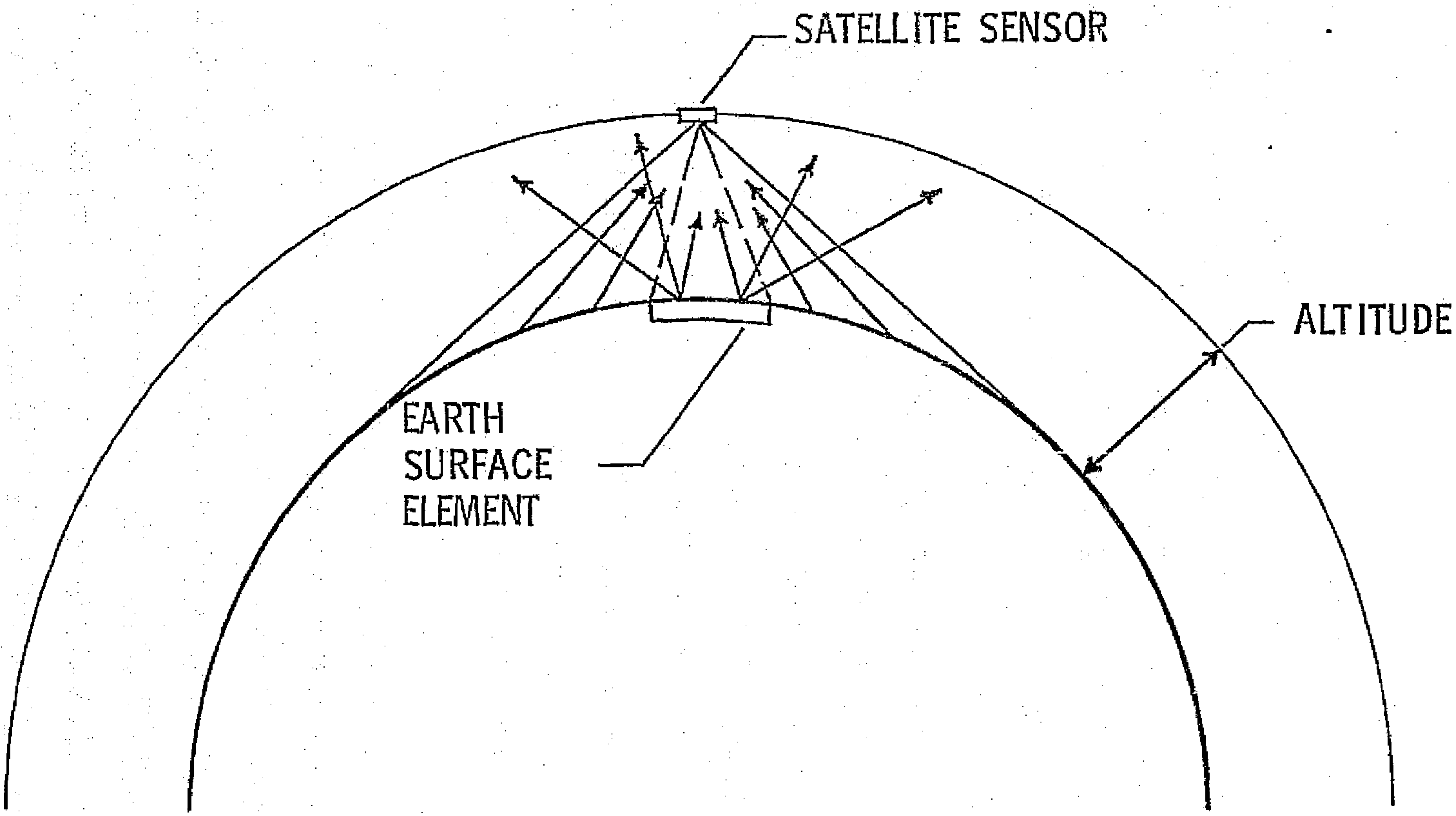


Figure 9.- Data Analysis Technique.

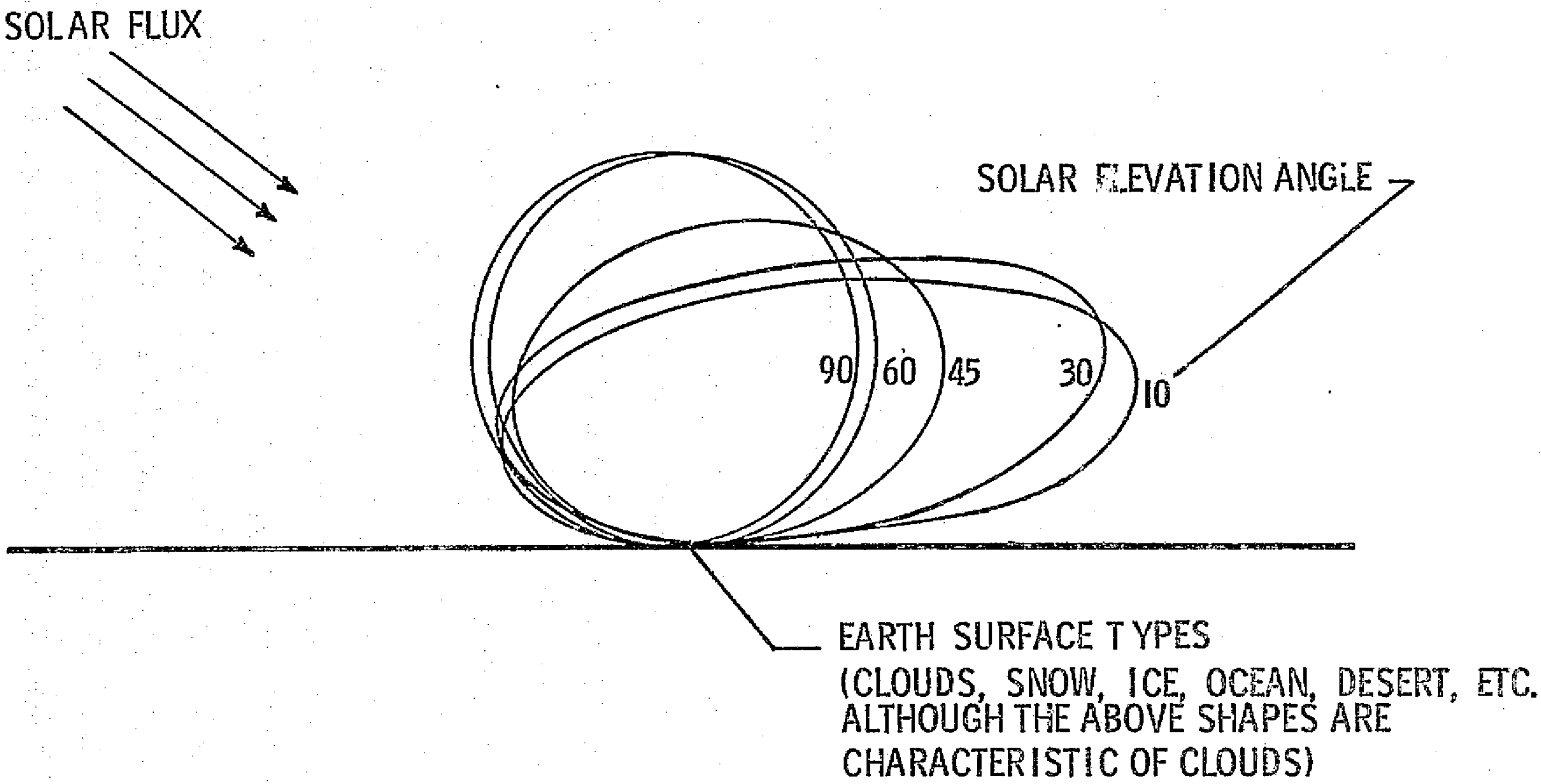


Figure 10.- Shape Models of Reflected Solar Flux.

Analysis of low resolution integrating radiometer data from the ESSA 7 and 9 satellites by Langley Research Center and Drexel University has provided experience in processing and statistically analyzing large sets of radiation measurements (House, 1975 and Weaver, 1976). Theoretical studies, including simulated radiation models, have been performed to expand the application of the height rectification analysis technique and to improve our understanding of this commonly employed method of analysis (Laughlin, 1977 and Weaver, 1977). Simulation results show that modeling error effects can be reduced significantly, and also show that the height rectification technique can be applied even when a limited number of radiation budget measurements are available.

In addition to the studies using earlier techniques, new techniques have been developed by the Langley Research Center, Drexel University, and Colorado State University for performing these computations. (For instance refer to the paper "A Simulation Study of Earth Radiation Budget Data Interpretation," by G. Louis Smith, Richard N. Green, James F. Kibler, Lee M. Avis, John T. Suttles, and George R. Young. Presented at the Summer Computer Simulation Conference, Washington, D.C., July 12-14, 1976.)

The WFOV sensor will measure the total amount of radiation impinging on it from all points on Earth from horizon to horizon, which for an 833 km altitude encompasses a circle with a diameter of about 50° arc on the Earth's surface. With the new techniques, large numbers of overlapping measurements are used to improve the resolution of the measurements over that of a single measurement. The results can thus be interpreted to a smaller scale than the field of view of the instrument.

These computations cannot be made using satellite measurements alone. As previously mentioned a model which specifies the radiation as a function of angles of departure from the Earth and Sun elevation is necessary. (See Raschke, Vonder Haar, Pasternak, and Bandeen, 1972 and Ruff, Koffler, Fritz, Winston, and Rao, 1968). The goal of the currently orbiting NIMBUS 6 and upcoming NIMBUS G Earth Radiation Budget (ERB) Experiment is to develop improved directional models. These improved directional models along with the "parameter estimation" method of Smith and Green should provide improved results for inferring the radiation budget of the Earth at resolution scales of 10° ECA or larger. The parameter estimation method considers the statistical nature of the atmospheric radiation and is applicable to discrete data. The inclusion of modeled directional characteristics of emitted and reflected radiation permit the treatment of orbital altitude variations, anisotropies in the Earth radiation field, and bringing of the data to the top of the atmosphere as a single problem. In addition, the method can be used to incorporate measurements from orbits with different inclinations, different altitudes, and different sensors.

To demonstrate the overall data interpretation and analysis methods, simulation studies were performed. The simulation consisted of two basic parts, a "real" Earth-atmosphere radiation system for computing simulated measurements and a "model" Earth-atmosphere radiation system for the data analysis. A known radiation field was used to generate satellite measurements which are corrupted with random errors and passed to the model system as simulated "real" data. The data interpretation technique was applied to these data, and the heat flux parameters were estimated. The comparison was then made between the "real" heat flux and the estimated heat flux. This comparison indicates the accuracy of the data interpretation technique. The simulation procedure, as outlined above, is graphically presented in figure 11, for example, in determining regional radiation budget at the Equator plus zonal resolutions at higher latitudes.

One of the major advantages of the simulation studies is that modeling errors can be investigated. The data analysis simulation demonstrates the accuracy of the estimation procedure in the presence of directional modeling errors. The simulations have been performed for both Earth emitted (longwave) and reflected (shortwave) radiation, and for WFOV and MFOV sensors. Regional and zonal resolutions were considered, as well as the equator-to-pole gradient and the global integration of plane flux. Further advantages of the simulation are that the following can be evaluated: (1) orbit inclinations, (2) number of measurements or sampling, and (3) effect of instrument errors.

Summary results of the simulation studies are shown in the combined error analysis, table VIII. Four major parameters contributing to the overall ability of the ERBSS in meeting the accuracy/resolution requirements of the science community are: (1) instrument or sensor accuracy, (2) directional modeling accuracy, (3) sampling or orbital constraints, and (4) solar constant measurements accuracy. The solar constant accuracy was based upon the instrument technology of the upcoming Solar Maximum Mission.

Analysis results of the satellite system capabilities for regional radiation budget are shown in table IX. WFOV and MFOV sensors should be able to measure the radiation budget of 10-20° ECA (1000-2000 km) regions to about 4.3 percent. The scanner is required for smaller resolutions, i.e., 250 to 500 km regions. Analysis of the area coverage at multiple angles for monthly averaged regional radiation budget using a scanner have shown that a scanner much simpler than the ERB experiment in NIMBUS 6 and NIMBUS G is sufficient, i.e. a one-axis cross-track scanner. The ERB scanner is complex by necessity to define directional models for many surface types: snow, ice, water, foliage, desert, etc.; however, it is not required for a global radiation budget program. The adequacy of a cross-track scanner has also been verified by comparing the

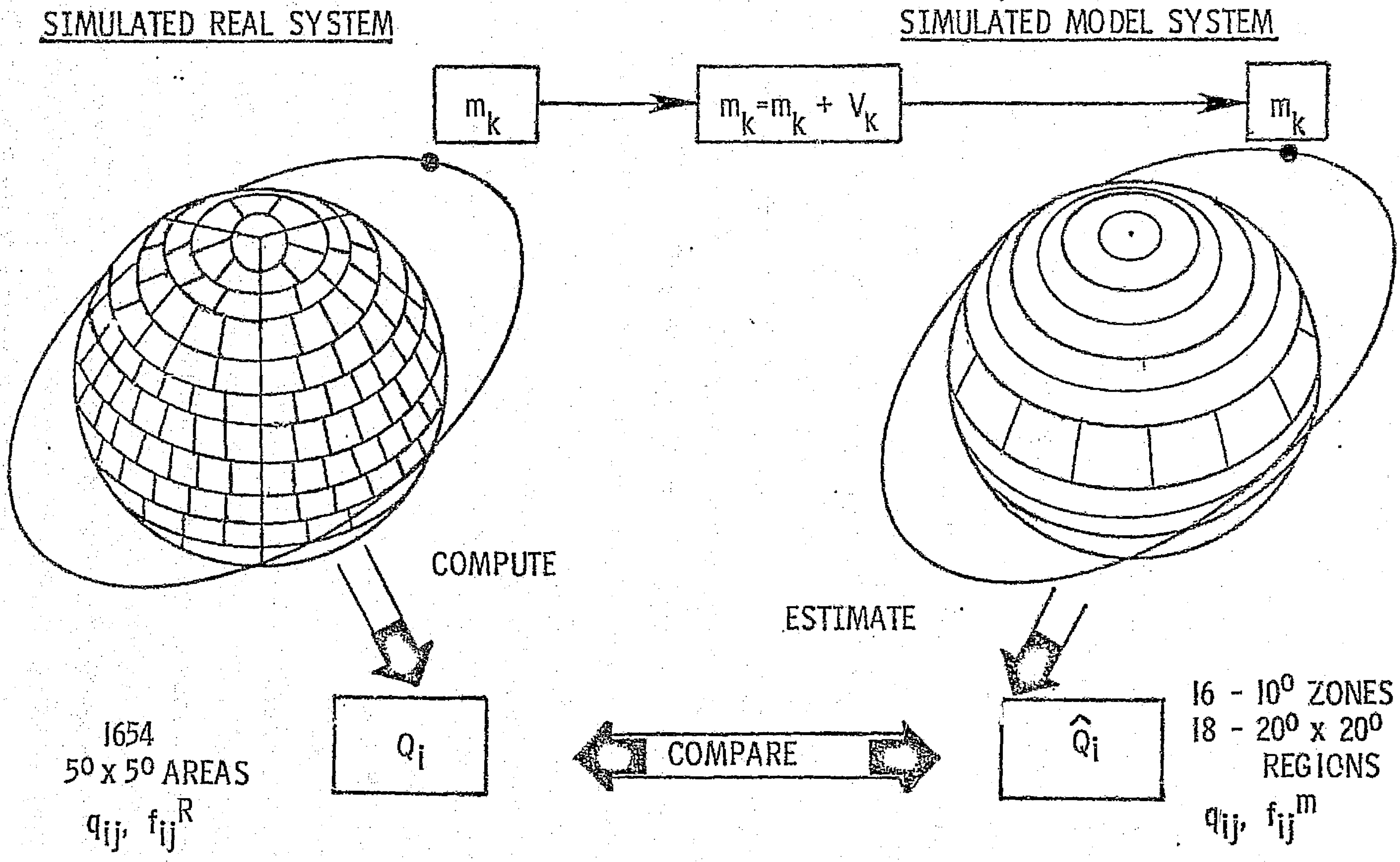


Figure 11.- Simulation of Parameter Estimation Technique.

TABLE VIII

EARTH RADIATION BUDGET SATELLITE SYSTEM COMBINED ERRORS $(1\ \sigma)$, W/M^2.

	10° ZONES		GLOBE		POLE TO EQUATOR GRADIENT	
ERROR SOURCE	SW	LW	SW	LW	SW	LW
SENSOR						
WFOV						
BIAS	1.4-2.3	1.4-2.3	1.4-2.3	1.4-2.3	NEGLIGIBLE	NEGLIGIBLE
PROPORTIONAL	1/3% of LW	1/3% of LW	0.8	0.8	0.2	0.2
MFOV						
BIAS	2.6-4.3	3.4 - 3.7	2.6-4.3	3.4 - 3.7	NEGLIGIBLE	NEGLIGIBLE
PROPORTIONAL	1/3% of LW	1/3% of LW	0.8	0.8	0.2	0.2
DIRECTIONAL MODELING						
WFOV	0.13	0.065	0.13	0.011	0.13	0.041
MFOV	0.33	1.4	0.42	2.0	0.83	
SAMPLING						
BIAS	1.2	2.0	0.17	0.075	0.5	1.28
RANDOM	1.0	0.50	0.25	0.12	0.50	0.24
SOLAR CONSTANT						
(1/6% 1σ error)	0.063-0.72	0	0.56	0	0.25	0
TOTALS	3.8-5.3	4.3-5.2	2.6-3.5	1.8-2.7	1.3	1.6
NET RADIATION	5.7-7.4		3.2-4.4 ASSUMES SPECTRAL (LW & SW) SEPARATION OF GLOBAL NET RADIATION. GLOBAL NET RADIATION CAN BE MEASURED TO 1.3 BY THE TOTAL CHANNEL.		2.1	

TABLE IX

SATELLITE SYSTEM CAPABILITIES FOR REGIONAL RADIATION BUDGET

		SATELLITE COMBINATIONS[1]		
TIROS - N (98°)		X	X	X
AEM - D (50°)		X		X
MMS (80°)			X	X
CAPABILITY OF DETERMINATION OF COMPONENTS: LONGWAVE (EARTH EMITTED) AND SHORTWAVE (ALBEDO) GLOBAL COVERAGE	SPACE AND TIME SCALES 10° ECA (1000 km)	4.3% MONTHLY AVERAGES	4.3% SEASONAL[2] AVERAGES ONLY	3-4% MONTHLY AVERAGES
	500 km	WITH SCANNERS 4.3% MONTHLY AVERAGES	4.3% SEASONAL[2] AVERAGES ONLY	3-4% MONTHLY AVERAGES
	[3]100 km WEEKLY AVERAGES	MULTIPLE SATELLITES WITH SCANNERS 36 SATELLITES: 5% 9 SATELLITES: 10%		

1. EXCEPT WHERE NOTED, SYSTEM INCLUDES 5 SENSORS: WFOV - TOTAL AND SW; MFOV - TOTAL AND SW; AND SOLAR.
2. SEPARATION OF DIURNAL FROM SEASONAL EFFECTS WILL BE DIFFICULT.
3. FEASIBILITY OF MEETING THIS REQUIREMENT WITH EXISTING TECHNOLOGY IS QUESTIONABLE. A NEW APPROACH USING GEOSTATIONARY SATELLITE MEASUREMENTS (DIURNAL SAMPLING) ALONG WITH POLAR, SUN-SYNCHRONOUS SATELLITES MEASUREMENTS (POLAR COVERAGE) SHOULD BE STUDIED.

monthly averaged cross-track pixels from the ERB longwave channel with the full ERB scans. Agreement was within a few tenths W/m^2. Multiple satellites with scanners are necessary to obtain 100 km regional resolutions with weekly averages of the radiation budget. Also, the combination of 98° and 80° inclined orbits provides seasonal averages but poor monthly averages.

Therefore, the overall expected accuracy of ERBSS for monthly averages is:

Area Resolution	Requirement (W/m^2)	Capability (W/m^2)
10° x 10° Regions in Tropics (LW&SW)	2-15	9.4 & 10.3 (4 & 4.3 percent)
10° Latitudinal Zones (LW&SW)	2-12	5.2 & 5.3
Equator to Pole Gradient (NET)	4	2
Global (NET - Total Sensor, WFOV)	1	1.3
250 to 500 km Regions (LW&SW)	2-14	9.4 & 10.4 (4 & 4.3 percent)(With Scanner)

SENSOR DESIGN STUDIES

The current ERBSS studies have focused on developing a satellite/sensor system approach for determining Earth radiation budget parameters on monthly and longer time scales and small, medium, and large space scales, i.e. regional, zonal, Equator to pole gradient, and global. Results to date indicate that a combination of wide field-of-view (WFOV) and medium field-of-view (MFOV) sensors flying on a multiple satellite system (i.e., two Sun-synchronous at 833 km and the 50° inclination at 600 km altitude) can provide the necessary sampling and resolution to determine monthly or longer time averages for 10° by 10° ECA regions, 10° latitudinal zones, and larger resolutions, and a cross-track scanning radiometer can provide the necessary sampling and resolution to determine monthly or longer time averages for resolutions smaller than 10° by 10° ECA (i.e., 250 to 500 km regions). This section describes the design definition for these systems. The system designs are based on simplicity, reliability, high accuracy, and low cost.

The ERBSS measurement channels are shown in table X. Five channels are included in the WFOV/MFOV instrument, and two in the scanning instrument. Detailed parameters for the WFOV/MFOV instrument are given in table XI, and the accompanying design concept is shown in figure 12. Four of these channels are mounted on a single axis gimbal which, when coupled with orbital motions, provides the net motions necessary for observing the Earth or the Sun. The fifth channel is not gimballed and provides a reference observation of the Sun and measurement of the solar constant periodically throughout the mission. The four gimballed sensors differ mainly in the spatial and spectral scales of their observations when viewing the Earth. Two of the sensors view the entire Earth disc from limb to limb, and are designated wide field-of-view (WFOV) channels. The baseline concept assumes the detectors are wire wound thermopiles which have a broadband spectral response from about 0.2 μm to 50 + μm. The detector of one of the WFOV channels is placed under a Suprasil-W hemispherical dome filter which provides spectral isolation for this channel since the filter cuts off at about 5 μm. Hence, one WFOV channel makes broadband or total radiation measurements and the other WFOV channel makes measurements over the shortwave spectral band characterized by the Suprasil-W dome. The other two gimballed sensor channels have a regional scale view of the Earth of about 10° Earth Central Angle (ECA) and are designated medium field-of-view (MFOV) channels. Their fields of view are approximately equivalent to a Texas sized footprint and, like the WFOV channels, one MFOV channel is placed under a Suprasil-W hemispherical dome to make measurements over the shortwave spectral band while the other MFOV channel measures total radiation. For both WFOV and MFOV, the Earth emitted longwave radiation component is determined by subtracting the shortwave (Earth reflected radiation) channel measurement from the total radiation channel measurement. Detailed engineering analyses have sized the hemispherical dome to minimize (essentially eliminate) the effects of polarized light and thermal contamination, and thereby minimize error sources.

The baseline concept for the four Earth viewing channels are circular wire-wound thermopiles similar to the ERB WFOV channels flown on NIMBUS 6 and planned for NIMBUS G. The NIMBUS 6 experience has demonstrated the stability of thermopiles in space. However, the ability to meet the desired sensor accuracies will depend on a rigorous preflight and inflight calibration program. Thus, there is a need for the gimballed configuration to turn all the detectors to view the Sun, space, and internal black-body sources for periodic inflight calibration. A layout of the instrument, figure 13, shows the various in-orbit positions of the instrument during measurements and calibrations. During launch and post-orbit insertion, the sensors are stored in the right-hand position to protect them from outgassing and contamination. The solar viewing of the shortwave channel also provides the solar reference with the same sensor for determining albedo, which overcomes a deficiency of past measurements.

The solar channel will be a narrow field-of-view (i.e., ≈ 5°) cavity radiometer measuring the total solar spectral range. It is baselined on proven technology (i.e., Kendall, Wilson, Hickey) being developed for the Solar Maximum Mission and recently flown (June 1976) on an Aerobee rocket flight for measuring the solar constant and intercomparison of instruments.

TABLE X

ERBSS MEASUREMENT CHANNELS

WFOV/MFOV INSTRUMENT

INSTRUMENT	GROUND COVERAGE
WIDE FIELD OF VIEW • SHORTWAVE CHANNEL • TOTAL CHANNEL	LIMB TO LIMB
MEDIUM FIELD OF VIEW • SHORTWAVE CHANNEL • TOTAL CHANNEL	10° EARTH CENTRAL ANGLE
• SOLAR MEASUREMENT	SOLAR CONSTANT & INSTRUMENT IN-FLIGHT CALIBRATIONS

SCANNER INSTRUMENT

• SHORTWAVE CHANNEL • LONGWAVE CHANNEL	CROSS-TRACK 87 KM AT NADIR

TABLE XI

ERBSS INSTRUMENT PARAMETERS

WFOV/MFOV INSTRUMENT

● WEIGHT	20 kg
● ENVELOPE	14.6(x'), 45.8(y'), 16.5(z')cm
● POWER	15 watts (Average Orbital)
● DATA RATE	160 bps
● NUMBER OF COMMANDS	20
● BASELINE ORBITS	AEM - 600 km; TIROS - 833 km

CHANNELS 1 THROUGH 4

● EARTH VIEWING FIELD-OF-VIEW (CHANNEL 1 AND 2)	LIMB-TO-LIMB (WFOV)
(CHANNEL 3 AND 4)	10° EARTH CENTRAL ANGLE (MFOV)
● SOLAR/SPACE FIELD-OF-VIEW	32°
● SPECTRAL BAND, CHANNELS 1 AND 3	0.2 to 50$^+$ µm
CHANNELS 2 AND 4	0.2 to 5 µm (Suprasil-W Dome)
● BASELINE DETECTOR TYPE	THERMOPILE
● MEASUREMENT FREQUENCY	EVERY 8 SECONDS
● INSTRUMENT UNCERTAINTY	$\pm$ 4 W/M^2

CHANNEL 5

- BASELINE IS CAVITY RADIOMETER SIMILAR TO SOLAR CONSTANT INSTRUMENT ABOARD SOLAR MAXIMUM MISSION.

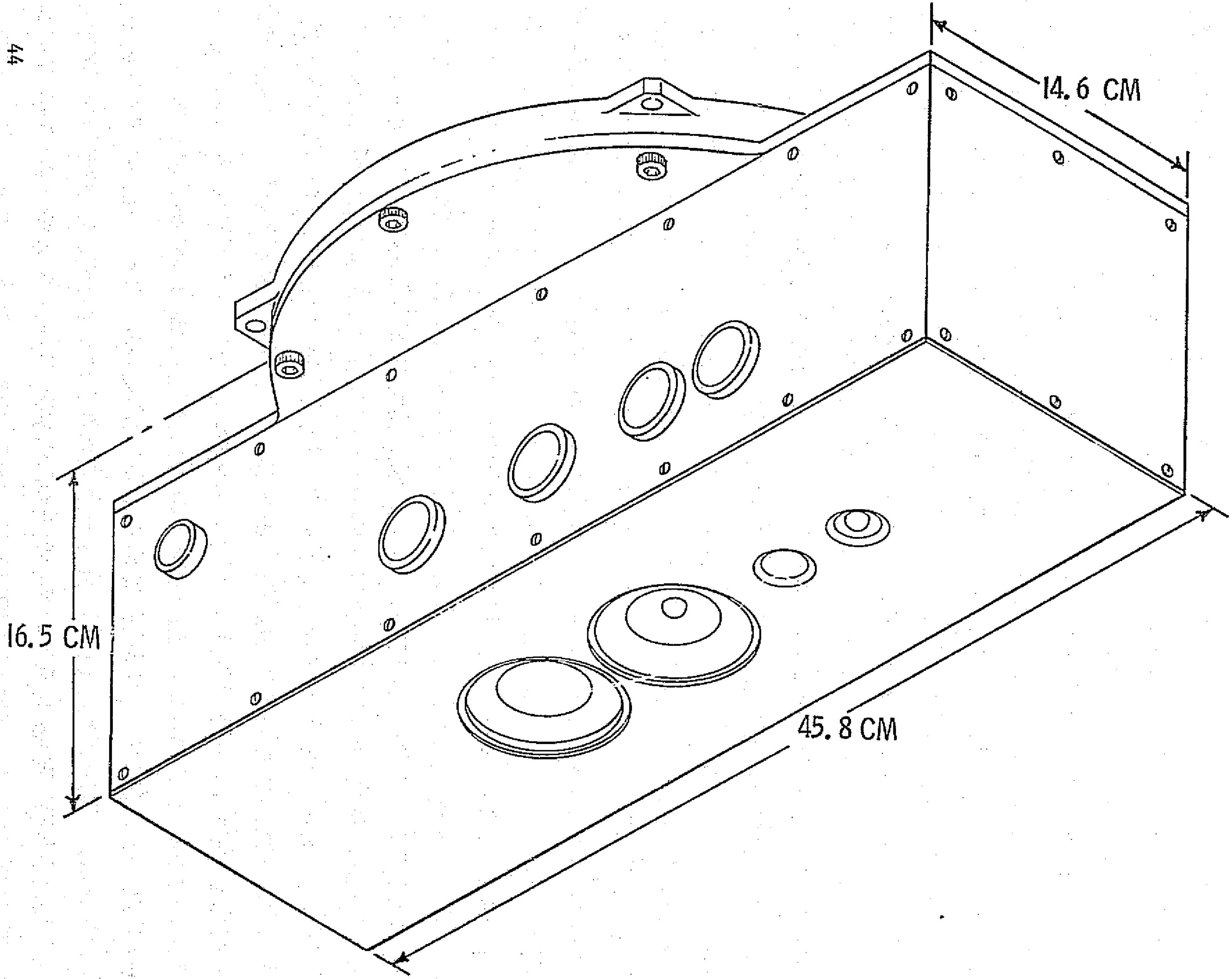


Figure 12.- ERBSS WFOV/MFOV Instrument Concept.

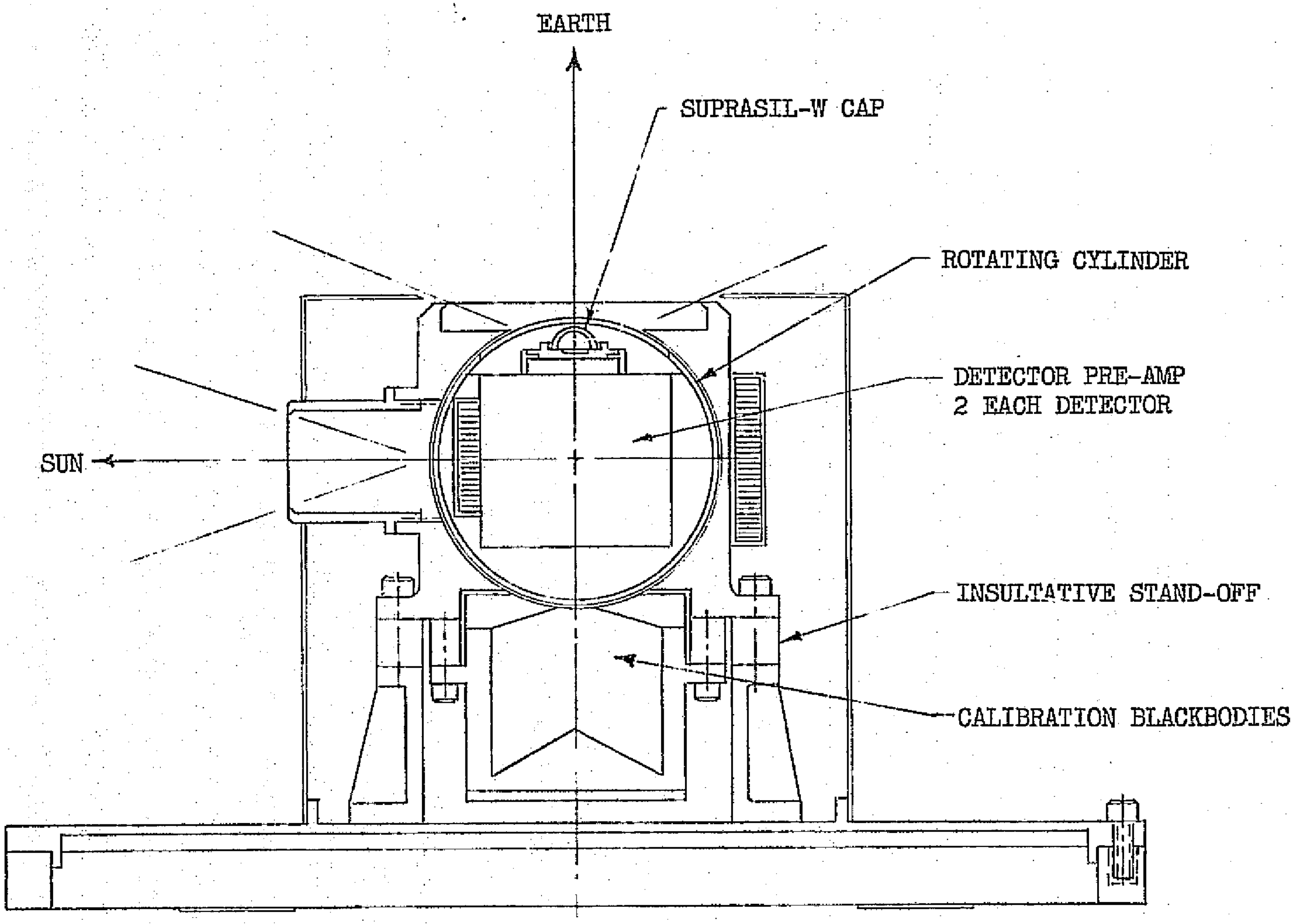


Figure 13.- ERBSS WFOV/MFOV Instrument Layout.

Although the current studies indicate circular wire-wound thermopiles will make sufficiently accurate measurements, the use of active cavity radiometers as a potential improvement for WFOV and MFOV sensors is currently planned for continued development studies in the F.Y. 1977-1979 time period.

The small spatial resolution (IFOV - 6° diameter) scanning instrument contains two separate channels (channels 6 and 7). Detailed parameters for the scanning instrument are given in table XII, and the accompanying design concept is shown in figure 14. Channel 6 isolates the SW spectral interval (0.2 to 5 μm), and channel 7 covers the LW spectral region (5 to 50+ μm). The spectral intervals are the same as the ERB (NIMBUS 6 and G) scanning channels. Both channels are located within a continuously rotating scan drum which scans the boresited IFOV's sequentially from horizon to horizon, and, for calibration purposes, to a space view and then within the instrument to diffuse reflectors illuminated by the Sun (SW channel), or a precision black body (LW channel). Each channel consists of a two-mirror telescope, field stop, bandpass filter, and pyroelectric detector-preamplifier assembly. The channels are all mounted within a single, temperature-controlled housing and are alined to view the same Earth area. This housing, in addition to providing alinement and support for the detectors and optical components, also incorporates an individual chopping reference black body for each channel, mounts for the chopper wheel, and a trunnion axis for the scan rotation. The rotating chopper is located in front of each telescope aperture and is shaped to allow each channel to alternately view the scene and the reference black body at a 55 Hz rate. The total scan assembly (drum) is rotated continuously by a motor direct drive system at a rate of 0.075 Hz. This scan rate allows the IFOV's of each scan line to be contiguous at the nadir for an orbital altitude $h = 833$ km. The 6° diameter IFOV corresponds to a ground resolution at the nadir of 87 km for $h = 833$ km.

The telescope assembly of each channel consists of an off-axis objective mirror which forms an image of the scene at the field stop. In order to eliminate variations in sensitivity due to detector nonuniformities, a relay mirror is used to form an image of the objective mirror on the detector. To reduce the polarization sensitivity of the system to a partially polarized scene, the relay mirror is tilted at right angles with respect to the objective mirror in such a manner that the S and P polarization components at the objective mirror are reversed at the relay mirror. The bandpass filter is located just beyond the field stop.

A two point, inflight calibration is provided for each channel. Both channels view space (zero radiance) for one point during each scan rotation. For example, when the spacecraft is over the dawn terminator for the Sun-synchronous orbit, the aperture door may be opened. During this period, the SW channel views, with the aid of relay mirrors, diffuse reflecting plates which are irradiated by the Sun. The Sun cones about the scanning instrument +Y axis at an angle γ' where $\gamma' = 180^\circ - \gamma$, where γ is the conventional solar "gamma angle" and is the angle between the orbit normal and the direction to the Sun. When the spacecraft is over the dawn

TABLE XII

ERBSS INSTRUMENT PARAMETERS

SCANNER CHANNEL MEASUREMENTS

CHANNEL NUMBER	SPECTRAL INTERVAL	FILTER MATERIAL	FIELD OF VIEW
6 (SW)	$0.2 - 5 \mu m$	SUPRASIL-W	6^0
7 (LW)	$5 - 50^+$	DIAMOND+ SW CUTOFF	6^0

SAMPLING FREQUENCY: ONCE PER 50 MSEC

IN-FLIGHT CALIBRATION:

- SPACE VIEW. BOTH CHANNELS
- BLACKBODY (CHANNEL 7, LW). AMBIENT TEMPERATURE (~300^0K)
- SOLAR DIFFUSER (CHANNEL 6, SW)

CROSS-TRACK SCANNER INSTRUMENT PARAMETERS

• WEIGHT	18 kg
• ENVELOPE	29.2(x), 36(y), 26.7(z) cm
• POWER	25 WATTS (AVERAGE ORBITAL)
• DATA RATE	750 bps

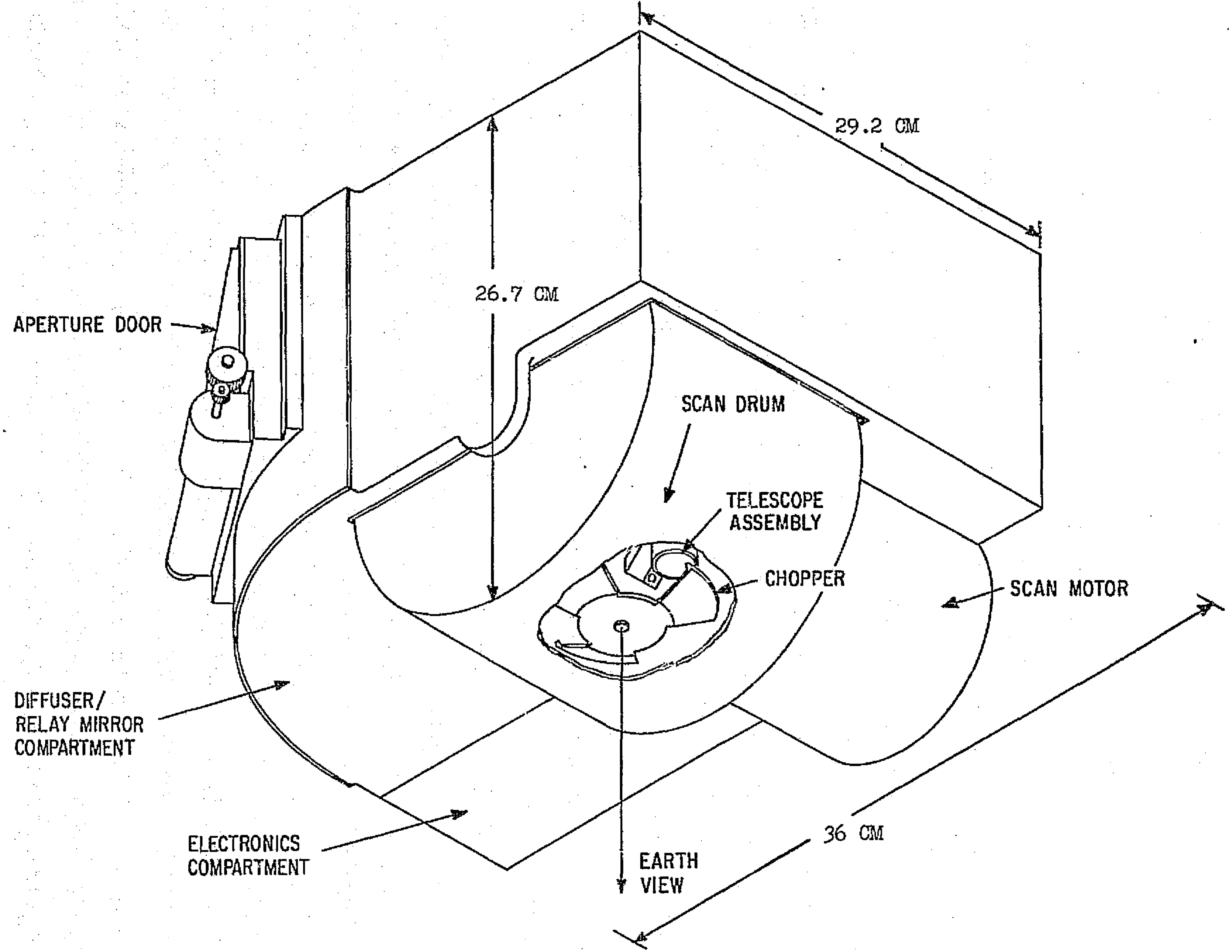


Figure 14.- ERBSS Scanning Instrument Concept.

terminator, the Sun is located in the instrument XY plane and, if the protective aperture door is opened, irradiates the diffuse reflectors. The diffuse reflectors are optical ground aluminum, overcoated with vacuum deposited aluminum as used in ERB[1]. They are oriented to produce a combination of solar incidence angles and viewing angles, such that small variations (seasonal) in the solar incidence angle produce minimum change in the sensed radiance. In order to accommodate different Sun-synchronous orbits (i.e., with different local times for the nodal crossing), the diffusers and relay mirrors are mounted on two-axis gimbals which are set before launch for the average γ' angle expected for that mission.

For the extreme average γ' angles near 0° and 90°, it will be necessary to move the position of the aperture door. The second calibration point for the LW channel is provided by a precision honeycomb black body. The black body is not heated and is at the nominal temperature of 30°C. It is baffled to minimize thermal loading and off-loading.

The 55 Hz ac signal produced by alternately viewing the scene and reference black body is amplified and synchronously rectified. A light-emitting diode and detector, in conjunction with the chopper, provides the reference signal. The rectified signal is summed in a gated integrator and then multiplexed to a single 12-bit analog-to-digital converter. The channels are sampled every 50 msec which, combined with the housekeeping data, results in a bit rate of $\leq$ 750 bits/sec. All timing functions are derived from the spacecraft clock. Connection between the electronic compartment and the scan drum is by slip rings.

The design/definition studies for the two instruments have also included compatibility/integration studies with the TIROS-N spacecraft and the Applications Explorer Mission (AEM) spacecraft. An artists concept of the two instruments on the TIROS-N spacecraft is shown in figure 15. A signal derived from the WFOV/MFOV instrument is used to synchronize the two instruments.

SUMMARY AND PROJECT READINESS

Earth radiation budget measurements in support of climate research are of paramount importance. Many scientific reports representing scientific associations and agencies have noted the importance of the data. The National Oceanic and Atmospheric Administration has noted an operational need for the data. Most recently, the NASA Climate Task Force has included radiation budget as "crucial" data. The mission implications have been thoroughly studied and show the need for a multisatellite mission with orbit inclinations of 98°, 98°, and 50°. The TIROS-N weather satellites could provide the two 98° opportunities with an Application Explorer Mission (AEM) at 50°. Improved data analysis methods have been developed for relating the satellite measurements to the top of the atmosphere.

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[1] This technology was developed for ERB and other NIMBUS experiments.

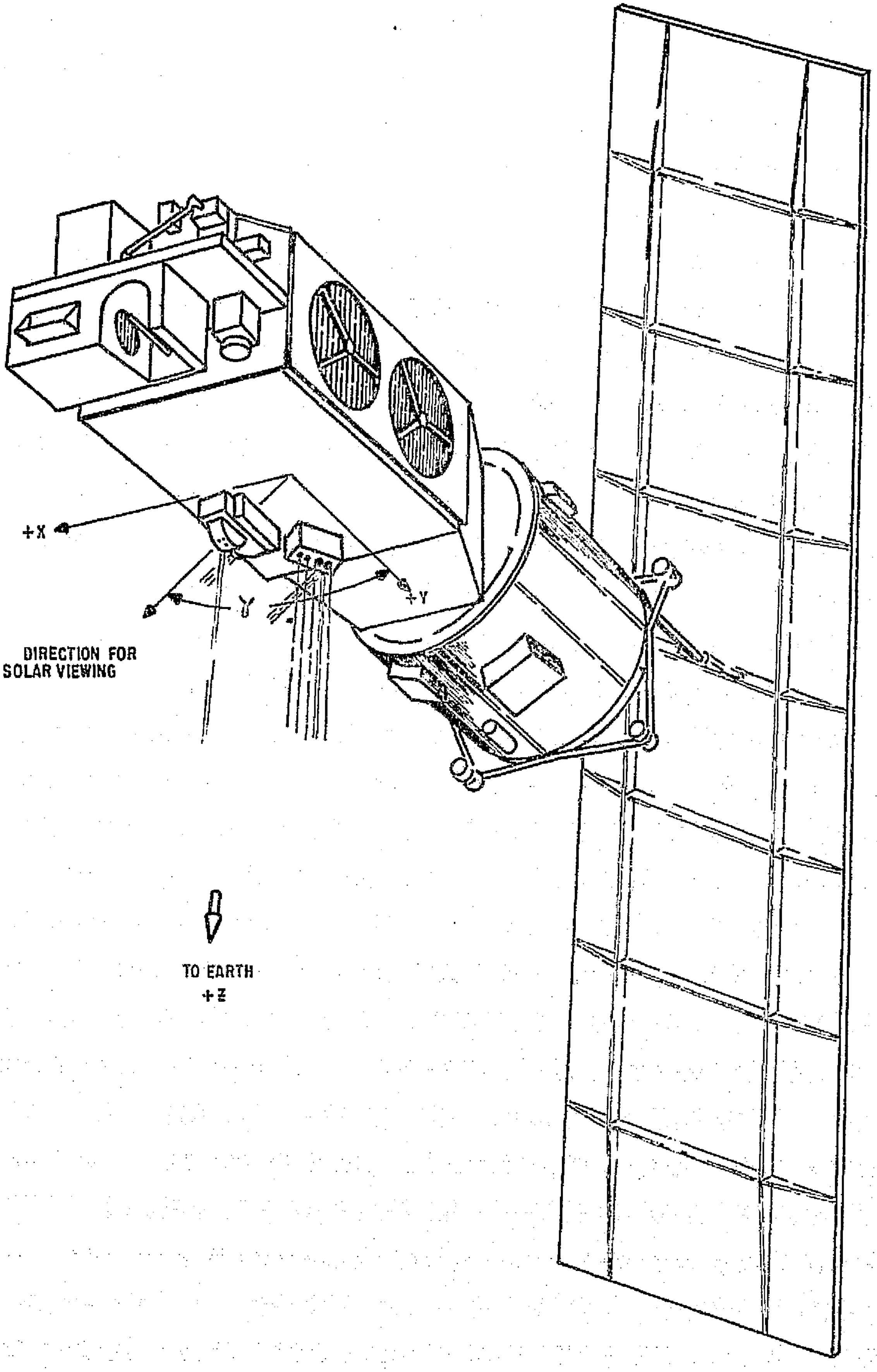

Figure 15.- Artist Concept of Instruments on TIROS-N Spacecraft.

Simulation studies using the improved methods have verified the mission orbit selections, effect of directional models, and effect of instrument errors. Results indicate that a high-quality data set will be provided to the users. Design definitions based upon state-of-the-art hardware have been developed for wide and medium field-of-view radiometers and the scanner. Radiometers are flight proven on several missions--most recently, ERB on NIMBUS 6 and upcoming NIMBUS G includes WFOV radiometers and comparable scanner technology. In addition, detailed engineering analysis of the system was performed during the design definition.

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16. Abstract

The ability to predict climate, in particular deviations from historic norms, is becoming of increasingly critical importance to the economic well-being of the United States and the world. The importance of the Earth's radiation budget in determining climate has long been recognized. An example of the United States' activities specifically noting the need for radiation budget measurements is included. The Earth-orbiting satellite provides a platform, outside the Earth's atmosphere, which is capable of simultaneously monitoring the outgoing reflection of the Sun's energy from the Earth's surface and atmosphere, and the longwave radiation emitted by the Earth and its atmosphere. Equally important, this satellite system is capable of monitoring these fluxes on a daily, monthly, seasonal, even yearly basis for extended periods of time. These capabilities provide the opportunity to conduct detailed studies of the variations in the Earth's radiation budget, the effects of natural and manmade changes in the environment on this budget, and the effects which changes in the energy budget produce on Earth's weather and climate. This document lists the scientific objectives and the associated mission analysis, instrument definition, and data analysis methods to meet those objectives.

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