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The Earth Radiation Budget Experiment: Science and Implementation

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This paper gives an overview of the Earth Radiation Budget Experiment. The experiment consists of scanning and nonscanning radiometer packages on three spacecraft. One is a satellite with a 57° inclination orbit which precesses around the earth once every 2 months. Packages are also flown on the sun-synchronous NOAA-F and NOAA-G operational meteorological satellites. The scanning radiometer includes three channels: shortwave, long-wave, and total. The nonscanner package encompasses a pair of wide-field-of-view radiometers and a pair of medium-field-of-view radiometers. Each pair consists of a total and a shortwave radiometer. The scientific importance and objectives of the mission are described, including the need for the three spacecraft and the utility of the complementary types of radiometers.

INTRODUCTION

The radiation from the sun which is absorbed by the earth and eventually emitted is the energy source which drives the motions of the earth's atmosphere and oceans and which causes our weather and climate. More radiation is absorbed at low latitudes than at high latitudes for the annual average. This excess is carried to the high-latitude regions, where more radiation is emitted than is absorbed for the annual average. Radiation is a very dynamical quantity, varying markedly with time and space. It changes with time because of diurnal and annual cycles, which have a large degree of regularity, and because of other effects, which are quite irregular although important. It also changes with location, on scales from global to local.

The mechanisms by which the atmosphere and ocean transport this energy are not fully understood from a quantitative standpoint and are the subject of much research. They are not steady but, like radiation, have variations on many scales of space and time.

The earth's radiation budget consists of three components: incoming solar, reflected solar, and earth-emitted radiation. In order to study the radiation budget it is necessary to get above the sensible atmosphere and to get enough measurements to satisfy the coverage and sampling requirements for each of these components. The only way to do this is by satellite. In fact, as will be explained, because of the diurnal variation of radiation, at least three satellites are necessary to get the needed sampling. This requirement resulted in the Earth Radiation Budget Experiment, which includes instruments on three spacecraft. These instruments include scanning and nonscanning radiometers for measuring reflected solar radiation and earth-emitted radiation and solar-monitoring radiometers. This paper gives an overview of the Earth Radiation Budget Experiment, its science objectives, and how these objectives will be accomplished.

In order to maximize the scientific return of the project a science experiment team consisting of university and government scientists was assembled. The members of this team were selected for their expertise in satellite radiometry, data analysis, and atmospheric science. They have guided the instrument design and data analysis formulation and will conduct the initial measurement validation and science use investigations. The principal investigators for the science team, their organizations, coinvestigators, and areas of particular interest are listed in Table 1.

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SCIENCE PROBLEMS AND OBJECTIVES

The absorbed solar and earth-emitted radiation provide the heat source and sink which drive the atmosphere and oceans like parts of a heat engine, as shown in Figure 1. As such, these radiation components are causes of weather and climate. Also, they are results of a number of processes which create temperature and humidity distributions and cloudiness, which in turn govern the reflected or absorbed solar radiation and earth-emitted radiation. Thus the radiation components are effects of weather and climate as well. The many scientific applications of radiation budget data are discussed by *Hartmann et al.* [this issue].

The range of space and time scales of interest in weather and climate investigations is shown in Figure 2. The strongest cycles are the diurnal and annual cycles, both of which are induced by cycles of the sun's heating input. A major feature of flow in the tropics is the Walker circulation, which is induced by deep convective activity, whereby the latent heat created during the day is transformed into potential and kinetic energy. This results in a strong cycle of reflected and earth-emitted radiation, which has been studied by *Bezanger and Kandel* [1979], *Saunders and Hunt* [1980], and *Minnis and Harrison* [1984*a*, *b*, *c*]. The desert regions which gird the earth in the subtropics have strong cycles of earth-emitted radiation because of the large temperature changes from day to night. In the mid-latitudes during the summer the diurnal cycle significantly influences weather on the mesoscale. This is most noticeable in the occurrence of afternoon and evening thundershowers. The annual cycle of earth-emitted radiation has been studied by *Heddinghaus and Krueger* [1981] using National Oceanic and Atmospheric Administration (NOAA) scanning radiometer data [*Winston et al.*, 1979] and by *Smith and Bess* [1983] using Nimbus 6 earth radiation budget (ERB) data. This cycle of earth-emitted radiation is the dynamic response of the atmosphere/ocean system to the cycle of incoming solar radiation. As such, its measurement provides fundamental information about the behavior of this dynamical system.

There are other variations in radiation due to the internal dynamics of the atmosphere and ocean. These include synoptic scale variations, mainly due to baroclinic processes. Ironi-

TABLE 1. Earth Radiation Budget Experiment Science Team

Principal Investigator	Institution	Coinvestigators	Investigation Description
B. Barkstrom*	NASA Langley Research Center	D. Crommelynck	Instrument thermal modeling and cloud variability algorithm development
A. Berroir	Laboratoire de Météorologie Dynamique, France	R. Sadoury K. Laval A. Chedin N. Scott Y. Fouquart J. Morcrette	Improvement of radiation parameterization in general circulation model
R. Cess	State University of New York, Stony Brook		Validation of models that predict radiation budget variations and investigation of climatic feedback effects
A. Gruber	NOAA National Environmental Satellite, Data and Information Service	H. Jacobowitz L. Stowe I. Ruff P. Abel P. Rao T. Chen J. Wydick	Angular model development and ERBE data comparison with atmospheric constituents and operational satellite measurements
E. Harrison	NASA Langley Research Center	D. Brooks P. Minnis	Diurnal variation studies of cloudiness and earth radiation budget
D. Hartmann	University of Washington	J. Wallace	Diurnal cycle investigation of radiation budget and effects of cloudiness on net radiation
F. House	Drexel University		Application of optimal estimation techniques to data use investigations
F. Huck	NASA Langley Research Center	N. Halyo S. Park W. Staylor S. Choi	Sensor performance and measurement accuracy assessment
G. Hunt	Imperial College, United Kingdom	B. Hoskins C. England	Comparison of regional radiation budgets with geostationary data and SAGE II to understand effects of other atmospheric constituents
R. Kandel	Centre National de la Recherche Scientifique, France		Diurnal variations and earth radiation measurements
M. King	NASA Goddard Space Flight Center	R. Davies	Effects of clouds on satellite albedo measurements
A. Mecherikunnel	NASA Goddard Space Flight Center	B. Guenther J. Gatlin	ERBE sensor calibration and evaluation
A. Miller	NOAA National Meteorological Center	A. Krueger	Proposal for dynamic interpretation of ERBE information
V. Ramanathan	National Center for Atmospheric Research	J. Coakley P. Downey B. Briegleb D. Baldwin	Use of ERBE measurements to validate and improve radiation models and general circulation climate models
E. Raschke	University of Cologne, Federal Republic of Germany	P. Speth E. Ruprecht R. Stuhlmann M. Wiegner K. Kriebel H. Quenzel	Surface and regional radiation budgets investigation and model parameterization improvement
L. Smith	NASA Langley Research Center	L. Avis T. Bess R. Green J. Suttles B. Wielicki	Algorithm development and investigation of radiation budget variability
W. Smith	University of Wisconsin	V. Suomi L. Sromovsky H. Revercomb F. Nagle	Time and space lag of radiation budget comparison with other meteorological variables
T. Vonder Haar	Colorado State University	G. Campbell E. Smith	Algorithm development for averaging ERBE data over time and space and synergistic investigations using SAGE II data

*ERBE experiment scientist and science team leader

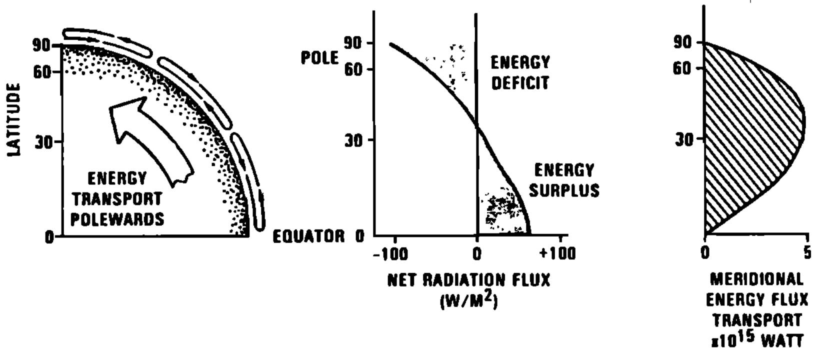

Fig. 1. Equator to pole heat transport.

cally, these effects are the best understood motions of the atmosphere and are among the few in which radiation may not play an active role. The zonal index cycle is an irregular cycle in which absorbed radiation builds up a temperature gradient, which produces baroclinic motions that redistribute the energy and carry the system toward equilibrium. The characteristic time for this process is 1–3 weeks. Interannual variations of climate have a great impact on mankind, and an understanding of these which would lead to skill in forecasting these changes would be extremely valuable. Studies of interannual variability of earth-emitted radiation have been made by *Heddinghaus and Krueger* [1981] and by *Lau and Chan* [1983*a*, *b*].

Another way in which data from the Earth Radiation Budget Experiment (ERBE) are useful is in tuning general circulation models (GCMs). Many processes in a GCM must be parameterized in order to simplify the formulation of the model enough to be practical, and likewise the resolution of the model is similarly limited. One important check on the behavior of a GCM is the energy balance of the resulting weather, which can be done with data such as will be provided by the ERBE. Also, if a GCM is not properly balanced radiatively, when it is run from a set of initial conditions it will drift, in the mean, toward the wrong mean [*Leith*, 1983]. Thus even for short-term forecasts the radiation balance of the GCM is important.

The impact of man on our climate is a recent concern. It is

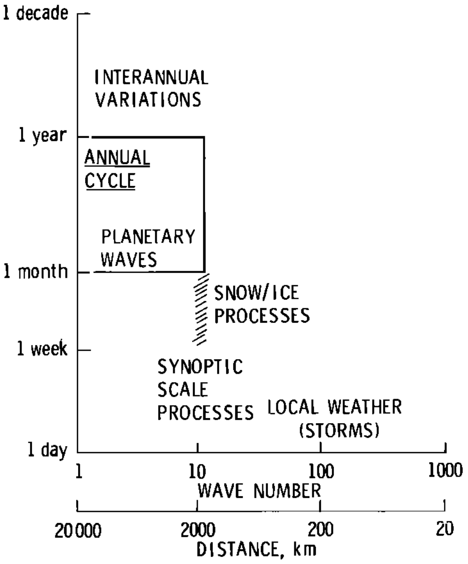

Fig. 2. Scales of radiation processes.

known that the burning of fossil fuels has resulted in increasing atmospheric carbon dioxide for much of the last century, and this trend is expected to continue for the foreseeable future. It is generally accepted in the atmospheric science community that the global average temperature has increased a few degrees Celsius in the last century also, and this is widely regarded as due to the increased carbon dioxide. Also, there is concern that other anthropogenic trace gases in the atmosphere could significantly alter the atmospheric absorption and emission of radiation. Another potential effect of man is due to slash and burn agriculture, whereby thousands of square kilometers of rain forest in the tropics have been denuded in the last half century. It has been conjectured that this could affect the evaporation of water over vast areas, which would influence the Hadley cell circulation and in turn significantly affect the global circulation. The ERBE will establish a data base for the radiation balance corresponding to the general circulation during the years in which ERBE is operational.

It is seen that the measurements from the ERBE will be highly useful for studying weather and climate in many ways. The science objectives of ERBE evolved through a series of steps which have been reviewed by *Barkstrom and Hall* [1982] and by *Barkstrom* [1984]. These objectives are (1) to determine for a minimum of 1 year, with 2 years desirable, the monthly average radiation budget on regional, zonal, and global scales, (2) to determine the equator to pole transport gradient, and (3) to determine the average diurnal variation of the radiation budget on a regional and monthly scale. A region is defined to be 250 × 250 km, and a zone is defined to be 10° wide. The accuracies required for each of these objectives are listed in Table 2.

PRESATELLITE WORK

Prior to the development of earth satellites, many scientists, recognizing the importance of radiation to weather and climate processes, attempted to establish the radiation components by computation. This was done by the use of radiative transfer models together with climatological data bases of temperature, humidity, clouds, and ozone. Because this was also prior to or early in the development of computers, the radiative transfer models available and practical at that time were quite limited by today's standards. Also, the climatological data base which was available at that time was very limited, observations over the southern hemisphere oceans being especially sparse. Considering these constraints, these studies led to a rather impressive understanding of the nature of the earth's radiation budget. This is due to the insight which these researchers brought to the problem.

TABLE 2a. Scientific Measurement Requirements and Estimated ERBE Capability: Solar Flux Density

	Value
Accuracy, %	
Required	0.1–1.0
Estimated ERBE capability	0.3
Sampling interval	monthly

Work on the earth radiation budget began early in this century with theoretical studies by *Dines* [1917] and *Simpson* [1928]. The empirically based theoretical work of *London* [1957] stands as a landmark in the science of the earth radiation budget. The latitudinal profiles and global averages which he computed for the northern hemisphere are remarkably close to the average monthly values as measured by satellite since then. *Hunt et al.* [this issue] have reviewed these investigations.

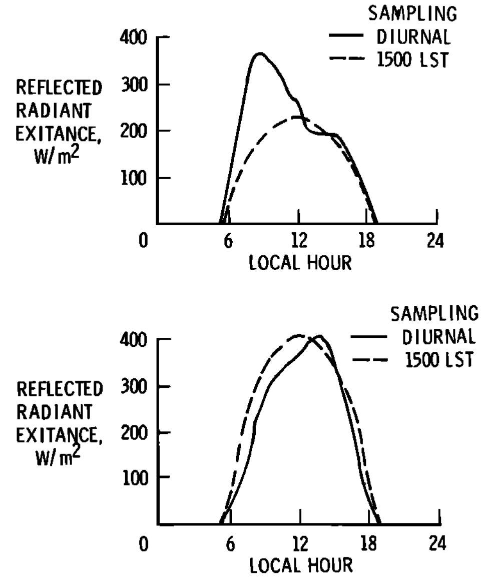

Fig. 3. Local time sampling error.

PREVIOUS SATELLITE MISSIONS

The studies which had been done prior to the advent of satellites had established the importance of the earth's radiation budget to weather and climate processes and the need for its measurement over the entire globe and outside the atmosphere. Thus the measurement of the earth's radiation was one of the first applications of satellites to scientific study. The history of observations of earth radiation by satellite is reviewed by *House et al.* [this issue]. There have been three generations of satellite instruments for measuring earth radiation [*Jacobowitz et al.*, 1984*a*]. In keeping with the primitive nature of early spacecraft the first radiation budget instruments were very simple devices. As such, they were spheres and flat plates used as wide-field-of-view radiometers on spinning spacecraft. With three-axis stabilization of satellites came the second generation of radiation budget instruments: scanning radiometers. These were not designed specifically for the radiation budget but for a multitude of uses, of which the radiation budget was but one. Nevertheless, the Nimbus 2 and 3 medium-resolution infrared radiometers (MRIR) contributed enormously to our knowledge of the earth radiation budget [*Raschke and Bandeen*, 1970; *Raschke et al.*, 1973]. The third generation of instruments began with the earth radiation budget (ERB) instrument, which was specifically designed for measurement of the earth radiation budget, as implied by its name. These instruments flew on the Nimbus 6 and 7 satellites [*Smith et al.*, 1977; *Jacobowitz et al.*, 1979, 1984*b*]. The scanning radiometer provided many measurements from which the directionality of reflected solar and earth-emitted radiation as well as regional radiation budgets can be determined. Also, the ERB wide-field-of-view radiometers and solar monitors have provided a high-quality continuous data set since 1975.

Another characteristic of the three generations of radiation measurements is the types of orbits from which they made observations. The earliest satellites were placed in midinclination orbits, because of the limited launch capability of the early launch vehicles. Thus their orbits precessed around the earth, which resulted in a varying local time of observation. This led to difficulties in interpreting the data, because the time required for the orbit to precess once around the earth is of the order of 2 months, and changes in radiation parameters due to the diurnal cycle as observed from the precessing orbit could not be unambiguously separated from those due to seasonal change. In order to eliminate this variable and to get global coverage the next generation of earth observation spacecraft was placed in sun-synchronous, near-polar orbits. Although the sun-synchronous orbits reduced the number of variables by keeping the local time constant for a given lati-

TABLE 2b. Scientific Measurement Requirements and Estimated ERBE Capability: Reflected Solar and Emitted Flux

	Accuracy, W/m²		
Spatial Resolution	Required	Estimated ERBE Capability	Data Averaging
Global, net	1 (net)	1.3 (net)	
Equator to pole gradient, net	4 (net)	2 (net)	
1000-km zones	2–12 (LW and SW)	5.2 (LW) 5.3 (SW)	monthly
1000-km regions	2–15 (LW and SW)	9.4 (LW) 10.3 (SW)	
250- to 500-km regions	2–14 (LW and SW)	9.4 (LW) 10.4 (SW) (scanner)	

Fluxes to be determined at top of atmosphere (30 km). Net, net radiation; LW, long-wave radiation; SW, shortwave radiation.

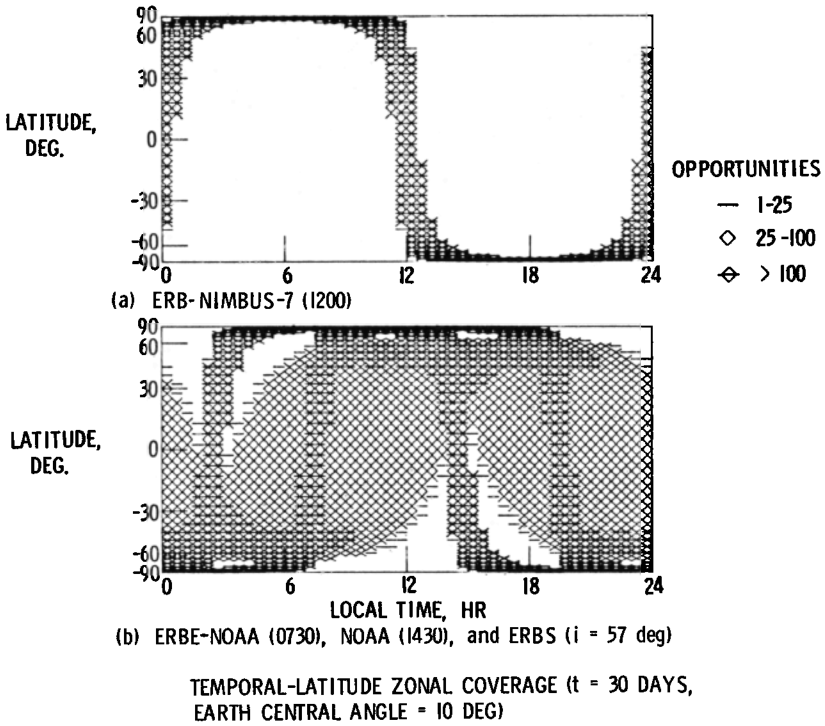

Fig. 4. Local time sampling strategies.

tude, this also produced a bias in time-averaged quantities due to the lack of sampling of the diurnal variations.

ERBE SYSTEM CONCEPT

As has been pointed out earlier, a single satellite cannot provide enough observations for one to unravel the effects of synoptic, seasonal, and diurnal variability at a point. A sampling study for single and multiple satellite coverage has been performed by *Harrison et al.* [1983]. Figure 3 shows the diurnal variation of reflected radiant exitance for two sites (solid lines) compared to that which would be inferred (dashed lines) from a single observation at 1500 local time (LT) with the

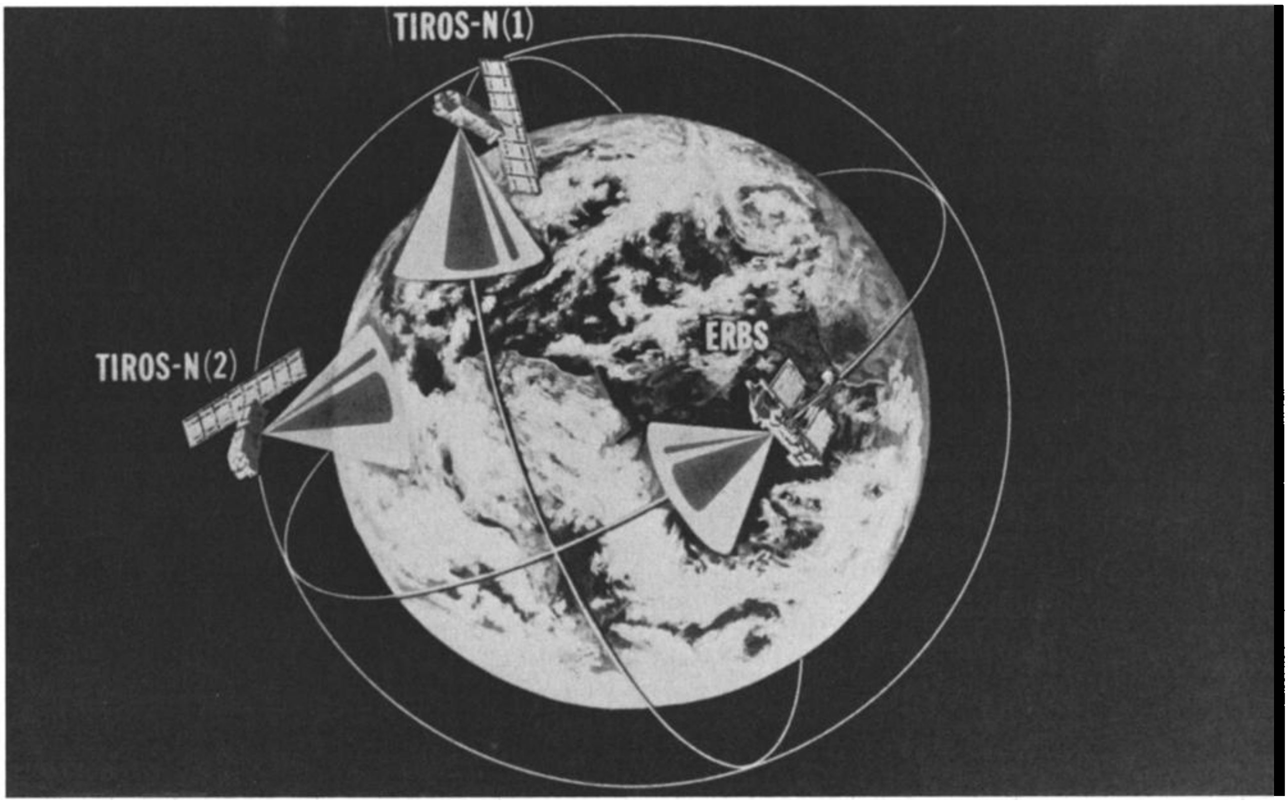

Fig. 5. Three-satellite orbit configuration.

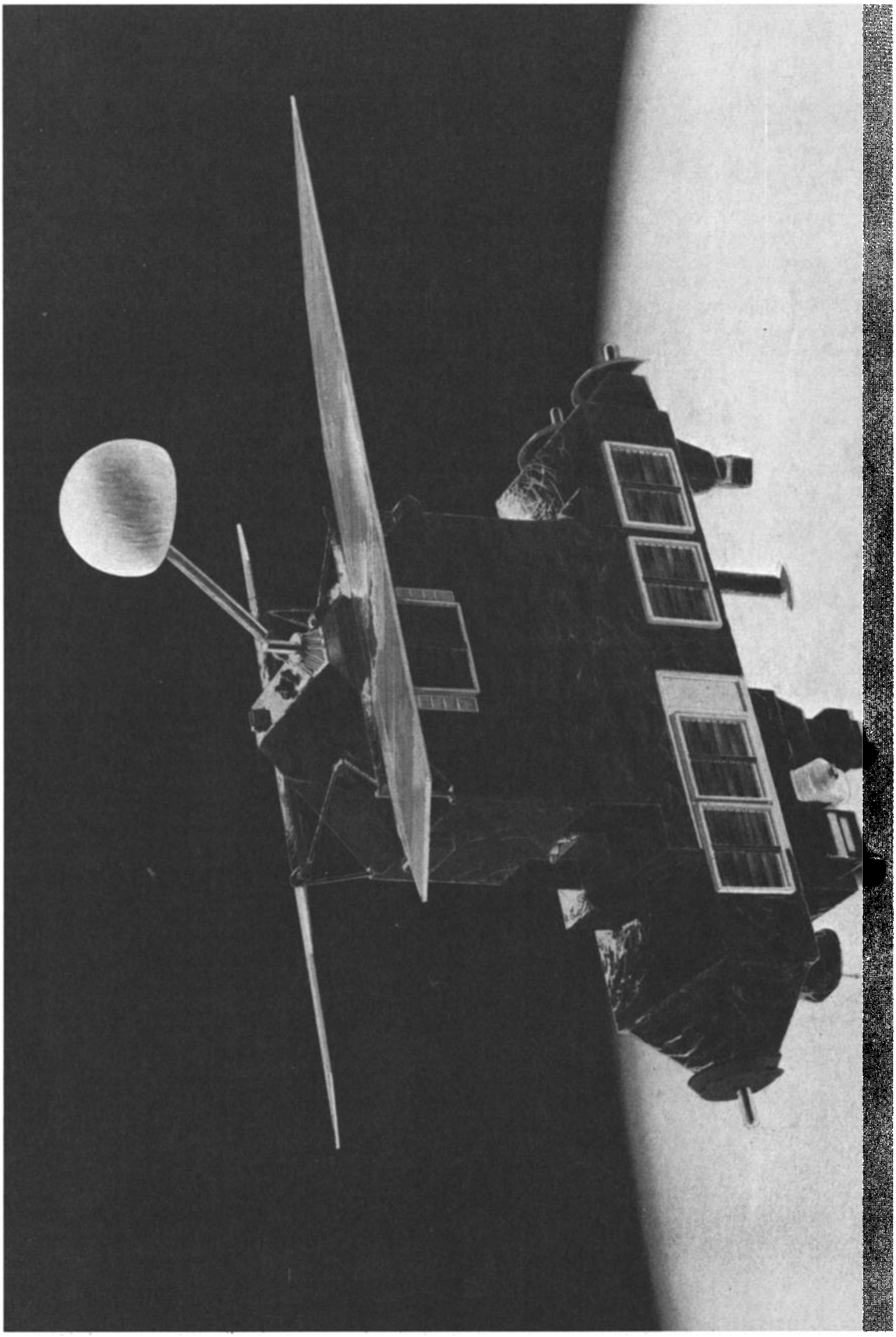

Fig. 6. ERBE spacecraft.

assumption of a constant albedo. Additional studies by *Brooks and Minnis* [1984*a*, *b*] have further defined the bias errors associated with limited diurnal sampling. A single satellite in a sun-synchronous orbit will give data from which one cannot separate synoptic and seasonal effects. An additional satellite in a 57° inclination orbit will precess so as to observe all points on the earth between 57°N and 57°S latitudes at all local times sometime every 2 months. With data from both satellites one can unravel the synoptic and seasonal variations from the diurnal variations. By using an operational NOAA TIROS satellite, not only is the spacecraft available, but data from all of the instrumentation on the TIROS satellite are also available as ancillary data for analysis of the ERBE data. Poleward of 57°, there are no data from the midinclination satellite, and only data from the sun-synchronous satellite are available. In order to provide additional data for adequate diurnal coverage, instruments are required on another sun-synchronous satellite. The resulting sampling is shown in Figure 4 in terms of latitude and local time coverage. It is seen that a three-satellite system is required to obtain sufficient sampling for accurate determination of the earth radiation budget. The resulting orbit configuration is shown pictorially in Figure 5.

The Earth Radiation Budget Satellite (ERBS), carrying a set of ERBE instruments and the Stratospheric Aerosol and Gas Experiment (SAGE II) instrument, was placed in near-earth orbit by the space shuttle *Challenger* (mission 41-G) on October 5, 1984. An artist's concept of ERBS in orbit is shown in Figure 6. ERBS performed the required orbit transfer maneuvers and attained an orbit with 57° inclination and altitude of 600 ± 7 km on October 8, 1984. The contamination covers were removed from the nonscanner and scanner packages on October 23 and November 5, 1984, respectively. Indications at present are that these instruments are operating satisfactorily.

The SAGE II instrument, which is also on the spacecraft, is an expanded version of the SAGE I and stratospheric aerosol measurement (SAM II) instruments [*McCormick et al.*, 1979; *Mauldin et al.*, 1985]. The SAGE II provides measurements of scattering in the stratosphere due to aerosols and molecules, as well as absorption due to ozone, water vapor, and nitrogen dioxide. The SAGE II instrument began routine operations on October 24, 1984.

The NOAA 9 spacecraft was placed into a sun-synchronous orbit of 99° inclination (81° retrograde), altitude 860 ± 10 km, and equatorial crossing time of 1430 LT for the ascending (northward) node. Figure 7 shows the ERBE instruments aboard the NOAA 9 spacecraft.

INSTRUMENT CONCEPT

The Earth Radiation Budget Experiment instruments are built in two packages: a scanner package and a nonscanner package. The scanner contains three scanning radiometers and the ancillary modules required for their operation and calibration. The nonscanning package contains wide-field-of-view (WFOV) and medium-field-of-view (MFOV) radiometers and the solar monitoring radiometer and the modules which are necessary for their operation and calibration. The details of the instruments, their design, construction, testing, calibration, and operation are given by *Kopia* [this issue] and *Luther et al.* [this issue] in companion papers for the scanner and nonscanner, respectively.

The scanner, shown in Figure 8, consists of a shortwave, a long-wave, and a total radiometer mounted in a single scan head and boresighted to receive radiation from the same field of view. A Cassegrain telescope for each radiometer collects radiation onto the detector. The axisymmetry of the optics virtually eliminates any effects of polarization of the radiation on the measurement. The scan head operates in a simple scan, from one horizon to the other. The scan head can also be rotated in azimuth, though at a slow rate. The usual operation is in a cross-track scan direction. This provides a maximum geographic coverage, though at the cost of limited angular coverage. Any given scene will be viewed only once in any given pass. The directional and bidirectional models produced by measurements from the ERB instrument will be used to account for anisotropy of the measured radiation.

In the design of the instruments their total data rate was limited by the memory capacity of the TIROS spacecraft, so that for a given accuracy, or bits per measurement, the number of samples per second was fixed. This number, together with the spacecraft velocity, determined the spacing of the scanning radiometer measurements. Aliasing considerations then determined the field-of-view size and shape.

The nonscanner package, shown in Figure 9, contains a total WFOV radiometer which measures all incident radiation and a shortwave WFOV radiometer which measures only incident shortwave radiation. Likewise, there are two MFOV radiometers, one for total radiation and one for shortwave radiation. The WFOV radiometers receive radiation from the entire earth disc, from one limb to the other. The MFOV radiometers have apertures which restrict their fields of view to a circle of nominally 5° radius at the top of the atmosphere. Also contained in the nonscanner package is a solar monitor, which is an active cavity radiometer measuring radiation over the entire spectrum from 0.2 to 50 μm. Its purpose is to provide a measurement of the sun's output during calibration of the various earth-viewing instruments. The solar monitor is patterned after the type IV active cavity radiometer [*Willson*, 1979], and it has an accuracy of better than $\frac{1}{2}$%. Unfortunately, the calibration occurs only twice per month. Because of the 3- to 4-day solar cycle, this sampling limitation restricts the utility of the solar monitor data set as a primary record of solar output. However, it will be a high-quality supplementary data set.

The WFOV radiometers have two major advantages in the measurement of large-scale features. The radiant exitance at the top of the atmosphere inferred from WFOV data for large scales is less sensitive to the directional models than that inferred from scanning radiometer data. Also, because of its mechanical simplicity, the WFOV radiometers typically have greater longevity than do scanning radiometers. However, because of the wide field of view, the resolution of the WFOV measurements is limited to very large scales. The MFOV radiometer is an intermediate instrument between the WFOV and scanning radiometer. It has better resolution than does the WFOV but is more sensitive to directional model errors. A major advantage of a MFOV radiometer is that because of the aperture, it is not "blinded" by sunlight at every satellite sunset as are the WFOV radiometers. The experience with the ERB data from Nimbus 6 and 7 showed that the use of scanning and WFOV radiometer data together provides an invaluable check between the two sets of data, which greatly aids the accuracy of the final data products.

Descriptions of the ground calibration facility and methods are given by *Barkstrom* [1984], *Luther et al.* [this issue] and

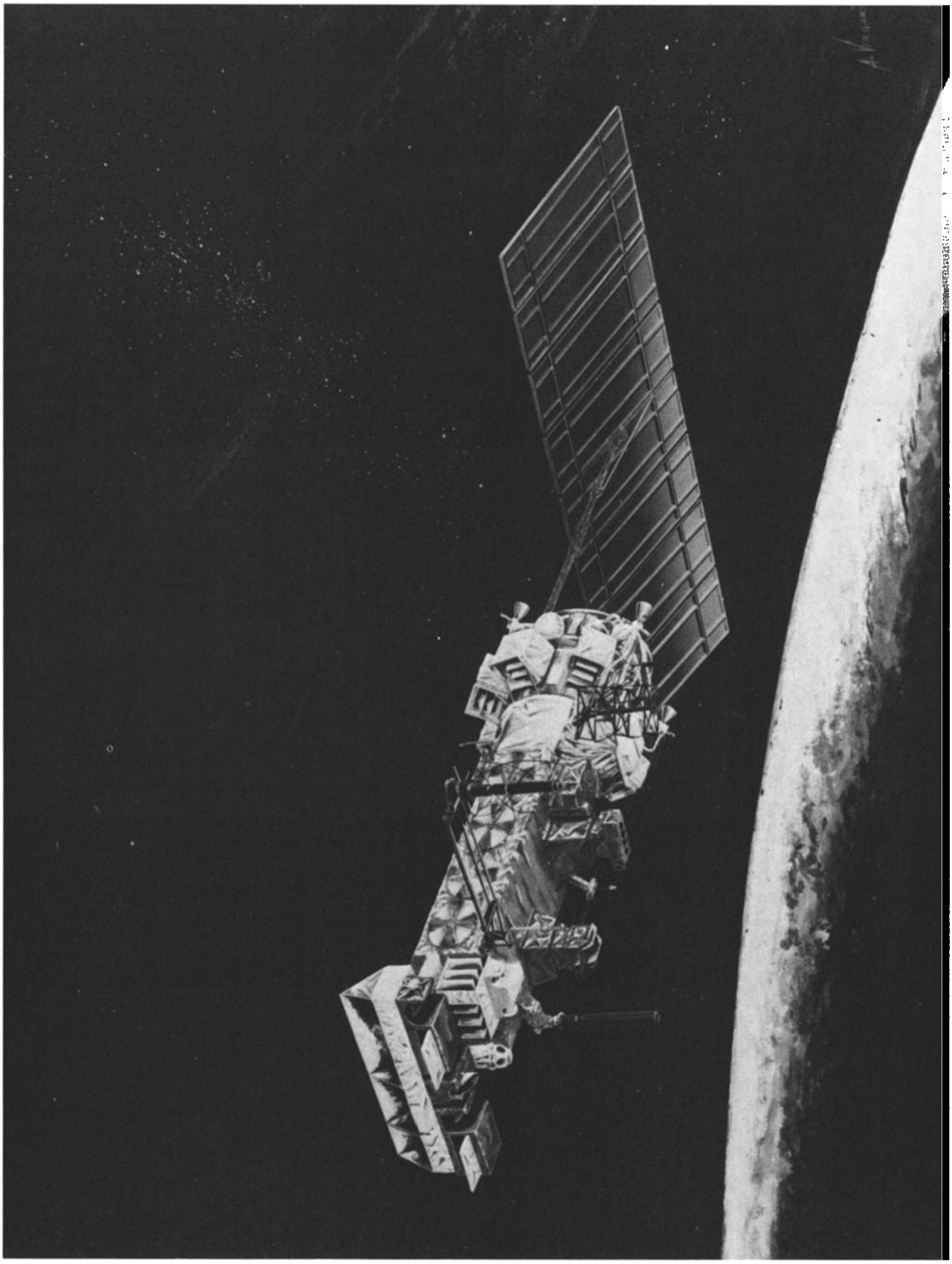

Fig. 7. NOAA operational meteorological spacecraft.

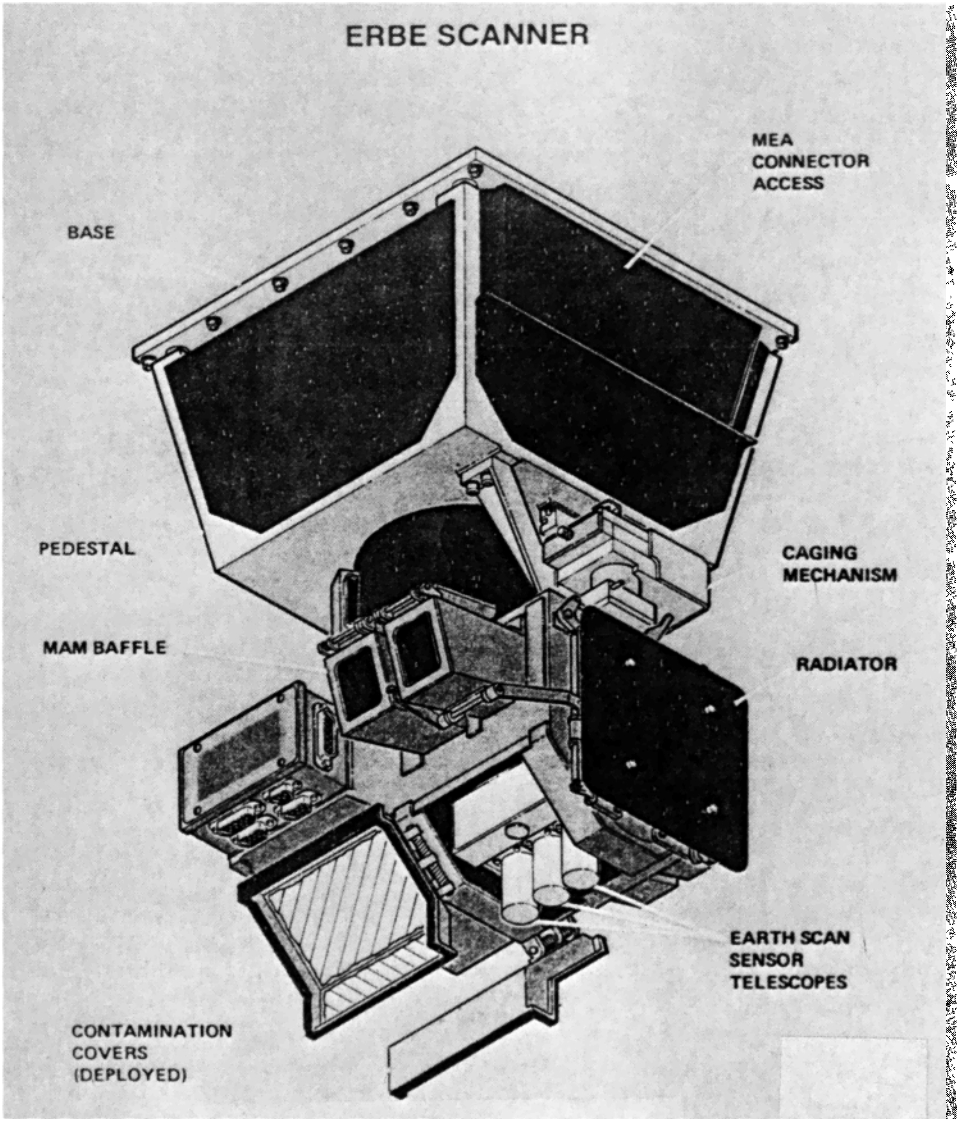

Fig. 8. Scanning radiometer.

Kopia [this issue]. The ERBE instrument calibration was tied to the International Practical Temperature Scale of 1968 (IPTS 1968) and the World Radiometer Reference in the design of the ERBE instruments and their calibration methods. Also, experience with previous satellite instrumentation has demonstrated the need for in-flight calibration, especially where high accuracy is required. For this reason, there is at least one on-board calibration device for each channel of the ERBE. These devices, together with a space look which provides a near-zero radiance, give basic offset and gain information for periodic in-flight calibration of the instruments.

One important feature of the ERBE instruments is the concurrent development of a mathematical model of each instrument which describes its response to radiation inputs and changes in ambient conditions. These models provide quantitative understanding of the instrument response in ground and in-flight calibration conditions and in space operation. Because of the differences among conditions of the ground calibration, in-flight calibration, and earth or solar observation, the models are useful for relating the results from these various modes of operation. Also, the models have been useful in the design process for understanding the quantitative effects of selections of parameters on instrument behavior.

DATA PROCESSING AND PRODUCTS

The data processing system, which converts telemetered data into scientifically useful information, is a crucial part of any satellite experiment. The data processing system for ERBE consists of major subsystems: count conversion, inversion, and time/space averaging subsystems. These subsystems act sequentially to produce data products for scientific investigations. The data flow is illustrated in Figure 10.

The count conversion subsystem begins with telemetry counts and uses the instrument model to produce radiances at the detectors for all channels, taking into account thermal transients, etc. This subsystem also includes the functions of merging the spacecraft telemetry with tracking data so that the measurement field-of-view locations on the earth can be determined. These results are all placed on a computer tape, which is then used by the inversion subsystem to compute the scene type and shortwave and long-wave radiances and the corresponding radiant exitances at the top of the atmosphere for each scanner pixel. Also, the WFOV and MFOV measurements are analyzed to produce resolution-enhanced estimates of the radiant exitances at the top of the atmosphere as well as estimates based on shape factor computations.

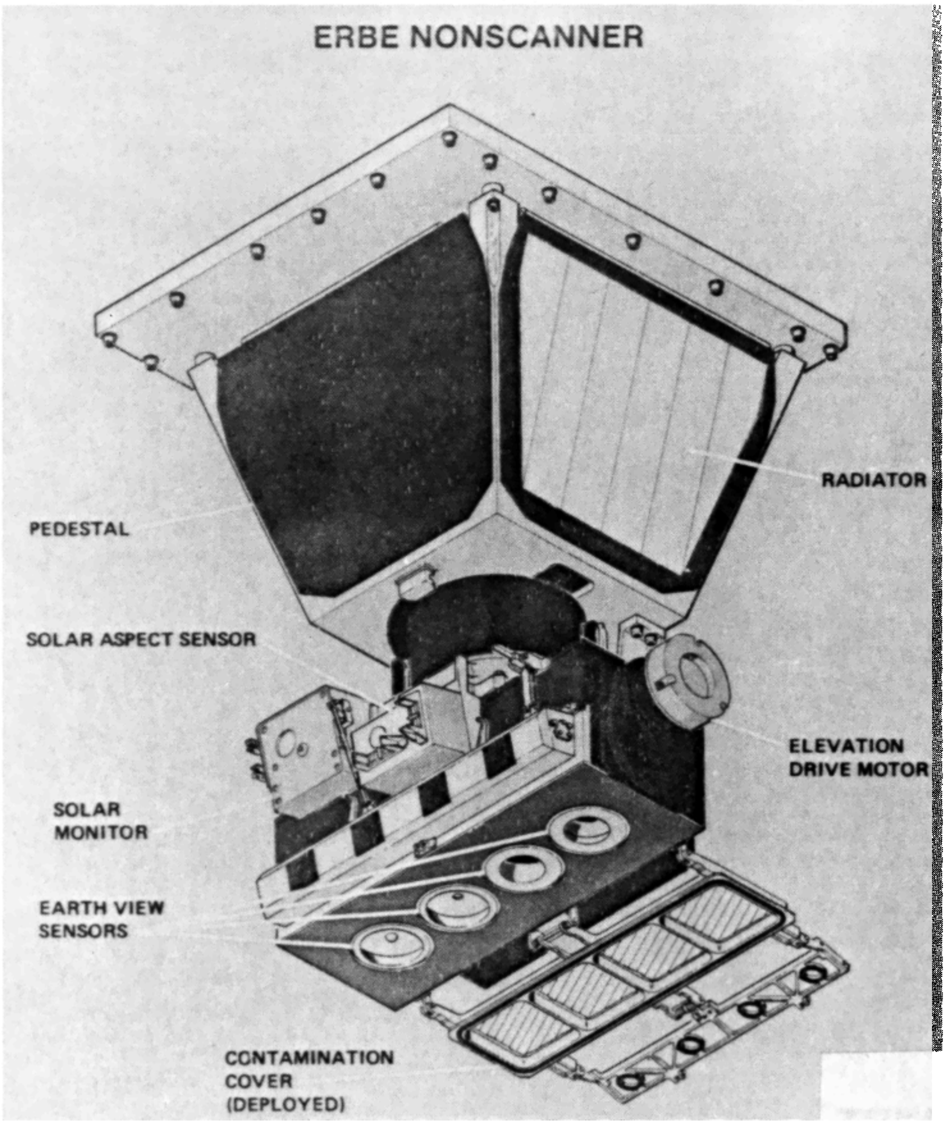

Fig. 9. Nonscanning radiometer.

The techniques by which the measurements from the earth-viewing channels are used to compute radiant exitances at the top of the atmosphere are described by *Smith et al.* [this issue]. The technique for analysis of the scanning radiometer data is a natural outgrowth of the methods used for analysis of the Nimbus 7 ERB scanning radiometer. The wide- and medium-field-of-view radiometers are analyzed by two techniques: the first a shape factor method, and the second a resolution enhancement method. The shape factor method is a point-by-point computation based on the assumption that the earth has constant albedo and long-wave exitance within the field of view. The resolution enhancement method is based on the concept that the data along the orbit track contain more information as a set of interrelated points than as a collection of unrelated points. This method is described and studied in detail by *Green* [1983].

The inversion subsystem records the radiant exitance at the top of the atmosphere on computer tape (the processed archival tape) as instantaneous values for each radiometer in a time-sequenced record. This tape serves as an input to the time/space averaging subsystem and is useful for research with instaneous values.

The time/space averaging subsystem evaluates the monthly averaged radiant exitance for each region for each radiometer type. This requires the integration over the diurnal cycle as well as over the month. It is in this subsystem that the multiple satellite system aspect of the project first enters the data processing.

The basis for the time/space averaging computation is a matrix for each region with hours of the day as columns and days of the month as rows. For a single spacecraft, two values per day would be entered for regions near the equator: one for the ascending node and one for the descending node. With two spacecraft there are up to four entries per day in the matrix, thus filling out the diurnal cycle. In order to compute a daily average radiant exitance this computation provides values for the remaining elements along a row of the matrix. The variation of the albedo of each region with solar zenith angle is accounted for at this point. The variation of the region due to meteorological variations is accounted for by the observations at the various times of day by the ERBS spacecraft. In order to compute the monthly average the computation averages the daily averages for each day of the month. In this way the time/space subsystem computes the diurnal cycle as well as daily and monthly averages for each region. The techniques used in the time/space subsystem are described in detail by *Brooks et al.* [this issue].

The resulting monthly averaged radiant exitances from the

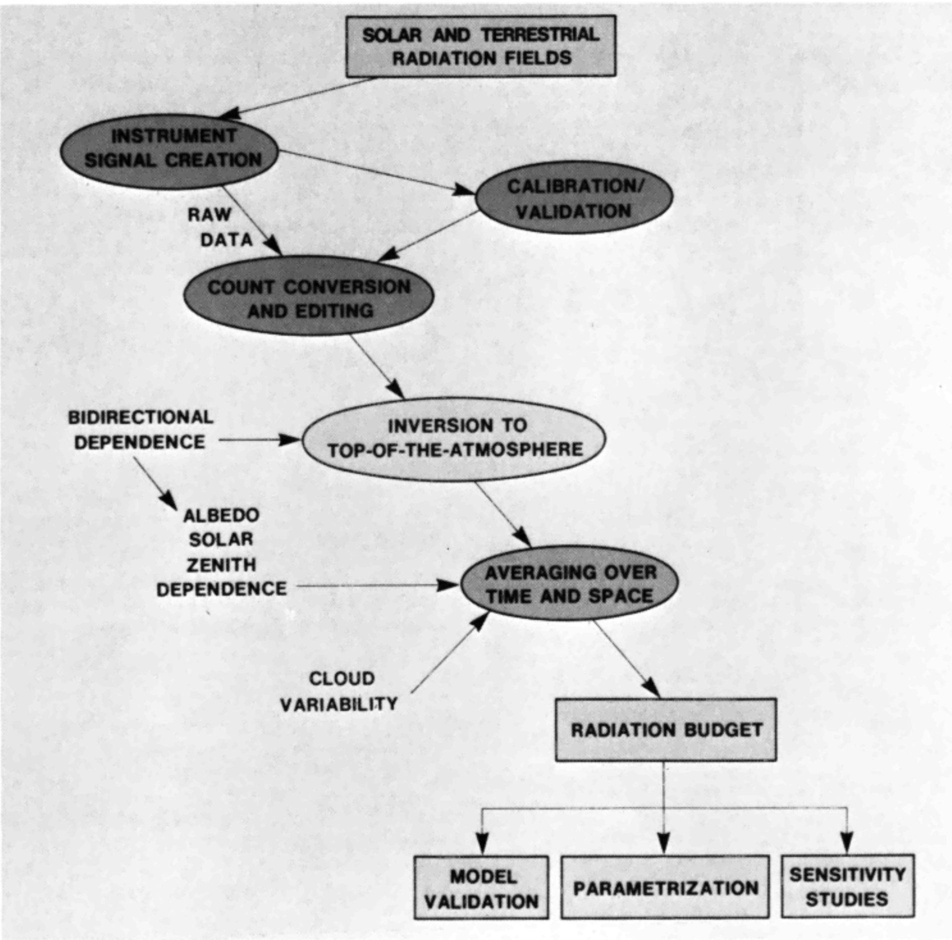

Fig. 10. Data flow chart.

time/space averaging subsystem are recorded on a computer tape, which can be used for scientific investigations. This tape also serves as input to the data products subsystem, which produces maps, tables, and other computer tapes. These maps include monthly averages of albedo, absorbed solar radiation, and emitted long-wave radiation for each radiometer class, i.e., scanning, and wide- and medium-field-of-view radiometers.

CONCLUDING REMARKS

The instruments aboard the ERBS spacecraft have recently begun to operate, and it appears that they will produce the high-quality data set which is needed for studies of the earth's radiation budget. The NOAA 9 satellite has been placed into its orbit, and the ERBE instruments will soon begin to operate. These instruments should provide radiation budget data through the middle to late 1980s.

The ERBE instruments operating in a multisatellite mission will provide sufficient spatial, temporal, and diurnal sampling and resolution to determine the monthly average radiation budget components on regional, zonal, and global scales. These data, together with the ERB data, will constitute the kind of multiple-year data set which is required for understanding interannual variability.

Acknowledgments. This paper would be impossible without the contributions of a very large number of individuals. Members of the ERBE science team have been invaluable in this regard. Indeed, the authorship might reasonably be considered to belong to the science team as a whole. In addition, Charles Woerner, ERBE project manager; J. E. Cooper, the ERBE experiment manager; G. Taylor, instrument manager; M. Luther and L. Kopia, the ERBE instrument engineers; and S. Carmen and R. Hesser of TRW have played crucial roles in the implementation of the ERBE project. Also, J. F. Kibler and the data management team have developed all of the software which is required for the processing of the data. Finally, we gratefully acknowledge the scientific initiative and dauntless resolve of the late George Sweet, who initiated the Earth Radiation Budget Experiment.

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