Orbital and Cloud Cover Sampling Analyses for Multisatellite Earth Radiation Budget Experiments

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Computer simulations have been performed to determine the geographical and temporal coverage of various satellite orbits and scanning and nonscanning radiometers for Earth radiation budget measurements. These results were used to simulate the sampling of a diurnally varying cloud and radiation field for several different satellite systems to estimate errors in regional monthly mean reflected radiation. The combined results indicate that coincident observations with a minimum of one sun-synchronous satellite and a midinclined orbit satellite are needed to obtain the required regional, zonal, and global coverage with sufficient temporal sampling for obtaining accurate estimates of monthly mean reflected solar radiation. Overall, the best sampling capability and lowest errors were obtained with a three-satellite system, i.e., two sun-synchronous satellites with different equatorial crossing times combined with either a 46 or 57-deg orbit satellite. The results from these analyses have been used in defining a joint NASA-NOAA multisatellite mission for an Earth radiation budget experiment.

Introduction

ONE of the key challenges in designing the Earth radiation budget experiment (ERBE) is to select satellite orbits which will provide adequate spatial and temporal sampling for scientific analysis. In the past, instruments for measuring the Earth's emitted and solar reflected radiation were flown on multipurpose satellites in orbits not specifically designed for Earth radiation budget (ERB) applications. The most recent ERB measurements have been made with instrumentation carried on sun-synchronous satellites [e.g., Nimbus 6 (Ref. 1), 1975, and Nimbus 7 (Ref. 2), 1978]. These satellite orbits provide sampling at only two local times of day throughout the mission. This limited sampling is not sufficient to measure diurnal variations in the Earth's radiation budget because of the high variability of clouds and changing solar incidence angle during the day.

The ERBE mission planned for the mid-1980's[3] will provide the first opportunity to utilize two or more satellites simultaneously to obtain a more comprehensive ERB data base. One or two NOAA satellites and a NASA Earth Radiation Budget Satellite (ERBS) will be flown to improve temporal and spatial coverage capabilities. The goal of ERBE preflight mission analyses is to define the best ERBS orbit to complement the sun-synchronous NOAA satellites in meeting the science requirements set forth for the ERBE. Computer simulations of various satellite orbits and sensor concepts are conducted to determine and evaluate geographical coverage and the range of local times at which measurements can be obtained. Sampling analyses of cloud cover variability obtained from the geostationary operational environmental satellite (GOES) are utilized to further evaluate the capabilities of the ERBE satellite systems and orbits for measuring the Earth's radiation budget.

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Science Requirements

Obtaining accurate measurements of Earth's radiation budget requires spatial and temporal coverage that accounts for variations in solar zenith angle, cloud conditions, and surface features (e.g., land, water, snow, and ice). Cloud cover variability, the most dynamic of these features, strongly affects both the Earth-reflected solar and the terrestrial-emitted radiation. In order to adequately sample these scene changes and obtain a useful radiation budget data base, several spatial and temporal factors must be considered. High resolution data over the entire globe are needed for climate diagnostic applications such as the development of sea-surface temperature anomalies and variations in albedo resulting from changes in cloud, ice, and snow cover and in the desert-vegetation boundaries. All of these factors can affect both large- and small-scale circulations within the atmosphere. Diagnosis of these and other features provides important information for better understanding of the relationship of radiative heating to climatic and synoptic changes in the circulation of the atmosphere and oceans. Global and zonal values of the radiation components are also needed to compute the equator-to-pole gradient of net radiation, a major driver of atmospheric circulation.

The needs of the various segments of the user community have been synthesized into several specific spatial and temporal requirements which are consistent with the scene variability characteristics. These requirements are as follows:

1) Short-wave (0.2-5.0 μm) and long-wave (5.0-50 μm) radiation for the following spatial scales: a) global, b) 10-deg latitudinal zones, c) 2.5-10 deg (or 250-1000 km) regions over the globe.

2) Equator-to-pole gradient of the net radiation budget.

3) Monthly average diurnal variation of the regional scale radiation budget.

Space-Time Coverage

Several orbital parameters, sensors, and operations factors were considered. The primary orbital elements affecting space-time coverage are orbital altitude and inclination. A comprehensive analysis and evaluation of the ERBE system must also include the capabilities of the various candidate sensor systems (narrow field-of-view scanning radiometers, and medium and wide field-of-view nonscanning radiometers). Although the wide field-of-view sensor observes the entire Earth's disk, only a region bounded by a 10-deg great circle of arc on Earth (e.g., 10° latitude and 10° longitude at the equator) was used in defining its coverage and sampling capability. The 10-deg angle is used since, due to geometrical considerations, the major portion of the radiation energy usually comes from near the subsatellite point. Also, the time of a measurement is generally related to the satellite-sensor nadir. Orbital simulations for these analyses were conducted using a modified version of a computer program developed by Brooks.[4]

The two NOAA sun-synchronous satellites, which will carry ERBE instrumentation, have orbital parameters already defined. The NOAA-F satellite will be launched into an 870-km altitude, 98.91-deg inclination orbit with an ascending node equatorial crossing at 1430 local time and a ground track repeat cycle of 19 days. The altitude of NOAA-G is 833 km, with an inclination of 98.75 deg, a descending node equatorial crossing at 0730 local time, and a ground track repeat cycle of 6 days. The change in local time coverage with latitude for the two NOAA satellites is illustrated in Fig. 1a. The greater the shading density on this figure, the more times of coverage or sampling of a particular latitude band at a given local time. Near-polar latitudes are covered during nearly all times of day. Low and middle latitudes, however, are only covered during the equatorial crossing hours. Thus there are large gaps in hourly latitudinal coverage for sun-synchronous orbits. More complete coverage can be achieved by adding a single satellite in a midinclined orbit which has an orbital precession rate relative to the sun of several degrees per day. Since the time resolution of the ERBE data set is 30 days, an orbit with a precession rate of 6 deg/day will progress through all hours at the equator during the month. An orbit with a 46-deg inclination and 600-km altitude has such a precession rate. This inclination-altitude combination gives a 3-day ground track repeat cycle which provides for a wide range of viewing zenith angles for each region while the orbit precesses through each hour. The local time and latitudinal coverage of this orbit is shown in Fig. 1b along with coverage for the two NOAA satellites. Thus a good satellite mix for sampling is a combination of high and middle inclinations. The range of orbit inclination capability of the Space Shuttle, which will launch ERBE, is 28.5-57 deg. Although not shown here, a 57-deg orbit provides an 11-deg increase in latitudinal coverage, but about 2 hr less diurnal coverage in a 30-day period than the 46-deg orbit. A 28.5-deg orbit provides concentrated sampling in the tropics but the required midlatitude, regional diurnal sampling is not obtained.

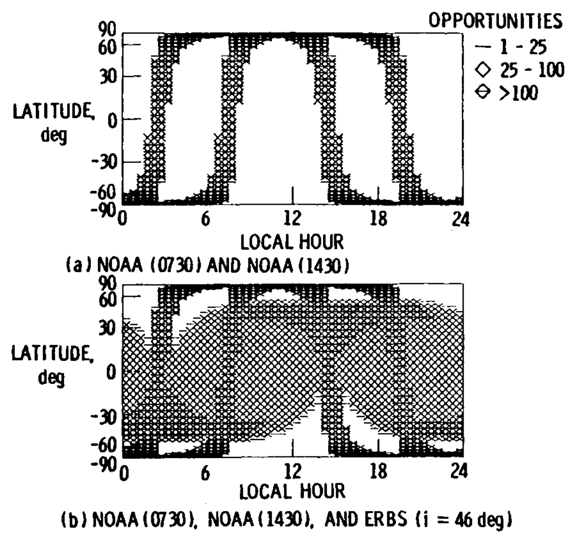

Fig. 1 Temporal/latitude zonal coverage in 1 month for a sensor field of view of 10-deg Earth central angle.

A summary chart illustrating the relative space-time coverage capabilities of the various satellite combinations is shown in Fig. 2. The coverage parameter is based on a product of latitudinal geographical area and local time coverage. As can be seen, for a two-satellite combination, a 98-deg (sun-synchronous) and a 46-deg orbit provide good latitude-local time coverage. The most effective coverage is obtained by the combination of the two sun-synchronous satellites with either the 46- or 57-deg orbit.

The latitude-local time representation of coverage tends to become less meaningful at polar latitudes. An alternate approach was selected to examine how well the satellites sampled the range of solar lighting conditions at the high latitudes.

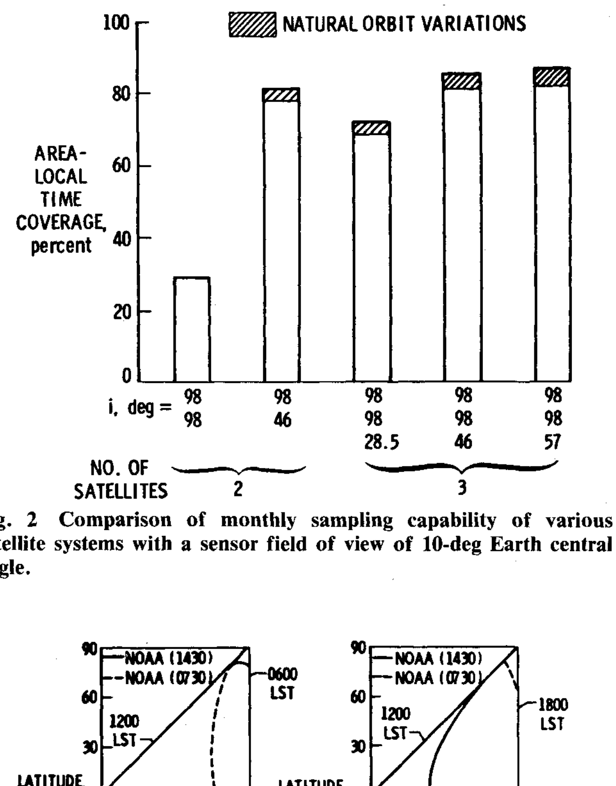

Fig. 2 Comparison of monthly sampling capability of various satellite systems with a sensor field of view of 10-deg Earth central angle.

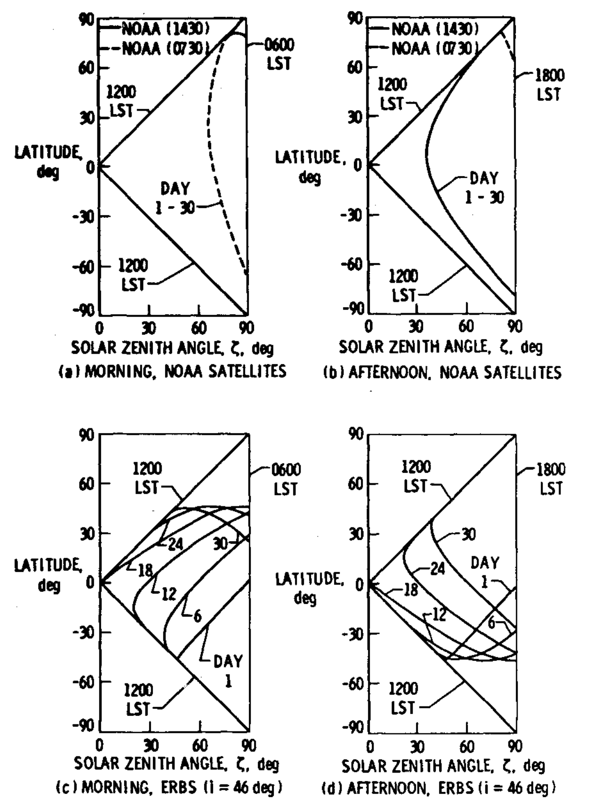

Fig. 3 Solar zenith/latitude coverage at nadir for ERBE satellites.

Plots of latitude vs solar zenith angle are presented in Fig. 3 to show the ground track coverage of the NOAA satellites and the 46-deg satellite at the equinoxes. The 1430 equatorial crossing time orbit covers the range of solar zenith angles at the high northern latitudes in the morning (Fig. 3a), while the 0730 orbit covers approximately the same range during the afternoon (Fig. 3b). The ground track is in darkness south of about 65° S latitude for the 0730 orbit, but coverage for the 1430 orbit extends to about 80° S latitude. In a month, the 46-deg inclined ERBS orbit precesses to cover the complete range of solar zenith angles at latitudes from 46° N to 46° S, as shown in Figs. 3c and 3d.

The wide field-of-view (WFOV) ERBE instrument on the 0730 orbit will observe part of the terminator during the entire orbit shown in Figs. 3a and 3b, which will make data reduction and interpretation difficult, whereas the area seen by the WFOV sensor on the 1430 orbit will generally be entirely in the sunlight or darkness, making it more valuable in meeting the science objectives of the mission. Although the WFOV measurements for the 0730 are somewhat better in the Northern Hemisphere in the summer season, the terminator is still in view for the Southern Hemisphere measurements.

Another primary consideration in the coverage analysis is the performance of the scanning radiometer. The scanner is the principal instrument for obtaining measurements for regional-scale analyses. A cross-track scanner was selected in order to maximize latitudinal coverage and provide continuous geographical coverage between successive orbital passes. The scanner can obtain useful measurements for regions well off the ground track and ensure good polar coverage by the NOAA satellites regardless of which equatorial crossing time is available. This is because the scanner measurements with their associated small field of view (<1000 km^2 at nadir) can be referenced directly to the region being viewed (both geographically and in terms of local time), whereas the WFOV and MFOV instruments will most likely require that measurements be referenced to the satellite nadir point.

It is also desirable that measurements for a given region during the month be made from as many different viewing directions and solar lighting conditions as possible to ensure that bidirectional reflectance effects are properly accounted for in the data analysis. A sketch of satellite-sun geometry relative to the viewed point on the Earth is shown in Fig. 4, where ζ is the solar zenith angle, θ the satellite zenith angle, and ψ the relative azimuth angle. For analysis purposes, the sun zenith angle was divided into six equal bins of 15 deg each. Satellite zenith bins were 7.5 deg each except for a 15-deg bin near the limb. Relative azimuth angle was divided into five bins, with symmetry assumed about the principal plane. The 7.5-deg satellite zenith bin directly over the target was assumed to be azimuth independent. A total of 306 bins was thus defined at the equator. At the higher latitudes, the total number of available bins gradually decreases to 51 at the poles. A computer simulation of the cross-track scanner was developed to determine the actual number of angular bins that could be covered for bidirectional sampling with the ERBE system of satellites.

Typical results of the cross-track scanner angular coverage analysis for an equatorial region at the equinox are presented in Fig. 5 for the NOAA satellites and the ERBS satellite. The overall coverage levels with a sun-synchronous satellite are low primarily because the complete range of sun zenith angles is not covered. Azimuthal coverage is mainly near the principal plane for equatorial regions at the equinox due to the high inclination of the orbit. Satellite zenith angles are covered uniformly because the ground track repeat cycle is 6 days for the NOAA 0730 and 19 days for the NOAA 1430 orbit. The ERBS orbit results in uniform coverage of the solar zenith angles since its precession carries it through all local hours at the equator. Relative azimuth coverage is basically in two bins adjacent to the principal plane, again due to the inclination of the orbit and the cross-track scan mode. Satellite viewing zenith coverage for the case shown here is typical of 250×250-km^2 regions at the equator, but coverage of specific bins is dependent on the exact location of the region with respect to the ground tracks. For the 46-deg orbit with its 3-day ground track repeat cycle, viewing zenith coverage gaps can occur for some regions, but the overall angular range is reasonably well covered.

Scanner coverage of angular bins as a function of latitude is summarized in Fig. 6 for the 46-deg inclined orbit and the two NOAA sun-synchronous satellites. This figure illustrates the contribution of each satellite over the entire latitude range. The NOAA satellite angular coverage is best at the high latitudes and the ERBS significantly complements the mid- and low-latitude coverage. By combining the three satellites, reasonably good angular coverage is obtained at all latitudes.

Cloud Cover Sampling Analyses

The space-time coverage characteristics defined thus far for the ERBE are sufficient to assess satellite system capabilities in general terms. However, the ultimate test of such a system lies in determining how well the Earth's radiation field can be estimated from the measurements. The accuracy of the Earth's radiation budget estimated with a given satellite system may be examined by applying its space-time coverage characteristics to a realistic reference radiation field and averaging the simulated measurements for comparison to the averaged reference field. A realistic radiation field for these purposes must include the effects of clouds. Clouds account for about two-thirds of the reflected short-wave (0.2-5.0 μm)

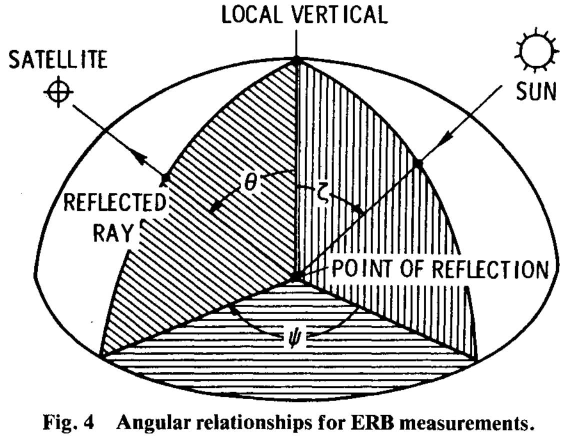

Fig. 4 Angular relationships for ERB measurements.

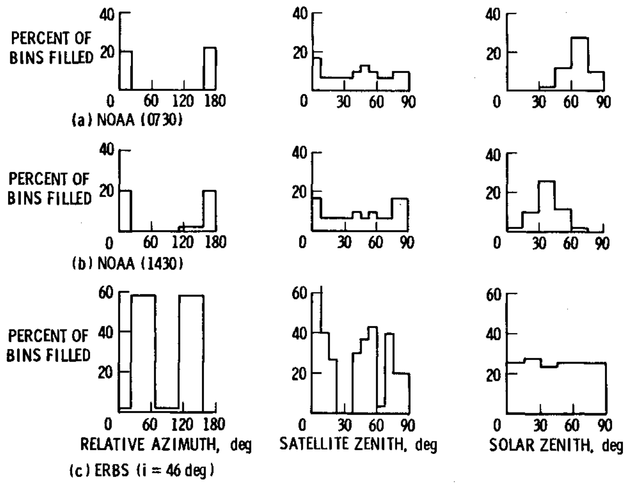

Fig. 5 Distribution of cross-track scanner angular coverage for a 250×250-km^2 equatorial region at equinox.

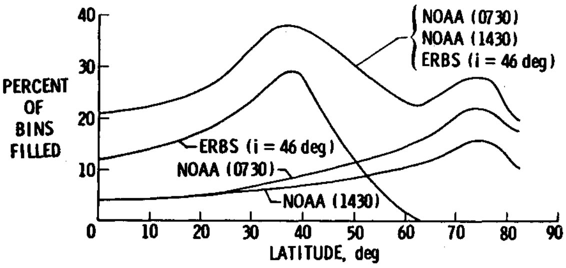

Fig. 6 Coverage capability of a cross-track scanner for 250×250-km² regions.

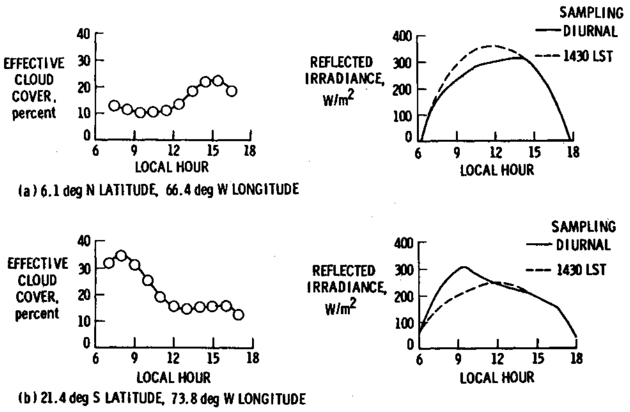

Fig. 7 Effect of cloud variability on the estimation of reflected radiation based on November 1978 GOES data.

and one-third of the emitted long-wave (5.0-50.0 μm) components of the radiation leaving the Earth. Cloud distributions and types and, therefore, their radiative characteristics, vary considerably in time and space. The nonrandom, mostly diurnal, variations in cloudiness may substantially impact estimates of the Earth's radiation budget derived from satellite measurements, even when they are averaged over long time periods.

Hourly visible (0.55-0.75 μm) and infrared (10.5-12 μm) data taken by the geostationary operational environmental satellite (GOES) were used to construct a reference radiation field which includes the diurnal variations of clouds. Data from GOES-East, located over the equator at 75°W longitude at an altitude of 37,800 km, were analyzed to determine hourly cloud cover and radiative properties for 1504 regions which encompass roughly 250×250 km² each for the month of November 1978. The area viewed by GOES-East includes most of the United States and South America, and parts of the Atlantic and Pacific Oceans. The cloud cover and radiation parameters were derived with the methodology of Minnis and Harrison[5] and are described by Harrison et al.[6] The present study focuses on the reflected radiation since it is the more variable component of the radiation field. Effective cloud cover, rather than apparent cloudiness, is used here to parameterize the combined effects of variable cloud amount and cloud albedo. It was derived from the GOES data from an energy balance approach which computes cloud amount in terms of its effect equivalent to that of a cloud having a maximum albedo of 0.9. Although the use of effective cloud cover is appropriate for radiation budget studies, its magnitude is generally much less than conventional cloud cover which has a highly variable albedo.

The diurnal variation of cloudiness in a given area may take many forms which depend on the air mass and surface conditions. For example, in Fig. 7a the mean effective cloud cover over a region in Venezuela reaches a maximum at 1500 local time for November 1978. If the reflected solar radiation were measured from a single sun-synchronous satellite at 1430 local time each day, an estimation of the mean hourly

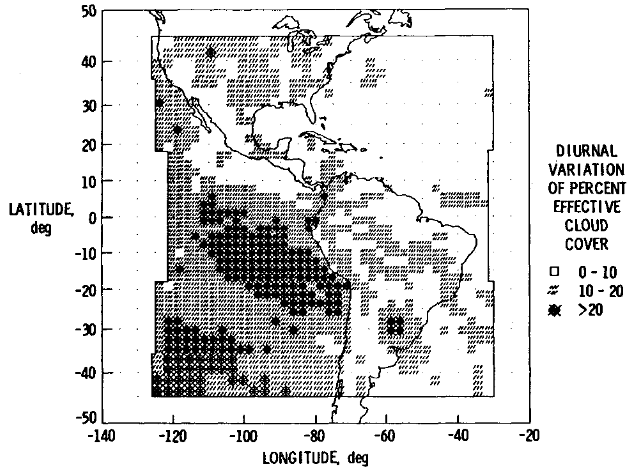

Fig. 8 Monthly mean diurnal variability of regional effective cloud cover from GOES for November 1978.

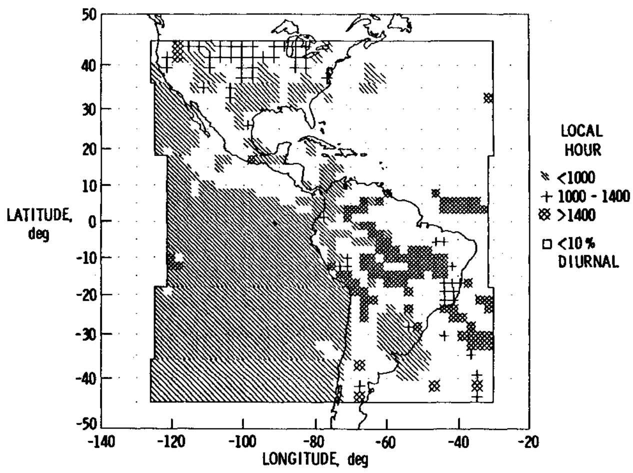

Fig. 9 Local time of maximum daytime monthly mean effective cloud cover for 250×250-km² regions from GOES for November 1978.

reflected irradiance (flux) would yield the dashed line of the right-hand curve. Integration of the dashed line over 24 h yields the estimate of the monthly mean reflected irradiance, M_e. The actual reflected irradiance as determined from the cloud amounts on the left is given as the solid line. Integration of this curve as above yields the true monthly mean reflected flux, M_t. It is apparent that the measurements from the lone satellite will result in a significant overestimation of the mean reflected radiation for the month. In this case, an error, $\Delta M = M_t - M_e$, of −10 W/m² is caused by a diurnal cloud variation of about 15%. This error is too large to meet the sampling accuracy requirement for the ERBE mission.[3]

Underestimation of the reflected component of the radiation budget will occur when this same satellite observes an area with a morning cloud maximum. Figure 7b shows the mean hourly effective cloud cover for a region off the west coast of South America. This diurnal cloud cycle results in a maximum of reflected radiation in the morning as shown by the solid line on the right. Measurement at 1430 local time would result in the dashed line. An error, $\Delta M = 12$ W/m², would result from this undersampling.

Mean diurnal variations of cloud cover would not be a significant problem if they were confined to only a few areas and followed similar patterns. However, the diurnal variability of clouds is not only widespread, but may be quite different from one area of the globe to the next. Figure 8 shows the distribution of the mean diurnal variation of percent effective cloud cover for November 1978, as determined from GOES-East data. This mean variation is simply the difference between the mean maximum and minimum hourly cloud amounts. Areas with a mean cloud variation greater than 10% are regions for which the monthly mean reflected irradiance estimated from measurements from a single sun-synchronous satellite may be highly inaccurate. Nearly 45% of the portion of Earth shown here has mean cloud variations which exceed 10%. In particular, a large number of regions off the west coast of South America have diurnal variability greater than 20%. These results demonstrate the levels of regional-scale cloud variability which may occur over the globe.

The map in Fig. 9 gives the distribution of the time of day at which the mean maximum effective cloud amount occurred during November 1978. Over the eastern Pacific, the peak cloud amount generally occurred in the morning, while over the western Atlantic Ocean and South America, the peak cloudiness was observed at various times of the day. The regions in the United States with significant diurnal variations show maximum cloud amounts during midday. This figure illustrates the potential for biases in both regional and larger scale estimates of reflected flux derived from daytime observations taken at only one local hour.

A preliminary analysis was conducted to determine the regional reflected radiation errors which would result from scanner sampling of the November 1978 GOES cloud data by the proposed NOAA and ERBS spacecraft. It is assumed that the errors resulting from the diurnal cloud variations seen in this data set are typical of those which will be observed over the remainder of the globe. Simulations of orbital tracks and scanner footprints were used to determine the times of measurement for a given region over the course of a month. The actual value of reflected flux at the time of measurement was used with a set of directional reflectance models[5] to estimate the reflected irradiance during the remainder of the day. Linear interpolation with the models was used for hourly values between measurements taken on the same day. The monthly mean hourly and total reflected irradiance, M_e, and error, ΔM, were computed for each region as described above. A regional error of 6 W/m^2 has been allocated for the effects of sampling in the total ERBE error budget. This value may be compared to the rms regional error plotted as a function of latitude in Fig. 10. This figure shows unacceptable error levels (>6 W/m^2) at many latitudes if only a single satellite is used. The sampling error is highest in the southern latitudes where the diurnal variability is most pronounced. Results are shown in Fig. 11 for the 46-deg inclined ERBS combined with each NOAA satellite combination. The addition of the ERBS to the NOAA 0730 orbit improved the sampling error to a more acceptable level, though high errors (6-10 W/m^2) are still in evidence for some latitudes. The 46-deg and NOAA 1430 satellites yield somewhat better results (<6 W/m^2) indicating that this is the preferred two-satellite combination. The three-satellite combination provided better sampling capability and, therefore, lower errors (<4 W/m^2) than any two-satellite combination. A more accurate assessment of sampling errors associated with the ERBE orbits is dependent on final selection of the space-time averaging algorithms and development of a more comprehensive cloud/radiation data base for simulations.

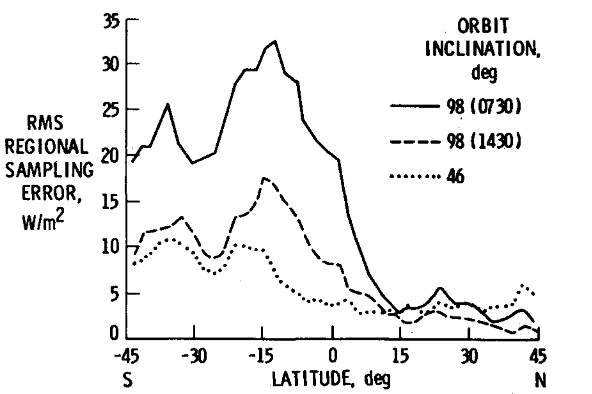

Fig. 10 Zonal regional reflected radiation errors based on single satellite scanner sampling of cloud data from GOES for November 1978.

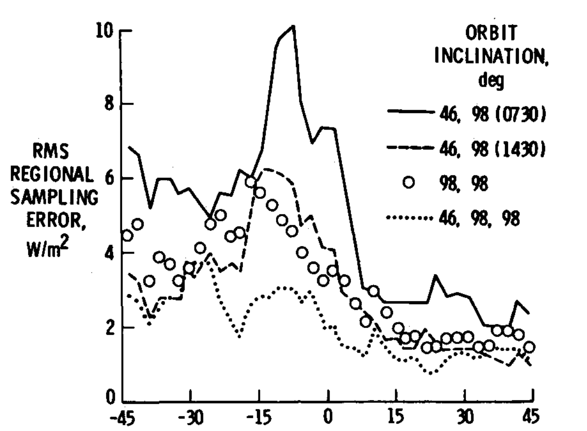

Fig. 11 Zonal regional reflected radiation errors based on multiple satellite scanner sampling of cloud data from GOES for November 1978.

Concluding Remarks

Computer simulations have been performed to determine the geographical and temporal coverage of various satellite orbits and scanning and nonscanning radiometers for Earth radiation budget measurements. Results from the sensor-orbital analysis were used in conjunction with cloud variability data in sampling simulations to determine how well the reflected component of the Earth's radiation budget can be estimated from the different satellite combinations. The combined results of these sampling and measurement simulations indicate that coincident observations with a minimum of one sun-synchronous satellite for polar coverage and the midinclined (46 – 57 deg) orbit satellite for mid- and low-latitude coverage are needed to meet the ERBE science requirements of global coverage, equator-to-pole gradient, and regional monthly mean radiation variations with complete diurnal coverage. A three-satellite system, including two sun-synchronous satellites with the midinclined orbit satellite, provides optimal coverage and accuracy for measurement of the Earth's radiation budget.

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