The First 18 Months of Planetary Radiation Budget Measurements from the Nimbus 6 ERB Experiment

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ABSTRACT

The Nimbus 6 satellite Earth Radiation Budget (ERB) experiment has continuously monitored the solar radiation input and the reflected shortwave and emitted longwave radiation exitance from the earth-atmosphere system since July 1975. In this paper, the planetary radiation budget parameters observed during the first eighteen months in orbit (July 1975–December 1976) are presented. The results show that the annual mean planetary albedo and longwave radiation flux are 31% and 234 W m⁻² (radiative equilibrium temperature of 254 K), respectively. The earth atmosphere system is observed to be in complete radiation balance over a one-year period to within the experimental error of observation. There is an annual cycle of the mean monthly planetary net radiation which is due predominantly to the annual cycle of incoming solar radiation caused by the time variation of earth-sun distance and the sun's declination. Monthly variations in outgoing longwave radiation due to variation in global cloudiness and snow and ice cover are generally compensated by the simultaneous variations in the planetary albedo so that there is generally little monthly variability of the total radiation to space compared to that of the net radiation.

1. Introduction

The earth radiation budget (ERB) experiment was launched into a circular sun-synchronous earth-orbit aboard the Nimbus 6 satellite on 12 June, 1975. ERB operation began about two weeks after launch, after which time outgassing of materials on the spacecraft would most likely have been complete, so that the likelihood of contamination of the optics would be minimal. On 2 July, a protective door covering an array of solar channels was opened and the array of scanning channel telescopes was moved away from the stowed position. Since that time the sensors on the ERB have continued to monitor the incoming solar radiation as well as the radiation exiting the earth-atmosphere system due to the reflection of shortwave solar radiation and the thermal emission of longwave radiation.

The incoming solar radiation is observed with an array of 10 telescopes that measure the total radiation (so-called “solar constant”) and the radiation contained within various subdivisions (broad and narrow) of the solar spectrum (see Table 1). The earth-radiation is measured by two separate arrays of sensors, each one of which views the entire earth's disc observable from the satellite altitude of 1100 km. They measure radiation in the shortwave region (0.2–3.8 µm) and in total (>0.3 µm) from which the planetary albedo, the total longwave radiation flux and the radiation “balance” can be accurately determined for the local time of the Nimbus 6 orbit. Another channel in this array observes in the spectral interval 0.7–3.0 µm. The other array consists of four identical, narrow-angle, bi-directional scanning telescopes that observe the earth-reflected solar radiation (0.2–4.8 µm) and the earth-emitted longwave radiation (4–50 µm). The radiation budgets of local regions of linear dimensions 250–500 km can be estimated from sets of observations made with these narrow-angle sensors.

The ERB experiment is the newest in a series of satellite experiments for measuring the radiation budget, which began with the observations on the Explorer-7 satellite. Vonder Haar (1968) and Vonder Haar and Suomi (1969, 1971) reported on results based on the earlier observations for the mean annual and seasonal cases for spatial scales of the order of 1000 ×1000 km. Later measurements from the Nimbus 3 satellite provided radiation budget data for the synoptic scale. These yielded the first data on the annual variation of the radiation budget for the synoptic scale (Vonder Haar et al., 1972).

In this paper, certain problems in the processing of the ERB data are discussed and also results are pre-
Table 1. Characteristics of ERB sensing channels.

<table>
<thead>
<tr>
<th>CHANNEL NUMBER</th>
<th>SOLAR CHANNELS</th>
<th>EARTH FLUX CHANNELS</th>
<th>SCANNING CHANNELS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1S  2S  3S  4S  5S  6S  7S  8S  9S  10S</td>
<td>11E  12E  13E  14E</td>
<td>15  16  17  18  19  20  21  22</td>
</tr>
<tr>
<td>SPECTRAL INTERVAL (µm)</td>
<td>0.2- 0.2- 0.5- 0.7- 0.45- 0.35- 0.30- 0.28- 0.25-</td>
<td>0.2-50 0.2-50 0.2-3.8 0.7-2.8</td>
<td>0.2-4.8 0.2-4.8 0.2-4.8 0.2-4.8 4.5-50 4.5-50 4.5-50 4.5-50</td>
</tr>
<tr>
<td>FIELDS-OF-VIEW (DEGREES)</td>
<td>3.8 3.8 50+ 2.8 2.8 0.51 0.46 0.41 0.36 0.30</td>
<td>133.3 133.3 133.3 133.3</td>
<td>ALL 0.25 x 5.14 DEGREES</td>
</tr>
<tr>
<td>MAXIMUM FULL RESPONSE</td>
<td>26 26 26 26 26 26 26 26 28 28</td>
<td>10 10 10 10 10 10 10 10 10 10</td>
<td></td>
</tr>
</tbody>
</table>

The terrestrial fluxes deduced from the wide-angle sensors are a product of a number of intermediate steps which turn the raw digital data into meaningful physical measurements. First, the raw data are converted to an irradiance (W m⁻²) by means of a calibration equation, which was developed as part of an extensive prelaunch thermal vacuum calibration. At this point, the irradiance is the power exiting from the earth that reaches each unit area at the satellite elevation. This irradiance can then be expressed in terms of a unit area located at the top of the atmosphere (≈15 km) by a simple application of the inverse square law. Actually, this procedure is correct only for converting the globally averaged total flux (W m⁻²) of radiation through a spherical shell at the satellite altitude to that which would pass through a shell at the top of the atmosphere. At any particular point, the inverse square transformation is valid strictly for isotropic radiation. However, for much of the earth, the approximation yields quite reasonable results. In large regions where strong forward scattering exists (e.g., Greenland), the approximation tends to underestimate the radiation from the surface when the satellite is directly over the region. (The strong forward scattering from Greenland is not observed by the wide-angle channels). In observations of a surface like Greenland near the limb of the Earth, where strong forward scattering is important, the approximation tends to overestimate the irradiance at the top of the atmosphere for the viewed region. Zonal-averages of the irradiances, which is the principal form the results will be presented and analyzed in this paper, suffer from these approximations to a lesser extent. Likewise, the problem is much less severe for the longwave observations than for the shortwave observations. Scanning channel observations for a given area, viewed from a number of directions, yield hemispheric fluxes that do not suffer from these limitations.

A comparison of the longwave fluxes deduced from the wide-angle channels with those computed from the scanning channels led to the surprising conclusion that the wide-angle observations were too low by ≈11%. This is the case for both the total radiation channel as well as for those that measure the reflection of solar radiation. Since the longwave scanning channels have an onboard calibration blackbody, the scanning channel observations are considered reliable. Also, they tend to agree with the magnitudes of the radiation indicated by other investigators on the radiation budget. Of necessity, the irradiances deduced from the wide-angle channels were adjusted to agree within 1% of those obtained from the narrow-angle scanning channels (Smith et al., 1977). We should note that the comparisons were made at the satellite altitude. The scanning channel irradiances were integrated over all directions for each complete scan cycle and the result was compared with an average of the wide-angle measurements over the same period (≈2 min).

Reasons for the low irradiances deduced from the
wide-angle channels are not yet completely known, although a number of theories have been considered. One of these, which is in favor at the present, is that the effective field-of-view of the channels is larger than originally supposed, as evidenced by laboratory observations of reflected laser light, with the source located at the detector, being seen at angles larger than the maximum field-of-view angle. Although no additional radiation can enter the instrument from outside the maximum field-of-view, since it is looking at space at these angles, a larger amount of thermal radiation can exit through the aperture than originally thought possible. This would lead to estimates of irradiance that would be too low by the amount of excess radiation exiting from the aperture. This is being thoroughly examined and will be the subject of a future publication.

Another problem with the wide-angle channels is the possible change in sensitivity due to degradation. Since the total-channel had no optics, no degradation was anticipated. This was verified by comparison of the total-channel observations with those obtained with a duplicate channel (one of the four wide-angle channels) which is normally shuttered. The duplicate channel was unsuttered generally no more than once a month for a short time interval, and its sensitivity was quite stable for the entire 18-month period.

The shortwave channels are expected to degrade somewhat since they are enclosed in hemispherical domes on which solar radiation and solar particles do impinge. However, since there is no duplicate, protected channel as is the case with the total channel, another means of monitoring degradation was necessary. Since the field of view of the channels is greater than the earth’s disc as viewed at the satellite, by a few degrees of nadir angle, the sun’s radiation can be directly incident on the channels at spacecraft sunrise and sunset. Any other source of radiation on the detectors at these times would be quite negligible. Therefore, by monitoring the radiation normalized to a mean earth-sun distance, at each spacecraft sunrise and sunset, one may deduce the degradation, if any, by noting the changes in channel output with time. One should note there that the solar energy in the spectral intervals observed by these earth-viewing channels varied very little over the 18 months according to the observations from the solar channels.

Fig. 1 shows the solar irradiance at spacecraft sunrise and sunset normalized to the mean earth-sun distance as observed by channel 13 (0.2–3.8 µm). It is quite apparent that there are two distinct radiative situations as viewed by channel 13 occurring at spacecraft sunrise and sunset. At sunset, no apparent degradation is noticed, while at sunrise a degradation of about 6% per year is observed. These results may be explained by the fact that during the time before sunset, the sun’s radiation can impinge on the

![Graph showing solar irradiance at spacecraft sunrise and sunset normalized to mean earth-sun distance observed by Nimbus 6 wide-angle channel (0.2–3.8 µm).](image-url)
dome, the dome from the adjacent channel blocks out most of the solar radiation that would have impinged on the portion of the dome through which the sunset would be observed. This is not the case for the sunrise, where no blocking can occur. Possible variations in the spacecraft pitch angle will not account for the observed variations. The peculiar degradation pattern observed at sunrise, with a six-months cycle superimposed, has been traced to the azimuthal variation of the sun with respect to the spacecraft. We have assumed therefore, that the variation as observed at sunrise is indicative of the degradation of the portion of the dome that views the earth. The actual degradation is probably somewhere between the values observed at sunrise and sunset. An analysis of the solar dosage (sun's energy/area of dome) as a function of position on the dome should yield the information required to make a better estimate of the actual degradation. The sunrise value is close to the value observed for the degradation of the corresponding solar channel (7% per year) as evidenced by occasional comparisons with an identical normally shuttered channel.

After correcting the irradiances for degradation, monthly mean-zonal and global averages were computed from the daily averages. Since the Nimbus 6 orbit is sun-synchronous, with the equator crossings at local noon and local midnight, the daily average of the outgoing longwave radiation is assumed to be equal to the average of the daytime and nighttime observations. The daily albedo was assumed to be equal to that computed from the observations near local noon.

3. Results

Fig. 2 displays the globally averaged monthly mean values of various radiation budget parameters from July 1975–December 1976. The most significant results shown in the figure are the annual cycles with the values observed during July 1976–December 1976 being nearly the same as those observed exactly one year earlier. The albedo and longwave radiation cycles are nearly 180° (6 months) out of phase—possibly the result of two phenomena. First, consider the variation of the longwave radiation with time. In the Northern Hemisphere the heating and cooling rates correspond to that expected for land surfaces, causing outgoing longwave radiation to peak in July and to reach a minimum in December. In the Southern Hemisphere only a very weak cycle is evident (see Fig. 6), because...
the sea surface temperature has negligible annual changes. Therefore, the variation of the globally averaged longwave radiation with time is dominated by that in the Northern Hemisphere. During the months when the longwave radiation is at a minimum, the snow and ice cover in the Northern Hemisphere are close to a maximum, resulting in a higher albedo. When the longwave radiation is at a maximum, the snow and ice cover are reduced considerably.

Of equal importance to the cycles observed is the annual cycle of cloudiness. There also tends to be more cloudiness in the Northern Hemisphere winter, compared to that in the Southern Hemisphere winter. This will tend to increase the albedo and simultaneously decrease the outgoing longwave radiation. The opposite effect occurs around June when the cloudiness is least. Which of the two effects discussed above is the dominant cause of the variations of the longwave radiation and albedo is uncertain at this time.

The variation in the absorbed solar radiation (incoming minus reflected solar radiation) with time is principally dependent on the variation of the incoming solar radiation. The annual variation of the incoming solar radiation about its mean value is \( \pm 11.4 \text{ W m}^{-2} \), while the variation of the reflected energy about its mean value is only about \( \pm 7.6 \text{ W m}^{-2} \), both nearly in phase with each other. As a result, the absorbed solar radiation is nearly in phase with the variation of the incoming solar radiation. If the earth was in a perfectly circular orbit around the sun such that there were no variations in the incoming radiation due to earth–sun distance variations, then the variation in absorbed solar radiation would be dominated by variation in the reflected energy. This would cause the phase of the absorbed solar radiation to be shifted \( \sim 180^\circ \) from what is actually observed. Minima and maxima of the absorbed solar radiation would correspond to maxima and minima, respectively, of the reflected radiation. Since the net radiation is the difference of the absorbed solar radiation and the outgoing longwave radiation which are nearly \( 180^\circ \) out of phase with each other, the variation in the net radiation will have an amplitude exceeding those of the absorbed and outgoing components and be nearly the same phase as the absorbed solar radiation. The variation of the net radiation is shown in the bottom half of Fig. 2, where radiative heating dominates over radiative cooling. As will be shown, however, this annual imbalance of the net radiation is most likely the result of a small uncertainty of the solar constant observation. The strong influence of the incoming radiation on the net radiation can be seen in Fig. 3 where the incoming, net and outgoing global radiation are plotted as deviations from their respective annual means versus time for one complete year starting July 1975. The reason for the dip in the net radiation in December is due to the stronger outgoing radiation (reflected solar radiation plus emitted longwave radiation) that occurs at this time of the year. This is caused by an increase in the reflected radiation due in part to an increase in the albedo and in part to an increase in the incoming solar radiation, which more than offsets the drop in the longwave radiation that is emitted.

As indicated above, the deviation of the annual mean net radiation from zero is believed to be due to a small uncertainty in the solar constant observation of 1391 W m\(^{-2}\) used in deriving the net radiation. Because of the concern that the ERB observations appeared to be much higher in value than anticipated, a rocket flight intercomparison of a number of instruments that could

![Diagram](image-url)

**Fig. 3.** Radiation balance of the earth as measured by the ERB instrument on Nimbus 6.
measure the solar constant was suggested. In June 1976, four cavity radiometers were flown along with a duplicate of the ERB thermopile detector, with the surprising conclusion that three of the four cavity instruments agreed to within 1 W m\(^{-2}\) around a mean value of 1368 W m\(^{-2}\) (Duncan et al., 1977). The ERB measurements as well as the cavity instruments aboard the rocket were all referenced to the new cavity radiometer scale which is ~2% higher than the older International Pyrheliometric Scale (IPS). The ERB detector agreed with the cavity detectors on the surface but disagreed with them in space, agreeing precisely with the ERB detector on the satellite. No convincing explanation of the anomaly exists today. In an effort to explain this, the ERB instrument on Nimbus 6 will contain a cavity radiometer in addition to a thermopile detector identical to the one flown on Nimbus 6. If one assumes the value of the solar constant to be 1368 W m\(^{-2}\) instead of the value of 1391 W m\(^{-2}\), then one must decrease the globally averaged incoming solar radiation by approximately 5.75 W m\(^{-2}\). In other words, the zero line in Fig. 2 would be raised to the position of the value at 5.75 W m\(^{-2}\). This would tend
to make the annual mean of the net radiation from July 1975 through June 1976 equal to \(-0.09\, \text{W m}^{-2}\). This value is less than the expected accuracy from the ERB observations and, therefore, one must conclude from this that the earth-atmosphere system is radiatively in balance over a complete year, to within the accuracy of the ERB observations.

Figs. 4, 5, 6 and 7 provide the time variations of the zonal mean distribution of albedo, absorbed solar radiation, outgoing longwave radiation, and net radiation, respectively, as observed by the ERB wide-angle sensors. (It should be remembered that the half-power resolution of the ERB wide-angle observations is \(\sim1800\, \text{km}\), while the complete field of view has a diameter of \(\sim7000\, \text{km}\).) The albedo and longwave radiation to space shown in Figs. 4 and 6 tend to reach a maximum and minimum, respectively, during the winter months of each hemisphere, regardless of latitude, due to increased cloudiness, ice- and snow-covered surfaces, and generally lower surface temperature. In the tropics, the outgoing long-wave radiation and albedo contours follow the progression of the ITCZ. At polar latitudes, the albedo and longwave radiation change very rapidly during the spring and fall due to the rapid variation in snow, ice cover, and surface temperature.

Fig. 5 reveals the strong dependence of the absorbed solar radiation on the incoming solar radiation. This can be seen by comparing the maximum value of 380 W m\(^{-2}\) in the Southern Hemisphere in December with the maximum value of 340 W m\(^{-2}\) in the Northern Hemisphere in June and July. Notice the strong latitudinal gradients in the winter as contrasted with the weaker gradients in the summer in both hemispheres. Fig. 7 shows the strong dependence between the seasonal change of the radiation balance and the variation of the sun's declination. The greatest radiation excess is shown to be near \(30^\circ\)S in December and the largest radiation deficit occurs over the polar regions in winter. The polar radiation deficit is greater in the Northern Hemisphere because of the high elevation of the Antarctic Continent whose low temperature leads to much lower longwave radiation to space than is observed over the North Polar region. The effective radiation temperature of Antarctica in winter is \(-54^\circ\text{C}\) as compared to \(-32^\circ\text{C}\) over the Northern Hemisphere winter pole.

### 4. Conclusion

The Nimbus 6 ERB experiment has provided continuous measurements of the planetary radiation budget over 18 months with high accuracy. Although the results imply that the earth-atmosphere system is close to radiational balance over an entire year, a strong seasonal variation occurs due to the seasonal variation of the incoming solar radiation produced by varying earth–sun distance, change in the solar declination, and variation of the snow and ice cover in the Northern Hemisphere, as well as variation in the global cloudiness. The importance of high resolution features in the radiation budget will be assessed in the near future from analyses of ERB observations from the scanning channels with higher spatial resolution (not presented here).

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**REFERENCES**


