Satellite Measurements of Aerosol Backscattered Radiation From the Nimbus F Earth Radiation Budget Experiment

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551.5      Meteorology
 .507.362.2  Satellites
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 .521.3     Radiation scattering in atmosphere

ABSTRACT. Satellite measurements offer a unique opportunity to investigate the backscatter from atmospheric aerosols in parallel with accurate quantitative determinations of earth-atmosphere radiation budgets on both synoptic and planetary scales. This report describes the general characteristics of the instrumentation being developed for this purpose by the National Oceanic and Atmospheric Administration and by the Eppley Laboratory. Also discussed is the possibility of obtaining measurements of the degree of polarization of backscattered radiation in the visible spectrum as part of a future satellite project that could be based upon the Earth Radiation Budget Experiment. These measurements, together with radiation intensity determinations, might permit diagnosing particulate pollutants (aerosols) and monitoring their transport. Simultaneous fixed (wide-angle) and scanning (narrow-angle) integral short-wavelength and long-wavelength outgoing energy flux determinations will permit detailed study of the regional and global influence of atmospheric aerosol pollutants on the heat budget. In 1974, the radiometer is to fly aboard the Nimbus F satellite.

1. INTRODUCTION

The Earth Radiation Budget (ERB) Experiment, under current specifications, provides for simultaneous measurement of incoming sun radiation and outgoing earth-reflected short-wave and earth-emitted long-wave radiation by (1) the fixed wide-angle sampling at the satellite altitude and (2) the scanned narrow-angle sampling of the angular dependent radiance components of (1).

The integral short-wavelength reflectance and integral long-wavelength emittance of earth will be measured in two ways. The first is an integration

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Table 1.—ERB solar and earth radiation measurement channels (wavelength, \( \lambda \), in micrometers, \( \mu m \))

<table>
<thead>
<tr>
<th>Solar</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25-0.30</td>
<td>0.20-1.0</td>
</tr>
<tr>
<td>.28-.35</td>
<td>.70-3.0</td>
</tr>
<tr>
<td>.30-.40</td>
<td>.20-50+</td>
</tr>
<tr>
<td>.35-.45</td>
<td></td>
</tr>
<tr>
<td>.40-.50</td>
<td></td>
</tr>
<tr>
<td>.53-3.0</td>
<td></td>
</tr>
<tr>
<td>.70-3.0</td>
<td></td>
</tr>
<tr>
<td>.20-1.0</td>
<td></td>
</tr>
<tr>
<td>.20-50+</td>
<td></td>
</tr>
</tbody>
</table>

over the entire earth's disc (wide angle field-of-view), to measure the total terrestrial flux passing through a unit area at satellite altitude. The second is a series of measurements by angular scanning (narrow-angle field) of the radiance reflected and emitted from relatively small areas on the earth's surface at a number of zenith and azimuth angles. The scan system has been designed to obtain up to nine different views of a terrestrial area. Knowledge of the angular variation will permit the determination of synoptic scale features of earth's heat budget. Independent in-flight calibration will permit comparison of the two methods. As a result, the outgoing terrestrial flux and the derived radiation budget will be determined on the required synoptic and planetary scales.

Regarding spectral subdivision, the solar channels detect radiation flux in seven well-defined wavelength intervals in the ultraviolet and visible regions (table 1), in addition to the (inherently) integrated principal wavelengths of 0.20-1.0 \( \mu m \) and 0.20-50+ \( \mu m \). A major separation is at 0.70 \( \mu m \) (i.e., the visible, near infrared boundary). This is duplicated in the fixed earth reflectance channels, thus permitting isolation of the spectral region where extinction of short-wave radiation by molecular and aerosol scattering predominates in the outward fluxes.

Heat budgets will be calculated by means of three complementary techniques. First, by use of the wide-angle (fixed) sensors, the net flux will be obtained directly for the largest area possible from the intended orbit. In the second, statistical samples of narrow-angle (scanning) data will be used to formulate models that describe the angular dependence of reflected and emitted radiation as a function of basic earth-atmospheric radiative features (e.g., background reflection, cloud condition, aerosol concentration, etc.). Heat budgets for local areas will then be obtained by using the angular distribution models in the integration of specific angular measurements of the radiation from these areas. In the third, regional heat budgets will be computed from the scanning radiometer data by integration over complete scans. This comparison of local and regional heat budgets
provides a means for ascertaining the relationships between the radiative fluxes of relatively small geographical areas and those of much larger areas. The global radiation budget will be extracted from the measurements obtained by both kinds of instruments.

2. INSTRUMENT DESCRIPTION

The ERB radiometer consists of 22 spectral channels for the measurement of intensities of incoming solar radiation, reflected solar radiation, and outgoing infrared radiation. Measurements will be made within various spectral intervals at angular resolutions sufficient for defining atmospheric outgoing radiative fluxes on synoptic and planetary scales.

Figure 1 is a sketch of the ERB radiometer. The nine solar channels, with a conical field of view of 29°, are for observing the solar spectrum within the integral wavelength region of 0.20 - 50+ µm as the satellite orbits over the poles. Simultaneously, various filters for measuring the intensities in the spectral subregions are listed in table 1. This capability is provided to obtain measurements in wavelength intervals in which there is specific interest or in which significant variability of solar emission is believed to occur. Values can be obtained in the following subregions by subtracting measurements obtained at instrumentally fixed intervals: λ<0.53, 0.20-0.53, 0.20-0.70, and 0.53-0.70 µm. In this treatment of data, account will be taken of the small solar radiation increment between the upper wavelength cutoff of the colored glass filtered channels (3.0 µm) and that of the quartz unfiltered channel (4.0 µm). A redundant total short-
wave earth flux channel (0.20-4.0 \mu m) normally will be shielded from solar ultraviolet, electron, and proton radiation. It will be occasionally unshuttered to detect possible deteriorations of the solar channels. Ground commands will be used for shifting the sensors as much as 20° out of the orbit plane to align them with the sun.

Four other earth flux channels will view continuously as much of the earth area as is visible from the spacecraft. These channels will permit separation of the atmospheric reflected radiation into the subregions \( \lambda < 0.70 \) and \( \lambda > 0.70 \ \mu m \) (table 1). As will be shown, these two spectral regions separate the molecular-plus-aerosol from aerosol-dominant spectral contributions to the total backscattered radiation. The total emitted infrared flux (4.0-50+ \mu m) will also be observed. A redundant shuttered total earth flux channel (0.20-50+ \mu m) is included for degradation detection.

The ERB includes four, narrow field-of-view scanning telescopes in a scanning head that alternately measures short-wave (0.2-4.0 \mu m) and long-wave (4.0-50.0+ \mu m) radiation as a result of a beam-splitting chopper. The head will scan in various vertical planes from nadir to horizon, to measure the angular distribution of a reflected solar and emitted infrared radiation from given geographical areas at a variety of solar angles. The instantaneous fields-of-view of the telescopes are 0.25° x 5.0°, the former in the scan plane. (From a satellite height of 600 n.mi., areas with linear dimensions of 2.5 x 50 n.mi. and 200 x 200 n.mi. are resolved when viewing downward and near earth's horizon, respectively.) The infrared channels will be aligned so that they will sight the horizon simultaneously when the scanning head is at the proper nadir angle, to measure the angular variations of the emerging ray at large local zenith angles. These observations are expected to be important as indicators of the amount of backscatter caused by atmospheric aerosols. A black body and a diffuser plate will be included to permit in-flight calibration of the scanning channels.

Recent ground observations indicate that the angular distribution of the polarization of scattered radiation may be more sensitive to the aerosol concentration than is the angular distribution of the radiation intensity. For the measurement of polarization, serious consideration is being given to adding four narrow-angle scanning channels to future ERB radiometers. The most important consideration in this complex experiment is that instrument performance at the ground and within the atmosphere be transferable to extraterrestrial conditions without significant degradation of signal reproduction, repeatability, and resolution needed for high absolute measurement accuracy. In this experiment, the radiometric and readout precision desired in flight operation is 0.1%, with an overall accuracy level approaching 1% in total flux and 2% in spectral flux. Independent in-flight calibration checks to monitor instrumental performance are provided for each of the three measurement programs.
3. RELATION OF RADIOMETRIC MEASUREMENTS TO AEROSOL CONCENTRATION

Theoretical computations and ground-based observations of various types of atmospheres are presented to indicate the effects of aerosols upon the radiation to be sensed by the ERB. Three aerosol models were chosen to describe clear, hazy, and very hazy atmospheres. In all the models, a single relative size distribution (independent of altitude) of the particles was chosen.

Figure 2 shows the particle concentration at the surface per unit interval of the logarithm of the particle radius \( r \), \( (dN/d \log r) \), versus \( \log r \) for the three aerosol models. These concentrations correspond to horizontal visibilities of 23, 5, and 1 km for clear, hazy, and very hazy atmospheres, respectively.

Figure 3 shows the vertical distributions of the aerosol concentrations that were assumed for the models. They were chosen so that the concentrations varied exponentially with height in two or more layers. The distributions for the clear and hazy atmospheres are very similar to those used by McClatchey et al. (1971). The vertical distribution of the aerosols for the very hazy atmosphere was assumed to be identical to that of the hazy atmosphere above the 1-km level. Below this level, the concentration was assumed to increase exponentially downward to a surface value corresponding to a horizontal visibility of 1 km.

For each of the above distributions, the optical thickness \( \tau \) was computed as a function of the wavelength of the incident radiation, by using the extinction cross sections computed by Zel'manovich and Shifrin (1971) for the size distribution shown in figure 2. The \( \tau \) of a layer of atmosphere is the negative logarithm of the fractional attenuation of the incident beam resulting from absorption and scattering by the aerosols. It is computed by means of

\[
\tau(H) = \int_0^H N(h)\sigma \, dh
\]

where \( N(h) \) is the total concentration of the aerosols at the altitude \( h \) and \( \sigma \) is the extinction cross section. The variation of \( \sigma \) with wavelength is presented in figure 4. \( H \) is the altitude chosen for the top of the aerosol atmosphere (20 km). As a result, the optical thickness for the model atmospheres were computed as functions of the wavelength.

Figure 5 shows the optical thickness versus wavelength for the three aerosol models of figure 2 and for a pure molecular atmosphere according to Penndorf (1957). As mentioned earlier, aerosol scattering is much stronger than molecular scattering at wavelengths greater than approximately 0.40 \( \mu \)m. Therefore, backscattering measurements in this region should be strongly dependent upon the concentration of aerosols. For a given background condition, an increase in the aerosol concentration should result in a marked increase in the intensity of the measured backscattered radiation. Also, the variation of intensity, as a function of local zenith angle, will increase with increasing aerosol concentration, regardless of the wavelength of measurement. Hence, the ERB measurements of the angular variation of the integral short-wavelength reflected radiation will be of use in estimating the aerosol concentrations over specific geographical regions.
Figure 2.--Aerosol size frequency distributions at the surface. (The $r$ is measured in $\mu$m, the $N$ in no./cm$^3$.)

Figure 3.--Vertical distributions of aerosol concentration
Figure 4.---Aerosol extinction cross section versus wavelength for a unit concentration (adapted from Zel'manovich and Shifrin 1971)

Figure 5.---Optical thickness versus wavelength for aerosol attenuation and molecular scattering
An important quantitative indicator of aerosol characteristics is the state of polarization of backscattered radiation, and the dependence of polarization on both wavelength and scattering angle. The degree of polarization of backscattered radiation in the principal plane (i.e., the plane containing the sun, viewed area, and sensor) is proportional to the difference between the squares of the horizontal and vertical vibrations of the electric vector in the plane normal to the direction of propagation of the radiation. Figure 6 is an example of the variation of the angular distribution of the degree of polarization for three atmospheric states and two different solar elevation angles, as obtained by Coulson (1969) with an upward-looking polarizing radiometer. These curves show that the degree of polarization decreases rapidly with increasing aerosol concentration, especially at large solar zenith angles. Similar characteristics are expected in measurements from a satellite-borne downward-looking polarizing radiometer. Although surface reflection, with its attendant polarization, plays a stronger role in the radiation directed outward from the atmosphere than it does for the skylight (thereby complicating the problem of interpretation), the polarization field measured from a satellite should contain retrievable information on aerosol effects. Hence, it should be possible to use scanning radiometer observations of polarization, obtained with ERB-type experiments for diagnosing aerosol concentrations and their horizontal transport over the earth's surface.

4. CONCLUSIONS

Information on the pollution of the atmosphere by particles and their horizontal transport should be obtainable from satellite measurements of the
solar short-wave backscattered radiation. The Nimbus F ERB Experiment is an attempt to measure the critical components of this backscattered radiation, as well as to obtain the outgoing flux measurements with the precision needed for determining the influence of pollution on the radiative balance of the terrestrial atmosphere. It is suggested that future ERB experiments be additionally instrumented to obtain scanning polarizing radiometer observations for the detection of aerosol pollutants. It is proposed that such satellite measurements obtained from the ERB be carefully investigated and, if successful, that full consideration be given to instrumenting operational satellites to obtain such measurements routinely as a means for continued monitoring and evaluating the effects of man's influence on his environment.

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