Measurements of Albedo and Earth Radiation from OSO-1

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The emissivity experiment on the first orbiting solar observatory (OSO) yields, as part of the data on the stability of temperature-control coatings in space, information on earth-reflected sunlight and earth-emitted energy. Localized values of both albedo and earth radiation deduced from these data are presented. A description of the experiment and radiometric technique and an analysis of possible error associated with the results are included.

Nomenclature

A = area of sensor surface, cm^2
c = specific heat of sensor, cal/g-°K
E = earth-emitted radiant flux, ly/min‡
F_E = earth view factor, defined by $H_E = F_E E$
F_S = solar view factor, defined by $H_S = F_S S$
F_β = albedo view factor, defined by $H_\beta = F_\beta \beta S$
H_E = earth-emitted radiant flux incident on sensor surface, ly/min
H_S = direct solar flux incident on sensor surface, ly/min
H_β = earth-reflected solar flux incident on sensor surface, ly/min
K = heat-exchange constant for sensor mount, cal/min-°K^4
Q_K = net heat flux incident upon sensor due to imperfect thermal isolation, equal to $K(T_b^4 - T^4)$, cal/min
S = solar constant, taken as 2.0 ly/min
T = temperature of sensor, °K
T_b = temperature of sensor mounting cup, °K
V = a function of n independent variables
w = mass of sensor disk, g
α_E = earth-radiation absorptance of sensor surface
α_S = solar-radiation absorptance of sensor surface
α_β = albedo-radiation absorptance of sensor surface
β = albedo, ratio of earth-reflected to incident solar energy
ϵ = infrared emittance of sensor surface
θ = time, min
σ = Stefan-Boltzmann constant, 0.813 × 10^{-10} cal/cm^2 min-°K^4

Introduction

KNOWLEDGE of the quantity of radiant energy reflected and emitted from the earth and its atmosphere is required, not only in analysis of the heat budget of the earth for meteorological purposes, but also in calculations of the heating of near-earth satellites. Until recently, values of earth-reflected solar energy, or albedo, and earth-emitted infrared radiation have been deduced from indirect measurements.[1–3] With the advent of scientific satellites, direct measurement of these quantities from outside the atmosphere has been made possible. The greatest amount of information has been obtained from the Tiros series of meteorological satellites which carried equipment designed specifically for measuring reflected and emitted radiation.[4,5]

An experiment on the first orbiting solar observatory (OSO-I) also produced data on the intensity of reflected sunlight and earth radiation. Although this experiment[6,7] was designed for another purpose (that of determining the long-term stability of radiation properties of several thermal-control coatings), deductions of albedo and earth radiation also have been made from the data. This paper presents the OSO results. Although the values of albedo and earth radiation are limited both in quantity and scope, they supplement previous measurements. In addition, an error analysis, having general application in radiometric measurements of this type, was performed on the OSO-I data.

Analysis of Radiometric Technique

Heat-Balance Equations

Consider the energy balance on a thin, flat plate, thermally isolated on its back side, and viewing the earth from a satellite orbit. The surface of the plate will intercept direct energy from the sun and energy emitted and reflected by the earth. A heat balance yields

$$\underset{\text{(solar input)}}{H_S A \alpha_S} + \underset{\text{(albedo input)}}{H_\beta A \alpha_\beta} + \underset{\text{(earth input)}}{H_E A \alpha_E} + \underset{\text{(heat leak)}}{Q_K} = \underset{\text{(emission by plate)}}{A\epsilon\sigma T^4} + \underset{\text{(heat storage)}}{wc(dT/d\theta)} \qquad (1)$$

The terms on the left side of the equation are the foremen-tioned heat inputs from the earth and sun plus the term Q_K, which represents heat input due to imperfect thermal isolation on the back side. The terms on the right represent the radiant heat emission and changes in heat storage of the disk.

To introduce the terms albedo or earth radiation into the energy equation, the heat-flux terms H_β and H_E must be expressed in terms of the total amount of energy reflected or emitted by the geographical area viewed by the sensor. The heat-input parameters H_β and H_E can be written as

$$H_\beta = F_\beta \beta S \qquad (2)$$

$$H_E = F_E E \qquad (3)$$

where F_β and F_E are albedo- and earth-radiation view factors. Analogously,

$$H_S = F_S S \qquad (4)$$

Albedo or earth radiation can be determined from Eqs. (1–4), provided that all of the other parameters are known.

In the subsequent analysis, the following assumptions were made: 1) the value of albedo-radiation absorptance of the radiometer surface α_β was assumed to equal the value of solar-radiation absorptance α_S; 2) the infrared absorptance α_E of the surface was taken equal to the infrared emittance ϵ; 3) the earth was assumed to emit and reflect according to a cosine distribution; 4) the term Q_K, which represents heat input to the sensor from its back side, was set equal to $K(T_b^4 - T^4)$, where K is a proportionality factor, T is the temperature of the radiometer surface, and T_b is the temperature of the object behind the surface with which it exchanges heat.

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‡ ly = langley = cal/cm^2; 1 ly/min = 0.070 w/cm^2 = 221 Btu/hr-ft^2.

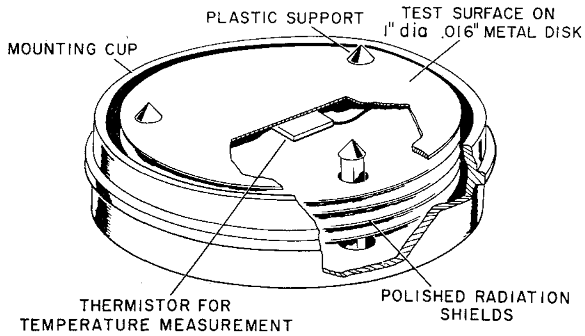

Fig. 1 Design of radiation sensors.

Earth-radiation determination

Earth radiation can be deduced from data recorded during either night or day portions of an orbit. The equation for earth radiation is

$$E = \frac{1}{F_E}\left[\sigma T^4 - \frac{\alpha_S}{\epsilon}(F_S S + F_\beta \beta S) + \frac{wc}{\epsilon A}\frac{dT}{d\theta} + \frac{K}{\epsilon A}(T^4 - T_b{}^4)\right] \quad (5)$$

If data from the night portion of an orbit are employed, the α_S/ϵ ratio of the surface need not be known, since the solar and albedo terms are zero. If data from the day portion of an orbit are employed, a value of albedo must be assumed. Because any assumed value of albedo has a large uncertainty, the former method of solution is preferable. Earth radiation can also be determined from the simultaneous solution of the energy equations for two surfaces. In this case, assumption of a value of albedo is not required. For two surfaces having the same α_S/ϵ ratios, the simultaneous solution is indeterminate. Therefore, surfaces with different values of α_S/ϵ should be employed.

Albedo determination

The equation for albedo is

$$\beta = \frac{1}{F_\beta S}\left[\frac{\epsilon}{\alpha_S}(\sigma T^4 - F_E E) - F_S S + \frac{wc}{A\alpha_S}\frac{dT}{d\theta} + \frac{K}{A\alpha_S}(T^4 - T_b{}^4)\right] \quad (6)$$

Solution of this equation requires an assumption of the value of earth radiation. Albedo can also be deduced from the simultaneous solution of equations for two surfaces, in which case no assumptions are required. However, surfaces with different α_S/ϵ ratios must be used, since, as in the case of earth radiation, the simultaneous solution becomes indeterminate when the ratios are equal.

Uncertainty Analysis

Uncertainties in albedo and earth radiation resulting from uncertainties in the individual terms from which they were deduced can be computed by the method of Kline and McClintock.[8] They define uncertainty as "a possible value the error might have." Maximum errors are not considered, since it is improbable that all errors would be additive.

The method of Kline and McClintock follows. If the quantity V is a function of n independent variables x_1, x_2, . . . x_n, then for small changes in these variables, the proportional change in V can be expressed as

$$\Delta V = (\partial V/\partial x_1)\Delta x_1 + (\partial V/\partial x_2)\Delta x_2 + \ldots + (\partial V/\partial x_n)\Delta x_n \quad (7)$$

Let Δx_n represent the uncertainty of each independent variable. If, in addition to being small, the uncertainties are independent and equally probable, and if the variables are estimated to fall within their uncertainty interval with odds of, say, 10:1, then V will fall within the interval $V \pm \Delta V$ with the same odds, when ΔV is defined by

$$\Delta V = \left[\left(\frac{\partial V}{\partial x_1}\Delta x_1\right)^2 + \left(\frac{\partial V}{\partial x_2}\Delta x_2\right)^2 + \ldots + \left(\frac{\partial V}{\partial x_n}\Delta x_n\right)^2\right]^{1/2} \quad (8)$$

The uncertainty interval of each variable should be determined by an analysis of the method by which it was obtained. Often, however, a complete analysis is too time-consuming, inconvenient, or even impossible to conduct. In general, an educated guess may be better than none at all. The values to be employed are not necessarily extremes, but are those within which the error should fall with reasonable odds

Earth radiation

Specific application of the method of Kline and McClintock will be made to determine the uncertainty of deduced values of earth radiation. For data recorded during night portions of the orbit, Eq. (5) can be written as

$$E = f[T, (dT/d\theta), T_b, \epsilon, A, wc, K, F_E] \quad (9)$$

The uncertainty of deduced values of E is described by

$$\Delta E = \left\{\left(\frac{\partial E}{\partial T}\Delta T\right)^2 + \left[\frac{\partial E}{\partial(dT/d\theta)}\Delta\frac{dT}{d\theta}\right]^2 + \ldots + \left(\frac{\partial E}{\partial F_E}\Delta F_E\right)^2\right\}^{1/2} \quad (10)$$

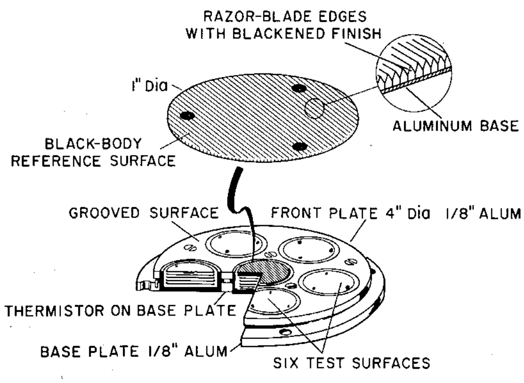

Fig. 2 Construction of razor-blade reference and mounting of sensors.

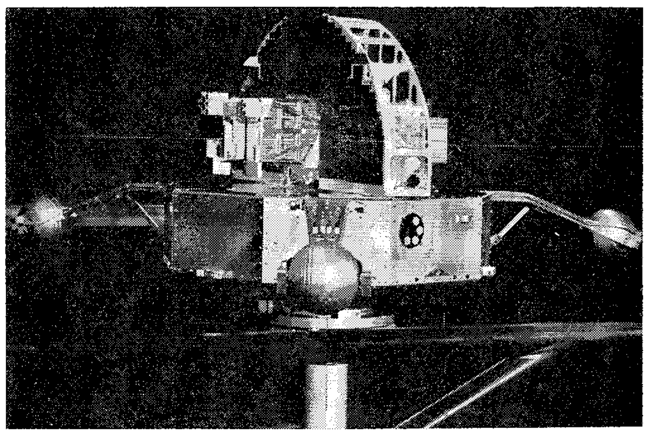

Fig. 3 Orbiting solar observatory with sensor plate installed on rim panel.

Albedo

Analogously, the uncertainty of deduced values of albedo may be determined. Equation (6) can be written as

$$\beta = f[T, (dT/d\theta), T_b, (\alpha_S/\epsilon), \alpha_S, A, S, E, wc, K, F_S, F_E, F_\beta] \qquad (11)$$

The view factors F_E and F_β are not independent. Both are functions of the geometrical area of the earth viewed by the sensors. For every error associated with the determination of F_E, there will be a corresponding error associated with F_β. Both errors will be in the same direction, that is, a simultaneous increase or decrease of both values. Provided that α_S/ϵ and α_S are obtained from independent measurements, all of the remaining terms may be considered to be independent. The uncertainty equation for this case is

$$\Delta\beta = \left\{\left(\frac{\partial\beta}{\partial T}\,\Delta T\right)^2 + \left[\frac{\partial\beta}{\partial(dT/d\theta)}\,\Delta\,\frac{dT}{d\theta}\right]^2 + \ldots + \left(\frac{\partial\beta}{\partial F_S}\,\Delta F_S\right)^2 + \left(\frac{\partial\beta}{\partial F_E}\,\Delta F_E + \frac{\partial\beta}{\partial F_\beta}\,\Delta F_\beta\right)^2\right\}^{1/2} \qquad (12)$$

Description of Experiment

The emissivity experiment on the first OSO consisted of a cluster of temperature-control surfaces thermally isolated from each other and the spacecraft and a means of recording their temperatures. Features of the experiment pertinent to the determination of albedo and earth radiation will be discussed.

Sensor Design

Each radiation sensor consisted of a surface, or coating, applied to a metallic substrate to which a thermistor was attached on the underside for measuring temperature. In order to minimize extraneous heat losses, each was mounted in a specially designed cup as shown in Fig. 1.

Test Surfaces

Seven surfaces were employed as part of the emissivity experiment. One of these was a reference surface designed to remain optically stable in the space environment. It was composed of razor blades, with blackened finish, stacked together, as shown in Fig. 2, to form a series of *V* grooves with small apex angles. Hence, most incident radiation experienced multiple reflections and eventual absorption. As a result, the reference surface was a good approximation of a blackbody. Because of the design, any change in the emittance or reflectance of the local surface would have had only a small effect on the over-all emittance or absorptance of the reference surface. A list of the surfaces studied in the emissivity experiment follows (for more complete information on the characteristics of the surfaces see Ref. 6): 1) razor-blade reference, 2) aluminum powder in silicone, 3) TiO_2 in epoxy, 4) TiO_2 in silicone, 5) white porcelain enamel, 6) Al–SiO–Ge, and 7) Al–SiO–Ge–SiO.

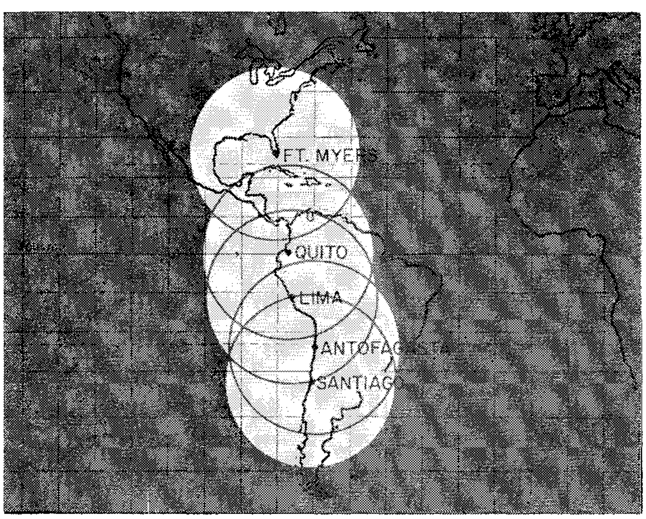

Fig. 4 Geographical areas viewed by satellite when over the Minitrack stations.

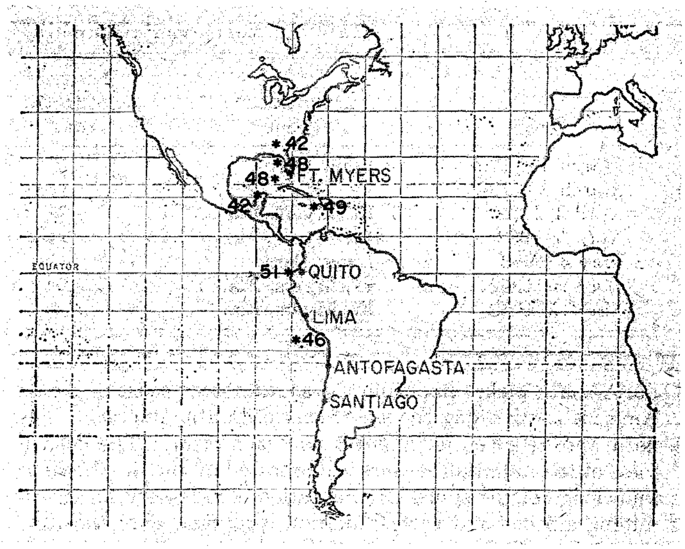

Fig. 5 Earth-radiation values deduced from OSO experimental data (values designated in *ly*/min).

OSO Satellite

The emissivity experiment was mounted on the first OSO, which was launched March 7, 1962. The orbit was approximately 350 statute miles above the earth and inclined about 33° with respect to the equator. Its period was 96 min.

The satellite was composed of two main parts (Fig. 3): a lower section, a nine-sided wheel that rotated at 30 rpm, and an upper section, a stabilized semicircular structure aimed at the sun. The spin axis of the rotating section was always maintained perpendicular to the satellite-sun line. However, the axis was free to rotate about this line. The axis position, which was determined from satellite instrumentation, is known for only about the first two months in orbit. The emissivity experiment was mounted on the periphery of the rotating wheel section, thereby alternately viewing the earth and sun.

Data Acquisition

Experimental data were obtained only when the OSO was over the vicinity of the Minitrack stations located in the

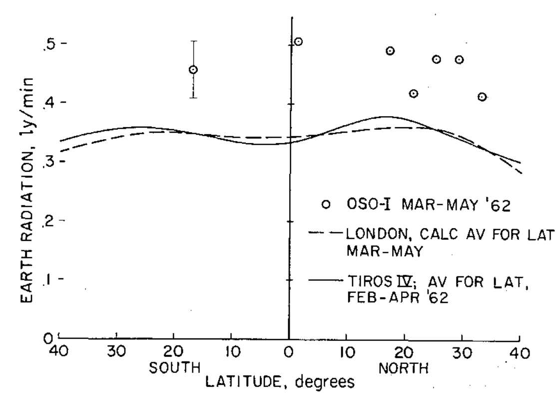

Fig. 6 Comparative data for earth radiation.

Table 1 Earth-radiation values deduced from OSO-I measurements

Date	Minitrack station	Latitude of OSO, deg	Longitude of OSO, deg	Earth radiation, ly/min	Equivalent blackbody temperature, °K
March 11, 1962	Lima, Peru	−17	−78	0.46	274
March 23, 1962	Ft. Myers, Fla.	17	−84	0.49	279
April 3, 1962	Ft. Myers, Fla.	25	−85	0.48	277
April 5, 1962	Ft. Myers, Fla.	21	−89	0.42	268
May 3, 1962	Lima, Peru	1	−81	0.51	281
May 15, 1962	Ft. Myers, Fla.	29	−85	0.48	277
May 15, 1962	Ft. Myers, Fla.	33	−85	0.42	267

north-south picket line from the southeastern coast of North America south along the west coast of South America. The data were received for about 5 min each orbit. The field of view of the radiation sensors is illustrated in Fig. 4. Because knowledge of the spin-axis orientation is necessary for determining albedo- and earth-radiation heat flux, only the time period for which this orientation is known was considered. As mentioned previously, this period is approximately two months.

Selection of Radiometer Surfaces

Because none of the test surfaces included as part of the emissivity experiment was specifically chosen to be a radiometric sensor surface it was necessary to determine which of them best qualified for such use. All surfaces were considered from the standpoint of usefulness in providing data on both day and night sides of the orbit. The primary requirement for a surface was that its optical properties be known with good accuracy. Hence, only stable surfaces, and those having infrared emittance independent of wavelength, and consequently α_E equal to ϵ, were selected as candidate radiometers.

Only three surfaces met these requirements. These surfaces were the razor-blade reference, aluminum powder in silicone, and TiO_2 in epoxy. The first two had stable α_S/ϵ ratios.[6] The razor-blade reference was selected for determination of albedo. Its measured radiation properties, as used herein, were $\alpha_S/\epsilon = 0.98$ and $\alpha_S = 0.97$.

The TiO_2 in epoxy surface was selected for determination of earth radiation. Only data recorded during the night portion of the orbit were employed. The advantage of using nighttime data is that no assumption of albedo is required, and knowledge of the infrared emittance is the only optical property of importance. The infrared emittance of the epoxy coating is known through laboratory studies to remain constant on exposure to simulated space environments, although its solar absorptance was found to be unstable.[6,9]

Results and Discussion

Earth Radiation

Values of earth radiation were deduced from measurements made with the surface composed of TiO_2 in epoxy. Data taken during the nighttime portion of the orbit were employed in Eq. (5). The results are given graphically in Fig. 5, and in Table 1 in terms of heat flux from the earth and the equivalent blackbody temperature. The most noticeable single feature of the results is that they are substantially higher than the commonly accepted global average of approximately 0.33 ly/min, which represents an equivalent blackbody temperature of 252°K.

Attempts were made to correlate the OSO results with simultaneous cloud cover and/or Tiros satellite measurements. Unfortunately, adequate data for such correlation were not available. As an aid to putting the results in proper perspective, however, the OSO results are plotted in Fig. 6 with the global-average values for latitude from Tiros IV measurements and London's comprehensive analytical study.[1] The Tiros IV data were obtained during February, March, and April 1962. London's study pertains to the northern hemisphere. If albedo and earth radiation are assumed to be functions of season and latitude only, for either hemisphere, values for the southern hemisphere can be inferred from London's results for the northern hemisphere.

Figure 6 shows the OSO results to be higher than the global-average values for latitude measured by Tiros and predicted by London. Factors that may contribute to the apparent differences among the results are differences in time and location of data acquisition and in geographical features and meteorological conditions.

Table 2 Albedo values deduced from OSO-I measurements

Date	Minitrack station	Latitude of OSO, deg	Longitude of OSO, deg	Albedo, %
March 8, 1962	Quito, Ecuador	−6	−75	23
March 9, 1962	Quito, Ecuador	5	−74	26
March 10, 1962	Ft. Myers, Florida	23	−86	12
March 11, 1962	Quito, Ecuador	−2	−78	23
March 11, 1962	Antofagasta, Chile	−22	−69	20
March 12, 1962	Quito, Ecuador	−5	−81	23
March 12, 1962	Antofagasta, Chile	−24	−71	27
March 13, 1962	Lima, Peru	−10	−80	17
March 13, 1962	Antofagasta, Chile	−27	−71	28
March 19, 1962	Antofagasta, Chile	−23	−73	38
April 3, 1962	Antofagasta, Chile	−26	−67	34
April 16, 1962	Ft. Myers, Fla.	27	−88	23
April 16, 1962	Ft. Myers, Fla.	32	−83	20
April 19, 1962	Ft. Myers, Fla.	32	−84	25
April 21, 1962	Ft. Myers, Fla.	30	−87	10
April 23, 1962	Ft. Myers, Fla.	25	−82	19
May 3, 1962	Quito, Ecuador	−1	−82	20

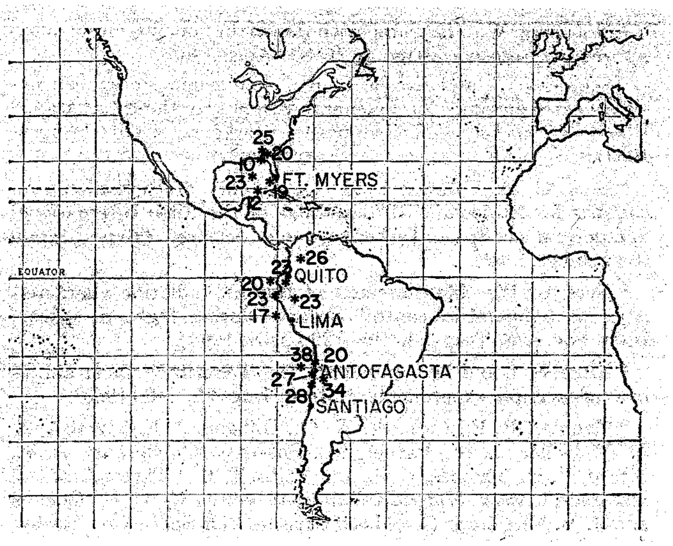

Fig. 7 **Albedo values deduced from OSO experimental data (values designated in percent).**

Albedo

Values of albedo were deduced from the data for the razor-blade reference surface by use of Eq. (6). Because solution of the equation requires knowledge or the assumption of earth radiation E, the average (0.47 ly/min) of the previously deduced values was employed. The values of albedo are presented graphically in Fig. 7, and in Table 2 as functions of date, latitude, longitude, and Minitrack station near which the satellite was located at the times of data acquisition.

Values of albedo deduced from OSO experimental data are plotted in Fig. 8 along with London's latitudinal averages and the experimental results from Tiros IV. It is interesting to note that all values fall within the range of 10 to 38%. Large variations in albedo detected by the OSO radiometer are not unexpected, since the sensor undoubtedly viewed a variety of meteorological conditions. Because of lack of sufficiently extensive meteorological observations at the times of data acquisition, correlation of the measurements with information on cloud cover was not possible. At lower latitudes, the OSO data are in somewhat general agreement with the Tiros IV results, which show an increase in albedo with decreasing latitude. At the other extreme, however, the OSO values decrease, whereas the Tiros IV and London's values increase with increasing latitude. The fact that the area viewed by the sensor contained a large percentage of water, which has low reflectance, may account in part for these results.

Uncertainty of Deduced Values

The accuracy of the OSO results was investigated by means of an uncertainty analysis applied to the various data utilized in their determination. Uncertainty intervals within which the individual variables are believed to fall, with odds of approximately 10:1, are tabulated in Tables 3 and 4. It might be noted that differences in values between the two tables result from the level of temperature measurement. The temperature measurements were most sensitive at high temperatures. As a result of application of Eqs. (10) and (12), the reported values of earth radiation and albedo are believed to be within approximately ± 0.04 ly/min and ± 0.10, respectively, of their true values. For example, this represents 50% of the magnitude of a reported albedo value of 20%. The extent of uncertainty in each case is indicated by the bars in Figs. 6 and 8. The order of magnitude of the uncertainties was not found to be due to any particular term, but to the many uncertainties involved.

The implications of the results of the analysis are not unique to the OSO-I experiment. Unfortunately, this experiment was not designed for radiometric determinations. As a result, the errors perhaps are larger than they would have been if the experiment had been designed for this purpose. Nevertheless, the resulting uncertainties are indicative of the general order of magnitude of errors that can be incurred. Consequently, differences in albedo- and earth-radiation values reported by various investigators and the variations recorded by OSO are probably not attributable solely to geographical and meteorological conditions. Rather, the differences may also result from measurement errors. It is therefore concluded that the inclusion of an uncertainty analysis is a necessary part of reporting radiometric measurements.

Table 3 Uncertainty values assigned to variables used for determining earth radiation

Variable	Uncertainty of variable
T	$\pm 1.5°$ K
$dT/d\theta$	$\pm 0.2°$ K/min
T_b	$\pm 1.5°$ K
ϵ	± 0.05
A	$\pm 0.01\ A$
wc	$\pm 0.05\ wc$
K	$\pm 0.05\ K$
F_E	$\pm 0.02\ F_E$

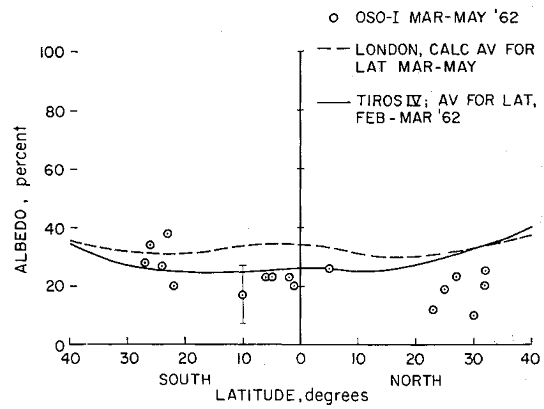

Fig. 8 **Comparative data for albedo.**

Concluding Remarks

Values of earth radiation and albedo were derived from an experiment on the first OSO. Values of earth radiation

Table 4 Uncertainty values assigned to variables used for determining albedo

Variable	Uncertainty of variable
T	$\pm 1°$ K
$dT/d\theta$	$\pm 0.15°$ K/min
T_b	$\pm 1°$ K
α_S/ϵ	± 0.04
α_S	± 0.03
A	$\pm 0.01\ A$
S	$\pm 0.02\ S$
E	± 0.05 ly/min
wc	$\pm 0.05\ wc$
K	$\pm 0.05\ K$
F_S	$\pm 0.01\ F_S$
F_E	$\pm 0.02\ F_E$
F_β	$\pm 0.05\ F_\beta$

ranged from 0.42 to 0.51 *ly*/min. Values of local albedo ranged from 10 to 38%.

An uncertainty analysis applied to the OSO-I data illustrates the difficulties involved in making accurate radiometric measurements. The principal problem is that a great many variables are involved in the measurements, each one contributing a possible error. Large uncertainties, therefore, can result. The results of this analysis strongly suggest the need for the inclusion of uncertainty analyses in the reporting of radiometric data.

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