Earth Albedo as Determined from Skylab Data

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Earth albedo calculated from Skylab flight data when correlated with latitude falls within the range of values obtained from previous investigations. The Skylab data ranged between latitudes of ±50°. Seasonal variations show higher values for the winter months and lower values for the summer months. Surface geometry and orbit altitude had little effect on the orbit averaged albedo which was a function of orbit inclination, solar declination, and beta angle. A range of values is presented as a function of orbit inclination.

Introduction

SUCCESSFUL spacecraft thermal design is dependent upon accurate determination of net energy transport across the vehicle control surfaces. External heat sources are significant contributors to the spacecraft energy balance. For near-Earth orbits the major external energy sources are solar radiation, earth emitted radiation, and Earth albedo radiation as shown in Fig. 1. Solar radiation is energy received directly from the sun, while Earth emitted radiation is energy received from the planet. Both are consequences of the respective bodies having an absolute temperature greater than zero. The sun is a significant contributor because of its high temperature and the Earth because of its proximity to the spacecraft. Earth albedo radiation is reflected solar energy from the Earth and is also influenced by the planet proximity. Albedo is defined as the ratio of radiation flux reflected from a given surface in all directions to the flux incident on the surface. It is with measurements of the Earth albedo derived from Skylab flight data that the present work is concerned.

Previous investigations[1-3] have shown that the Earth albedo is a function of latitude and season being principally influenced by such physical features as cloud cover, ice or snow cover, and type of underlying surface such as land or water. The bulk of the albedo measurements were determined with sensors specifically designed for that purpose. By contrast the present investigation was a by-product of unforseen circumstances affecting the physical configuration of the Skylab vehicle. A segment of the vehicle skin because of its surface properties and orientation was sensitized to Earth albedo. With the aid of a thermal math model, temperature data from the affected area was used to calculate Earth albedo. The results were correlated with latitude and season.

Skylab Configuration

The Orbital Workshop[4] portion of the Skylab utilized a thermal design consisting of a known structural heat leak controlled by insulation and radiation barriers in the vehicle sidewall. A thermally isolated, externally mounted meteoroid shield formed a radiation barrier, which limited heat transfer through the vehicle pressure wall. A low emissivity gold foil on the exterior surface of the pressure wall minimized the radiant interchange across the annulus formed by the pressure wall and meteoroid shield. During launch the meteoroid shield was lost, thus removing an integral part of the thermal control system.

After the failure of the meteoroid shield, the sidewall configuration consisted of goldize Kapton tape bonded to the exterior of the aluminum pressure wall. Behind the pressure wall was one inch of polyurethane foam insulation which was covered on the inside surface by a fire retardant liner. A cross section of the sidewall is shown in Fig. 2. Thermocouples installed on the exterior of the aluminum pressure wall[5] responded readily to variations in the external environment because the pressure wall was insulated from the vehicle interior, and because the solar absorptivity to emissivity ratio of the exterior gold surface was greater than 5.0.

Calculations to determine the optical properties of the gold foil on the tank wall exterior were made at selected times during the mission. Results of these studies[4] show a variation of ±10%. A nominal value for the α/ϵ ratio of the gold foil during the mission was 0.275/0.05. Variation in the α/ϵ ratio had the most significant effect in determining the orbit averaged albedo. The influence is shown in Fig. 3. Although the original configuration was insensitive to Earth albedo variations, the post launch configuration without the meteoroid shield exhibited the opposite behavior.

Albedo Radiation

An expression for the absorbed albedo radiation per unit area q_{albedo} averaged over n orbit points is given by

$$q_{\text{albedo}} = \frac{\alpha E_s}{360} \sum_{\theta=1}^{n} F_\theta a_\theta \Delta\theta \tag{1}$$

where E_s = solar constant; α = solar absorptivity of the surface; θ = orbit position; F_θ = geometry factor at orbit position θ; and a_θ = Earth albedo at orbit position θ. In general the albedo, a, varies with latitude and season. The spacecraft latitude, ϕ is a function of the orbit beta angle β defined as the angle between the orbit plane and the Earth-sun line, solar declination ψ, orbit inclination i and orbit position θ as shown in Fig. 4, where

$$\gamma = \mathrm{Sin}^{-1}\left[\frac{-\sin\beta + \sin\psi\cos i}{\cos\psi\sin i}\right] \tag{2}$$

$$\lambda = \mathrm{Tan}^{-1}\left[\frac{\cos i\sin\gamma\cos\psi + \sin i\sin\psi}{\cos\psi\cos\gamma}\right] \tag{3}$$

and

$$\phi = \mathrm{Sin}^{-1}\left[\sin i\sin(\lambda+\theta)\right] \tag{4}$$

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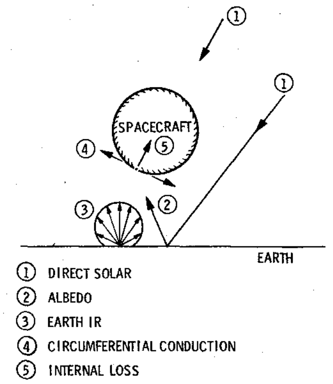

Fig. 1 Energy balance on vehicle sidewall.

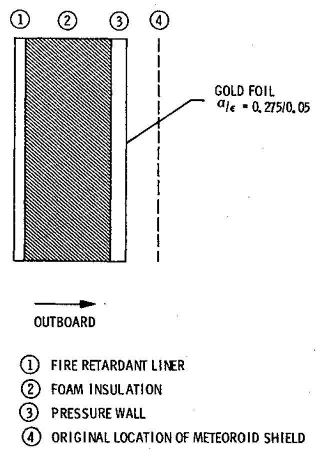

Fig. 2 Workshop sidewall construction.

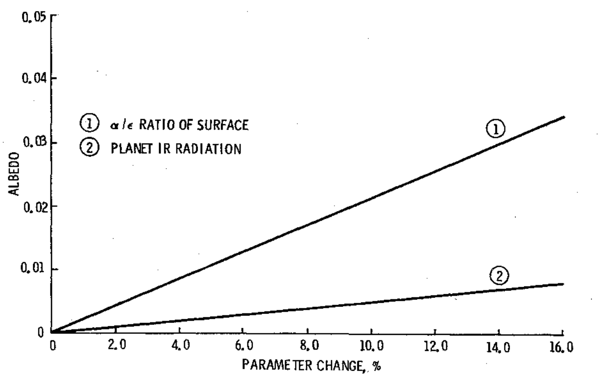

Fig. 3 Sensitivity of albedo to surface properties and planet IR radiation.

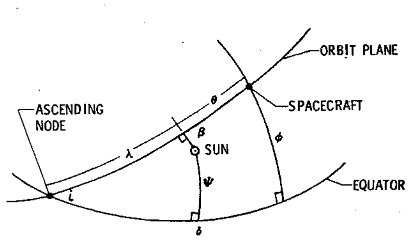

Fig. 4 Orbit geometry.

For a given altitude H and surface shape, the geometry factor, F is a function of β and θ. Equation (1) can be rewritten in general form as

$$q_{\text{albedo}_{i,\beta,\psi}} = \frac{\alpha E_s}{360} \sum_{\theta=1}^{n} F_{\beta,\theta} a_{\phi} \Delta\theta \tag{5}$$

It is convenient to define an average albedo $\bar{a}$ for the sunlit portion of the orbit which can be treated as a constant in an analysis. Such an average albedo can be defined for a particular orbit from the following expression

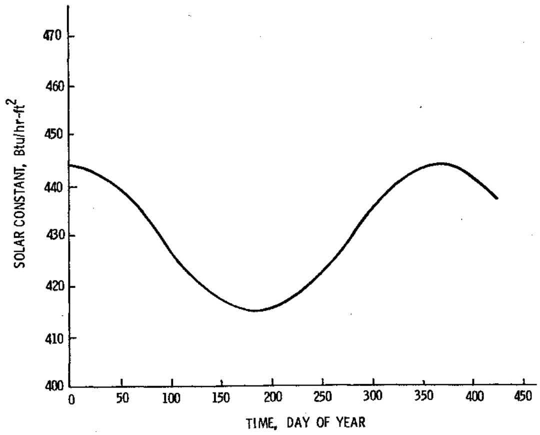

Fig. 5 Seasonal variation of solar constant.

$$q_{\text{albedo}} = \frac{E_s \alpha \bar{a}}{360} \sum_{\theta=1}^{n} F_{\theta} \Delta\theta \tag{6}$$

Equating Eq. (6) to Eq. (1) and solving for $\bar{a}$ gives

$$\bar{a} = \frac{\sum_{\theta=1}^{n} F_{\theta} a_{\theta} \Delta\theta}{\sum_{\theta=1}^{n} F_{\theta} \Delta\theta} \tag{7}$$

Since albedo, a is a function of latitude, ϕ Eq. (7) can be rewritten more generally as

$$\bar{a}_{i,\beta,\psi} = \frac{\sum_{\theta=1}^{n} F_{\beta,\theta} a_{\phi} \Delta\theta}{\sum_{\theta=1}^{n} F_{\beta,\theta} \Delta\theta} \tag{8}$$

Equation (5) was expanded into a system of linear simultaneous equations using the Skylab orbit parameters. Values of $\Delta\theta$ were chosen such that a_{ϕ} was the independent variable and the product $F_{\beta,\theta}\Delta\theta$ was the coefficient. β and ϕ were varied over the following ranges: $-50° \leq \beta \leq 50°$, and $-50° \leq \phi \leq 50°$. For the Skylab orbit parameters, $i = 50°$, $\psi = 0°$, and $H = 235$ n mi.

Values for $F_{\beta,\theta}$ were calculated for the orbit using a radiation analysis program.[6] The set of simultaneous equations was then solved for values of a_{ϕ} based on values of q_{albedo} obtained from the flight data.

Thermal Models

Thermal Analyzer

A thermal analyzer program using a finite difference solution[7] was used to compute values of q_{albedo} such that when imposed on the thermal network the resulting temperatures matched those obtained from the flight data. Data were collected at beta angle increments of 5° during both manned and unmanned phases. Although data were collected for all β angles encountered, because of accuracy limitations and the transient nature associated with the high beta angle periods, only data for $|\beta| \leq 50$ were used in the correlation. Accuracy limitations at high beta angles arose because the incidence angle of the Earth albedo radiation was large. Since the geometry factor, $F_{\beta,\theta}$ in Eq. (1) is proportional to the cosine of the incidence angle, the incident flux is reduced at high beta angles and changes in surface temperatures become correspondingly small in this region.

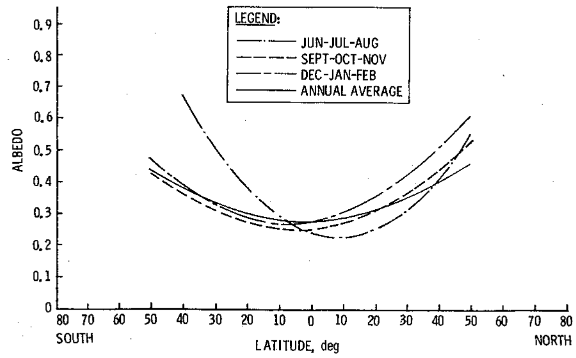

Fig. 6 Albedo as a function of latitude and season.

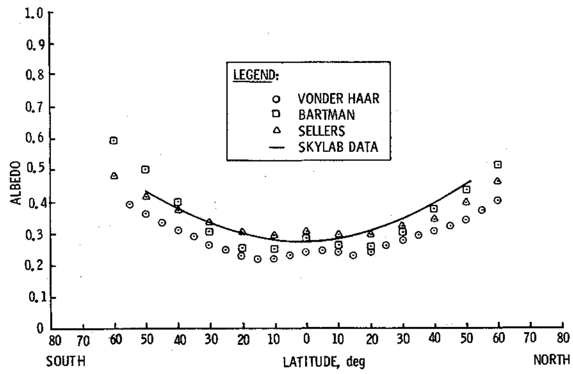

Fig. 7 Annual averaged albedo.

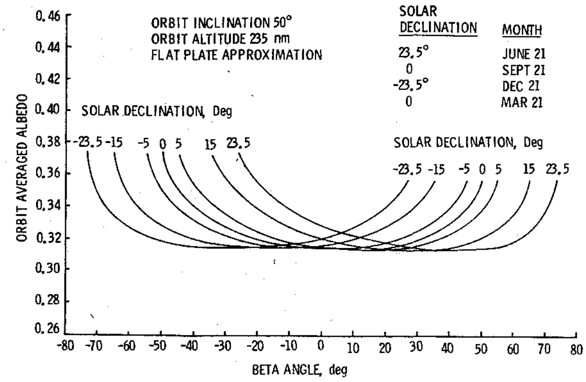

Fig. 8 Orbit averaged albedo for Skylab orbit based on the annual average data from figure 7.

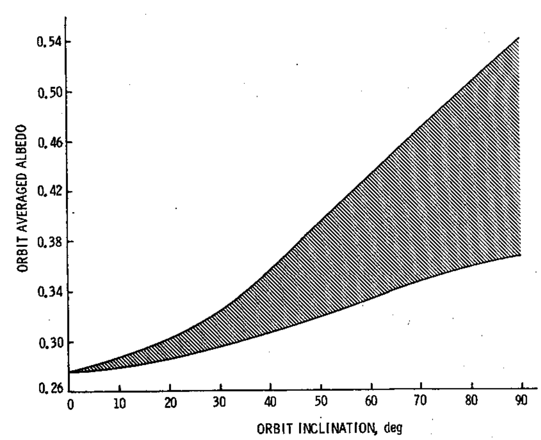

Fig. 9 Variation of orbit averaged albedo based on Skylab data.

Radiation and External Environment Program

The orbit environments were generated[6] for a right circular semicylinder. The external heat flux was divided into albedo and planet radiation components. Because of the orientation of the surface, there was no direct solar radiation. The albedo component, q_{albedo}, was then varied as required to obtain matching temperatures in the thermal analyzer. Geometry factors from Eq. (1) were calculated in orbital increments of 15° up to 90° on either side of the orbit noon.

A nominal value for the solar constant of 429.0 BTU/hr-ft^2 was used with a seasonal variation based on the Earth-sun distance.[8] The values of the solar constant used in the analysis are shown in Fig. 5. These values were also used in the Skylab thermal analysis giving successful correlations[4] with the flight performance.

Skin temperatures on the antisun side of the Workshop were also influenced by Earth emitted radiation in the infrared portion of the electromagnetic spectrum. However, because of the high α/ϵ ratio of the gold coating, the energy contribution at the noon point in the orbit from Earth albedo radiation was ten times greater than from Earth emitted radiation. Since the planetary contribution was small, a nominal constant value of the planet flux of 75.4 BTU/hr-ft^2 was assumed.[9] The influence of the variation in the planet flux on the orbit averaged albedo is shown in Fig. 3.

The principal Skylab orientation was solar inertial thereby fixing the vehicle's attitude with respect to the sun. Brief excursions away from solar inertial were frequently made during the mission to perform science experiments, however, these periods were easily detected in the flight data and their influence on the results was minimized by avoiding these periods when collecting data samples.

Results

Albedo

The albedo results are shown in Fig. 6 for June through August, September through November, December through February, and the average. There were no data available for the March through May period. At low latitudes the lowest values of albedo were found in the summer months and the highest values in the winter months. These trends are in agreement with earlier investigations.[9] The other predominant feature of the results is the general shape of the curve with the lower values of albedo occurring in the vicinity of the equator and the highest values occurring near the poles. The trend is consistent with the existence of increased cloud cover in the middle latitudes and extensive snow and ice cover at the underlying surface at higher latitudes. Both of these characteristics along with a decreasing sun angle increase the albedo with increasing distance from the equator.

Figure 7 shows a comparison between results of previous investigators by Vonder Haar,[3] Bartman,[1] Sellers,[2] and the present data using the annual average. Although the present correlation includes data from only nine months of the year it is presented for comparison with previous investigations. The previous investigations show a small rise in albedo near the equator. There were a total of 182 data points taken at six hour intervals during the Skylab Mission. Because of the small number of data points, the best correlation was obtained with second and fourth order polynomials which did not indicate perturbations in the data in the vicinity of the equator.

Orbit Averaged Albedo

For most spacecraft thermal analyses variations of Earth albedo from near-Earth orbits do not significantly affect the thermal balance of the spacecraft because either the thermal time constant is large compared with the orbital period or because the selected surface properties minimize the contribution of albedo radiation in comparison to other sinks and sources of energy. However, the total albedo flux incident to the spacecraft during an orbit is usually a significant term that requires consideration.

Equation (8) can be used to calculate an orbit averaged albedo for any surface geometry and orbit using the albedo data from Fig. 6. Evaluation of the geometry factor, $F_{\beta,\theta}$ generally requires the use of a thermal radiation analyzer program[6] or tabulations for selected simple geometries[10] and is a function of the spacecraft configuration and the orbit altitude, H as well as β and θ. Figure 8 presents the orbit averaged albedo for the 235 n mi. Skylab orbit. The data are presented as a function of solar declination and beta angle for a 50° inclination. Note that the 50° inclination limits the beta angle range to ±73.5°.

The maximum variation of the orbit averaged albedo from Fig. 8 is 22.5% which for a spacecraft configuration that is sensitive to albedo, as was Skylab, is a significant variation. While the albedo, a_ϕ is only a function of latitude and season, the orbit averaged albedo, $\bar{a}$ defined in Eq. (8) is a function of the spacecraft orbit parameters, i, β, and ψ; the orbit altitude; and the surface geometry. This dependence results from the geometry factor, $F_{\beta,\theta}$ in the right side of Eq. (8). As expected studies showed that orbit averaged albedo was insensitive to changes in surface geometry and orbit altitude. Surface geometries consisting of a flat plate, a sphere, and a right circular cylinder were compared, as well as altitudes ranging between 100 and 10,000 n mi. The change in orbit averaged albedo resulting from these variations was less than 2%. Therefore, the orbit averaged albedo remained only a function of the orbit parameters; i, β, and ψ. Figure 9 shows the variation of orbit averaged albedo as a function of orbit inclination. The range of orbit averaged albedo at each inclination results from variations in β and ψ. Since the orbit inclination determines the latitude range the variation in orbit averaged albedo is proportional to orbit inclination as shown in Fig. 9. In general the higher values of orbit averaged albedo in Fig. 9 correspond to the higher beta angles and conversely. Since the importance of albedo to the energy balance of the spacecraft decreases with increasing $|\beta|$ the higher orbit averaged albedo values shown in Fig. 9 are of lesser importance in most spacecraft analyses than the lower values. This inverse dependence results from the relationship between geometry factor, F_θ and beta angle, β.

Conclusions

Earth albedo calculated from Skylab flight data when correlated with latitude falls within the range of albedo obtained from previous investigations.[1,2,3] The Skylab data ranged between latitudes of ±50°. The data were also correlated as a function of season with the exception of the March-April-May period for which there were no data available. The seasonal data show higher values for the winter months and lower values for the summer months as expected.

A method was presented to calculate the orbit averaged albedo as a function of orbit inclination, beta angle, solar declination, surface geometry, and orbit altitude. The method was used to calculate Skylab orbit averaged albedo data for the 235 n mi altitude, 50° inclination Skylab orbit. It was found that surface geometry and orbit altitude had little influence on the orbit averaged albedo which remained primarily a function of orbit inclination, solar declination and beta angle. A range of orbit averaged albedo was presented as a function of orbit inclination.

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