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Guidelines for the Selection of Near-Earth Thermal Environment Parameters for Spacecraft Design

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October 2001

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1.0 INTRODUCTION

In 1992 the natural environment thermal environment parameters used in the Space Station program came under review. These were basically the same parameters which had been used for many years for a variety of low Earth orbit applications including the Space Shuttle. However, design difficulties with both "hot case" and "cold case" requirements on various subsystems caused a reevaluation of the natural environment specification. By this time a new and extensive data base had become available to the scientific community as a result of the Earth Radiation Budget Experiment.[1,2,3] From ERBE, 28 monthly data sets of 16-second resolution wide field data were obtained and analyzed to produce a new set of environmental parameters. This set was incorporated into the Space Station Program[4] and additionally documented in NASA TM 4527.[5]

This updated environment definition provides more detailed statistical description of the variations of the thermal environment than previously was available. Moreover, greater use of lightweight structures sensitive to rapid thermal fluctuations greatly increased the importance of this definition. Numerous questions arose concurrently about how to best interpret and apply the new information. These guidelines and a companion document, "Simple Thermal Environment Model" (STEM),[6] were developed to aid in selecting environment parameters that most appropriately characterize the thermal environment. In the process, portions of the original analysis were repeated and extended, leading to corrections and improvements in the summary results.

2.0 SCOPE

The intent of this document is to provide recommendations on the selection of natural thermal environment parameters for use in design analysis of spaceborne systems. The recommendations are based on analysis of data from the Earth Radiation Budget Experiment. These results provide a comprehensive and accurate statistical picture of the thermal environment encountered in low Earth orbit (LEO).

3.0 FUNDAMENTAL THERMAL ENVIRONMENT PARAMETERS

Space vehicles in Earth orbit receive radiant thermal energy from three sources and reflect or radiate it to the cold sink of space. The three primary sources are the incoming solar radiation, Earth-reflected solar energy (albedo radiation), and outgoing longwave radiation emitted by the Earth and atmosphere (OLR). If one considers the Earth and its atmosphere as a whole and averages over long time periods, the incoming solar energy and outgoing longwave radiant energy are essentially in balance; the Earth/atmosphere is very nearly in radiative equilibrium with the Sun. However, it is not in balance everywhere on the globe and important variations exist with respect to local time, geography, and atmospheric conditions. A space vehicle's motion with respect to the Earth results in its viewing only a "swath" across the full global thermal profile. Hence, the vehicle sees these variations as functions of time and responds in accordance with the thermal time constants of the hardware systems.

3.1 Solar Constant

The direct solar flux is the greatest source of heating for most spacecraft. The mean value of this solar flux at mean Earth-Sun distance is termed the "solar constant". Specifically, the solar constant is defined as the radiation that falls on a unit area of surface normal to the line from the Sun, per unit time and outside of the atmosphere, at one astronomical unit (mean Earth – Sun distance). However, as seen by an Earth-orbiting spacecraft the incoming solar flux is not quite constant; two factors influence its variability. First, the amount of radiant energy emitted by the Sun is known to vary slightly throughout the 11-year solar cycle. The exact amount differs from cycle to cycle but is estimated to be only a fraction of a percent. Second, the slightly elliptical orbit of the Earth about the Sun results in a variation in the solar flux incident on the Earth or upon an Earth orbiting spacecraft. This ± 1.7 percent departure from the mean distance leads to about a ± 3.4 percent difference in radiation. That is, a few days following winter solstice 3.4 percent more solar energy falls on a unit area normal to the line from the Sun at the outside of the atmosphere; just after summer solstice the amount is 3.4 percent less. The solar constant recommended in this document corresponds to the value recommended by the World Radiation Center (WRC) in Davos, Switzerland, and is based on a summary of eight measurements made from 1969 to 1980.[7,8]

Hot Case: $S_{hot} = 1414\ W/m^2$.

Median Case: $S_o = 1367\ W/m^2$ = the solar constant.

Cold Case: $S_{cold} = 1322\ W/m^2$.

This variation from median to hot or cold case covers the Earth-Sun distance variation. An additional ± 5 W/m^2 could be added (subtracted) to account for measurement uncertainties and solar cycle variations, but is not included in the above values.

3.2 Albedo

The fraction of incident solar energy reflected (or scattered) by a planet back into space is termed the albedo. Values typically are expressed as a fraction or percent. For spacecraft in low Earth orbit and in this report, the term is more precisely defined as the "local bolometric" albedo. Bolometric implies wavelength independence, i.e., the albedo representing the integrated short wavelength band. Local because it is characteristic of only a small portion of the planetary surface, the portion viewed by a spacecraft close to Earth. Values presented in this report are derived from wide field measurements made by the ERBS satellite at 610-km altitude and the NOAA 9 and 10 satellites at, respectively, 849 and 815 km. Altitude dependence has been removed by transforming the data to a standard surface, the "top of atmosphere" ≡ 30 km above the Earth's surface.[9] "Top of atmosphere" represents the virtual source of the albedo radiation and the outgoing long wave radiation. To evaluate the albedo radiation for any satellite at a known altitude the thermal analyst simply assumes the source is at this level, i.e., Earth radius + 30 km, not Earth surface. Obviously, a spacecraft only receives reflected (albedo) radiation when a portion of the Earth or atmosphere seen by the spacecraft is sunlit. Albedo radiation has approximately the same spectral shape as the Sun's spectrum which approximates a blackbody with a characteristic temperature of 5777K.

Albedo is highly variable across the globe and is dependent on the distribution of reflective properties of the surface and the amount and type of cloud cover. Reflectivity increases with increased cloud cover. Continental areas generally have higher albedo values than ocean areas. Because of snow and ice cover, decreasing solar elevation angle, and increasing cloud cover, albedo tends to increase with latitude if viewed on a large scale. From the spacecraft design perspective, the most important systematic albedo variation is with solar zenith angle which, when averages are used, depends on the spacecraft's beta angle. Care must be taken to correctly account for this effect, especially near the terminator. (See paragraph 3.4 on Geometric Factors)

3.3 Outgoing Longwave Radiation

In addition to direct solar and reflected (albedo) solar radiation, the third primary component of a spacecraft's thermal environment is the outgoing longwave radiation (OLR) emitted by the Earth itself. This Earth emitted thermal radiation is a combination of radiation emitted in infrared wavelength bands by atmospheric gases and radiation emitted by the Earth's surface and cloud tops but is partially absorbed in the atmosphere. Thus, the spectral distribution is somewhat complex. For the purpose of spacecraft thermal analysis, however, it is generally sufficient to assume a graybody spectrum corresponding to a temperature in the 250 to 300K range.

OLR is not constant over the globe but the localized variations are much less severe than for albedo. Outgoing longwave radiation is principally influenced by the temperature of the Earth's surface and the amount of cloud cover. A warmer region of the Earth's surface emits more radiation than a colder area. On a large scale, highest values of OLR occur in tropical and desert regions (regions of the globe receiving the maximum solar heating) and decrease with latitude. Increasing cloud cover tends to lower OLR because cloud tops are cold and clouds effectively block upwelling radiation from the Earth's warmer surface below.

The diurnal effects on OLR as experienced by a satellite were studied in this analysis. For low inclination orbits (< 60 degrees), inclusion or exclusion of the nighttime data and changes in solar zenith angle cutoff made no significant difference in the net OLR distribution functions. Thus, for these orbits no special accounting for diurnal effects is needed. This is not true, however, for high inclination orbits. Passage over the nighttime and lighted but high solar zenith angle polar regions contributes significantly to the low (cold case) OLR populations. This effect was overlooked in earlier studies which only checked diurnal variations at low inclination.[4,5]

3.4 Geometric Factors

3.4.1 Orbital Altitude and "Top of Atmosphere"

The OLR and albedo radiation received on a satellite surface diminishes as its altitude increases, i.e., as satellite moves away from the source. This effect is accounted for as part of the "view factor" in thermal calculations. Derived OLR and albedo data measurements from satellites at several altitudes (610, 815, and 849 km) were corrected to the apparent source surface (30 km above Earth surface) or "top of atmosphere." Thus, in applying this data the analyst should assume a source at R_e + 30 km, where R_e is the Earth radius, 6378.140 km equatorial. Failure to do so leads to a slight underestimate of the OLR and albedo radiation by a factor of

$$F_a = (Re + A)^2/(Re + 30\text{ km} + A)^2$$

where A is the orbital altitude. The error is quite small ($F_a = 0.9911$ at A = 300 km) and decreases (F_a approaches one) with increased altitude.

3.4.2 Orbital Inclination, Beta Angle, and Solar Zenith Angle (SZA)

Orbit "inclination" refers to the angle between the Earth's polar vector and the vector normal to the satellite's orbit plane. Thus, an equatorial orbit has an inclination of zero; a perfect polar orbit has an inclination of 90 degrees. The orbital "beta" angle is the minimum angle between the satellite's orbit plane (the closest to a Sun-pointing vector possible in the plane) and the Sun-Earth vector. The beta angle can be thought of as the solar elevation angle with respect to the orbit plane. The angle between the Sun-Earth vector and the Earth-satellite vector is termed the "solar zenith" angle. The solar zenith angle is zero when the Sun is directly above the satellite (Earth–satellite–Sun in a straight line) and 90 degrees when a satellite is directly over the terminator. Except for special Sun synchronous cases, the SZA varies rapidly over an orbit; the minimum solar zenith angle is equal to the absolute value of the beta angle.

4.0 TECHNICAL BASIS FOR RECOMMENDED GUIDELINES

As noted in the introduction, this work originally began in the early 1990's on behalf of the Space Station Freedom Program and in 1994 led to the improved thermal environment definitions for the International Space Station[4] and for general low Earth orbits.[5] From experience applying these results to various programs it became clear that additional clarification of the environment definition and simplified and improved guidelines were needed to assure that the engineering community could fully and efficiently use the information. Thus, portions of the original analysis were repeated, extended, and resulted in a few corrections and improvements. These results are summarized in this report and discussed in detail in the "Simple Thermal Environment Model."[6]

4.1 The Earth Radiation Budget Experiment

As in prior studies for Space Station, data used to define the thermal environment were collected by the Earth Radiation Budget Experiment (ERBE).[1,2,3] ERBE is a multisatellite experiment with the primary objective of global data collecting such Earth radiation budget parameters as incident sunlight, reflected sunlight (albedo) and outgoing longwave radiation (OLR). This experiment was selected because of its thorough coverage and high quality data. The experiment consisted of three satellites: the low inclination Earth Radiation Budget Satellite (ERBS) and two NOAA Sun-synchronous satellites. The data used here are from the active cavity, flat plate radiometers in the fixed, nonscanning, wide field-of-view mode. This type instrument was chosen because it directly measures the albedo and OLR as they would be received by a spacecraft surface. The available, separated data sets are: daily averaged values (S-4), hourly averaged values (S-10), and raw 16-second instrument measurements along the ERBS or NOAA satellite trajectory (S-7). The S-4 and S10 data products were inappropriate for this application becase the averaging times are too long compared to the thermal time constant of typical space systems. Therefore, the design criteria presented below are based on 28 files, representing one month of 16-second data each of S-7 data obtained directly form the ERBE Program Office. The measurements, made from November 1984 through July 1987, represented all seasons well.

4.2 Details of Application

4.2.1 Albedo Correction For Solar Zenith Angle

Often in scientific studies of the Earth and Earth radiation balance results are based on albedo data associated with a restricted range of solar zenith angle (SZA) centered about zero for improved accuracy. In these cases and to a first approximation, albedo may be assumed to be independent of SZA, that is, the scattering is "Lambertian" or equal in all directions. This approximation was also assumed in the past for most spacecraft engineering applications even though it is less appropriate for this application. For large SZA the Earth reflects radiation more strongly in the forward direction than to the sides or backward. The effect on albedo can be significant; thus, ERBE data quality and the capability of current engineering analysis methods warrant an improved approach. For low and medium inclination orbits which see a wide range and rapidly changing SZA, the correction is most significant for subsystems with short thermal time constants (less than 10 minutes). For certain Sun-synchronous orbits (those flying near the terminator) the solar zenith angle is always relatively large and the correction is important to even orbit-average albedos.

Treatment of this topic in the scientific literature is generally "scene specific", e.g., it depends on geographic features in the field of view, data generally not available to the design engineer. Also, the algorithms tested did not fully remove the zenith angle dependence from this data set. Therefore, a zenith angle correction was derived specific for this data set in a manner specifically tuned to the analysis tools most commonly used for engineering analysis: TRASYS, Thermal Desktop, and TSS. Used with this correction and the proper parameters for the ERBS and NOAA satellites, these tools should accurately reproduce the measurements.

The correction term, derived from four months of data restricted to the –30 to +30 latitude band, was verified by testing another four months of data to wider latitude bands. This removes the solar zenith angle dependence to within ± 0.04. The correction is

$$\text{Albedo(SZA)} = \text{Albedo(SZA} = 0) + \text{Correction}$$

$$\text{Correction} = [C_4(\text{SZA})^4 + C_3(\text{SZA})^3 + C_2(\text{SZA})^2 + C_1(\text{SZA})]$$

where SZA is the Solar Zenith Angle in degrees and the albedo is expressed as a fraction.

$C_4 = +4.9115\text{ E-}9$,
$C_3 = +6.0372\text{ E-}8$,
$C_2 = -2.1793\text{ E-}5$,
$C_1 = +1.3798\text{ E-}3$.

Figure 4.2.1-1 illustrates the albedo correction term as a function of solar zenith angle. To evaluate the albedo at a specific SZA, this term must be added to the SZR = 0 albedo values presented in the tables. Correction terms to obtain orbital average albedo values are provided in Table 4.2.1-1.

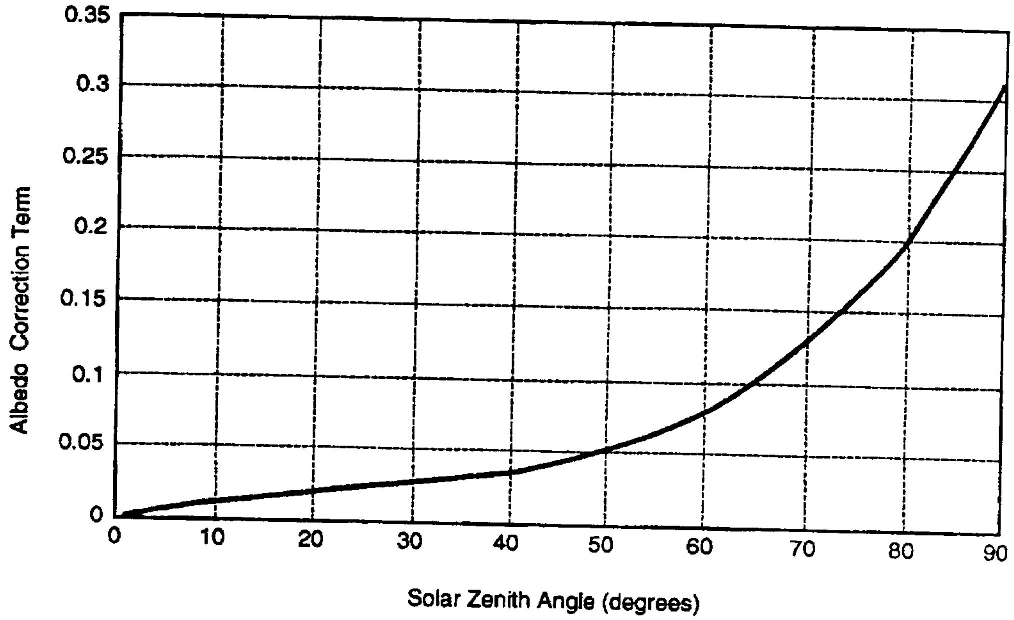

Figure 4.2.1-1. Albedo correction term, c(SZA), as a function of solar zenith angle.

Table 4.2.1-1. Values of orbital-average albedo correction term, <c>.[6] Add this correction to the SZA = 0 albedo value. For other than full-orbit averages see Table A-2 in the Appendix.

Orbital Beta Angle (°)	Orbital Average Albedo Correction <c>
0	0.04
10	0.04
20	0.05
30	0.06
40	0.07
50	0.09
60	0.12
70	0.16
80	0.22
90	0.31

4.2.2 Temporal and Orbital Variations

For any satellite system, different portions of the hardware have different thermal response times, ranging from a few minutes to hours. Conceptually the thermal performance of these systems could be analyzed by inputting either a real or simulated time series of albedo and OLR values, solar exposure, and internal heat sources. All have a time resolution finer than the shortest system time constant. In practice, however, the usual design objective is only to assure the system remains within selected operational temperature range, not to model its detailed temporal variability. Thus, high resolution time series analysis is not warranted. The problem can be solved with adequate accuracy by modeling only the primary orbital variations (light – dark cycles) and assuming extreme albedo and OLR values appropriate to the thermal time constant(s) of the system. The systematic dependence of albedo on solar zenith angle, discussed above, must also be considered, especially for short time-constant systems.

To provide appropriate values of extreme albedo and OLR for this analysis approach, running means of the albedo and OLR variations, transformed to top of the atmosphere (30 km) to remove the altitude dependence, were derived from the ERBE data sets. The results are latitude dependent, so the choice of appropriate values for a particular mission depends on the orbital inclination of the satellite in question. Since the satellite inclination seldom equals the inclination of the ERBE satellites, approximation is required to deal with this miss-match. Fortunately, the latitude dependence is sufficiently weak that adequate resolution is obtained by dividing the possible range of inclinations into three regions and deriving a single set of albedo and OLR extremes for each region. The inclination ranges selected are 0 to 30 degrees, >30 to 60 degrees, and > 60 degrees. Running averages are presented for times ranging from a few seconds to 24 hours. Averaging periods to 10 days failed to show substantial variation from the 24- hour results.

A series of subtle choices must be made in reducing the data and calculating the running means and the "best" choice varies depending on the application, inclination range, averaging time, and other factors. Four primary choices are listed below with the rationale for selection. In each case the ultimate use of the data – realistic estimation of the limits of temperature excursions in satellite systems – was the primary choice determinant.

- Spread in the albedo data, even with the SZA correction applied, increases for SZA values above 65 degrees, and there also seems to be a small data anomaly in this region. Eliminating this data reduces the total amount of data considered, but retaining it leads to an unrealistically broad albedo distribution applied at smaller SZA values where the albedo radiation is relatively important. Thus, the albedo data for SZA > 65 degrees was not used. The most important effect of reducing the amount of data – assuring that the Earth's dark side and polar regions are represented – was ameliorated by accounting for all the OLR data, independent of SZA value, in the STEM model and the design point recommendations.

- Comparison of the total OLR data set with the "paired" OLR subset, i.e., data accompanied by albedo data not excluded by the 65-degree SZA cutoff, shows a significant difference in the OLR distributions for high inclinations. As illustrated by Figure 4.2.2-1, the difference between the paired and unpaired data sets is negligible for the low inclination orbits. For the middle (30 to 60 degrees) inclinations the difference is becoming obvious but hardly significant for engineering applications. The mean differs by only 8 W/m^2 between the unpaired and paired 60-degrees data and, more importantly, the upper and lower limits are very similar and also very similar to the 30-degree data limits. The separation is more significant at 90 degrees inclinations. As Figure 4.2.2-2 illustrates, in this case the unpaired data set is about three times the size of the paired set. A large fraction of the data is excluded because much of the time the SZA is greater than 65 degrees over polar regions. More problematic is the substantial difference in the extreme cold-side values which, clearly, must be accounted for in the thermal design process.

- A similar issue is whether portions of the NOAA –9 and –10 data taken over low latitudes should be included with the ERBS satellite data to derive the low inclination extremes, or would the ERBS data alone be sufficient. The NOAA satellites were in Sun-synchronous orbits. Hence, inclusion of NOAA data biases the sample to the local solar time of their orbits and makes a small but noticeable difference in the hot OLR extremes. Because we are looking for extremes and these values could clearly be encountered in other low inclination orbits, the NOAA satellite data were included.

- Within a data set a correction for differences in dwell time over the various latitudes can be made. This small correction, made in all cases, only partially accounts for the differences expected from collecting data in one orbit and flying a satellite in another.

4.2.3 Engineering "Worst Case" Values

For critical applications the designer generally likes to select environment design points associated with some defined risk of occurrence during the mission lifetime. For example, he might select a design point associated with a five percent (or 1 percent or 0.01 percent… any reasonable value for the particular application) probability of being encountered during the design life of the system. Unfortunately, this type information cannot be derived from the limited data set available for this study. The required data set would cover a very long time period compared to the mission design life. So long that multiple independent samples, each the duration of the design life, could be drawn from the data set. A distribution function can then be formed of the extreme values encountered in each draw. In this work 28 monthly data sets drawn from a 33-month period were studied; 10 months were sampled twice by two separate satellites. Typical mission design lifetimes are usually one to 10 years. This data set is large enough to provide only a distribution of extremes for mission lifetimes of about one week or less. Thus, this data resource is limited to a

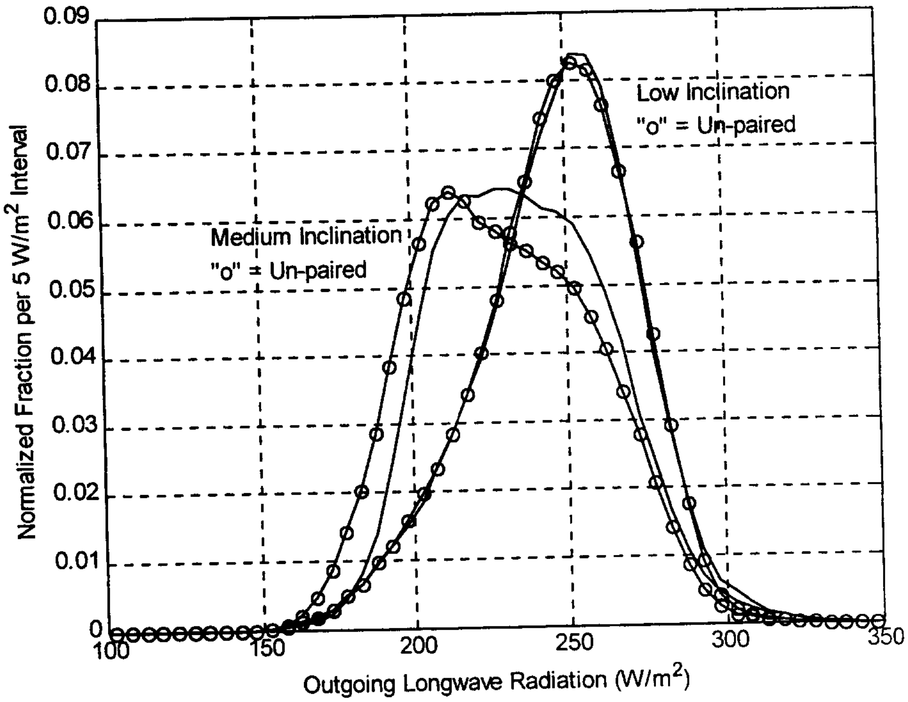

Figure 4.2.2-1. OLR Distributions for Low Inclination (≤ 30°) and Medium Inclination (30° to ≤ 60°) Orbits, 128-second Averaged Paired and Unpaired Data.

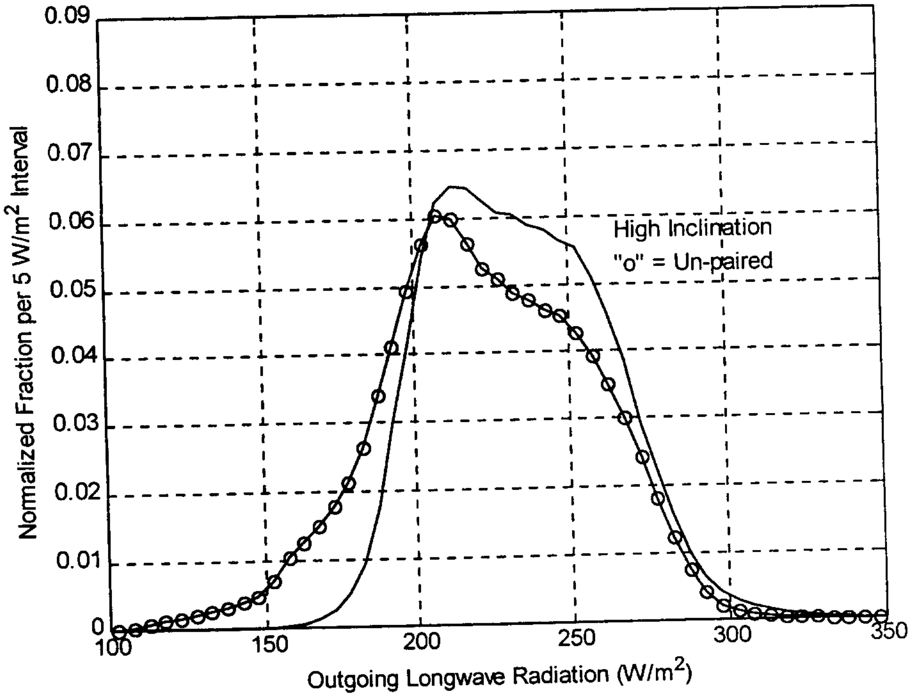

Figure 4.2.2-2. OLR Distributions for High Inclination (≥ 60°) Orbits, 128-second Averaged Paired and Unpaired Data.

selection of design point recommendations of expected extremes of the distributions (one for each system time constant – averaging time) of the total data. These "worst case" values are appropriate for "critical" applications, i.e., situations where the temperature limit is not to be exceeded. Use should be coupled with a design margin selected considering the application, level of confidence in the design analysis, and comparison of mission life to duration of database.

For noncritical applications, i.e., applications where the design limit may be exceeded a certain fraction of the time, less extreme environmental parameters based on the information provided in the appendix may be selected. Note: the percentiles indicated in the appendix represent the distributions from this single data set. Thus, they are to be associated with the fraction of time the values are expected to be exceeded; not the probability that they will be exceeded over a mission lifetime.

Selection of the extremes of these distributions to define "worst case" engineering minima and maxima involves an arbitrary process of deciding where to cut the tails of the distributions. As with any data set of this type, the larger the data set the more extreme the values that appear in the distribution tails. We have generally selected the 0.04 and 99.96 percentile values (equivalent to about ±3.3 σ if a Gaussian distribution) as "engineering worst case" points for practical applications. One point in 2500 is above this upper limit and one point is below this lower limit. OLR values in the tails of the distributions reached 20 to 25 W m^{-2} beyond these percentile values for the 16- and 128-second running mean data, and about 5 W m^{-2} for the 30-minute running means. At longer averaging times the number of independent data points diminishes to less than 2500 and collapses the tails. The interpolated 0.04 or 99.96th value may actually lie slightly outside the minimum (or maximum) value observed. In these cases the extreme observed value was selected. For the long averaging times there is usually about 5 W m^{-2} difference between the first (or 99th) percentile values, extremes of the data set, and the interpolated 0.04 (or 99.96th). Likewise, the albedo data tends to show the same characteristics on the hot side of the distributions. The albedo data reaches 0.04 to 0.08 above the engineering values for the shortest averaging times and less for the longer average data. On the cold side of the albedo distribution the cutoff is naturally sharp.

Once an engineering extreme value has been identified, either OLR or albedo, the next step is to determine the proper value of the other parameter used to form a pair. As illustrated by the contour plots of 128-second running mean paired-data distributions (Figures 4.2.3-1 to –3) the albedo and OLR data are partially correlated. Low OLR values tend to be paired with high albedos, high OLR values tend to be paired with low to moderate albedos. To select an appropriate albedo to pair with the extreme hot OLR, for example, we started with paired data sorted into bins ranked by both OLR and albedo value. The highest OLR value bins were selected until at least 0.04 percent of the data set is accumulated; the associated albedo values were then averaged to find the match for the OLR "engineering maximum" pair. The same process is used to find the engineering minimum OLR, high and low albedo cases.

From the spacecraft perspective, however, what proves to be the extreme hot or cold case for a particular system depends on the emissivity of the spacecraft surfaces and its absorptivity for solar radiation. Depending on the ratio between these parameters the extreme spacecraft temperatures may be associated with extreme OLR cases, extreme albedo cases, or some intermediate "combined" case where both OLR and albedo run high (or low) together but neither is near its individual extreme. To provide hot and cold combined extremes, points where normalized variates for albedo and OLR are equal were determined and the 0.04 and 99.96 percentile points from this subset were identified to provide the cold and hot combined extremes. A normalized variate is the deviation from the mean value divided by the standard deviation of the distribution, i.e., $x_N = (x-x_m)/\sigma_x$ where x_N is the normalized variate, x_m is the mean of x in the distribution, and σ_x is the standard deviation. Basically, take the distributions of two variables, OLR and albedo, (illustrated in Figures 4.2.3–1, –2, –3) select the subset defined by $OLR_N = ALB_N$, and find the 0.04 and 99.96 percentile points in the tails. The resulting values for engineering extreme cases of albedo and OLR are given in Tables 4.2.3-1 through -3 for low, medium, and high inclination orbits. These tables provide values of engineering extreme albedo and OLR for various averaging times (time constants) and extreme types (extreme albedo case, extreme OLR case, and extreme "combined" case).

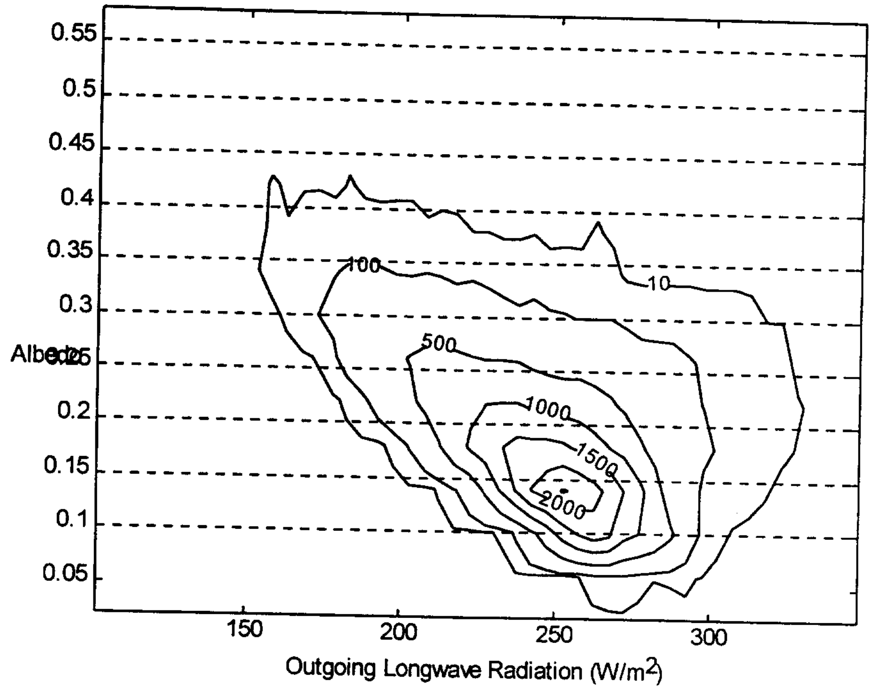

Figure 4.2.3-1. Albedo – OLR Correlation for Low Inclination Orbits, 128-second Averaged Data. Contour intervals indicate relative frequency of occurrence.

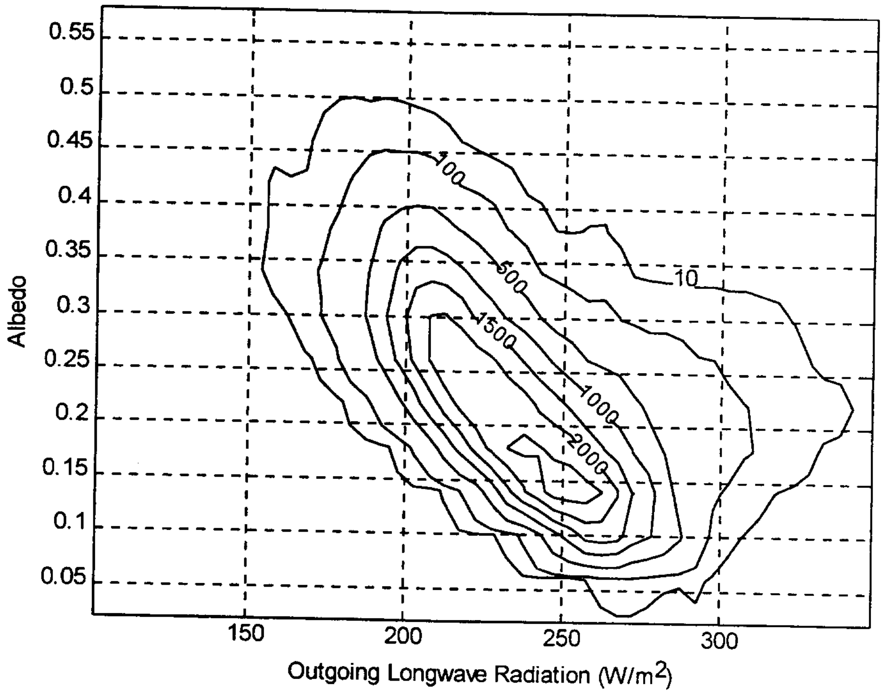

Figure 4.2.3-2. Albedo – OLR Correlation for Medium Inclination Orbits, 128-second Averaged Data. Contour intervals indicate relative frequency of occurrence.

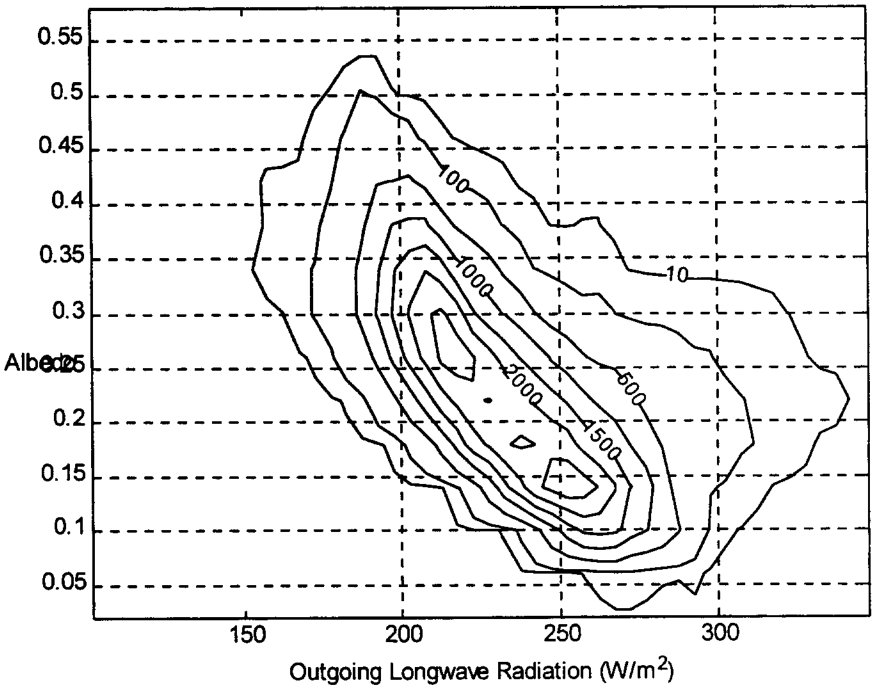

Figure 4.2.3-3. Albedo – OLR Correlation for High Inclination Orbits, 128-second Averaged Data. Contour intervals indicate relative frequency of occurrence.

Table 4.2.3-1. Engineering Extreme Cases for Low Inclination Orbits

Albedo and OLR values are referenced to the "top of the atmosphere", R_E + 30 km.

	COLD CASES		
Averaging Time	**Minimum Albedo** Alb ⇔ OLR (W/m^2)	**Combined Minimum** Alb ⇔ OLR (W/m^2)	**Minimum OLR** Alb ⇔ OLR (W/m^2)
16 second	0.06 ⇔ 273	0.13 ⇔ 225	0.40 ⇔ 150
128 second	0.06 ⇔ 273	0.13 ⇔ 226	0.38 ⇔ 154
896 second	0.07 ⇔ 265	0.14 ⇔ 227	0.33 ⇔ 173
30 minute	0.08 ⇔ 261	0.14 ⇔ 228	0.30 ⇔ 188
90 minute	0.11 ⇔ 258	0.14 ⇔ 228	0.25 ⇔ 206
6 hour	0.14 ⇔ 245	0.16 ⇔ 232	0.19 ⇔ 224
24 hour	0.16 ⇔ 240	0.16 ⇔ 235	0.18 ⇔ 230
	HOT CASES		
Averaging Time	**Maximum Albedo** Alb ⇔ OLR (W/m^2)	**Combined Maximum** Alb ⇔ OLR (W/m^2)	**Maximum OLR** Alb ⇔ OLR (W/m^2)
16 second	0.43 ⇔ 182	0.30 ⇔ 298	0.22 ⇔ 331
128 second	0.42 ⇔ 181	0.29 ⇔ 295	0.22 ⇔ 326
896 second	0.37 ⇔ 219	0.28 ⇔ 291	0.22 ⇔ 318
30 minute	0.33 ⇔ 219	0.26 ⇔ 284	0.17 ⇔ 297
90 minute	0.28 ⇔ 237	0.24 ⇔ 275	0.20 ⇔ 285
6 hour	0.23 ⇔ 248	0.21 ⇔ 264	0.19 ⇔ 269
24 hour	0.22 ⇔ 251	0.20 ⇔ 260	0.19 ⇔ 262
Mean Albedo: 0.18		**Mean OLR:** 246	

Table 4.2.3-2. Engineering Extreme Cases for Medium Inclination Orbits

Albedo and OLR values are referenced to the "top of the atmosphere", $R_E + 30$ km.

	COLD CASES		
Averaging Time	**Minimum Albedo** Alb ⇔ OLR (W/m^2)	**Combined Minimum** Alb ⇔ OLR (W/m^2)	**Minimum OLR** Alb ⇔ OLR (W/m^2)
16 second	0.06 ⇔ 273	0.15 ⇔ 213	0.40 ⇔ 151
128 second	0.06 ⇔ 273	0.15 ⇔ 213	0.38 ⇔ 155
896 second	0.08 ⇔ 262	0.17 ⇔ 217	0.34 ⇔ 163
30 minute	0.12 ⇔ 246	0.18 ⇔ 217	0.27 ⇔ 176
90 minute	0.16 ⇔ 239	0.19 ⇔ 218	0.30 ⇔ 200
6 hour	0.18 ⇔ 238	0.19 ⇔ 221	0.31 ⇔ 207
24 hour	0.19 ⇔ 233	0.20 ⇔ 223	0.25 ⇔ 210
	HOT CASES		
Averaging Time	**Maximum Albedo** Alb ⇔ OLR (W/m^2)	**Combined Maximum** Alb ⇔ OLR (W/m^2)	**Maximum OLR** Alb ⇔ OLR (W/m^2)
16 second	0.48 ⇔ 180	0.31 ⇔ 267	0.21 ⇔ 332
128 second	0.47 ⇔ 180	0.30 ⇔ 265	0.22 ⇔ 331
896 second	0.36 ⇔ 192	0.28 ⇔ 258	0.22 ⇔ 297
30 minute	0.34 ⇔ 205	0.28 ⇔ 261	0.21 ⇔ 282
90 minute	0.31 ⇔ 204	0.26 ⇔ 257	0.22 ⇔ 274
6 hour	0.31 ⇔ 212	0.24 ⇔ 248	0.21 ⇔ 249
24 hour	0.28 ⇔ 224	0.24 ⇔ 247	0.21 ⇔ 245
Mean Albedo: 0.22		**Mean OLR:** 234	

Table 4.2.3-3. Engineering Extreme Cases for High Inclination Orbits
Albedo and OLR values are referenced to the "top of the atmosphere", R_E + 30 km.

	COLD CASES		
Averaging Time	**Minimum Albedo** Alb ⇔ OLR (W/m^2)	**Combined Minimum** Alb ⇔ OLR (W/m^2)	**Minimum OLR** Alb ⇔ OLR (W/m^2)
16 second	0.06 ⇔ 273	0.16 ⇔ 212	0.40 ⇔ 108
128 second	0.06 ⇔ 273	0.16 ⇔ 212	0.38 ⇔ 111
896 second	0.09 ⇔ 264	0.17 ⇔ 218	0.33 ⇔ 148
30 minute	0.13 ⇔ 246	0.18 ⇔ 218	0.31 ⇔ 175
90 minute	0.16 ⇔ 231	0.19 ⇔ 218	0.26 ⇔ 193
6 hour	0.18 ⇔ 231	0.20 ⇔ 224	0.27 ⇔ 202
24 hour	0.18 ⇔ 231	0.20 ⇔ 224	0.24 ⇔ 205
	HOT CASES		
Averaging Time	**Maximum Albedo** Alb ⇔ OLR (W/m^2)	**Combined Maximum** Alb ⇔ OLR (W/m^2)	**Maximum OLR** Alb ⇔ OLR (W/m^2)
16 second	0.50 ⇔ 180	0.32 ⇔ 263	0.22 ⇔ 332
128 second	0.49 ⇔ 184	0.31 ⇔ 262	0.22 ⇔ 331
896 second	0.35 ⇔ 202	0.28 ⇔ 259	0.20 ⇔ 294
30 minute	0.33 ⇔ 204	0.27 ⇔ 260	0.20 ⇔ 284
90 minute	0.28 ⇔ 214	0.26 ⇔ 244	0.22 ⇔ 250
6 hour	0.27 ⇔ 218	0.24 ⇔ 233	0.22 ⇔ 221*
24 hour	0.24 ⇔ 224	0.23 ⇔ 232	0.20 ⇔ 217*
Mean Albedo: 0.23		**Mean OLR:** 211	

* Dark side OLR data was included to reach these figures; thus they may underestimate the maximum to always-daylight sun synchronous satellites by perhaps 15 W/m^2.

5.0 GUIDELINES AND LIMITATIONS

5.1 Engineering Margin and the "Worst Case" Limits

Examination of the OLR distribution tails for the 16-second and 128-second averaging times reveals a similarity. The most extreme observations occur an average of 17 W/m^2 outside the 0.04 or 99.96 percentile values, while the 1 and 99 percentile values average 26 W/m^2 to the inside. See Figure 5.1-1 for an illustration. Considering that LEO satellites traverse about 120 km per 16-second interval, this is to be expected. The wide field viewing satellite sees the same scene for several sequential 16-second intervals. For longer averaging times, the numerical averaging process causes the tails to shrink. In an 896-second interval the satellite traverses over 6600 km, thus, many scene types are included in the average. The extreme data point is about 8 W/m^2 outside the 0.04 or 99.96 percentile values while the 1 and 99 percentile values are displaced about 18 W/m^2 toward the inside. The distributions for longer intervals cutoff even more sharply. Note: the basic confidence limits in the OLR data is about 5 W/m^2; widths of the distribution tails are at most a few multiples of the measurement uncertainty.

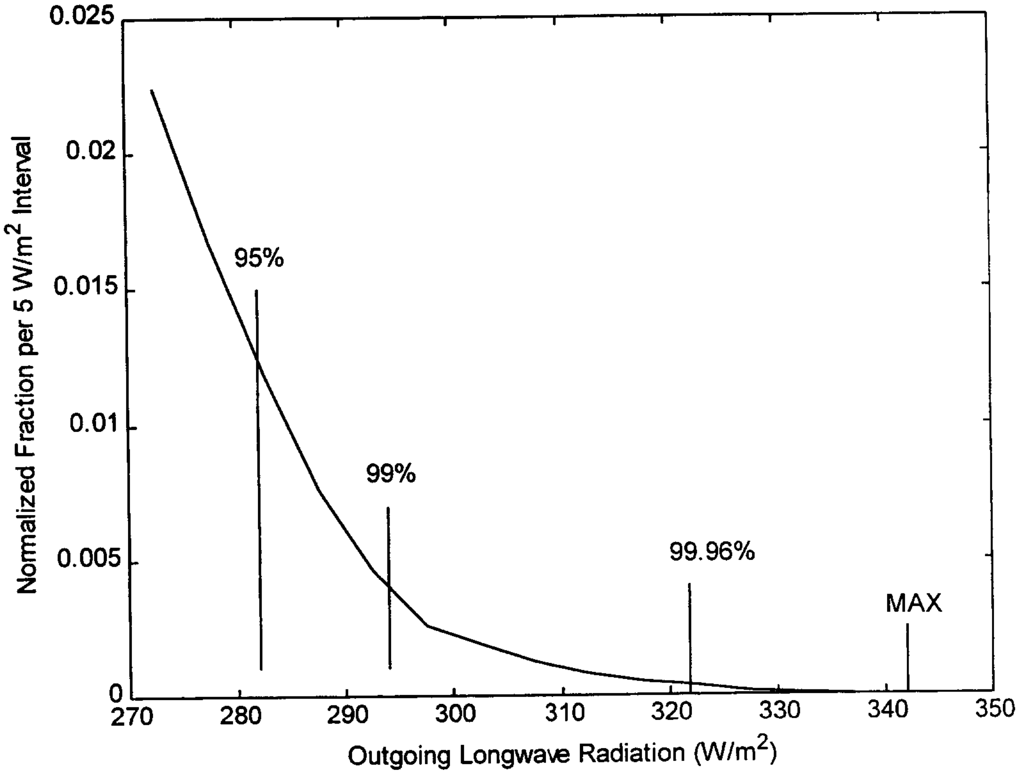

Figure 5.1-1. Hot side tail of the 128-second average OLR distribution for low inclination orbits. Ninety-fifth, 99th, 99.96th, and maximum observed points are indicated.

Examination of the albedo distribution tails reveals the same characteristics on the hot (high albedo value) side, except the tails are more narrow in comparison to the basic measurement uncertainty of approximately 0.02. For the 16-second and 128-second intervals, the separations between the 99th and 99.96th percentiles average 0.07, between the 99.96th and the extreme observations 0.06. Because the cold side cuts off very sharply, there is no tail; separations between the minimum observation, the 0.04 and first percentiles are 0.02 or less.

One key factor in selecting the engineering "worst case" design point was the shape of the tails and the relationship to the measurement uncertainty. Another key factor was the probable encounter frequency for exceeding the worst case. This is also termed the "return time" or the mean time between exceedances. Selecting the 0.04 percentile implies that one in 2500 data points lies outside the design point. If these points were uncorrelated and random, the expectation is to encounter one every 2500 by 16 seconds or 11 hours (for the 16-second averaging time data). In fact, the points are not usually isolated so the return time will be longer. However, comparing the 16-second and the 128-second distributions reveals the 16-second points exceeding the worst case are unlikely to be in groups larger than eight, thus, the average return time must be less than 2500 by 128 seconds (89 hours). Eighty-nine hours is short compared to the duration of most space experiments and missions. Selecting the 0.04 and 99.96 percentile values as design points is not being overly conservative. A reasonable expectation exists that these values will actually be encountered. In fact, if a system is critically sensitive to such short duration fluctuations in the environment, i.e., a tether might become brittle and break, it is appropriate to design not only for the "worst case" limits but also with some appropriate margin. On the other hand, if the system is sensitive in only a non-critical sense, i.e., a temperature exceedance results in a momentary loss of science data, it may suffice to have little or no design margin at the "worst case" environment and simply tolerate the occasional loss of data. Similar arguments can be made for longer averaging times. Coupled with the collapse of the tail width to within a factor of two or less of the measurement uncertainty the same conclusion is apparent.

5.2 Less Than "Worst Case" Design Conditions

Per section 4.2.3, in addition to the "Worst Case" recommended design points associated with the 0.04th and 99.96th percentiles, the corresponding points associated with the 5th an 95th percentiles in the appendix are provided as an optional output from the Simple Thermal Environment Model (STEM) tool. Fifth and 95th percentile reference points are associated with the percentile from the distribution of a single parameter, albedo or OLR. System temperature is determined by several parameters including albedo and OLR, plus the absorptance / emittance ratio. Thus, it cannot be said that system temperatures derived using 5th / 95th percentile reference points will be exceeded 5 percent of the time, for the correlation is only approximate. Also, the reference here is to the fraction of time the conditions will be exceeded, not to risk of exceedance during mission lifetime.

5.3 Applications and the Simple Thermal Environment Model (STEM)

A simple method for incorporating this information into design specifications and requirements documents was devised by Dr. Eugene Ungar and his colleagues at the Johnson Space Center on behalf of the International Space Station Program. In Space Station they were dealing with a complex vehicle with multiple components requiring thermal analysis and control, each with different thermal time constants. The approach was to specify two sets of albedo and OLR-value profiles that would drive the thermal analyses. Each profile covered an initialization time plus one orbit. One set was a functional set; conditions during which the components must function within specification. The other was an extreme set; components were required to return to a proper functioning condition after the conditions were applied and then removed. Each set consisted of four albedo–OLR profiles, two hot (max albedo and max OLR cases) and two cold (low albedo and low OLR cases). Each profile consisted of albedo–OLR pairs from Tables 4.2.3-1 to 4.2.3–3. An example, *not* from the Space Station, is provided in Figure 5.3-1. The figure illustrates an "albedo extreme" hot case for low inclination orbit with pulse-averaged SZA correction terms added to the albedos. Table A-2 in the appendix provides pulse-averaged SZA correction terms. For specification writing, typically, profiles without SZA corrections are provided because the system will usually fly at multiple beta angles.

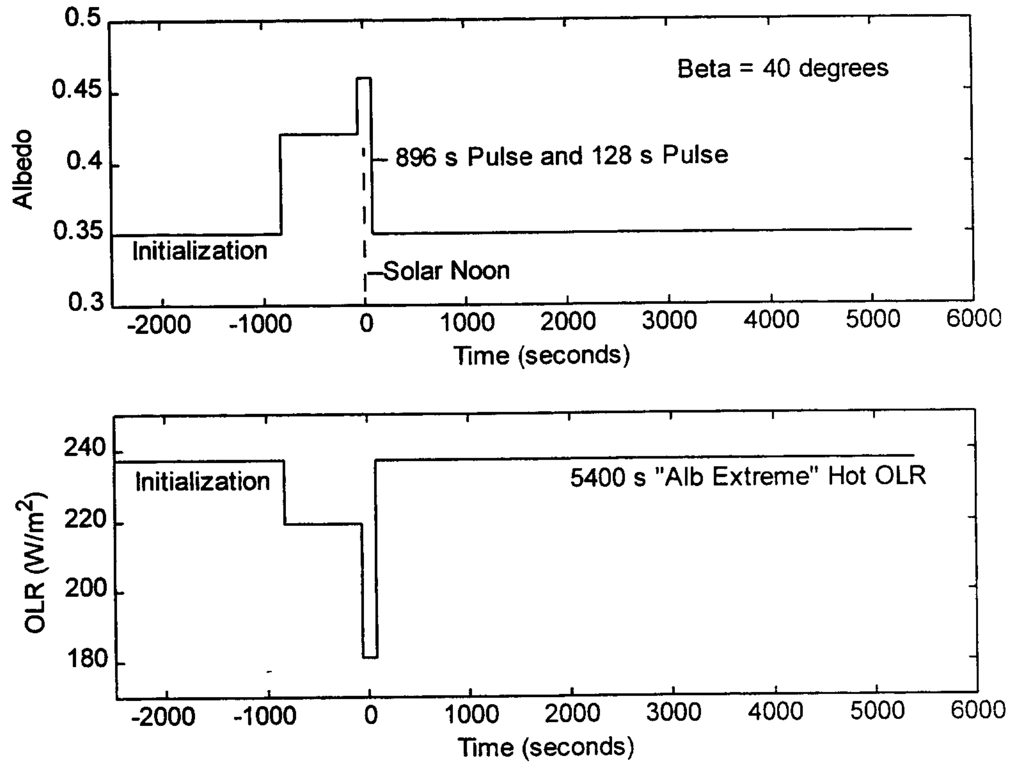

Figure 5.3-1. Example Albedo – OLR Profile for Low Inclination Orbit, Beta of 40 Degrees. This is an "Albedo Extreme" Hot Case with Pulse Averaged SZA corrections included. The initialization and base albedo is the 5400 s value, 0.28, plus the 0.07 orbit average SZA correction. Data from Tables 4.2.3-1 and A-2.

Several points are important about this approach. First, the profiles are tied to specific orbits with the hot or cold short duration pulses modeled as step functions. The hot-case albedo and OLR step functions are specified to encompass orbital noon so the maximum short-term values are encountered at the time of greatest heating. Likewise, the cold case step functions are applied at the opposite side of the orbit, orbital noon plus 180 degrees, when the vehicle is in shadow or at least the albedo radiation is at minimum. By locking the pulse locations with respect to the orbit, the solar zenith angle correction is known and can be applied at the time the specification is derived rather than requiring the analyst to determine the correction. It this illustration, and in the Space Station cases, each pulse is modeled as a double square step function, one on top of the other to represent two time constants. Of course, actual variations are not simple step functions. The TESTSTEM routine in STEM gives a good indication of hardware response when using step functions compared to measured profiles. Finally, the orbit is preceded by an initialization period with conditions set at the 90-minute average conditions (hot or cold) of interest. Thus, the model temperatures are stabilized before the short-period pulses are applied.

The Space Station approach is especially useful for a situation like Space Station where a single set of albedo/OLR conditions need to be specified for a variety of hardware elements. However, in simpler cases, i.e., a single hardware element and surface treatment, this approach can lead to unneeded analysis when the extreme hot and cold cases can be selected directly. To aid this process and to identify cases when a "combined" albedo/OLR case leads to the temperature extremes, a Simple Thermal Environment Model (STEM) was developed. STEM is fully documented[6] and provides a shortcut by

(1) Estimating the thermal time constant for the hardware

(2) Selecting, based on the absorptance/emittance ratio for the surface, whether extreme albedo, extreme OLR, or combined extreme conditions, yields extreme system temperatures

(3) Providing the complete set of thermal parameters to model the thermal environment with correct time constant, solar zenith angle correction, etc.

STEM accomplishes this shortcut by analyzing the energy balance for a simple spherical satellite. Provision is made for inclusion of internal energy sources. Data in Tables 4.2.3-1 to 4.2.3–3 are used and return values suitable for returning the extreme temperatures, hot and cold, when used in actual system analysis. As an option, STEM also outputs reference points associated with the 5th and 95th percentile extremes (see section 5.2 and appendix). This option is included primarily to aid the analyst in determining the sensitivity of system temperature to environmental inputs near the limits of the distribution. Use as a design specification is *not* recommended except for rare noncritical circumstances where periodic excursions beyond the design limit can be easily tolerated. In STEM output the solar zenith angle corrections are applied to the albedo values and associated locations are identified in the orbit.

Note that since STEM models the system as a sphere, the environmental parameters selected might not yield the extreme temperatures in a thermal analysis of a system with complex geometry. For example, reflected radiation from adjacent spacecraft surfaces could alter the balance. Thus, when the system involves complex geometry and the extreme temperatures derived from STEM for the different types of environmental conditions are close to one another, the analyst should check system performance using alternate types of environmental extremes, not just conditions identified by STEM. STEM will identify the alternate extremes if the user resets the "coldcase" and "hotcase" parameter switches.

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APPENDIX

ANCILLARY TABLES

Table A-1 gives albedo–OLR pairs for thermal analysis sensitivity studies. The "Albedo Extreme Type" cases are 5 percentile (cold) and 95 percentile (hot) albedos and an associated OLR (obtained by averaging the OLR's paired to the albedos outside the indicated percentile). "Combined" types are pairs with equal normalized variates identified with the 5th or 95th percentile (see paragraph 4.2.3). "OLR extreme types" were obtained in the same manner as the albedo extreme types but with the parameters switched. One may expect system temperatures to lie outside values derived with parameters from this table for a small fraction of the total mission duration. This fraction cannot be specified but should be on the order of a few percent.

Table A-1. Less Than Extreme Albedo-OLR Pairs

		Cold Case Data						Hot Case Data					
Ext-reme Type	Avg. Time (sec)	30 deg		60 deg		90 deg		30 deg		60 deg		90 deg	
		Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR	Alb	OLR
Alb	16	0.09	270	0.10	267	0.10	267	0.29	205	0.36	201	0.38	197
Alb	128	0.09	267	0.10	265	0.10	265	0.29	211	0.35	202	0.37	199
Alb	896	0.10	261	0.13	252	0.14	252	0.26	225	0.29	213	0.28	213
Alb	1800	0.12	257	0.16	242	0.17	244	0.24	234	0.27	223	0.26	223
Alb	5400	0.13	249	0.18	238	0.18	230	0.22	246	0.26	229	0.24	219
Alb	21600	0.15	241	0.19	233	0.19	230	0.20	252	0.25	231	0.23	224
Alb	86400	0.16	240	0.19	235	0.19	230	0.20	252	0.25	232	0.23	224
Comb	16	0.15	236	0.19	227	0.20	225	0.21	260	0.23	240	0.24	237
Comb	128	0.16	237	0.19	227	0.20	225	0.21	260	0.23	240	0.24	238
Comb	896	0.16	237	0.20	226	0.20	227	0.21	261	0.23	241	0.23	240
Comb	1800	0.16	237	0.20	225	0.20	226	0.21	258	0.23	240	0.23	242
Comb	5400	0.16	237	0.20	225	0.21	224	0.20	258	0.23	241	0.23	232
Comb	21600	0.17	237	0.20	226	0.21	226	0.19	255	0.23	242	0.22	230
Comb	86400	0.17	236	0.20	226	0.20	225	0.19	257	0.23	241	0.23	230
OLR	16	0.30	195	0.33	183	0.35	164	0.17	285	0.17	280	0.17	280
OLR	128	0.29	198	0.33	184	0.34	164	0.17	284	0.17	279	0.17	279
OLR	896	0.26	209	0.28	189	0.27	172	0.18	279	0.18	264	0.18	263
OLR	1800	0.23	216	0.25	200	0.25	190	0.18	274	0.20	258	0.20	258
OLR	5400	0.20	225	0.23	209	0.24	202	0.19	268	0.21	254	0.21	242
OLR	21600	0.18	231	0.23	212	0.23	205	0.19	261	0.21	242	0.21	216
OLR	86400	0.17	233	0.23	212	0.23	207	0.18	258	0.21	241	0.21	215

Table A-2 provides pulse-averaged SZA correction terms for albedo for pulses beginning at or symmetrical about solar noon. That is, the average was taken from solar noon to the time indicated, assuming a 90-minute circular orbit and using the method in STEM. As the numbers indicate, the correction term is not a strong function of orbit position because the average has been weighted with cos(SZA) in accordance with variation of albedo energy.

Table A-2. Pulse-averaged SZA Correction Terms for Albedo Assuming a 5400-s Orbit. Add the Indicated Correction to the Value for SZA = 0.

Beta Angle	Max Time From Solar Noon			
	128 s	448 s	896 s	1350s or More (Orbit Average)
0	0.01	0.02	0.03	0.04
10	0.01	0.02	0.03	0.04
20	0.02	0.02	0.04	0.05
30	0.03	0.03	0.04	0.06
40	0.04	0.04	0.05	0.07
50	0.05	0.06	0.07	0.09
60	0.08	0.09	0.10	0.12
70	0.13	0.13	0.15	0.16
80	0.20	0.21	0.22	0.22
90	0.31	0.31	0.31	0.31

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13. ABSTRACT *(Maximum 200 words)*

Thermal analysis and design of Earth orbiting systems requires specification of three environmental thermal parameters: the direct solar irradiance, Earth's local albedo, and outgoing longwave radiance (OLR). In the early 1990s data sets from the Earth Radiation Budget Experiment were analyzed on behalf of the Space Station Program to provide an accurate description of these parameters as a function of averaging time along the orbital path. This information, documented in SSP 30425 and, in more generic form in NASA/TM–4527, enabled the specification of the proper thermal parameters for systems of various thermal response time constants.

However, working with the engineering community and SSP-30425 and TM–4527 products over a number of years revealed difficulties in interpretation and application of this material. For this reason it was decided to develop this guidelines document to help resolve these issues of practical application. In the process, the data were extensively reprocessed and a new computer code, the Simple Thermal Environment Model (STEM) was developed to simplify the process of selecting the parameters for input into extreme hot and cold thermal analyses and design specifications. In the process, greatly improved values for the cold case OLR values for high inclination orbits were derived. Thermal parameters for satellites in low, medium, and high inclination low-Earth orbit and with various system thermal time constraints are recommended for analysis of extreme hot and cold conditions. Practical information as to the interpretation and application of the information and an introduction to the STEM are included. Complete documentation for STEM is found in the user's manual, in preparation.

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