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The Mars Climate for a Photovoltaic System Operation

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THE MARS CLIMATE FOR A PHOTOVOLTAIC SYSTEM OPERATION

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ABSTRACT

Detailed information on the climatic conditions on Mars are very desirable for the design of photovoltaic systems for establishing outposts on the Martian surface. This paper addresses the distribution of solar insolation (global, direct and diffuse) and ambient temperature. This data are given at the Viking lander's locations and can also be used, to a first approximation, for other latitudes. The insolation data is based on measured optical depth of the Martian atmosphere derived from images taken of the sun with a special diode on the Viking cameras; and computation based on multiple wavelength and multiple scattering of the solar radiation. The ambient temperature (diurnal and yearly distribution) is based on direct measurements with a thermocouple at 1.6 m above the ground at the Viking lander locations. The insolation and ambient temperature information are short term data. New information about Mars may be forthcoming in the future from new analysis of previously collected data or from future flight missions. The Mars climate data for photovoltaic system operation will thus be updated accordingly.

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*This work was done while the author was a National Research Council - NASA Research Associate; on sabbatical leave from Tel Aviv University.

INTRODUCTION

NASA, through its Project Pathfinder, has put in place a wide-ranging set of advanced technology programs to address future needs of manned space exploration. Included in the mission sets under study is the establishment of outposts on the surface of Mars. The Surface Power Program in Pathfinder is aimed at providing ultralightweight photovoltaic array technology for such an application (as well as for the lunar surface). Detailed information on the climatic conditions on Mars at the photovoltaic system location is very desirable. These include the distribution of solar insolation; ambient temperature; albedo; and wind speeds and directions; with latitude, season, and time of the day. In addition, the effect of dust accumulation on the photovoltaic panels and radiation damage causing degradation of the output power needs to be assessed.

As on the planet Earth, the solar insolation on the surface of Mars is composed of two components: the direct beam, and diffuse component. The direct beam is affected by scattering and absorption along the path from the top of the Martian atmosphere to the Martian surface. Measurement of the optical depth [1,2] of the Martian atmosphere allows an estimate of the absorption and scattering out of the beam. These estimates were derived from images taken of the Sun and Phobos with a special diode on the Viking lander cameras. Since the cameras are sitting on the Martian surface, the measured intensity is directly related by Beer's law to the optical depth of the intervening atmospheric haze:

$$G_b = G_o \exp\left[-\frac{\tau}{m(z)}\right] \qquad (1)$$

where G_o is the unattenuated insolation at the top of the Martian atmosphere; G_b is the direct beam insolation on Martian surface normal to the solar rays; τ is the optical depth; and $m(z)$ is the airmass determined by the zenith angle z.

Earth-terrestrial insolation data are accumulated over many years at different locations around the world and are given as long term average values. The optical depth data for Mars are derived for only two Mars years. Consequently, the calculated solar insolation corresponds to short term data. Furthermore, the measured opacities (optical depth) and the calculated insolations pertain to just two locations on the Mars planet; Viking lander 1 (VL1) is located at 22.3° N latitude and 47.9° W longitude, and Viking lander 2 (VL2) is located at 47.7° N latitude and 225.7° W longitude. However, the similarity in the properties of the dust suspended above the two landing sites suggests that they are also representative of ones at other locations, at least, at latitudes not too far from the lander's sites. Data from landers VL1 may be used for latitudes 40° N to 40° S and data from lander VL2 for higher latitudes. The Martian atmosphere consists mainly of suspended dust particles, the amount of which vary daily, seasonally, and annually dependent on local and global storms intensities and their duration. The optical depth of the atmosphere was determined from the measurements taken in the morning and in the afternoon. The afternoon values are more representative due to solely suspended dust particles, whereas the morning values are higher indicating the presence of a ground fog. The optical depth values given in the section entitled OPTICAL

DEPTH are the afternoon values, and are assumed to be constant throughout the day. Large values of optical depth correspond to global storms, i.e., days with low insolation ("dark days").

The albedo of the Martian surface varies in the range of about 0.1 to 0.4. The insolations derived in the section entitled SOLAR INSOLATION correspond to 0.1 albedo but can be also used for other values of albedo, to the first approximation.

The ambient temperature at the Viking lander's locations was measured for more than two Martian years at the height of 1.6 m above the ground. The ambient temperature sensors consists of chromel-constantan thermocouples. Again, these are short term data and pertain to the two Viking locations.

In this paper we calculated the distribution of solar insolation and report the ambient temperature: the two major climatic components for photovoltaic system design. We do not report here data on wind speed and direction, albedo and the effect of dust on the output power of the photovoltaic panels. New information about Mars may be forthcoming in the future from new analysis of previously collected data, from new Earth-based observation, or from future flight missions. The Mars climatic data for photovoltaic system design will thus be updated accordingly.

SOLAR CELL ARRAY

The effect of temperature and insolation on the I-V characteristic of a solar cell array can be related to empirically observed properties of the type of solar cell used. The approximate (neglecting the shunt resistance) I-V equation of the solar cell array is given by:

$$V = -IR_s + \frac{1}{\Lambda} \ln\left(\frac{I_{ph} - I + I_o}{I_o}\right) \quad (2)$$

where I_{ph} is the photocurrent, I_o is the reverse saturation current, R_s the series resistance, I and V the array terminal current and voltage, $\Lambda = q/AkT$, q being the electron charge, A the completion factor, k the Boltzmann's constant and T the absolute temperature. The solar cell array I-V equation as function of the cell temperature T, at a given insolation level, may be written as:

$$V = -IR_s + \frac{1}{\Lambda(T)} \ln\left[\frac{I_{ph}(T) - I + I_o(T)}{I_o(T)}\right] \quad (3)$$

where

$$I_{ph}(T) = I_{ph}(T_r)\left[1 + \alpha(T - T_o)\right] \quad (4)$$

$$\Lambda(T) = \Lambda(T_r)\frac{T_r}{T} \quad (5)$$

$$I_o(T) = I_o(T_r)\left(\frac{T}{T_r}\right)^3 \exp\left[-\beta\left(\frac{1}{T} - \frac{1}{T_r}\right)\right] \quad (6)$$

where T_r is a given reference temperature, and α and β are coefficients corresponding to the given solar cells. For a constant temperature and a variable insolation G, the photocurrent is:

$$I_{ph}(G) = I_{ph}(G_r)\frac{G}{G_r} \quad (7)$$

where G_r is a given reference insolation.

OPTICAL DEPTH

The most direct and probably reliable estimates of opacity are those derived from Viking lander imaging of the Sun. Figures 1 and 2 show the seasonal variation of the normal-incidence of the optical depth at the Viking lander locations VL1 and VL2, respectively. The season is indicated by the value of L_S, areocentric longitude of the Sun, measured in the orbital plane of the planet from its vernal equinox (L_S = 0° and 180° corresponding to spring and fall equinox for the northern hemisphere, respectively; and L_S = 90° and 270° corresponding to northern and southern summer solstices, respectively). Figures 1 and 2 were derived from references by Pollack [1,2] and Zurek [3] and were discretized for each 5°. As mentioned before, the optical depth is assumed to remain constant throughout the day. Opacities are minimum during the northern spring (L_S = 0° to 90°) and summer (L_S = 90° to 180°), and maximum during southern spring (L_S = 180° to 270°) and summer (L_S = 270° to 360°), the seasons during which most local and major dust storms occur. When dust storms are not present, the optical depth are typically about 0.5. Two global dust storms occurred during the period of the observation as indicated by the high values of the optical depth (lower bound values).

GLOBAL AND LOCAL DUST STORMS

The intensity of Martian global and local dust storms is defined in terms of opacity of the dust it raises. Global dust storms are those which obscure planetary-scale sections of the Martian surface for many Martian days (sols), whereas local dust storms are less intense, and form and dissipate in a few days or less. From the photovoltaic system design point of view, the intensity, frequency, and duration of these storms may be viewed as "partially cloudy" and "cloudy" days for which additional energy storage in the photovoltaic system must be taken into account. The characteristics of global and local dust storms are listed below.

Global Dust Storms

(1) One, or occasionally two global dust storms of planetary scale may occur each Martian year. The duration may vary from 35 to 70 days or more. Although global dust storms do not occur every year, their occurrence is fairly frequent.

(2) Global dust storms begin near perihelion, when solar insolation is maximum (southern spring and summer) in the southern mid-latitude.

(3) The first global dust storm (1977) spread from a latitude of 40° S to a latitude 48° N in about 5 to 6 days.

(4) The opacity during the global dust storm is greater than 1.

Local Dust Storms

(1) Local dust storms occur at almost all latitudes and throughout the year. However, they have been observed to occur most frequently in the approximate latitude belt 10° to 20° N and 20° to 40° S, with more dust clouds seen in the south than in the north, the majority of which occurred during southern spring.

(2) Based on Viking orbiter observations, it is estimated that approximately 100 local storms occur in a given Martian year.

(3) Local dust storms last a few days.

(4) The opacity of local dust storms may be assumed about 1.

AMBIENT TEMPERATURE

Ambient temperature data are needed for the determination of the solar cell temperature, Eqs. (3) to (6). In this section we show yearly variation of the ambient temperature as well as diurnal variation of some particular Martian days. This information was supplied to us by Tillman [4]. Figure 3 shows the variation of the ambient temperature at Viking lander VL1 for part of the first year after landing. The top time coordinate (abscissa) has units of sol number, the number of Martian solar days from touchdown on sol 0 (1 sol = 24.65 hr). The bottom abscissa is the seasonal date L_S. The diurnal ambient temperature variation at VL1 for sols 75 and 76 (summer), and sols 191 and 192 (autumn), are shown in Figs. 4 and 5, respectively. The figures show large (60°) diurnal ambient temperature variation. Figure 6 shows the variation of the ambient temperature of Viking lander VL2 for the first year after landing. During dust storm events, the Martian atmosphere is strongly heated up by absorption of solar radiation due to the suspended dust. As a result, the maximum ambient temperature decreases significantly while the minimum increases, especially during the more intense 1977 B storm. The diurnal ambient temperature variation for sols 285 and 286 at the time of 1977 B global storm is shown in Fig. 7. The variation in temperature is rather small (16°). For the less intense 1977 A global storm, the diurnal temperature variation is larger (28°) as shown in Fig. 8, for sols 177 and 178; and for a local storm, the diurnal ambient temperature variation is still larger (38°), as shown in Fig. 9, sol 160.

SOLAR INSOLATION

The solar insolation on the surface of Mars is composed of the direct beam and the diffuse components. The net solar flux integrated over the solar spectrum, on the Martian surface was calculated by Pollack [5] based on multiple wavelength and multiple scattering of the solar radiation. Derived data of this calculation is shown in Table 1 by the function $f(z,\tau)$ where the parameters are the cosine of the zenith angle z and the optical depth τ. This table pertains to albedo of 0.1 but can be used for higher albedo values to a first approximation. Using this data we calculated the global solar insolation. We assumed that the diffuse insolation is obtained by subtracting the beam from the global insolation, and we further assumed isotropical Martian skies.

The solar insolation components, on a horizontal Martian surface, are related by:

$$G_h = G_{bh} + G_{dh} \tag{8}$$

where

G_h global insolation on a horizontal surface;

G_{bh} direct beam insolation on a horizontal surface; and

G_{dh} diffuse insolation on a horizontal surface.

The diffuse insolation of the Martian atmosphere may be a result of a different mechanism than that for the Earth atmosphere, nevertheless, to a first approximation, we will apply Eq. (8) as for Earth-terrestrial calculations. The beam insolations G_b (Eq. (1)) and G_{bh} are related by:

$$G_{bh} = G_b \cos z \exp(-\tau/m(z)) \tag{9}$$

For zenith angles $z < 70°$ one can approximate the airmass by:

$$m(z) = \cos z \tag{10}$$

The beam insolation at the top of the Martian atmosphere is given by:

$$G_o = \frac{S}{r^2} \tag{11}$$

where

S is the solar constant at the mean Sun-Earth distance of 1 AU, i.e., $S = 1371\ W/m^2$; r is the instantaneous Sun-Mars distance (heliocentric distance) given by [6]:

$$r = \frac{a(1 - e^2)}{1 + e \cos \theta} \tag{12}$$

where a is the Mars memimajor axis, and e is the Mars eccentricity, i.e., e = 0.093377; and θ is the true anomaly given by:

$$\theta = L_s - 248° \tag{13}$$

where L_s is the areocentric longitude and 248° is the areocentric longitude of Mars perihelion. The Sun-Mars mean distance in AU units is 1.5236915, therefore, the mean beam insolation at the top of Mars atmosphere is: $1371/1.5236915^2 = 590\ W/m^2$. The instantaneous beam insolation is given by Eqs. (11) to (13):

$$G_o = 590 \frac{\left[1 + e \cos(L_s - 248°)\right]^2}{\left(1 - e^2\right)^2} \tag{14}$$

The following figures of solar insolation were calculated using the Table 1 data and the mean insolation of $590\ W/m^2$. Insolation values for any desired seasonal data L_s are easily obtained using Eq. (14).

The global insolation G_h on a horizontal Martian surface is obtained by:

$$G_h = 590 \frac{f(z,\tau)\cos z}{(1 - b)} \tag{15}$$

where b is the albedo. The variation of the global insolation G_h with optical depth τ is shown in Fig. 10 for various zenith angles (cos z).

The beam insolation G_{bh} on a horizontal surface is obtained using Eq. (9) for $G_b = 590$ W/m^2, and is shown in Fig. 11 as a function of the optical depth with the zenith angle as a parameter. The figure shows a sharp exponential decrease in insolation with increasing τ.

The diffuse insolation G_{dh} on a horizontal surface is obtained from Eq. (8) for $G_b = 590$ W/m^2, and is shown in Fig. 12 as a function of the optical depth with the zenith angle as a parameter. The diffuse insolation has a sliding maximum with the variation of the solar zenith angle.

CONCLUSIONS

The two major climatic components needed for photovoltaic system design are the distributions of solar insolation and ambient temperature. These distributions for the Martian climate are given in the paper at the two Viking lander locations but can also be used, to the first approximation, for other latitudes. In absence of long term insolation and temperature data for Mars, the data presented in this paper can be used until updated data are available. The ambient temperature data are given as measured directly by the temperature sensor; the insolation data (global, direct beam, and diffuse) are calculated and believed to be published for the first time. Additional insolation data, such as daily insolations, can be further derived based on Table 1 and the above expressions.

ACKNOWLEDGMENT

We are very grateful to James B. Pollack from the Space Science Division, NASA Ames Research Center for supplying us with the $f(z,\tau)$ table; to James E. Tillman from the Department of Atmospheric Sciences, University of Washington for supplying the ambient temperature distribution graphs; and for their informative discussions.

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[4] J.E. Tillman, Director and N.C. Johnson Viking Computer Facility, Department of Atmospheric Sciences, University of Washington, Seattle, Washington, private communication.

[5] J.B. Pollack, et al., in preparation, private communication.

[6] E.v.P. Smith and K.C. Jacobs, Introductory Astronomy and Astrophysics, W.B. Saunders Co., 1973.

TABLE 1. - THE FUNCTION f(z,τ) FOR THE CALCULATION OF THE GLOBAL INSOLATION[a]

τ \ cos z	0.013	0.067	0.160	0.283	0.426	0.574	0.717	0.840	0.933	0.987
0.1	0.3407	0.5854	0.7456	0.8147	0.8470	0.8637	0.8730	0.8783	0.8813	0.8827
.3594	.2724	.3478	.5094	.6432	.7261	.7750	.8041	.8215	.8313	.8365
1.0000	.2004	.2377	.3057	.4111	.5157	.5969	.6535	.6907	.7134	.7251
2.1540	.1362	.1604	.1965	.2487	.3183	.3915	.4550	.5030	.5351	.5523
5.9950	.0547	.0643	.0778	.0949	.1155	.1400	.1670	.1929	.2137	.2262

[a]J.B. Pollack, private communication.

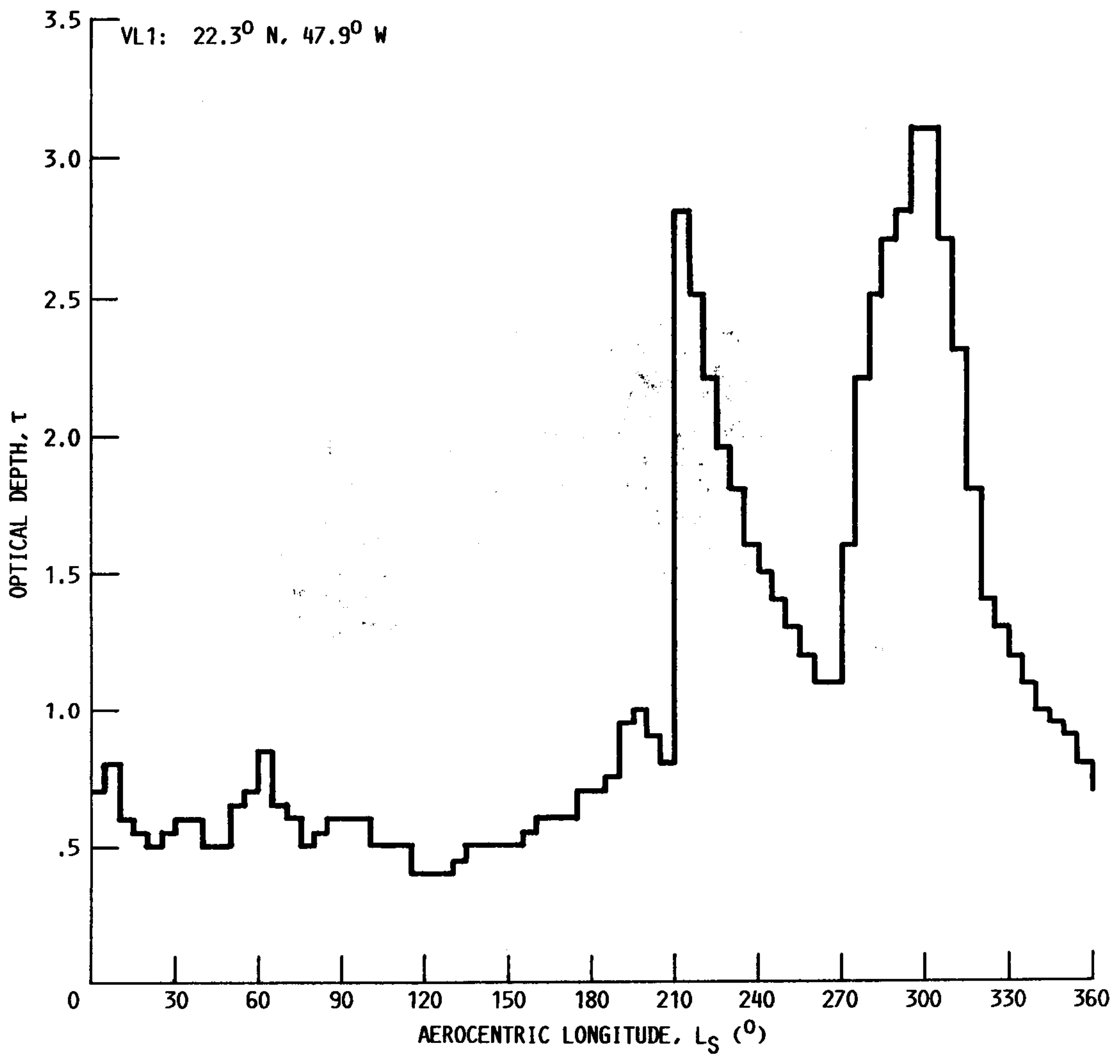

FIGURE 1. - OPTICAL DEPTH (τ) AS FUNCTION OF AEROCENTRIC LONGITUDE (L_S) AT VIKING LANDER VL1.

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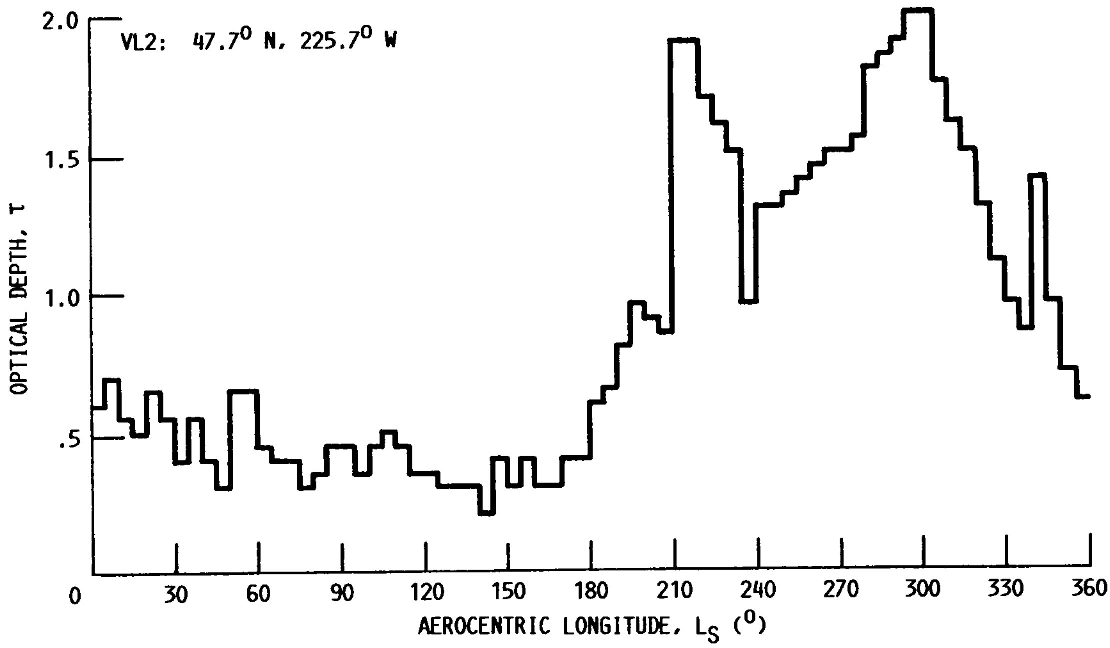

FIGURE 2. - OPTICAL DEPTH (τ) AS FUNCTION OF AEROCENTRIC LONGITUDE (L_S) AT VIKING LANDER VL2.

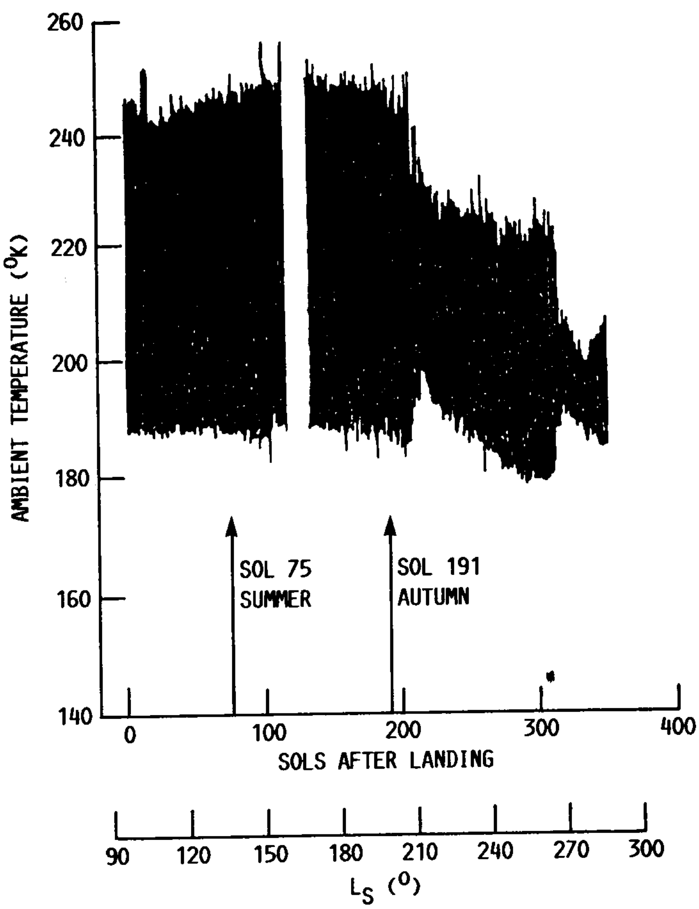

FIGURE 3. - AMBIENT TEMPERATURE VARIATION AT LANDER VL1 FOR THE FIRST YEAR. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

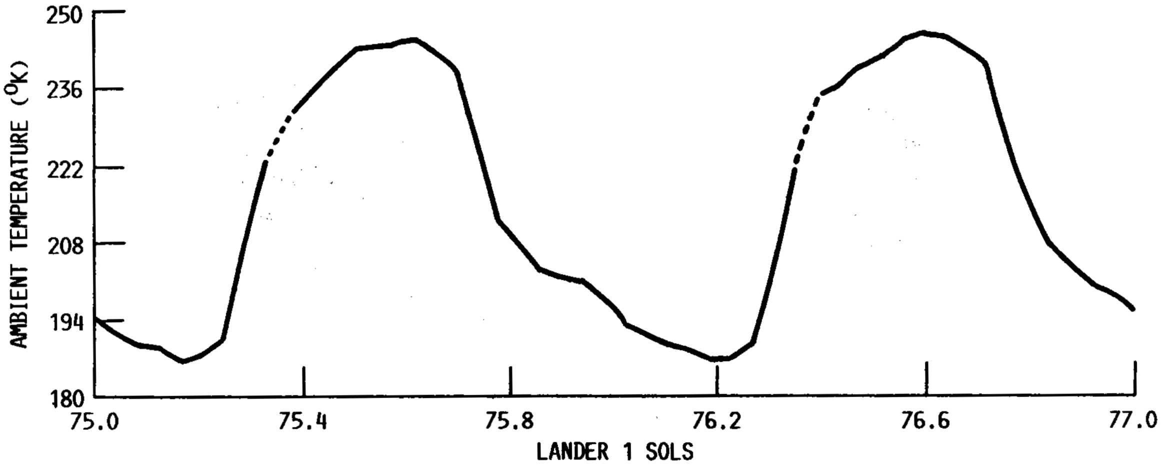

FIGURE 4. - DIURNAL AMBIENT TEMPERATURE VARIATION AT LANDER VL1, FIRST YEAR, FOR SOLS 75 AND 76, SUMMER. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

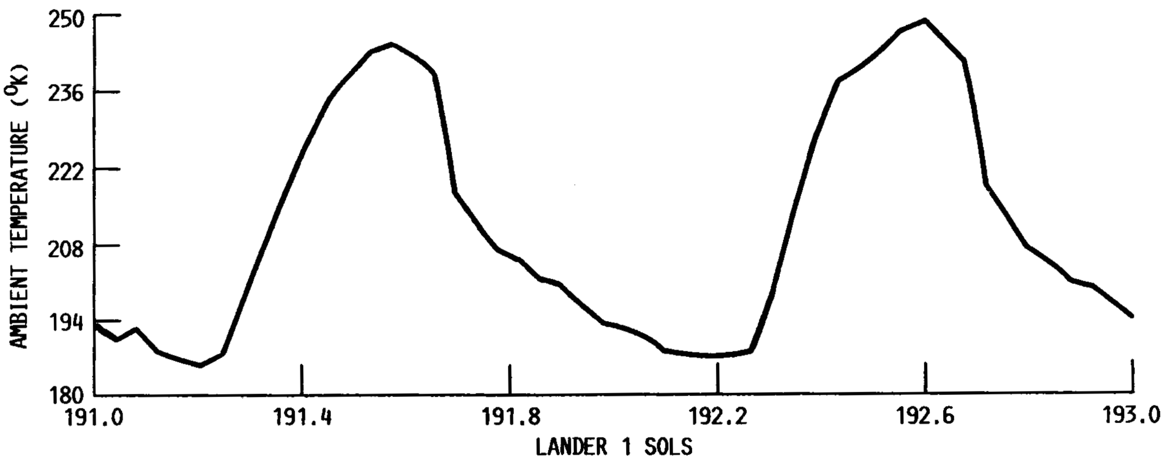

FIGURE 5. - DIURNAL AMBIENT TEMPERATURE VARIATION AT LANDER VL1, FIRST YEAR, FOR SOLS 191 AND 192, AUTUMN. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

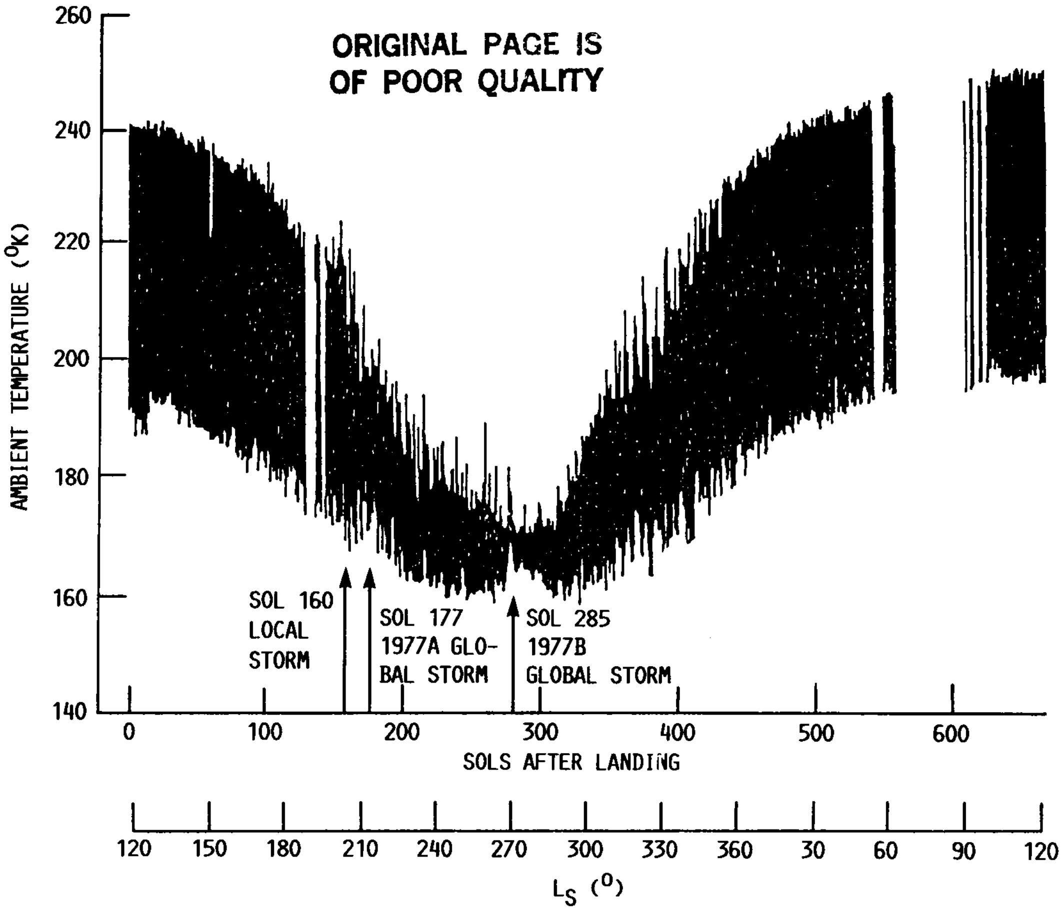

FIGURE 6. - AMBIENT TEMPERATUARE VARIATION AT LANDER VL2 FOR THE FIRST YEAR. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

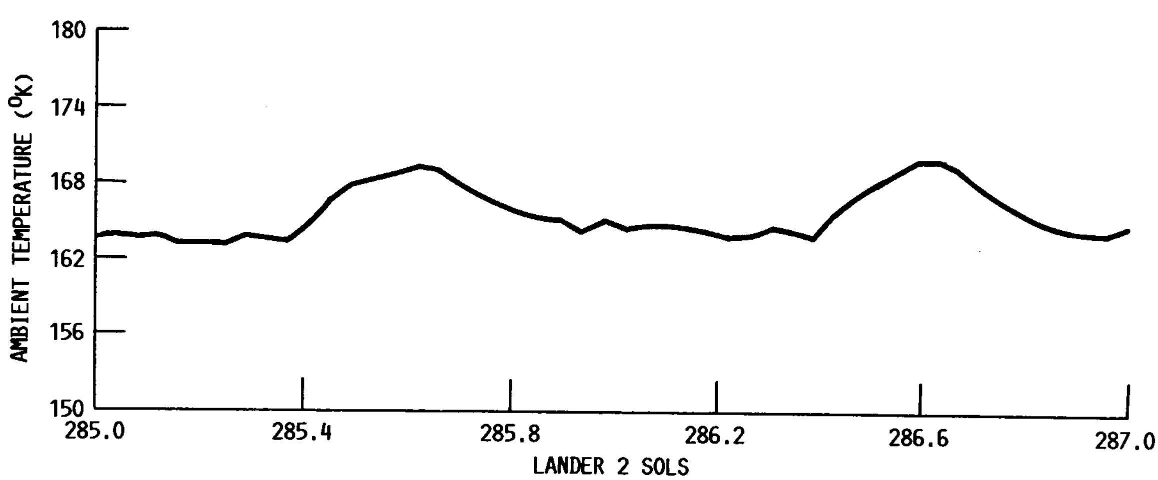

FIGURE 7. - DIURNAL AMBIENT TEMPERATURE VARIATION AT LANDER VL2, FIRST YEAR, FOR SOLS 285 AND 286, DURING 1977B GLOBAL STORM. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

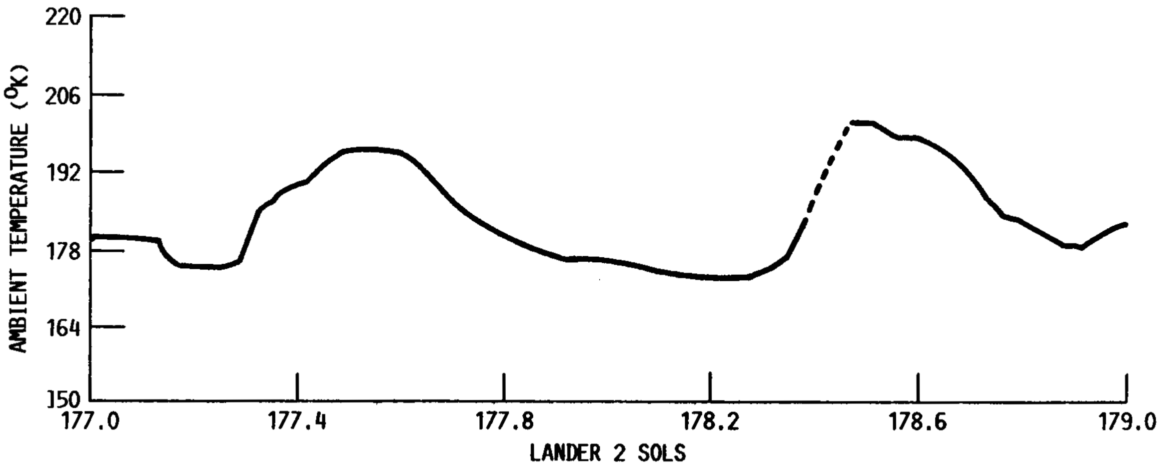

FIGURE 8. _ DIURNAL AMBIENT TEMPERATURE VARIATION AT LANDER VL2, FIRST YEAR, FOR SOLS 177 AND 178, DURING 1977A GLOBAL STORM. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

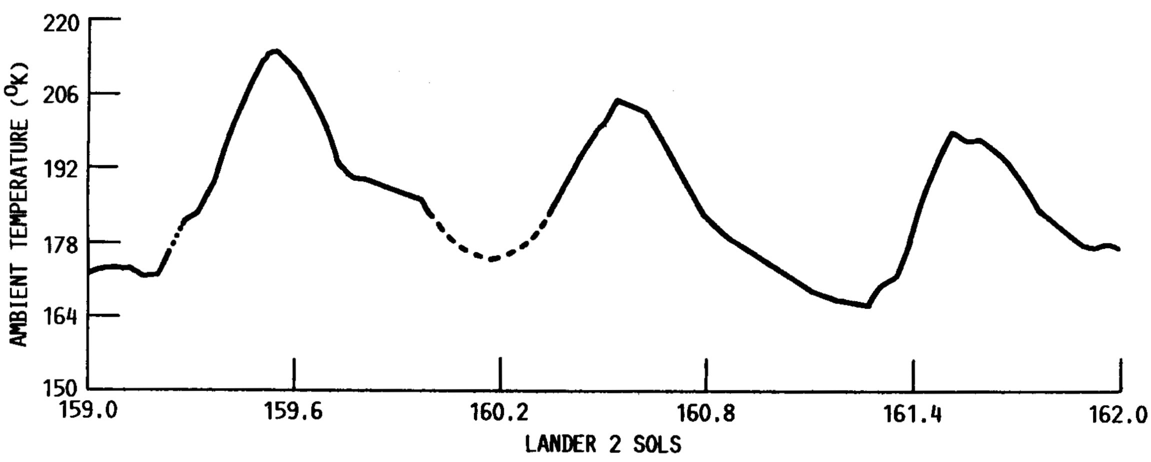

FIGURE 9. - DIURNAL AMBIENT TEMPERATURE VARIATION AT LANDER VL2, FIRST YEAR, FOR SOLS 159, 160, AND 161 DURING LOCAL STORM. (J. E. TILLMAN, PRIVATE COMMUNICATION.)

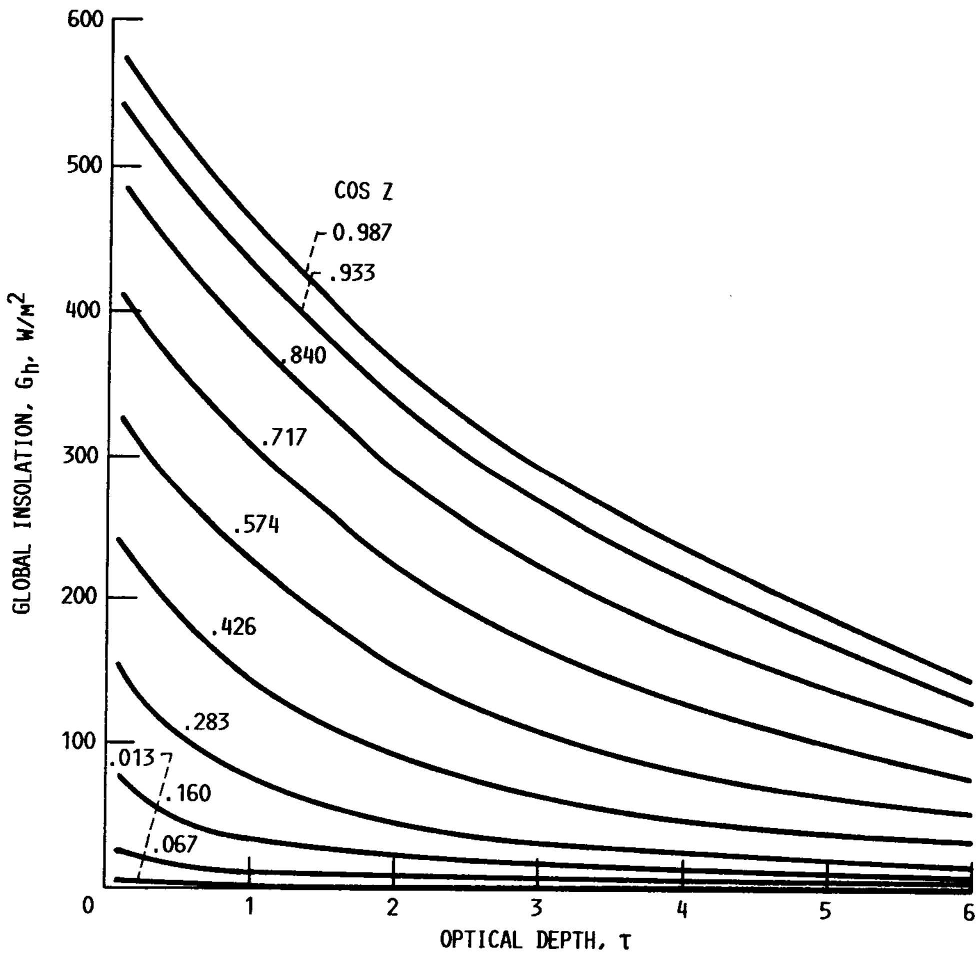

FIGURE 10. - VARIATION OF GLOBAL INSOLATION WITH OPTICAL DEPTH ON A HORIZONTAL SURFACE.

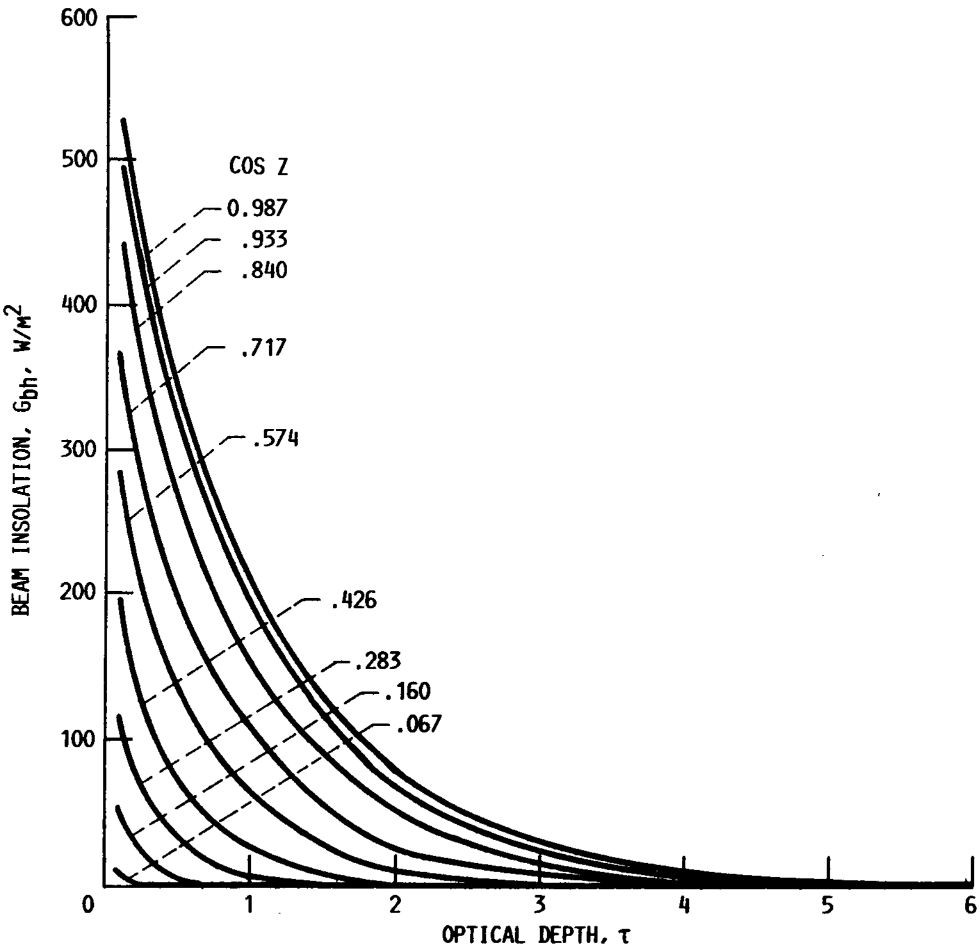

FIGURE 11. - VARIATION OF DIRECT BEAM INSOLATION WITH OPTICAL DEPTH ON A HORIZONTAL SURFACE.

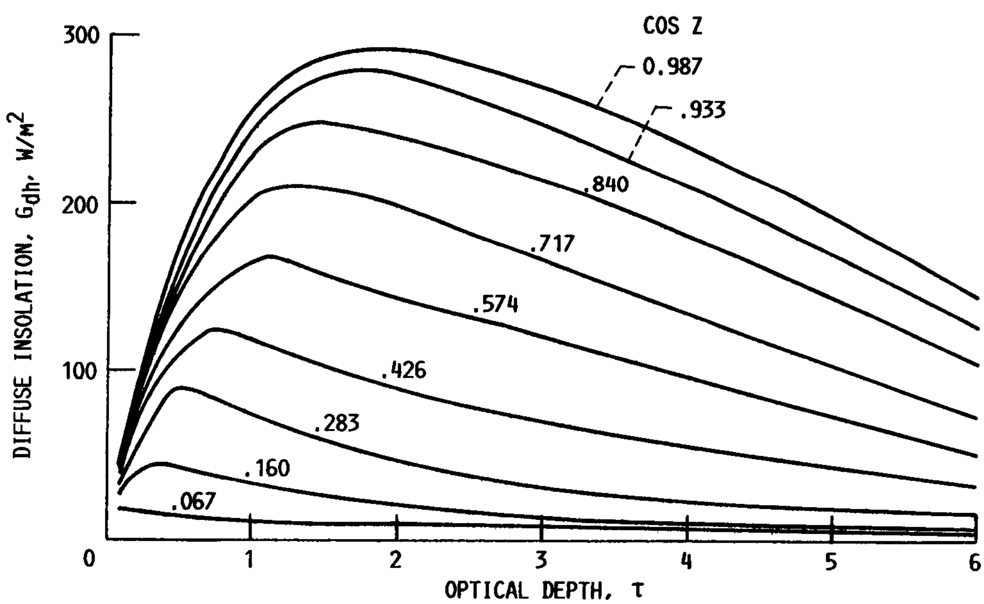

FIGURE 12. - VARIATION OF THE DIFFUSER INSOLATION WITH OPTICAL DEPTH ON A HORIZONTAL SURFACE.

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16. Abstract

Detailed information on the climatic conditions on Mars are very desirable for the design of photovoltaic systems for establishing outposts on the Martian surface. This paper addresses the distribution of solar insolation (global, direct and diffuse) and ambient temperature. This data are given at the Viking lander's locations and can also be used, to a first approximation, for other latitudes. The insolation data is based on measured optical depth of the Martian atmosphere derived from images taken of the sun with a special diode on the Viking cameras; and computation based on multiple wavelength and multiple scattering of the solar radiation. The ambient temperature (diurnal and yearly distribution) is based on direct measurements with a thermocouple at 1.6 m above the ground at the Viking lander locations. The insolation and ambient temperature information are short term data. New information about Mars may be forthcoming in the future from new analysis of previously collected data or from future flight missions. The Mars climate data for photovoltaic system operation will thus be updated accordingly.

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