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ABSTRACT

Detailed information on solar radiation characteristics on Mars are necessary for effective design of future planned solar energy systems operating on the surface of Mars. In this paper we present a procedure and solar radiation related data from which the diurnally, hourly and daily variation of the global, direct beam and diffuse insolation on Mars are calculated. The radiation data are 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.

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. Detailed information on solar radiation data on the Martian surface is necessary to allow more accurate estimates of photovoltaic power system size and mass in system analysis and trade-off studies of relevant technology options. Of major concern are the dust storms, which have been observed to occur on local as well as on global scales, and their effect on

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solar array output. In general, the assumption has been that global storms would reduce solar array output essentially to zero, because the opacity of the atmosphere may rise to values ranging from 3 to 9, depending on the severity of the storm. Furthermore, such high values of opacity may persist for long periods of time such that the requirement for energy storage quickly becomes much too large to be practical. As shown in Refs. 1 and 2 (and is believed to be published for the first time to the best of our knowledge), there is still an appreciable large diffuse component, even at high opacitites, so that solar array operation is still possible.

Calculation of solar radiation incident on the top of Martian atmosphere and on the Martian surface has been previously published (Refs. 3 to 5) taking into account the direct beam component only of the solar radiation. The introduction of the diffuse component in this paper became possible with the normalized net flux function described in the paper. This paper is an extension of the study in Refs. 1 and 2.

As on the planet Earth, the solar radiation 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 (Refs. 6 and 7) 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.

Earth-terrestial 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 from less than two Mars years. Consequently, the calculated solar insolation, in the present paper, corresponds to short term data. Furthermore, the measured opacities (optical depth) and the calculated insolation 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 lander 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 amounts of which vary daily, seasonally, and annually, depending on local and global storm intensities and their duration. The optical depth values given in the section entitled Optical Depth 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 irradiances derived in the section entitled Solar Radiation correspond to 0.1 albedo, but can be also used for other values of albedo, to the first approximation.

In this paper a normalized net solar flux function is introduced from which, together with the variation of the opacities, characteristics of the solar radiation on the Martian surface are calculated. This includes, among others, the diurnal and hourly variation of the global, beam and diffuse radiation on the horizontal surface. The results are presented in a series of figures and tables. The solar radiation data and the procedure presented in this paper can be used for the calculation of any desired solar radiation quantity in engineering design. 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 solar radiation data will thus be updated accordingly.

NOMENCLATURE

Radiation values:

G_b	beam irradiance on Mars surface
G_h, G_{bh}, G_{dh}	global, beam and diffuse irradiance on Mars horizontal surface
G_{ob}	beam irradiance at the top of Mars atmosphere
G_{obh}	beam irradiance on a horizontal surface at the top of Mars atmosphere
H_h, H_{bh}, H_{dh}	global, beam and diffuse daily insolation on Mars horizontal surface
H_{obh}	daily beam insolation on a horizontal surface at the top of Mars atmosphere
I_h, I_{bh}, I_{dh}	global, beam and diffuse hourly insolation on Mars horizontal surface
I_{obh}	hourly beam insolation on a horizontal surface at the top of Mars atmosphere

Subscripts:

b	beam values
d	diffuse values
h	horizontal values
o	values on top of Mars atmosphere

Other values:

e	eccentricity = 0.093377
L_s	areocentric longitude
m(z)	airmass
r	Sun-Mars distance
S	solar constant = 1371 W/m^2 at the mean Sun-Earth distance of 1 astronomical unit (AU).
T	Mars solar time

T_d	Mars daylight hours
z	zenith angle
δ	declination angle
δ_O	obliquity
θ	true anomaly
τ	optical depth
ϕ	latitude
ω	hour angle
ω_{ss}	sunset hour angle

OPTICAL DEPTH

The most direct and probably most 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 the value of L_s, areocentric longitude of the Sun, measured in the orbital plane of the planet from its vernal equinox, $L_s = 0°$. Figures 1 and 2 were derived from references by Pollack (Refs. 6 and 7) and Zurek (Ref. 8) 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 is typically about 0.5. Two global dust storms occurred during the periods of each observation as indicated by the high values of the optical depth (they are lower bound values).

Mars has seasons comparable to those of Earth. However, the seasons are on the average about twice as long as on the Earth, corresponding to the greater length of the Martian year (Table I). Furthermore, they are distinctly unequal in duration as a result of the appreciable eccentricity of the Martian orbit. For that reason, the Martian year is not divided into months. Table I gives the duration of the Martian seasons in terrestrial and Martian days (a Martian day $\underline{\Delta}$ sol, 1 sol = 24.65 hr). Areocentric longitudes $L_s = 0°$ and 180° correspond to the spring and fall equinox for the northern hemisphere, respectively, and $L_s = 90°$ and 270° correspond to northern and southern summer solstices, respectively.

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 a 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 observed by VL (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 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.

SOLAR RADIATION AT THE TOP OF MARS ATMOSPHERE

The variation of the solar radiation at the top of the Mars atmosphere is governed by the location of Mars in its orbit and by the solar zenith angle, and is of direct beam radiation. The beam irradiance, in W/m^2, is given by:

$$G_{ob} = \frac{S}{r^2} \tag{1}$$

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 in AU (heliocentric distance) given by (9):

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

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

$$\theta = L_s - 248° \tag{3}$$

where L_s is the areocentric longitude and 248° is the areocentric longitude of Mars perihelion. The Sun-Mars mean distance in astronomical units (AU) is 1.5236915; therefore, the mean beam irradiance at the top of the Martian atmosphere is: $1371/1.5236915^2 = 590\ W/m^2$. The instantaneous beam irradiance is given by Eqs. (1) to (3):

$$G_{ob} = 590 \frac{[1 + e \cos(L_s - 248°)]^2}{(1 - e^2)^2} \tag{4}$$

and is shown in Fig. 3.

The beam irradiance on a horizontal surface is:

$$G_{obh} = G_{ob} \cos z \tag{5}$$

where z is the zenith angle of the incident solar radiation given by:

$$\cos z = \sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega \tag{6}$$

where

ϕ latitude

δ declination angle

ω hour angle measured from the true noon westward

The solar declination angle is given by:

$$\sin \delta = \sin \delta_o \sin L_s \tag{7}$$

where $\delta_o = 24.936°$ is the Mars obliquity of rotation axis. The variation of the solar declination angle is shown in Fig. 4. The four seasons pertain here to the northern hemisphere, the reverse is true in the southern hemisphere. The ratio of Mars to Earth length of day is 24.65/24. It is convenient, for calculation purposes, to define a Mars hour by dividing the Martian day into 24 hr. Using the same relationship between the Mars solar time T and the hour angle as for the Earth, we write:

$$\omega = 15T - 180 \tag{8}$$

This is shown in Fig. 5. The final solar radiation results can then be adjusted by the above ratio to correspond to actual (terrestrial) time.

Examples of the solar radiation calculation procedure and results in this paper pertain to L_s = 69°, 120°, 153°, 249° and 299° at Viking lander VL1 location ϕ = 22.3° N. Areocentric longitude L_s = 69° corresponds to aphelion; L_s = 249° to perihelion; L_s = 153° to mean radiation of 590 W/m^2; L_s= 120° corresponds to the lowest atmosphere opacity of 0.4; and L_s = 299° to the highest opacity of 3.25 (Fig. 1). For a given L_s and latitude ϕ, one can calculate the zenith angle z as function of solar time T using Eqs. (5) to (7). The beam irradiance on a horizontal surface is then determined using Eqs. (4) and (5). The diurnal variation of the beam irradiance on a horizontal surface at the top of the Mars atmosphere for the above mentioned values of L_s is shown in Fig. 6. Because of symmetry, only the afternoon values are shown in the figure. The sunset hour angle is given by:

$$\omega_{ss} = \cos^{-1}(-\tan\phi \tan\delta) \tag{9}$$

and the number of Mars daylight hours is

$$T_d = \frac{2}{15}\cos^{-1}(-\tan\phi \tan\delta) \tag{10}$$

It is of interest to calculate the solar beam insolation on a horizontal surface in watt hours per square meter (Whr/m^2), for a desired period of time between hour angles ω_1 and ω_2. This is obtained by integrating Eq. (5), i.e.,

$$I_{obh} = \frac{12^*}{\pi} G_{ob} \int_{\omega_1}^{\omega_2} (\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega)\, d\omega \tag{11}$$

or

$$I_{obh} = \frac{12^*}{\pi} G_{ob} \left[\frac{2\pi(\omega_2 - \omega_1)}{360} \sin\phi \sin\delta + \cos\phi \cos\delta (\sin\omega_2 - \sin\omega_1)\right] \tag{12}$$

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*Replace the 12 hr by 12.325 in Eqs. (11) and (12) to get the insolation with reference to actual (terrestrial) time.

A commonly used quantity is the hourly insolation, in Whr/m^2-hr. In that case ω_1 and ω_2 define an hour. The daily solar insolation, H_{obh}, on a horizontal surface, in Whr/m^2-day, is often needed. This is obtained by integrating Eq. (11) over the period from sunrise to sunset. One gets:

$$H_{obh} = \frac{24^*}{\pi} G_{ob} \left[\frac{2\pi\omega_{ss}}{360} \sin\phi \sin\delta + \cos\phi \cos\delta \sin\omega_{ss} \right] \qquad (13)$$

Table II gives the hourly beam insolation I_{obh}, and the daily beam insolation H_{obh}, on a horizontal surface at the top of the Mars surface. The diurnal variation of the hourly beam insolation data in Table II is shown in Fig. 7. To obtain the terrestrial watt-hours one needs to multiply the values in Tabel II by the ratio 24.65/24.

SOLAR RADIATION ON THE SURFACE OF MARS

The variation of the solar radiation on the Martian surface is governed by three factors: (1) the Mars-Sun distance, (2) solar zenith angle, and (3) by the opacity of the Martian atmosphere. The global solar radiation is composed of the direct beam and diffuse components. The direct beam irradiance, G_b, on the Martian surface normal to the solar rays is related by Beer's law to the optical depth, τ, of the intervening atmospheric haze:

$$G_b = G_{ob} \exp[-\tau\, m(z)] \qquad (14)$$

where $m(z)$ is the air mass determined by the zenith angle z, and can be approximated by:

$$m(z) \cong \frac{1}{\cos z} \qquad (15)$$

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*Replace the 24 hr by 24.65 hr in Eq. (13) to get the insolation with reference to actual (terrestrial) time.

The net solar flux integrated over the solar spectrum on the Martian surface was calculated by Pollack (Ref. 10) based on multiple wavelength and multiple scattering of the solar radiation. Derived data from this calculation are shown in Table III by the normalized net flux function $f(z,\tau)$ where the parameters are the zenith angle z and the optical depth τ. This table pertains to an albedo of 0.1 but can be used for higher albedo values to a first approximation. Using this data we calculated the global solar irradiance. We assumed that the diffuse irradiance is obtained by subtracting the beam from the global irradiance.

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

$$G_h = G_{bh} + G_{dh} \tag{16}$$

where

G_h global irradiance on a horizontal surface

G_{bh} direct beam irradiance on a horizontal surface

G_{dh} diffuse irradiance on a horizontal surface

The diffuse irradiance 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. (16) as for Earth-terrestrial calculations. The global irradiance G_h on a horizontal surface is given by:

$$G_h = G_{ob} \cos Z \, \frac{f(z,\tau)}{0.9^*} \tag{17}$$

The beam irradiance G_{bh} on a horizontal surface is obtained by:

$$G_{bh} = G_{ob} \cos Z \exp\left(\frac{-\tau}{\cos z}\right) \tag{18}$$

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*The factor 0.9 comes from the expression (1-albedo) in the denominator. For an albedo of 0.1, the denominator is 0.9.

The diffuse irradiance on a horizontal surfaces is obtained from Eqs. (16) to (18). Figures 8 to 10 describe the variation of the global, beam and diffuse irradiances, respectively, on a horizontal Martian surface; and are given in pairs as functions of the optical depth τ and zenith angle z. The irradiances were calculated based on Table III data and the mean irradiance of 590 W/m^2. The variation of the global irradiance G_h, Eq. (17), is shown in Figs. 8(a) and (b). The beam irradiance G_{bh} is obtained using Eq. (18) and is shown in Figs. 9(a) and (b). The beam irradiance shows a sharp decrease with increasing of the optical depth, and a relative moderate decrease with increasing of the zenith angle. The diffuse irradiance G_{dh} is shown in figure 10(a) and (b). The diffuse irradiance shows a sliding maximum with the variation of the zenith angle.

The solar radiation (global, beam and diffuse) variation (diurnal, hourly and daily) can be calculated based on the preceeding equations and the $f(z,\tau)$ table data. The following examples pertain again to the Viking lander VL1 location and areocentric longitudes L_s = 69°, 120°, 153°, 249°, and 299°. Daily solar insolation are also given for L_s = 0°, 30°, 60°, 90°, 150°, 180°, 210°, 240°, 300°, and 330°. For a given L_s and ϕ, one can calculate the variation of the zenith angle z as function of the Mars solar time T using Eqs. (5) to (8). Referring to Fig. 1 for the given L_s, the optical depth τ is determined; with Table III and Eqs. (16) to (18) one can calculate the solar radiation variation for the given day. The results are shown in Figs. 11 to 13. Because of symmetry around 12:00, the graphs in Figs. 12 and 13 are the forenoon or afternoon variation. The figures show clearly that for higher opacities, the diffuse component dominates the solar radiation.

The hourly solar insolation (global, beam and diffuse) on a horizontal surface, in Whr/m^2-hr, can be calculated based on Figs. 11 to 13 by integrating hourly areas. The daily insolation H_h on a horizontal surface is the summation of the hourly values. The beam insolation, for a desired period of time, can be also calculated by:

$$I_{bh} = \frac{12^*}{\pi} G_{ob} \int_{\omega_1}^{\omega_2} (\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega) \exp[-\tau/(\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega)] d\omega \qquad (19)$$

Tables IV to VI give the hourly global I_h, beam I_{bh} and diffuse I_{dh} insolation as well as the daily global H_h, beam H_{bh} and diffuse H_{dh} insolation. Included in the tables are also the number of Martian daylight hours and the daily mean irradiance. For a day (L_s = 299) with a relative high opacity, the daily mean global irradiance is still appreciable and is about 30 percent of that in a clear day. The diurnal variation of the hourly global insolation data in Table IV is shown in Fig. 14. The percentage of diffuse and beam insolation for the five analyzed L_s days is shown in Fig. 15. The daily global insolation on a horizontal surface on Mars is shown in Fig. 16 for twelve areocentric longitudes covering a Martian year. Using the procedure outlined, one can calculate the variation of the solar radiation for any desired day to use for any engineering system design.

CONCLUSIONS

Effective design and utilization of solar energy depend to a large extent on adequate knowledge of solar radiation characteristics in the region of solar energy system operation. In this paper we presented a procedure and solar radiation related data from which the diurnally, hourly and daily variation of insolation on Mars were calculated. This includes the global, beam and diffuse insolation on a horizontal surface, from which any desired

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*Replace the 12 hr by 12.325 hr in Eq. (19) to get the insolation with reference to actual (terrestrial) time.

solar radiation quantity can be derived for an engineering design. The global insolation on the surface of Mars was derived based on the normalized net solar flux function $f(z, \tau)$; the beam insolation was determined by Beer's law relating the isolation to the optical depth of the Martian atmosphere; and the diffuse insolation was calculated as the difference between the global and the beam insolation. The optical depths were measured at the two Viking lander locations, but can also be used, to the first approximation, for other locations. One of the most important results of this study is that there is a large diffuse component of the solar insolation, even at high optical depth, so that solar energy system operation is still possible. In absence of long term insolation data on Mars, the data presented in this paper can be used until updated data are available from new analysis or future flight missions.

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TABLE I. - MARS SEASONAL DURATION

Areocentric longitude of the sun, L_s	Season		Duration of the season Mars	
	Northern hemisphere	Southern hemisphere	Martian days	Terrestrial days
0 to 90°	Spring	Autumn	194	199
90 to 180°	Summer	Winter	178	183
180 to 270°	Autumn	Spring	143	147
270 to 360° or 0°	Winter	Summer	154	158
			669	687

TABLE II. - HOURLY AND DAILY BEAM INSOLATION ON A HORIZONTAL SURFACE AT TOP OF MARS ATMOSPHERE

[VL1: ϕ = 22.3°N]

Hourly* I_{obh} (Whr/m^2-hr) for hours ending at:								Daily* H_{obh}, Whr/m^2-day
Day-L_s	13:00	14:00	15:00	16:00	17:00	18:00	19:00	
69°	488	460	405	328	234	128	25	4136
120°	528	497	437	353	249	134	23	4442
153°	572	536	467	368	247	113	7	4620
249°	496	455	376	263	126	8	--	3449
299°	478	439	364	257	127	10	--	3350

*Multiply by 24.65/24 to obtain actual (terrestrial) Whr/m^2

TABLE III. - NORMALIZED NET FLUX FUNCTION $f(z,\tau)$ AT THE MARTIAN SURFACE

Optical depth	Zenith angle Z, deg									
τ	0	10	20	30	40	50	60	70	80	85
0.1	0.885	0.883	0.882	0.880	0.876	0.870	0.857	0.830	0.755	0.635
0.2	.866	.865	.860	.858	.851	.836	.813	.758	.640	.470
0.3	.847	.846	.841	.836	.826	.806	.774	.708	.562	.412
0.4	.828	.827	.821	.815	.802	.778	.740	.667	.502	.373
0.5	.810	.810	.802	.796	.778	.752	.708	.628	.452	.342
0.6	.793	.791	.785	.775	.755	.725	.677	.593	.414	.318
0.7	.776	.773	.766	.755	.733	.700	.646	.555	.383	.298
0.8	.760	.756	.750	.736	.710	.675	.616	.520	.360	.280
0.9	.745	.740	.733	.717	.690	.650	.587	.487	.336	.264
1.0	.732	.725	.717	.700	.670	.628	.560	.455	.317	.252
1.1	.713	.709	.700	.682	.651	.604	.539	.433	.300	.239
1.2	.697	.692	.683	.662	.632	.585	.518	.413	.288	.230
1.3	.682	.677	.667	.646	.613	.567	.498	.394	.273	.220
1.4	.666	.661	.650	.629	.596	.546	.478	.379	.262	.210
1.5	.651	.646	.633	.612	.580	.530	.460	.362	.251	.202
1.6	.637	.630	.618	.597	.563	.512	.441	.348	.240	.195
1.7	.622	.615	.601	.581	.546	.494	.424	.332	.232	.188
1.8	.609	.600	.586	.568	.531	.480	.408	.318	.224	.181
1.9	.596	.587	.571	.551	.514	.464	.393	.304	.217	.176
2.0	.582	.573	.558	.537	.500	.448	.378	.293	.208	.170
2.25	.552	.542	.522	.501	.462	.410	.343	.265	.190	.156
2.50	.518	.509	.492	.469	.430	.378	.316	.242	.174	.145
2.75	.486	.478	.462	.440	.401	.353	.293	.224	.158	.136
3.00	.460	.450	.434	.414	.376	.330	.273	.206	.150	.128
3.25	.434	.424	.410	.390	.354	.308	.254	.193	.140	.120
3.50	.411	.400	.387	.367	.333	.290	.240	.180	.132	.110
4.00	.370	.360	.347	.330	.296	.258	.212	.160	.118	.100
5.00	.294	.286	.275	.258	.230	.203	.166	.130	.094	.080
6.00	.228	.223	.215	.200	.178	.153	.130	.103	.080	.068

TABLE IV. - HOURLY AND DAILY GLOBAL INSOLATION ON A HORIZONTAL SURFACE AT MARS SURFACE

[VL1: ϕ = 22.3°N]

Hourly global insolation* I_h (Whr/m^2-hr) for hours ending at:									Daily global insolation,* H_h, Whr/m^2day	Daylight hours* T_d, hr	Daily mean global irradiance, W/m^2
Day-L_s	τ	13:00	14:00	15:00	16:00	17:00	18:00	19:00			
69°	0.65	420	390	338	263	170	78	11	3340	13.34	250
120°	.40	477	446	387	306	201	98	15	3860	13.24	292
153°	.50	508	471	399	302	185	73	3	3882	12.62	308
249°	1.40	307	270	204	122	45	2	--	1900	10.66	178
299°	3.25	170	149	107	61	24	1	--	1024	10.75	95

*Multiply by 24.65/24 to obtain actual (terrestrial) Whr/m^2 or hours

TABLE V. - HOURLY AND DAILY BEAM INSOLATION ON A HORIZONTAL SURFACE AT MARS SURFACE

[VL1: ϕ = 22.3°N]

Hourly beam insolation* I_{bh} (Whr/m^2-hr) for hours ending at:									Daily beam insolation*, H_{bh}, Whr/m^2day	Daylight hours* T_d, hr	Daily mean beam irradiance, W/m^2
Day-L_s	τ	13:00	14:00	15:00	16:00	17:00	18:00	19:00			
69°	0.65	252	230	186	128	67	20	3	1768	13.34	133
120°	.40	352	322	265	190	103	33	2	2534	13.24	191
153°	.50	345	310	244	163	77	15	--	2308	12.62	183
249°	1.40	69	50	26	10	2	--	--	314	10.66	29
299°	3.25	3	2	1	---	--	--	--	12	10.75	1

*Multiply by 24.65/24 to obtain actual (terrestrial) Whr/m^2 or hours

TABLE VI. - HOURLY AND DAILY DIFFUSE INSOLATION ON A HORIZONTAL SURFACE AT MARS SURFACE

[VL1: = 22.3°N]

Hourly diffuse insolation* I_{dh} (Whr/m^2-hr) for hours ending at:									Daily diffuse insolation,* H_{dh}, Whr/m^2day	Daylight hours* T_d, hr	Daily mean diffuse irradiance, W/m^2
Day-L_s	τ	13:00	14:00	15:00	16:00	17:00	18:00	19:00			
69°	0.65	168	160	152	135	103	58	10	1572	13.34	118
120°	.40	125	124	122	116	98	65	13	1326	13.24	100
153°	.50	163	161	155	139	108	58	3	1574	12.62	125
249°	1.40	238	220	178	112	43	2	--	1586	10.66	149
299°	3.25	167	147	106	61	24	1	--	1012	10.75	94

*Multiply by 24.65/24 to obtain actual (terrestrial) Whr/m^2 or hours

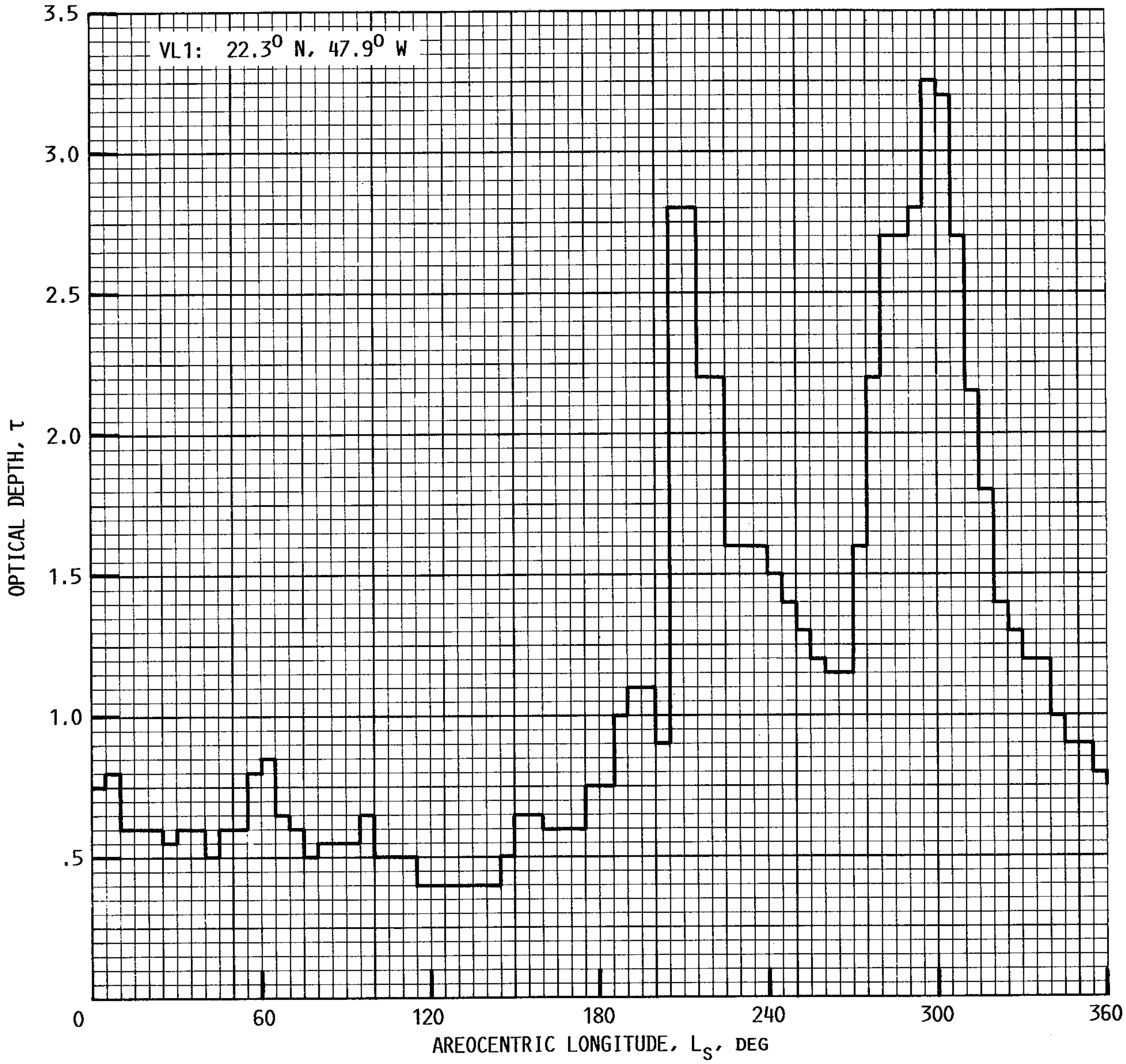


FIGURE 1. - OPTICAL DEPTH AS MEASURED FOR VIKING LANDER VL1 AS FUNCTION OF AREOCENTRIC LONGITUDE

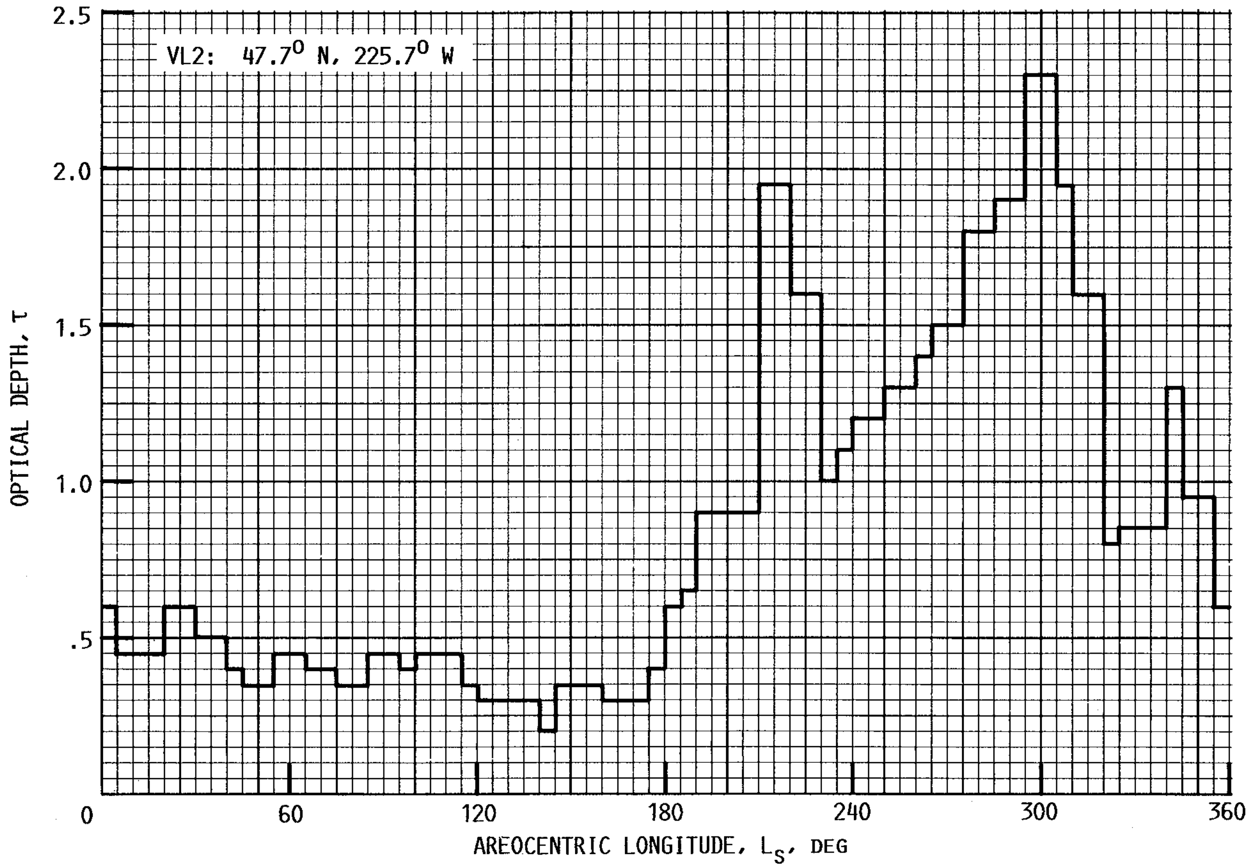


FIGURE 2. - OPTICAL DEPTH AS MEASURED FOR VIKING LANDER VL2 AS FUNCTION OF AREOCENTRIC LONGITUDE

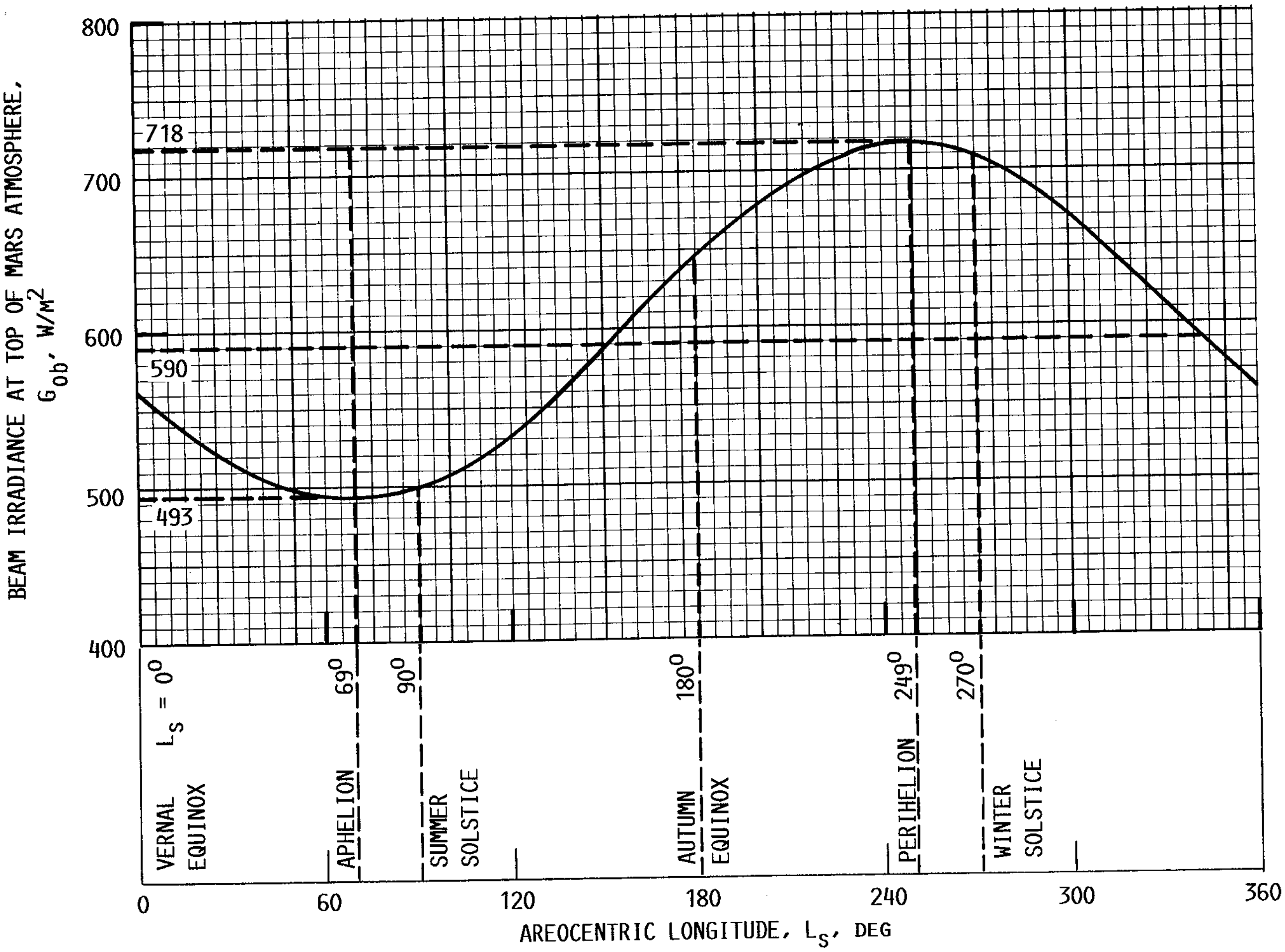


FIGURE 3. - BEAM IRRADIANCE AT THE TOP OF MARS ATMOSPHERE AS FUNCTION OF AREOCENTRIC LONGITUDE.

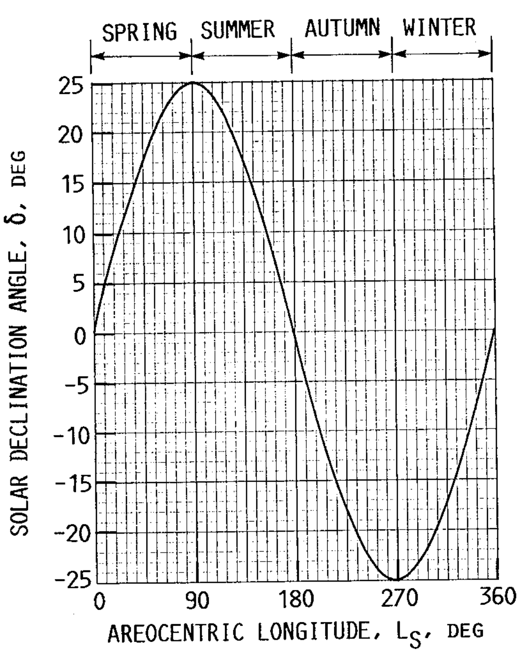


FIGURE 4. - VARIATION OF SOLAR DECLINATION ANGLE δ, WITH AREOCENTRIC LONGITUDE, L_S.

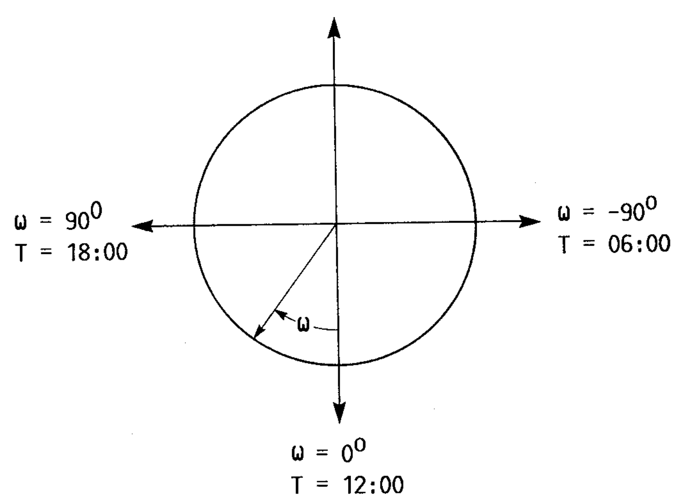


FIGURE 5. - SOLAR TIME AND HOUR ANGLE RELATION.

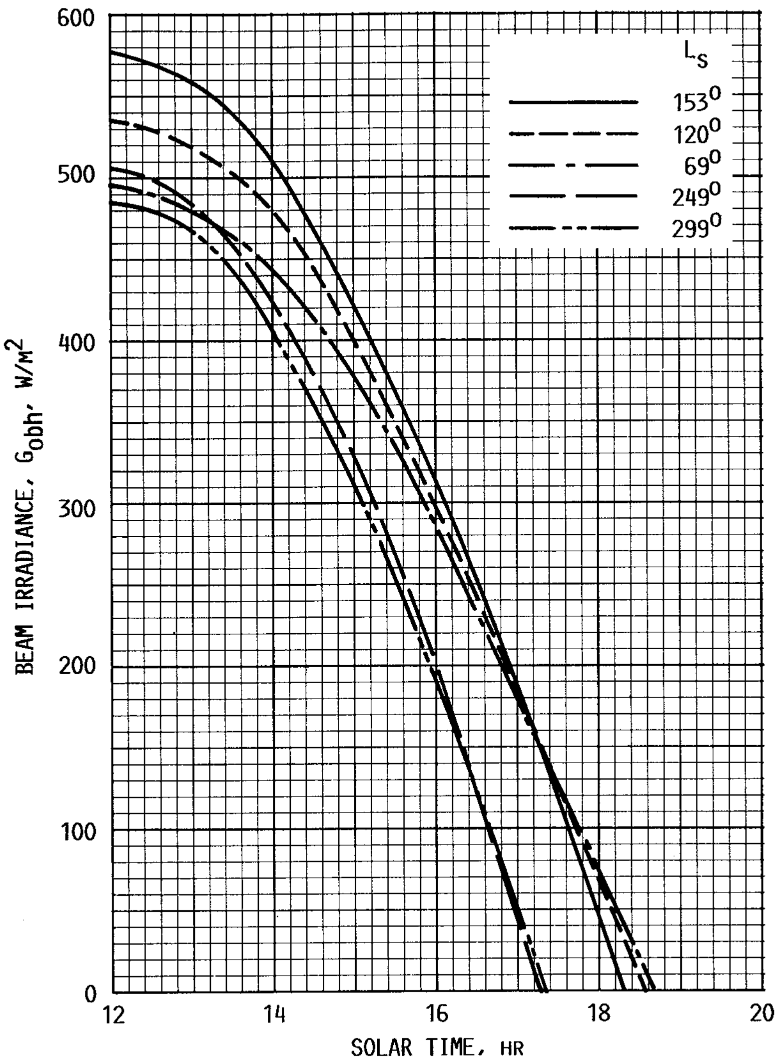


FIGURE 6. - DIURNAL VARIATION OF BEAM IRRADIANCE ON A HORIZONTAL SURFACE AT TOP OF MARS ATMOSPHERE.

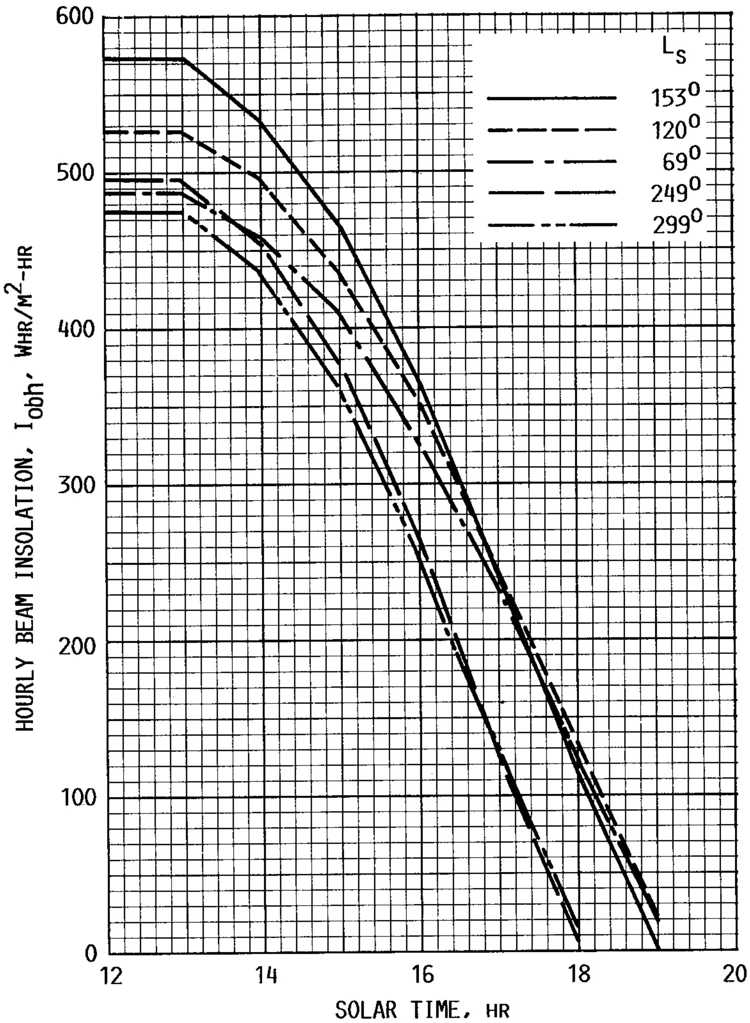
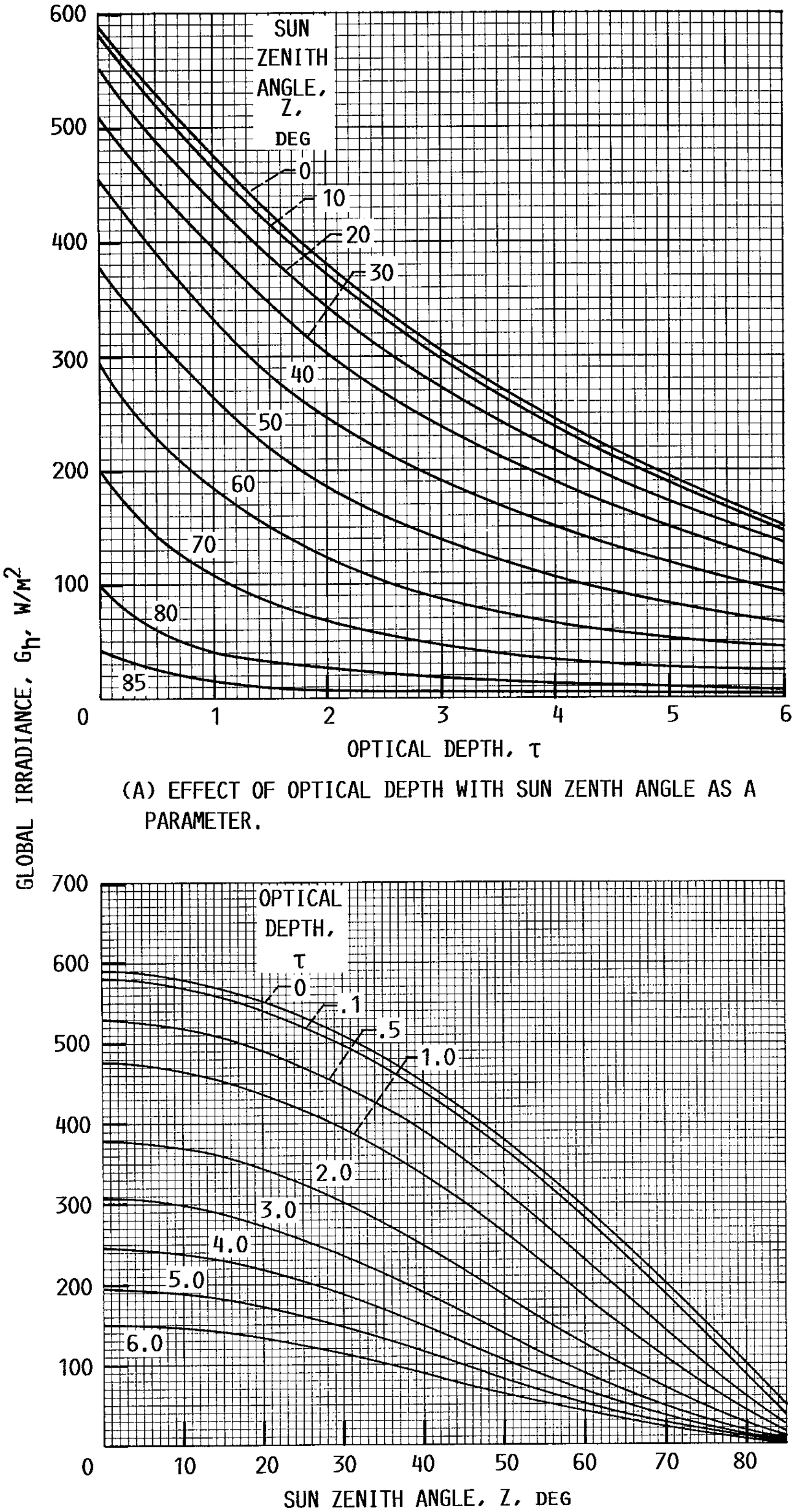


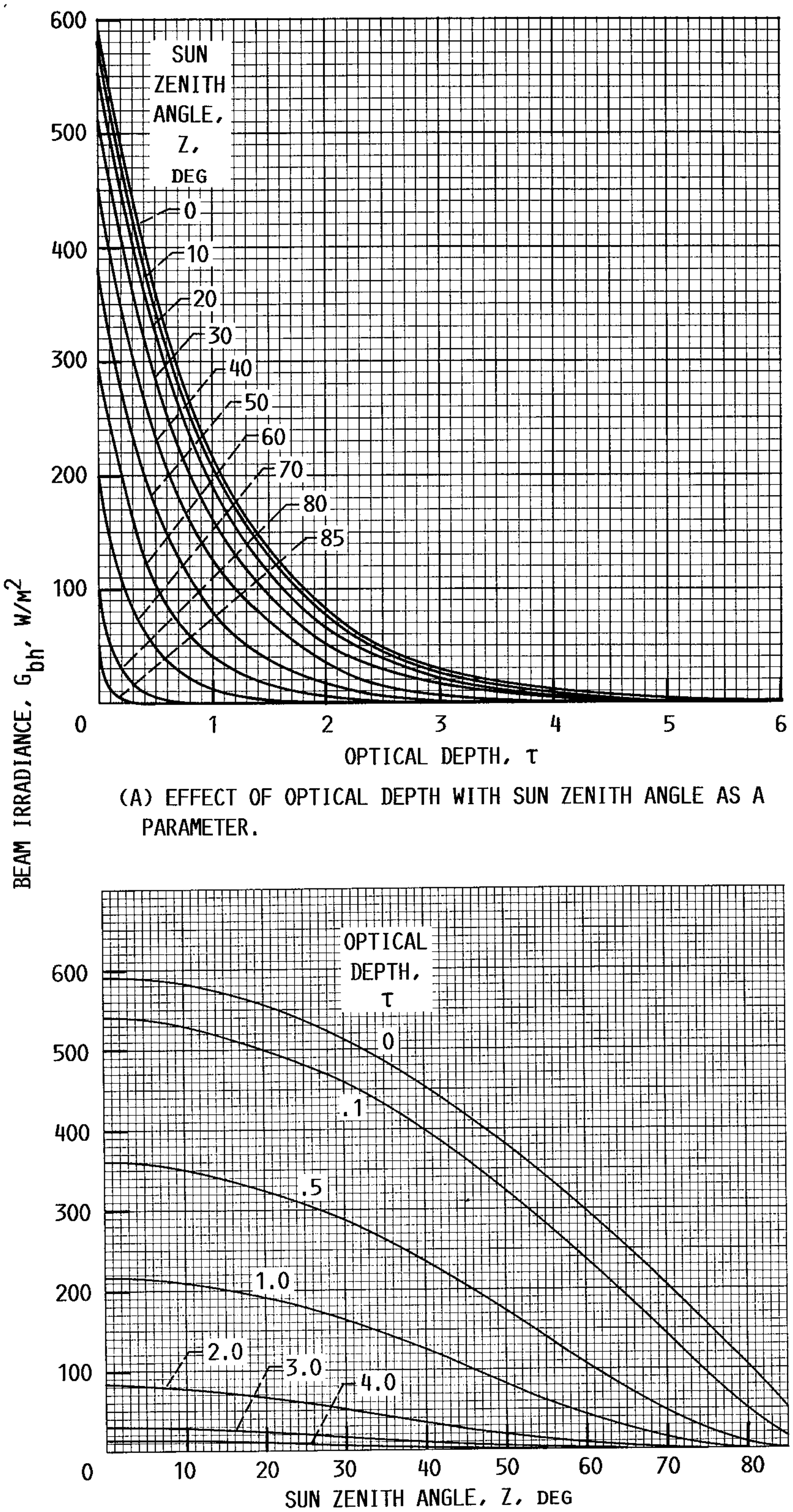
FIGURE 7. - DIURNAL VARIATION OF HOURLY BEAM INSOLATION ON A HORIZONTAL SURFACE AT TOP OF MARS ATMOSPHERE.



(A) EFFECT OF OPTICAL DEPTH WITH SUN ZENTH ANGLE AS A PARAMETER.

(B) EFFECT OF SUN ZENITH ANGLE WITH OPTICAL DEPTH AS A PARAMETER.

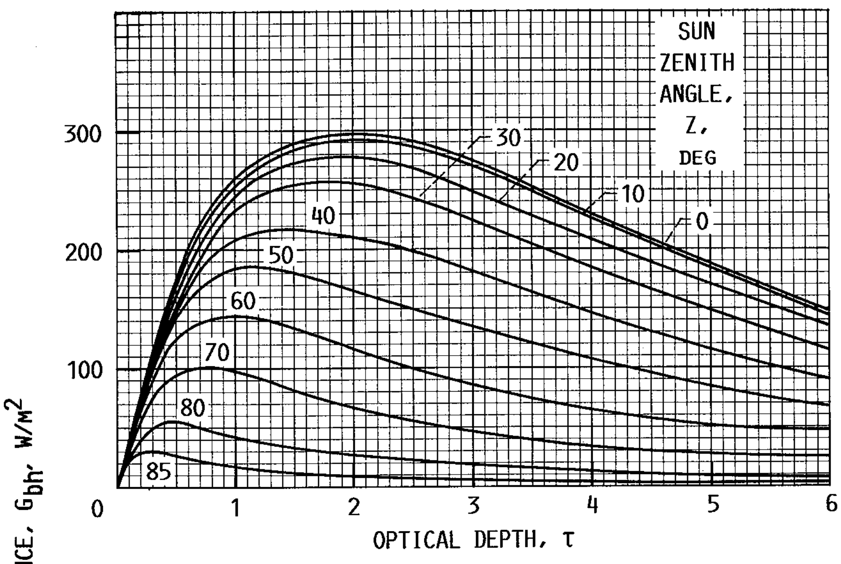
FIGURE 8. - VARIATION OF GLOBAL IRRADIANCE WITH OPTICAL DEPTH AND SUN ZENITH ANGLE ON A HORIZONTAL SURFACE.



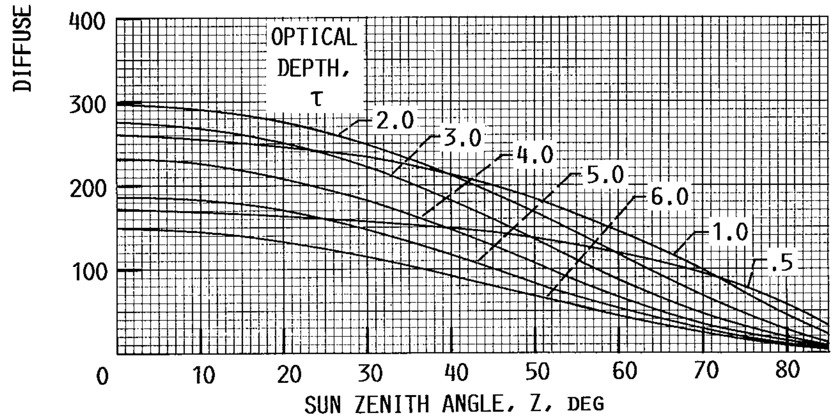
(A) EFFECT OF OPTICAL DEPTH WITH SUN ZENITH ANGLE AS A PARAMETER.

(B) EFFECT OF SUN ZENITH ANGLE WITH OPTICAL DEPTH AS A PARAMETER.

FIGURE 9. - VARIATION OF BEAM IRRADIANCE WITH OPTICAL DEPTH AND SUN ZENITH ANGLE ON A HORIZONTAL SURFACE.



(A) EFFECT OF OPTICAL DEPTH WITH SUN ZENITH ANGLE AS A PARAMETER.



(B) EFFECT OF SUN ZENITH ANGLE WITH OPTICAL DEPTH AS A PARAMETER.

FIGURE 10. - VARIATION OF DIFFUSE IRRADIANCE WITH OPTICAL DEPTH AND SUN ZENITH ANGLE ON A HORIZONTAL SURFACE.

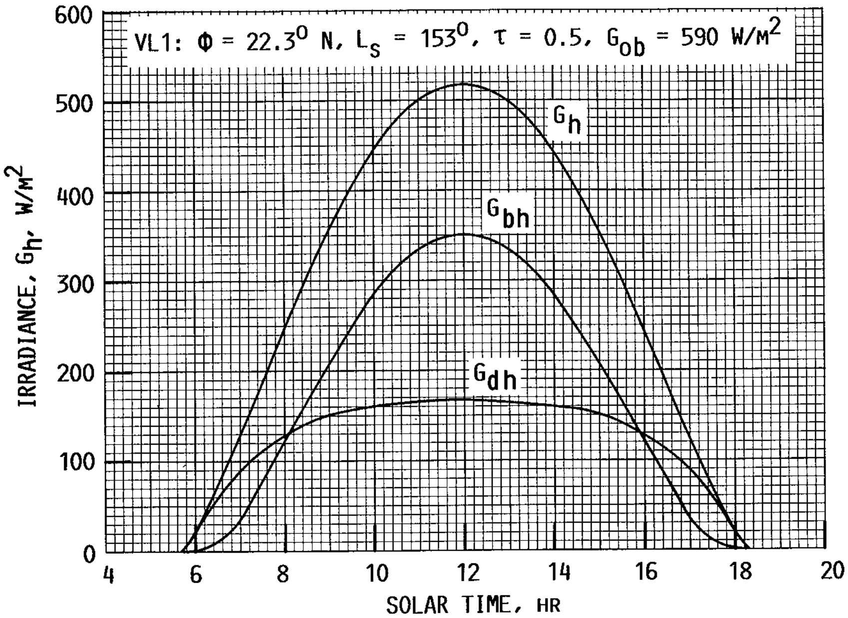


FIGURE 11. - DIURNAL VARIATION OF GLOBAL G_h, BEAM G_{bh} AND DIFFUSE G_{dh} IRRADIANCE ON A HORIZONTAL MARS SURFACE AT VIKING LANDER VL1.

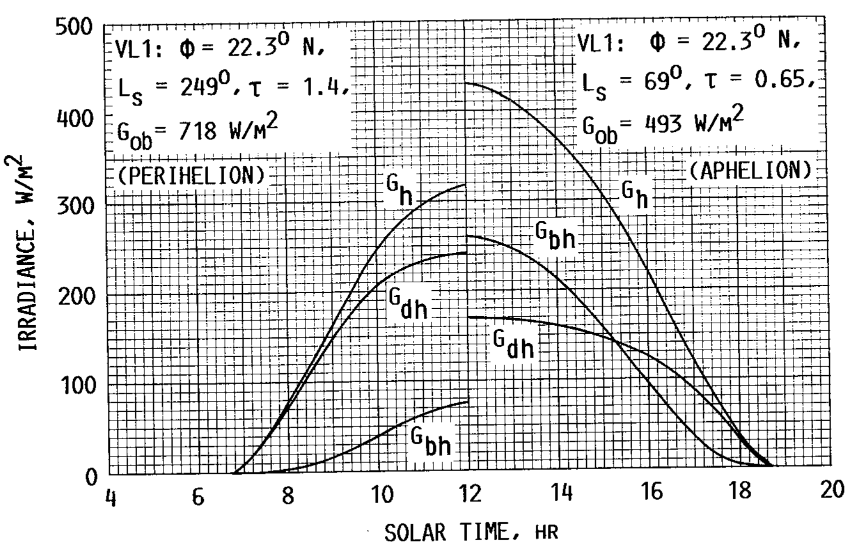


FIGURE 12. - DIURNAL VARIATION OF GLOBAL G_h, BEAM G_{bh} AND DIFFUSE G_{dh} IRRADIANCE ON A HORIZONTAL MARS SURFACE AT VIKING LANDER VL1.

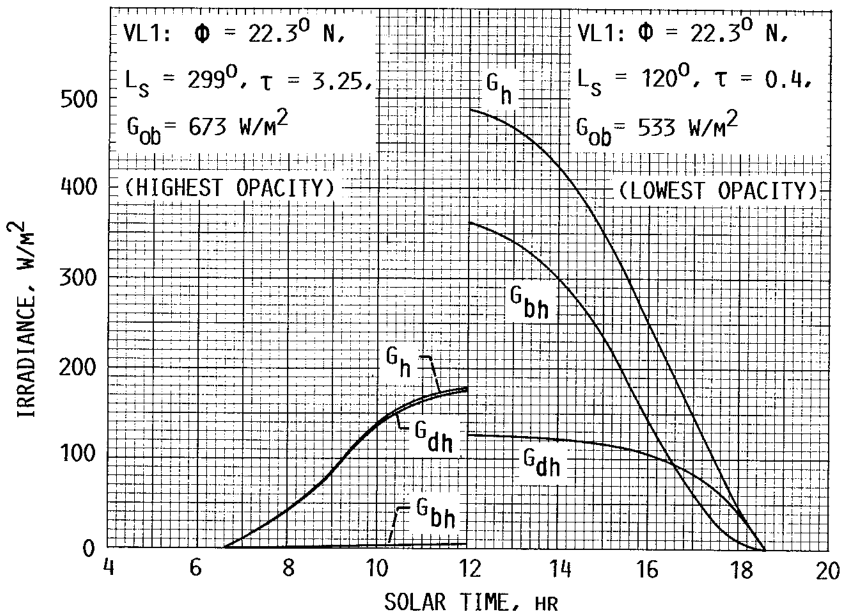


FIGURE 13. - DIURNAL VARIATION OF GLOBAL G_h, BEAM G_{bh} AND DIFFUSE G_{dh} IRRADIANCE ON A HORIZONTAL MARS SURFACE AT VIKING LANDER VL1.

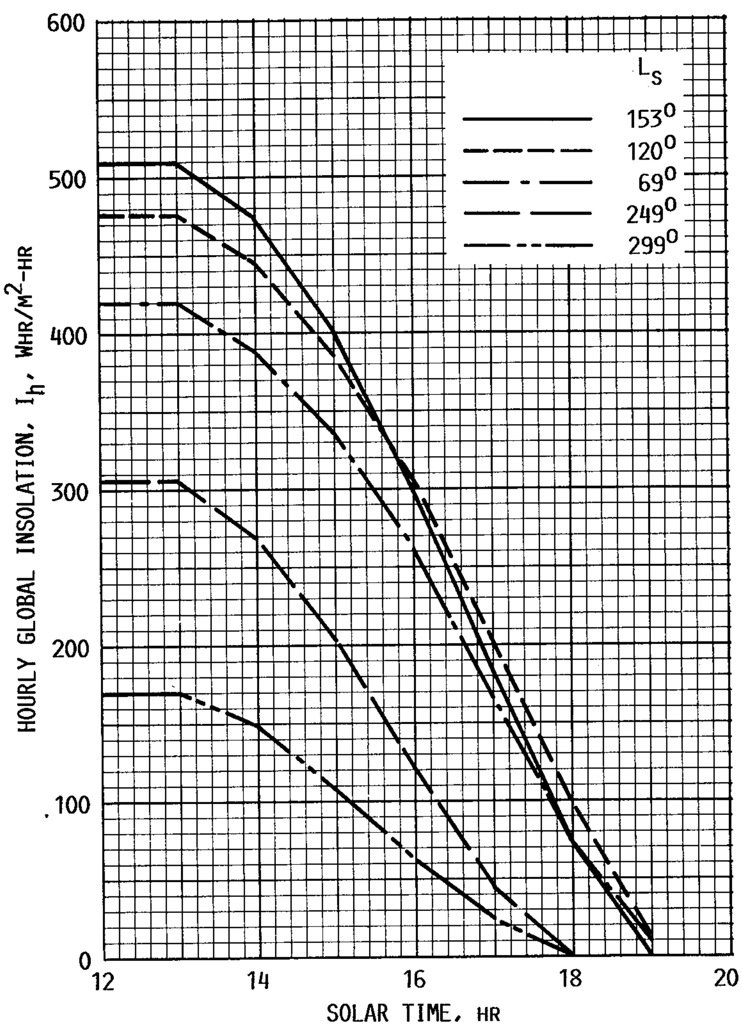


FIGURE 14. - DIURNAL VARIATION OF HOURLY GLOBAL INSOLATION ON A HORIZONTAL SURFACE ON MARTIAN SURFACE.

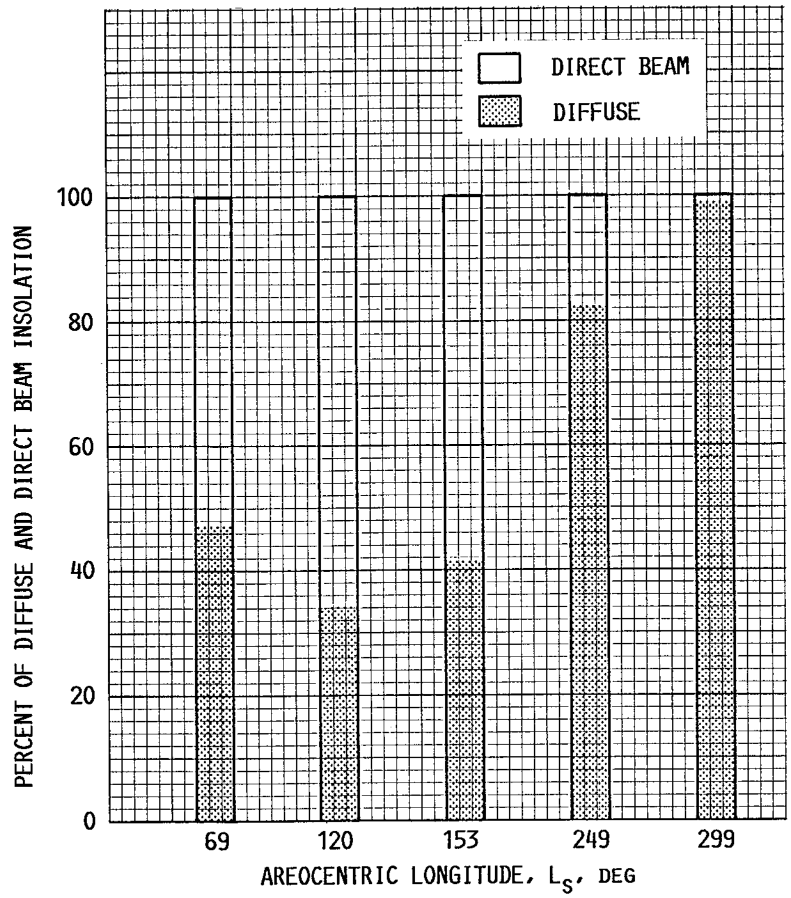


FIGURE 15. - PERCENT OF DIFFUSE AND DIRECT BEAM INSOLATION ON A HORIZONTAL MARS SURFACE.

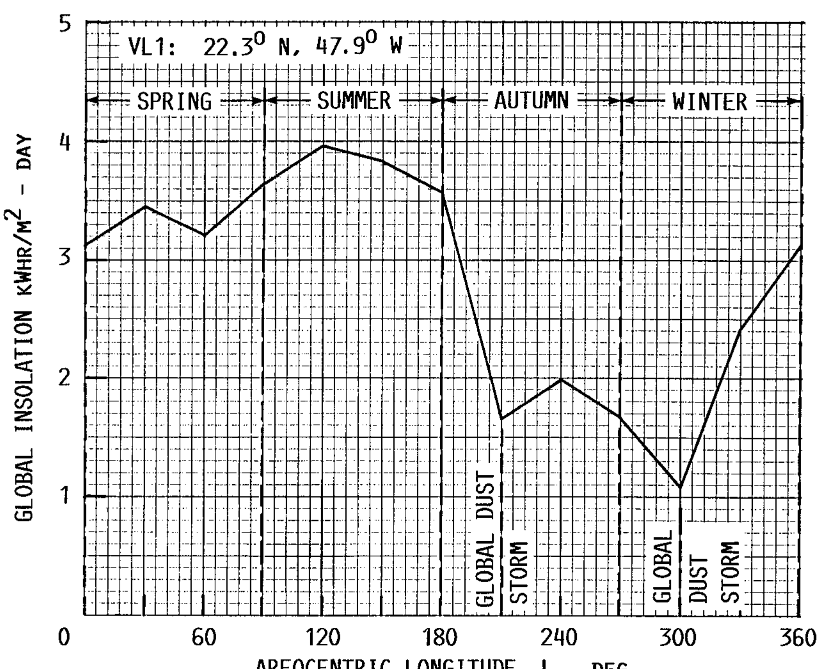


FIGURE 16. - DAILY GLOBAL INSOLATION ON A HORIZONTAL MARS SURFACE AT VIKING LANDER VL1.

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15. Supplementary Notes

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16. Abstract

Detailed information on solar radiation characteristics on Mars are necessary for effective design of future planned solar energy systems operating on the surface of Mars. In this paper we present a procedure and solar radiation related data from which the diurnally, hourly and daily variation of the global, direct beam and diffuse insolation on Mars are calculated. The radiation data are 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.

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