A new method to estimate the solar irradiance on Martian slopes

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Purpose A realistic description of the illumination conditions on the Martian surface is a necessary prerequisite for

- space exploration studies (solar panel engineering and landing site selection),
- remote-sensing retrievals (especially over complex terrains),
- energy balance models (surface temperature calculations and ice stability issues),
- meteorological models (radiative forcing of the atmosphere by the surface).

Neglecting the influence of slope tilting on the solar irradiance reaching the topographically uneven Martian terrains could lead to wrong diagnostics in those studies.

Contribution We found an accurate and computationally efficient method to calculate, in a Mars-like dusty atmosphere, the solar irradiance reaching an inclined surface assuming the value in the horizontal case is known. What follows is a brief summary of our method : a complete description was published recently in [1].

Compared to previous work [2], our method ensures realistic estimations of the contribution of scattered irradiance by the Martian atmospheric dust. The parameterization is validated by complete 3D Monte-Carlo radiative transfer calculations.

General facts Three components of the total shortwave flux reaching the surface should be taken into account : the direct incoming flux from the sun $\mathcal{D}$, the scattered flux by the atmospheric dust $\mathcal{S}$, and the reflected flux from the neighboring terrains $\mathcal{R}$. The contribution of $\mathcal{S}$ on the total flux $\mathcal{F} = \mathcal{D} + \mathcal{R} + \mathcal{S}$ is of particular significance in the case of the dusty Martian atmosphere.

The practical problem is the following (see figure 1) : given the sun position (μ_0, ψ_0), the atmosphere opacity at a reference wavelength τ, the Lambertian albedo A_L, and the radiative fluxes on an horizontal surface $(\mathcal{D}_0, \mathcal{S}_0)$, how can the solar irradiance $\mathcal{F}$ on a slope of given inclination θ and orientation ψ be parameterized ?

Direct and reflected fluxes An accurate estimation of $\mathcal{D}$ and $\mathcal{R}$ can be based on geometrical considerations only. Two quantities are critical :

1. the cosine μ_s of the angle i between the incident sun rays and the normal to the slope (see figure 1),
2. the sky-view factor σ_s which quantifies the proportion of the sky in the half hemisphere "seen" by the slope that is not obstructed by the surrounding terrain (assumed to be flat).

Scattered flux: Background Calculating the scattered flux $\mathcal{S}$ by the atmospheric dust is more difficult than estimating $\mathcal{D}$ and $\mathcal{R}$. In terrestrial studies of solar energy, the formula for scattered flux known as the Hay-Perez model [3,4] yields good approximations of the diffuse irradiance $\mathcal{S}$

$$\frac{\mathcal{S}}{\mathcal{S}_0} = \kappa_1 \frac{\mu_s}{\mu_0} + (1 - \kappa_1)\,\sigma_s + \kappa_2 \sin\theta \qquad (1)$$

The three components of the equations accounts respectively for

1. the anisotropic component, assumed to be predominantly caused by the forward scattered flux enhancement in the circumsolar region of the sky,
2. the isotropic component, which predominates in the case of overcast skies,
3. the "horizon brightening" anisotropic component (due to enhanced aerosol scattering in the direction of the horizon).

κ_1 and κ_2 are linear functions of atmospheric transmittance and solar zenith angle, with sets of linear coefficients empirically defined for different categories of sky brightness.

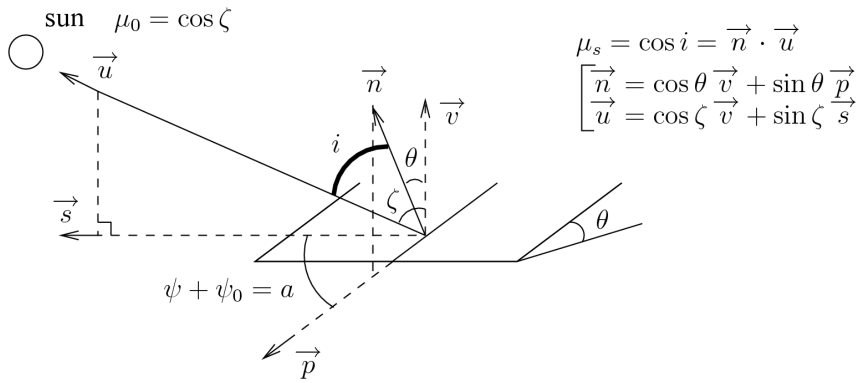

Figure 1: The slope problem and the corresponding geometrical parameters. The solar zenith angle is ζ. The local vertical is $\mathbf{v}$. The normal vector to the slope is $\mathbf{n}$.

Scattered flux: new model For the Martian applications, the Hay-Perez model yields unsatisfactory results. We thus propose a generalization of this linear three-component Hay-Perez model which captures most of the complexity of the variations of $\mathcal{S}$ with μ_0, τ and (θ, ψ). The scattered flux reaching the slope can be expressed by a physically-based simple formula

$$\boxed{\mathcal{S} = \mathcal{S}_0\,\mathbf{s}^{\mathrm{t}} \times (\mathbf{M} + \mu_0\,\mathbf{N}) \times \mathbf{g}} \tag{2}$$

where

- **s** is a "scattering" vector (slope versus sky), both accounting for the isotropic scattered component and the anisotropic horizon brightening component:

$$\mathbf{s} = \begin{bmatrix} 1 \\ e^{-\tau} \\ \sin\theta \\ e^{-\tau}\sin\theta \end{bmatrix} \tag{3}$$

- **g** is a "geometry" vector (slope versus sun), with first component accounting for the circumsolar contribution:

$$\mathbf{g} = \begin{bmatrix} \mu_s/\mu_0 \\ 1 \end{bmatrix} \tag{4}$$

- $\mathbf{M}$ and $\mathbf{N}$ are two numerical 4×2 coupling matrices, empirically determined from the Monte-Carlo reference calculations using the dust optical properties from [5,6] (two coefficients in the matrices are multiplied by the sky-view factors σ_s).

Scattered flux: accuracy Performance of the parameterization is very good for a wide range of insolation conditions, dusty atmosphere, slope orientation and inclination : satisfactory linear behavior is observed for $\theta \leqslant 30°$, $\tau \leqslant 1$, and $\mu_0 \geqslant 0.5$ and linear assumptions also yield correct results (if not perfect) for the extended cases $\theta \leqslant 40°$, $\tau \leqslant 9$, and $\mu_0 \geqslant 0.15$. The root mean square error (respectively the mean absolute error) of the linear parameterization for scattered flux with respect to the Monte-Carlo reference is 2.2 (1.4) W.m^{-2} for $\theta \leqslant 30°$ and $\tau \leqslant 1$; 2.7 (1.6) W.m^{-2} if $\theta \leqslant 40°$; and 3.6 (2.2) W.m^{-2} if $\tau \leqslant 4$.

In difficult cases such as clear Martian atmosphere and steep slope not facing the sun, or sun rather low in the sky, the *maximal* error might reach 15 W.m^{-2} (corresp. relative error 15%) or 33% (corresp. absolute error 9 W.m^{-2}). In most cases, the maximal error on the scattered irradiance is however below 5 W.m^{-2} and the maximal relative error is below 7% (note that the relative error on the total flux $\mathcal{F}$ is lower).

Conclusion An example of surface temperature calculations using our solar irradiance scheme is shown in figure 2. Future improvements of the present parameterization, consisting in slight modifications of the matrices coefficients to be in better agreement with the upcoming revised dust optical properties [7], will however be considered. Alternative formula for σ_s based on more realistic considerations, inclusion of directional effects in the $\mathcal{R}$ calculations, and solutions for better accuracy on terrains receiving less irradiance, will be investigated too as future improvements of the model.

Note: Thermal radiation To complete the description of the Martian radiative environment, an estimation of the thermal infrared incident flux $\mathcal{T}$ on the inclined surface can be obtained by assuming that the atmospheric thermal radiation is isotropic

$$\mathcal{T} = \sigma_s \, \mathcal{T}_0 + (1 - \sigma_s) \, \mathcal{E}$$

where $\mathcal{T}_0$ is the atmospheric incident thermal IR flux on an horizontal surface and $\mathcal{E} = \epsilon \sigma \, T_s^4$ is the thermal emission (σ is the Stefan-Boltzmann constant) from the surrounding terrains with emissivity ϵ and temperature T_s.

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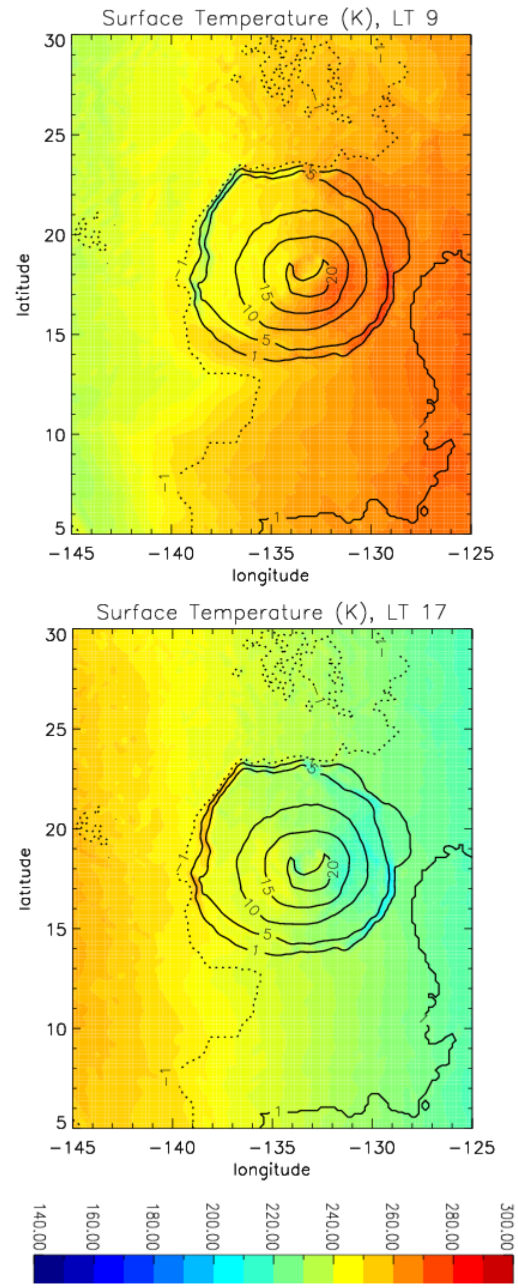

Figure 2: An example of surface temperature estimated on Olympus Mons at $L_s = 175°$, using our slope irradiance scheme. Local time is $09:00$ (top) and $17:00$ (bottom). The surface temperature is very sensitive to the variations of incoming flux on the surface in the low thermal inertia Olympus Mons terrains (note that in order to highlight the slope effect the thermal inertia was supposed to be constant $I = 85$ J m^{-2} s$^{-1/2}$ K^{-1}).