OPTICAL DEPTH OF THE MARTIAN ATMOSPHERE AND SURFACE ALBEDO FROM HIGH RESOLUTION ORBITER IMAGES.

E. V. Petrova, *Space Research Institute RAS, Moscow, Russia, (epetrova@iki.rssi.ru),* **N. M. Hoekzema, W. J. Markiewicz,** *MPS, Katlenburg-Lindau, Germany,* **N. Thomas**, *Space Research and Planetology Division, Physikalisches Institut, Bern, Switzerland.*

Introduction: The atmosphere of Mars contains a considerable amount of reddish airborne dust and other aerosols. As a consequence, it commonly has an optical depth of 0.3-0.7. This haze of aerosols reddens orbiter images and diminishes their contrast and spatial resolution, so that their interpretation should consider the effects of the haze. For quantifying these effects one needs at least to know the optical depth of the atmosphere and the haze therein.

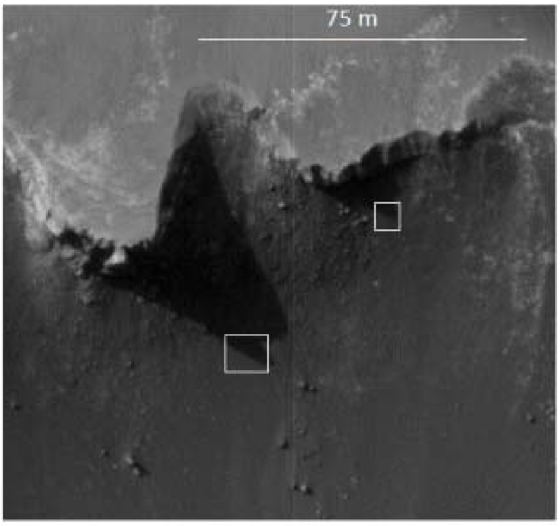

Figure 1 A fragment of the HiRISE red image TRA_0873_1780 analyzed in this work. It shows the northern edge of the Victoria crater. The two analyzed regions are marked by white rectangles.

Obviously, the brightness difference between a shadowed and a sunlit region depends on the optical depth of the atmosphere. For example, during sunny weather on Earth, a region in the sun is commonly several times brighter than a shadowed one, but the brightness difference is negligible on a cloudy day. The translation of this difference into optical depth is what we named the “shadow method.” However, there is no general analytically correct way to do this “translation” because the radiative transfer is too complex. Hoekzema et al. 2011 [1] presented a basic version of the shadow method which in essence is not much more than a fit between optical depth as measured by the MER rovers and the observed brightness differences between nearby shadowed and sunlit comparison regions.

Continuing their work we here present results from a more sophisticated version that does not assume, as their work did, that the underlying surface is Lambertian, but more realistically, assumes non-isotropic scattering. It requires, in general, a model that describes how the aerosols scatter radiation, but it is possible to diminish the influence of this model on the estimate of optical depth, by analyzing two pairs of shadowed and sunlit comparison regions on differently facing slopes This is possible if a good Digital Terrain Model is available so that the slope angles can be calculated accurately.

For this work we used the image shown in Figure 1. It is a part of the HiRISE image TRA_0873_1780 taken on October 3, 2006. It shows the northern rim of the Victoria crater in Meridiani Planum (1.95°S, 5.53°W). At that time, this crater was the exploration site of the Opportunity rover. On that day, the rover measured the optical depth both before and after the moment that the HiRISE image was taken. These rover measurements yielded optical depths in the range $\tau = 0.46 \pm 0.02$.

Theory: The intensity of the radiation in orbiter images of Mars depends on the reflectance properties of the surface, and on the optical depth of the aerosols and their scattering properties. Figure 2 shows the various contributions to the radiation field that is measured by an orbiter camera.

Obviously, term 4 is absent in a shadow because there is no direct illumination into a shadowed region. Above shadows that are more than several kilometers large, term 3 is small because there is not much radiation from surrounding sunlit terrain that is scattered upwards towards the camera. In this case the brightness of shadows can be well approximated by the sum of the first three terms. Above a small shadow, as in here described case, term 3 is very nearly as large as above the surrounding sunlit terrain. With this approximation the difference between shadowed and sunlit regions is simply, $\Delta B = B_{sunlit} - B_{shad} = B_{S4}$.

In the general version of the method, we use single scattering properties of atmospheric aerosols as given by Markiewicz et al. 1999 [2], and now the remaining two unknown quantities – the optical depth τ and the surface albedo a_s – can be estimated from the two equations that describe B_{sunlit} and ΔB. If the surface reflectance is approximated with the Lambert law, then the surface terms in the radiative transfer equation (Sobolev, 1975 [3]) can be separated, and the problem can be solved from a single comparison between a shadowed and a sunlit region. That is, if these two regions have the same surface albedo a_s. For non-isotropically scattering surfaces (i.e., non-Lambertian surfaces) the result can be obtained with a more sophisticated procedure. We tested the Akimov law for surface reflectance with different roughness parameters v that are valid for the lunar surface Kreslavsky et al. 2000 [4]).

The advantage of the approximation $\Delta B=B_{S4}$ is that it is independent of the atmospheric model. Moreover, if we assume that the surface albedo a_s is similar to the TOA albedo (Top Of Atmosphere albedo) then we can directly estimate the optical depth τ' from the ratio $\Delta B/B_{sunlit}$, but this simplification yields large errors. However, these errors appear mostly systematic when the analyzed orbiter images are taken in colors between yellow and red [1], meaning that one can obtain a reasonably accurate optical depth in these colors by dividing the result by an empirical factor, obtained for example by comparison with optical depth measured by rovers.

Another way to avoid the need of using an atmospheric model (or at least to weaken its influence) is to analyze two pairs of sunlit/shadowed regions that are on differently orientated slopes. Then B_{sunlit} can be eliminated from the procedure, and τ can be found from the ratio $\Delta B^{(1)}/\Delta B^{(2)}$. When analyzing small shadows, as in this case, this ratio only contains the contributions directly transmitted through the atmosphere, i.e. term B_{S4}. If the albedos of these two regions differ significantly, their ratio is required to reduce the error in the estimate of the optical depth. This ratio can be obtained from separate shadow analysis of each of the two regions. For such simultaneous analysis of two pairs of regions, it is crucial to accurately know the geometry of the slopes.

Results: The table below shows shadow method estimates of optical depth τ and of surface albedo a_s. These values were retrieved from the regions indicated in Figure 1. The second estimate, τ', uses approximation $\Delta B=B_{S4}$, others the full formulation and assuming known scattering properties of aerosols.

It has been shown that simple formulas, requiring no atmospheric models, can be applied to small shadows observed on Mars. The obtained estimates of the optical depth at the northern rim of Victoria crater agree quite well with the value measured by the *Opportunity* rover. However, if the part of a shadowed region that is analyzed is far away from the shadow border then, these estimates can be considered as a lower limit. The upper limit is provided by the exact formulas.

Conclusions: The shadow method translates the difference in brightness between shadowed and sunlit comparison regions into optical depth. The surface albedo can be also obtained. In its general version, the shadow method is sensitive to; (i) the model of atmospheric aerosols that is used, (ii) the assumed surface reflectance function, and (iii) the surface albedo if the surface is non-Lambertian. However, the influence of the surface albedo and of the aerosol model can be removed, or at least weakened, by analyzing two pairs of sunlit/shadowed regions that differ enough in observing geometry (i.e., are located on differently orientated slopes). This approach yields estimates of the optical depth that agree well with the accurate measurements by the Opportunity rover. Moreover, it is possible to estimate the parameters of surface reflectance laws if the optical depth is known from rover (or other accurate) measurements.

References:

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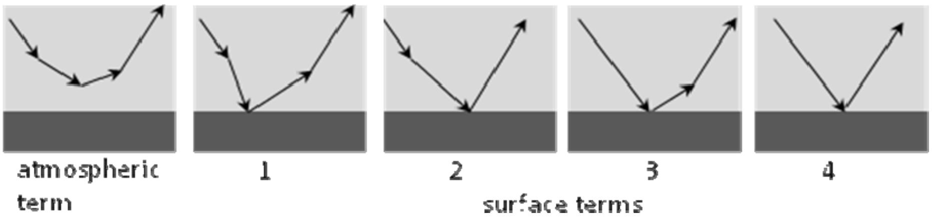

Figure 2. The five components that together yield the observed orbiter image (see text for details).

	Region1		Region 2		Joint analysis
	τ	a_s	τ	a_s	τ
Lambert τ_L	0.575	0.173	0.575	0.197	0.5-0.525
Lambert τ'_L	0.455	0.18	0.455	0.20	0.432-0.464
Akimov v=0.1	0.5-0.525	0.18-0.20	0.475-0.5	0.18-0.20	0.475
Akimov v=0.6	0.45-0.475	0.18-0.20	0.475-0.5	0.20	0.425