THE SCALE-HEIGHT OF OPTICAL DEPTH IN VALLES MARINERIS AS DERIVED FROM SHADOWS IN HRSC IMAGES.

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Introduction: The atmosphere of Mars has a considerable optical depth, often in the range 0.3-1.0, because it contains a large amount of reddish airborne dust and other aerosols. This optical depth can be estimated from the brightness of shadows with the so called "shadow method". We used this method, in the version that was described by Hoekzema et al. 2011 [1], to analyze a set of stereo images taken with the High Resolution Stereo Camera (HRSC) of the Mars-Express orbiter (MEX). The images show part of Valles Marineris during late afternoon and contain numerous shadows. Because the analyzed regions span altitude differences of about eight kilometers, we could study the relation between altitude and shadow method measurements.

HRSC on Mars Express. HRSC was developed and build by DLR (Deutsches Zentrum für Luft- und Raumfahrt) in Berlin (Neukum et al. 2004 [2], Jaumann et al. 2007 [3]). It is a multiple line push-broom scanning instrument; nine CCD line detectors are mounted inside one optical system. As the MEX spacecraft moves along its orbit, HRSC acquires superimposed image tracks. The line detectors, often referred to as sensors or channels, have 5184 pixels each. Four of them are equipped with color filters, the other five are panchromatic (675 ± 90 nm) and are used for stereo imaging. For this work we only used images from the five panchromatic stereo channels. These are named S_1, P_1, nadir (or ND), P_2, and S_2. The panchromatic stereo channels observe at -18.9º, -12.8º, 0º, 12.8º, and 18.9º as measured from the nadir channel. The image that we call the 'nadir image' was taken by the panchromatic stereo sensor called 'nadir' or 'nadir channel', but the sensor is not always nadir looking. Also, images of the other channels are never observed with surface emission angles that are equal to their angle with the nadir channel, whereas there are always differences because of the influences of the spacecraft orientation, the image swath, and of the curvature of the planet.

The spatial resolution of the HRSC on MEX from the nominal periapsis altitude of 300 km above Mars is 12 meter per pixel with an image swath of 62 km (11.9º), and a minimum swath length of about 300 km.

Theory: Shadows obviously contain information about the optical depth of the overlying atmosphere. If the optical depth becomes larger, then the brightness difference between a shadowed and a nearby sunlit region becomes smaller. The translation of this difference into an optical depth is what we named the "shadow method". Petrova et al. 2011 [4] describe a way to do this translation accurately, but using the shadow method in the form in which they present it is complicated and not always possible because it needs inputs, such as a very accurate Digital Terrain Model (DTM), that are not often available. Here we use the simpler version of Hoekzema et al. 2011 [1] which needs fewer inputs. This version is largely a fit between observed brightness differences near the exploration sites of the two MER rovers and optical depths that were accurately measured by these rovers by looking into the sun. It is easier to use because it makes several crude simplifications:

1. The surface is Lambertian.
2. All pixels in an analyzed pair of shadowed and sunlit comparison regions receive the same amount of diffuse radiation from the sky.
3. The shadow method needs the albedo of the surface, which is usually unknown. It is approximated by the measured TOA albedo (Top Of Atmosphere albedo).

These simplifications make it possible to derive the below formula that gives an estimate of the optical depth τ_{shad}

$$\tau_{shad} = -\frac{\mu_0 \mu}{\mu_0 + \mu} \ln\left(\frac{\Delta I}{I_{sunlit}}\right)$$

where μ_0 and μ are the cosines of the solar incidence angle and of the emission angle with the nadir respectively, $\Delta I = I_{sunlit} - I_{shad}$ in which I_{shad} is the average intensity that was measured for the analyzed pixels in shadow and I_{sunlit} is that average for the pixels of the sunlit comparison region. In the analysis of Hoekzema et al. 2011 [1], τ_{shad} appeared to be about 65-75% of the optical depth as measured by the two MER rovers, an (apparently largely systematic) difference of roughly 30%. Point 2 and 3 probably introduce the largest part of the difference.

Data: For this work we used the five HRSC panchromatic stereo images that were acquired during orbit 1944 of MEX on July 21, 2005. The area that was used for our analysis is shown in Figure 1 and is located around the equator and 94° longitude. The solar longitude was 253.3° (late northern hemisphere autumn), and the true solar local time between 16.30 h and 17.00 h.

There usually are differences between observed stereo images that are caused by the perspective, i.e., topography on the surface changes its appearance with changing viewing angles. These perspective differences can largely be taken out by re-projecting the images onto the corresponding Digital Terrain Model (DTM). The products of such re-projections are so-called ‘ortho-images’. Details on the software and photogrammetric processing techniques that were used to derive DTMs and ortho-images, are given by Scholten et al. 2005 [5] and Gwinner et al. 2010 [6].

The original images have a spatial resolution of a few tens of meters per pixel, but for this study we used ortho-versions of the images with 125 meter per pixel. For each pixel of each image, values for solar incidence, emission, and phase angles are available. At any given location there is less than 2° of difference in solar incidence angles between the images; over the images these vary from 66°-72°. For the nadir image, the emission angles range between 0° and 9°. For S_2 and S_1 the ranges are 22°-24° and 21°-23° respectively, for P_1 and P_2 14°-17°. The ranges for the phase angles are: S_2 58°-72°, P_2 60°-72°, nadir 63°-78°, P_1 68°-84°, S_1 73°-88°.

The surface elevation varies between almost 300 m below zero on the floor of Valles Marineris and 9050 m above zero for the highest mountains inside the Valles. The plains to the South of the canyon are at altitudes of about 6300—7300 m

Results: We present results of shadow method retrievals from five panchromatic images with more than one hundred and fifty retrievals per image. These are from regions in and around the Valles Marineris and cover an altitude range of about 8 km. Figure 1 shows examples of shadowed regions in white and the sunlit comparison regions in black overlaid onto the nadir image. Each region in shadow is paired to a nearby sunlit one. Each pair yields an estimate of the optical depth. All were manually selected from the P_1 image (an arbitrary choice) and for the eight other images we then used the same pixel locations. Because we use ortho-images that were co-registered to within about half of an observed pixel, the analyzed pixels in the images correspond to the same locations on Mars within a few tens of meters. Pixel locations with imaging errors in any of the HRSC channels (1-2%) were excluded from our analysis

The altitude that we assign to an analyzed region is the average altitude of the sunlit comparison region, not that of the shadowed one, because generally, the DTM is more reliable in a sunlit region. We selected shadowed regions with less than a few hundred meters altitude difference with the sunlit comparison regions and it typically is 100—200 m.

Figure 2 shows the derived optical depth plotted versus altitude in the Valles Marineris for the five panchromatic stereo channels. The smooth curves in the plots are Linear Mean Square Regression fits on the natural logarithm of the optical depth versus altitude. The individual measurements are plotted with one sigma error ranges as measured from the spread.

From the General Circulation Model available via the website http://www-mars.lmd.jussieu.fr/ (Forget et al. 1999 [7], Lewis et al. 1999 [8]) the expected temperatures and pressure scale-height are 232-240 K and 12-13 km respectively. The five panchromatic images yield five estimates of the scale-height of optical depth in the Valles. Their average is 12.2 ± 0.7 km. This is equal to the expected local pressure scale height within the accuracy of our measurements.

Discussion: We found a scale-height of optical depth that was similar to the expected pressure scale-height and this suggests that the airborne dust was well mixed into the atmosphere during the observations. Many papers offer similar results. For example: Jaquin et al. 1986 [9], Kahn et al. 1981 [10], Thomas et al. 1999 [11], Lemmon et al. 2004 [12].

Hoekzema et al. 2010 [13] studied images of Valles Marineris. They found regions where the airborne dust appeared well mixed into the atmosphere, and other regions where it was not. Probably, a part of Valles Marineris was covered by a banner cloud in their observations. Our present work does not indicate the presence of any inhomogeneous cloud cover above the Valles Marineris.

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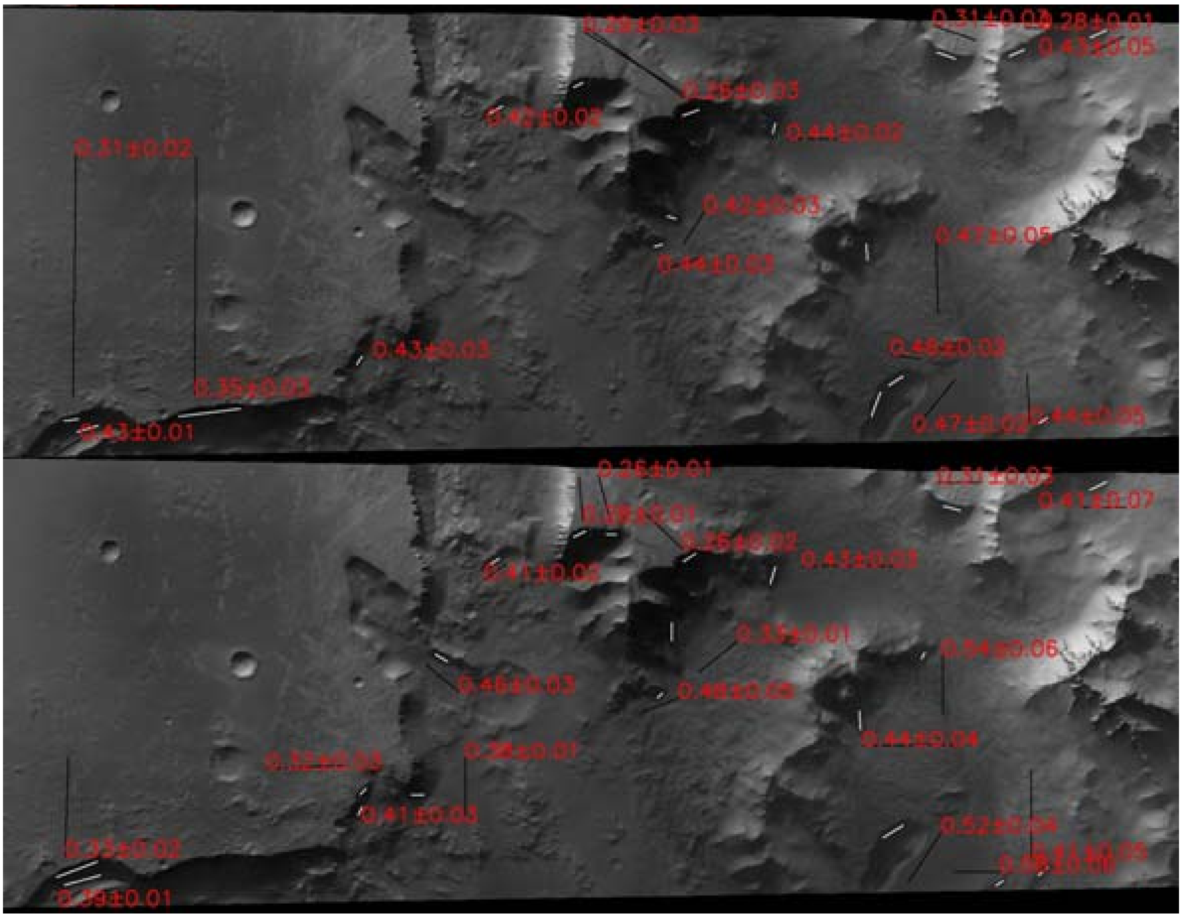

Figure 1 Detail of the used HRSC nadir ortho-image. As an example, the image is overlaid with a sample of 37 retrievals. For clarity the sample is split over two panels. The shown region is 100 km wide and 515 km long. South is to the left. Black lines denote analyzed sunlit pixels and white ones analyzed pixels in shadow. Each black line is paired to a nearby white one and each pair was used for a shadow method estimate of the optical depth τ_{shad}. See text for details. The retrieved τ_{shad} are printed into the image. We used all five panchromatic stereo images from orbit 1944 and retrieved over 150 τ_{shad} from each. We used the same black and white lines for all nine images.

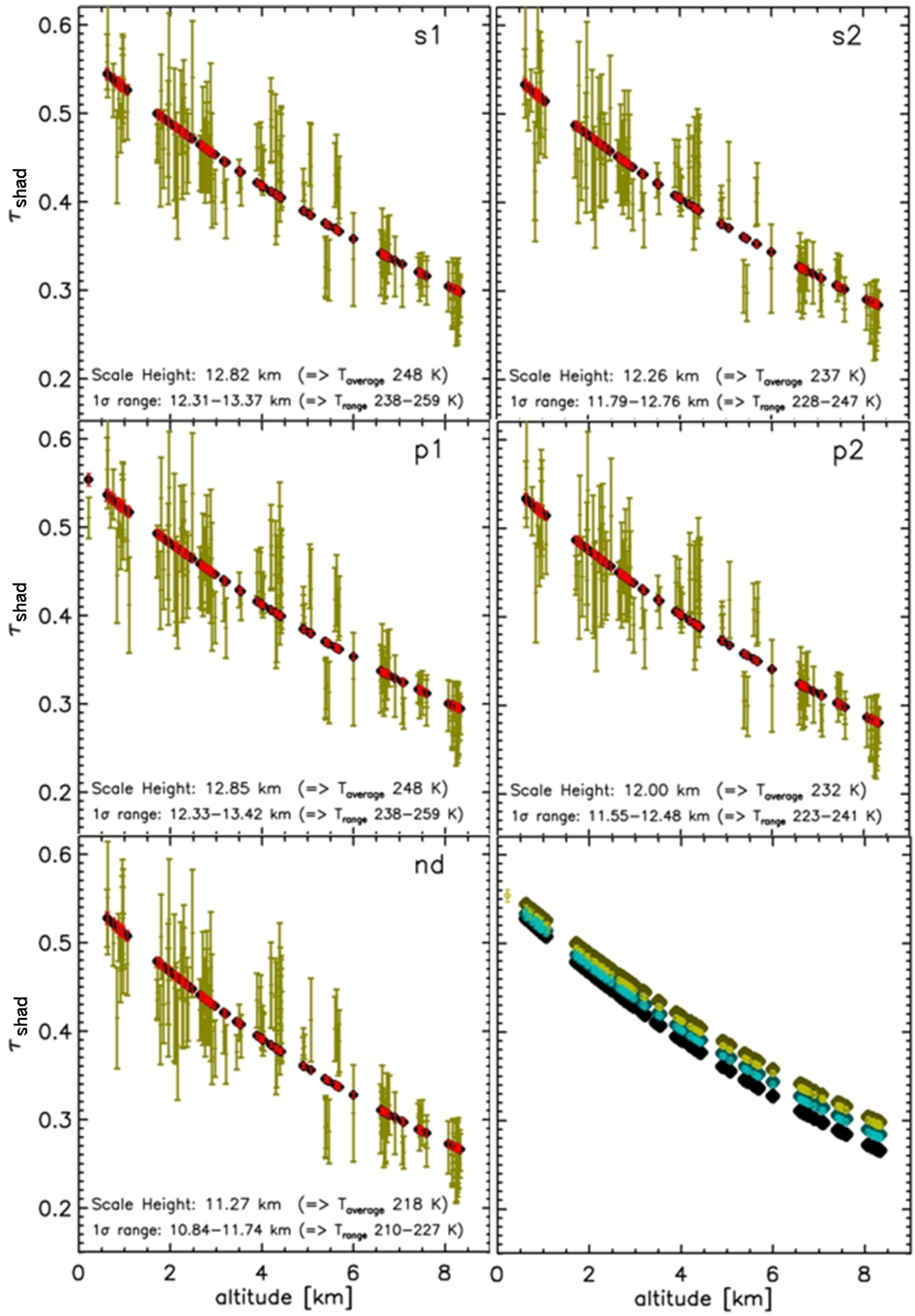

Figure 2 Altitude versus shadow method estimates τ_{shad} for the over 150 regions that were analyzed in each of the five panchromatic images with least square fits. The lower right hand panel shows these fits for the five images together in one plot; going from top to bottom the curves are for: S_1, P_1, S_2, P_2, and nadir. Each fit is used to calculate a scale-height of optical depth and their average is 12.2 ± 0.7 km, which is very close to the expected local pressure scale height, see text for details.