THE SCALE-HEIGHT OF DUST AROUND PAVONIS MONS FROM HRSC STEREO IMAGES.
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Abstract: The Martian atmosphere contains large and variable amounts of dust and other aerosols. The High Resolution Stereo Camera (HRSC) onboard the European orbiter Mars Express is a powerful tool for studying how these aerosols are distributed. An essential parameter for such studies is the optical depth, which can often be estimated from contrast differences between HRSC stereo images with the so called 'stereo method'. Software for this purpose has been developed at MPS in Lindau Germany. The method uses map-projected ortho-images and complementary data on the imaging geometry from photogrammetric software developed at DLR.

During orbit 902 of Mars Express, HRSC observed the volcano Pavonis Mons. On the summit plateau and at its foot we selected 6 regions that span more than 10 km in altitude to study how optical depth depends on altitude. We found a scale-height for the optical depth of 10.8 km +0.9/-0.8 km. This is equal to, or very close to, the expected local gas-scale-height.

Introduction: The optical depth of the Martian atmosphere is almost completely determined by the amount of aerosols it contains, and is considerable since this amount is large. Most aerosols are particles of airborne dust. Knowledge of the amount of this dust, of its distribution through the atmosphere, and of its composition is important for understanding the Martian environment. First of all, since this airborne, or atmospheric, dust is quite important for shaping it; i.e., aerosols determine how much insolation reaches the surface and how much is absorbed in the atmosphere. Thus they have a big influence on the climate, the weather, the circulation patterns, and with that on Aeolian processes. Most aerosols, at least those in the lower atmosphere, are reddish dust agglomerates that can act as condensation kernels for vapors, invoking white hazes when they become covered with ice.

Knowledge of the aerosols is also important for interpreting observations of Mars since they have a big impact on much of the remote sensing data; e.g., they diminish the contrast and spatial resolution of images and the light they scatter creates a strong and diffuse reddish illumination of the surface. Interpretation of (surface) images and spectra should consider such effects.

The impact of the dust partly depends on where it resides in the atmosphere. For instance, is it homogeneously mixed in the air so that the dust has a scale-height comparable to that of the air itself, or is there strong layering, for example close to the surface? This paper intends to contribute to a better understanding of such questions. It describes a stereo method analysis as conceived by [1] of Pavonis Mons. The images were taken with the High Resolution Stereo Camera (HRSC) onboard Mars Express (MEX).

During the last decennia, the distribution of aerosols in Mars' atmosphere, and more in particular their scale-height, have been investigated by several authors. [2] used limb scans from the Viking orbiters and observed discrete, optically thin, detached haze layers between 30 and 90 km elevation that may have consisted of water ice. Below about 50 km they observed a continuous, reddish haze. In the 30 to 45 km altitude range the scale height of the reddish haze was typically 5 to 7 km, while its color implies that it was mostly dust. The authors can not offer much useful information on the lowest 10 to 15 kilometers of the atmosphere, since these regions are optically thick when viewed from the limb.

[3] analyzed the changing sky brightness during the Martian twilight as observed by the Viking landers. They concluded that the dust is exponentially distributed in the lowest 30 km, with a scale-height close to that of the atmosphere.

The Pathfinder mission yielded new estimates. [4] used egress observations of Phobos. Their data best fit models with dust-scale-heights of 10 to 15 km, but they remark that a dust-scale-height that decreases with increasing altitude would provide a better fit.

Since 2004, the stereo imagery of HRSC, and the Digital Elevation Models (DEMs) that are derived from these, offer a new way to measure the optical depth of the Martian atmosphere. By comparing optical depths above surfaces at varying altitudes, these can be estimated as a function of altitude. This technique has disadvantages: obviously, it can only measure the total optical depth from surface to space, thus can not resolve any vertical structure above a given location. Also, the method merely allows measuring dust-scale-heights between the lowest and the highest surface in the image. Moreover, since it depends on comparing (nearby) regions at various elevations it will be hampered by horizontal fluctuations in the concentration of aerosols. On the other hand, this offers an important advantage as well, in that it allows studying the horizontal scales on which the total optical depth above the surface changes.

Recently, [1] used HRSC stereo images to measure the dust-scale-height on the volcano Apolinaris Patera and found 6 to 8 km. However, they note that the local dust-scale-height may well have been unusually low at the moment of observation because of nearby dust storm activity. They suggest using HRSC observations for a similar analysis of an other region that was imaged during quiet weather. This paper reports on such an analysis. As region we choose Pavonis Mons since it spans large altitude differences. We checked for the presence of bright clouds, which could easily inhibit accurate retrievals, by studying the blue and green images of this dataset. Such clouds show up on the flanks of the volcano. We selected regions near the summit and foot that appear largely free of bright clouds.

Instrument: The HRSC camera has been developed and build by DLR in Berlin [5] and is a multiple line pushbroom scanning instrument. As the spacecraft moves along its orbit, its nine CCD line detectors acquire superimposed image tracks. The line detectors, with 5184 pixels each, are mounted in parallel inside one optical system. Four of these are equipped with color filters between blue and near infra red. The other five are panchromatic (675 ± 90 nm) and are used for stereo imaging. During standard observations the panchromatic line-detectors observe at -18.9º, -12.6º, 0º, 12.6º, and 18.9º as measured from nadir, but the MEX spacecraft can be tilted to introduce an offset. While observing Pavonis Mons during orbit 902 HRSC's nadir channel was looking sideways by around 5º. Details on the photogrammetric processing techniques applied to derive DEMs and images that are corrected for perspective effects, the so called 'ortho-images', are given by [6] and [7].

Theory:

The stereo method: Let τ be the optical depth of the atmosphere, $B(i,j)$ be the upward radiation from the surface before extinction by the atmosphere in pixel i,j of an image $I(i,j)$. Let $A(i,j)$ be the contribution of the atmosphere and the aerosols therein, and let μ be the cosine of the emission angle with the nadir. The radiance above the atmosphere that is measured by the orbiter scanners $I(i,j)$ will then be:

$$I(i,j) = B(i,j)e^{-\tau/\mu} + A(i,j) \quad \text{or} \quad I = Be^{-\tau/\mu} + A$$

when omitting the subscript i and j. For an observation with a spatial resolution of kilometers or less the contrast in the observed image I will usually be strongly dominated by the contrast on the surface (i.e., the contrast in B) since the aerosol layer, and thus A, will generally not show large variations on scales of a less then a few kilometers on Mars. However, images may frequently contain clouds. If these cover part of an analyzed field then there can be considerable contrast in the aerosol layer. This can easily prevent a proper retrieval.

There are numerous ways to quantify contrasts, many give a formula:

$$contrast(I) = contrast(Be^{-\tau/\mu} + A) \approx e^{-\tau/\mu} contrast(B)$$

HRSC observes in three or five-fold stereo, each image having its own value of μ. If the reflection functions of the surface and the overlying atmosphere are known, then it is in principal possible to retrieve τ from such stereo imagery. However, a most serious problem is that the reflection function can vary significantly from place to place, and generally is not well known anyhow. Therefore, we work with a simple approximation $B_1 = \alpha * B_2 = B$ (in which α is a constant) and use tools, that will be discussed below, to check how good these are for an analyzed region. We approximate the constant α with:

$$\alpha = \frac{<B_1>}{<B_2>} \approx \frac{<I_1>}{<I_2>} \tag{1}$$

where $<B>$ and $<I>$ are the average values of B and I over the analyzed region. The appendix of [1] elaborates on the accuracy of this approximation. From two images with different emission angles, and using (1) we can solve for τ.

$$contrast(I_1) \approx e^{-\tau/\mu_1} contrast(B)$$
$$contrast(I_2) \approx \alpha * e^{-\tau/\mu_2} contrast(B)$$
$$\downarrow$$
$$\tau \approx \frac{\mu_1 \mu_2}{\mu_1 - \mu_2} * \ln\left(\frac{\frac{contrast(I_1)}{<I_1>}}{\frac{contrast(I_2)}{<I_2>}} \right) \tag{2}$$

Selection and processing of images before applying the method. Although the mathematics of the stereo-method is simple, applying it on real data is not. The images have to be processed in several ways before stereo method retrievals can be successful, and even after that it will not always work. [1] elaborate on this; we will only give a short summary here:

The intensity resolution of the observed HRSC images of 8 bit or less is not good enough. However, usually it can be increased sufficiently by trading spatial for intensity resolution. I.e., by averaging the observed pixels into pixels at a much lower spatial resolution, since ideally the average intensity of ***N*** observed pixels is known with an accuracy that is a factor $\sqrt{N}$ higher than that of the individual observed pixels.

Perspective is very important, since topography can look very different from different viewing angles. Ideally, on a macroscopic scale, perspective effects can be taken out of an image via an ortho-projection if a Digital Elevation Model (DEM) of sufficient quality is available. For stereo-method analyses one should always use ortho-images, but these are rarely perfect, even if they are of high quality. In particular steep topography will often introduce errors. Moreover, ortho-projection can never correct for differences on a sub-pixel scale.

The approximation $B_1 = \alpha * B_2$ often is not very accurate for the surface of Mars. When images are taken with the Sun close to zenith, then it usually is so bad that the stereo-method will fail. On the other hand, if Mars Express circles close to the terminator, then the approximation usually is quite acceptable.

Also, it helps to define contrasts in a proper way. Empirically, the approximation $B_1 = \alpha * B_2$ often is good when the contrast is defined as the difference in intensity between the 'bright' and the 'dark' pixels of an analyzed field. Here we define 'bright' as the intensity at which e.g., 10% of the pixels of the analyzed field are brighter and 90% are darker, and then correspondingly 'dark' as the intensity at which 90% are brighter and 10% are darker. We use the above definition of contrast, at various percentages: 10, 9, 8, 7, 6, and 5% for bright and correspondingly 90, 91, 92, 93, 94, and 95% respectively for dark. Each pair of bright and dark percentages gives a separate retrieval of the optical depth; the spread between these retrievals is a measure of the accuracy.

Obviously, the surface must have enough contrast. [1] show examples and discuss errors due to a lack of surface contrast.

Applying the method on selected images After dealing with the above, one can try to retrieve optical depths from a selected region in the images. An effective approach is using the so called 'McRuqo' procedure as introduced by [1]. It works as follows: first use the forward and the nadir image to retrieve an optical depth $\tau_{forward}$, and then use the backward and the nadir images for a second one $\tau_{backward}$. Typically, there will be a large difference between these two retrievals. Now change the size and the location of the selected region of the images slightly from the original ones, and by trial and error manually iterate until the retrievals are almost equal. The average can be taken as the final estimate of the optical depth; half of the remaining difference can be taken as an error estimate. Or, if the error estimated from varying the percentages that are used to define 'bright' and 'dark' (as discussed in the previous sub-section) is larger, then take this value.

[1] showed that McRuqo optical depths are usually reliable, but not always, and every now and then the reliability is unclear. One has to use common sense to omit bad and suspect retrievals.

Data: We used forward, nadir, and backward images from a set that was acquired during orbit 902. The analyzed regions are shown in Fig. 1 and are located around 1° North and 112° East. For each pixel of the forward, nadir, and backward images, values for solar incidence, emission, and phase angles are available. At any analyzed location there is less than 2° of difference in *solar incidence angles* between the images; they are in the range 70°--75°. For the nadir image, the *emission angles* range between 0° and 10°, for the forward and backward ones between about 21° and 24°. The *phase angles* for the nadir image range between 67° and 85°, that of the backward one from about 77° to 95°, and that of the forward image from about 60° to 76°.

Results: Area 1, located on the summit plateau at an altitude of 14516 ± 43 m, yielded an optical depth of 0.53 ± 0.16. Since this is the only data point at high altitude, we checked the reliability of Area 1 by splitting it into 9 sub-regions. All sub-regions showed an optical depth that was very similar to that of Area 1 as a whole and thus we deem the result for area 1 reliable.

Areas 11—15, at altitudes 4087—4384 m, yielded optical depths in the range 1.33—1.66 with an average of 1.50 ± 0.15.

The regions provide a good sampling of altitudes and yield a dust-scale-height of 10.8 km with an 1 sigma error of +0.9 -0.8 km. Fig 2 shows the results.

Conclusions:

- We retrieved optically depths on the summit plateau and at the foot of Pavonis Mons.
- The large altitude differences between these allowed a rather accurate estimate of the local dust-scale heights.
- We measured a dust-scale-height of 10.8 +0.9 -0.8 km.
- For Martian air with temperatures in the range 209 ± 16 K, this is very similar to the local scale height of the Martian atmosphere.
- Since the expected temperatures are in this range, the results are consistent with airborne dust that is homogeneously mixed into the atmosphere.

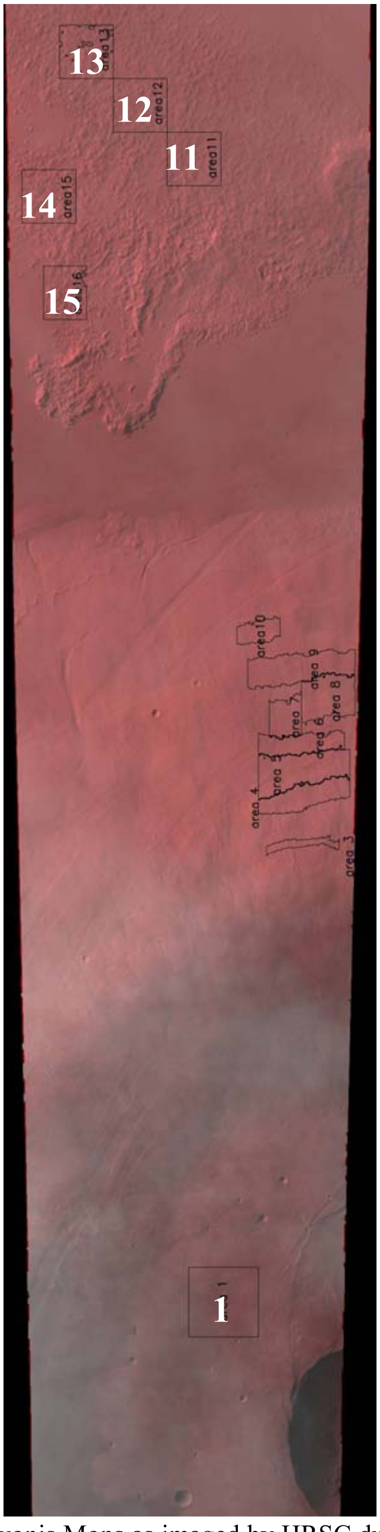

Fig. 1. Pavonis Mons as imaged by HRSC during orbit 902. The displayed region is 88 km wide, north is up. Bright clouds show up around the summit. We concentrated our analysis on area 1 on the summit plateau, and on areas 11—15 at the foot, because these appear largely free of bright clouds.

Acknowledgement: We thank the HRSC Experiment Teams at DLR Berlin and Freie Universitaet Berlin as well as the Mars Express Project Teams at ESTEC and ESOC for their successful planning and acquisition of data as well as for making the processed data available to the HRSC team.

We acknowledge the effort of the HRSC Co-Investigator Team members and their associates who have contributed to this investigation in the preparatory phase and in scientific discussions within the Team.

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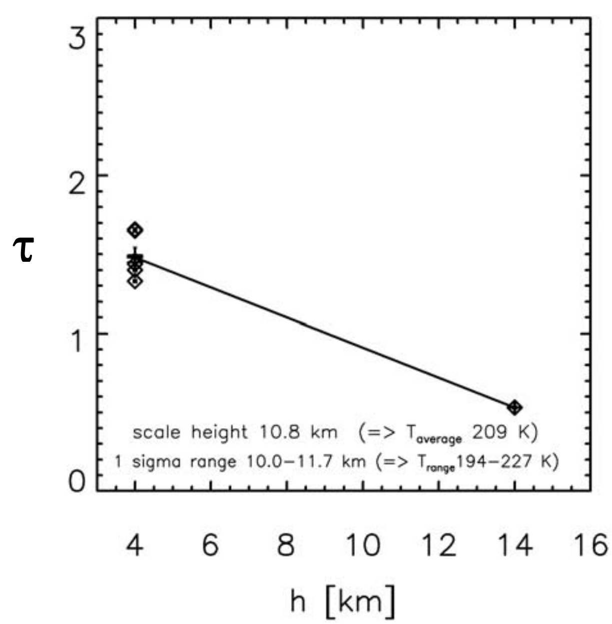

Fig. 2 Optical depths retrieved with the stereo-method as a function of altitude on Pavonis Mons. A linear-log fit on the measurement yields a dust-scale-height of 10.8 +0.9 -0.8 km. This is equal to, or very close to, the expected scale-height of gas which suggests that the airborne dust is well mixed with the atmosphere.