OPTICAL DEPTH RETRIEVALS FROM HRSC STEREO IMAGES.

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Abstract: Mars Express is due to arrive in orbit around Mars during the last days of 2003. A primary task of its mission is to map Mars in stereo with the High Resolution Stereo Camera (HRSC) at a spatial resolution of up to 12 m. The Martian atmosphere contains large amounts of dust and other aerosols that scatter light and influence the images. Therefore, image analysis requires careful consideration of these atmospheric effects. An essential parameter to consider is the optical depth. It will be possible to map the optical depth of the Martian atmosphere from HRSC stereo images by analyzing contrast differences. Software to this purpose has been developed at the Max-Planck Institute for Aeronomy in Lindau Germany. We present examples of optical depth-retrievals from airborne HRSC-A images of a region in the French Alps.

Introduction: Stereo imaging is a valuable tool for e.g. deriving Digital Elevation Models (DEM), atmospheric correction, and for atmospheric science. With the launch of Mars-Express stereo remote sensing leaves Earth orbit. A primary task for this orbiter is the mapping of almost all of Mars in stereo with the onboard High Resolution Stereo Camera (HRSC). HRSC will image the surface in three or five-angle stereo and in five spectral bands between blue and near infra-red. The DEMs will have a horizontal resolution of up to 50 m and a point accuracy of up to 25 m. By combining DEMs from the stereo images with MOLA altitude measurements a further improvement of the surface description will be possible. Furthermore, the stereo images offer unprecedented opportunities to study the Martian atmosphere and its aerosols.

It is well known from many observations of Mars [1] that the remote sensing of the Martian surface is complicated by the strong scattering of solar radiation by aerosols. Thus, interpretation of images requires careful consideration of these effects. As in Earth remote sensing, stereo information of Mars will be useful for atmospheric correction. It will also offer a powerful tool for studying the abundant Martian aerosols. An essential parameter for both atmospheric correction and aerosol studies is the total optical depth of the atmosphere.

The Martian environment poses slightly different problems on optical depth retrievals than the Earth environment. In Earth remote sensing one often can look at regions that have well known surface albedos, such as e.g., dense dark vegetation and seas. The difference between surface albedo and the albedo observed at the sensor altitude provides a means for measuring optical depth. Such surface regions do not (yet) exist on Mars and therefore one has to use alternative methods.

Contrast measurements offer such an alternative. Usually, the surface invokes almost all of the contrast in a remote sensing image. The atmospheric contribution lowers it, since the aerosol layer generally shows very low contrast. Since an inclined view has a longer path-length through the atmosphere than a nadir view, and will thus show a larger atmospheric contribution, the forward and backward looking images of a stereo sensor will on average display smaller contrasts than the nadir looking images. The differences are a measure of the optical depth. We present a routine to measure optical depths from stereo images, using the above method of measuring how contrasts change with viewing angle. The routine is called MPAE_OPT_ST and was developed at the Max-Planck-Institute for Aeronomy for analyzing the coming stereo images of Mars, and is available in IDL as well as in C. We present results of demonstration runs on HRSC stereo images taken from an airplane of the French Alps.

Instrument: HRSC cameras have been developed by DLR in Berlin [2]. They are multiple line pushbroom scanning instruments. As the airplane moves over the surface, or as the spacecraft moves along its orbit, its nine CCD line detectors acquire superimposed image tracks. These tracks are always observed at time distances of less than a few minutes, thus usually only small temporal variations will exist between them. The line detectors, with 5184 pixels each, are mounted in parallel inside one optical system. Four of them are equipped with color filters between near-infra-red and blue. The other five are panchromatic (675 ± 90 nm) and are used for stereo imaging. The multiphase imagery allows for mapping of the surface topography. Table 1 offers more details on the HRSC instrument for Mars Express as well as the airborne HRSC-A which was used to acquire the test data used in this study. Details on the photogrammetric processing techniques applied to derive DEM and orthoimages are given by Wewel et al. (2000) [3], an overview of previous Earth-oriented campaigns is given in Gwinner et al. (2000) [4].

Theory: *The stereo method formula:* Let τ be the nadir optical depth of the atmosphere and $\boldsymbol{B}$ the image of the surface before extinction of the outgoing radiation by the atmosphere, and let μ be the cosine of the observation angle with the nadir. The observed image I will then be:

$$I = Be^{-\tau/\mu} + A$$

where A is the contribution of the atmosphere and the aerosols therein. 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 A will rarely show large variations on such scales on Mars.

There are various ways to quantify contrasts in an image: e.g., the difference in brightness between the intensity at which 10% of the pixels is brighter and the intensity at which 10% of the pixels is darker. Or, a very straightforward way: the root-mean-square variation (rms) of a region. All such methods give a similar formula. Using rms as an example gives:

$$\begin{aligned} &rms(I) = rms(Be^{-\tau/\mu} + A) = \\ &rms(Be^{-\tau/\mu}) + rms(A) \approx \\ &e^{-\tau/\mu} rms(B) \end{aligned}$$

HRSC will observe in three or five-fold stereo, each image having its own value of μ.. Ideally two observations suffice for retrieving τ. If B_1=B_2=B and if the two intensities I_1 and I_2 are well enough calibrated with respect to each other then:

$$rms(I_1) \approx e^{-\tau/\mu_1} rms(B)$$
$$rms(I_2) \approx e^{-\tau/\mu_2} rms(B)$$
$$\downarrow$$
$$\tau \approx \frac{\mu_1 \mu_2}{\mu_1 - \mu_2} * \ln\left(\frac{rms(I_1)}{rms(I_2)}\right)$$

By combining results for several pairs of stereo angles it is possible to estimate the error in the retrieved τ. Since the stereo angle of the HRSC is only 18.9°, the difference in contrast between the stereo and nadir images will generally be small, i.e., the term containing μ_1 and μ_2 in formula (1) is as large as 17.6. Therefore, precise measurements of τ depend strongly on accurate calibration of the observed intensities.

Reducing effects from topography and perspective: Perspective effects pose a serious problem since generally B_1 and B_2 differ due to topographic effects. I.e., usually the scenery changes (a bit) with a change of perspective; the appearance of hills and depressions, the shape and cover-factor of shadows, they all depend on the viewing angle. Thus, precise measurement of τ is highly dependant on accurate separation of topographic from atmospheric effects. Topography related artifacts can be minimized by using orthoimages, i.e., images reprojected on a precise DEM.

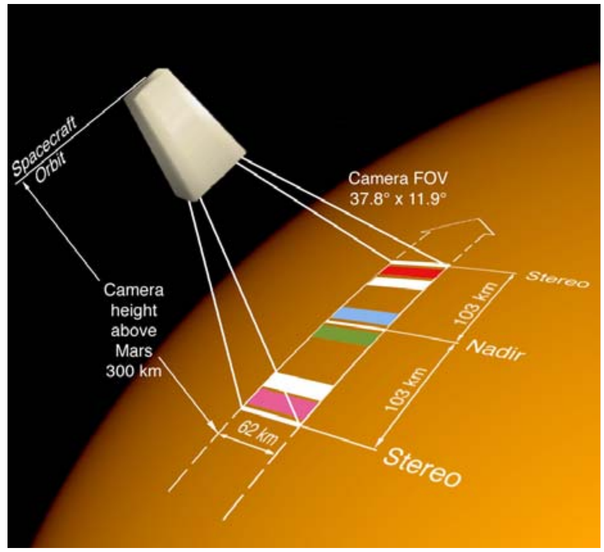

Fig. 1 HRSC is a scanning camera with 9 line CCDs in parallel. Images are built line after line as the spacecraft moves along its orbit. By combining nadir, backward, and forward-views the surface can be mapped in stereo.

Focal length	175 mm
F number	5.6
Stereo angles in degrees	-18.9, -12.6, 0, +12.6, +18.9
Cross-track fov	11.9º
Pixel size	7 x 7 µm
Pixel on the surface	12 x 12 m from 300 km
Fov per pixel	6.25 arcsec
Swath width on the ground	62.2 km
Radiometric resolution	8 bit
SNR for color lines	> 80, blue >40
SNR for panchromatic lines	>>100
Active pixels per sensor	5184
Typical operations duration	4—30 min
Expected coverage	> 50% at 15m/pix in nadir
Operational lifetime	> 4 years
Typical image	62 x 330 km
Spectral filters	**Wavelength**
Nadir	675 ± 90 nm
Outer stereo (2)	675 ± 90 nm
Inner stereo (2)	675 ± 90 nm
Blue	430 ± 45 nm
Green	530 ± 45 nm
Red	750 ± 20 nm
Near Infrared	970 ± 45 nm

Table 1 Some properties of the HRSC camera on the Mars Express orbiter.

On Contrasts and on the Errors that Shadows can invoke: One way in which MPAE_OPT_ST quantifies contrasts is the RMS variation in images. However, this method, as well as many alternative methods to quantify contrasts, is rather sensitive to non-Lambertian properties of surfaces such as (micro) shadow cover. It is best to use data in which the solar incidence angle is larger than several tens of degrees and is perpendicular to the flight path of the camera so that the cover factors of shadows do not vary by much between images. Therefore, the most accurate retrievals of optical depths of the Martian atmosphere can be expected when the spacecraft circles the terminator.

MPAE_OPT_ST also uses an alternative method to quantify contrasts: i.e., by looking at the difference in intensity between its few percent brightest and its few percent darkest pixels. Typically the darkest pixels deal with locations in deep shadow and the brightest pixels with locations with minimal micro-shadowing. As compared to for instance RMS measurements, this method proves to be much less sensitive, but not insensitive, to differences in shadow cover between the stereo images.

For each image an intensity distribution ***I(i)*** is given: i.e., ***i%*** of the pixels has an intensity that is larger than ***I***. The contrast is defined as ***(I(i) – I(100-i))***. Optical depth τ is calculated as a function of ***i***. Empirically, the best results are obtained for ***5% < i < 10%***. As a default the routine gives τ as the average from the six measurements with ***i = 5, i = 6,…,i=10*** and uses the spread between these six retrievals as an estimate of the error. However, especially with unfavorable geometries, it may be preferable to select other percentages manually; often a careful look at the intensity distribution ***I(i)*** suffices to reveal problems with the default choice and to choose a better one.

On absolute and other intensity calibrations: The stereo method will yield its most robust results when using images with absolutely calibrated intensities such as I/F values. HRSC measures intensity per pixel, ideally, with a precision of about 0.5% per pixel (8 bit). If this uncertainty is systematic it results in an error in the derived τ of about 0.1. If it is random and variable the error can be reduced by averaging over many pixels.

When absolute calibrations (with sufficient accuracy) are not available, but when intensities scale linearly with DN and do not contain any offset, then the stereo method can still be used. The routine retrieves τ in two ways. The first presumes absolute calibration of the images, the second recalibrates the images before retrieving τ. In the recalibration process the intensities in the images are rescaled so that they have the same average. Or, slightly more sophisticated, by rescaling so that the average of the ***i***% brightest and the ***i***% darkest pixels are equal for all images in a stereo set. These assumptions are not completely valid, but educated guesses on Martian aerosol properties predict that the resulting errors in the retrieved optical depths will usually be as small as 0.02--0.06. Moreover, since these errors can to some degree be estimated, they can partly be corrected for.

Data: A set of airborne triple stereo ortho-images of the French Alps is used for demonstrating the routine. They were taken around local noon while the plane was flying on an East-West trajectory. Thus, the Sun illuminates the scene perpendicular to the direction of flight, thus minimizing the differences in shadow cover between the images. The images were taken at almost 30 cm per pixel, 5,184 pixels wide and over 53,000 pixels long.

To emulate well calibrated future HRSC images of Mars, the contrasts and average intensities of the images were processed in such a way that the full field average optical depth from rms contrasts was 0.5. Also, they were reduced to 300 by 3100 pixels at a spatial resolution of 5 m per pixel to offer a more Mars-like spatial resolution and to fasten computations.

Results & Discussion: Routine MPAE_OPT_ST yields four estimates of the optical depth. tau and tau1 use rms to measure contrast. tau2 and tau3 use the brightest and darkest pixels. The estimates tau and tau2 presume accurate absolute calibration. tau1 and tau3 use recalibrated intensities. Results for the full field:

tau	0.50 ± 0.09	tau1	0.50 ± 0.04
tau2	0.48 ± 0.17	tau3	0.53 ± 0.16

The results for tau (and tau1) only prove that the images were indeed successfully processed to an rms optical depth of 0.5. Both tau2 and tau3 give values very close to 0.5. They display rather large uncertainties which may mainly be induced by the altitude variations and corresponding variations in airmass and Raleigh scattering in the very mountainous region; the altitude differences over the imaged surface are 1500 m or 30% of the airplane altitude above the lower parts.

Next, two sub-regions of 100 by 1250 pixels were selected from the image. These are enclosed by the white lines in Fig. 2. The upper sub-region largely covers dark valley, the lower one mainly contains brighter high mountain slopes.

upper sub region	lower sub region
tau 0.66 ± 0.09	tau 0.65 ± 0.09
tau1 0.52 ± 0.04	tau1 0.69 ± 0.04
tau2 0.72 ± 0.10	tau2 0.53 ± 0.20
tau3 0.51 ± 0.10	tau3 0.47 ± 0.17

Retrievals tau, tau1, and tau2 prove unreliable. Both retrievals of tau3 are quite good, the difference between them is consistent with an average difference in elevation of almost a kilometer between the two sub-fields.

Finally, for each pixel location the optical depth was retrieved from a field of 40 by 40 pixels around it. Although ortho projection minimizes differences from topographic effects between stereo images, some differences remain and become important for such small sub-fields. Therefore, we checked for such differences by calculating correlations. Only when all correlations between corresponding forward, backward, and nadir sub-images were larger than 0.9, tau3 was calculated. The results are given by the middle strip in Fig. 2; the darkest grey regions have tau3 < 0.2, white regions have tau3 > 1.0. For black regions tau3 was not calculated because of low correlation. It is obvious from the image that the results show an unrealistically large spread. The average tau3 of all sub-fields is 0.7 ± 0.3.

The spread can be decreased by concentrating on those sub-fields with the highest contrasts and highest correlations. Selecting the 30% of the sub-fields with the highest contrast, and selecting from these only those subfields with correlations larger than 0.98 yields the grey pixels in the third strip of Fig. 1. They have average tau3 of 0.61 ± 0.14. Although correct within the error range, this result is less then optimal. We suspect that the use of small sub-fields generally yields too high values for the optical depth.

To demonstrate the importance of using images of high correlation we present tau3 as a function of correlation factors between the sub-images.

correlation > 0.98 ➔tau3 0.61 ± 0.14
correlation 0.96--0.98 ➔tau3 0.64 ± 0.17
correlation 0.94--0.96 ➔tau3 0.9 ± 0.2
correlation 0.92--0.94 ➔tau3 1.0 ± 0.2

As with the use of (too) small sub-fields, the use of sub-fields that do not perfectly match seems to overestimate the optical depths.

Conclusions:

- Favorable observing geometries, i.e., incidence angle more than a few tens of degrees from the zenith and close to perpendicular to the flight path, will usually allow optical depth retrievals with an accuracy of better than 0.1.
- Using the brightest and darkest pixels and recalibrated intensities will probably usually yield the most reliable results.

References:

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Fig. 2 *Left*: Part of the Nadir image, with white lines enclosing the two sub-regions that were analyzed separately. *Middle*: corresponding map of tau3, calculated per pixel location over a sub-region of 40 by 40 pixels around each location. Darkest grey: tau3 < 0.2. White: tau3 > 1.0 Black: no tau3 calculated because of too low correlation between fw, nd, and bw sub-images. *Right*: tau3 for sub-images belonging to the 30% with the highest contrast and with correlations > 0.98.