TOPOGRAPHIC MAPPING OF MARS:
FROM HECTOMETER TO MICROMETER SCALES

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ABSTRACT:
We describe USGS topomapping of Mars at resolutions from 100 m to 30 μm with data from the latest spacecraft missions. Analysis of NASA 2001 Mars Odyssey Thermal Emission Imaging System (THEMIS) data combining daytime visible reflected, daytime IR emitted, and nighttime IR emitted images allows us to isolate the physical effects of topography, albedo, and thermal inertia. To a good approximation these physical influences interact linearly so that maps showing topographic shading, albedo, and relative thermal inertia can be produced by simple algebraic manipulation of the coregistered images. The shading map resembles an airbrush shaded relief portrayal of the surface, and can be used as the input for quantitative reconstruction of topography by photoclinometry (PC) at 100-m resolution over most of the planet. The High Resolution Stereo Camera (HRSC) of the ESA Mars Express orbiter includes a 9-line scanner for color and stereo imaging and a Super-Resolution Channel (SRC). We analyze these images with a combination of USGS ISIS cartographic software and commercial photogrammetric software, providing an independent check on the stereo processing pipeline developed by the HRSC team. In particular, we are producing very high resolution digital elevation models (DEMs) from the SRC images by photoclinometry and by stereoanalysis, using Mars Orbiter Camera images to complete the stereopair. The NASA Mars Exploration Rovers (MER) carry a diverse set of cameras: two wide-angle hazard camera pairs, panoramic stereo imagers (Pancam and Navcam), and a Microscopic Imager (MI) that images a 3-cm-square area at 30 μm/pixel resolution. Our work emphasizes MI data and includes geometric calibration, bundle-adjustment, mosaicking, generation of DEMs by stereanaalysis and focal sectioning, and combination of MI images with color data from Pancam. The software being developed to support these analyses can also be used to produce high-precision controlled mosaics, DEMs, and other products from the Pancam and Navcam images.

1. INTRODUCTION
The four spacecraft sent from Earth to Mars during the 2001 and 2003 opportunities each carry novel imagers that open up new possibilities for topographic mapping of Mars. In this paper we describe the techniques that we are developing at the U.S. Geological Survey in order to exploit these datasets and show examples of the results. A noteworthy aspect of the work described here is the enormous range in spatial scales at which mapping is possible. The THEMIS imagery is relatively low resolution and nonstereo but we have developed a novel processing technique that effectively "strips away" the albedo variations that normally limit photoclinometry (or "shape-from-shading") techniques to small areas of more uniform properties. The dataset and method make topographic mapping of most or all of the planet at hectometer resolution possible for the first time. The HRSC multilane stereo scanner is the first instrument of its kind to be used in planetary exploration, and is returning color and robust, single-pass stereo imagery of large areas of Mars at decameter resolutions. We have developed an independent processing capability for these images, but our efforts are currently focused on our unique capabilities within the HRSC team for topographic mapping with images from the SRC at resolutions of a few meters. The MER rovers achieve higher resolution yet from their positions on the surface of Mars. In particular, the Microscopic Imager is also the first instrument of its kind on Mars and has an unprecedented 30 μm resolution. The other cameras on the rovers bridge the gap between this scale and what can be seen from orbit. The software and procedures we are developing for MER allow us to work flexibly with images from all of the onboard cameras, individually or in combination.

2. 2001 MARS ODYSSEY ORBITER THEMIS

2.1 Source Data
The NASA 2001 Mars Odyssey Orbiter began its mapping mission in February 2002. The THEMIS instrument on Odyssey acquires images (Christensen et al., 2003) in both visible and thermal infrared wavelengths. Visible-light (VIS) images can be acquired in five spectral bands (0.43-0.86 μm) although a single image in Band 3 (a red band ~0.65 μm) is usually collected. This band is ideal for our work because it shows surface albedo variations with high contrast and signal/noise ratio. VIS image strips are ~18 km wide with resolution of ~18 m/pixel. The IR images are of lower resolution (~100 m/pixel), cover a wider swath (~32 km), and can be acquired in 9 bands between 6.8-14.9 μm. For the work described here we use only Band 9 (~12.6 μm), which is always acquired and which has the highest signal/noise for targets at or below 230 K. The VIS images and daytime IR images that we use were acquired simultaneously; those collected at equatorial latitudes have solar incidence angles between ~45° and ~75° (between ~15 h and 16:30 h local time). The nighttime IR images are acquired on the opposite part of the orbit (i.e. between ~3 h and 4:30 h).

2.2 Physical Basis of the Method
A necessary condition for analysis described here is the match between the number of available THEMIS datasets (VIS, day IR, and night IR) and the number of dominant physical influences on these observables: surface orientation, albedo, and thermophysical properties in the guise of thermal inertia (Elachi, 1987). Thermal inertia (I, units are J m⁻² sec¹/₂ K⁻¹) is equal to √(ρcρk), where k is the

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thermal conductivity, $\rho$ is the density and $c_p$ is the specific heat. For Mars, $I$ ranges from ~50 for very fine dust, to ~300 for fine sand, to ~2000 for solid dense rock (cf. Jakosky and Mellon, 2001; Mellon et al., 2000). A further condition for the success of our analysis is that the influence of these parameters on the observables is sufficiently distinct that they can be disentangled. The VIS image, formed by reflected sunlight, is sensitive to slope orientation as described by the surface photometric function and is proportional to albedo $A$, but is not affected by thermal properties. The day IR image is formed by energy that has been absorbed and reradiated. For small $I$ this reradiation is mostly instantaneous, and the day image has a Lambertian orientation dependence and is proportional to (1-4); the former is similar to the VIS image but the latter is of the opposite sense. For finite $I$, the daytime temperature is reduced by thermal conduction to the subsurface and retains a "fading memory" of the past history of insolation. Increasing $I$ has the opposite effect on night temperatures, raising them by conduction from below. Albedo and orientation have weaker influences on the night temperature through the total energy absorbed during the day. From this description it is evident that the THEMIS observations have distinct responses to orientation, $A$, and $I$, so that an inversion for these parameters is likely to be robust.

2.3 A "Magic Airbrush"

Mathematically, it is a given that the full thermal model can be linearized for small departures of orientation, albedo, and thermal inertia from some mean values, but will such a linear approximation be valid over a useful parameter space? Theoretical considerations, preliminary investigations with the numerical thermal code "KRC" (Kieffer et al., 1977), and empirical results with THEMIS data suggest the answer is yes. Work now underway with the KRC code will guide us to a strategy for inverting the THEMIS data in the general (nonlinear) case, provide error estimates for the recovered parameters, and lead to an empirical "photometric function" that describes how day IR radiance depends on east-west and north-south slopes.

If $p_r$ represents the visible-band photometric function of the surface and $p_{IR}$ an effective photometric function for the infrared emission, then the accuracy with which albedo variations can be cancelled in a linear combination of the visible image $A_p$ and the IR image $(1-A)p_{IR}$ depends on the degree of resemblance between $p_r$ and $p_{IR}$. As described above, $p_{IR}$ will be nearly Lambertian for small $I$, whereas $p_r$.

Figure 1. Extraction of topographic radiance image accounting for variations both in relative albedo and thermal inertia. a. Image V0881003DR.QUB (Band 3), b. Image I0881002RDR.QUB (Band 9), c. Nighttime Image I0151006DR.RQB (Band 9). d. "Magic airbrush" weighted sum of images with coefficients chosen to cancel variations of albedo and thermal inertia. Images cover part of Gusev crater, with the MER-A Spirit landing point to the left of the triangle of hills in the top center.

Figure 2. MOLA-controlled photoclinometry to derive high resolution DEM: a. "magic airbrush" as in Fig. 1d, b. MOLA gridded topography, c. THEMIS-based photoclinometry modeled DEM, d. model of relative albedo derived by simulating the VIS image with the DEM and dividing out topographic modulation. For the martian surface at the phase angles of interest is slightly less limb-darkened (Kirk et al., 2000b) and will have only 70–80% the contrast of a Lambertian function. In practice, we find that it is straightforward to determine an empirical combination of the images that cancels both albedo and thermal inertia variations and leaves only slope-related effects as shown in Figure 1. The existence of such a solution depends on the properties of the thermal model as described above; the ease with which it is found is a result of the extreme acuity with which the visual system can distinguish intrinsic effects like albedo (which can affect arbitrarily large patches of the surface in a similar way) from topographic shading (in which dark and bright slopes are typically paired within a small region). We use the informal term "magic airbrush" for the empirical processing of THEMIS images, because it leads to a product (Fig. 1d) that resembles a shaded relief map yet is the result of surprisingly simple image processing rather than the painstaking efforts of an airbrush illustrator.

A further requisite for the production of "magic airbrush" maps that requires mention is the accurate coregistration of the component images. The VIS and IR images (Fig. 1a–c) were aligned by resampling them to a common map projection at a sample spacing of 80 m/pixel (a compromise between the VIS and IR resolutions) and then interactively adjusting the position of each dataset to register it to the others and to a control base prepared from Mars Orbiter Laser Altimeter (MOLA) gridded radius data (Smith et al., 2001). We are currently developing tools for correcting the positional errors in THEMIS data by rigorous least-squares bundle adjustment (Archinal et al., 2004).

2.4 Quantitative Topography

The use of the "magic airbrush" images is not limited to qualitative photointerpretation of the morphologic features that they reveal by suppressing albedo variations. The product can also be subjected to analysis by two-dimensional photoclinometry (Kirk, 1987; Kirk et al., 2003b; http://astrogeology.usgs.gov/Teams/Geomatics/pc.html) to produce a DEM with single-pixel resolution. Because of the use of thermal infrared data, this may also be referred to as "thermoclinometry," or "shape-from-heating." A weighted combination of $p_r$ and $p_{IR}$ should properly be used to interpret the weighted sum of VIS and IR images. Until the form of $p_{IR}$ is determined, we empirically resort to a Lambertian function and adjust the contrast of the input image to produce a DEM in which the heights of selected features agree with an independent (but generally lower resolution) source of topographic data such as MOLA (Smith et al., 2001). Such "calibration" of the photoclinometric
process would be required even if the photometric function
were precisely known (e.g., even for visible band images
without "magic airbrush" processing; see section 3 below
and Kirk et al., 2003b) because the image contains a uniform
additive offset that affects its constant. This offset comes in
part from atmospheric haze in the VIS image, which varies
with time and is not known a priori. Figure 2 shows the
photoinclometer DEM from the example of Fig. 1, with a
MOLA DEM of the same area for comparison. The photoinclometer adds local details while preserving long-
wavelength topography such as the height of the 10-km
wide mesa at the bottom. The detailed DEM can be used to
simulate the VIS image with realistic photometric function
p, but no albedo variations. Dividing the VIS image (after
subtraction of a constant haze value) by the simulation
yields a map of albedo variations that can reveal subtle
effects, e.g., the dark slopes on the sides of the mesa in Fig.
2d. The DEM can also be used to map absolute and
directional slopes.

We extended the analysis shown in Figs. 1–2 to neighboring
THEMIS VIS/IR triplets in order to produce topographic,
slope, and albedo maps of essentially the entire MER-A
(Spirit) and MER-B (Opportunity) region. These land- ing sites are among the first areas on Mars
for which nearly complete VIS coverage is available, but
current mission plans will lead to the eventual collection of
global IR imagery and VIS images of about half the planet.
MOLA-resolved features that could be used to calibrate
photoinclometry were present in only a few of the images, so
the remainder were calibrated to have similar slopes on
small-scale features. As it happened, Spirit landed within
the images shown here, about 2 km west of the triangle
of hills seen at the top center. Our THEMIS maps were useful
in the early days of the mission for locating the landing point
to ±100-m accuracy by tracing sightlines to features visible
from the lander. Hypothetical lander locations were also
tested by using the DEM to simulate the appearance of the
visiting vehicle as it approached a selected landing site (comparing,
e.g., to MOLA) was critical for this application.

3. MARS EXPRESS HRSC

3.1 Source Data

In early January 2004, the ESA Mars Express mission
started its science phase in orbit around Mars. Imaging and
mapping the Martian surface by the High Resolution Stereo
Camera (HRSC) is one of the main goals of Mars Express.
The HRSC experiment (Alibert et al., 1992; Neukum et al.,
2004) is a pushbroom scanning instrument with 9 CCD line
detectors mounted in parallel on the focal plane. Its unique
feature is the ability to nearly simultaneously obtain
imaging data of a specific site at high resolution, with
along-track triple stereo, with four colors, and at five
different phase angles, thus avoiding any time-dependent
variations of the observation conditions. An additional
Super-Resolution Channel (HRSC-SRC, a framing device) is
yielding nested-in images in the meter-range thus serving as
the sharpening eye for detailed photogeologic studies. The
spatial resolution from the nominal periapsis altitude of 250
km is 10 m/pixel for the HRSC proper and 2.3 m/pixel for
the SRC. The SRC images are normally acquired vertically,
but a subset are oblique because of spacecraft maneuvers to
fill gaps in image coverage.

3.2 Stereo Mapping Methodology

Our approach to processing HRSC data is largely independent
of those used by other members of the camera
team, which are described in several papers in this volume
(Hauber et al., 2004; Oberst et al., 2004; Ehren et al., 2004;
Heipke et al., 2004; Dorrer et al., 2004). We start with images in
VICAR format that have been radiometrically calibrated at
the German Aerospace Center (DLR) in Berlin. These images
are ingested into the USGS in-house digital cartographic
software ISIS (Eliason, 1997; Gaddis et al., 1997; Torson and
Becker, 1997; see also http://isis.astrogeology.usgs.gov).
In particular, the supporting cartographic information in the
VICAR labels is converted into its ISIS equivalents.
Because ISIS, unlike VICAR, does not currently accommodate
changing line exposure times within a scanner image, the
images are if necessary broken into multiple files that each
have a constant exposure time.

From this point onward, our approach to topographic
mapping with the HRSC images is similar to those we have
used for a wide range of planetary datasets (Kirk et al.,
2000a), and, in particular, for the Mars Global Surveyor
MOC images as described in detail in a recent paper (Kirk et
al., 2003a). We use ISIS for image registration and for
processing such as map-projection and image mosaicking.
The ISIS projection capability now includes orthonormal
textured, and detailed photometric models of the surface
and atmosphere (Kirk et al., 2000b, 2001) can be used to
correct the images for variations in illumination and atmos-
pheric haze before mosaicking. Two dimensional
photoinclometry is also implemented in ISIS (Kirk et al.,
2003b).

Our commercial digital photogrammetric workstation
running BAE Systems SOCET SET software (Miller and
Walker, 1993; 1995) is used for "3D" processing steps such as
georeferencing the images and automatic extraction and
manual editing of DEMs. SOCET SET includes a pushbroom
scanner sensor model that is physically realistic but
"generic" enough to describe the individual HRSC scanner
lines, as well as most images from the Mars Global Surveyor
Mars Orbiter Camera (MOC). SRC images can be imported
and used with the frame sensor model. We have written
software to import these and other types of images from ISIS
into SOCET SET and to translate the orientation data in ISIS
into the necessary format. In this process, each HRSC
false color array must be georeferenced (compared to the
original, e.g., to MOLA) at an appropriate pitch angle to match the true
geometry of the instrument. Because SOCET SET is unaware
that the images from the different HRSC lines are collected at
the same time, the intrinsic robustness of the multistereo
system is unfortunately lost. This is a relatively
minor disadvantage, given the availability of the MOLA
global topographic database, which provides control with an
accuracy on the order of 10 m vertically and 100 m
horizontally (Smith et al., 2001; Neumann et al., 2001).
The disadvantage is more than made up for in practice by
the ability of SOCET SET to perform bundle adjustments that include
images from sensors of different types (e.g., SRC and
MOC), and to produce DEMs from stereopairs of mixed type.
Nevertheless, we plan to extend the bundle-adjustment
software being developed for the THEMIS IR scanner
(Archinal et al., 2004) to model the HRSC with proper
accounting for the constraints between image lines. This
software may also eventually be extended to model the high-
frequency pointing variations ("jitter") that affect many
MOC narrow-angle (NA) images. Because the SOCET SET
adjustment software we are now using includes only
smoothly varying pointing corrections, we must use ad hoc
processing by spatial filtering to remove the jitter-related artifacts from
MOC DEMs.

The MOC NA images are well suited in terms of resolution
for stereomapping in conjunction with SRC images. The
horizontal resolution of the camera is 1.4 m/pixel, yet
images are most often obtained by pixel summation at
resolutions close to 3 or 6 m (Malin and Edgett, 2001).
More than 50,000 NA images have been obtained so far (see
www.wr.usgs.gov), and we have been able to locate vertical or
near-vertical images that overlap several of the handful of
oblique SRC image sets that have been obtained while the
Mars Express spacecraft is rolled off of its normal vertical
orientation. A larger number of pairs combining off-vertical
MOC images with the hundreds of vertical SRC images are
likely to exist. Figure 3 shows an example of a stereopair of part of the caldera of Olympus Mons, consisting of a 6-m/pixel MOC image and a set of three overlapping 4-m/pixel SRC frames. The anaglyph was prepared by projecting the two image sets in ISIS. Figure 4 shows an orthomosaic and contour map derived from a 15 m/post DEM produced from these images in SOCET SET.

3.3 Photoclinometry

Photoclinometry provides another means of producing DEMs with horizontal resolutions of a few meters from SRC images, and one that will be more widely applicable because no high resolution stereo partner is needed. As mentioned previously, photoclinometry must be "calibrated" by determining how much atmospheric haze has reduced the contrast of each image, if quantitatively accurate results are to be obtained for Mars. An independent estimate of the topography is required but can be of lower resolution. Calibration can then be accomplished either by performing trial photoclinometry and adjusting the amount of atmospheric haze subtracted from the image until feature heights agree with the a priori data, or by simulating an image from an a priori DEM and comparing its contrast with the real image (Kirk et al., 2003b). The accuracy of calibration depends on the possibility of finding adequately resolved common features in the image and the topographic dataset. If the only available topography comes from MOLA (which has an effective horizontal resolution of hundreds of meters at best), finding such features can be difficult or impossible, but if a stereo DEM closer to the resolution of the image is available, the photoclinometric topography can be calibrated to 10–20% accuracy in amplitude (Kirk et al., 2003a). Because HRSC stereo images are obtained simultaneously with every SRC frame, nearly every SRC image should be usable for calibrated photoclinometry, provided the surface albedo is uniform in the area imaged. This opportunity is also being exploited by Dorrer et al. (2004).

4. MARS EXPLORATION ROVERS ATHENA

4.1 Source Data

The Mars Exploration Rover Spirit landed in Gusev crater on January 4 (UTC), 2004. It was followed 21 days later by the rover Opportunity, which landed on Meridiani Planum. Each rover carries a copy of the Athena science payload (Squyres et al., 2003; Squyres and Athena Science Team, 2004), which includes two science camera systems. The topography, morphology, and mineralogy of the scene around each rover are revealed by the Pancam stereo camera (and also by the
we characterize the coordinate frames implemented by the PanCam software. Our implementation of the multi-terrain alignment tool (MTAT) for PanCam images is a natural coordinate frame that can be used to register PanCam images to each other and to mosaics of other imaging systems. For example, we used PanCam images from the Mars Exploration Rover mission to reconstruct the tracks of the rover using a combination of PanCam and HiRISE images. Our implementation of MTAT is available online at the PanCam software repository.

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