HIGH-RESOLUTION TOPOMAPPING OF CANDIDATE MER LANDING SITES WITH MOC: NEW RESULTS AND ERROR ANALYSES.

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Introduction: This abstract describes the continuation of work initially reported last year [1] on topographic mapping and roughness analysis of candidate Mars Exploration Rover (MER) landing sites using high-resolution images from the Mars Global Surveyor Mars Orbiter Camera Narrow-Angle subsystem (MGS MOC-NA; [2]). The main goal of this work at present is to contribute to assessments of whether the MER spacecraft could land safely at each site. To this end our data suggest that the sites now being considered are much more likely to be safe than several sites reported on previously [1] and since eliminated. Topographic data for the sites that are ultimately selected will also be useful in planning mission operations and analyzing the scientific return from the rovers, however, and it is likely that the topographic models we report on here will be augmented by more extensive coverage in the coming year.

Since our earlier report there have been several changes and advances in the process of mapping the candidate landing sites and assessing their safety. First, the approach to quantifying landing safety has become much more elaborate. Topography affects the landing process in a number of ways on different lengthscales, necessitating the use of different input datasets. Our high-resolution (typically 3–10 m) mapping with MOC provides information that is needed to evaluate safety as the spacecraft bounces to a stop on the surface. Initially, slopes ≥ 15° on a 5-m baseline (approximately the diameter of the MER airbag cluster) were determined to be "unsafe" and sites with ≥ 1% probability (later, ≥ 2%) of such slopes were to be excluded. This simple criterion has been replaced by the requirement that Monte Carlo simulations of the trajectory carried out by mission engineers at JPL result in an acceptably low failure rate as determined by various criteria (e.g., excessive vertical or horizontal velocity). For sites with a significant range of surface roughnesses, these simulations must be carried out for each "hazard unit" and the results combined in a weighted average that represents the overall failure rate for the site. Our digital elevation models (DEMs) of hazard units, rather than the roughness statistics derived from them, are thus the input to the safety assessment process. Summary roughness statistics are nevertheless useful for comparing sites and for making a rough, unofficial assessment of site safety, based on the prevalence of 15° slopes. We therefore report slope statistical measures for the DEMs described here.

In addition, the list of candidate sites has changed in the past year, and many additional images of the sites have become available. We have now processed more than four times as many image sets as reported on previously. Finally, we have carried out several studies using simulated and real data to assess the errors in our topographic models and summarize the results below.

Sites and Images: Early in 2002 the primary sites under consideration were located in Gusev crater, Isidis Planitia, Melas Chasma, and Terra Meridiani ("Hematite"), with backups in Eos Chasma and Athabasca Vallis. We reported results for one stereopair each in Gusev, Isidis (where the only pair then available was ~150 km outside the landing ellipse), Melas, and Eos in our previous abstract [1] and by the XXXIIIrd LPSC had added results for Athabasca. Two further stereopairs in Melas were analyzed soon thereafter, but the Melas and Eos sites were eliminated because of concerns about strong winds (both were also found to be quite rough). The Athabasca site was also disqualified because radar data indicated extreme roughness at scales much smaller than those resolved by MOC. Finally, a new "wind safe" site in Utopia Planitia (near the border with Elysium Planitia and therefore commonly referred to as the Elysium site) was added. At this writing all four remaining sites, Gusev, Isidis, Meridiani ("Hematite"), and "Elysium" (Utopia) are being considered on an equal basis, with a decision assigning two sites to specific rovers as primary and naming the other two as backups expected in the near future. As shown in Table 1, we have analyzed 6 images or stereopairs in Gusev, 4 in Meridiani, and 1 each in Isidis and "Elysium", as well as 2 at the Mars Pathfinder landing site. Pairs at the eliminated sites are not shown for lack of space. Our primary tool in identifying candidate stereopairs has been the maps of the landing sites produced by T. Parker of JPL (earlier versions online at marsoweb.nas.nasa.gov/dataViz/datamaps.html). The availability of Mars Odyssey THEMIS images [3] as context for the MOC frames has enormously simplified the process of identifying usable image overlaps by reducing errors in the placement of images in the site maps. Candidate pairs of images identified based on overlap are checked for in the MOC cumulative index table for adequate stereo convergence angle and compatible illumination, and examined visually for adequate signal-to-noise ratio and lack of surface changes that would preclude mapping. The MER Landing Site Selection Committee makes the final selection of images to be mapped from among those that pass these tests.

Methodology: Our techniques for stereomapping and photoclinometry (PC) are described in more detail in several recent abstracts and conference papers [4] and are similar to those used for a wide range of planetary datasets [5]. We use the USGS in-house digital cartographic software ISIS [6] for mission-specific data ingestion and calibration steps, as well as "2D" processing such as map-projection and image mosaicking. Photoclinometry [7,8] and slope analysis are also performed with (unreleased) programs that read ISIS image files. Our commercial digital photogrammetric workstation, an LH Systems DPW-790 running SOCET SET ® BAE Sytems software [9] is used for "3D" processing steps such as control of 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 most MOC-NA (and WA) images and allows low-order (bias, drift and acceleration) adjustments to register the images to the globally adjusted MOLA coordinates [10]. Many MOC images are also affected by high-frequency pointing variations ("jitter") that cannot be corrected with the available software for image control. Jitter in the stereobase direction gives rise to topographic artifacts in the form of stripes across the DEM; these were suppressed by highpass filtering. Severe jitter at right angles to the stereobase interferes with matching; a workaround is to segment the image into regions that can be controlled and DEMs collected separately. Development of bundle adjustment software incorporating high-frequency oscillations would avoid the need for such time consuming *ad hoc* fixes.

The two-dimensional PC algorithm of Kirk [7] was used to construct DEMs of selected image regions with single-pixel resolution. Accuracy of these DEMs depends crucially on the validity of photometric assumptions [11]. While the surface photometry of Mars is adequately constrained [12], the atmospheric haze contribution to any given image is essentially an unknown; mis-estimating this haze level leads to errors in the overall scale of topography (and slopes). We therefore calibrate the PC analysis by choosing a haze estimate that gives results consistent with stereogrammetry. This can be done in either the image or the topographic domain. By shading the stereo DEM with a realistic surface photometric function and comparing the result to the image, one obtains the haze estimate as the constant offset in a regression between the two. Conversely, trial PC can be done with different haze values and the case that gives best agreement between PC and stereo DEMs selected [8]. In either method errors in the stereo DEM limit the resemblance to the image and can make the comparison difficult. Finally, despite the selection of image areas with little or no visible albedo variations, it was usually necessary to filter the PC DEMs to suppress albedo-related artifacts in the form of ridges and troughs aligned with the sun direction.

We analyze our DEMs to generate slope statistics by a combination of explicit finite-difference calculations (yielding probability distributions, quantiles, and root-mean-square or RMS values of bidirectional and adirectional slopes over a fixed baseline) and Fourier transform techniques (yielding the variation of RMS bidirectional slope with baseline). The Fourier results are useful not only for interpolating or extrapolating statistics to the 5-m baseline relevant to MER, but for assessing whether the features seen in the images are adequately resolved in the DEMs.

Error Analyses and Calibration:

Stereo Matching Error: To evaluate errors caused by the automatic stereomatching software used to produce DEMs, which are dependent on the contents of the images being matched, we used MOC data to simulate a stereopair with no topographic relief. The nadir image of pair Gusev 1 (Table 1) was scaled, rotated, and skewed to reproduce the geometry of the oblique image partner as closely as possible, then input to SOCET SET with the geometric data for that image and used to produce a DEM. Variations in this DEM could be attributed purely to the matcher, and had a RMS value equivalent to 0.22 pixel matching error, very close to the 0.2 pixel commonly cited and to values estimated by us for other planetary image sets [13]. Taking account of spatial correlations of the errors, we obtained an estimate of the matcher-induced error in local slope estimates that could be scaled to other image pairs with different resolutions and stereo convergence angles. Our estimate of the slope error is less than the recovered slope estimate for all but the smoothest parts of Meridiani, where the matcher failed entirely.

Independent DEM Comparisons: We compared our DEM produced from images E02-00270 and E05-01626 in Melas Chasma with DEMs produced from the same images by the Harris Corporation (supplied by M. Caplinger of MSSS) and by A. Ivanov of JPL [14]. SOCET SET was used to resample the latter DEMs to the same resolution and coordinate system as ours. The RMS difference after registration was 4.2 m for the MSSS model, consistent with equal, statistically independent matching error of 0.22 pixel in each model. The RMS difference between the USGS and JPL models was only 1.8 m, suggesting that the errors in the two are partially correlated as a result of similarities in the matching algorithms used.

A second image pair at the Pathfinder landing site (Table 1) provided a test of the consistency of our own DEMs and hence their errors. Comparison of the new DEM with the previous one [1,4], which we remapped with control to MOLA, was complicated by the presence of both jitter-related undulations and a systematic center-to-edges variation (discussed below). After filtering to suppress these errors, the RMS difference between the overlapping DEMs was 4.8 m, corresponding to 0.3 pixel RMS matching error. The new MOC

DEM, like the previous one [1,4], yields slope statistics in excellent agreement with those from Viking Orbiter [15] and IMP [13] data.

Geometric Calibration of MOC-NA: The center-to-edges pattern is seen in many of our MOC stereomodels, (and identically in those from MSSS/Harris and JPL) with the center high in some cases but low in others. This artifact can be attributed to low-order geometric distortion of the optical system, and depends on the distance between the optical centers of the two images on the ground as well as the amount of distortion. Our preliminary analysis indicates that a pincushion distortion of ~1% at the edges of the detector accounts for the DEM errors. A refined value for the distortion coefficient will be reported in our poster and transmitted to the NAIF for inclusion in the MOC Instrument Kernel.

Photoclinometry Tests: By simulating images from a known DEM and attempting to recover this DEM by PC we can assess some of the errors of this method. Self-affine fractal topography [16] is convenient for such tests: it is easy to produce, and its statistical properties can be controlled to approximate those of natural surfaces. Our simulations show that errors in the PC DEMs have negligible effect on slope statistics (estimated RMS slopes within 0.01–1% of true values) when the photometric function and atmospheric haze are known. We also confirm that slopes estimated by our two-dimensional PC [7] agree closely with estimates obtained from the same image by point PC [17] provided we calculate the slope across pixels rather than the (interpolated, hence slightly smoother) slope from pixel center to pixel center that we normally report for 2D PC. This distinction is important for the fractal models but not for MOC images, which have relatively little variation at the single-pixel scale. Using a different (but still Mars-appropriate [12]) photometric function for PC than was used in simulating the image results in errors on the order of 5% in the scale of topography and slopes. Variations in surface albedo (not accounted for in the PC analysis) can lead to substantial slope errors, especially on baselines that cross the sun direction, but filtering the DEM to remove albedo-related artifacts is highly effective in correcting the slope estimates. In general, we find that error in estimating the haze correction of the images, which can easily affect topographic amplitude and hence slopes by 10–20%, is likely to be the dominant error source. The morphologic and hazard units in the candidate MER landing sites are readily distinguished despite errors of this magnitude.

Results:

Gusev crater: This site has been studied most because it has the greatest variety of morphologic/hazard units. Surprisingly, our first DEMs captured much of this variety, yielding low slopes on cratered plains inside the 22-km crater Thyra at the east end of the landing ellipse (set 1d) and much higher slopes on knobby etched plains outside the ellipse south of Thyra (set 1e) [1]. Our subsequent results show that cratered plains (set 3, and also a dense crater cluster, set 6) inside the ellipse are similar to those outside, while etched plains southwest of Thyra (set 2) and surrounding a ~2-km crater in the center of the ellipse (sets 4, 5) resemble those south of Thyra. Most units have relatively little albedo variation, and slopes from PC agree with those from stereo. Although the etched unit is quite rough, its area is small so there is reason to expect that the site as a whole will be judged safe.

Isidis Planitia: Our new pair inside the Isidis ellipse is dominated by a dense cluster of secondary impact craters and is slightly rougher than the cratered plains (~150 km outside the ellipse but resembling those inside) previously mapped [1]. The dark floors of the craters preclude use of PC. We therefore plan to map another stereopair in the Isidis ellipse that is more representative and has small albedo variations, such that PC is possible. This result will be reported in our poster.

Meridiani Terra ("Hematite"): This site is so smooth that stereo-matching failed to produce usable results for the first and third pairs studied. We therefore attempted PC on a single image (set 2) by using a haze estimate that produced similar slopes on duneforms to those found previously in Melas Chasma [1]. Slopes obtained in a typical bland area were extremely small and those for slightly more textured material that appears to protrude from the smooth plains only slightly greater; apparent slopes in areas with easily visible albedo variations were higher but can be discarded as artifacts. We have since successfully stereomapped two image pairs (sets 4, 5) with larger convergence angles, finding slopes very similar to those previously obtained from PC.

"Elysium" (Utopia Planitia): A single stereopair in this ellipse has been analyzed, yielding slopes comparable to the smooth cratered plains in Gusev. A large wrinkle-ridge crosses the stereopair, so the model may be rougher than typical for the ellipse. Unfortunately, localized albedo variations made it impossible to obtain a consistent haze estimate by comparing the image and stereo DEM in either the radiance or elevation domain, so PC could not be attempted. We will therefore select and map a second stereopair in the ellipse and attempt to obtain a PC DEM to confirm the stereo results at higher resolution.

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Table 1. MOC Stereopairs of MER Landing Sites & Roughness Statistics

Site	Set	Image 1	Image 2	Lon (°)	Lat (°)	Res (m)	c.a. (°)	EP (m)	Method	GSD (m)	RMS Slope (°)	MER Slope (°)	P(15°) %
Pathfinder	1a	SP1-23703	SP1-25603	326.	19.2	3.2	9.3	2.9	ST	10	3.2	16.1	1.2
	2a	M11-02414	E04-02227	326.	19.3	1.9	12.3	1.4	ST	10	3.3	20.2	2.0
Gusev	1d	E02-00665	E02-01453	175.	-14.5	3.3	22.1	1.5	PC	3	4.2	15.0	1.0
	1e	E02-00665	E02-01453	175.	-14.8	3.3	22.1	1.5	PC	3	9.4	32.0	16.3
	2c	E01-00341	E05-00471	175.	-14.9	3.0	10.0	3.3	PC	3	9.0	30.5	16.6
	3c	M03-01042	E17-01547	174.	-14.6	7.1	11.8	5.2	PC	3	3.0	13.7	0.7
	4c	E18-00184	E17-00827	175.	-14.7	3.7	10.7	3.1	PC	3.1	8.1	30.2	4.7
	5a	E05-03287	E18-00184	175.	-14.7	3.2	18.1	1.8	ST	10	8.3	41.5	19.5
	6c	E19-00218	E21-00256	174.	-14.7	3.0	10.2	3.2	PC	3.3	3.0	13.5	0.6
Isidis	1b	E02-02016	E02-01301	85.0	4.6	3.1	13.0	2.6	ST	10	4.7	30.8	3.7
	2a	E13-00965	E14-01522	88.7	4.3	3.1	16.9	2.0	ST	10	5.9	29.1	8.8
Meridiani	2b	E03-01763		353.	-2.1	2.9			PC	2.9	1.3	4.7	0.1
	2c	E03-01763		353.	-2.2	2.9			PC	2.9	2.2	8.8	0.1
	4a	E12-03255	E18-01595	353.	-2.0	3.0	21.2	1.6	ST	10	1.6	7.9	0.1
	5a	E15-00023	E21-01653	354.	-1.9	3.6	32.1	1.1	ST	10	1.3	5.4	0.1
"Elysium"	1a	E18-00429	E21-00118	124.	11.8	3.6	29.4	1.2	ST	10	3.5	13.6	0.6

Set indicates image or pair within landing site in order of processing; letter indicates specific subarea of dataset for which slopes are given. Lon and Lat are approximate east longitude, planetocentric latitude at center of model. Res is the coarser of the two image resolutions. c.a. is convergence angle. EP is expected vertical precision, approximately equal to 0.2 Res / tan(c.a.). Method indicates source of DEM for which statistics are given (ST=stereo, PC=photoclinometry). GSD is ground sample distance (post spacing) of DEM. RMS Slope is bidirectional, at given GSD. "MER Slope" is 99th %ile adirectional slope corrected to 5 m baseline; mission safety limit for this type of slope is ~15°. P(15°) is percent probability of encountering $\geq$ 15° slope on 5-m baseline.