LANDERS AND ROVERS NEED HIGH RESOLUTION TOPOGRAPHIC MAPS: LESSONS FROM THE NASA MARS EXPLORATION PROGRAM.

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Introduction: The Astrogeology Science Center of the USGS has provided topographic mapping support for landing site selection since the beginning of the US Mars program. The authors of the present abstract have been involved in landing site mapping for every successful US Mars landing starting with Mars Pathfinder. Here, we review this activity and draw some important lessons for future Mars exploration planning. Our main conclusions are

- High resolution topographic data are an essential ingredient in the process of selecting a safe landing site, and are also valuable for evaluation of site science and for planning and executing surface operations.
- The desire for topographic data is nearly insatiable…the volume required for site certification has grown phenomenally to the current standard of covering the entire landing and operations zone with maps that resolve every feature that could endanger the spacecraft (Figure 1).
- The capability to make high resolution topographic models must be maintained if the Mars program is to flourish. This means providing orbital stereo imaging capabilities that benefit from lessons learned regarding data needs for high quality for mapping, and maintaining ground processing capabilities for stereomapping.

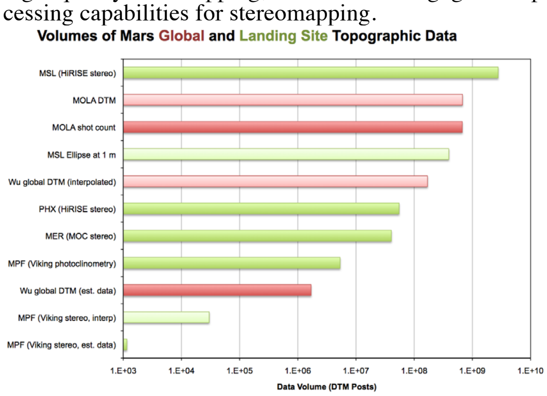

Figure 1. Volumes of topographic data processed for Mars landing site selection compared to key global topographic datasets. Note the logarithmic scale spanning 7 orders of magnitude.

What Constitutes a Topographic Hazard? The detailed engineering constraints vary with the landing system [1–4] but they can be divided generally into (a) slopes over 100s-1000s of m, which can "spoof" the altimeter used to control the landing sequence, and (b) topography, slopes, and rocks at the scale of the lander itself, which can cause the vehicle to break, tip over, or high-center at the moment of touchdown. In the early history of Mars exploration, addressing the latter class of hazards required wild extrapolation of the available data, but they can now be addressed directly.

How are Topographic Maps Made? Historically, the most important data source has been orbital imagery. Photogrammetric analysis of stereopairs generally yields digital topographic models (DTMs) with a horizontal resolution of at best 3-5 image pixels. Vertical precision depends on the stereo geometry but is typically an order of magnitude smaller than the horizontal resolution [5,6]. Absolute accuracy and slopes across multiple stereopairs depend on the ability to control images to some reference dataset. Photoclinometry (PC, also called shape from shading) [7,8] can yield extremely accurate slopes at the limit of image resolution but methods that work on a single image depend on the albedo being constant; errors due to even tiny albedo variations accumulate rapidly over distances greater than a pixel. In addition, the overall scaling of topography and slopes from PC depends on correction for atmospheric haze, so calibration to stereo or other data is essential. The strengths and weaknesses of stereo and PC make these methods highly complementary.

The Mars Orbiter Laser Altimeter (MOLA) [9] revolutionized Mars mapping. Its vertical precision and accuracy (~1 and 10 m, respectively) are very high but horizontal resolution is limited by the laser spot size (<100 m), spot spacing (300 m) and profile spacing (which can be several km in the equatorial zone). Thus, MOLA has definitively measured long-baseline slopes but cannot address rover-scale slopes. Its greatest importance to high resolution mapping is as a reference for geodetic control of other datasets. Tens of millions of crossings between ~9000 orbit profiles allowed an extremely robust global adjustment [10] so MOLA defines absolute coordinates to ~100 m accuracy globally and other datasets can be tied to it.

Landing Site Mapping 1994–2012: Our experiences supporting LS selection for four missions illustrate the improvements in camera and processing technology and the explosion of the volume of data acquired and processed.

Mars Pathfinder: The best available data in the early 1990s were ~1 Mpixel frame images from the vidicon camera on the Viking Orbiters, so site selection was necessarily limited to areas that had been imaged intensively in the 1970s because they were considered as VL sites. The Ares Vallis (former Viking A1) site [1] had multi-stereo coverage at 40 m/pixel collected on a single orbit by pitching the camera platform. We used an analog stereoplotter to produce a contour map of the landing ellipse [11], then interpolated the few thousand points on contours to produce a DTM. In addition, we used photoclinometry to collect slope statistics at baselines ≥80 m [12]. Without global altimetry, our data were tied to control networks derived from low resolution global Viking images, limiting absolute accuracy to several km, fortunately small compared to the landing ellipse.

Mars Exploration Rovers (MER): The advent of digital or "softcopy" photogrammetry [13,14], which uses automated image matching to produce dense DTMs, revolutionized site mapping as much as did the availability of MOLA data. Images from the Mars Orbiter Narrow Angle Camera (MOC-NA) pushbroom scanner [15], were used. Stereo was obtained by rolling the spacecraft to image a target on multiple orbits. To improve signal to noise ratio (SNR), most images were obtained at ~3 m/pixel, yielding 10 m/post DTMs. These DTMs were supplemented by PC to obtain 3 m/post topographic data [5]. The overall site certification strategy was to sample initial candidate sites with at least one image set, then to map out and sample each terrain type in the final sites [2]. Most stereo DTMs were distorted across track because the camera had not been geometrically calibrated before flight, and many contained "washboard" ripples because of spacecraft vibration ("jitter") during the acquisition of the images. In some cases severe jitter in the cross-stereo direction made collecting DTMs difficult or impossible [5].

Phoenix: The site selection process began as for MER with MOC data, but was hampered by atmospheric conditions that limited imaging to a short period per Mars year. In the second such imaging season, Mars Reconnaissance Orbiter HiRISE [16] images became available and revealed numerous boulders (initially counted manually) in the prime site, forcing a search for alternates [3]. We sampled each of the new candidate areas with one HiRISE DTM at 1 m/post and mapped the area around the spacecraft after landing [6].

Mars Science Laboratory (MSL): HiRISE was the sole resource for evaluating rover-scale topographic hazards.

Automated methods first developed for Phoenix [17] were used to evaluate rock densities and distributions. We made numerous stereo DTMs, initially a single one each of several candidate sites, later with the goal of covering the 20x25-km landing ellipse (75-95% complete coverage was obtained) in the final 4 sites [18]. The average volume of topographic data *per site* equaled the entire MOLA global dataset (Fig. 1). After the Gale site was selected, DTM coverage was doubled to fill remaining gaps and cover the science target area outside the ellipse. Jitter was a problem in many of these images, but a method was developed to model and correct jitter distortions based on the multiple overlapping detector segments in the camera [19]. The HiRISE DTMs were controlled individually to MOLA as they were made, but to mosaic them after the fact they were adjusted to one another and to a hierarchical set of DTMs from MRO CTX (25 m/post) and HRSC (50 m/post) [20].

Beyond Site Safety: DTMs are crucial for removing parallax distortions from orbital remote sensing data so datasets can be coregistered and compared. The need is particularly stringent for change detection, where static features must be registered to subpixel precision in order to measure changes [21]. Pixel-scale slope data are also needed for photometric correction of spectral data. These applications are relevant to evaluating the relative science merit of sites that pass the preliminary test of safety. Operational experience during the MER missions has also shown that high resolution images and DTMs can be used to increase the efficiency of traverse planning [22]. The MSL mission is already using our HiRISE DTMs to evaluate traverse routes [23].

Lessons Learned: The overwhelming lesson is that the demand for topographic data for landing site selection and certification has increased with the technical capabilities of the orbital missions. We may now have reached a plateau in terms of required coverage (100% of the landing ellipse and science target) and resolution (sub-meter pixel scale to assess the hazard of meter-scale rocks and slopes to the lander) but retreating to incomplete or lower resolution coverage for future missions seems unthinkable. This means that a HiRISE-scale sub-meter stereo imaging capability will be needed in Mars orbit to support future missions lest (like Pathfinder) these be restricted to previously considered landing sites. HiRISE itself has a finite life expectancy and has imaged only ~0.25% of Mars in stereo. As we emphasize in a companion abstract [24], these observations have been targeted based on the best current understanding of Mars science and the limitations of current landing systems. Shrinking the landing ellipse will open up vast numbers of new candidate sites that may have greater science value than any considered so far, but they will be off limits unless they can be mapped with new stereo images.

Our experience described above leads to the following list of requirements for effective stereo mapping:

Resolution: HiRISE-scale imaging with 3-4 pixel/m is needed to resolve meter-scale obstacles that endanger landing and roving spacecraft. Higher resolutions face diminishing returns of increased safety in relation to cost, data volume and processing effort, and lower resolutions will fail to detect critical hazards.

Context: Lower resolution (e.g., 2–20 m/pixel) stereo observations with much wider coverage are useful for "prescreening" sites and are invaluable for controlling high resolution coverage into seamless mosaics.

Image size and camera complexity: Covering the same area in fewer, larger images reduces the effort needed to control the data and to edit poorly mapped areas near the image edges. These benefits offset the disadvantage that pushbroom cameras are susceptible to jitter distortions. More complex cameras generally require development of more complex and expensive processing software, but using multiple detectors has the positive effect of allowing jitter to be corrected. Pushframe cameras combine the deficiencies of frame and pushbroom systems (i.e., numerous small images and susceptibility to jitter) and are inappropriate for stereo mapping.

Rapid stereo acquisition: The longer the time interval between images of a pair, the greater the chance that lighting variations, weather, and/or surface changes will make stereo comparison difficult. A significant fraction of MOC, CTX, and HiRISE stereopairs are unusable for this reason. Use of multiple detector lines (as by HRSC) or articulation of the camera (as by VO) to obtain stereo on a single pass over the target greatly improves the chances that a given stereopair will be useful, as well as simplifying stereo targeting.

SNR and compression: HiRISE is designed to have SNR>100 in its red bandpass [16], and automated stereo image matching is normally highly effective as a result. The resolution and error rate of such matching degrade when high atmospheric opacity reduces SNR. Other sensors with lower SNR (e.g., MOC) and/or visible artifacts from lossy image compression (HRSC, CTX) produce less satisfactory stereo results in relation to the pixel scale. Future stereo cameras need to optimize SNR and limit image compression artifacts.

Jitter: The distortion of pushbroom images by spacecraft motion can distort the DTM in a washboard pattern, but, more importantly, jitter at right angles to the stereobase can make image matching difficult or impossible. Given multiple detector lines (e.g., HRSC) or overlapping detectors in a single line (HiRISE) it is possible to model and correct jitter distortions, so future cameras should include these features. Pausing known sources of vibration during imaging is desirable. Consideration should also be given to simplifying spacecraft and payload designs to avoid unnecessary moving parts that contribute to jitter.

Stereo processing capabilities: Production of high quality, high resolution DTMs requires specialized software for controlling images and automated image matching, special hardware needed for interactive viewing and editing of three dimensional data, and the expertise needed to use these tools. Trying to extract the highest possible DTM resolution from given images substantially increases the need for human intervention and expertise. The capability to make the DTMs needed by surface missions must be protected by providing steady and reliable funding to ensure that capabilities are not dismantled and key staff dispersed in between missions.

Research and development: Significant opportunities exist to improve the quality and efficiency of topographic mapping by developing new and improved techniques. Notable among these are improved image matching algorithms that would require less interactive editing to produce useful DTMs; better approaches to jitter modeling, and hybrid methods that combine both stereo and shading clues from multiple images to produce shape and albedo models at the image resolution.

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