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Near-complete 1-m topographic models of the MSL candidate landing sites: Site safety and quality evaluation

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Abstract

To support landing site selection for the Mars Science Laboratory (MSL) we have produced digital topographic models (DTMs) of the candidate sites with 1-m grid spacing from Mars Reconnaissance Orbiter High Resolution Imaging Science Experiment (MRO HiRISE) stereo image pairs. The delivered DTMs cover 75-95% of each landing uncertainty ellipse plus key traverse areas outside the ellipse containing science targets that the MSL rover would be likely to visit. Rover-scale slopes derived from these DTMs are in the range of 1–2 times those at the roughest past landing site, but meet the criteria for MSL landing safety at all sites. The extensive overlaps between neighboring stereo DTMs in the MSL sites provide a unique opportunity to assess the quality (accuracy, precision, resolution) of our stereo DTM. The results of such assessment agree closely with theoretical estimates of quality based on the image resolution and geometry.

1. Introduction

The importance of topographic and slope data for selecting a safe landing site has been understood since the first soft landers were sent to the Moon and planets, but the quantity and quality of such information that is available has increased dramatically. We have been involved in mapping candidate landing sites for all successful Mars surface missions (and none of the unsuccessful ones) beginning with Mars Pathfinder, for which we mapped the landing uncertainty ellipse with 40 m/pixel Viking Orbiter stereo images [1]. The Viking contour map contained only ~1000 directly measured height points, from which elevations elsewhere in the ellipse were interpolated. Landing site mapping for subsequent missions introduced higher resolution images: 3 m/pixel MOC Narrow-Angle images for the MER rovers [2] and 0.25–0.3 m/pixel HiRISE images for Phoenix [3], but these were limited to small samples of representative terrain types [4]. In 2008, we began mapping MSL sites with HiRISE images, sampling the most important candidates [5] with a single DTM each. After downselection to the “final four” candidate sites (Eberswalde, Holden, Gale, and Mawrth) [6] at the end of 2008, we began intensive mapping of these sites with the goal of producing DTMs for the entire ellipses and key science targets nearby. The 25 HiRISE DTMs needed to achieve this coverage contain a total of 2.8 billion height points, several million times the information in the Mars Pathfinder contour map and four times the volume of the Mars Orbiter Laser Altimeter (MOLA) global DTM [7].

2. Methodology

Our approach to stereomapping with HiRISE images described in detail in [3] and is summarized in brief here. Stereo coverage is obtained by imaging the same target on two different orbits, with the MRO spacecraft rolled off its normal nadir orientation on one or both orbits to provide convergent viewing, typically at angles of 20–30°. Data obtained by the 10 red-filtered CCD detectors, which provide the widest cross-track field of view, are used for stereo processing. The individual CCD images are radiometrically calibrated and “balanced” in brightness and contrast at the HiRISE Operations Center (HiROC) [8]. The USGS software system ISIS [9] is used to resample and combine the CCD images into a single 20,000-pixel wide image, correcting for the relative offsets and rotations of the CCD segments and optical distortion. This step can also be used to correct image distortions that result from rapid angular motions (“jitter”) of the spacecraft after modelling the jitter with the HiRISE Jitter Adjusted Camera Kernel (HiJACK) pipeline [10]. HiJACK processing is generally used only if the angular motions exceed 2 to 3 pixels (2–3 μRad), the level found to interfere with stereo matching [3]. Before this jitter-correction process became available, it was necessary to request the acquisition of a new HiRISE stereopair in cases where the initial pair exhibited jitter of this magnitude.

Once the CCD images are distortion-corrected and combined in a mosaic, the resulting full-swath image and its trajectory and pointing history are output from ISIS in formats understood by BAE Systems SOCET SET ® software [11]. This commercial stereoanalysis package is then used to control the images, create the DTM by automated image matching, and interactively edit the DTM. Control is based on ~10 ground points in flat areas where elevations are constrained to agree with MOLA data [7], plus a smaller number of points on features that can be identified in both the HiRISE and MOLA data sets and thereby used to constrain the horizontal position as well. Because of the high resolution and signal/noise ratio of HiRISE, the need for DTM editing is minimal and is usually restricted to shadows, smooth featureless areas, and a few of the steepest slopes.

3. Data Products

The main products generated for each stereopair are a DTM at 1 m/post and orthorectified (i.e., projected onto the DTM to remove parallax distortions) versions of each image at 1 m/pixel (to match the DTM) and 0.25 m/pixel (the approximate scale of the source imagery). To facilitate the MSL landing site analysis, products are delivered to the project upon completion as ISIS "cube" files and GeoTIFFs, in Equirectangular projection with planetocentric latitude type, center latitude 0°, scaling based on the equatorial radius of Mars, and heights expressed as radii. DTMs and orthoimages are subsequently archived along with other HiRISE DTMs in NASA Planetary Data System (PDS) format and with slightly different cartographic parameters [12]. Supplementary products for MSL include maps of adirectional (downhill) slope computed from the DTM over 1x1, 2x2, and 5x5 m squares [2]; page-sized "layout" figures showing the image and color shaded relief DTM with scale, graticule, and annotation; and color-coded slope maps downsampled to 10 m/pixel.

We have also mosaicked the DTMs for each site, after making horizontal and vertical adjustments to improve the consistency of the DTM segments, which were controlled independently over a period of years. Horizontal errors were reduced by incorporating the DTM segments into a landing site GIS model developed at JPL [13], in which an intermediate resolution MOLA-controlled Mars Express HRSC DTM and orthoimage (DA4 product) [14] were used to improve registration of low emission angle 6 m/pixel CTX images [15] by measuring tiepoints and carrying out a "rubber sheet" transformation. The HiRISE DTMs and orthoimages were then registered to the CTX images by a similar process. Vertical errors were reduced by using the ISIS program "equalizer" to determine and apply vertical offsets to the HiRISE DTMs to minimize mismatches between overlapping segments, and then to match the mosaicked HiRISE data to HRSC. The end result is to reference all data sets to the MOLA base, which provides a well-understood conversion from inertial space in which the spacecraft are flown into cartographic space on the surface of Mars [4].

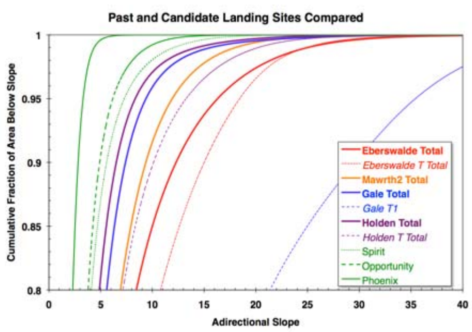

Figure 1: Cumulative slope distributions over 5 m baseline for the final four MSL sites and three past landing sites.

4. Topographic and Slope Results

The 25 HiRISE stereopairs cover from 75% (Gale) to 96% (Eberswalde) of the target ellipses, plus traverse areas for Eberswalde, Holden, and Gale. Figure 1 shows cumulative probability distributions of adirectional (downhill) slope over 5-m baseline for the four ellipses and three traverse areas. Comparable probability distributions for the MER and Phoenix landing sites, also based on HiRISE stereo data, are shown for comparison. Slopes in the candidate ellipses range from comparable to those at the MER Spirit site (Gusev cratered plains, excluding Columbia Hills [3]) at Holden to about twice as great for Gale, but slopes in excess of 25°, which would begin to present a landing hazard [13], occur over <1% of the roughest site. The traverse areas are rougher, which is, of course, why these science targets are designated as "go to" destinations rather than being included in the landing ellipse. Detailed studies based on our DTMs indicate that, even in the exceptionally rough Gale traverse area it will be possible to navigate the rover to the science targets of interest at all stratigraphic levels in the lower Gale sediment mound.

5. Quality Assessment

In addition to supporting the MSL mission, the large collection of overlapping DTMs described here offers a unique opportunity to assess the quality of our HiRISE products. Based on the tiepoint offsets between HiRISE and HRSC products, we find that the horizontal accuracy with which our single HiRISE stereopairs were controlled is 50–100 m RMS (root mean squared). The precision of our ties to HRSC is 10–20 m RMS. The offsets calculated by equalizer indicate that the vertical accuracy of control is 10–20 m. Comparison of overlapping HiRISE DTMs indicate that the control solution includes erroneous tilts on the order of 1 mRad, corresponding to ~10 m variation from true level over the extent of a DTM. The overlaps can also be used to estimate the vertical precision (EP) as 0.1–0.4 m RMS, with smaller values in areas with more surface texture for the stereo matching algorithm to correlate. These errors correspond to ≤2° RMS error in adirectional slope. All of these accuracy and precision values are consistent with the estimates we have previously made based on the HiRISE image resolution and stereo geometry [3]. Finally, by comparing HiRISE DTMs to a coregistered HRSC DTM we were able to assess the vertical precision and true horizontal resolution of the latter. The Gale traverse area provides an especially favorable location for this test because of its strong surface texture and the availability of a 50 m/post DTM from 12.5 m/pixel (nadir) imagery. The best fit between HRSC and HiRISE data is obtained when the latter are smoothed with a 750 m wide lowpass boxcar filter, indicating that this is the effective resolution of the HRSC DTM. The estimated vertical precision is 12.5 m or about 1 pixel.

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