DESCENT IMAGING OF SUB-METER TOPOGRAPHY FROM VERTICAL BASELINE STEREO ANALYSIS OF CURIOSITY MARDI IMAGES, GALE CRATER, MARS.

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Background: The Mars Science Laboratory *Curiosity* rover acquired a systematic set of horizontal and vertical baseline stereo images by means of the Mars Descent Imager (MARDI) during its terminal descent on Sol 0, each with an HD format (1600 x 1200 pixels with SNR ~ 90) with an angular field of view of 70 x 52 degrees [**1**]. The MARDI sol 0 descent imaging dataset has been reprocessed with improved calibrations to facilitate vertical-baseline-stereo (VBS) computation of Digital Elevation Models (DEMs) from different altitude intervals in order to evaluate vertical precision and scientific utility at scales finer than those attainable by MRO's HiRISE [**2**]. Because the *Curiosity* rover traversed the region covered in the highest resolution MARDI descent images and witnessed the cm-scale terrain features, the question at hand is whether high resolution DEM's from planetary descent imaging systems such as MARDI provide additional sub-regional geomorphologic insights <u>not possible</u> from orbit or landed, roving vehicles. The MSL MARDI sol 0 dataset is a test case that goes along with the Huygens DISR experience at Titan [**3**], where there were no other sources of 1-10 m scale imaging data. A similar situation exists for the planet Venus (i.e., where descent imaging has yet to be attempted) in order to bridge the spatial resolution gap between orbital SAR (imaging radar) and lander panoramas. Here we make use of the MSL MARDI descent images acquired between ~ 2.3 km above local terrain and ~ 60 m above the surface (when rocket exhaust dust plume obscuration became a factor). The MARDI frames utilized in this assessment ranged in spatial resolution from ~ 1.8 m/pixel to 3.5 cm/pixel, across the range of altitudes involved. Lossless compressed data were used exclusively in this analysis, although experiments with *jpeg85* compressed images were also conducted. A stereogrammetry processing pipeline that makes use of a front-end feature matching algorithm adapted from state-of-the-art *Shape from Motion* (SfM) was employed (SIFT/SURF), together with classical bundle adjustment and related steps to produce DEMs on the basis of different sets of MARDI images [**4**]. A widest possible field of view DEM was generated from the 147 images acquired with dominantly vertical baseline (nested) geometry covering a FOV of ~ 2.3 km x 2.5 km (**Figs. 1 and 2**) from 2.3 km to near the surface.

MARDI Descent Images: MARDI is a fixed-focus, nadir-pointing RGB camera attached to the bottom of the rover chassis above the left front wheel. MARDI's primary task was to record *Curiosity*'s descent and landing, and here we present the first high-resolution results of DEM processing of the best-available descent data in comparison with independently acquired HIRISE DEMs [**2**]. All of the MARDI descent images included in this analysis were nested by at least 90% providing a dominantly vertical-baseline [VBS] geometry.

In addition, as part of descent imaging for topography analyses conducted at NASA GSFC/WFF, a UH-1 helicopter descent imaging experiment was conducted in August 2016 over a planetary analogue test surface with Mars and Venus-relevant landscape features in order to quantify DEM topography performance under both vertical and horizontal baseline geometries, at scales similar to those achieved by MARDI, with comparable results.

Observations: MARDI DEM's from the final ~ 2.3 km of descent cover fields of regard that range from about 2.3 km x 2.5 km down to patches as small as 90 m x 85 m at various ground-scale distances (GSD). Our analysis here is focused on terrain characteristics at scales finer than 1 m (x,y) and with better than ~50 cm vertical precision. The finest scale DEM that was generated has a GSD of 20 cm and a vertical noise floor (*St. Dev.* of flat-area relief z) of < 15 cm within the landing zone. DEM's were processed using all 147 available frames, as well as the final 5, 12, 20, and 30 frames to evaluate vertical precision as a function of horizontal (GSD) resolution and different vertical baselines. It should be mentioned that the local region in the immediate vicinity of the rover touch-down position is topographically benign, with fines mantling the bedrock exposures that were studied at Yellowknife Bay and other areas where outcrops of sedimentary rocks were encountered.

***Widest Area DEM**:* The DEM computed on the basis of the 147 frames described previously has a GSD of 1 m and displays a regional tilt before correction by means of HiRISE/MOLA ground control points. This DEM (**Fig.1**) displays a vertical noise floor of ~ 30 cm. The field of view covered is larger than 4 km^2, and included in this region are partially buried impact features and curvi-linear outcrops. Analysis of this DEM indicates that high-frequency topography at vertical scales not visible in HiRISE DEM's exists, as measured independently in surface terrain analysis [**5**,**6**]. Using the methods described by

Jaraciewz and Stepanski [**7**], a '*geomorphons*' classification has been performed on the MARDI DEM computed from all 147 frames (**Fig. 2**). Results indicate that spatially-organized outcrops in this region at 1-2 m scales are consistent with the surfaces observed in exposures at Yellowknife Bay for example. Further, by removing longer wavelength topography at 5m scales and larger via spatial filtering, the resulting *residual DEM* (**Fig. 1**) illustrates a pattern of what appears to be buried topographic elements as outcrops with patterns similar to those in areas of minimal mantling. The combination of these analyses points to the possibility that multi-kilometer scale regions around the base of Mt. Sharp, including those with 1-3m thick mantling of fine sands, are broadly similar to the outcrop-rich regions that showcase the Kimberly and Yellowknife formations. Using sub-meter quality DEM's constructed from descent images reveals details of shallowly-buried topography that are largely invisible in orbital stereo images. This may have implications for Mars 2020 Rover landing site.

LOCAL AREA DEMs**:** Finer scale DEM's, with horizontal (GSD) sampling as fine as 20 cm, have been computed using different bundles of MARDI descent images starting ~ 0.6 km above the local surface and continuing down to the final frame before dust obscuration at ~ 60 m. These DEMs reveal the fine-scale texture at 10's of cm's scale in the vicinity of the touch-down point, and when residual DEMs are computed by removing all 2m and longer wavelength tilts, the signature of buried outcrops appears, consistent with the geometry of such features illustrated in areas where no mantling deposits are observed, including Yellowknife Bay. This suggests the thickness of the mantling fine deposits is restricted to < 2m in most cases and that the fines are dominantly eolian in origin.

ROUGHNESS/SLOPES: MARDI-based DEM's at scales from 20 cm to 110 cm GSD have been computed and from these topographic datasets slope magnitudes, slope azimuths (facet orientation), and RMS roughness can be computed on baselines from 40 cm to many meters. For the roughest areas sampled by the fine-scale MARDI DEMs, the power-law relationship between local slope magnitudes μ (deg) and horizontal baseline Δx (m) behaves as:

$\mathbf{\mu = 38\ \Delta x^{-0.20}}$ at $R^2 = 0.95$. While this relationship only applies to locally rough outcrop zones such as YKB, it showcases how rugged non-mantled martian surfaces are on more regional scales.

Interpretations: Descent imaging can produce DEMs with higher spatial and vertical sampling than high-quality orbital stereo-pairs from systems such as HiRISE on MRO. Such DEM's can reveal subtle, sometimes-buried textures that are otherwise invisible in images, as well as permit measurement of local slope and roughness distributions. We suggest that acquisition of MARDI-like descent imaging data on all future Mars, Venus, and Europa landed missions will provide high-fidelity scientific DEM data for interpretation of planetary landscapes at new scales.

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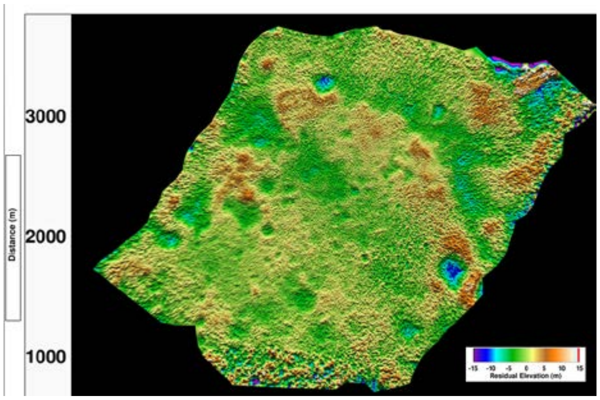

Fig. 1: MARDI DEM using 147 frames, after processing to remove longer wavelength (> 5m) regional topography. The typical roughness (σ_z) here is ~ 3m with a dynamic range of ~ 30 m (FOV: 2.3 x 2.5 km). The GSD here is 100 cm. See text for details.

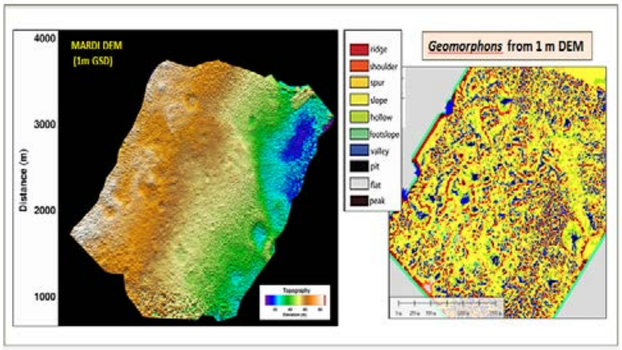

Fig. 2: Geomorphic classification of 1m GSD MARDI DEM (left) using "geomorphons" (right); see text for details and Ref # **7**.

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