REVEALING ACTIVE MARS WITH HIRISE DIGITAL TERRAIN MODELS AND ORTHOIMAGES. S.S. Sutton[1], M. Chojnacki[2], A.S. McEwen[1], R.L. Kirk[3], C.M. Dundas[3], E.I. Schaefer[4], S.J. Conway[5], S. Diniega[6], G. Portyankina[7], M.E. Landis[7], N.F. Baugh[1], R. Heyd[1], S. Byrne[1], L.L. Tornabene[8], L. Ojha[9], C.W. Hamilton[1]. [1]Lunar and Planetary Lab., U. of Arizona, Tucson, AZ, USA (ssutton@lpl.arizona.edu), [2]Planetary Science Institute, Lakewood, CO, USA, [3]U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ, USA, [4]Washington U., Dept. of Earth and Planetary Sciences, St. Louis, MO, USA, [5]LPG CNRS UMR 6112, Nantes Université, France, [6]Jet Propulsion Laboratory, California Inst. of Technology, Pasadena, CA, USA, [7]U. of Colorado, Laboratory for Atmospheric and Space Physics, Boulder, CO, USA, [8]Western U., Dept. of Earth Sciences, Inst. for Earth & Space Exploration, London, Canada, [9]Dept. of Earth and Planetary Sciences, Rutgers U., Piscataway, NJ, USA

Introduction: High resolution digital terrain models (DTMs) generated from High Resolution Imaging Science Experiment (HiRISE) [1] stereo pairs are one of the key data products used to support studies of active surface processes on Mars. The ability of the Mars Reconnaissance Orbiter (MRO) [2] to point repeatedly at a target, combined with the duration of the MRO mission (15 years, or 8 Mars years and counting), has allowed for details of the surface to be observed over many Mars seasons and years (**Fig. 1**).

A time series of images acquired over the same target, orthorectified to a corresponding DTM, enables pixel-scale evaluation of surface changes in three dimensions. We present here an overview of the processes used to generate HiRISE DTMs and orthoimages, with an emphasis on products created specifically for monitoring active landforms. Our intention is to provide information about the factors that affect the precision, accuracy, and effective resolution of HiRISE DTMs, and their use in change detection analyses.

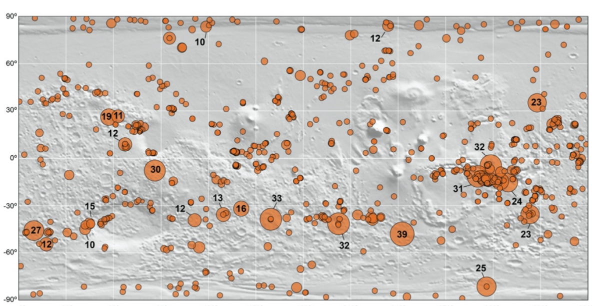

Figure 1. Global map of the 834 HiRISE DTMs and corresponding 2,732 unique orthoimages available in the PDS, and at https://www.uahirise.org/dtm/, as of the end of 2021. The symbol size represents the number of observations orthorectified to each DTM, not the actual footprint of the DTM, which is much smaller. The smallest circles represent a stereo pair. Larger circles represent monitoring sites. Labels indicate the number of orthoimages at the sites with the most images.

Change detection studies: Advances in the study of many types of surface activity on Mars have been made possible by the development of the products described here. For example, it is now possible to measure the rates of migration of aeolian bedforms on Mars, such as megaripples and sand dunes, to a degree that is comparable to analogous features on Earth (e.g., [3,4]). The discovery and analysis of recurring slope lineae (RSL) would not have been possible without HiRISE DTMs and orthoimage sequences [5–9]. HiRISE DTMs with repeat orthoimages acquired from early spring through late fall over multiple years have also been instrumental in revealing that CO_2 frost sublimation is the primary agent of present-day gully activity on Mars [10,11]. Although topographical changes have not yet been detected in south polar araneiforms (**Fig. 2**)—extensive but shallow landforms that are uniquely controlled by seasonal CO_2 ice deposition and sublimation [12,13]—HiRISE DTMs are the only data currently available that may be able to resolve their evolution. A better understanding of the mass balance of the north polar layered deposits (NPLD) is enabled by new studies of the variation in ice deposition measured in time series of orthoimages and HiRISE DTMs of small craters within the NPLD [14]. These studies highlight just a few of the surface processes that utilize HiRISE DTMs and orthoimages.

Methods: The methods described here are used to produce the HiRISE DTMs that are available in the PDS, and build on the workflow first described in [15].

Preprocessing. HiRISE images undergo radiometric and geometric calibration in ISIS [16] before being converted to the formats and metadata expected by SOCET Set [17], the commercial photogrammetry software used to make the DTMs. After radiometric calibration, precision geometric calibration is performed to remove distortion across the focal plane [15], and optionally correct for spacecraft jitter [18]. HiRISE images are subject to distortions by high-frequency spacecraft jitter due to their pushbroom mode of acquisition. HiRISE is more sensitive to the jitter than other cameras because of its small IFOV (1 µrad, or ~30 cm/px from an orbital altitude of 300 km) [1]. Jitter distortions in individual HiRISE images cause misregistration of overlapping CCD image strips which can lead to poor stereo image correlation and artifacts in the DTMs.

Photogrammetric processing in brief. Within SOCET Set, the majority of interactive steps take place during the Multi-Sensor Triangulation (MST) step. An initial relative correction is followed by controlling the stereo images in an absolute sense to geodetic control, if available. The quality of the solution achieved in MST largely determines the absolute accuracy of the DTM, and also influences how well the stereo matcher can extract elevation values from the stereo images, which affects internal precision. Additional images can then be tied to the stereo pair by remeasuring tie and control points, and solving in a relative sense. Following MST, the DTM is created at 1 or 2 m ground sample distance (GSD) in the terrain extraction stage. The DTM is evaluated for quality, and any interactive editing is performed, if necessary. The DTM and orthorectified images are then exported from SOCET Set to ISIS for post-processing to convert the files to standard PDS formats.

Quality metrics: An understanding of the quality of a DTM in terms of its vertical precision and horizontal resolution (e.g., [19]) is necessary to constrain the error on any quantitative analysis. Absolute positional accuracy and vertical precision are especially important for understanding the limits of what can be resolved in sequences of orthorectified images for time series analysis, or for measuring volumetric changes in multi-temporal DTMs of the same target (**Fig. 2**). Vertical precision is defined as the relative error of individual elevation values within a DTM. For HiRISE DTMs, the estimated vertical precision (EP) [20] is typically better than the GSD, and is on the order of a few tens of cm for a 1 m DTM, or ~1 m for a 2 m DTM. While the GSD of a DTM can be chosen freely as a processing parameter, it sets a hard lower bound on the horizontal resolution of the DTM. The effective resolution of many DTMs, including those made in SOCET Set, is unlikely to be better than 3–5 image pixels, and is typically 10–20 image pixels [19].

Conclusion: HiRISE DTMs are the best and often only way to get accurate slope and height estimates at high-resolution from existing Mars datasets. HiRISE DTMs, along with orthorectified time series images, are necessary to make accurate and precise measurements of surface and volumetric changes on Mars, which are key constraints on models of present-day surface activity.

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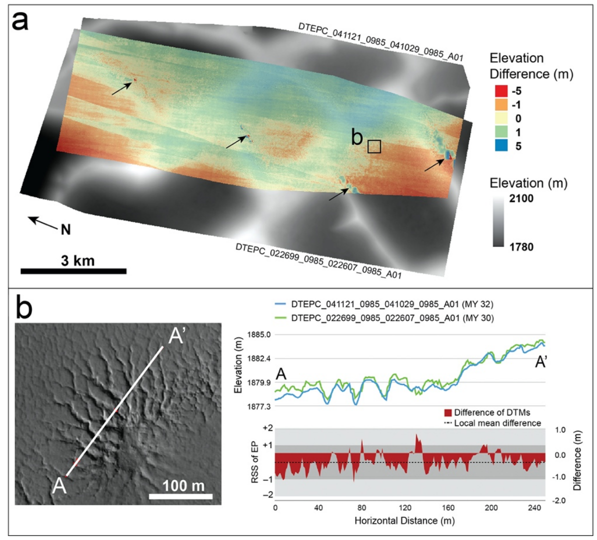

Figure 2. (a) Co-registered DTMs at the site dubbed Inca City (81.4º S, 295.8º E), with overlapping area in color showing the difference map. Black arrows indicate interpolation artifacts in dark shadows. **(b)** Detail of orthoimage ESP_041121_0985, located at the small black square in (a), showing an araneiform with no apparent changes from the MY 30 stereo pair. Profile A–A' is shown from both DTMs. Gray shaded regions on the lower plot illustrate that the differences are less than ±2 times the root summed squares of the EP (RSS EP) of both DTMs about the local mean difference.

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