PRECISION AND ACCURACY OF SIMULTANEOUSLY COLLECTED HIRISE DIGITAL TERRAIN MODELS
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Introduction: High precision Digital Terrain Models (DTMs) made from High Resolution Imaging Science Experiment (HiRISE) [1] stereo pairs are being produced for geomorphic and geologic analyses (e.g. [2, 3, 4]) as well as landing site assessment [5, 6, 7]. In many cases, they are being used to orthorectify sequences of images, making change detection of the martian surface possible at unprecedented detail. Stereo pairs separated by one or more Mars years are acquired over selected active sites in order to attempt to quantify volumetric changes in topography such as dune migration [8] and gully activity [9].

Here we present some examples where two HiRISE stereo pairs are controlled simultaneously in order to measure such changes. These special cases provide an opportunity to investigate the internal precision and accuracy of HiRISE DTMs. Quality can be affected by spacecraft jitter, observation angles, image quality, albedo differences and illumination angles. Although the dynamic range and signal-to-noise ratio of HiRISE images are very good, the changes we wish to measure are not large and may be smaller than the differences between the DTMs. This work presents a review of vertical precision, horizontal accuracy and internal precision in HiRISE DTMs, and what effect these values might have on studies of topographic change.

Precision and Accuracy in Individual DTMs: Within a single HiRISE DTM, precision and accuracy can be estimated or measured by several methods.

Expected vertical precision: This value can be estimated based on the observation geometry and the pixel scale, as well as the quality of the triangulation. The formula used to derive EP is based on [10]:

$$EP = \Delta p * IFOV/(parallax/height)$$

where Δp is the quality of pixel matching given by the RMS error in SOCET SET (usually < 0.6 px), IFOV is the pixel scale of the stereo images in meters, and (parallax/height) can be estimated by taking the tangent of the convergence angle between the stereo images. For most HiRISE DTMs, the EP is < 0.5 m.

Horizontal precision: HiRISE DTMs are typically generated at ~4 times the source image pixel scale (i.e. 1 m/post for 30 cm/px stereo images and 2 m/post for 50 cm/px images).

Horizontal accuracy: HiRISE stereo pairs are controlled to laser altimetry from the Mars Orbiter Laser Altimeter (MOLA) [11], which has much lower spatial resolution (~150 m footprint per laser shot). In an absolute sense, the horizontal accuracy of a HiRISE DTM cannot be better than the spatial resolution of the MOLA data set.

Vertical accuracy: When controlling HiRISE stereo to MOLA, the goal is to get within ± 5 m difference, with a mean difference close to 0 m. This goal is often acheived through a combination of manual and automated triangulation methods [7, 12].

Error Between DTMs: In order to minimize any subjective differences made by the operator, the most accurate way to create two DTMs is to control both stereo pairs simultaneously. This ensures that static surface features are used to tie all four images together, and that the control to the laser altimetry is identical. The remaining differences, that are not actual topographic change, are due to intrinsic issues as discussed be-

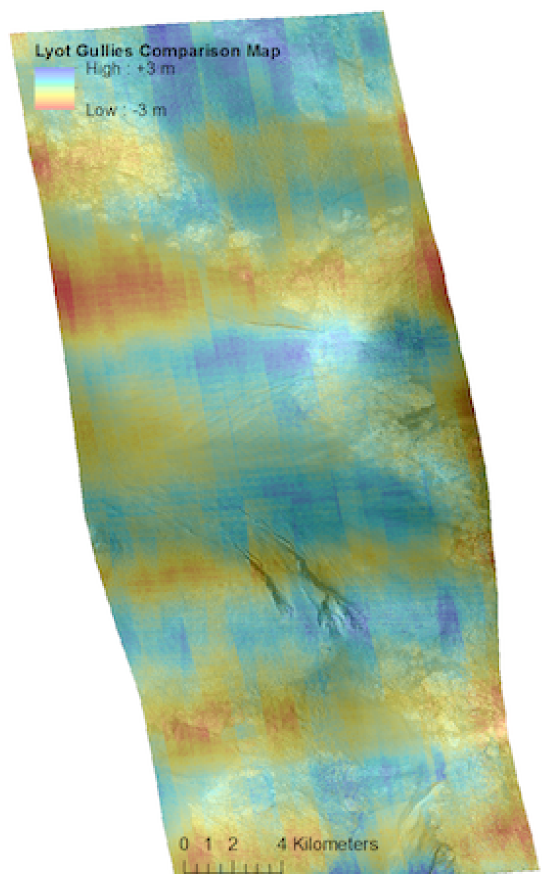

Figure 1: Difference map of two DTMs made from the image pairs PSP_008823_2310, PSP_009245_2310 and ESP_027297_2310, ESP_027376_2310 draped over orthoimage. Color ramp indicates difference between the two DTMs in meters, red is negative, blue is positive. The main effects are due to jitter, not topography. Note the horizontal banding, which is due to cross-track jitter. Vertical striping is due to misalignment along CCD seams due to along-track jitter. Overall differences range between ± 3 m.

low. Difference maps are made by subtracting the DTM made from the more recent stereo pair from that made from the earlier pair. Error magnitude can be quantified from analysis of the difference map.

Jitter: Spacecraft jitter (oscillations or vibrations from moving parts on the spacecraft) causes subtle geometric distortions in pushbroom cameras with high spatial resolution (such as HiRISE), because the images are built line by line along the orbit track. Cross-track jitter, if large enough, can cause shifts in the x-direction, which causes mis-estimation of heights by the stereo matcher. Along-track jitter causes distortions in the y-direction, making it difficult for the stereo matcher and introducing noise into the DTM. The HiRISE camera has the additional complicating factor of being comprised of 10 Charge Coupled Devices (CCDs) in a staggered array across the full swath width [1]. Despite careful optical calibration and jitter correction algorithms [5, 13], the effects of spacecraft jitter are the largest source of systematic error in HiRISE DTMs. In most cases, the jitter is minimal within a single image; jitter error has been corrected to be less than 1 μrad, or 1 pixel. However, the combined effects of even low amounts of jitter can still have a significant effect on stereoanalysis.

Image noise: Noise in HiRISE images can come from several sources including: electronic noise, calibration, saturation, haze or dust in the atmosphere. Image noise has a negative effect on the stereo matching algorithm, which introduces a noisy surface texture into the DTM, and in the worst case causes the stereo matcher to fail altogether.

Case Studies:

Lyot Crater gullies: These two DTMs were collected by controlling two stereo pairs together, along with a fifth image (non-stereo), with the goal of detecting any changes in the gullies visible on the central peak of Lyot Crater (Fig. 1). The two stereo pairs were collected 3 Mars years apart. Jitter is the dominant source of differences between the two, as can be seen by the low-frequency horizontal banding, with an amplitude of ± 3 m. The topography of the scene is not apparent in the difference map, vaidating that the two stereo pairs are well-controlled together.

Ganges Chasma dunes: In this case, the goal is to quantify the volumetric changes in the active dunes [14] present in the scene (Fig. 2). Stereo pairs were acquired 3 Mars years apart, but at similar solar longitude, in order to minimize seasonal illumination differences. Errors here are mostly due to along-track jitter, which affected mostly the non-dune areas to the left of the peak near the center of the scene. CCD seams are visible as vertical banding, also due to along-track jitter. Other errors present in this scene are due to shadows (e.g. next to the peak) where terrain could only be estimated in one pair. Measurable topographic change is visible along the leading edges of some of the dune forms. An additional consideration in HiRISE DTMs over relatively dark dunes is that they often require manual editing to resolve the dunes well, as the stereo matcher often fails over dark, featureless surfaces [8, 15].

Discussion and Conclusion: The timing of stereo pair acquisition should take into consideration the types and magnitudes of potential error discussed here, as well as the intrinsic accuracy and precision of HiRISE DTMs, as they relate to the magnitude of surface changes. There has been a considerable amount of data collected documenting changes occurring on Mars today [16]. These data give us information about the rates of changes that are happening at various landforms. The amount and rate of these changes should determine the optimal time separation for stereo pair acquisition in order to unambiguously quantify topographic change.

References: [1] A. S. McEwen, et al. (2007) *JGR-Planets* 112:E05S02 doi. [2] J. L. Bishop, et al. (2013) *JGR-Planets* 118:487 doi. [3] A. S. McEwen, et al. (2014) *Nat Geos* 7:53 doi. [4] C. H. Okubo (2014) *US Geol Survey*. [5] R. L. Kirk, et al. (2008) *JGR-Planets* 113:E00A24 doi. [6] M. Golombek, et al. (2012) *Space Sci Rev* 170:641 doi. [7] E. Howington-Kraus, et al. (2015) *LPSC, this conference*. [8] J. Avouac, et al. (2012) *AGU Fall Meeting Abstracts* B6. [9] C. M. Dundas, et al. (2012) *Icarus* 220:124 doi. [10] R. L. Kirk, et al. (2003) *JGR-Planets* 108:8088 doi. [11] D. E. Smith, et al. (2001) *JGR-Planets* 106:23689 doi. [12] A. Kilgallon, et al. (2015) *LPSC, this conference*. [13] S. Mattson, et al. (2009) in *EPSC* 604. [14] M. Chojnacki, et al. (2014) *Icarus* 230:96 doi. [15] S. Mattson, et al. (2012) *LPI Contributions* 1673:68. [16] S. Mattson, et al. (2014) in *EGU* vol. 16 of *EGU General Assembly Conference Abstracts*

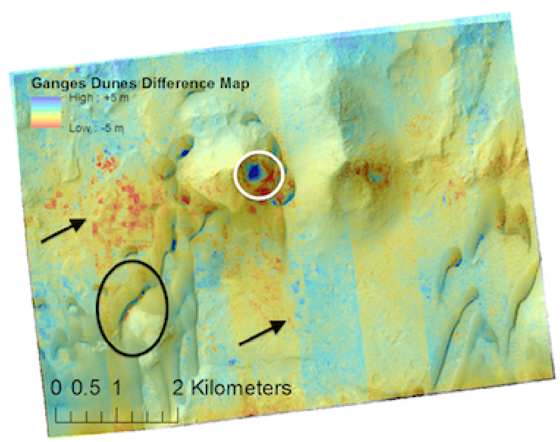

Figure 2: Difference map of two DTMs made from the image pairs PSP_008536_1725, PSP_009604_1725 and ESP_034671_1725, ESP_035172_1725 draped over orthoimage. Color ramp indicates the difference between the two DTMs. Noise due to along-track jitter is evident as "boxes" indicated by black arrows. The large error near the peak (white circle) is due to a large shadow and unresolvable topography within it. The actual changes along dune slip faces are evident by the negative/positive changes in the direction of dune motion (black oval).