MARS 2020 TERRAIN RELATIVE NAVIGATION SUPPORT: DIGITAL TERRAIN MODEL GENERATION AND MOSAICKING PROCESS IMPROVEMENT. R. L. Fergason[1], T. M. Hare[1], D. P. Mayer[1], D. M. Galuszka[1], B. L. Redding[1], Y. Cheng[2,] and R. E. Otero[2]. [1]U.S. Geological Survey, Astrogeology Science Center, Flagstaff, AZ, USA, rfergason@usgs.gov, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA.

Introduction: The Mars 2020 rover will explore Jezero crater, Mars, and will investigate an ancient delta for evidence of past microbial life and to better understand the geologic history of the region. The landing system onboard Mars 2020 will use new technology developed at the Jet Propulsion Laboratory (JPL) called Terrain Relative Navigation (TRN), which will enable the spacecraft to autonomously avoid small hazards (e.g., rock fields, crater rims) that exceed the safety requirements of the landing system. This capability allows small-scale hazards to be present in the landing ellipse, providing greater flexibility in spacecraft landing location. In support of TRN, the USGS Astrogeology Science Center is generating two precision mosaics: 1) the Landing Verification System (LVS) map generated from three Context Camera (CTX) [1] orthoimages that will be onboard the spacecraft and will be the "truth" dataset that TRN will use to orient itself relative to the surface during Entry, Decent, and Landing; 2) a High Resolution Imaging Science Experiment (HiRISE) [2] orthomosaic that will be the basemap onto which surface hazards will be mapped. The hazard map will be onboard the spacecraft and used by TRN to help identify the final, hazard-free landing location.

Because these products will be directly used to help land the spacecraft safely, there are strict processing, vertical, and horizontal co-registration requirements that must be met. For example, the TRN horizontal registration requirements include: 1) High Resolution Stereo Camera (HRSC) [3] to CTX horizontal coregistration less than 60 meters at the 99%tile; 2) CTX to HiRISE horizontal coregistration less than 6 meters at the 99%tile; and 3) HiRISE to HiRISE horizontal coregistration less than 3 meters at the 99%tile. These requirements are significantly stricter than landing site characterization and have necessitated the development of new digital terrain model (DTM) generation procedures and capabilities with a focus on improving the ability to co-register adjacent DTMs (and thereby orthoimages) both vertically and horizontally.

CTX Landing Verification System Elevation and Orthoimage Mosaic Generation Methods: To achieve the required horizontal and vertical co-registration requirements, we have developed a DTM mosaic generation pipeline using a combination of SOCET Set® from BAE Systems [4] and the Ames Stereo Pipeline (ASP) software [5-6]. We first improved our CTX image pre-processing pipeline to include capabilities that utilize camera model and jitter-correction improvements developed and provided by JPL. These modifications have significantly improved the position knowledge of the images relative to the martian surface and have allowed us to generate DTMs using this position knowledge alone (i.e., without a bundle adjustment). No bundle adjustment is desirable, as TRN is sensitive to non-linear distortions that could potentially be introduced.

The underlying DTMs are produced using SOCET Set® from input images and image metadata provided by JPL. The initial DTMs are then rigidly aligned to one another using the *pc_align* program from ASP, allowing only a translation adjustment. The relatively-aligned DTMs are then simultaneously aligned using ASP to the HRSC Level 5 DTM to bring them into absolute alignment with an independent reference. The exported DTMs are then mosaicked using the *dem_mosaic* tool from ASP. The orthoimages derived from the nadir-most member of each stereopair are similarly mosaicked using *dem_mosaic*.

To assess the vertical and horizontal differences, vertical differencing of the DTMs and horizontal registration measurements were made using the Open Source software package IMCORR (https://nsidc.org/data/velmap/imcorr.html). The approach used by IMCORR is the same basic matching strategy used in a variety of stereo photogrammetry software, and when applied to a pair of orthorectified images, the results can be interpreted as a measure of the co-registration of the images. In each comparison, we performed tests to measure differences between the individual CTX products, as well as between each of the CTX products and the HRSC L5 products. The comparison between the individual CTX products provides information regarding their three-dimensional relationship to one another, and potentially provides information regarding the consistency of DTMs produced using the JPL-provided metadata alone. The comparisons between each CTX product and the HRSC products provides information about the absolute accuracy of the CTX products.

The vertical registration between individual CTX DTMs is within submeter accuracy (figure 1) and we adjusted the mosaic by 183.3 meters vertically to align with HRSC. The individual CTX images have an average median horizontal displacement of 30.6 meters (figure 2). The IMCORR results also illustrate that the CTX orthoimages are preferentially offset to the southeast relative to the HRSC reference. Thus, these products and the resulting mosaic meet – and often exceed - the requirements for TRN.

HiRISE Hazard Basemap Elevation and Orthoimage Mosaic Generation Methods: Because we do not have improved image location information for HiRISE, additional method development was required to meet the strict co-registration requirements for the hazard basemap. This process deviates significantly from that of our standard DTM generation process and supports optimizing the co-registration of DTM and derived products. Initially, we begin with our standard HiRISE DTM generation process developed for InSight landing site characterization [7-8] where we initialize 16 tie points. We then perform a height adjustment to the CTX LVS DTM to improve the vertical registration and remove any significant tilt between the HiRISE DTM and the CTX LVS DTM. Next, we densify the tie points and generate a 1-meter post-spacing DTM. This DTM is imported into ASP where we again check and correct for any residual tilt in each HiRISE DTM, perform a sequential horizontal alignment between each HiRISE DTM, and generate a temporary mosaic. We then align the temporary mosaic vertically to the CTX LVS DTM to further refine the vertical registration. Rather than mosaicking DTMs that have already been resampled multiple times in *pc_align*, the affine transformation matrices determined by *pc_align* are applied to the tie points associated with each stereo pair in SOCET Set®. The transformed tie points are then treated as ground control points and used to perform a final bundle adjustment of each stereopair in SOCET Set®. We then create a single SOCET Set® project and import the individual HiRISE DTMs and ancillary information into this single project. We add additional tie points to each image and run a final bundle adjustment to refine the relative alignment between images. We then generate a 1-meter post spacing DTM, manually edit this DTM to remove artifacts produced by the automatic matching software, and export final DTMs and orthoimages.

The methods we have developed, and are in the process of refining, have enabled us to generate DTM and orthoimage mosaics from CTX and HiRISE that meet the strict image co-registration requirements of TRN. The combination of SOCET Set® and ASP produces superior results to either software package alone. Although used for CTX and HiRISE data these methods have broad applicability to other data sets as well.

Acknowledgements: References to commercial products are for identification purposes and do not imply an endorsement by the U.S. Government.

References: [1] Malin M. et al. (2007) *JGR, 112*(E05S02), doi:10.1029/2005JE00 2605.[2] McEwen A. S. et al. (2007) *JGR, 112* (E05S02), doi:10.1029/2005JE002605. [3] Jaumann R. et al. (2007) *Planet and Space. Sci., 55*, 928-952. [4] Miller S. B. and Walker A. S. (1993) *ACSM/ASPRS Annual Conv., 3*, 256–263. [5] Moratto Z. M. et al. (2010) *LPS, XLI*, 2364. [6] Beyer R. A. et al. (2018) *ESS, 5*, doi: 10.1029/2018EA000409. [7] Fergason R. L. et al. (2016) *SSR*, doi:10.1007/s11214-016-0292-x. [8] Golombek M. et al. (2016) *SSR*, doi:10.1007/s11214-016-0321-9.

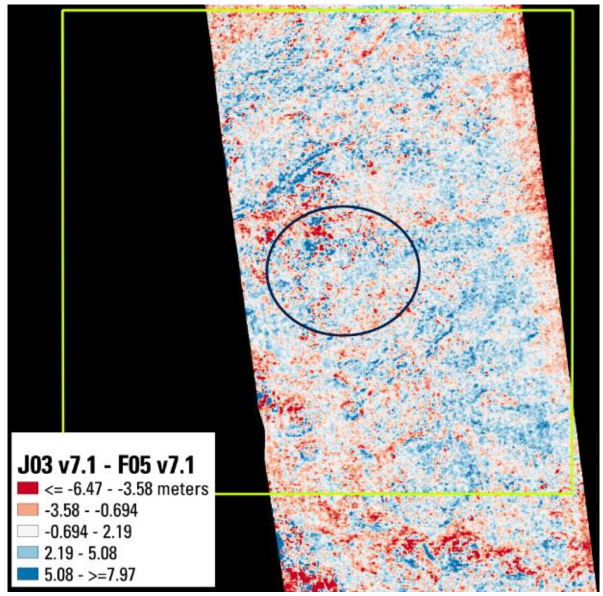

Figure 1. Vertical difference raster between two CTX DTMs. They are offset from one another by ~0.99 meters. This comparison is typical of elevation differences between the CTX LVS DTM and the HRSC DTM.

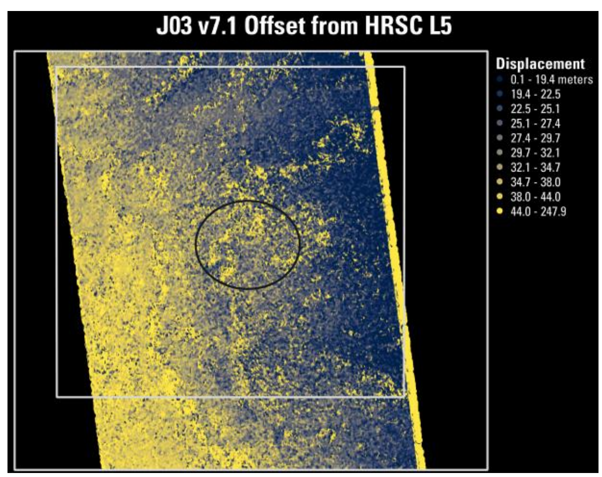

Figure 2. IMCORR run output illustrating the magnitude of displacement of the a CTX orthoimage from the HRSC L5 orthoimage. The CTX orthoimage is displaced by a median magnitude of 29.7 meters preferentially oriented to the southeast. This comparison is typical of horizontal registration differences between the CTX LVS orthomosaic and the HRSC L5 orthomosaic.