MARS 2020 TERRAIN RELATIVE NAVIGATION FLIGHT PRODUCT GENERATION: DIGITAL TERRAIN MODEL AND ORTHORECTIFIED IMAGE MOSAICS. R. L. Fergason[1], T. M. Hare[1], D. P. Mayer[1], D. M. Galuszka[1], B. L. Redding[1], E. D. Smith[1], J. R. Shinaman[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 to 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 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 selecting a landing location. In support of TRN, the USGS Astrogeology Science Center has generated and delivered two precision mosaics: 1) the Lander Vision System (LVS) map generated from three Context Camera (CTX) [1] orthorectified images 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; and 2) a High Resolution Imaging Science Experiment (HiRISE) [2] orthomosaic that will be the basemap onto which surface hazards are being 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 used to help land the spacecraft safely, there are strict processing, vertical, and horizontal co-registration requirements that must be met. These requirements are significantly stricter than those previously required for landing site characterization and have necessitated the development of new digital terrain model (DTM) generation procedures and capabilities with a focus on improving the accuracy by which one can co-register adjacent DTMs (and derived orthorectified images) both vertically and horizontally.

CTX Lander Vision System Elevation and Orthorectified Image Mosaic Generation: 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 [3] and the Ames Stereo Pipeline (ASP) software [4-5]. We first improved our CTX image preprocessing pipeline to include capabilities that utilize camera model and jitter-correction improvements developed and provided by JPL. These modifications have significantly improved the positional knowledge of the images relative to the martian surface and have allowed us to generate DTMs without the need for a typically required bundle adjustment. Omitting this step was desirable, as TRN is sensitive to non-linear distortions that could potentially be introduced by a bundle adjustment.

After DTMs were produced using SOCET SET® from input images and image metadata provided by JPL, the initial DTMs were then rigidly aligned to one another using the *pc_align* program from ASP, allowing only a translation adjustment. The relatively-aligned DTMs were then simultaneously aligned using ASP to the High Resolution Stereo Camera (HRSC) [6-7] Level 5 DTM to bring them into absolute alignment with an independent reference. The exported CTX DTMs (20 meters per pixel) were then mosaicked using the *dem_mosaic* tool from ASP. The orthorectified images derived from the nadir-most member of each stereopair (6 meters per pixel) were similarly mosaicked using *dem_mosaic*.

To assess the vertical differences, DTMs were simply differenced. To assess the horizontal registration, measurements between orthorectified images were made using the Open Source software package IMCORR [8]. The approach used by IMCORR is the same basic matching strategy used in a variety of stereo photogrammetry software packages, and when applied to a pair of orthorectified images, the results can be interpreted as a measure of the co-registration of the images. The vertical registration between individual CTX DTMs is 3.8 meters after adjusting the mosaic by 183.3 meters vertically to align with HRSC. The individual CTX images have an average horizontal displacement of 9.6 meters. Thus, these products and the resulting mosaic meet – and often exceed - the requirements for TRN.

HiRISE Hazard Basemap Elevation and Orthorectified Image Mosaic Generation Methods: Because we do not have improved image location information for HiRISE, additional updates to our workflow were required to meet the 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 DTMs and derived products. We begin with our standard HiRISE DTM generation process developed for InSight landing site characterization [9-10] 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 observable tilt between the HiRISE DTM and the CTX LVS DTM. Next, we densify the tie points and generated 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 bundle adjustment of each stereopair in SOCET SET®. We then create a single SOCET SET® project and import the individually controlled stereo pairs and ancillary information into this single project, and use the above image positions as the starting point for performing a joint bundle adjustment of all 14 images in SOCET SET®. We added additional tie points to each image and ran a final bundle adjustment to refine the relative alignment between images. We then generated a 1-meter post spacing DTM from each of the seven stereo pairs, and manually edited each individual DTM to remove artifacts produced by the automatic matching software.

After editing, a single two-dimensional (or first-order) affine transformation (translation, rotation, and scale) was applied to correct a scale distortion between the CTX LVS orthomosaic and the HiRISE orthomosaic that was outside flight requirements. This transformation was determined based on an intermediate HiRISE mosaic product (rather than individual images) in order to preserve the excellent horizontal co-registration accuracy between individual HiRISE images. After the transform was applied, final DTMs (1 meter per pixel) and orthorectified images (1 meter and 0.25 meters per pixel) were exported.

The vertical differences were again evaluated using simple differencing of the HiRISE and CTX DTMs. Horizontal differences between the HiRISE orthomosaic and the CTX LVS orthomosaic were evaluated using IMCORR. The HiRISE DTM mosaic has a median vertical offset from the CTX LVS DTM of ~0.4 meters. All pairwise combinations of HiRISE orthorectified images derived from the nadir-most members of each stereopair are registered to better than 3 meters at the 99th percentile, with most registered to better than 1.1 meters at the 99th percentile. The median magnitude of horizontal displacement of features in the transformed HiRISE orthomosaic from CTX is 2.1 meters and 95.4% of features are displaced <6 meters.

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] Miller S. B. and Walker A. S. (1993) *ACSM/ASPRS Annual Conv*., *3*, 256–263. [4] Moratto Z. M. et al. (2010) *LPS*, *XLI*, 2364. [5] Beyer R. A. et al. (2018) *ESS*, *5*, doi: 10.1029/ 2018EA000409. [6] Neukum et al. (2004) *ESA Special Publications*, SP-1240. [7] Jaumann R. et al. (2007) *Planet and Space. Sci*., *55*, 928-952. [8] System for Automated Geoscientific Analysis (SAGA) GIS's implementation of IMCORR https://nsidc.org/ data/velmap/imcorr.html. [9] Fergason R. L. et al. (2016) *SSR*, doi:10.1007/ s11214-016-0292-x. [10] Golombek M. et al. (2016) *SSR*, doi:10.1007/s11214-016-0321-9.

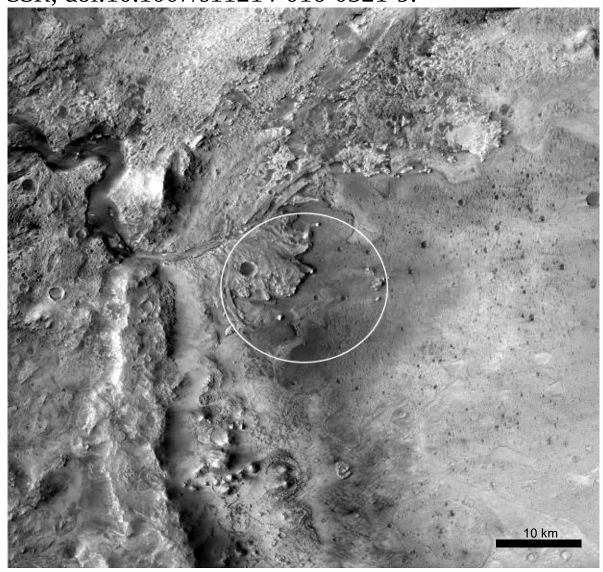

Figure 1. Final CTX LVS orthorectified image mosaic after manual editing, tone matching, and seam removal methods were applied. The black circle indicates the current landing ellipse location.

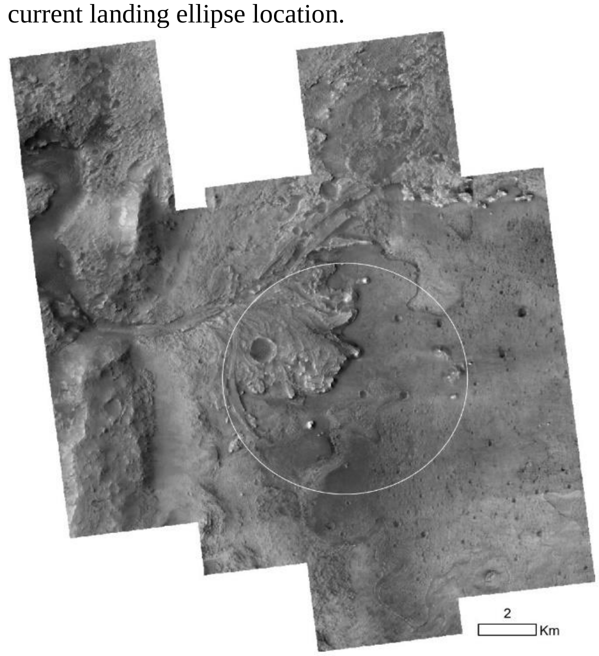

Figure 2. Final HiRISE orthorectified image mosaic after manual editing, tone matching, and seam removal methods were applied. The white circle indicates the current landing ellipse location.