BUILDING A CTX-BASED DIGITAL TERRAIN MODEL MOSAIC OF THE SOUTH POLE OF MARS: POINT CLOUD ALIGNMENT.
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Introduction: This abstract provides an update on ongoing efforts to create a semi-controlled digital terrain model (DTM) mosaic to fill the southern "pole gap" on Mars [1] and describes a workflow for rigidly aligning a set of DTMs derived from the Context Camera (CTX) both to each other and to an absolute elevation reference.

Currently, the only systematic topographic data available poleward of 87.3°S latitude on Mars comes from a DTM mosaic derived from High Resolution Stereo Camera (HRSC) image data [2]. Although this HRSC DTM mosaic is gridded at 50 meters/pixel, the native resolution of the HRSC input images varies from 12.5-50 meters/pixel, and the effective horizontal resolution of the derived DTMs is likely coarser than these values by a factor of 3, even in the most optimistic scenario (R. Kirk, *pers. comm.*, 2019). The orbital inclination of Mars Global Surveyor permitted only limited collection of Mars Orbiter Laser Altimeter (MOLA) measurements over the region poleward of 87.3°S latitude. Although individual laser shots yield vertical accuracy of ~1 meter, the spatial distribution of shots is too sparse to be useful for most geomorphic analyses.

By contrast, the Context Camera (CTX) on the Mars Reconnaissance Orbiter (MRO) has imaged >98% of the area from 87°S to the pole at a spatial resolution of 6 meters/pixel, including extensive areas of repeat coverage at multiple viewing angles. These areas of repeat coverage create the potential for topographic information to be extracted via stereo photogrammetry at effective horizontal and vertical spatial resolutions intermediate between those of the HRSC DTM mosaic and sparse MOLA data.

Stereo Image Processing: More than 3000 CTX stereopair candidates covering the area from 87°S to the pole were identified using methods described in [1]. The large number of candidate stereopairs necessitated an automated approach to stereo image processing and point cloud extraction. Candidate stereopairs were therefore processed using the Ames Stereo Pipeline (ASP) [3] following a workflow described in [4].

Approximately 1500 (~45%) of the candidate stereopairs failed relative bundle adjustment and were discarded. The remaining ~1700 candidate stereopairs were successfully processed into point clouds and interpolated into preliminary DTMs at 100 meters/pixel.

Not all of the extracted point clouds yielded usable DTMs due to some combination of cloud cover, excessive spacecraft "jitter," or because the Martian

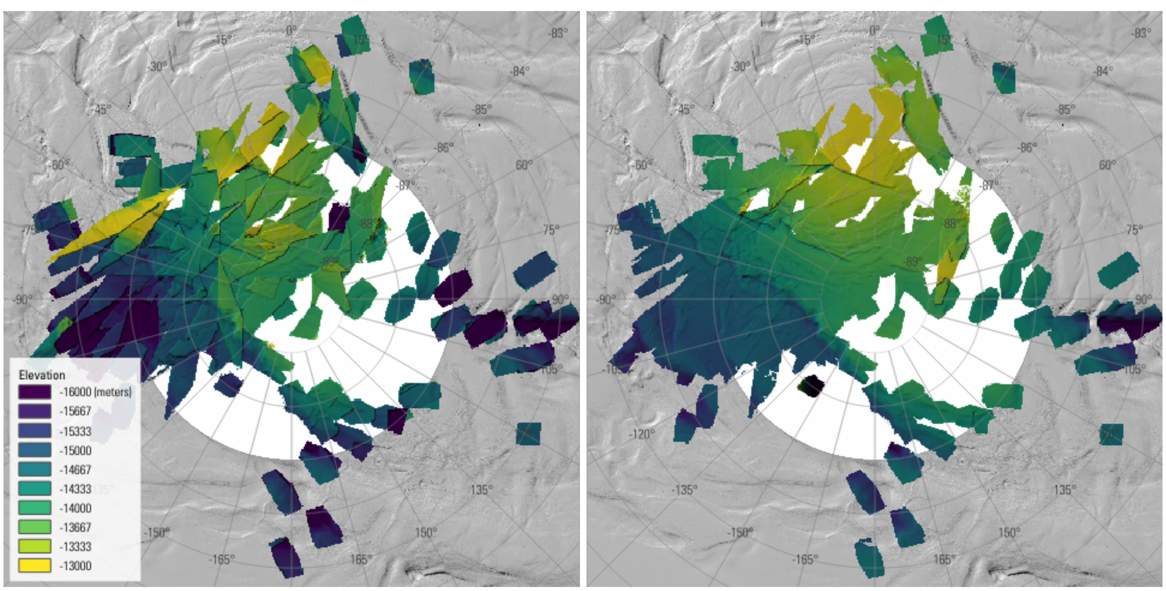

Figure 1: (Left) Preliminary CTX DTMs categorized as "good" quality. Note large DTM-to-DTM misalignment.(Right) CTX DTMs after initial alignment of individual point clouds to MOLA shot data. Background is MOLA hillshade.

surface is characterized by smooth, featureless terrain at the scale of the CTX spatial resolution.

The preliminary DTMs were categorized as good (n=415, Figure 1), fair (n=426), or poor (n=842) based on visual inspection of hillshade images. Only DTMs classified as "good" were selected for further processing.

Point Cloud Alignment: Although 415 preliminary DTMs were classified as having good textural quality, errors in spacecraft position and pointing cause the elevation values associated with these DTMs to be misaligned both relative to each other and to an absolute elevation reference. It is therefore necessary to estimate a series of three-dimensional transforms (rotation and translation) to bring the underlying point clouds into alignment with a reference data set.

For this project, point cloud alignment proceeds in three stages: (1) initial alignment, (2) relative alignment, and (3) absolute alignment. The three dimensional transforms at each stage are estimated using the *pc_align* program from ASP. This program implements an iterative closest points algorithm to estimate rigid transforms between a source point cloud and a reference [3].

Absolute Elevation Reference. A version of the MOLA shot data reprocessed by the Planetary Geology, Geophysics and Geochemistry Laboratory at NASA's Goddard Spaceflight Center, called the Ultimate MOLA Point Cloud (https://pgda.gsfc.nasa.gov/products/62), was selected as the absolute elevation reference data set. This version of the MOLA data corrects significant errors in shots collected poleward of 87°S when the spacecraft was pointing >10° off-nadir [5]. These corrections are not available in the MOLA PEDR products archived in the Planetary Data System (PDS).

Initial Alignment. In this stage, individual CTX point clouds are aligned to MOLA shot data in order to remove gross errors in the absolute three-dimensional position of each CTX point cloud.

Relative Alignment. Although the MOLA data have high absolute vertical precision and accuracy, the sparse distribution of shots and large projected spot size of individual laser shots prevent *pc_align* from being able to eliminate misalignments between overlapping CTX point clouds. However, these relative misalignments can be reduced by constructing a graph of overlapping CTX point clouds and sequentially aligning them to one another. At each step, the relatively-aligned point clouds are merged to form a new relative reference for the next step in the sequence until all point clouds have been aligned.

Absolute Alignment. After reducing CTX-to-CTX misalignments in the relative alignment stage, it is possible that the overall position of the relatively-aligned CTX point cloud has drifted from the MOLA reference used in the initial alignment. This can be corrected by merging the relatively-aligned point clouds into a single point cloud and aligning this to the MOLA shot data. The resulting absolutely-aligned CTX point cloud may then be interpolated into a final DTM mosaic.

Preliminary Results: The results of the initial alignment stage are shown in the right panel of Figure 1. Initial alignment has reduced typical CTX-to-CTX misalignments from on the order of 100 meters to on the order of ~10 meters.

Next Steps: Work on the relative alignment stage is ongoing. At the conference, I will present a provisional version of the absolutely-aligned DTM mosaic, including an analysis of post-alignment residuals relative to MOLA, and discuss lessons learned from the point cloud alignment process with the intention that they will inform other efforts to produce regional DTM mosaics using stereo photogrammetry.

Acknowledgments: CTX data from the MRO-M-CTX-2-EDR-L0-V1.0 data set were obtained from the Planetary Data System: https://pds-imaging.jpl.nasa.gov/data/mro/mars_reconnaissance_orbiter/ctx/

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