Rigorous Photogrammetric Processing of HiRISE Stereo Images for Mars Topographic Mapping

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Abstract theme
WG IV/7 – Extraterrestrial Mapping

Keywords:
1. Area: Digital photogrammetry
2. Topic: Sensor models
3. Techniques/methodology: Digital photogrammetry
4. Processing/analysis: Adjustment
5. Application field: Topographic mapping
6. High resolution image
7. Matching
8. Extraterrestrial

Abstract

High-precision topographic information is critical to Mars surface exploration. Such information can be derived from both orbital (satellite) and ground (lander/rover) data. The availability of HiRISE stereo images has made great progress possible in high resolution imaging and topographic and morphological information derivation for Mars surface exploration. To take advantage of this opportunity, we have developed the necessary rigorous photogrammetric model for HiRISE stereo image processing, testing our results using data from the Mars Exploration Rover mission.

HiRISE is a push-broom imaging sensor with 14 CCDs (10 red, 2 blue-green and 2 NIR). After excluding overlapping pixels, it can generate images with up to 20,264 cross-track observation pixels and a 30 cm/pixel resolution at 300 km altitude. At such a high resolution, the IFOV (instantaneous field-of-view) is extremely small, and as result the ground track speed becomes very fast. To improve the signal strength of fast-moving objects, Time Delay Integration (TDI) technology is incorporated in the instrument design. Signals in TDI block are transferred from line to line at ground track speed. A single pixel is formed by accumulating signals from the TDI block. According to the HiRISE instrument kernel, the observation time of a single pixel is defined as the ephemeris time (et) when the center of the TDI block is exposed. The USGS ISIS 3 HiRISE Instrument Kernel provides the calibrated interior-orientation parameters needed to calculate the pixel view direction with respect to HIRISE frame (MRO_HIRISE_OPTICAL_AXIS).

The orbiter's initial position and pointing angles are provided in the SPICE kernels. For any given ephemeris time, the EO parameters can be retrieved by interpolating the spacecraft's trajectory and pointing vectors. For short segments of the orbital trajectory, second-order polynomials can be used to model change in the EO parameters of the optical axis with respect to time. Since all the CCDs are fixed to the HiRISE frame, only one set of polynomial parameters is needed to model the EO parameters for all the CCD arrays. Based on our rigorous sensor model, we have developed a method for bundle adjustment (BA) of HiRISE stereo images that removes or reduces measurement inconsistency and improves mapping precision.

We have also developed a hierarchical stereo matching process. Before processing, systematic strip noise in each raw HiRISE image is removed. In HiRISE EDR (Experiment Data Record) data sets, the image acquired by each CCD strip (total 14) is stored as two sub-image strips, each of which is 1024-pixel wide. Brightness values of the two sub-image strips may be inconsistent. We adjusted bright values and combined them together into one seamless image with 2048-pixel swath. Then we removed strip noise occurring systematically. Then, an image pyramid is constructed that consists of 5 levels. Starting with the original image, each subsequent level is created by sub-sampling of each previous level. Interest points are generated by Förstner operator at every image scale. Matching starts from the images of the lowest resolution; results are transferred to the next higher level, with more interest points being extracted and matched. At the lowest level, geographic locations of interest points are estimated by assuming a flat terrain. The search radius is then confined in the neighborhood of the corresponding interest points, and matched points are selected based on correlation coefficient values. At subsequent levels, points from the previous level are matched again to achieve higher matching precision. A TIN surface of parallax differences is generated from these matched points and is used to estimate the corresponding points of other points. After matching the highest-resolution images, evenly distributed, matched interest points are selected as tie points between the stereo images. In the end, grid points are defined to generate a DTM of the terrain.

Using the HiRISE images of Victoria Crater (TRA_000873_1780 and PSP_001414_1780), 136 evenly distributed tie points and 135 check points were automatically selected for BA. The study area is approximately 1 km by 1 km. Before BA, the mean residual of image coordinates in the along-track direction was 24.6 pixels with a standard deviation of 0.77 pixel, and the mean residual in the cross-track direction was 0.017 pixel with a standard deviation of 0.23 pixel. After BA, the mean residual in the along-track and cross-track directions were 0.30 and 0.0047 pixel, respectively, with standard deviations of 0.37 and 0.024 pixel. This improved precision ensures the high quality of topographic and morphological information. Based on these results, 13611 interest points and 337286 grid points were used to generate DTM of Victoria Crater with grid spacing of 1 m.

We also processed a stereo pair of HiRISE images that cover Husband Hill and the Home Plate area (TRA_001513_1655 and TRA_002133_1650), which is 400 m by 600 m in extent. The mean residual in the along-track direction before bundle adjustment was 10.1 pixels with a standard deviation of 2.2 pixels. The mean residual in the cross-track direction was 0.071 pixel with a standard deviation of 0.28 pixel. After bundle adjustment, the mean residual in the along-track direction was reduced to 0.0015 pixel with a standard deviation of 0.18 pixel. In the cross-track direction, residuals are reduced to almost zero. Finally, we used 10236 interest points and 156677 grid points to produce DTM of Husband Hill and the Home Plate area with 1 m resolution.