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Investigation of boresight offsets and co-registration of HiRISE and CTX imagery for precision Mars topographic mapping

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ABSTRACT

Images from two sensors, the High-Resolution Imaging Science Experiment (HiRISE) and the Context Camera (CTX), both on board the Mars Reconnaissance Orbiter, were used to generate Digital Elevation Models (DEMs) of the Martian surface. However, the DEMs generated from the images acquired by these two sensors show discrepancies for various reasons, such as variations in the boresight alignment between the two sensors while flying in the complex environment of space. This paper presents a systematic investigation of the discrepancies between the DEMs generated from the HiRISE and CTX images and further the boresight offsets between the HiRISE and CTX sensors. A bundle adjustment approach is presented for the co-registration of HiRISE and CTX images. The experimental analyses were carried out using eight sets of HiRISE and CTX images collected from different regions. The results indicate that the systematic offsets between the DEMs derived from HiRISE and CTX images reach several hundred meters in object space and dozens of pixels in image space along the north-east direction. After co-registration, the offsets were reduced to about 10 m in object space and to sub-pixel level in image space. From the co-registration results, relatively consistent angular boresight offsets were found, which deviated from the default values. The findings are significant for the synergistic use of HiRISE and CTX images for precision Mars topographic mapping.

1. Introduction

NASA's Mars Reconnaissance Orbiter (MRO) spacecraft has been orbiting Mars since March 2006 (McEwen et al., 2007). Both High-Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) imaging systems are on board the MRO. Images collected by HiRISE and CTX have been widely used for Mars scientific research and to derive Mars topographic products such as DEMs (Digital Elevation Models) to support Mars exploration missions (Kirk et al., 2009; Kim and Muller, 2009; Li et al., 2011a,b; Tao et al., 2014). Although the HiRISE and CTX systems are mounted on the same platform, their boresight parameters can change due to the complex environment during flight in space. These changes may lead to inaccuracies in the exterior orientation (EO) parameters of the instruments and further result in inconsistencies between the 3D topographic mapping products obtained from HiRISE and CTX images.

The 3D topographic data on the surface of Mars derived from different sources generally show varying levels of inconsistencies. Poole (2013) investigated the misregistration issue between the images collected by HiRISE and the High Resolution Stereo Camera (HRSC) on board ESA's Mars Express. The misregistration was reduced to pixel level by using a number of homologous tie points and applying a second-order transformation. Tao et al. (2014) reported that the misregistrations between the DEMs derived from the HiRISE and HRSC images on the Mars Exploration Rover and Mars Science Laboratory landing sites ranged from 100 to 200 m.

Inconsistencies have seldom been reported between the DEMs derived from HiRISE and CTX images. Kim and Muller (2009) mentioned that the DEMs from HiRISE and CTX images had elevation offsets ranging from several meters to more than 30 m. Kim and Muller (2009) and Tao et al. (2014) proposed co-registration methods based on tie-point matching to co-register the DEMs generated from HiRISE, CTX, and HRSC images and thus reduce the inconsistencies among them. However, the misregistration problem between HiRISE and CTX images has not yet been systematically investigated. Effective co-registration of the two datasets through direct adjustment of the image orientation parameters has not been adequately studied.

This paper presents a systematic study of the misregistration between the HiRISE and CTX images and a co-registration method to eliminate the inconsistencies between the DEMs derived from the two types of images by improving the image orientation parameters. Section 2 describes the instrument specifications of HiRISE and CTX and the

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experimental datasets used in this research. Section 3 presents the inconsistencies between the topographic products derived from HiRISE and CTX images. Section 4 describes the co-registration method in detail, and the experimental results are presented in Section 5. Section 6 investigates the boresight offsets between HiRISE and CTX that result in DEM inconsistencies. Finally, the findings are discussed and concluding remarks are presented in Section 7.

2. Camera and data description

2.1. HiRISE, CTX, and their boresight offsets

HiRISE is a push-broom imaging sensor with 14 charge-coupled devices (CCDs; 10 red, 2 blue-green, and 2 near infrared). Each CCD consists of a block of 2048 pixels in the across-track direction and 128 pixels in the along-track direction. In the across-track direction, the average width of the overlap between adjacent CCDs is about 48 pixels. Ten CCDs covering the red spectrum are located in the middle. After the exclusion of overlapping pixels, HiRISE can collect images with a swath of up to 20,048 pixels. At an altitude of 300 km, the resolution of HiRISE images is 0.3 m per pixel. The effective focal length of HiRISE is 12 m (McEwen et al., 2007; Kirk et al., 2008). A stereo pair of HiRISE images is taken from adjacent orbits to form an across-track stereo configuration for DEM generation. The convergence angle of the stereo pair is determined by the emission angles of the stereo images. Because the alignment of the CCDs involves small shifts and rotations in relation to the HiRISE optical axis, the DEMs generated from the raw HiRISE images exhibit small internal inconsistencies among the strips that correspond to each CCD. Effective approaches have been developed to remove these internal inconsistencies in the DEMs. For example, Li et al. (2011) developed a bundle adjustment approach to remove the inconsistencies between overlapping CCDs. In this study, the internal inconsistencies between overlapping CCDs of the HiRISE images were removed before the co-registration process with the CTX images, using the method described by Li et al. (2011). Examples of DEMs generated from HiRISE images are shown in Figs. 1 and 2.

CTX is used to provide context images for the data acquired by other MRO instruments and to observe scientific features of interest (Malin et al., 2007). CTX consists of a telescope with a focal length of 350 mm and 5000 CCD sensor elements and is operated as push-broom camera. It acquires images with a spatial resolution of about 6 m per pixel over a swath width of about 30 km of the Mars surface (Malin et al., 2007; Shean et al., 2011). Similar to HiRISE, a stereo pair of CTX images is taken from adjacent orbits to form an across-track stereo configuration for DEM generation. Examples of DEMs generated from CTX images are also shown in Figs. 1 and 2.

The position and pointing information of HiRISE and CTX images is archived in a series of binary and text based Spacecraft, Planet, Instrument, C-Matrix, and Events (SPICE) kernels, which are maintained by NASA's Navigational and Ancillary Information Facility (Acton, 1996). The HiRISE and CTX mounting alignment information on the MRO platform is calibrated before launch and can be found in the MRO Frames Definition Kernel, according to which the relative direction matrix from CTX to HIRISE is as follows:

$$A_0 = \begin{bmatrix} 0.99999994 & 0.00021198 & -0.00026011 \\ -0.00021196 & 0.99999998 & 0.00005486 \\ 0.00026012 & -0.00005481 & 0.99999996 \end{bmatrix} \quad (1)$$

According to the above relative direction matrix, the angular boresight offsets between the HiRISE and CTX can be calculated as $\Delta\omega = 0.003°$, $\Delta\varphi = 0.015°$, and $\Delta k = 0.012°$, where ω, φ, and k are the pointing angles around the coordinate axes of X, Y, and Z of the MRO spacecraft, of which X is flight direction, Y to the right, and Z downward (Kirk et al., 2008). As aforementioned, the boresight parameters of HiRISE and CTX may change during spaceflight. These changes must be investigated and dealt with, otherwise they will lead to inconsistencies between the DEMs generated from them, such as the examples shown in Section 3.

2.2. HiRISE and CTX datasets

The datasets used in this research include eight sets of HiRISE and C TX images. Each set consists of a stereo pair of HiRISE images and a stereo pair of CTX images. The CTX imagery has a larger coverage that is partially covered by the corresponding HiRISE imagery. These eight sets of images were collected from 2006 to 2013 and were taken from different regions on Mars.

The first dataset (named "Landing-Site") was collected at the landing site of the Mars Exploration Rover – Spirit. The CTX images cover the region 14.19–14.95° S and 175.24–175.77°E, whereas the HiRISE images cover 14.50–14.68°S and 175.45–175.56°E. The HiRISE images cover about 5% of the CTX coverage. Fig. 1 shows the DEMs

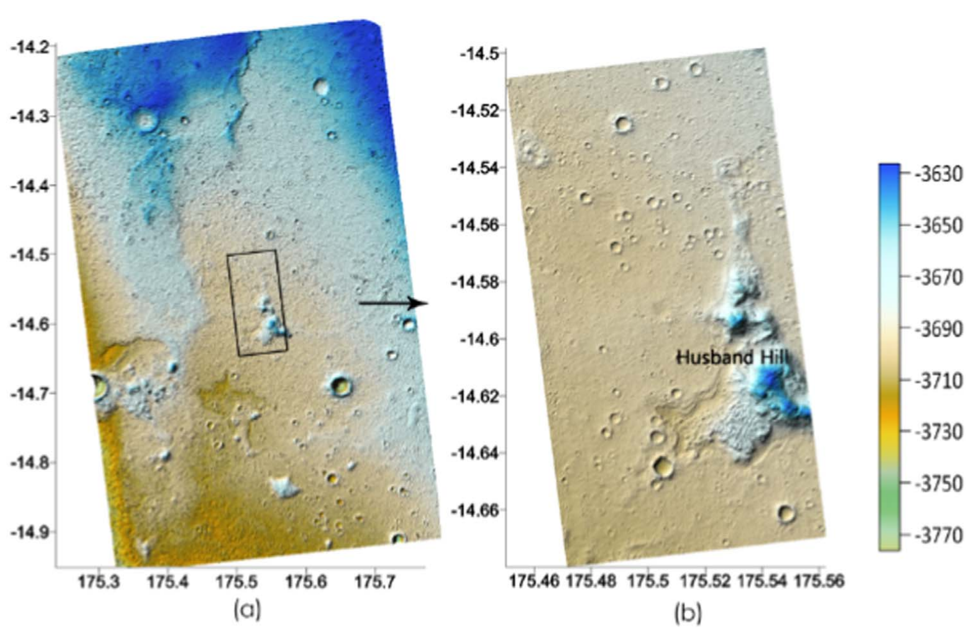

Fig. 1. DEMs of Landing-Site of Mars Exploration Rover – Spirit. (a) DEM generated from CTX stereo pair, and (b) DEM generated from HiRISE stereo pair.