Camera Orientation of Mars Express using DTM Information

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Abstract. In January 2004 the High Resolution Stereo Camera (HRSC) on board the ESA mission Mars Express started imaging the surface of planet Mars in colour and stereoscopically in high resolution. The Institute of Photogrammetry and GeoInformation (IPI) of the University of Hannover and the Chair for Photogrammetry and Remote Sensing (LPF) of the Technische Universität München are jointly processing the data of the HRSC: Using automatically extracted tie points and Mars Orbiter Laser Altimeter (MOLA) data, the exterior orientation of the Mars Express spacecraft is being calculated perpetually in a combined photogrammetric bundle adjustment during the two years lasting mission. This paper describes the used approaches for tie point matching and bundle adjustment. On the basis of two selected orbits the results of the matching and the achieved accuracy of the bundle adjustment are presented and evaluated.

1 Introduction

In June 2003 the European Space Agency (ESA) launched the Mars Express spacecraft from the Baikonur launch pad in Kazakhstan. After a journey of about six months the orbiter was successfully inserted into a polar orbit around Mars. During its two years mission the High Resolution Stereo Camera (HRSC) on board of Mars Express images large parts of the Mars surface. The HRSC is a multisensor pushbroom camera consisting of nine charge coupled device (CCD) line sensors mounted in parallel for simultaneous high resolution stereo, multispectral, and multiphase imaging [1]. At pericenter about 300 km above the surface of Mars a ground resolution of approximately 12 m is attained. The Camera Unit (CU) of the HRSC additionally comprises a Super Resolution Channel (SRC) which captures frame images embedded in the basic HRSC swath at a ground resolution of up to 2.5 m.

The three-dimensional position and attitude of the spacecraft is constantly determined by the European Space Agency (ESA) by combining techniques of measuring Doppler shifts, acquiring ranging data, triangulation measurements and a star tracker camera. These measurements result in a three-dimensional position and attitude of the spacecraft over time which can be considered as approximate exterior orientation in classical photogrammetry. However, these values are not consistent enough for high accuracy photogrammetric point determination. Therefore, a bundle adjustment (EO) has to be performed using these values as direct observations for the unknown EO parameters. As further input for the bundle adjustment automatically extracted tie points derived via digital image matching (DIM) are being used. Additionally, ground control points (GCPs) are necessary to transform the results into a Mars-fixed coordinate system. Because on Mars very few classical GCPs exist, a globally available digital terrain model (DTM) is applied.

In section two of this paper the approach for the determination of the EO of Mars Express is presented. In section three the results of the tie point matching and the bundle adjustment derived from two selected test orbits are shown and discussed.

2 Photogrammetric Point Determination

The processing of the HRSC data is divided into two steps. At first tie points are being extracted using software developed at IPI in Hannover. The derived tie points serve together with the observed EO and the DTM as input for the bundle adjustment developed at LPF in Munich. With the resulting adjusted EO of the Mars Express Orbiter it is possible to derive high level products such as DTMs, ortho photos and shaded reliefs from the imagery.

The principle of the transformation from object (X, Y, Z) to image coordinates (x, y) is explained in [2]. The starting point is the set of collinearity equations [4]:

$$\begin{pmatrix} x - x_0 \\ y - y_0 \\ -c \end{pmatrix} = \lambda M^T \left(\Delta\varphi, \Delta\omega, \Delta\kappa\right) D^T \left(\varphi, \omega, \kappa\right) \left[\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} - \begin{pmatrix} X_0 + \Delta X_0 \\ Y_0 + \Delta Y_0 \\ Z_0 + \Delta Z_0 \end{pmatrix} \right] \qquad \textbf{(1)}$$

The EO refers to a camera coordinate system common to all CCD lines and is expressed for a given readout cycle n as X_0, Y_0, Z_0, φ, ω, κ. The interior orientation (IO) parameters x_0, y_0, c are defined in the image coordinate system, three separate values exist for each line. The transformation between the image coordinate system and the camera coordinate system is given by ΔX_0, ΔY_0, ΔZ_0, $\Delta\varphi$, $\Delta\omega$, $\Delta\kappa$, which have been determined in the geometric calibration for each line separately. M as well as D are rotation matrices, λ is a scale factor. The image coordinates are given by x and y, which are derived automatically in this case via DIM.

The IO of the HRSC has been calibrated in a laboratory at Dornier, Friedrichshafen and has been verified during the six month journey to Mars by means of star observations. So far no deviations from the calibration have been experienced so that the IO of the HRSC is considered to be stable.

2.1 Image Matching

Our matching approach follows a coarse to fine strategy which means the matching result is refined step by step through image pyramids. As input data the HRSC imagery, the observed EO and the calibration data of the IO are needed. As an optional input it is possible to use a DTM as approximate information. On Mars a high accuracy DTM derived from data of the MOLA instrument is available [10].

At first point features are extracted using the Förstner operator [6] and the images are matched pairwise in all combinations using the cross correlation coefficient as similarity measure. Each image is divided into subareas to ensure an even distribution of the tie points over the whole area. To reduce ambiguities and computing time the matching location and a search space for the corresponding feature is computed when transferring a feature from one image to the other. Since no epipolar geometry exists for linescanner imagery a feature in one image is transferred to the next image via equation (1). For the transformation from object space to image space as a function of the image line (readout cycle) n an additional condition (2) has to be applied where x points in flight direction.

$$\mathrm{x(n)=x}\left(\mathrm{n},\ \mathrm{X}_0(n), Y_0(n), Z_0(n), \varphi(n), \omega(n), \kappa(n)\right)=0 \qquad (\mathbf{2})$$

This problem can be solved using the well known Newton-method for the above zero-crossing detection where the derivative x'(n_i) is replaced by the pixelsize of the image.

$$\begin{aligned} &n_0 = initial\,value\;\;for\,the\,image\,line \\ &n_{i+1} = n_i - x\left(n_i\right) / \;pixelsize \qquad i = 0,1,\ldots \end{aligned} \qquad (\mathbf{3})$$

After matching all overlapping images pairwise in all combinations an undirected graph is generated. The nodes of the graph are the point features, the edges are the matches between them. This graph is divided into connected components. The next step is the generation of the point tuples, whereas one point tuple is characterised by the property that not more than one feature per image is admissible. The complexity of this problem can grow exponentially. Instead of using tree search or binary programming techniques a RANSAC (Random Sample Consensus) procedure [5] is applied. The method relies on the fact that the likelihood of hitting a good configuration (correct tuple) by randomly choosing a set of observations (features of the subgraph) is large after a certain number of trials. The advantage of this method is the high probability of obtaining a good point. Including a geometric consistency check, the method also eliminates blunders [3].

From the start pyramid level (lowest resolution) to the so-called intermediate level (medium resolution) feature based matching is carried out using the whole images. Going down the image pyramid the image size increases, as well as the number of extracted features. Besides the heavily increasing computational time, the matching of the complete images would result in too many tie points for the camera orientation. Therefore the matching procedure is carried out only for selected ”image chips”, starting below the intermediate pyramid level. This means that tie points are searched in areas only where points have been found before due to good texture [13].

To further refine the result Multi Image Least Squares Matching (MILSM) is carried out following the approach of Krupnik [9]. In this approach the tie points are matched in all images simultaneously. A detailed description of the implemented MILSM can be found in [7]. Because it is the most accurate matching technique available it is possible to further refine the result of the feature based matching. In our implementation we can decide whether to apply MILSM or not for each pyramid level. To save computing time it is advisable to carry out MILSM only on the last level, which denotes the original resolution.

Finally, model points are derived via a forward intersection of the image coordinates of the tie points. They serve as an approximation for the reduction of the search space on the next lower pyramid level instead of the MOLA points. A more detailed description of the application flow can be found in [11].

2.2 Bundle adjustment using control information

In the bundle adjustment the concept of orientation images proposed by Hofmann et al. [8] is used. This approach estimates the parameters of the EO only at a few selected image lines, at so-called orientation images [12]. The EO for all other image lines is interpolated from the values at the orientation images. The differences for each image line can be considered as correction terms that have to be added to the interpolated values. This solution keeps the number of orientation parameters small and, what is more important, allows to exploit the good relative accuracy of the observed orientation parameters. The mathematical model for photogrammetric point determination with a 3-line camera is based on the well known collinearity equations (1).

The starting point of the discussion about bundle adjustment using a DTM as control information is an approach presented in [12]. This approach uses a least squares adjustment with additional conditions to obtain a relation between a DTM and the bundle adjustment without control information. In case of Mars it is possible to use the MOLA DTM as control information. One suitable way is to use the terrain surface derived by MOLA points and fit the matched HRSC points into the MOLA DTM. This is advantageous because there are more MOLA points than HRSC points.

At locations where HRSC points are available the MOLA data can be described as a local surface. The surface is defined either by three original MOLA points or by four points of a DTM grid, which are interpolated using the original MOLA measurements. In the first case the local surface is described by three irregularly spaced MOLA points, which stem from the original MOLA measurements. This structure is based on original MOLA points and the vertical distance d of HRSC point H to the plane defined by M_1, M_2, and M_3 (Fig. 1, left). In the second case, the HRSC points have to lie on a bilinear surface defined by four neighbouring DTM points, which enclose the HRSC point and show a grid structure. The distance d is defined as vertical distance between HRSC point H to the bilinear surface defined by the four points M'_1, M'_2, M'_3, and M'_4 (Fig. 1, right). In the current implementation the approach using the MOLA DTM has been applied because the advantages of using the MOLA DTM outweigh the usage of the raw MOLA points.

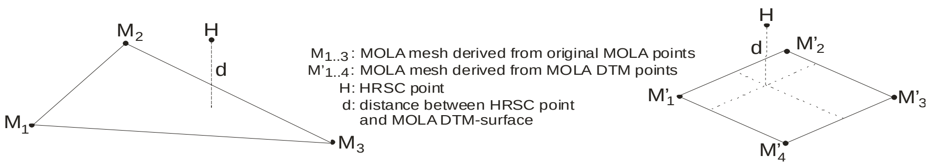

Fig. 1. Left: Structure based on original MOLA points. Right: Regular DTM grid

The mathematical model of the bundle adjustment is given in equation (4):

$$\begin{aligned} v_x &= f\left(X, Y, Z, x_0, y_0, c, X_0, Y_0, Z_0, \varphi, \omega, \kappa\right) - x_i \\ v_y &= f\left(X, Y, Z, x_0, y_0, c, X_0, Y_0, Z_0, \varphi, \omega, \kappa\right) - y_i \end{aligned} \qquad \textbf{(4)}$$

with:

$$X_0 = \bar{X}_{B_0} + \bar{X}_0,\ Y_0 = \bar{Y}_{B_0} + \bar{Y}_0,\ Z_0 = \bar{Z}_{B_0} + \bar{Z}_0,\ \varphi = \bar{\varphi}_B + \bar{\varphi},\ \omega = \bar{\omega}_B + \bar{\omega},\ \kappa = \bar{\kappa}_B + \bar{\kappa}$$

whereas the EO is composed of biases $\left(\bar{X}_{B_0}, \bar{Y}_{B_0}, \bar{Z}_{B_0}, \bar{\varphi}_B, \bar{\omega}_B, \bar{\kappa}_B\right)$ valid for the entire strip and terms $\left(\bar{X}_0, \bar{Y}_0, \bar{Z}_0, \bar{\varphi}, \bar{\omega}, \bar{\kappa}\right)$ valid for a single CCD line only.
Additionally one observation equation (5) is used for each HRSC point

$$v_d + d = f(X_H, Y_H, Z_H, X_{M_i}, Y_{M_i}, Z_{M_i})\ \ i = 1..4 \qquad \textbf{(5)}$$

with three unknowns (X, Y, Z of HRSC tie point), one observation (difference d between HRSC point and MOLA surface) and twelve constants (X, Y, Z for all four MOLA DTM points) for each surface. The accuracy of the observed difference is determined by the accuracy of the MOLA points.

3 Processing of HRSC imagery

In this section, first the used HRSC imagery will be described. In the second part the results of the matching and bundle adjustment will be presented and discussed on the basis of the orbits 18 and 68.

3.1 Data

For the evaluation of the matched tie points and the achieved accuracy of the bundle adjustment, imagery of the orbits 18 and 68 have been chosen which have been received in the early phase of the Mars Express mission. The observations of the EO and the calibration data of the IO as well as the MOLA DTM are used as input for the DIM and the bundle adjustment. The a priori accuracy has been introduced into the bundle adjustment with a value of 1000 m for the position and 28 mgon for the attitude. The trajectory of the orbiter is considered to be very stable. Additionally the HRSC imagery is used for the matching.

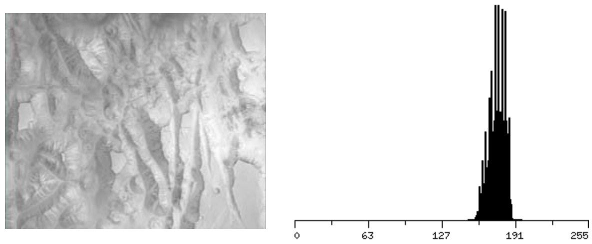

Fig. 2. Left: Part of orbit 68 with high texture. Right: Histogram of region with low contrast

The CCD arrays of the HRSC consist of 5176 active pixels each, which yields a swath width of about 65 km on the surface of Mars. The strips can have a length of up to 300.000 lines, spanning about 4.000 km on the surface. Due to a limited bandwidth between Mars and Earth only the nadir channel is able to operate at full resolution. Generally the resolution of the two stereo channels has to be reduced by a factor of 2 and the remaining channels by a factor of 4. To obtain an equivalent scale the nadir channel has to be resampled to the resolution of the stereo channels for the matching. Depending on the covered region on Mars the imagery shows areas with high texture and areas with hardly any texture and low contrast (Fig. 2).

3.2 Results

3.2.1 Results of the matching

In a first evaluation the ray intersections of the tie points are analysed. The values of the EO from ESA have been fixed in the bundle adjustment and no DTM as control information has been introduced. This can be considered as a forward intersection. The obtained values are compared to the results calculated by the bundle adjustment improving φ and κ. This means a constant bias is estimated for both angles along the entire orbit. Biases for φ and κ were introduced, because only these two parameters can be improved using tie points.

Tab. 1. Theoretical standard deviations of the object coordinates

orbit	altitude [km]	σX [m]	σY [m]	σZ [m]
18	275 - 375	11.0 / 5.9	13.0 / 6.6	34.0 / 18.0
68	269 - 505	30.3 / 10.3	26.6 / 10.9	48.8 / 17.8

In Tab. 1 the accuracies of the object coordinates of the ray intersections are shown for the selected orbits. The left value is the standard deviation of the ray intersections using the EO from ESA. The right value shows the achieved theoretical standard deviation of the ray intersections after improving φ and κ. The accuracies of all computed orbits are in a range of about 6 to 11 m in X and Y, depending on different imaging altitudes. Z accuracies of all orbits are about 18 to 22 m. The standard deviations of the ray intersections are improved by a factor of 2 to 3 and a final accuracy of about 0.4 pixel in X and Y and 0.8 pixel in Z is achieved.

3.2.2 Results of the bundle adjustment

The second part of the results shows the evaluation after HRSC object points have been fitted to the MOLA DTM. Here, the biases of all six parameters of the EO (X_0, Y_0, Z_0, φ, ω, κ) have been improved along the trajectory. Tab. 2 shows the improved values and their standard deviations for the three orbits. In most cases the values can be determined with high significance, because the standard deviations of the bias values are lower than the bias values themselves.

The standard deviations of the object coordinates for the orbits 18 and 68 are shown in Tab. 3, which depend on two results. At first there are the accuracies of the ray intersection (Tab. 1) determining the accuracies within the orbit itself. Second, there are the accuracies of the absolute orientation between orbit and MOLA DTM (Tab. 2). Thus, the precision of the point determination is a combination of these two accuracies. The standard deviations of the object points in all three dimensions are less than 20 m (Tab. 3).

Tab. 2. Theoretical standard deviations of orbit determination

orbit		X_0 [m]	Y_0 [m]	Z_0 [m]	φ [mgon]	ω [mgon]	κ [mgon]
18	bias value	90.4	-64.6	-38.2	-51.1	-64.4	-6.2
	bias σ	7.3	11.0	1.6	0.3	1.5	0.1
68	bias value	-12.1	-112.3	-41.2	-24.9	-12.1	-35.9
	bias σ	10.7	16.7	6.7	0.4	1.9	0.6

Tab. 3. Theoretical standard deviations of HRSC points fitted to MOLA DTM

orbit	σ X [m]	σ Y [m]	σ Z [m]
18	9.1	10.6	17.0
68	14.4	16.7	17.5

Finally, the root-mean-square (RMS) Z differences between object coordinates of the HRSC tie points and the MOLA DTM were investigated. In one case the result is computed without DTM as control information and in the other case with DTM information. The RMS Z differences between DTM and HRSC object points are in the range of 200 m (orbit 18: 177 m, orbit 68: 200 m). After the bundle adjustment including DTM control information the RMS Z differences decrease by a factor of three (orbit 18: 84 m, orbit 68: 63 m). Therefore, the adaptation of HRSC data to the MOLA reference system has succeeded.

4 Conclusion

The results show the efficiency of the image matching and bundle adjustment approaches to achieve an improved exterior orientation with MOLA DTM as control information. The tie points are distributed evenly over the whole block with a good rate of 3-fold points. An accuracy of 0.4 pixel in position and 0.8 pixel in height is achieved. The significant improvement of the position of the exterior orientation increases from an a priori accuracy of 1000 m to less than 20 m in all three dimensions (Tab. 2). The accuracy of the attitude increases from 28 mgon to 1-2 mgon in all angles. The position and attitude could be improved by an average factor of 30 to 50. Thus, after the bundle adjustment the object coordinates of the tie points have a very high accuracy. Finally, there is a high consistency between HRSC points and MOLA DTM, which constitutes the valid reference system on Mars.

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