ORIENTATION OF MARS EXPRESS/HRSC IMAGERY USING LASER ALTIMETER DATA AS CONTROL INFORMATION

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ABSTRACT

In this paper we focus on the estimation of exterior orientation parameters of the High Resolution Stereo Camera (HRSC) orbiting planet Mars during the European Mars Express mission. One of the challenges for the photogrammetric processing of HRSC images will be the low number of Ground Control Points (GCP's) on Mars which can be identified and measured in the images in the usual way. Therefore, Mars Observer Laser Altimeter (MOLA)-data is employed as control information in the photogrammetric bundle adjustment of HRSC images. We discuss advantages and disadvantages of alternative approaches to improve exterior orientation parameters employing MOLA-data. Further, we describe set-up of our simulation studies.

1 INTRODUCTION

The reconstruction of the exterior orientation is a fundamental task in photogrammetry. An established process to determine these orientations parameters is bundle block adjustment, i.e., simultaneous estimation of exterior orientation parameters and coordinates of object points. In general, the classical photogrammetric point determination requires conjugate points, interior orientation, approximations for exterior orientation, and Ground Control Points (GCP's). On earth a reduction of GCP's is possible in many cases because highly accurate GPS/INS-data is available. On Mars we do not have GPS and the observed exterior orientation parameters are not accurate enough to do bundle adjustment without GCP's.

For Mars Express mission conjugate points will be measured automatically by means of image matching. Interior orientation is supposed to be known from calibration. Observations for the exterior orientation will be derived from Inertial Measurement Unit (IMU) measurements and orbit analysis. The orbit determination errors at the perigee reach amounts up to 2000 m (Hechler and Yáñez, 2000). However, the measurements can serve as approximate values. Therefore, we need additional control information in order to fit photogrammetrically derived object points into the existing reference system on Mars.

On Mars there are only few precisely known points which can serve as classical GCP's. But there is a large number of ground points measured by MOLA. Unfortunately, it is hard to automatically identify MOLA points in images, because they are usually not related to image features. In some cases the approach to match MOLA and image data as proposed by (Kim et al., 2000) can be helpful. However, it might be too difficult to embed this approach in the operational photogrammetric processing.

In Section 2 we describe the MOLA- and HRSC-data and their quality. Previous approaches are given in Section 3. Then, in Section 4 we discuss different approaches to integrate MOLA-data in a bundle adjustment of HRSC-data. For each approach the mathematical model is described. The set-up of our simulation studies is explained in Section 5. Section 6 concludes this paper with a summary and an outlook.

2 DATA SOURCES

2.1 Mars Observer Laser Altimeter (MOLA)

In February 1999 the Mars Global Surveyor (MGS) spacecraft entered the mapping orbit at Mars. During the recording time (February 1999 to June 2001) the MOLA instrument acquired more than 640 million observations by measuring the distances between the orbiter and the surface of Mars. In combination with orbit and attitude information these altimeter measurements can be processed to object coordinates of points on the ground. Each orbit results in one track of MOLA points.

The along track resolution is about 330 m with a vertical neighboring precision of 40 cm from shot to shot, i.e., from laser point to laser point. The absolute vertical accuracy is in the order of 10 m. The surface spot size is about 130 m (Smith et al., 2000), (Smith and Zuber, 2002), (Smith, 2003). The across-track shot to shot spacing depends on the orbit and varies with latitude. In general, the distance between neighboring tracks on the ground is up to more than 1 km (Kirk et al., 2002).

In addition to the surface described by the original, irregularly distributed MOLA points there exists a grid-based global Digital Terrain Model (DTM) which is derived from these MOLA points (see Figure 1).

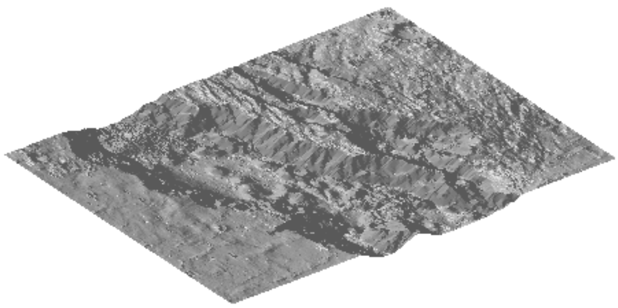

Figure 1: Part of Mars DTM derived from MOLA-data

As mentioned before, the special thing about the laser points is, that they can not be identified in the images in an easy way. I.e., image coordinates of most of these points can not be measured, and therefore, we are not able to treat them as normal GCP's in a bundle adjustment.

Another problem of MOLA data is that the surface points contain scan errors due to referencing errors of the spacecraft. The elimination of the scan error is possible with a robust interpolation. However, due to roughness of Mars, points in regions without scan error will be eliminated, too. Better result can be reached by analyzing scan line segments (Briese et al., 2002, Dorninger et al., 2003).

2.2 High Resolution Stereo Camera (HRSC)

The HRSC-data are not yet available because Mars Express with the HRSC (see Figure 2) on board is launched at June 2, 2003. In December 2003 the orbiting phase will begin and the first images will be acquired.

The HRSC is a line sensor with nine CCD-lines. It has one nadir channel, four stereo channels, and four color channels. The images are generated by catenating the continuously acquired line-images. The result is one image per sensor-line and orbit. One image strip includes all images of one orbit. The pixel size

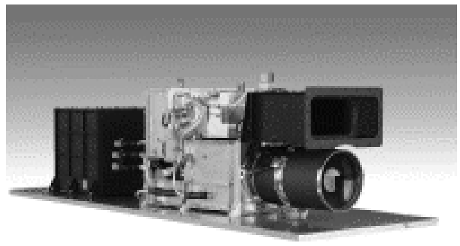

Figure 2: High Resolution Stereo Camera (©DLR, Berlin)

on ground of 12 m will be reached at an altitude of 270 km at perigee and increase to 50 m at an altitude of 1000 km (Neukum and Hoffmann, 2000).

Conjugate points will be measured automatically in the HRSC images by means of image matching. In addition, the delivered data will contain the position- and attitude-data of the orbiter. Interior orientation parameters of HRSC have been calibrated in laboratory and are expected to be stable.

2.3 Comparison of data

The MOLA points are characterized by their relative low point density compared to the point density we could get from HRSC images. However, for the reconstruction of the exterior orientation of the HRSC images it is not necessary to use as many conjugate points as possible. A comparably small set of well distributed points would probably sufficient. We expect that in a typical HRSC scene there will be at least 300.000 MOLA points and "only" a few hundreds or a few thousands of conjugate points from HRSC. With respect to our goal the most important feature is the good global accuracy of the MOLA points. The relative accuracy between neighboring points derived from HRSC-data is supposed to be high but the global accuracy will be poor. This is because the accuracy of HRSC points is limited by the observed exterior orientation parameters.

Our intention is to improve the estimation of the exterior orientation parameters using the advantages of both data sources. Therefore, the MOLA-data is supposed to serve as control information in the bundle adjustment of the HRSC-, position-, and attitude-data.

3 PREVIOUS APPROACHES

Related work on the use of control surfaces for the orientation of aerial images has been presented, e.g., by (Strunz, 1993). He investigates the conditions for the datum determination by exclusive use of DTM. Finally, by means of simulations he analyzes the accuracy achievable with DTM as control information.

(Jaw, 2000) describes a model in which the surface information is integrated into the aerial triangulation workflow. The surface information is derived from airborne laser range finder and the object points are derived from manual measurements or matching. The object points together with the adjusted surface points provide an improved description of the surface.

An approach to optimize orientation parameters is given in (Oda et al., 2000). They use a method, called Digital Surface Model Based Orientation Technique, that is based on image registration techniques. The concept is to optimize the six orientation parameters of each image in a stereo pair. The approach does not require classical GCP's but uses a digital surface model.

Starting point of our discussion in Section 4 is the approach of (Ebner and Ohlhof, 1994). This approach describes a point determination without classical GCP's. As control information they use terrain points which have not to be identified in the images. In their approach the conjugate points are acquired in such a way, that at least three object points are arranged in the surrounding of each GCP (see Figure 3).

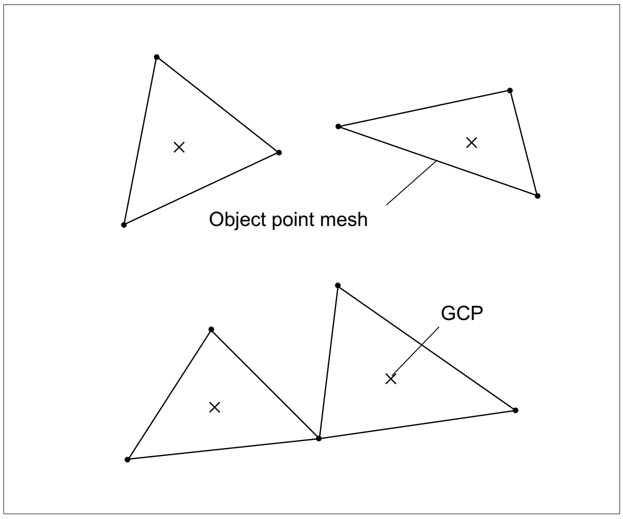

Figure 3: Fitting GCP's in planes defined by object point meshes

The approach assumes that all these points lie on the terrain surface. The mathematical model for the bundle adjustment includes three observation equations for each GCP (Equation (1))

$$\begin{aligned} \hat{v}_{X_{GCP}} &= \hat{X}_{GCP} - X_{GCP} \\ \hat{v}_{Y_{GCP}} &= \hat{Y}_{GCP} - Y_{GCP} \\ \hat{v}_{Z_{GCP}} &= \hat{Z}_{GCP} - Z_{GCP} \end{aligned} \quad (1)$$

and one condition equation (Equation (2)).

$$\hat{Z}_{GCP} - \hat{Z}_{GCP}(\hat{X}_{GCP}, \hat{Y}_{GCP}, \hat{X}_k, \hat{Y}_k, \hat{Z}_k) = 0 \quad (2)$$

The condition equation postulates that the GCP, is located in an inclined plane, which is defined by the tree surrounding object points ($k = 1, 2, 3$).

(Ebner and Ohlhof, 1994) have carried out computer simulations with additional or exclusive control information to validate the use of this approach. The simulations were based on a block of 121 aerial images, with an image scale of 1:10000. Four different cases have been investigated. In case A a classical block triangulation was used with 20 conventional 3D-GCP's and 16 height GCP's. The height control points are replaced by 16 new GCP's in case B. In case C four conventional 3D-GCP's are located in the block corners and in addition 32 new GCP's were used. In case D the conventional GCP's are completely replaced by 36 new GCP's. In case D also the influence of the terrain slope has been analyzed.

The results of case A and B show that the height control points can be replaced without any loss of accuracy. In case C the height accuracy is similar as in cases A and B but the planimetric accuracy becomes slightly worse. The results of case D again show a similar height accuracy independent of terrain slope. Whereas, the planimetric accuracy depends on the terrain slope and more accurate results can be achieved for rougher terrain.

4 POSSIBLE APPROACHES FOR MARS EXPRESS

If we transfer the approach of (Ebner and Ohlhof, 1994) to our goal, we have to consider that in each image strip we will use more MOLA points than conjugate points from HRSC. Therefore, we have to use the MOLA points as the points defining the inclined plane. Whereas the conjugate points from HRSC must be fitted in these MOLA-planes. The observations in the least squares adjustment are position- and attitude data, image coordinates of tie points, and some MOLA points. The unknowns are the exterior orientation, the object coordinates of tie points, and the coordinates of MOLA points.

Since HRSC points as well as MOLA points are treated as unknowns in the proposed condition equations, this would result in a least squares adjustment with conditions between unknowns. This imposes some disadvantages and additional effort compared to a least squares adjustment with observation equations only. Furthermore, the number of unknowns will become quite high, because for every conjugate point also coordinates of three additional MOLA points have to be estimated.

4.1 Fitting HRSC points in MOLA surface

A possibility to simplify the approach would be to take the distance d (see Figure 4) from the HRSC

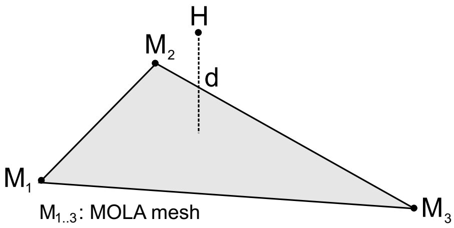

Figure 4: Fitting HRSC point in plane defined by MOLA points

point to the plane defined by three neighboring MOLA points as observation.

In the mathematical model of the bundle adjustment the condition equation (Equation (2)) can be reduced to an observation equation (Equation (3)).

$$\hat{v}_d + d = f(\hat{X}_H, \hat{Y}_H, \hat{Z}_H, X_{M_i}, Y_{M_i}, Z_{M_i}) \qquad (3)$$

For each mesh the number of unknowns is only three ($\hat{X}_H, \hat{Y}_H, \hat{Z}_H$). We have one observation ($d = 0$) and nine constants ($X_{M_i}, Y_{M_i}, Z_{M_i}$, $i = 1...3$). The standard deviation σ_d will be determined by the standard deviations of three MOLA points M_1, M_2, and M_3. Thus, the mathematical formulation is slightly less exact, but the implementation of the least squares adjustment becomes much easier avoiding conditions between the unknowns.

4.2 Fitting HRSC points in grid based MOLA DTM

Another approach we want to apply uses a DTM which is derived from MOLA points. This approach is equivalent to (Strunz, 1993). In this case, the HRSC points have to lie on a bilinear surface defined by four neighboring DTM points, which enclose the HRSC point (see Figure 5).

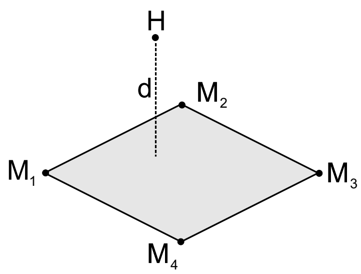

Figure 5: Fitting HRSC point in bilinear surface defined by MOLA DTM

The advantage of this approach is that the effort to search for adequate neighboring MOLA points is reduced because the DTM is regular. The main drawback of this approach is that it does not use the original MOLA points but interpolated DTM points.

In this case the observation equation is similar to the preceding approach (Equation (3)). Only the number of constants increases to twelve ($X_{M_i}, X_{M_i}, Z_{M_i}$, $i = 1...4$) and the standard deviation σ_d will be determined by the standard deviations of four DTM points M_1, M_2, M_3, and M_4. The number of unknowns and observations ($d = 0$) are the same.

5 SET-UP FOR SIMULATIONS

In this section we describe the set-up of our simulation studies and we discuss different aspects, which we want to analyze in the simulations by means of adjustment methods. The simulations are based on some of the predicted Mars Express Orbits and employ the currently available MOLA-DTM of Mars. The computations are carried out with a bundle block adjustment program that combines both, HRSC- and MOLA-data. The HRSC-data include observations of the exterior orientation parameters for each image-line (see Section 2.3). As mentioned above, the absolute accuracy of the observations is rather poor, however, the relative accuracy, i.e., the accuracy of the differences between observations for neighboring image-lines is quite good.

In the bundle block adjustment we follow the concept of orientation images proposed by (Hofmann et al., 1982) and estimate the parameters of the exterior orientation only at a few selected image-lines, at the so-called orientation images. Figure 6 gives an example with orientation images at the beginning, at the middle, and at the end of the image strip. Assuming a smooth course between the orientation images the exterior orientation is interpolated for all other image-lines. Usually, there will always occur differences between interpolated and measured parameters. Their size depends on the distance between the orientation images and the smoothness of the trajectory. Usually small deviations, e.g., caused by measurement noise, can be ignored. However, for large distances between orientation images the differences between interpolation and measurement might exceed the measurement noise and, therefore, must not be neglected. In principle there are two ways to cope with this problem: One possiblility is to reduce the distance between the orientation images in order to adapt the model to the roughness of the data. An alternative solution is to compute the differences for each image-line and consider them as correction terms, that have to be added to the interpolated values. In our case the latter solution is more favourable, since it keeps the number of orientation parameters small and, what is even more important, it allows us to exploit the good relative accuracy of the observed orientation parameters.

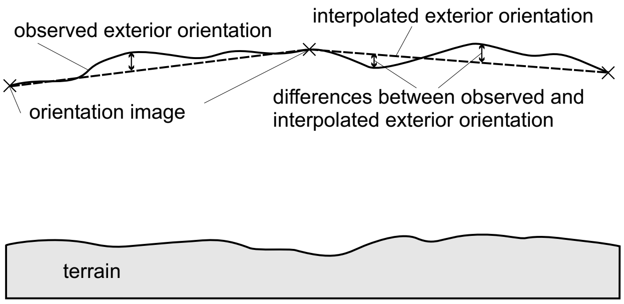

Figure 6: Simulation configuration

In the following sections we discuss the variation of the number of conjugate points, the variation of distance between orientation images, and the use of different control information. For each case we give reasons for the variation of these parameters and explain which result we expect.

5.1 Number of Conjugate Points

The number of conjugate points will be defined by the result of the automatic matching. The number of matched conjugate points depends on terrain, geometry, visibility, texture, radiometric differences between stereo images, dust in the atmosphere, and sandstorms. We expect that the matching will deliver 500 up to 5000 points. Therfore, we simulate configurations with approximately 500, 1500, and 5000 points in one image strip. With these simulation we will investigate the influence of the number of conjugate points on the accuracy of the estimated orientation parameters.

5.2 Distance between Orientation Images

The number of orientation images is variable, but not less than two. For two and three orientation images we do a linear interpolation (see Figure 7). If we use four or more orientation images we apply a Lagrange interpolation of third degree (see Figure 8).

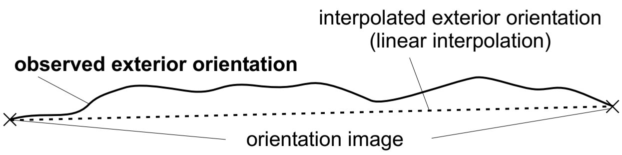

Figure 7: Example with two orientation images

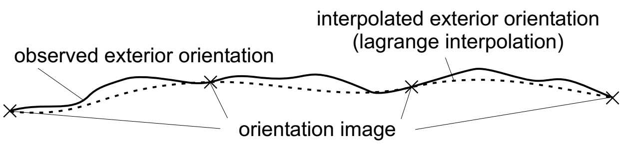

Figure 8: Example with four orientation images

For the simulations we use 2, 3, 4 and 8 orientation images. The modification of number of orientation images will take into account the neighboring and absolute accuracy of exterior orientation (Hechler and Yáñez, 2000). If the neighboring accuracy much better than the absolute accuracy of exterior orientation then it is reasonable to adjust only bias and drift of the exterior orientation parameters (see Figure 9). In this case we take only two orientation images. The use of eight and more orientation images should be applied in cases of worse neighboring accuracy, because this allows to correct also distortions of longer wavelengths. But, considering the expected accuracy of the observations we assume that we have to adjust only bias and drift parameters of exterior orientation.

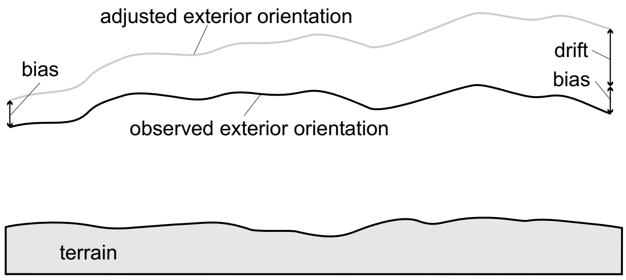

Figure 9: Bias and drift

5.3 Control information

The use of control information is important in order to improve the exterior orientation and to get better point accuracy. In this section, we discuss the use of a DTM and classical GCP's as control information.

5.3.1 DTM as control information Here, we apply the approach to use a MOLA DTM (see Section 4.2). This approach is possible, because we have grid based MOLA DTM on Mars with a planimetric accuracy of 200 m and a height accuracy of 10 m. Not every HRSC point will be fitted in the existing DTM, i.e. we will vary the number of DTM meshes serving as control information. The benefit to use fewer MOLA meshes will be shown in the faster computation time. On the one hand we use DTM meshes only for few HRSC points. On the other hand we take for each HRSC point a surrounding DTM mesh. With this variations we can find out how many DTM meshes are at least necessary to get an optimal result.

Considering the different topography of the surface and the previous simulations of (Ebner and Ohlhof, 1994) which are outlined in Section 3 we carry out simulations for different regions, more precisely, for different terrain types on Mars. We take one image strip over the Valles Marineris with high variation in terrain slope and another image strip in relative flat terrain. In view of the simulations studies of (Ebner and Ohlhof, 1994), which have been based on aerial images, we expect that our simulations will deliver qualitatively comparable results for HRSC. For example, the height accuracy might be independent of terrain slope. Whereas, the planimetric accuracy will increase with the roughness of the terrain.

5.3.2 Use of Classical GCP's Despite the fact, that our primary goal is to do bundle block adjustment without GCP's we make also some tests using GCP's as control information. First, because these tests are useful to evaluate and to compare the use of DTM as control information. Second, because on Mars there is a limited number of classical GCP'S from the new MDIM 2.1 control network with an accuracy of 100–200 m (Archinal et al., 2003). Simulations will include configurations without, with 4, with 10, and with 20 points of the MDIM control network.

6 SUMMARY AND OUTLOOK

In principle, all the approaches described in Section 4 can be employed in a bundle adjustment to achieve an improved exterior orientation. But the effort to integrate them in a bundle adjustment program differs and what is even more important, some approaches cause implications on previous image matching steps.

Based on the results of the simulations in (Ebner and Ohlhof, 1994) with aerial imagery and our simulations described in Section 5 we expect that the use of MOLA points as control information will lead to a high global accuracy of exterior orientation and object coordinates. As previous simulations show the planimetric accuracy depends on terrain slope. If the terrain slope increases, the planimetric accuracy increases, too.

The next step will be to carry out the simulation studies which we described in Section 5 to evaluate the potential of different configurations of the input values of bundle adjustment.

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