IMPROVING THE EXTERIOR ORIENTATION OF MARS EXPRESS REGARDING DIFFERENT IMAGING CASES

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ABSTRACT

The High Resolution Stereo Camera (HRSC) on board of ESA Mission Mars Express started imaging the surface of planet Mars in color and stereoscopically in high resolution in January 2004. The Institute of Photogrammetry and GeoInformation (IPI) of the University of Hannover and the Department Photogrammetry and Remote Sensing (FPF) of the Technische Universitaet Muenchen are jointly processing the data of the HRSC. The primary goal is to register the HRSC data to the Mars Observer Laser Altimeter data (MOLA). In this Paper the HRSC and MOLA data, the concept, and results of photogrammetric point determination regarding to different imaging situations is described.

1 INTRODUCTION

The ESA mission Mars Express with the High Resolution Stereo Camera (HRSC) on board started the orbiting phase in January 2004. During the first two years more than 1000 stereo images were acquired.

The primary goal of the Photogrammetry and Remote Sensing (FPF) at the Technical University of Munich is to determine the exterior orientation of HRSC orbiting planet Mars during Mars Express mission. In general, the classical photogrammetric point determination requires image coordinates of tie points, interior orientation, and ground control points (GCP). In case of HRSC on Mars Express tie points will be measured automatically in the images by means of image matching. Interior orientation is assumed to be known from calibration. Observations for the exterior orientation will be derived from star observation, Inertial Measurement Unit (IMU) measurements, and orbit analysis. Unfortunately, these observations for the parameters of the exterior orientation will probably not be precise enough for a consistent photogrammetric point determination on a global level. Nevertheless, they can serve as good approximate values.

Additional control information is necessary 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 GCPs. But there is a large number of ground points measured by MOLA. The characteristics of the laser points are, 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, it is not possible to treat them as normal GCPs in a bundle adjustment. As a remedy it is proposed to use control surfaces derived from the MOLA points.

In Section 2 the principle of nine-line HRSC, the acquisition of the imagery, and the MOLA-data is described. The concept of photogrammetric point determination with MOLA data as control information in the bundle adjustment is given in Section 3. The focus in Section 4 is on different imaging cases. Results of all computed images are given in Section 5. Section 6 concludes the paper.

2 DATA SOURCES

2.1 High Resolution Stereo Camera (HRSC)

The HRSC (see Fig. 1) is a multi-sensor pushbroom camera consisting of nine Charge Coupled Device (CCD) line sensors for simultaneous high resolution stereo, multispectral, and multi-phase imaging. It has one panchromatic nadir channel, four panchromatic stereo channels, and four channels for color. The convergence angles between the nadir- and the stereo sensors are 21 and 14 gon.

Figure 1: High Resolution Stereo Camera (©DLR, Berlin)

The sensor arrays with 5176 active pixels each are arranged perpendicular to the direction of flight in one focal plane. The images are generated by catenating the continuously acquired line-images. The result is one image per sensor and orbit. One image strip includes all images of one orbit. The pixel size on ground of 12 m will be reached at an altitude of 270 km at pericentre and increase to 50 m at an altitude of 1000 km (Neukum and Hoffmann, 2000). At pericentre one image strip covers an area of about 60 km across trajectory. In general, the strip has a length of about 300 km up to 4000 km.

In addition to the nine sensors of HRSC, there is another sensor called Super Resolution Channel (SRC). The SRC delivers frame images with 1024 x 1024 Pixel with a ground resolution of 2 - 3 m. This sensor delivers no stereo images. Therefore, a photogrammetric point determination is not possible and the sensor will be not longer considered in this paper.

The three-dimensional position of the spacecraft is constantly determined by the European Space Agency (ESA) applying a combination of doppler shift measurements, acquisition of ranging data, triangulation measurements, and orbit analysis. The orbit accuracy at the pericentre is given as an interval of maximum and minimum accuracy for the whole mission duration (Hechler and Yáñez, 2000). Table 1 shows the accuracy interval for X (direction of flight), Y (perpendicular to the direction of flight), and Z (radial).

X	Y	Z
10 - 2120 m	2.5 - 795 m	1 - 80 m

Table 1: Orbit accuracy at pericentre (Local frame)

The attitude of the spacecraft is derived from measurements of star tracker cameras and from an Inertial Measurement Unit (IMU). The accuracy of the nadir pointing results from a combination of attitude errors and navigation errors. The values for accuracies are 25 mdeg for all three angles φ (pitch), ω (roll), and κ (yaw). They are supposed to be valid for the whole mission (Astrium, 2001).

These measurements result in an observed three-dimensional position and attitude of the spacecraft which can be considered as the approximated exterior orientation in classical photogrammetry. However, these observations are not consistent enough for high accuracy photogrammetric point determination.

The interior orientation of the HRSC has been calibrated by Dornier at Friedrichshafen (Carsenty et al., 1997). During the six month journey to Mars the interior orientation has been verified by the means of star observations. So far no deviations from the calibration have been experienced and the interior orientation parameters of the HRSC is considered to be stable.

2.2 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 have been 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 37.5 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 168 m in a 400-km-elevation mapping orbit (Smith et al., 2001). 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 spaced MOLA track points NASA (Neumann et al., 2003) distributed a grid-based global Digital Terrain Model (DTM) which is derived from these MOLA points. The accuracy of DTM is 200 m in planimetry and 10 m in height.

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, it is not possible to treat them as normal GCPs in a bundle adjustment.

3 CONCEPT

In this Section the automated measurement of image coordinates of tie points applying the matching software *hwmatch1* of the Institute of Photogrammetry and GeoInformation (IPI) of University of Hannover and the bundle adjustment software *hwbundle* of FPF will be described.

3.1 Matching

For automatic extraction of image coordinates of tie points software *hwmatch1* is used. Originally, *hwmatch1* was developed at the FPF in Munich for frame images. The IPI implement in *hwmatch1* the extended functional model for three line imagery (Ebner et al., 1994) and modified the software according to the requirements of the Mars Express Mission (Heipke et al., 2004, Schmidt et al., 2005).

As input data the matching needs images, the observed exterior orientation, and the calibrated interior orientation parameters. As an optional input it is possible to use a MOLA DTM as approximate information.

The matching uses feature based techniques. Point features are extracted of the entire images using the Förstner operator. The images of all sensors are matched pairwise in all combinations using the cross correlation coefficient as similarity measure. The results of pixel correlations are sets of image coordinates of tie points for each image. In addition, the results are refined step by step through different levels of image pyramids.

3.2 Mathematical model of bundle adjustment without DTM

In the bundle adjustment the concept of orientation images proposed by (Hofmann et al., 1982) is used. This approach estimates the parameters of the exterior orientation only at a few selected image-lines, at the so-called orientation images.

The mathematical model for photogrammtric point determination with a three-line camera is based on the well known collinearity equations. These equations describe the fundamental geometrical condition that the rays through the three corresponding image points and the corresponding perspective centers intersect in the object point (see Fig. 2).

Two collinearity equations (Equation (1)) are established for each image point. For every object point there are several equations, because corresponding image points are found in images of different sensors.

$$\begin{aligned} \hat{x}_i &= c\,\frac{\hat{r}_{11}(\hat{X}_i-\hat{X}_0)+\hat{r}_{21}(\hat{Y}_i-\hat{Y}_0)+\hat{r}_{31}(\hat{Z}_i-\hat{Z}_0)}{\hat{r}_{13}(\hat{X}_i-\hat{X}_0)+\hat{r}_{23}(\hat{Y}_i-\hat{Y}_0)+\hat{r}_{33}(\hat{Z}_i-\hat{Z}_0)} \\ \hat{y}_i &= c\,\frac{\hat{r}_{12}(\hat{X}_i-\hat{X}_0)+\hat{r}_{22}(\hat{Y}_i-\hat{Y}_0)+\hat{r}_{32}(\hat{Z}_i-\hat{Z}_0)}{\hat{r}_{13}(\hat{X}_i-\hat{X}_0)+\hat{r}_{23}(\hat{Y}_i-\hat{Y}_0)+\hat{r}_{33}(\hat{Z}_i-\hat{Z}_0)} \end{aligned} \quad (1)$$

$\hat{x}_i, \hat{y}_i$	:	image coordinates of object point P
c	:	calibrated focal length
$\hat{X}_i, \hat{Y}_i, \hat{Z}_i$	:	coordinates of object point P
$\hat{X}_0, \hat{Y}_0, \hat{Z}_0$	:	coordinates of projective center
$\hat{r}_{11}, ..., \hat{r}_{33}$	:	elements of rotation matrix

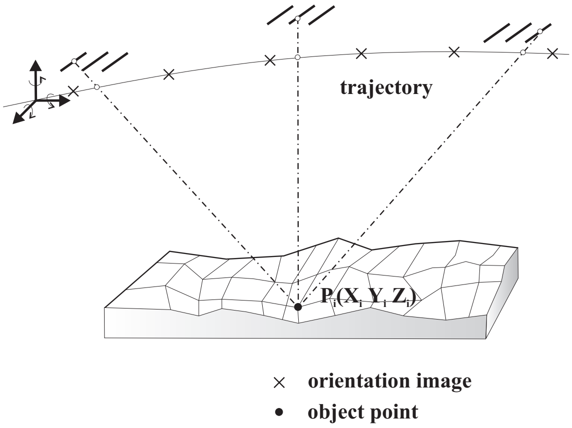

Figure 2: Imaging principle with three line camera

The collinearity equations are not in linear form and must be linearized by a truncated Taylor's expansion. Therefore, approximations for the orientation parameters and the object points are required in bundle adjustment. All observations are used in a simultaneous least squares adjustment to estimate the unknowns. There are two groups of unknowns, the exterior orientation parameters at few orientation points and the coordinates of the object points. Furthermore, the observations are the image coordinates of object points. The reduced normal equations containing only the unknown exterior orientation parameters shows a band structure. Because of the non-linearity of the problem, several iteration steps are necessary.

3.3 Mathematical model of bundle adjustment using MOLA DTM as control information

Starting point of this discussion about DTM data as control information is the approach of (Strunz, 1993). This approach describes the use of DTM as additional or exclusive control information for aerial triangulation. (Strunz, 1993) investigates the conditions for datum determination by exclusive use of DTM. Finally, by means of simulations they analyse the accuracy achievable with DTM as control information which don't have to be identified in the images. Transferring this approach to the case of Mars Express and HRSC means that, the control information is the surface defined by MOLA DTM and HRSC points lie on these surfaces. A drawback of this approach is that it does not use the original MOLA track points but interpolated DTM points. The advantage of this approach is that the effort to search for adequate neighboring MOLA points is reduced because the DTM has a regular grid structure (Ebner et al., 2004, Spiegel et al., 2005).

This approach use a least squares adjustment with additional conditions to get a relation between a DTM and the HRSC points. As already mentioned, the HRSC points have to lie on a bilinear surface defined by four neighboring MOLA DTM points, which enclose the HRSC point (see Fig. 3). This condition can be formulated as a constraint on the vertical distance d from the HRSC point to the bilinear surface. Furthermore, this constraint can be substituted by a fictive observation, used as additional observation in the bundle adjustment.

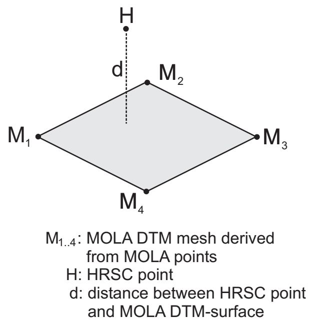

Figure 3: Fitting HRSC point in bilinear surface defined by MOLA DTM

The mathematical model for this observation equation is given in (Equation (2)).

$$\hat{v}_d + d = f(\hat{X}_H, \hat{Y}_H, \hat{Z}_H, X_{M_i}, Y_{M_i}, Z_{M_i}) \qquad (2)$$

For each equation the number of unknowns is three $(\hat{X}_H, \hat{Y}_H, \hat{Z}_H)$. It contains one observation ($d = 0$) and twelve constants ($X_{M_i}, Y_{M_i}, Z_{M_i},\ i = 1...4$). The standard deviation σ_d will be determined by the standard deviations of four MOLA DTM points M_1, M_2, M_3, and M_4. Thus, the implementation of the least squares adjustment with observation equations only is quite easy.

With this approach an improvement of the height (Z) can be expected, of course. An improvement in planimetry (X, Y) can only be determined, if there are different local terrain slopes at the different MOLA surfaces (Ebner and Ohlhof, 1994).

4 DIFFERENT IMAGING CASES

In this section the focus of this approach is on two different imaging cases. The first case deals with the number of extracted image coordinates of tie points. Second, the improvement of exterior orientation by using MOLA DTM registration is investigated with respect to the terrain slope.

4.1 Dependence on number of image coordinates of tie points

In General, the number of image coordinates of tie points depending on texture and length of the image strip. The number of object points can differ between about 500 and more as 50000 in one stereo imagery. Here, the orbit h2025_0000 (see Fig. 4) with 50000 matched object points is chosen. The Bundle adjustment is processed with a variation of object point density ranging from 100 to 50000 points.

The bundle adjustment results without using a DTM (see Fig. 5) show, that the theoretical standard deviation of object points is independent of the amount of used object points. The lower accuracy of Z in comparison with X/Y depends on the the geometry of the HRSC.

After bundle adjustment using a DTM the accuracy of object points will be quite different (see Fig. 6). Using only a few 100 points the accuracy of X/Y is very bad. With the increasing number of object points the accuracy will be better. The registering to MOLA DTM in component Z is possible with a few of 100 points and will be not better using more as 1000 points.

Figure 4: Orbit h2025_0000

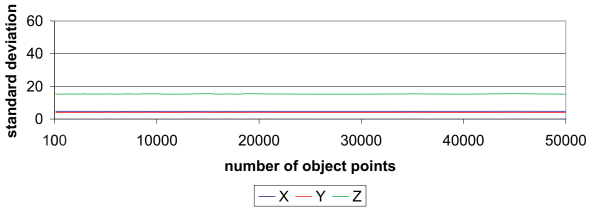

Figure 5: Bundle adjustment results without using DTM

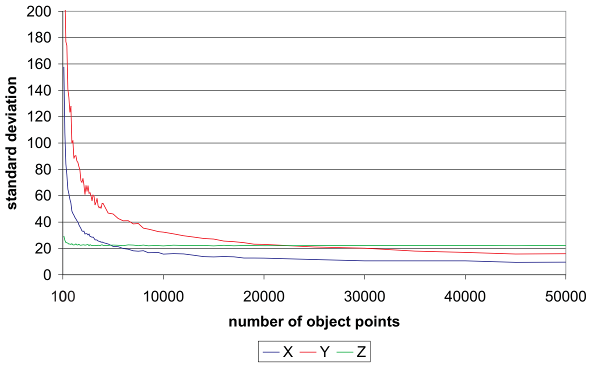

Figure 6: Bundle adjustment results using DTM

4.2 Dependence on terrain slope using DTM as control information

The improvement of exterior orientation by using MOLA DTM registration is investigated with respect to the terrain slope. In this case all successful adjusted exterior orientation data are used. The terrain in these data have different mean terrain slopes. In most of cases the terrain have mean slopes from 5 to 15 percent.

The results of the plane components X/Y (see Fig. 7) showing an increasing accuracy for increasing terrain slopes. Fig. 8 shows, that the height accuracy is independently of terrain slopes.

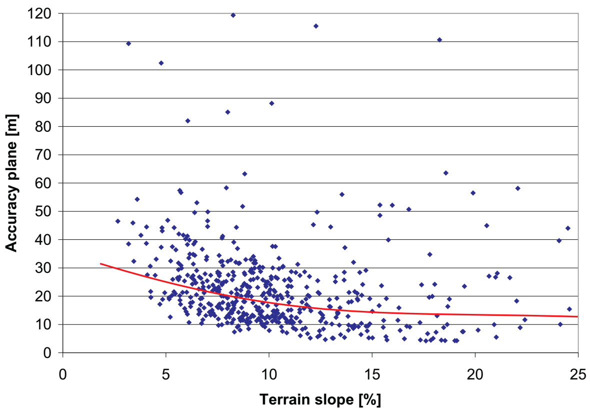

Figure 7: Different terrain slopes and resulting accuracy in plane

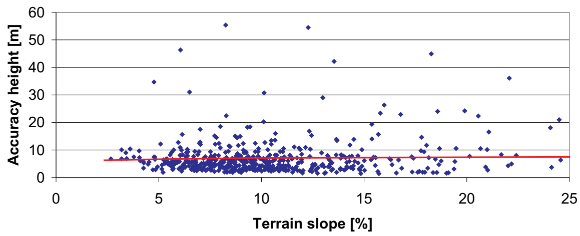

Figure 8: Different terrain slopes and resulting accuracy in height

All these results are equivalent to theoretical results showing in section 3.3.

5 PROCESSING OF HRSC IMAGERY

The results of bundle adjustment with the MOLA DTM as control information is presented in Section 3. The a priori accuracy has been introduced into the bundle adjustment with a value of 1000 m for the position and 25 mdeg for the attitude. One whole trajectory of the orbiter is considered to be very stable. Therefore, only a bias over the whole trajectory will be corrected. The MOLA DTM is introduced with an accuracy of 100 m instead of 10 m in order to cope with differences between HRSC object points and MOLA track points due to the limited spatial resolution of MOLA. As mentioned before, the resolution on ground of HRSC is up to 12 m compared to the MOLA surface footprint of about 168 m. Regarding local areas, the MOLA data describe the surface less detailed as HRSC object points.

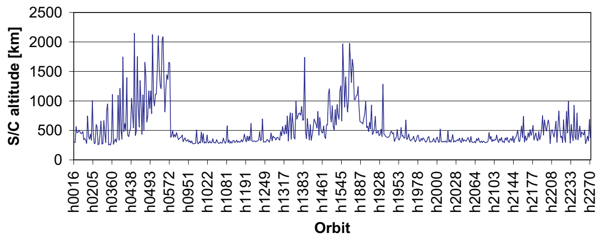

Figure 9: S/C altitude for each orbit

The bundle adjustment process is divided in two parts. First, there is a bundle adjustment without control information. The reason for this part is to improve the angles φ and κ along the entire orbit and point out possible matching problems by a robust adjustment. The second part is to register HRSC object points to MOLA DTM with a bundle adjustment using MOLA as control information. Here, all six parameters of the exterior orientation $(X_0, Y_0, Z_0, \varphi, \omega, \kappa)$ have been improved along the trajectory.

The current state of the investigation of all HRSC imagery is in June 2006: a photogrammetric point determination is possible for 750 orbits recorded between January 2004 and October 2005. Successfully registered to MOLA DTM are 544 orbits (73%). The S/C altitude is in most cases fewer as 500 km and can increase up to 2000 km (see Fig. 9).

5.1 Bias of improved exterior orientation parameters

Fig. 10, 11, and 12 show the improved bias of the positions for all orbits. The average of all image strips is for X = 220 m, for Y = 151 m, and for Z = 98 m. Furthermore, there is no identification for a systematic or periodic error. Because a lot of orbit corrections from the beginning of the mission to orbit about h0572 and short before and after the deployment of MARSIS (h1545 - h1887) the orbit determination by ESA is worse.

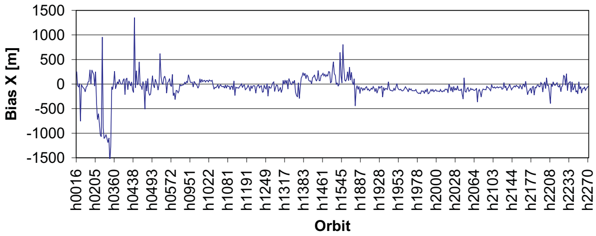

Figure 10: Bias X

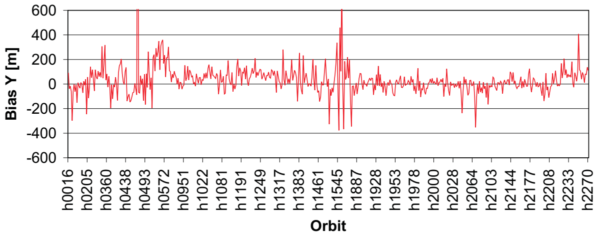

Figure 11: Bias Y

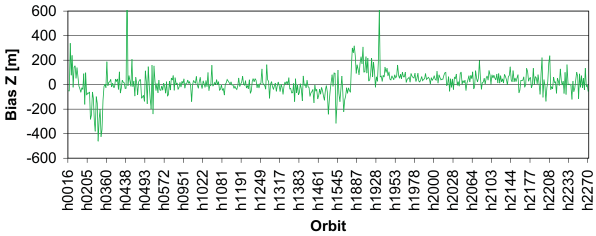

Figure 12: Bias Z

Fig. 13, 14, and 15 represent the improved bias of the attitude for all orbits. In detail, Fig. 15 shows periodic improvements of the bias parameter κ of the exterior orientation. The reason for these attitude deviations is given by the two star trekker cameras and a different misalignment of each star trekker camera. During the mission, at several times the star trekker camera A switch to star trekker camera B.

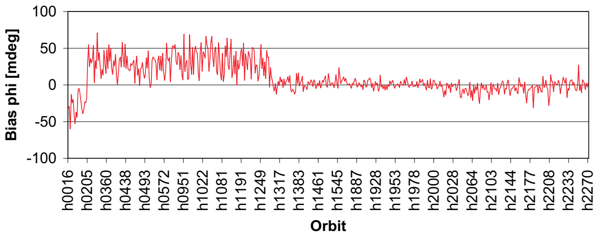

Figure 13: Bias φ

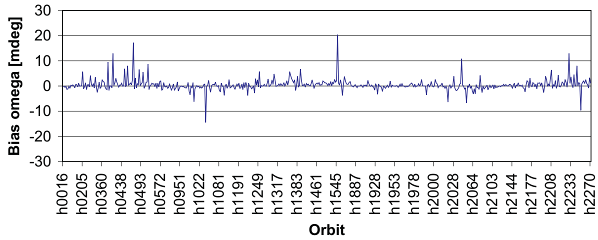

Figure 14: Bias ω

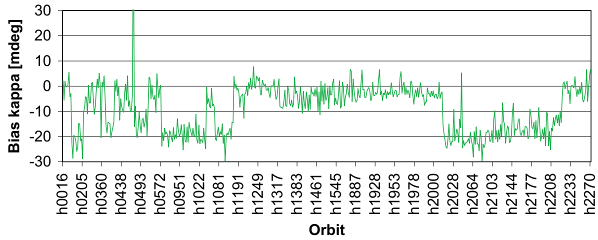

Figure 15: Bias κ

5.2 Accuracies of object coordinates

The accuracies of the coordinates of the object points for the orbits are shown in Fig. 16, 17, and 18. They depend mainly on two factors. First, there are the accuracies of the ray intersection determining the accuracies within the orbit itself. Second, there are the accuracies of the absolute exterior orientation parameters determined with MOLA DTM. Thus, the precision of the point determination is a combination of these both accuracies. The absolute accuracies of the object points in the dimensions X and Y are between 10 and 50 m.

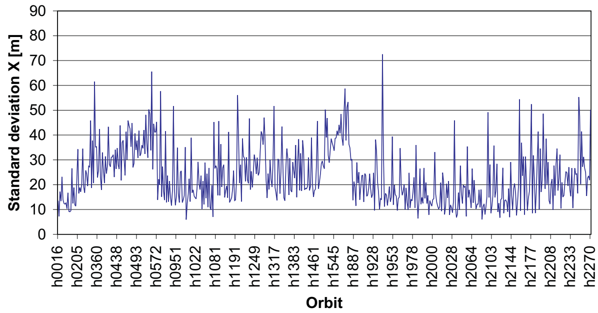

Figure 16: Accuracy of object points in X dimension

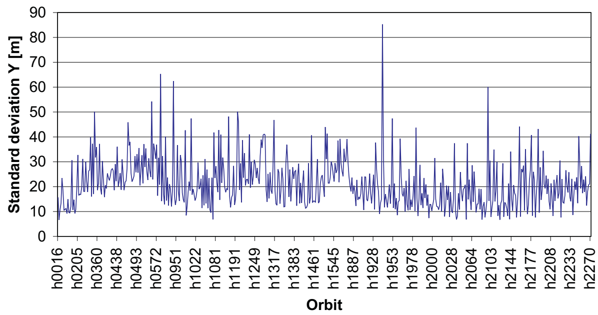

Figure 17: Accuracy of object points in Y demension

The accuracy of the dimension Z is between 20 and 80 m. Regarding to all tree dimensions there are a high correlation between the accuracies of object points and the S/C altitude (see Fig. 9).

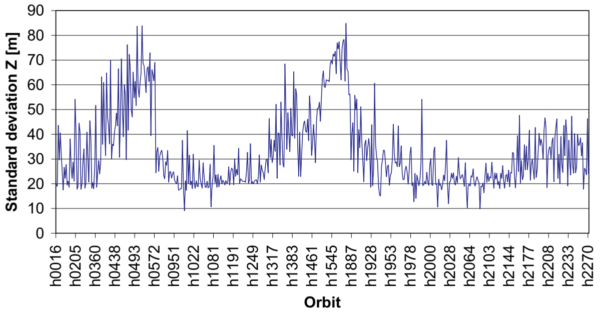

Figure 18: Accuracy of object points in Z dimension

6 CONCLUSION

The results show the potential of the image matching and bundle adjustment approaches to achieve an improved exterior orientation with MOLA DTM as control information. The average correction of all image strips is for X = 220 m, for Y = 151 m, and for Z = 98 m. The improvement of the attitude is in the range of 25 mdeg and fewer.

The examples are showing, that the approach to register the object points to MOLA DTM is dependent of the terrain slopes of each orbit. Also, the number of image coordinates of tie points is important for registering to DTM. Thus, after the bundle adjustment the object coordinates of the tie points have a very high absolute 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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