

PHOTOGRAMMETRIC POINT DETERMINATION USING DIGITAL GALILEO SSI IMAGES FROM ASTEROID IDA

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ABSTRACT

The paper deals with the photogrammetric point determination using digital images of the asteroid 243 Ida, which were acquired during the second asteroid flyby of the Galileo spacecraft in August 1993. The photogrammetric point determination was carried out with three different methods: Forward intersections assuming error-free orientation parameters, bundle adjustment without orbital constraints, and bundle adjustment including orbital constraints. The forward intersections lead to poor results, since, in fact, the orientation parameters of the images are not error-free. Thus the functional model has significant systematic errors. Much better results could be achieved by the conventional bundle adjustment, where the exterior orientation parameters were treated as unknowns in the collinearity equations and, in addition, introduced as direct observations. The best results were obtained from the bundle adjustment with orbital constraints. This approach guarantees that all exposure stations are lying on a physically consistent trajectory. With the help of the image and orbit information from the Ida flyby the efficiency of the bundle adjustment incorporating orbital constraints was clearly demonstrated.

1 INTRODUCTION

At Oct 18, 1989, the NASA spacecraft Galileo was launched from the Space Shuttle Atlantis to explore Jupiter, who was reached at Dec 8, 1995. During the flight to Jupiter was the opportunity to have a short rendezvous with the small S-type asteroid 243 Ida, where a set of high-resolution images of Ida's surface were recorded. At all, 79 images of the asteroid were obtained by the Solid-State Imaging (SSI) camera of the spacecraft. The camera consists of 800×800 sensor elements with $15 \times 15 \mu m^2$ size each (Belton et al. 1992). Due to the very large focal length of 1.5 m the field-of-view of the camera is extremely narrow ($0.5^\circ \times 0.5^\circ$). During the 5 h flyby the Galileo spacecraft passed Ida at a minimum distance of 2390 km, and the ground pixel size of the images varies between 25 m and 1740 m. A first analysis of the images showed that Ida is an odd-shaped body with a size of approximately $30 \times 12 \times 10 \text{ km}^3$ (Figure 1).

2 PREPROCESSING

From the photogrammetric point of view only 27 images are useful, covering one hemisphere of Ida. Within these images 768 image points of 81 tie points were measured interactively and introduced into the bundle block adjustments with $\sigma = 10 \mu m$ (0.7 pixel). The points are typically located in the center of craters.

The measured pixel coordinates were transformed into image coordinates using the interior orientation parameters derived from a star calibration. To this end, star locations of the Pleiades star cluster were measured in the images and interior orientation parameters were estimated in a least-squares adjustment (Davies et al. 1994). Besides the 3 image orientation angles, the calibrated focal length $c = 1500.467 \text{ mm}$ and the radial distortion coefficient $k = -0.00002498 \text{ mm}^{-2}$ were determined in the least-squares adjustment in the order of 0.1 pixel accuracy.

The pixel coordinates (*row*, *col*) can then be transformed by

$$x = ps(col - 400.5) \quad (1)$$

$$y = ps(row - 400.5) \quad (2)$$

$$u_x = x(1 + kr^2) \quad (3)$$

$$u_y = -y(1 + kr^2) \quad (4)$$



Figure 1: Part of image #0202562339 (left) and image #0202562439 (right)

with

$$r^2 = x^2 + y^2 \quad (5)$$

where ps is the pixel size ($15.24 \mu\text{m}$) and (u_x, u_y) denotes the image coordinates.

The orbit determination of the spacecraft was based on S-Band Doppler tracking, where the orbit has an accuracy of about 500 m (position) and $0.5 \frac{\text{m}}{\text{s}}$ (velocity), respectively. The attitude parameters of the images were derived from star images and are given with an accuracy of about 0.03° .

The origin of the Ida-fixed reference system coincides with Ida's center of mass, the Z -axis is parallel to the spin axis and the X -axis lies in the prime meridian plane intersecting the surface at the crater Afon (Davies et al. 1996). The crater Afon has been chosen arbitrarily, and serves as an error-free ground control point (GCP) in Y for the definition of the global datum. The forward intersections and the conventional bundle adjustment were performed completely in the Ida-fixed reference system, while the bundle adjustment with orbital constraints makes also use of the inertial coordinate system J2000. The rotational parameters of Ida are the link between the inertial and the body-fixed reference system. The rotational parameters $\omega = (\alpha, \delta, \psi, \dot{W}_0, \dot{W})$ are known with a certain accuracy according to Davies et al. (1996).

3 POINT DETERMINATION

The photogrammetric point determination was carried out with three different methods:

- Forward intersections assuming error-free orientation parameters
- Bundle adjustment without orbital constraints
- Bundle adjustment including orbital constraints

3.1 Forward intersections

Forward intersections are the simplest way to compute object coordinates of tie points. To this end, the collinearity equations had been set up for all image coordinate measurements ($\sigma = 10 \mu\text{m}$), where the exterior orientation parameters of the images were treated as constant values. The exterior orientation parameters were taken from the orbit and attitude data and transformed into the Ida-fixed system using the rotational parameters of Davies et al. (1996). This point determination method lead to poor results, since, in fact, the orientation parameters of the images are not error-free. Thus the applied functional model has significant systematic errors. The achieved standard deviations of the object point coordinates (rms-values) amount to 750 m in X , 1290 m in Y and 1030 m in Z .

3.2 Conventional bundle adjustment

In the conventional bundle adjustment observation equations were formulated for the image coordinates ($\sigma = 10\mu\text{m}$), position parameters ($\sigma = 500\text{ m}$) and attitude parameters ($\sigma = 0.03^\circ$) of the 27 images. The position and attitude parameters were transformed into the Ida-fixed coordinate system using Davies' rotational parameters. Two different cases were investigated: In the first case no GCP was used, whereas in the second case the crater Afon was introduced as a GCP ($Y = 0\text{ m}$ with $\sigma = 0\text{ m}$).

The results of the two bundle block adjustments are summarized in Table 1. It can be seen that the position parameters were improved ($\hat{\sigma} = 370\text{ m}$) in contrast to the attitude parameters ($\hat{\sigma} = 0.035^\circ$). The accuracies for the object point coordinates are much better compared to the forward intersections. Using the GCP the standard deviations amount to about 600 m in X , 190 m in Y and 830 m in Z .

# GCP	$\hat{\sigma}_0$	Residuals [rms]		$\hat{\sigma}$ [rms]				
		Position [m]	Attitude [$^\circ$]	Position [m]	Attitude [$^\circ$]	X [m]	Y [m]	Z [m]
0	0.76	131	0.030	373	0.034	589	1081	826
1	0.77	164	0.034	379	0.035	595	189	828

Table 1: Results of conventional bundle adjustment

3.3 Bundle adjustment with orbital constraints

In the conventional bundle adjustment approach without orbital constraints all image positions are treated as independent of the flight behaviour of the spacecraft. The advanced bundle adjustment approach, however, exploits the fact that the spacecraft proceeds along an orbit trajectory and all camera positions lie on this trajectory. To this end, the position parameters of each individual image are now replaced by the 6 parameters of the epoch state vector. The rigorous incorporation of orbital constraints into the bundle adjustment has been realized and successfully applied to practical MOMS-02/D2 and simulated HRSC/WAOSS Mars96 multi-line imagery for the first time (Montenbruck et al. 1994, Ohlhof 1996). This approach was also tested with Viking data of planet Mars (Zeitler 1999). Since the influence of Ida's gravitational field is below the precision of the ground-based S-Band Doppler tracking observations, the spacecraft orbit can be described by a simple linear model (Gill et al. 1995). The three velocity components of the epoch state vector can be therefore treated as nearly constant ($\sigma_v = 0.001\frac{\text{m}}{\text{s}}$). The position components of the epoch state vector were introduced into the bundle adjustment as direct observations with ($\sigma_p = 500\text{ m}$). The image coordinates, attitude parameters and GCP coordinates were incorporated as observations in the same way as in the conventional bundle adjustment. The rotational parameter W_0 which is related to the prime meridian of Ida was estimated as a free unknown in the adjustment to avoid discrepancies with the GCP. The other rotational parameters were introduced as direct observations with the standard deviations given by Davies et al. (1996).

The results of the bundle block adjustment are listed in Table 2. The 6 orbit parameters could only slightly be improved in the adjustment, but the attitude parameters were improved by factor 2.5. The standard deviations of the estimated object point coordinates amount to 460 m in X , 180 m in Y and 300 m in Z , which is a significant improvement compared to the results of the conventional bundle block adjustment, especially in X and Z .

# GCP	$\hat{\sigma}_0$	Residuals [rms]			$\hat{\sigma}$ [rms]					
		Pos. [m]	Vel. [$\frac{\text{m}}{\text{s}}$]	Att. [$^\circ$]	Pos. [m]	Vel. [$\frac{\text{m}}{\text{s}}$]	Att. [$^\circ$]	X [m]	Y [m]	Z [m]
1	0.73	1810	0.0003	0.033	342	0.0007	0.013	463	175	297

Table 2: Results of bundle adjustment with orbital constraints

4 SUMMARY AND CONCLUSIONS

In Table 3, the rms values [m] of the standard deviations of the estimated object point coordinates are summarized for the 3 different cases. Poor results were achieved in case of the simple forward intersections. Much better results could be obtained by the conventional bundle adjustment, where the exterior orientation parameters were treated as unknowns in the collinearity equations and, in addition, introduced as direct observations. The best results were achieved from the bundle adjustment with orbital constraints. This approach guarantees that all exposure stations are lying on a physically consistent trajectory, and the reduced number of unknown exterior orientation parameters stabilizes the solution of the normal equations.

With the help of the image, attitude, ground control and orbit data from the Ida flyby the efficiency of the bundle block adjustment incorporating orbital constraints was clearly demonstrated. This method can be recommended also for other extraterrestrial missions.

	<i>X</i> [m]	<i>Y</i> [m]	<i>Z</i> [m]
Forward intersections	750	1290	1030
Conventional bundle adjustment	600	190	830
Bundle adjustment with orbital constraints	460	180	300

Table 3: Rms values of the standard deviations of the estimated object point coordinates

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