PHOTOGRAMMETRIC PROCESSING OF DIGITAL GALILEO SSI IMAGES FROM ASTEROID IDA

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ABSTRACT

This paper deals with the photogrammetric processing of digital SSI images, which were acquired during the second asteroid flyby in August 1993. The ground pixel size of the images varies between 25 m and 1,740 m. The results of the photogrammetric processing comprise a ground control network and a DTM covering one hemisphere of Ida. The control net consists of 96 points with an (interior) accuracy of 180 m. Based on the control net and on 7,300 ground points derived from digital image matching a $1° \times 1°$ DTM was obtained using a sphere as reference surface. The DTM represents the global surface characteristics quite well, as verified by comparison with the images.

1 INTRODUCTION

79 images of the S-type asteroid 243 Ida and its satellite Dactyl were obtained by the Solid-State Imaging (SSI) camera in the course of the second Galileo asteroid flyby in August 1993. During the 5 h flyby the Galileo spacecraft (Figure 1) passed Ida at a minimum distance of 2,390 km. The ground pixel size of the images varies between 25 m and 1,740 m. These images provide a novel opportunity for direct measurements of the size, shape and motion as well as possibly also for mass and density of Ida. However, precise estimates of size and shape cannot be achieved easily, as the images have different ground resolutions and show the odd-shaped asteroid rotating under varying illumination conditions. Unfortunately, the available orbit and attitude information of the spacecraft as well as the ephemeris of Ida are of limited accuracy. Hence, a combined evaluation of all images together with the navigational information is required to extract the geometrical and physical parameters of the asteroid.

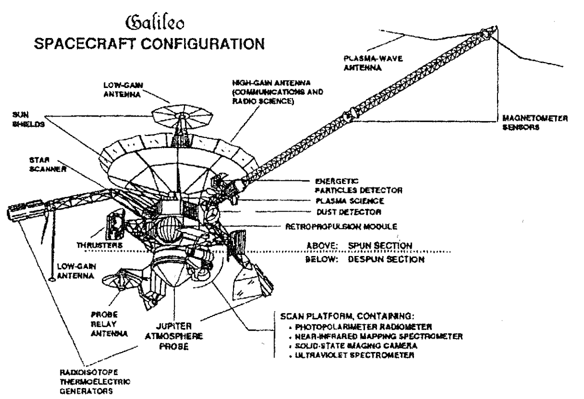

Figure 1: Galileo spacecraft with the SSI camera mounted on a scan platform

The shape of asteroid Ida, which is a member of the Koronis family, is more irregular than that of any solar system object previously imaged by spacecraft. The radii from the center of figure to the terrain surface range from 3.8 km to 32 km, and the axes of a triaxial fit ellipsoid amount to 29.9 km, 12.7 km and 9.3 km (Thomas et al. 1995). A global $2° \times 2°$ shape model was derived from limb, terminator and shadow data and about 100 control points (Thomas et al. 1995).

2 PHOTOGRAMMETRIC PROCESSING OF SSI IMAGES

2.1 Data Flow

The data flow for the photogrammetric processing of SSI imagery and additional navigation data is shown in Figure 2.

The input data for photogrammetric processing are SSI image data and preprocessed navigation data. The images of Ida were taken by the 2-D SSI CCD camera consisting of 800×800 sensor elements with $15 \times 15\ \mu m^2$ size each. The spectral range extends from approximately 375 to 1,100 nm (Belton et al. 1992). Due to the very large focal length of 1,500 mm the field-of-view of the camera is extremely narrow ($0.5° \times 0.5°$).

The image orientation procedure comprises the manual

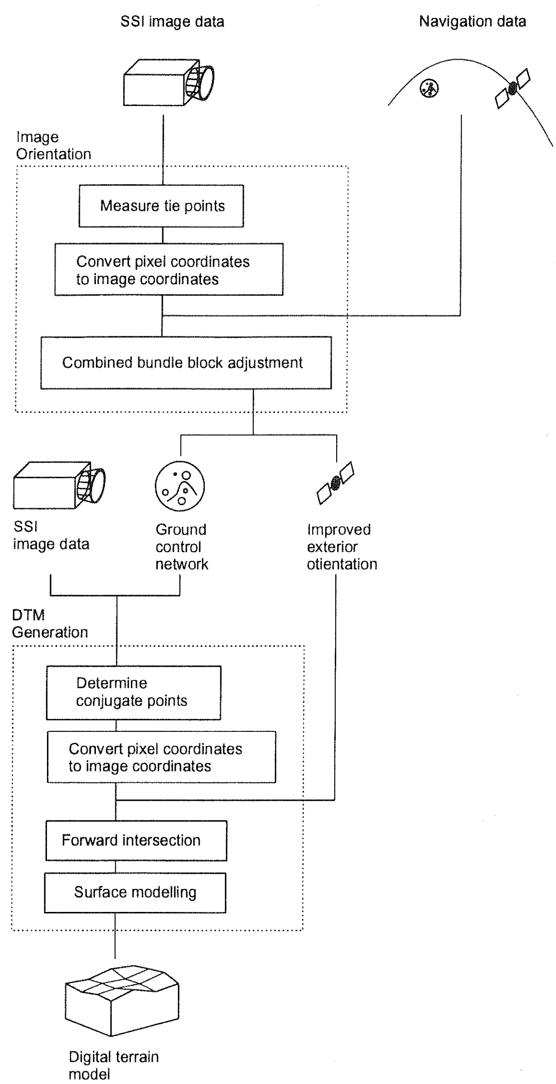

Figure 2: Data flow for photogrammetric processing

measurement of tie points as well as the combined block adjustment and provides improved exterior orientation parameters and a 3-D ground control network on Ida. For the acquisition of DTM primary data, digital image matching is applied leading to a large number of conjugate points in the images. With the help of improved exterior orientation parameters the image coordinates of conjugate points can be transformed into ground coordinates using forward intersections. Finally a DTM is generated using a sphere as reference surface.

2.2 Image Orientation

The first photogrammetric processing step involves the determination of a couple of tie points in the images. Point identification and point measurement were carried out by a human operator. All points are related to topographic features (mostly craters) on Ida's surface and are distributed uniformly on the ground surface in order to build up a dense global network.

Altogether 96 points were measured interactively in 36 images with a precision of 10 μm (0.7 pixel), where the ground pixel size ranges from 25 m to 600 m. The point identification was impaired by the varying image scale and by the fact that the asteroid rotated on its spin axis 235° during the time period covered by the images.

The following step is to convert the measured pixel coordinates into image coordinates taking the interior orientation into account. To this end, a geometric star calibration was carried out by measuring star locations of the Pleiades star cluster in the images and solving for free parameters in a least-squares adjustment (Davies et al. 1994). Besides the 3 image orientation angles, the calibrated focal length c = 1500.467 mm and the radial distortion coefficient $k = -0.00002498$ mm^{-2} were determined in the least-squares adjustment in the order of 0.1 pixel accuracy. This simple model is sufficient for images taken by narrow-angle cameras like SSI.

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

$$x = ps(col - 400.5) \qquad y = ps(row - 400.5) \qquad (1)$$

$$u_x = x(1 + kr^2) \qquad u_y = -y(1 + kr^2) \qquad (2)$$

with

$$r^2 = x^2 + y^2 \qquad (3)$$

where ps is the pixel size (15.24 μm) and (u_x, u_y) denotes the image coordinates.

In the next processing step, 3D ground coordinates of the tie points are determined and the exterior orientation (position and attitude) of all images is reconstructed in a bundle block adjustment. The block adjustment was performed in the Ida-fixed reference system, where the origin 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 defined by the crater Afon (Davies et al. 1995). The crater Afon was introduced as error-free ground control point (GCP) for the definition of the global datum.

Additional observation equations are formulated for preprocessed position and attitude data, which have been derived from S-Band Doppler tracking data and star images respectively. The relative accuracy of the position (attitude) data is assumed to be 100 m (0.1°), whereas the absolute accuracy amounts to 5 km (0.2°). In order to incorporate these navigation data into the bundle adjustment, they are transformed from inertial space into the Ida-fixed non-inertial coordinate system. The rotational parameters of Ida are treated as constants using the values of Davies et al. (1995).

The following data were introduced as observations:

- Image coordinates of 95 conjugate points and 1 GCP ($\sigma = 10\,\mu$m)
- Object coordinates of 1 GCP ($\sigma_X = \sigma_Y = \sigma_Z = 0$ m)
- Position parameters (x^c, y^c, z^c) for 36 images (σ = 100 m relative, σ = 5 km absolute)
- Attitude parameters (ϕ, ω, κ) for 36 images ($\sigma = 0.1°$ relative, $\sigma = 0.2°$ absolute)

The results of the bundle block adjustment are summarized in Table 1. After 6 iterations a $\hat{\sigma}_0$ of 7.8 μm was achieved. The rms value $\mu_{\hat{X}\hat{Y}\hat{Z}}$ of the theoretical standard deviations of the adjusted object point coordinates amounts to 180 m, which gives a measure of the interior accuracy of the block. The exterior accuracy of the block, however, is in the order of 4 km (= mean absolute accuracy of the adjusted position parameters).

		Value
$\hat{\sigma}_0$	[μm]	7.8
$\mu_{\hat{X}}$	[m]	289
$\mu_{\hat{Y}}$	[m]	99
$\mu_{\hat{Z}}$	[m]	64
$\mu_{\hat{X}\hat{Y}\hat{Z}}$	[m]	180

Table 1: Results of the bundle block adjustment

In addition, the coordinates of 33 object points have been compared with those, which were determined independently by M. Davies, RAND Corp., Santa Monica, USA (Davies et al. 1995). Both control networks correspond well, as the rms value of the coordinate differences $\mu_{\Delta X \Delta Y \Delta Z} = 200$ m indicate.

In a separate processing step, which has been not yet realized, the existing bundle block adjustment will be supplemented by a rigorous dynamical modeling of the spacecraft motion to account for orbital constraints (Montenbruck et al. 1994, Ohlhof 1996a). This advanced concept ensures the proper utilization of Galileo trajectory information in the bundle block adjustment and, vice-versa, allows the use of image information to improve the orbit determination and supports the estimation of dynamical parameters, e.g. the rotational parameters of Ida or the ephemeris of Ida's satellite Dactyl.

The incorporation of orbital constraints into the bundle adjustment has been first realized and successfully applied to practical MOMS-02/D2 and simulated HRSC/WAOSS Mars96 multi-line imagery (Ohlhof 1996b).

Based on a theoretical analysis of the Galileo spacecraft trajectory, Gill et al. (1995) have been found out, that a simple linear model of the spacecraft position w.r.t. time describes the orbital motion quite well. Within a 30 min interval around encounter time the deviations from the linear model due to Ida's gravitational field stay below 25 cm for the position and 0.1 mm/s for the spacecraft velocity, that was below the precision of the ground-based S-Band Doppler observations (2 mm/s).

2.3 DTM Generation

Third, a Digital Terrain Model (DTM) is generated. The DTM covers one hemisphere of Ida with a resolution of $1^\circ \times 1^\circ$, which can be interpreted as a shape model of the asteroid. It uses a sphere as reference surface.

DTM generation involves the determination of a large number of conjugate points in the images, the computation of ground coordinates for these points and the approximation of the object surface. Digital image matching is a suitable technique to find the required number of conjugate points automatically. Using the least squares *region-growing* matching algorithm (Otto, Chau 1989) about 32,000 image points on Ida's surface were found in 10 images having 30–110 m ground pixel size. The lower resolution (< 110 m ground pixel size) images of Ida are not suited for image matching, so that the conjugate points cover only one hemisphere of the asteroid. The tie points determined previously by the human operator are utilized as starting (seed) points for the matching procedure.

Special methods were developed for automatic point transfer in multiple images and for the consideration of scale differences between the images up to factor 3.5. In addition, 4,200 matched image points in deep space were deleted automatically as blunders using a given treshold value. After that, the computation of ground coordinates was carried out via forward intersection using the adjusted exterior orientation parameters.

The ground coordinates were processed using an approximation method for scattered data on a sphere (Brand et al. 1995; Brand, Fröhlich 1996). The height information of irregular distributed data points is transferred to a regular grid by calculating weighted means in a spherical cap around a grid point. Repeating this calculation for different radii of the spherical caps, the irregular data can be handled adequately. In a hierarchical algorithm these calculations are only done in regions in which the error is above a threshold. Note, that the radius of the spherical cap, which is comparable with the mesh size of the usual planar approaches, is fitted to the resolution of the data. The $1^\circ \times 1^\circ$ DTM, which is visualized in Figure 3, was calculated from the regular grid using the smoothing technique described above.

In Figure 3 an illumination from the upper left direction is assumed and the DTM is shaded using a Gourand shading algorithm. The part of Ida image s0202561900 presented in Figure 4 can be found on the upper left side of the DTM in Figure 3. Due to the scale of the DTM and the distribution of the DTM primary data, local features such as craters cannot be represented.

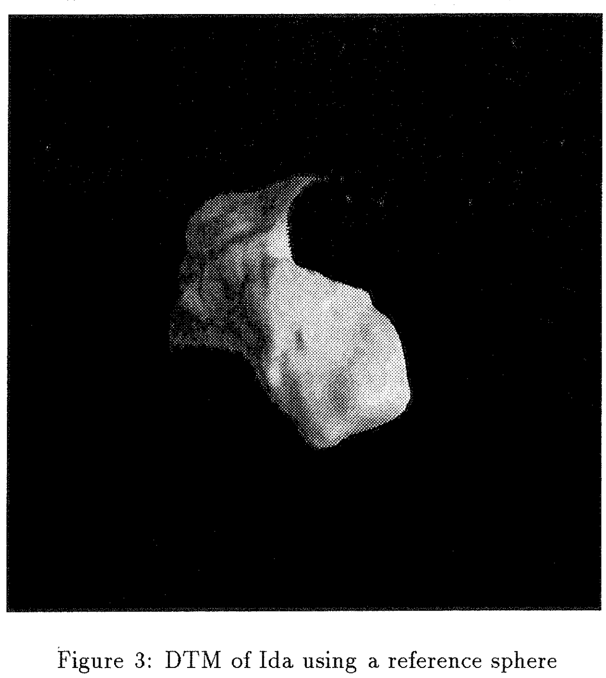

Figure 3: DTM of Ida using a reference sphere

With the help of digital terrain models, color orthoimages

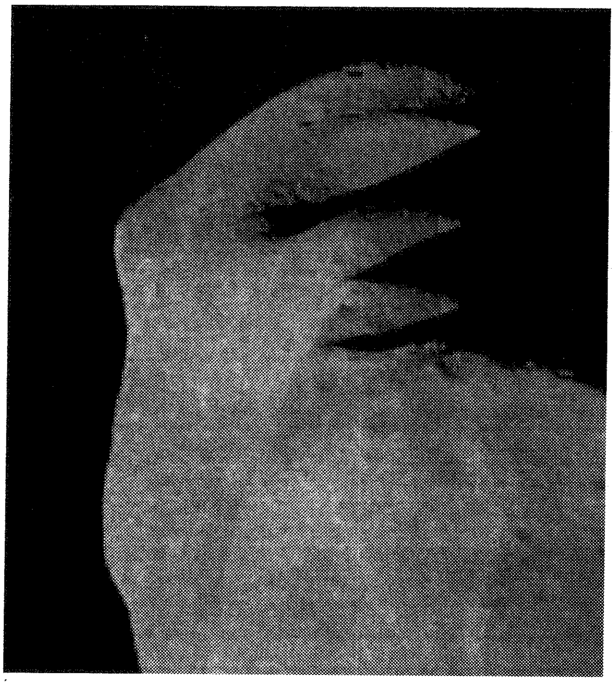

Figure 4: Part of Ida image s0202561900 (66 m ground pixel size)

may be generated using images with different spectral filters. What is more, precise photometric corrections will be possible, as the incidence and emittence angles of sunlight on the surface which are a prerequisite for the utilization of photometric functions, may be determined from the high resolution DTM. This will allow us to perform more precise spectral studies of the asteroid.

3 SUMMARY AND OUTLOOK

In this paper the photogrammetric processing of digital SSI images of asteroid Ida is described. The results of the photogrammetric processing comprise a ground control network and a DTM covering one hemisphere of Ida. The control net consists of 96 points with an (interior) accuracy of 180 m. Based on the control net and on 7,300 ground points derived from digital image matching a $1° \times 1°$ DTM was obtained. The DTM represents the global surface characteristics quite well, as verified by comparison with the images.

Goals of future investigations are

- to improve the rotation parameters of Ida,
- to determine the ephemeris of Ida's moon Dactyl,
- to improve the DTM by shape-from-shading techniques,
- to apply the developed methods to Galileo SSI images of Jupiter's satellites

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