THE TOGRAPHY OF ASTEROID IDA: A COMPARISON BETWEEN PHOTOGRAMMETRIC AND TWO-DIMENSIONAL PHOTOCLINOMETRIC IMAGE ANALYSIS

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ABSTRACT

We derived high resolution Digital Terrain Models from stereo images of the asteroid Ida that were obtained by the Galileo spacecraft during the flyby in August 1993 and compared these results with terrain models derived from two-dimensional photoclinometry. The comparison shows that there are striking discrepancies between the results from the two models depending on the spatial scale lenght of surface features. While photogrammetry resolves large- and medium-scale features, photoclinometry successfully resolves small-scale features. Ideally, both methods should be combined to optimize terrain modeling.

1. INTRODUCTION

Photogrammetry and photoclinometry (commonly termed "shape-from-shading") are complimentary methods to infer information on surface topography from image data. Traditionally, photogrammetry has been used to analyze aerial stereo imagery for many decades. More recently, photogrammetric methods also have been applied to images acquired by spacecraft orbiting the earth, such as the SPOT satellite and the SPACE SHUTTLE, as well as by deep space missions. With the availability of digital image data and digital processing techniques, our means to recover topographic data from imagery have improved significantly. In contrast, the "shape-from-shading" method was not fully developed until digital and radiometrically precise image data became available. The fact that photoclinometry can obtain topography using single images has made this method especially popular in planetary sciences, as space missions have data storage and transmission capacity too limited for multiple imaging, i.e., stereo coverage. In addition, it is often the properties of planetary surfaces with limited variations in albedo and the lack of atmospheres that make shape-from-shading analyses feasible.

The basic procedure in photoclinometry is to use observed pixel brightness to derive local slopes, from which topography can be generated by integration. There are two different approaches to photoclinometry: The one-dimensional model returns the topography along a linear profile for which, however, the topographic strike must be known in advance. The method was originally developed to determine the topography of lunar mare ridges the slopes of which are too gentle for the traditional shadow-lenght method to be employed (van Diggelen, 1951). It has since been used to analyze images from Mars (McEwen, 1985; Herkenhoff and Murray, 1990; Goldspiel et al., 1993) and the outer planet satellites (Squyres, 1981; Schenk, 1989; 1990). The two-dimensional approach to photoclinometry recovers the topography from the entire image, but requires a number of a priori knowledge of the surface properties. The technique was suggested for use in computer vision (Horn, 1975), and has also been used in planetary science (Kirk, 1987), but its popularity suffers from the complexity of the approach and the computational efforts to be taken.

In summer 1993, the Galileo spacecraft obtained images of the asteroid Ida (Belton et al., 1994). There is quite some interest in the topography of this planetary body, because of the implication for its geology (Sullivan et al., 1996). In this paper, we therefore present high-resolution terrain models of Ida determined by methods of photogrammetry and compare these with models derived from two-dimensional photoclinometry. Some of the latter were previously reported (Sullivan et al., 1996) and some are new. The results are discussed in terms of the limitations of both methods, and it is shown how a combined analysis could improve the results significantly.

2. DATA BASE

The Galileo spacecraft is equipped with the SSI framing CCD camera (800x800, f=1500.467 mm). During the Ida flyby, 57 images were obtained from distances between 236,000 km and 2,500 km with resolutions ranging from 2.4 km/pixel to 25 m/pixel (Belton et al., 1994), acquired in different spectral bands. However, the data base we used in this study comprises 36 images taken from ranges closer than 60,000 km acquired within a time period of 81 min. During this sequence Ida performed a rotation of 105°, which was essential for viewing of Ida from different perspectives and thus for having good stereo coverage.

Navigation data are available in an inertial frame with an accuracy of 2 km for spacecraft position and 2 mrad for camera pointing. To convert these to the Ida-fixed system we used the rotational elements of Ida that were derived in an earlier photogrammetric analysis of Galileo SSI images (Davies et al., 1996).

3. METHODS

3.1 Photogrammetry

The photogrammetric analysis of the image data was carried out in three different stages:

3.1.1 Adjustment of the image orientation parameters: The adjustment of the image orientation parameters was performed in the body-fixed frame of Ida (cf. Ohlhof et al., 1996). First, we identified 95 image points in the 36 images resulting in 883 image point measurements. Then, the image point coordinates and the observed camera navigation data were subjected to a least squares adjustment procedure, assuming that the errors of the observations are distributed at random. One ground control point of the existing control point network (Davies et al., 1996) was used, in addition. This turned out to be essential for the accuracy of the adjusted data. Object point coordinates agree with those of this previous network within 2%. We obtained a final accuracy of 0.5 pixels for image point coordinates (a priori accuracy: 1 pixel), 1 km for the spacecraft position data, and 0.1–1 mrad for the camera pointing data.

3.1.2 Determination of conjugate image points: We determined conjugate image points by an adaptive least squares correlation algorithm (Gruen, 1985) in which the pattern of grey values between patches in a reference and a search image are compared. This algorithm was suggested to be less sensitive against differing pixel resolution than cross-correlation (Förstner, 1995).

An optimum patch size must be chosen. The transformation between the image patches assumes that the surface viewed by the patches is approximately planar. This suggests that the patch size be small, as otherwise, smoothing effects in the terrain model, matching failures, or in the worst case, topography blunders occur. On the other hand, the prevalence of image noise and a required minimum of texture rather suggest to choose large patch sizes.

Matching of images from different spectral filters failed; therefore, only single-filter images were used to derive DTMs.

3.1.3 DTM generation: The coordinates of conjugate image points (in terms of line, sample) in the two stereo images were converted to ground coordinates (in terms of x,y,z) using adjusted navigation data and applying the co-linearity equations and least squares fitting. For comparison with the photoclinometry models, the resulting three-dimensional cloud of object points was then transformed into the frame of the image which the photoclinometry model was based on, i.e., x,y, and z were converted to line, sample, and height, where height is measured with respect to a plane parallel to the image plane that contains the center of Ida. Finally, a digital terrain model was interpolated in image space using the "inverse distance" approximation. This sometimes resulted in topography gaps if the number of points required for the interpolation was too small.

3.2 Two-dimensional photoclinometry

3.2.1 Approach: Topographic modeling of subareas of several Galileo images of asteroids by photoclinometry was previously carried out in order to facilitate crater-depth studies (Carr et al., 1994; Sullivan et al., 1996). The method used is the two-dimensional photoclinometry algorithm of Kirk (1987): The surface shape is parameterized with finite elements in image space; that is, the projection of each image pixel onto the surface is an "element" and the displacements, measured toward the camera, of the corners of the pixels are the topographic unknowns being solved for. Standard finite-element techniques are used to set up nonlinear equations relating the unknowns (displacements) to the knowns (pixel brightnesses) via the gradients of displacement and the photometric function. A number of numerical techniques are then used to solve these equations, such as iterative linearization of the nonlinear equations (i.e., the Newton-Raphson method), iterative solution of the linearized equations by the method of relaxation, as well as multi-gridding to speed convergence of long-wavelength portions of the topography.

Practical experience indicates that considerable judgement is needed to determine when to change the number of relaxation steps before relinearizing, the over/under-relaxation parameter, and the conditions for changing grid resolution. All models shown here were therefore generated with direct supervision of iteration.

As the photoclinometric equations are underdetermined, additional boundary conditions must be introduced. Here, we use a measure of the "roughness" of the surface model, $(dz/dx)^2 + (dz/dy)^2$, integrated over the surface, which is minimized at the same time that the image is modeled. The quantities in this squared gradient are in image coordinates; in particular, z is the displacement towards the camera.

Determination of when the solution has converged adequately could be problematic. In the multi-resolution algorithm, an estimate of the trunctation error, i.e., the unavoidable error introduced by coarsening the resolution, is generated at each resolution except the finest one. The truncation error can, however, be extrapolated to the finest resolution based on the others. Iteration was continued until the residuals were less than the truncation error at all resolutions.

3.2.2 Input Data: As the starting point of the iterations, a global model of the shape of Ida (Thomas et al., 1996) with 2 degree resolution was used. It was also used to estimate the surface scattering properties, i.e., the photometric function that relates surface slopes to the image brightness, to be used in the analysis. The global shape model was shaded with photometric functions combining the Lommel-Seeliger (lunar) and Lambert functions linearly in various proportions (McEwen, 1991), and the proportion that best fit each observed image was adopted to define the model photometric function for that image. This was consistent with Hapke's physically based scattering model (Hapke, 1993) with a low single-scattering albedo across a range of phase angles (McEwen, 1991). These results lend confidence that the surface scattering properties have been modeled adequately.

4. RESULTS

4.1 Photogrammetry models

We derived digital terrain models from two stereo pairs of images, respectively, in three distinct regions (termed I, II, and III in the following) in which photoclinometric terrain models were available (Fig.1). The first step of image correlation was carried out successfully throughout most of the study area. However, parts of region III show little texture and large distortions in the topography (see the scarp in the lower part of region III) which caused the matching to fail, and therefore resulted in gaps in the terrain model (Fig.4a).

The effect of patch sizes of 10, 14, 18, and 22 pixels on resulting topography was thoroughly analyzed: While large patch sizes of 18 and 22 pixels resulted in smoothing effects (i.e. small-scale features vanished and medium-sized craters became flater), the topography became noisy at a patch size of 10 pixels. We therefore selected a patch size of 14 pixels for the matching.

4.2 Comparison with photoclinometry models

The first inspection of the terrain models (Fig. 2a, 3a, and 4a) shows that photogrammetry and photoclinometry reflect the surface features seen in the images rather differently. The photoclinometry models are smoothly shaped but clearly show craters at large and small scale. The photogrammetry models are rough on small scale and resolve only large and medium sized craters. Moreover, the large scale topography seems to differ in both models, especially in regions I and II.

We attempted a more quantitative comparison between the two models and computed height profiles along specific image lines (Figs. 2b, 3b, and 4b). Apparently, height differences with respect to the regional trends of up to 600 meters occur (cf. Fig. 2a). Topography of some large-scale features such as the large crater in Fig.3b shows striking differences. This crater is more than 50% deeper in the photogrammetry model than in photoclinometry. Small-scale craters in the range of 10 pixels are fully recovered by "shape-from-shading" but are not seen in the photogrammetry models. Very small features covered by less than 5 pixels are not even resolved by photoclinometry.

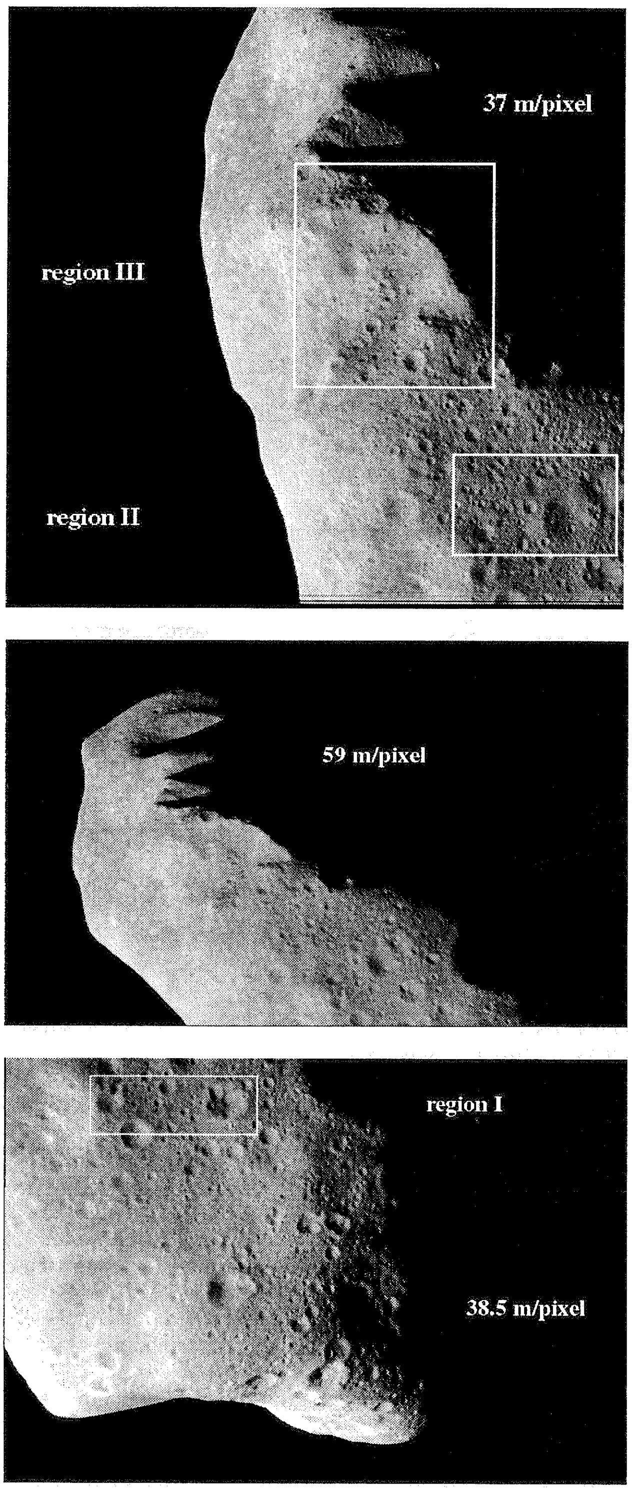

Fig.1: This figure shows the images involved in the matching procedure. The images at the top and bottom were taken as a reference, the search image is shown in the center of the figure. Only regions I, II, and III were considered for matching.

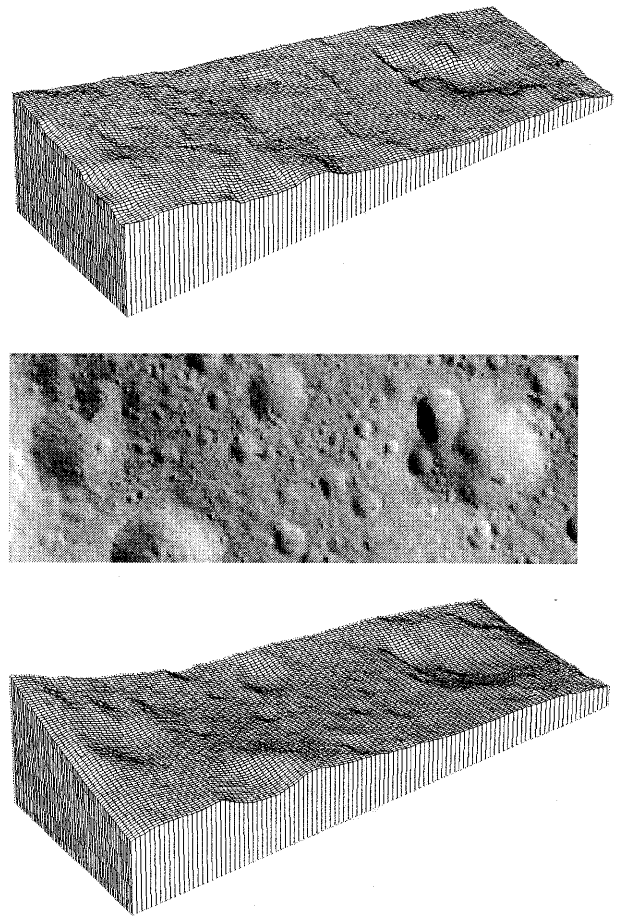

Fig.2a. Region I :terrain models derived from photogrammetry (top) and 2D photoclinometry (bottom).

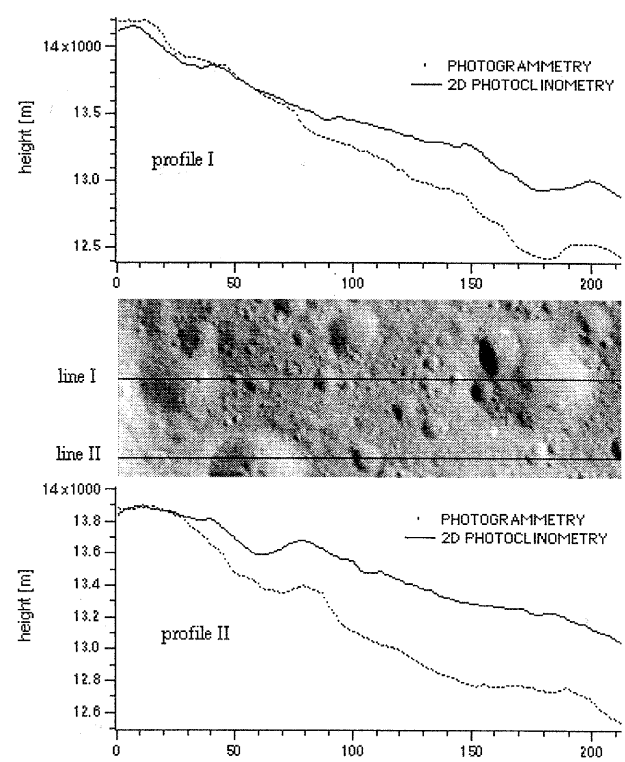

Fig.2b. Region I: height profiles along image lines

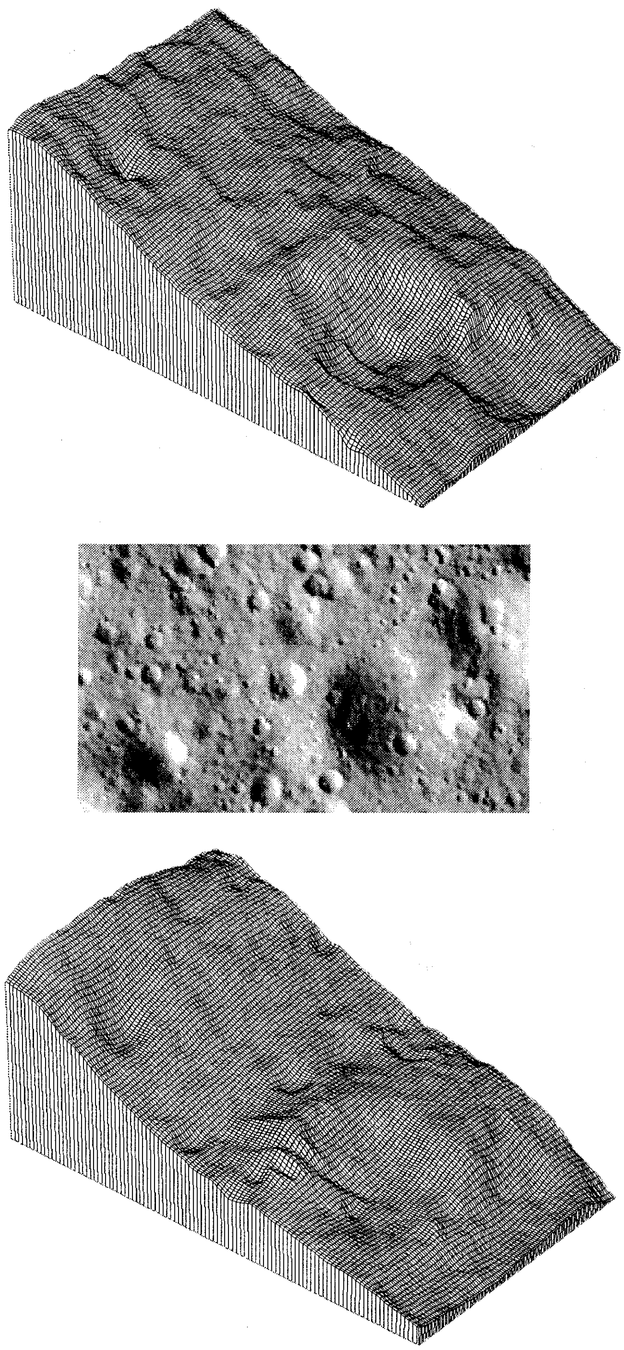

Fig.3a. Region II :terrain models derived from photogrammetry (top) and 2D photoclinometry (bottom).

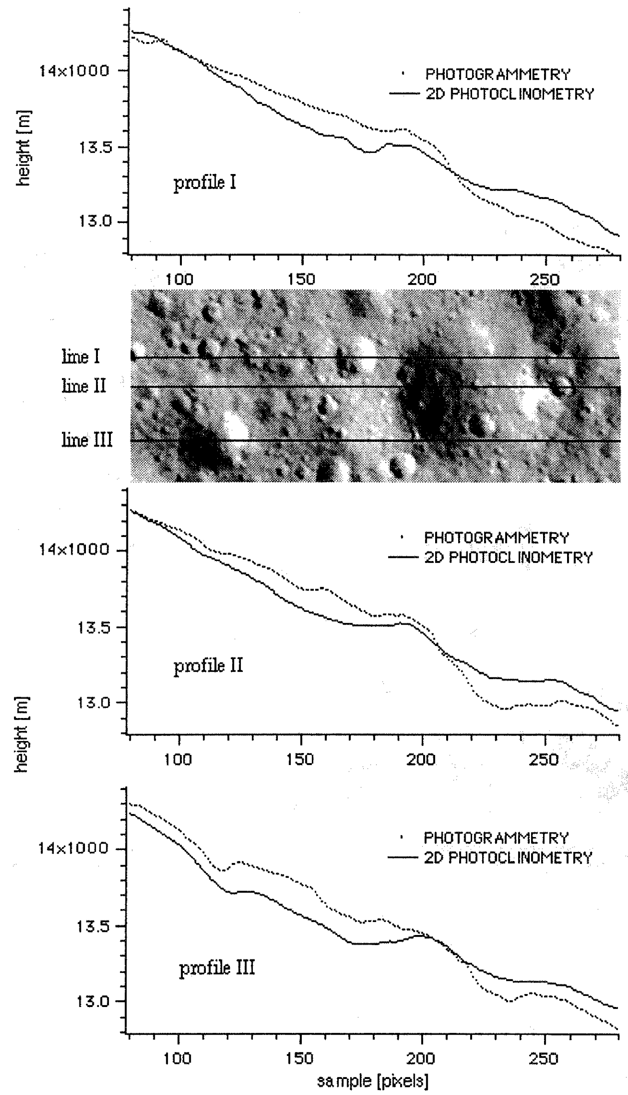

Fig.3b. Region II: height profiles along image lines

5. DISCUSSION

An admitted weakness of our approach is that we have no access to absolute „truth" concerning the configuration of Ida's surface. Hence, we have to restrict the discussion to the limitations of both models that give a priori arguments for the realiability of the data.

The most serious limitation in the photogrammetry models here is connected with the use of patches at the image correlation, as discussed in chapt. 3.1. This has in consequence that surface features with wave lenghts smaller than about 14 pixels are not resolved adequately. Especially, craters equal or smaller than this size are not resolved, and sharp rims of larger craters are smoothed (Fig.2b, 3b). Moreover, the use of patches tends to introduce small scale roughness in form of spurious „blocky" structures with steep slopes at the patch edges. So, what we can trust in only is the large scale topography, the small scale features are not reliable.

The photoclinometry models suffer mostly from two facts: First, it is assumed that albedo is constant across the considered part of image. This is because all contrast in the image data is interpreted in terms of topographic slopes to build the terrain model (note that for photogrammetry albedo features are appreciated because of enhancing the image texture). But for impact dominated surfaces it cannot be ruled out completely that albedo features are present due to spreading of fresh material over the surface. To cope with varying albedo, photoclinometry prefers images at oblique illumination, such that topography is the overwhelming source of contrast. Under the considered conditions this seems to be fulfilled. Nevertheless, albedo features remain a serious source of error.

To search for albedo features or to verify other model assumptions and parameters of the photoclinometry, we computed a number of shaded reliefs at different illumination. Inconsistencies will lead to artifacts in the derived topography, characteristically in the form of „stripes" in the up-and-down used a smooth photogrammetric terrain as the starting model for photoclinometry. It turned out that the large scale topography of the starting model remained unchanged, i.e. large craters were now as deep as in photogrammetry, but the small scale features that could not be resolved by photogrammetry were added. This method looks very promissing and will be discussed in more detail in a forthcoming paper.

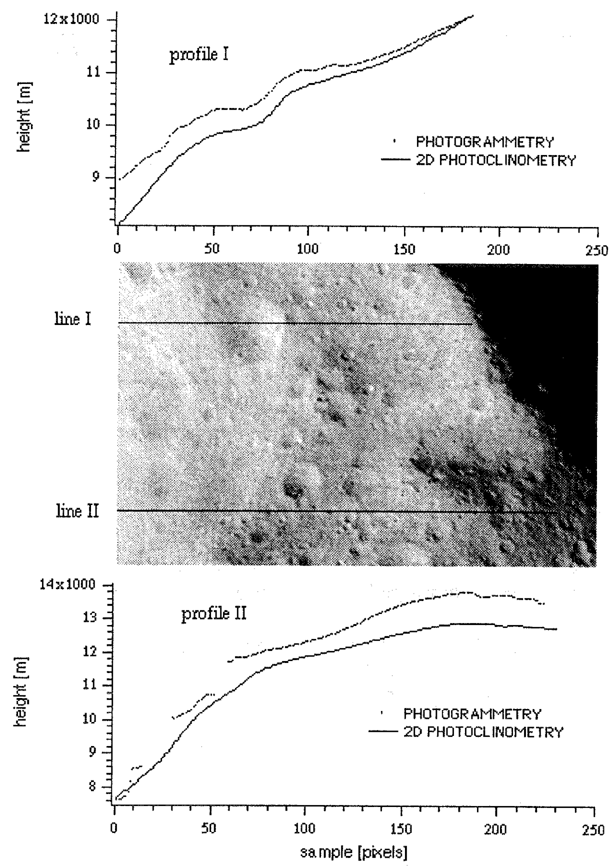

Fig.4b. Region III: height profiles along image lines

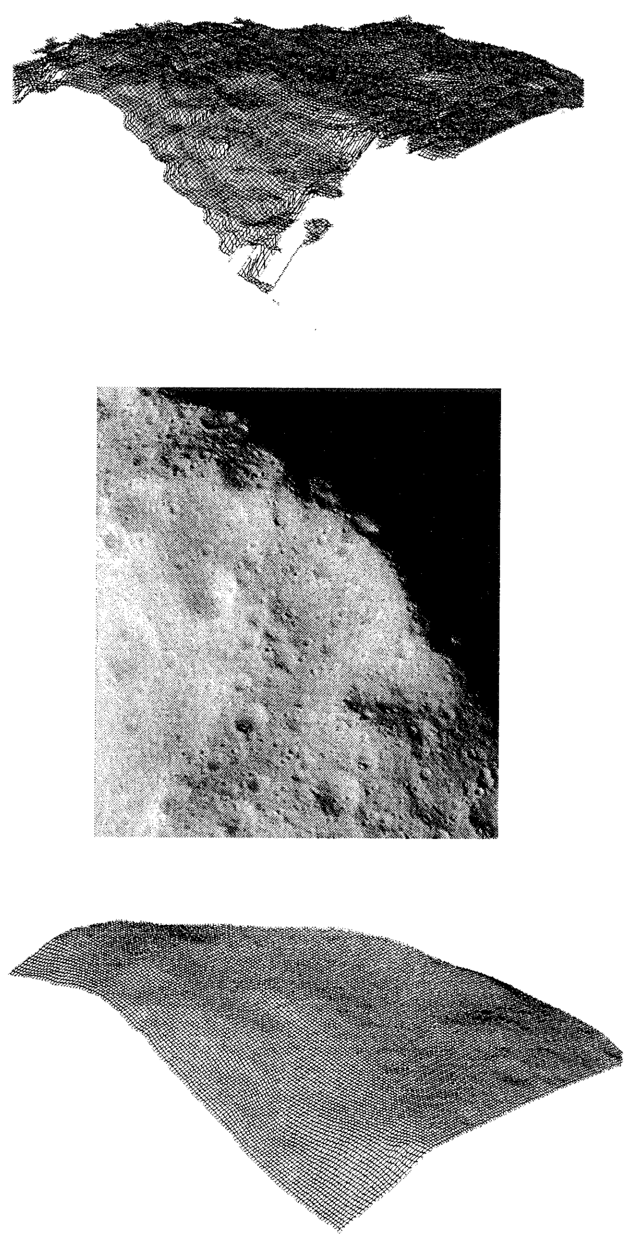

Fig.4a. Region III :terrain models derived from photogrammetry (top) and 2D photoclinometry (bottom).

sun direction. Indeed, we found evidence for albedo features in the shaded reliefs, e.g. at the rim of the large crater in Fig.3a. Second, the surface model used to start the iterations strongly effects the speed of convergence. Generally, small features converge before large ones, and the more the starting model is in accord with the real topography the faster convergence is reached. The iterations are stopped if the height residuals decrease below a threshold value. So, if the starting topography does not match the real topography on a large scale convergence is reached for small-scale features but not for large ones, allthough the residuals are small. Since the global shape model used as the starting surface model differs significantly from the large scale photogrammetric solution convergence was probably not reached for the large scale topography. This would explain why the large scale craters are much deeper in the photogrammetric models. Strong arguments for this explaination were obtained in a recent analysis, in which we

6. CONCLUSIONS

There are significant differences in the terrain models of Ida derived from photogrammetry and from two-dimensional photoclinometry. These differences are due to the limitations of both methods and can be classified in terms of spatial scale. The photogrammetrically derived terrain models are expected to reliably show surface features with scale lengths larger than the patch size. Smaller-scale topography is not adequately resolved. Especially, surface features with very high spatial frequencies such as scarps, may result in topography gaps or even blunders. In contrast, the two-dimensional photoclinometric analysis can resolve the small-scale surface features with a reliability determined by model parameters such as albedo and photometric function parameters. The large-scale topography is determined by the large-scale properties of the starting surface model, that is, with this respect it is reliable only as the starting model is.
Photogrammetry and two-dimensional photoclinometry in combination may give us terrain models much improved over those as of the two models alone.

REFERENCES

Belton, M.J.S., C. Chapman, J. Veverka, K. Klaasen, A. Harch, R. Greeley, R. Greenberg, J.W. Head III, A. McEwen, D. Morrison, P.C. Thomas, , M.E. Davies, M.H. Carr, G. Neukum, F.P. Fanale, D.R. Davis, C. Anger, P.J. Gierasch, A.P. Ingersoll, C.B. Pilcher, 1994. First images of asteroid 243 Ida. *Science,* **265**, 1543-1547.

Carr, M., R. Kirk, A. McEwen, J. Veverka, P. Thomas, J. Head,, and S. Murchie, 1994. The geology of Gaspra. *Icarus*, **107**, 61-71.

Davies, M.E., T.R. Colvin, M.J.S. Belton, J. Veverka, and P.C. Thomas, 1996. The direction of the north pole and the control network of asteroid 243 IDA. Submitted to *Icarus, in press*.

Förstner, W., 1995. Matching strategies for point transfer. *Photogrammetric Week' 95*, edited by Fritsche&Hobby, pp. 173-183.

Goldspiel, J.M., S.W. Squyres, and D.G. Jankowski, 1993. Topography of small martian valleys. *Icarus* **105,** 479-500.

Gruen, A.W. 1985. Adaptive least squares correlation: a powerfull image matching technique. *S Afr J of Photogrammetry, Remote Sensing, and Cartography* **14** (3), 175-187.

Hapke, B., 1993. Theory of Reflectance and Emittance Spectroscopy. Cambridge University Press.

Herkenhoff, K.E., and B.C. Murray, 1990. High-resolution topography and albedo of the south polar layered deposits on Mars. *J. Geophys.Res.* **95,** 14, 511-14,529.

Horn, B.K.P., 1975. Obtaining shape from shading information, in *The Psychology of Computer Vision.* edited by P.H. Winston, pp. 115-155, McGraw-Hill, New York.

Kirk, R.L., 1987. A fast finite element algorithm for two-dimensional photoclinometry, part III, Ph.D. theses, pp. 165-258, Calif. Inst. of Technol., Pasadena.

McEwen, A.S., 1985. Topography and albedo of Ius Chasma, Mars. *Lun. Planet. Sci.* XVI, 528-529.

McEwen, A.S., 1991. Photometric Functions for Photoclinometry and Other Applications. *Icarus*, **92**, 298-311.

Schenk, P.M., 1989. Crater formation and modification on the icy satellites of Uranus and Saturn: Depth/diameter and central peak occurrence. *J. Geophys. Res.* **94,** 3813-3832.

Schenk, P.M., 1990. Crater morphology and modification on Ganymede, Callisto, and Tethys. *Lun. Planet. Sci.* XXI, 1081-1082.

Squyres, S.W., 1981. The topography of Ganymede's grooved terrain. *Icarus, **46***, 156-168.

Sullivan, R., R. Greeley, R. Pappalardo, E. Asphaug, D. Morrison, J. Moore, M.J.S. Belton, M. Carr, C.R. Chapman, P. Geissler, R. Greenberg, J. Granahan, J.W. Head III, R. Kirk, A. McEwen, P. Lee, C. Thomas, J. Veverka, 1996. Geology of 243 Ida. Submitted to *Icarus, in press*.

Thomas, P.C., J. Veverka, B. Varcich, M..J.S. Belton, R. Sullivan, M.E. Davies, and the Galileo imaging team, 1996. The shape of Ida. Submitted to *Icarus, in press.*

Van Diggelen, J., 1951. A photometric investigation of the slopes and the heights of the ranges of hills in the maria of the Moon. *Bull. Astron. Inst. Neth.* **11,** 283-289.