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A new 3D reconstruction method of small solar system bodies

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Abstract

The 3D reconstruction of small solar system bodies consitutes an essential step toward understanding and interpreting their physical and geological properties. We propose a new reconstruction method by photoclinometry based on the minimization of the chi-square difference between observed and synthetic images by deformation of a 3D triangular mesh. This method has been tested on images of the two asteroids (2867) Steins and (21) Lutetia observed during ESA's ROSETTA mission, and it will be applied to elaborate digital terrain models from images of the asteroid (4) Vesta, the target of NASA's DAWN spacecraft.

1. Introduction

The 3D reconstruction of small bodies is required to characterize their global physical properties (volume, density, rotational parameters) and to perform geomorphological studies of their surface through the characterization of topographic features, such as craters, faults, landslides, grooves, hills, etc. Digital terrain models (DTMs) are further used to identify geological units. They are also an important input for thermal, photometric and hydrodynamic models.

Several techniques are used to retrieve 3D global shapes and/or DTMs from visible images obtained by visiting spacecrafts, either flybys or orbiters. The most accurate one "Shape-from-Shading" includes photogrammetry and photoclinometry [2], often used in conjunction with stereography. Stereophotogrammetry has been used to reconstruct the shape of several bodies, among them the nucleus of comet 19P/Borrelly [6]. Stereophotoclinometry (SPC) has allowed to retrieve an accurate shape of the asteroid (25143) Itokawa [1]. We present here a new photoclinometry method based on the deformation of a 3D triangular mesh.

2. Photoclinometry by deformation

Our 3D reconstruction method needs as input a starting shape model, described as a triangular mesh, and the parameters of the bi-directional reflectance of the surface elements [3]. It is based on the minimization of the chi-square difference between a set of observed images (typically from 4 to 16) and the corresponding synthetic images. The minimization is achieved by small deformation of the triangular mesh.

2.1. Deformation of the shape model

We use the two different deformation schemes described below. The first scheme relies on the parametrization of a triangular mesh shape model in terms of spherical harmonics as used since several decades [7]. In this description, a radius $R(\theta, \phi)$ is calculated for each direction (θ, ϕ) from a linear expansion in spherical harmonics involving linear coefficients. The vertices (R, θ, ϕ) form the triangular mesh. The deformation is performed via the coefficients of the spherical harmonics expansion and can only be used to retrieve global shape models.

We also introduce a more general deformation scheme in which we modify the height of individual vertices of the triangular mesh in the direction of the local normal to the surface. The slope of all the facets sharing the vertex are thus modified during the deformation. This scheme can be used both for global shape models and for local DTMs.

2.2. Optimization of the parameters

The goal is to minimize the reduced chi-square difference between the pixel values of the observed images and those of the corresponding synthetic images. The synthetic images are generated using a software tool called OASIS (Optimized Astrophysical Simulator for Imaging Systems) [4]. The terms in the chi-square are normalized by the instrumental noise of the individual pixels. The free parameters of the chi-square

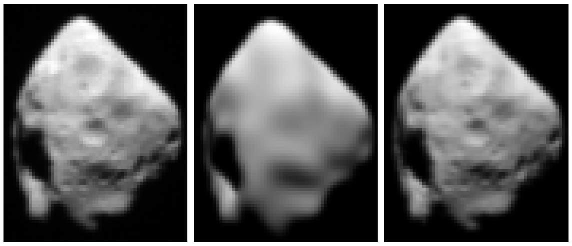

Figure 1: Illustration of the reconstruction methods used for asteroid Steins. Left panel: Observed image. Middle panel: synthetic image calculated from the spherical harmonics model. Right panel: synthetic image calculated from the final optimized model.

function can be either the coefficients of the spherical harmonics expansion or the heights of the vertices. The minimization is performed using a nonlinear optimization algorithm called "limited memory Broyden-Fletcher-Golbfarb-Shanno" (L-BFGS), a quasi-Newton method especially developed for large-scale optimization problems.

The method requires the calculation of partial derivatives of the chi-square with respect to the free parameters. In the case of the vertex-based deformation of section 2.1, we implemented a method allowing a very fast calculation of these derivatives. A typical number of $\sim 50-100$ iterations are required before it converges to a stable value of the free parameters.

For each pixel of the images, we calculate the residual value in units of the instrumental noise at the end of the optimization. From this value, we estimate a local error on the slope of each facet.

2.3. Applications

The Rosetta spacecraft flew by two asteroids, (2867) Steins in September 2008 and (21) Lutetia in July 2010. We have tested our method on images acquired by the OSIRIS instrument aboard the spacecraft. Fig. 1 shows its application on Steins. A good agreement is already achieved with the spherical harmonics model (middle panel). Deformations of the vertices at a smaller scale allow to recover the high-frequency information (right panel).

Fig. 2 shows the result of preliminary tests performed on a DTM of the asteroid Lutetia applying the vertex-based deformation. Our input model is a "maplet" (DTM) extracted from the SPC model constructed by Jorda et al. [5] based on the software developed by Gaskell [1] (middle panel). Here again, the high-frequency information is recovered (right panel).

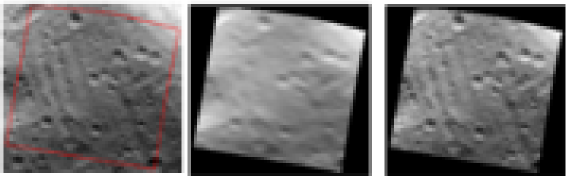

Figure 2: Illustration of the reconstruction method used on asteroid Lutetia. Left panel: Observed image. Middle panel: synthetic image calculated from Gaskell's shape model. Right panel: synthetic image calculated from the final optimized model.

3. Future work

We are currently working on building a deformation scheme especially designed for our optimization algorithm in order to improve both the speed and the robustness of the method. Finally, we will apply it to the images of the asteroid (4) Vesta acquired by the DAWN spacecraft and later on, to the high-resolution images of the nucleus of comet 67P/Churuymov-Gerasimenko to be acquired by OSIRIS.

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