

3D RECONSTRUCTION AND MODELING OF CELESTIAL BODIES

Ghada H. Machtoub

Max-Planck-Institute for Solar System Research, Katlenburg-Lindau, Germany
machtoub@mps.mpg.de

Commission IV, WG IV/8

KEY WORDS: shape reconstruction, stereo-photoclinometry, shape from shading, terrain model, point cloud

ABSTRACT:

Study of celestial bodies provides clues about the origin, history, and evolution of the solar system. The advanced research on the small bodies that reside in the extensive zone (asteroid belt) between Mars and Jupiter has played a significant role in the planning of recent space missions. Spacecraft images and radar observations have revealed that asteroids come in a variety of shapes, configurations, and structures. This justifies the need for a large number of detailed shape models to match the ground truth from the few space probe flyby missions. This work presents a 3D visualization software to facilitate high-accuracy shape modelling, encapsulating the body's shape, orientation and rotation in novel synthetic environment. A combined method is employed for the global shape reconstruction using 3D imaging data and a sequence of registered views. The shape from limb profile estimates the convex hull of the object, and the stereo-photoclinometry determines the 3D coordinates in the object reference frame. The optimized global shape model is then obtained via a constrained deformation technique based on an iterative refinement of the model synthetic images.

1. INTRODUCTION

Advances in astronomical techniques have made it possible to explore the mysteries of the planetary evolution in early solar system. Asteroids and comets are thought to be remnants that have remained largely intact since the time of planetary system formation. The atmospheric composition, surface topography, internal structure, and physical properties of these celestial bodies are investigated by many recent interplanetary spacecrafts, and several numerical models attempted to match the observations. Topographic information is of much interest in all phases of exploration and created a need for 3D shape models and flyby mission simulations. Recent space observations are focused on exploring the massive asteroids (planetoids) such as 4Vesta and 1Ceres (Russel, 2005). More photometric information about the global shape and surface terrains of these bodies will be provided by the Dawn mission in the closest approach (flyby 2011, 2015).

This paper presents an overview of the framework, detail structure and operation of the developed 3D visualization software, Shape Reconstruction Model (SRM). The software is specifically designed to comply with the current space scientific objectives providing the tools for depicting the global shape of an observed celestial object in 3D modeling, mapping its surface structure and terrains. A hybrid algorithm is employed using a sequence of some available images of asteroids provided by recent flyby missions.

The mission planning of flyby geometry is described in Section 2. The key features of the developed software are outlined in Section 3. The design, operation, and framework of the shape and surface reconstruction are presented in Section 4-5.

2. FLYBY MISSION PLANNING

Mission planning of a flyby geometry requires information on the observer (spacecraft) and the optical instruments (camera, filter, detector,...), the optical positions and orientations of the observer and the target object, area and phase angle coverage, rotational parameters, and exposure time schedule. These geometric parameters are obtained from the SPICE kernels (NAIF-JPL) and extracted from the labels of the selected observed images.

The coordinate system defining the orientation of a target object fixed frame with respect to spacecraft location is described in detail by (Sidelmann, 2002). Transformation of coordinates into other reference frames is required for the computation of the intersection of the pixels with the facets of the predicted global shape model. A model frame is used to describe the 3D coordinates of the vertices with origin at the body center of mass (CM). Other frames are used to represent the inertial reference frame with origin at the CM of the Sun, and the inertial frame of the camera attached to the line of sight of the instrument.

3. MODEL DESCRIPTION

The developed Shape Reconstruction Model (SRM) facilitates shape and surface modeling of irregular shaped objects. The tool is particularly intended for the generation of a global digital terrain shape model. The SRM is operated in novel synthetic environment. The key features are a set of utility modules for importing and processing a large set of captured images with different resolutions, registering collection of views into a common object centered coordinate system, integrating registered views into a single surface representation, optimizing and simplifying meshes, and rendering synthetic images from arbitrary viewpoints and under arbitrary lighting conditions. The SRM also supports loading mission Kernels (geometric data set

provided in NAIF standard format (NAIF-JPL), and generating geometric data and mission configuration files. A screen-shot of a developed SRM utility tool supports processing a large set of images is shown in Figure 1.

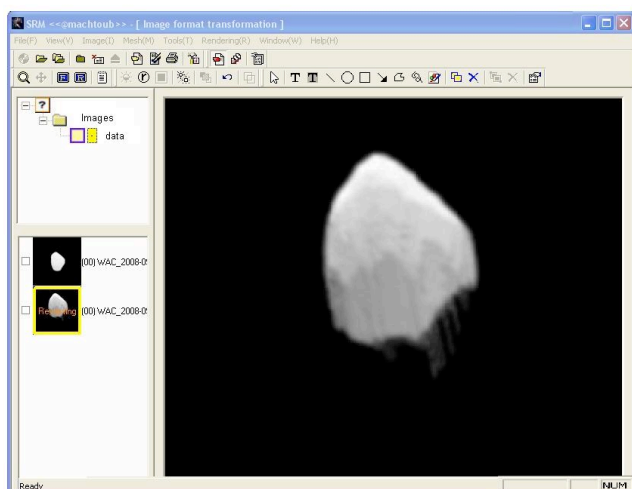


Figure 1. Screen-shot of a developed SRM utility tool supports processing a large set of images

Most utility tools are developed with a graphical user interface (GUI) to provide a user-friendly post-editing toolbox. The user can have access to a large amount of information about the parameter settings. Buttons and slide controls are provided to change the working grid resolution and iteration parameters. Other utility tools are designed in a way to facilitate viewing geometry and propagating information about illumination from input calibrated images, multi-image mosaicking in an orthographic projections, deriving and editing elevation maps, performing a fixed number of iterations with various fixed parameters. Fitting over a distribution of surface slopes about a mean plane with known (incidence emission, and phase angles). Selecting a proper surface photometric function to determine the amount of contrast (shading) in non-Lambertian surfaces. The reflectance of surfaces are described by either Minnaert's or Hapke's photometric parameters (Minnaert 1941, Hapke 1981). A screen-shot of the developed SRM utility tool for 3D surface rendering, using images of the asteroid Steins, is shown in Figure 2.

The reconstruction of an optimal digital terrain shape model employs a hybrid algorithm, stereo-photoclinometry and limb profile, using 3D geometric data and a sequence of registered views. The limb profile provides an initial global shape estimate from the boundary pixels, constraining the maximum envelop of the body. The stereo-photoclinometry (multi-view surface reconstruction) describes local elevations in prominent surface features, determining the 3D coordinates of the ground control points in the body reference frame (Kirk 1987, Simonelli, 1999). The SRM software pipeline is described below.

4. SRM PIPELINE: DESIGN AND OPERATION

The shape model can be constructed from a set of generated point clouds (GPC) or other available control point network. Figure 3 presents the flowchart of the SRM pipeline (detail design and operation).

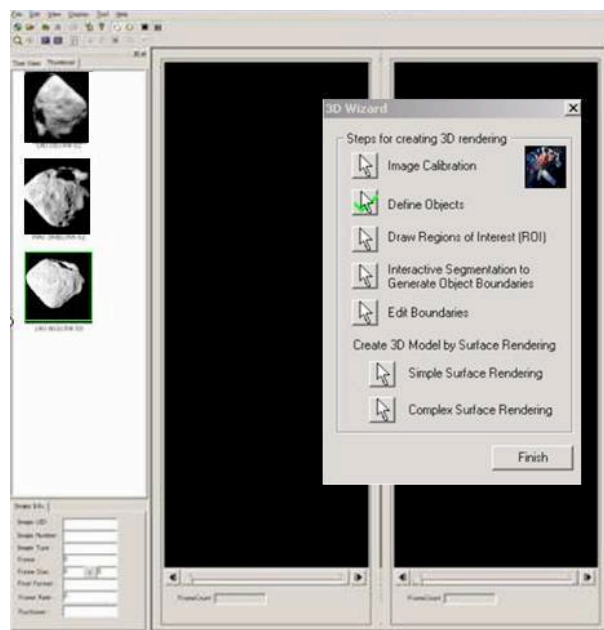


Figure 2. Screen-shot of a developed SRM utility tool for 3D surface rendering

The image-based reconstruction utility tool generates a set of GPC from a sequence of selected observed images of the target object captured from a prescribed set of viewpoints. The images must first be radiometrically and geometrically calibrated. Such processing is necessary to remove artifacts caused by pixel-to-pixel offset and gain variations, which might be misinterpreted as topographic shading. The reconstruction from the GPC is processed in three successive phases: the initial surface estimation, subdivision and sampling, and smooth mesh optimization. The point clouds are connected in a concise dense triangular mesh. The triangulation is based on defining a distance function in association with an oriented plane computed for each data point. These planes then serve as local approximations to the surface, and improve the fit to the data points through optimization. The free variables in the optimization are the number of vertices in the mesh, their connectivity and positions. The optimized mesh is obtained with an energy function that directly measures deviation of the final mesh from the original one. The final mesh adapts to curvature variations in the original mesh by further segmentation of the derived geometric shape model (GSM) into smooth connected components. The GSM data set is then used as an input to the diagnostic mission simulator (DMS) for generating the synthetic images and geometric maps. The main key functions of the DMS are: importing spacecraft instrumental data and object geometrical kernels (SPICE), converting the uploaded kernels into supported format, propagating reflectance parameters, and generating synthetic images of the model. The package of the mission-setting configuration is a link library with several routines for generating the configuration files and geometrical kernels for a specific space mission. The kernels provides information on the flyby geometry, the rotation period, and the coordinate system defining the orientation of the observed object in fixed frame with respect to spacecraft location.

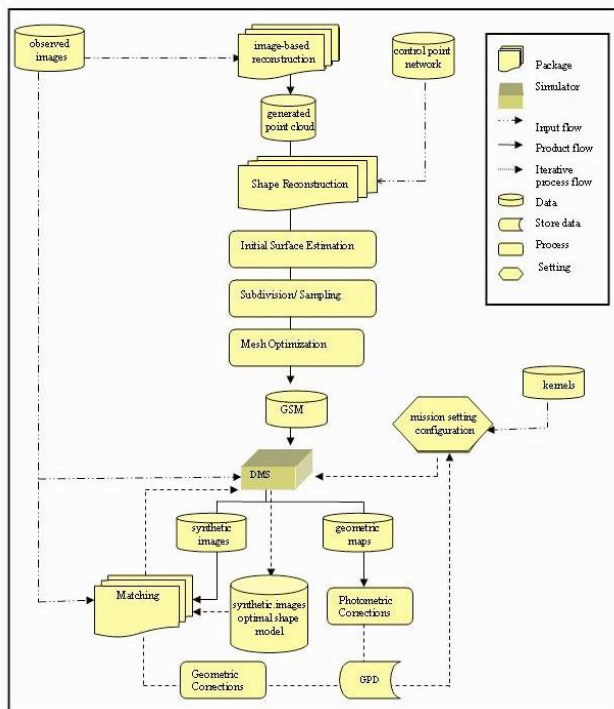


Figure 3. Flowchart of the SRM software pipeline

The optimal shape model is iteratively retrieved through refinement based on simplex mesh. The matching is processed with varying the geometry and size of the shape model, using more images with different views of the object and different lighting geometries, reflectance parameters and geometric/photometric correction data (GPD). The photometric parameters of the surface are iteratively enhanced and used as input to the minimization of the model. Enhancement in the global surface topography of the refined model to retrieve an optimal digital terrain shape model is finally processed by the stereo-photoclinometry (multi-view surface reconstruction).

5. SURFACE RECONSTRUCTION

The global representation of a surface terrain requires the availability of depth information, reflectance properties and surface normals (needle maps). A utility tool is developed to generate local elevation maps of the surface. The maps are then collected and rendered for the global surface reconstruction (global terrain model). A hybrid approach is employed to derive an optimal topographic model. Dense distribution of the surface information, potentially determining the location of every imaged point on the body, is produced by use of the shape-from-shading (Horn, 1970) and much larger number of points found to correspond on multiple images is produced by implementing the shape-from-stereo (Lohse 2003).

5.1 One-View Reconstruction

In order to solve for topography from a single image, it is necessary to select an image in which most of the contrast results from topographic shading rather than from variations in reflectivity (albedo). Images with very large incidence angles should not be used because of the prevalence of shadows, which not only hide parts of the surface but can also make the shape from shading iteration process unstable. The shape from shading method is very sensitive to albedo variations. Terrain

model constructed from a single image with broad albedo variations might have a distinctive pattern of artifacts. A dark patch might be modeled as a slope away from the sun and might be flanked by a ridge on the up-sun side and a trough on the down-sun side. These artifacts can be removed by digital filtering if they are not too severe. A low-pass-filtered version of the image can be used as the albedo estimate. The accuracy can be improved if a stereo terrain model of the region is available. Dividing the image by this model, the shading due to broad topographic features is not removed when the albedo estimate is divided out. However, the accuracy depends on how much remained albedo variations over scales smaller than what the model resolves (Kirk, 1987).

The accuracy of the model constructed from one-view is also affected by the choice of the parameterization. For a surface terrain constructed from contour maps, slopes can be enhanced with the addition of skeleton points along the locations of sharp features (ridges, valleys, summits). However, the accuracy of height estimates mainly depends on slope consistency, and the prediction of control information (Thibault, 2000). Other drawback of this technique is the tedious input requirement of many parametric surfaces. The user needs to insert several boundary contours appropriately in the parameter space grid with consideration of the topology of the object. And placement of many boundary contours may distort the surface with over oscillations.

Other alternative technique using one-view reconstruction is the convex variational approach (Oswald, 2009). This method generates a model using silhouette information and requires relatively less user input. However the validity of this approach targets a limited class of real world objects.

5.2 Multi-View Reconstruction

The reconstruction of a surface using only the shape-from-stereo might have deficiency when there is a large texture and little detail that makes it harder to find the same point in the selected images. The developed multi-view reconstruction tool makes use of shape-from-stereo and shape-from-shading methods. Using such a combined reconstruction approach, surface information obtained from shading is used to create a point-to-point correspondence that shape from stereo requires. This can be processed by directly matching the local elevation maps, retrieving high level topological information about the surface. The multi-image shape-from-shading improves the accuracy of reconstruction of the surface heights as the same selected point on a surface will have exactly the same value when viewed from different view points (McEwen 1991, Simonelli, 1999). Figure 4 shows a screen-shot of the developed shape refinement tool and a retrieved shape model of an asteroid with partial orthographic projection of registered views.

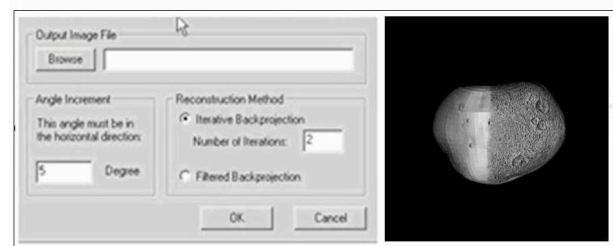


Figure 4. Screen-shot of the developed shape refinement tool (left) and a retrieved shape model of an asteroid with partial orthographic projection of registered views (right)

The projected texture is a set of overlapping digital topographic maps which partially tile the surface of the body. The slopes are obtained by the stereo-photoclinometry and then integrated to produce the elevation maps relative to a local coordinate system.

6. CONCLUSION

This paper gives an overview of the detail design and operation of the developed 3-D visualization software (SRM) intended to facilitate retrieving optimal digital terrain shape models for the irregular-shaped celestial bodies. A hybrid algorithm is employed and evaluated using a class of captured images provided by recent space missions. Future work is focused on improving the quality of reconstruction. Also much consideration is given to enhancing and developing more utility tools to provide a fully integrated toolkit applicable for retrieving models of forthcoming space observations.

ACKNOWLEDGEMENTS

The author would like to thank the OSIRIS team for providing some captured images of asteroids.

REFERENCES

- Hapke, B., 1981: Bidirectional Reflectance Spectroscopy, I - Theory, *Journal of Geophysical Research*, Vol. 86, No. B4, pp. 3039-3054.
- Horn, B.K.P., 1970: Shape from Shading: Obtaining the Shape of a Smooth Opaque Object from One View. PhD thesis, MIT.
- Kirk, R.L., 1987: A Fast Finite-Element Algorithm for Two Dimensional Photoclinometry. Ph.D.Thesis, California Institute of Technology. pp. 165-258.
- Lohse, V., Heipke, C. 2003: Derivation of digital terrain models by means of multi-image shape-from-shading: results using Clementine images. In Heipke, C., Jacobsen, K., Schroeder, M. (Eds.): *High Resolution Mapping from Space 2003: Joint ISPRS/EARSeL Workshop*. (CD).
- McEwen, A.S., 1991: Photometric Functions for Photoclinometry and Other Applications. *Icarus* 92. pp. 298 - 311.
- Minnaert, M., 1941: The Reciprocity Principle in Lunar Photometry, *Astrophysical Journal*, Vol. 93, pp. 403-410.
- NAIF-JPL. The Planetary Science Division's Ancillary Information System. <http://naif.jpl.nasa.gov/>
- Oswald, M.R., Töppe, E., Kolev, K., Cremers, D., 2009: Non-parametric Single View Reconstruction of Curved Objects Using Convex Optimization. In: Denzler, J., Notni, G., Süße, H. (Eds.): *Pattern Recognition. Lecture Notes In Computer Science* Vol. 5748, pp. 171-180, *Proceedings of the 31st DAGM Symposium*, Jena.
- Russel, C.T., Raymond C.A., Fraschetti T.C., Rayman M.D., Polansky C.A., Schimmels K.A., and Joy, S.P., 2005: Dawn Mission and Operations. *Proceedings of the International Astronomical Union*, Cambridge University Press, 1: pp.97-119.
- Seidelmann, P.K. et al., 2002: Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: *Celestial Mechanics and Dynamical Astronomy*, Vol. 82, pp. 83-110.
- Simonelli, D.P., Kay J., Adinolfi D., Veverka J., Thomas P.C., Helfenstein P., 1999: Phoebe: Albedo Map and Photometric Properties, *Icarus*, Vol. 138, pp. 249-258
- Thibault, D., Gold, C.M., 2000: Terrain Reconstruction from Contours by Skeleton Construction, *Geoinformatica*. Vol. 4, Issue 4, pp. 49 - 373.