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Prologue: Stereophotoclinometry (SPC) began as a challenge/assignment issued to me by S.P. Synnott my group supervisor at JPL: Find a way to characterize control points so that they can be quickly identified and located in images under all illuminations and viewing geometry. My first baby steps took me to Jupiter's satellite Io where crude 2d surface maps were aligned with images and used to solve for control point positions and a crude shape model.

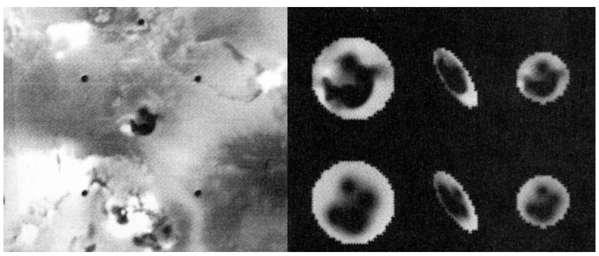

Figure 1. A very early landmark on Io (1988)

Beginnings: The reflected brightness of a surface point is governed by a photometric function f(cosi,cose,α) where cosα=**s·e**, cosi=**n·s** and cose=**n·e** are the phase, incident and emission cosines. A control point became described by the center of a small digital surface "template" with values t_1, t_2, t_3 at each grid point. The normal vector is $\mathbf{n}=(t_1,t_2,1)/\surd(1+t_1^2+t_2^2)$ and $(1+t_3)$ is the relative albedo over the grid. Imaging data scaled and projected onto the grid (orthorectified) could be correlated with the template's photometric realization to precisely locate the landmark in image-space. Data so aligned from many images could be used in a least squares solution for the template parameters. Shadows were (and are) ignored in the solution. If the grid is viewed as a DEM with heights h at the grid points then $t_1=-\partial h/\partial x$ and $t_2=-\partial h/\partial y$. The slopes can be integrated to produce a height/albedo DEM "maplet" and since the surface is no longer flat, the projection of the image is improved.

Interlude: Fake images produced while testing this concept led to a diversion into building artificial Martian surfaces for rover studies. A procedure was developed that could build a small region at high resolution in a manner consistent with building an entire surface at that resolution. Soon this would be used to make an artificial Eros model for NEAR navigation studies in the Implicitly Connected Quadrilateral (ICQ) format that is now used in SPC. Surface points (i,j,f) have the connectivity of grid points on the surface of a cube with i and j from 0 to q ($=2^k$) and f from 1 to 6. This makes finding your way around the surface very easy and eliminates the need for a separate facet table.

Early Applications: The first application of the new MAPPER software was building Martian landmarks from Viking Orbiter and MO images for precision landing studies.

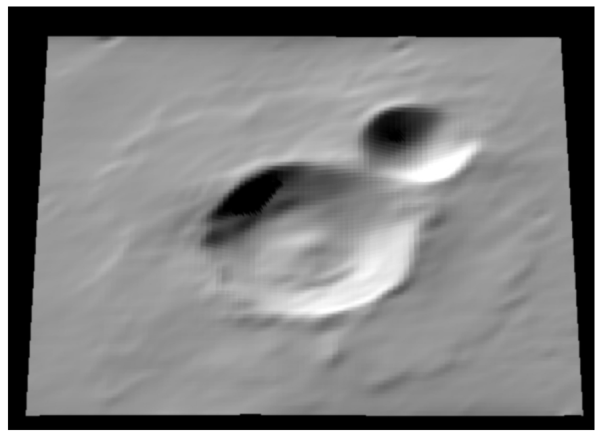

Figure 2. A Mars maplet.

Landmarks were sparsely distributed on the surface but enough could be identified in a landing image to locate the lander to within 50 m.

A second application was to build a Phobos model for use in determining canter of mass to center of brightness offset in Mars approach navigation images. The original idea was to use the same MAPPER software that constructed maplets for Mars, and use the resulting control points to build the model. The software at this time used a JPL program called XROVER and gathered all images and landmarks together in a picture sequence file (PSF). Three things occurred to change my plans. First, something happened to XROVER (it was being used heavily for NEAR navigation using craters as landmarks and suddenly became incompatible with my computer). Second, I realized that the maplets were no longer isolated as they had been on Mars, but overlapped each other, allowing neighboring maplet topographies to influence one another. Third, maplets could be found on the lit limbs of some images and this data cold be used to constrain their topography. All this led to a completely new ROCKER set of software. Rather than using control points to determine the shape, the entire topography data from each of a large set of maplets was used, and rather than combining all data into a single PSF, each landmark had its own .LMK file referencing all the images used and each image had its own .SUM file referencing all of its landmarks. The model used 235 Viking Orbiter and Phobos 88 images to construct 456 99x99 pixel maplets of various pixel scales. There were 18345 observation pairs with a postfit RMS of 25 m/dof.

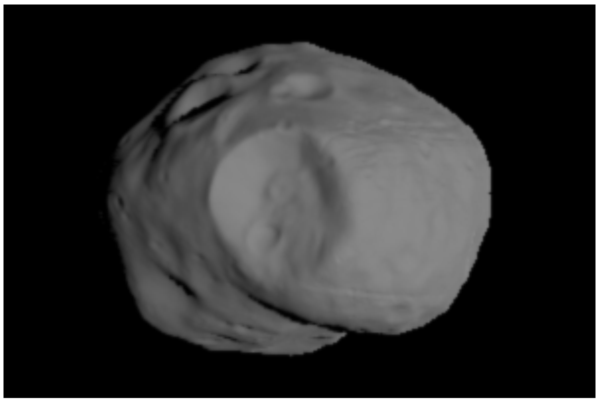

Figure 3. Shape model of Phobos

Each new body brings something new. When Eros was constructed using NEAR images, the first shape model looked like a unicorn with a spike sticking out of a crater near one end. A new method had to be developed to turn maplets into shape for bodies whose radii are not single valued with latitude and longitude.

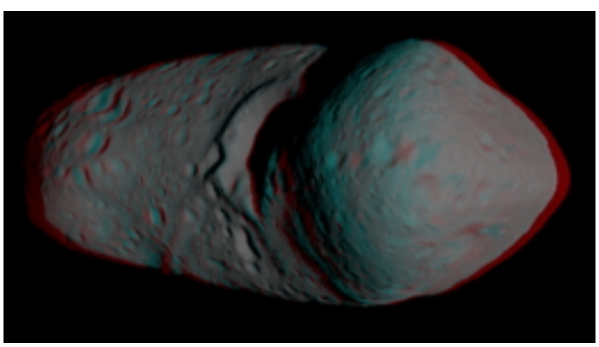

Figure 4. Eros in 3D

Without the DENSIFY program to find shape models for the more grotesque bodies, modeling Itokawa for the Hayabusa mission would have been impossible. Both NEAR and Hayabusa missions provided the opportunity to combine imaging and laser ranging data to improve both topography and navigation. This enabled a complete solution for the NEAR landing on Eros.

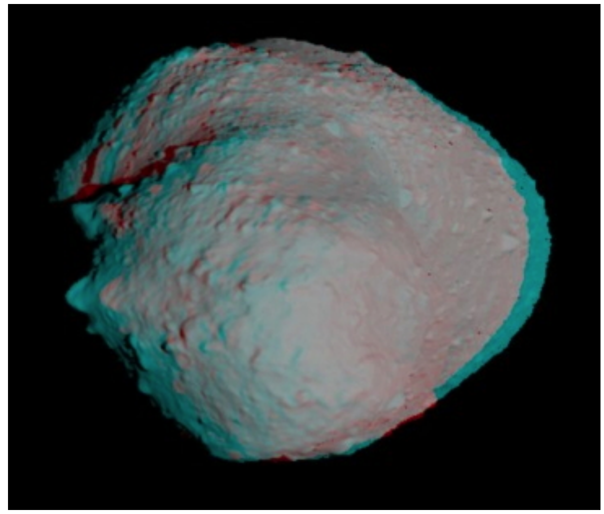

Figure 5. Itokawa in 3D

Recent Applications: Over the last decade, SPC has been used for many more bodies including the Moon, Satellites of Saturn (Cassini), Mercury and Vesta. ROCKER had to be replaced by the LITHOS suite of software as the number of landmarks and/or images became very large, in excess of several hundred thousand. Iterating on so many landmarks could take years, so a parallel version of LITHOS was developed as well as provisions for carrying out work on multiple machines and importing the results into a central directory. Finally, the comet 67PCG exhibited changes in rotational state during ROSETTA's two year's of observation. The LITHOS suite had to be modified to handle this contingency. Hopefully, we will be prepared for the upcoming OSIRIS_Rex and Hayabusa 2 encounters with Bennu and Ryugu coming up later this year.

Shape models, while useful, do not have the resolution to do justice to the data, so surfaces were tiled with a set of high resolution "bigmaps".

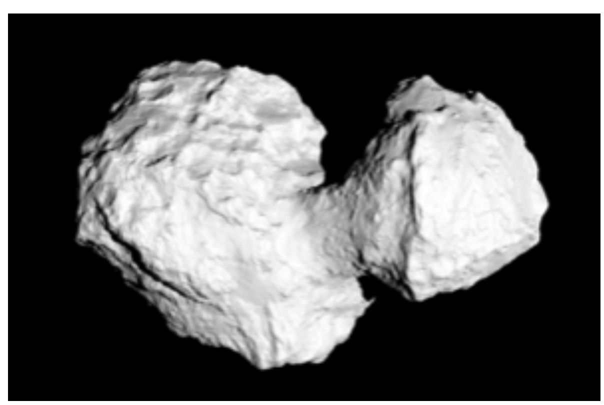

Figure 6. 67PCG shape model from ROSETTA data

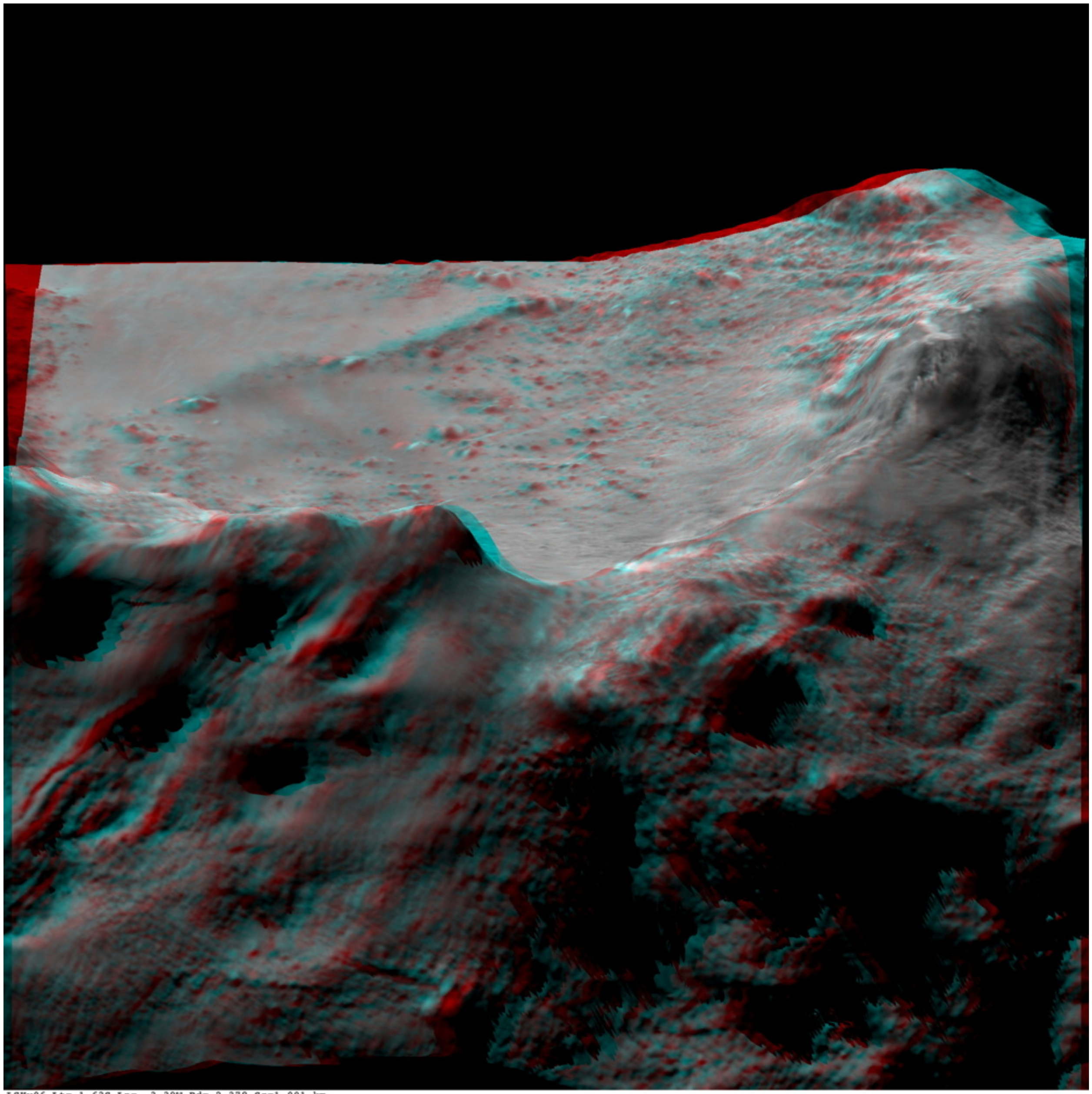

Figure 7. Bigmap of a portion of 67PCG. Background is area where Philae lander first touched down. Center foreground is where it came to rest.