THE EFFECT OF INCIDENCE ANGLE ON STEREO DTM QUALITY: SIMULATIONS IN SUPPORT OF EUROPA CLIPPER.

R.L. Kirk[1], E. Howington-Kraus[1], T.M. Hare[1], L. Jorda[2]. [1]Astrogeology Science Center, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff AZ 86001 (rkirk@usgs.gov), [2] Université de Provence/CNRS, F-13388 Marseille cedex 13, France.

Summary: We are investigating how the quality of stereoscopically measured topography degrades with varying illumination, in particular the range of incidence angles over which useful digital topographic models (DTMs) can recovered. Our approach is to make high-fidelity simulated image pairs of known topography and compare DTMs from stereoanalysis of these images with the input data. Our study is motivated by the needs of the proposed Europa Clipper mission, but the approach and results described here are relevant to a wide range of planetary investigations.

Background: One of the primary objectives of the Europa Clipper mission [1] is to determine the thickness and structure of Europa's icy shell by probing it with an ice penetrating radar (IPR). A high resolution topographic model of a strip straddling the ground track is essential to "declutter" the radar echoes, i.e., to determine which features in them arise from subsurface reflectors and which are generated by surface reflections to the sides of the ground track. The notional payload includes a Topographical Imager (TI) that operates simultaneously with the IPR to obtain the needed stereo image coverage. The quality of the images will vary along track because neither the range (hence, image resolution) nor the illumination is constant. As an extreme example, topographic mapping and decluttering will not be possible on the night side. Some degradation of DTM quality is also to be expected in areas of both low incidence angle (where the surface appearance will be bland) and high incidence angle (where shadows will be present). We aim to estimate what fraction of stereo coverage from a typical flyby is likely to be useful.

DTM quality assessment is a complex subject [2] involving multiple quality measures such as absolute accuracy, vertical precision (often called *EP*), horizontal resolution, and the characteristics as well as the abundance of gross errors ("blunders"). Scaling relations exist that permit some but not all of these factors to be predicted from the image geometry. For example, a lower limit on the horizontal resolution of a stereo DTM is 3 times the image ground sample distance (GSD), because stereoanalysis is based on comparing ("matching") features defined by small clusters of pixels. Vertical precision scales according to the equation $EP = \rho \text{ GSD} / (p/h)$ where the GSD and parallax/height ratio p/h can be calculated from the imaging geometry but ρ, the typical error of matching measured in pixels, depends on the surface appearance and image quality, must be determined empirically. We have investigated ρ in different ways for a variety of planetary image types (e.g., [3-6]) and the results have generally validated the rule of thumb that ρ is ~ 0.2 pixel for images of good quality. The degradation of ρ for non-ideal images has received less study, but we know that ρ increases as images are lossily compressed [3].

Technical Approach: Simulating images of known topography and trying to recover that topography provides a straightforward way of investigating the factors that affect DTM quality. It is important that the input data represent the target of interest fairly realistically, and crucial that the simulations be of sufficiently high fidelity to capture key effects such as realistic photometric behavior and cast shadows. It is less important that the source DTM be perfectly accurate, because the test of success is how well we recover the input data rather than how accurately it represents the target. This is a key advantage of carrying out numerical simulations rather than the alternative approach of physically imaging a planet-like target and comparing stereo DTMs to some independent source of information about its shape. Nor is it crucial to match the resolution of the target TI images exactly, because Europa has similar geologic features at a range of scales and we can express our results in terms of image pixels so they can be scaled to the TI or other cameras.

Source Data: In the late 1990s we produced more than 20 high-resolution DTMs of Europa by photocli-

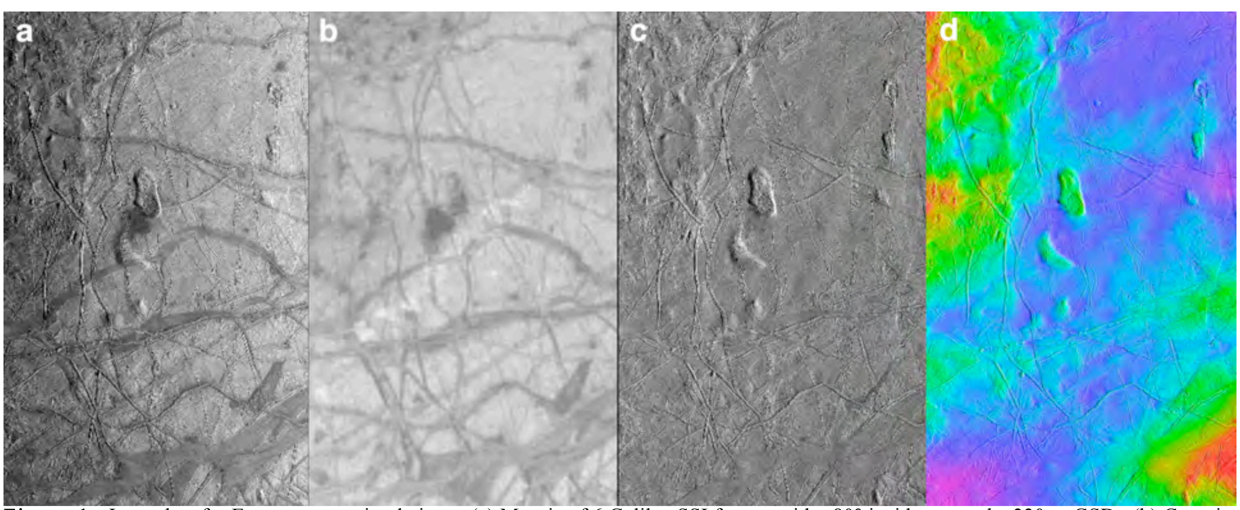

Figure 1. Input data for Europa stereo simulations. (a) Mosaic of 6 Galileo SSI frames with ~80° incidence angle, 220 m GSD. (b) Coregistered single frame with 21° incidence, 1570 m GSD serves as an albedo map of the region. (c) Ratio of a to b is effectively albedo corrected. (d) DTM generated from c by two-dimensional photoclinometry [7] shown as color-coded elevations overlaid on c. Range of elevations from purple (low) to red (high) is 3200 m. All images are 350x530 km, Equirectangular projection centered at 0.7°N, 134.7°E, north at top.

nometry (shape from shading [7]) applied to Galileo SSI images with GSD ranging from 26 to 630 m. The largest of these data sets [8] was centered on Castalia Macula at -0.7°N 134.7°E and was based on 3 images with ~220 m GSD and incidence angle ~80° along with one having lower resolution (1570 m GSD) and 21° incidence. For the present work we regenerated this DTM after adding three additional high-resolution images, allowing us to map 1600x2400 pixels or 350x530 km (Figure 1). The mosaic of high-incidence images was divided by the low-incidence image to provide first-order correction of albedo variations before photoclinometry was performed. The resulting DTM contains topographic features (e.g., single and double ridges, wedge bands, and domes) down to the limit of the image resolution.

Image Simulation: We use the image simulation package OASIS [9] to generate synthetic images. Its advantages include the following:

- Flexible setup of hypothetical cameras, hypothetical camera orientations, and hypothetical illumination via text files.
- Rigorous photometric modeling including Hapke [10] scattering with spatially varying single-scattering albedo. We use the low-incidence SSI image appropriately scaled, as our albedo map and choose Europa-appropriate values of other Hapke parameters [11,12].
- Modeling of cast shadows, camera optical point spread function (PSF), and finite signal to noise ratio (SNR).

For simplicity, we have set up a framing camera with *p*/*h* similar to that of the Clipper TI and GSD matched to the 220 m raster of the source data. We generate images in pairs with identical illumination and offset camera stations providing the needed stereo convergence. Pairs will be generated at incidence angles spanning the full range from 0° to 90° and at two different sun azimuths in order to assess the extent to which results are affected by chance alignments of topography and illumination.

Stereoanalysis: We will use the commercial stereo mapping software package SOCET SET® [13] from BAE Systems to produce DTMs from the images simulated. This software, which we use for a wide range of planetary mapping projects, is state-of-the-art and a world leader in terms of number of licenses sold. Results from different image matching algorithms can be expected to differ slightly, but those from SOCET SET should be representative, particularly in terms of the degradation of quality factors with extreme incidence angles. Time permitting, we may also investigate DTMs produced with the Ames Stereo pipeline [14]. Controlling the images, usually a time consuming step of DTM production, is not necessary because the simulated camera stations are exactly known. Manual editing of the DTMs, the other time-consuming step, will also be omitted because the objective is to evaluate automated image matching.

DTM Assessment: The DTM quality measures of greatest interest are the horizontal resolution and vertical precision. Vertical precision can be estimated by collecting statistics on the difference between the input "truth" DTM. By smoothing the truth DTM with a lowpass filter and adjusting the size of this filter to give the best agreement with the stereo DTM, we can simultaneously estimate the resolution of the latter (cf. [6]). We will also make a qualitative assessment of the abundance and appearance of artifacts in the DTM as a function of incidence angle, as well as the extent to which they are associated with shadows.

Additional Simulations and Future Prospects: An important concern about the program of simulations just described is that we rely on a low-incidence image with a resolution ~7 times coarser than the images that will be used for photoclinometry as a model of surface albedo variations. As noted above, the distortions of the DTM that will result can probably be "forgiven" and the DTM considered as truth for simulation purposes. The real concern is that the actual Europan surface probably has albedo variations at smaller scales. As a result, images of Europa may not become as bland at hectometer scales, and stereo imaging may be easier in reality. We have considered a variety of alternative data sets to address this issue. Our favorite is not "Europa-like" but provides a look at very different (but still real) terrain with a fractal-like hierarchy of features (mostly impact craters) down to the limit of the simulated resolution. It thus may set a strong lower bound on the range of incidence angles suitable for mapping, in contrast to the smoother Europa data. Numerous stereo DTMs of the Moon have beenproduced from Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC-NAC) images [15] by the USGS [16] and others [17]. These 1 m/post products are very large (10000 image pixels, 2500 DTM pixels wide) so they can be reduced by averaging until stereo matching artifacts are negligible and still provide abundant data for simulations. The corresponding orthoimages can be photometrically corrected to serve as albedo maps.

The simulation process described here can be used to study the utility of stereo images from almost any camera and any planetary target, and the results may be useful for planning future stereo observations as well as for constraining instrument design. For example, the Clipper TI, like the Mars Express HRSC [2] obtains stereo in a single pass over the target and the illumination in the paired images is effectively the same. Many other cameras acquire stereo on separate passes over the target. A crucial question for such investigations is how great a difference in the illumination conditions can be tolerated without significantly degrading the resulting DTM quality. At the moment the upper limit on illumination differences is only loosely constrained [18] but stereo simulations offer the promise of well-documented guidance.

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