COMPARISON OF DIGITAL TERRAIN MODELS FROM TWO PHOTOCLINOMETRY METHODS.

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Introduction: Topography is a foundational data set for planetary science [1] with a wide range of applications. The most commonly used method for deriving topographic data is via stereogrammetry using images acquired from different viewing angles. An alternative approach is photoclinometry (PC), also called shape-from-shading (SFS). Such methods offer the prospect of higher spatial resolution matching the pixel scale of individual images, and can be done with single images, but they require information about the surface photometric function and can give erroneous results on surfaces with varying albedo.

We are comparing two software packages that create PC/SFS-based Digital Terrain Models (DTMs): the multi-image *sfs* tool [2] in the Ames Stereo Pipeline (ASP) version 3.0.0 [3] and the single-image *pc2d/pcsi* code [4] implemented in ISIS2 (Integrated Software for Imagers and Spectrometers, version 2.x). This builds on our previous efforts to compare different methods for making DTMs by stereo [5, 6] and stereo plus PC [6].

Data: We use LROC NAC [7] images of the Moon. Two study areas, in Schrödinger crater and the South Pole Aitken Basin, were identified as having extensive, overlapping stereopairs with ~0.5 m/pixel ground sample distance (GSD) and a variety of illumination directions. Because there is no independent source of higher resolution topographic data, we constructed target DTMs from downsampled images and made reference DTMs by analyzing the same images at full resolution, as described in [2]. The initial results reported here are from a single stereopair in Schrödinger, M123681855 and M123668289, centered near 138.3°E, 75.2°S, incidence angles ~77°. Use of a single image with numerous shadows is an edge case for *sfs*.

Methods: All 348 images identified in the Schrödinger site, including those used here, were controlled together in ISIS to ensure subpixel spatial alignment. Stereo DTMs were then prepared from the original (0.5 m/pixel) pair and after 8x8 averaging to create 4 m/pixel images, by using the block matching algorithm with subpixel refinement in ASP [3]. The former were generated at 2 m/post and averaged to yield the 16 m reference DTM, while the latter were used to produce the initial target DTM at 16 m/post. A simulated image computed from this initial target DTM was used to estimate the uniform radiance ("haze") present in addition to the surface contribution, and to produce a low-resolution map of albedo variations [6]. The additive offset was surprisingly large for an airless body (~30% of the total radiance), perhaps as the result of stray light in the camera, so correction for it was essential.

The initial DTM was refined with *pcsi* [4] based on a 16 m/pixel orthorectified (projected onto the DTM so it aligns pixel by pixel) version of image M123668289, first without and separately with correction using the albedo map. The initial DTM was also refined by *sfs* [2] based on the unrectified image, first the 4 m version from which the stereo DTM was made and then averaged to 16 m/pixel. For both software packages, results were analyzed after 1, 2, 4, … iterations in order to study how the algorithms converged. The horizontal resolution and vertical precision of each product were computed as described in [4]: the standard deviation of the difference between the target and versions of the reference DTM with different amounts of smoothing were computed. The minimum difference is an estimate of precision, and the (interpolated) filter width at which the minimum obtains is an estimate of resolution.

Results: The initial stereo DTM was found to have a resolution of ~16 pixels (4 posts). On the reasonable assumption that a similar ratio applies to the full-resolution images, this justifies *post priori* our reducing the images by a factor of 8 to ensure that the reference DTM will have the full resolution allowed by its GSD.

The ISIS PC algorithm uses a relaxation method that converges faster for short spatial wavelengths than for longer ones, so choosing an appropriate stopping point was crucial. The first steps improved resolution to ~3 posts with nearly constant precision, but after 32 iterations errors increased rapidly, consistent with [6]. The increasing error results from the growth of streak-like artifacts associated with uncorrected albedo variations. Unsurprisingly, the optimal stopping point occurred earlier (8 vs 32 iterations) when the image was not albedo corrected. The DTM quality results were similar with and without albedo correction, however.

In contrast, the solver used by the ASP *sfs* algorithm converged after only a few iterations and did not change thereafter. With the 16 m/pixel image, a resolution of ~2 posts was achieved but the precision was ~30% worse than for the starting DTM or the PC results. Using the 4 m/pixel image yielded a visibly noisy DTM with even higher errors, likely as the result of aliasing of image features smaller than the DTM cells.

Examination of the DTMs and synthetic images computed from them showed that both algorithms qualitatively added the small craters seen in the reference DTM that were absent from the unrefined stereo target DTM. To shed light on the quantitative agreement, we examined profiles through the DTMs.

The example shown in Figure 1 is representative of the appearance of small craters. The small craters added by both *pcsi* and *sfs* tend be 10–20% shallower than in the reference DTM (whereas they are entirely absent from the starting target DTM). Crater shapes from *pcsi* are symmetrical and match the reference, but most small craters in the *sfs* DTM appear distorted, with the shadowed portion appearing almost level. In planform these craters show a "streak" of high terrain down-sun and a low streak up-sun. The distortion probably results from how the software handles shadows, by enforcing both smoothness of the terrain and similarity to the starting DTM (which is flat because the crater is not resolved). In contrast, the ISIS PC algorithm enforces only smoothness in shadows.

One surprising result is that the vertical errors in all our target DTMs are substantially smaller than expected based on the image GSD, stereo convergence, and the likely precision of image matching. It is unlikely that the ASP stereo matcher, which achieved a documented precision of 0.25 pixels for images of Mars [6] can match LROC images with a precision of 0.03 pixels. A more plausible explanation is that errors in our reference and target DTMs are partially correlated and cancel when the difference is computed. This points to a disadvantage of not having a strictly independent source of reference topography. Although this effect makes our estimates of the precision of the stereo DTMs unreliable, conclusions about whether the refinement process adds or reduces errors should still be valid. Our estimates of horizontal resolution are also unaffected.

Future Work: The dataset and methods described here could be used to investigate many other aspects of DTM production with PC/SFS, including:

- What are the optimal weights for smoothness and the starting DTM in *sfs*? In particular, can the distortion of small shadowed features be reduced?
- To what extent can DTM resolution be improved beyond the GSD of the stereo starting DTM by enlarging the DTM and using the images at 4 m/pixel?
- How does DTM quality (as well as the optimal parameter settings at which it is obtained) vary for single images with larger or smaller incidence angles than the example presented here?
- How do DTM resolution and precision change if *sfs* is run with multiple images having different illumination directions? Are the distortions associated with shadows reduced? Does the precision with which images can be coregistered set a limit on resolution?
- What quality is achievable when DTMs are produced *without* access to a stereo product as a starting point? Are the requirements on illumination different in this case? How can the additive offset to the image be estimated and corrected?

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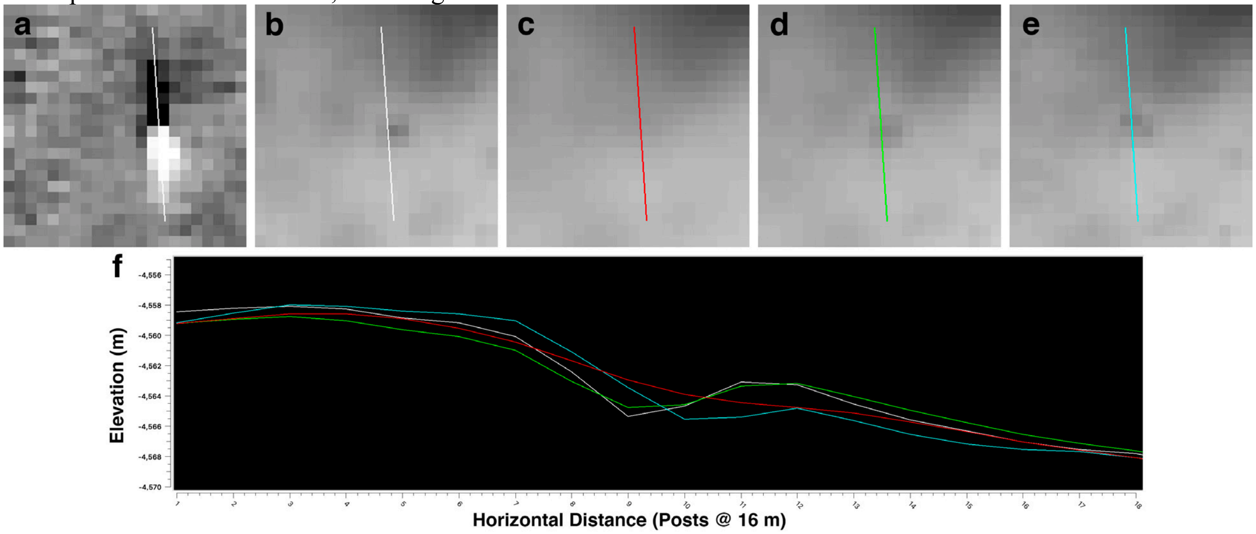

Figure 1. Appearance of a typical small (80 m diameter) crater in the DTMs. (a): difference between SFS and PC, (b) reference DTM, (c) starting stereo DTM, (d) ISIS PC DTM, (e) ASP SFS DTM, (f) elevation profiles, color-coded to profile locations in (b)-(e). All DTMs are in Orthographic projection at 16 m/post, north at top; sun direction in the image is approximately from the top. Area shown is 700 m wide. Note that crater is nearly symmetrical in PC DTM whereas the SFS profile is high on the down-sun side and low up-sun of the crater. This behavior is typical of all small, added features steep enough to cast shadows.