**3D MODELING OF LUNAR PIT WALLS FROM STEREO IMAGES.** R. V. Wagner, M. R. Manheim, and M. S. Robinson. School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85287-3603 (rvwagner@asu.edu).

**Introduction:** The Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) consists of two line-scan cameras aimed side-by-side with a combined 5.7° FOV and a nominal pixel scale of 0.5 m from an altitude of 50 km [**1**]. To date, over 300 lunar pits have been discovered, all but three from analysis of NAC images [**2**], and recent measurements suggest that some may be associated with extant lava tubes [**3**,**4**].

For four of the 16 known mare pits, LROC has acquired multiple oblique views at different slew angles, often with similar lighting, providing off-nadir stereo pairs that allow the construction of a depth map of one or both walls. From these models, we have evaluated the internal structure of mare pits, and mapped the extent of layering in the walls [**5**]. Here we compare multiple methods for producing pit interior models: a custom trigonometric solver, USGS ISIS *jigsaw* [**6**], and Agisoft PhotoScan [**7**].

**Preprocessing Steps:** There are three major complications with the use of NAC oblique stereo images: 1) As the NAC is a line-scan camera, image pixels are not square; their down-track size varies with exposure time and altitude. 2) Due to the orbital configuration of LRO, a given NAC image may be flipped vertically, horizontally, or both. 3) Most potential oblique stereo observations were not intentionally acquired as stereo, and have varying lighting and resolution.

Non-square pixel aspect ratio was corrected by scaling each image in the down-track direction such that the pixel width and height were identical when projected on a plane perpendicular to the boresight, and all images were flipped to a north-up, east-right orientation. These corrections made manual selection of match points faster and more accurate. As ISIS keeps track of image scaling transformations relative to the SPICE data, scaling does not affect the output from *jigsaw*. Flipping is not automatically handled, so we edit our control network files to invert coordinates as needed before passing them to *jigsaw*.

*Control network creation:* All of our methods require or can benefit from dense control networks of corresponding points. For stereo pairs with matching lighting and pixel scale, we produced an initial control network using the ISIS tool *findfeatures* [**6**]. The automatic match points were manually verified. In general, automatic point matching worked well on smooth horizontal surfaces, but required significant manual adjustment on vertical walls. In all cases, we added additional manually-placed control points (usually ~300) over the wall, focusing on inflection points in the topography. Point spacing averaged ~4 pixels (4-10 m), depending on density of high-contrast features.

*SOCETSET DTMs:* SOCETSET, commercial software from BAE Systems, is used by the LROC team to produce high-resolution DTMs [**8**]. While we have not used SOCETSET to produce models of pit walls, we used new SOCESET-derived DTMs of the Mare Tranquillitatis (MTP) and Mare Ingenii (MIP) pits to align our wall point clouds. These DTMs were carefully edited during processing around the pit rims to ensure that there were no erroneous points, and both DTMs include small sections of floor. We used these DTMs as "truth" surfaces for testing our models.

**Trigonometric Method:** Using the assumptions that the orbit tracks of two images are parallel and that the recorded spacecraft positions are exactly correct (close to true, given LRO's polar orbit with >88° inclination and <20 m positional uncertainty [**7**]), we treat the position of each tie point relative to an arbitrary reference point as a 2D trigonometric problem to obtain cross-track and vertical position, plus a down-track offset based on the number of lines between the tie point and reference point in each image. The resulting point cloud is reoriented in 3D space using control points collected from surrounding surface in NAC DTMs tied to the LOLA reference frame [**8**]. This

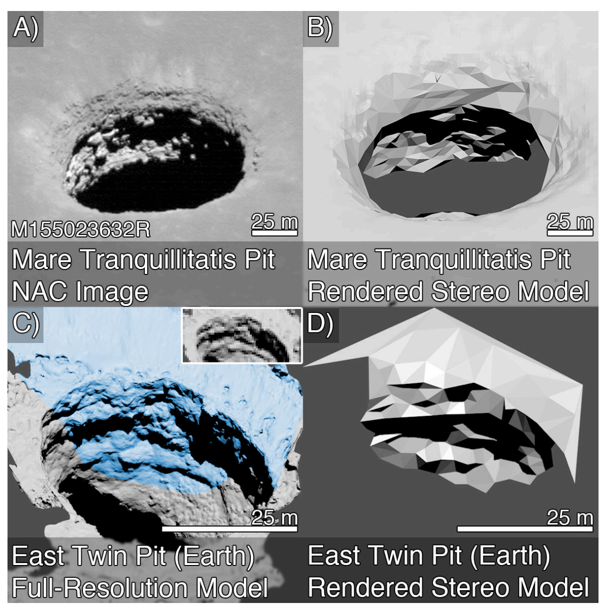


**Fig. 1:** *A)* NAC image of MTP east wall with grazing sunlight. *B)* Our model, merged with a NAC DTM of the surrounding surface. *C)* Full-resolution model of the east Twin Pit in Hawai'i. Blue region shows the approximate area visible in the images used for the stereo model. *Inset:* Same view, at the resolution used to produce our stereo model. *D)* Our model of east Twin Pit. All panels have matching lighting.

method produces minor rotational errors due to the assumed orbital inclination, but provides a simple, verifiable comparison model to test the other (black-box) methods against.

*Verification:* As a qualitative verification of the wall modeling, we produced triangle meshes from the wall point clouds merged with NAC DTMs of the surrounding surface, and rendered "synthetic NAC images" using the 3D modelling software Blender [**10**] with matching lighting, viewing, and camera parameters to actual NAC pit images. Comparing the synthetic images to NAC images that were not involved in the creation of the models indicates that the overall geometry is correct (**Fig. 2**), although small features such as 5-10 m wide rocks are sometimes absent when not easily identifiable in the original stereo images.

For an additional quantitative test, we produced a model of a terrestrial pit crater using synthetic NACs of a high-resolution 3D model **[5]** with the same imaging parameters, including resolution, as the images we used to model MTP. We aligned the low-resolution point clouds for each wall to the original model via the Iterative Closest Point algorithm, and measured the distance using the software CloudCompare [**11**]. The overall RMS error was 65 cm (80 cm east wall, 40 cm west wall), with no correlation between X/Y/Z position and error, indicating that this method produces dimensionally accurate models, with errors on the order of the source image pixel scale.

***Jigsaw*:** We also produced point clouds from our control networks using USGS ISIS software *jigsaw*, bundle-adjustment software that reports tie point positions in 3D [**6**]. We set *jigsaw* to only correct the camera pointing, not the position. The *jigsaw* results are very similar to those from the trigonometric method; when the jigsaw and trigonometric models are aligned via ICP, the median point-to-point offset is <1.6 m at all sites, so the internal geometry of the *jigsaw* models is accurate. The *jigsaw* models, however, are better controlled to their surroundings than the trigonometric models. This is particularly noticeable in the floor of MTP, where the two stereo reconstructions (east floor and central floor) do not align well with each other or with the SOCETSET model in the trigonometric model, but align perfectly in the *jigsaw* model (**Fig. 2**).

**Agisoft PhotoScan:** PhotoScan is a commercial structure-from-motion package that can create 3D models from uncontrolled photographs with no requirement for *a priori* position, pointing, or camera model information, which we have previously used to model terrestrial pits [**12, 13**]. Although PhotoScan does not support line-scan cameras, the stretched images described above should have minimal distortion over this small area from the lines being acquired by a moving camera, rather than from a single perspective, due to the very long focal length of the NAC.

The main difficulty with using PhotoScan is that the initial alignment step frequently fails, often inverting the topography or producing other gross topological errors. This is probably due to the focal length and small number of images, not the preprocessing to create pseudo-framing-camera images, as we have observed similar problems using images from the MESSENGER NAC, which is a true framing camera.

A second point of concern is that the automatic camera parameter estimation produces a focal length 1/30th of the actual value for the LROC NAC. Setting the focal length correctly prior to alignment always produces the invalid results described above, even after importing a 300-point ISIS control network as either tie points or ground-control points. In a test model of the west wall of MIP, the floor is misplaced horizontally by ~10m relative to the *jigsaw* model, and maximum point-to-point distance between the *jigsaw* and PhotoScan clouds (from CloudCompare) increases linearly with depth, suggesting that the incorrect focal length significantly degrades the model accuracy.

PhotoScan can create much higher-density models than the other methods described, and qualitatively the results look reasonable on vertical surfaces. However, results are quite poor on horizontal regolith-covered surfaces, with high-frequency vertical noise of ±~3 m.

**Conclusions:** Of the stereo processing methods we have tested so far, the ISIS tool *jigsaw* produces the most accurate results, although there are complications with handling images pre-processed to reduce geometric distortion. We have not found any reliable method of automatically extracting high-quality tie points on vertical surfaces.

**References:** [**1**] Robinson et al. (2010), *Space Sci. Rev*. doi: 10.1007/s11214-010-9634-2. [**2**] Wagner and Robinson (2014), *Icarus*, 237C, 52–60. doi: 10.1016/j.icarus. 2014.04.002 [**3**] Chappaz et al. (2017), *GRL*, 44, 105-112 [**4**] Kaku et al. (2017) *GRL*, 44, 10,155-10,161, doi: 10.1002/2017GL074998. [**5**] Wagner and Robinson (2019), 50th LPSC, #2138. [**6**] Sides et al. (2017), 48th LPSC, #2739. [**7**] Agisoft [**8**] Henriksen et al. (2017), *Icarus*, 283, 122-137 doi: 10.1016/j.icarus.2016.05.012 [**9**] Mazarico et al. (2018), *PSS*, 162, 2-19, doi:10.1016/j.pss.2017.10.004 [**9**] Robinson et al. (2012), *PSS*, 69, 1, 18-27. doi: 10.1016/j.pss.2012.05.008 [**10**] www.blender.org [**11**] www.cloudcompare.org [**12**] www.agisoft.com [**13**] Wagner et al. (2018), 49th LPSC, #1538.

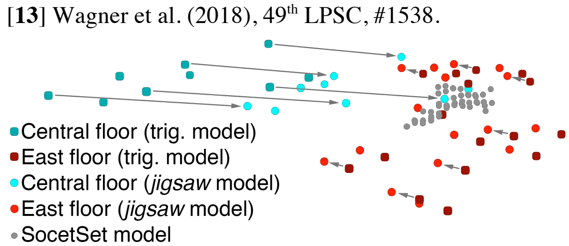


**Fig. 2:** Trigonometric models (poorly aligned), *jigsaw* models (well-aligned), and SOCETSET model (grey) of the MTP floor. View is from the southeast, up is up.