TESTING THE ABILITY FOR DECONVOLUTION AND NYQUIST-SAMPLING TO ALLOW DETECTION OF SMALL IMPACT CRATERS: LUNAR PROOF-OF-CONCEPT WITH LUCY'S L'LORRI CAMERA.

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Introduction: In the exploration of planetary surfaces, one of the most ubiquitous scientific instruments is an imager. Images returned to Earth permit a myriad of scientific investigations into these foreign bodies. While imaging systems are designed to specifications that allow them to fulfill each mission's primary goals, there is always a desire to read between the lines – to try to interpret features only be a few pixels across.

On NASA's *New Horizons* mission to the Pluto-Charon system, images from the LOng-Range Reconnaissance Imager (LORRI; [1]) were taken with slight pointing variations as the spacecraft drifted slightly, effectively creating sub-pixel dithering. These images were combined and deconvolved to produce images with better-than-native LORRI resolution (hereafter "deconvolved" images in contrast with "native" images, though the term does not fully capture the processing). Some *New Horizons* team members used these images to try to identify impact craters across terrains that were better imaged later in the flyby. The impact craters were compared using crater size-frequency distributions (SFDs), which demonstrated the deconvolved images could be used to identify features that produced an SFD similar to one when using native LORRI images with higher resolution [2].

The same concept is being employed by NASA's *Lucy* mission to the Trojan asteroids with the *Lucy* LORRI (L'LORRI; [3]). The goal is to allow the deconvolved images to be used to accurately interpret landforms that are close to the resolution limit of a native L'LORRI image.

Lucy science flyby targets have never been observed at high spatial resolutions, which is problematic for understanding the accuracy of future deconvolved images. However, *Lucy*'s Earth Gravity Assist (EGA) in October 2022 provided an opportunity to test this technique on the well-imaged lunar surface. The team used EGA lunar imaging to test if deconvolved images can identify real features smaller than visible in native L'LORRI images, given the ground-truth of better lunar images from other spacecraft.

Lunar Imaging Campaign, Image Processing: The spacecraft pointed at a fixed RA/DEC in space, and the Moon was allowed to drift through the L'LORRI field, which covered ≈⅓ of the lunar disk. Ten times during the fixed stare, or 10 "driftings," 40 images were taken of both lunar maria and highlands, with solar incidence angle spanning ≈40° to >90°. Nominal pixel scale was ≈1.25 km. Due to L'LORRI's extended point-spread function (PSF), one "resolution element" ("resel") in *Lucy* planning is approximated as 3 native L'LORRI pixels, or 3.75 km during EGA.

Basic image calibration was run using existing *Lucy* pipelines. A set of four driftings was selected that showed the most lunar surface, and the deconvolution process was run. In brief, 10 images from the 40 within each drifting were combined to generate a Nyquist-sampled super-image using [4]. The pixel scale of each super-image was 2× native and then deconvolved using the Lucy-Richardson algorithm and a Nyquist-sampled reconstruction of the L'LORRI PSF. Each final deconvolved image – one per drifting – was paired with its counterpart from the middle of each of the four selected sequences (Figure 1).

We imported both deconvolved and native images into ESRI's *ArcMap* software and used 50–100 manual tie points to georectify each image into the lunar coordinate system, using the *Lunar Reconnaissance Orbiter* Camera's Wide-Angle Camera (LROC-WAC) mosaic as reference. Images needed to be referenced so crater-matching could be done later.

Crater Identification: Craters were identified and measured in each image with several days' pause between them to try to avoid the researcher remembering what they did or did not include. At the time of this abstract, SJR is the sole mapper, but it is anticipated that by LPSC, additional researchers will have repeated the experiment. Therefore, all results here are preliminary and based on one researcher's interpretation.

Analysis— Overall SFD: Ideally, if a crater SFD were approximately linear on a relative SFD (RSFD or R-plot), we would expect a horizontal line of craters from large to small that would reach some minimum diameter and then curve down due to incompleteness. Ideally, we would expect the RSFD from deconvolved L'LORRI images to simply have a smaller minimum diameter at which the downturn begins.

Figure 2 shows the RSFD from SJR's crater identifications compared with a ground-truth lunar crater database made with topography, gravity, and much higher resolution images at a variety of solar incidence angles [5]. It shows that the deviation from native L'LORRI images occurs for crater diameters ≲10 native pixels. It also demonstrates that the deviation for craters on deconvolved L'LORRI images *does* occur at a smaller diameter, ≈7.5 native pixels (corresponding to ≈15 deconvolved pixels), but the RSFD goes well above the reference at ≈1 pixel smaller than that.

True Positives, False Negatives, and False Positives: In the *New Horizons* study, only SFDs were compared. It was unknown if the SFD matched because the processing created the appearance of craters ("cratering by deconvolution") or if the craters were real. In this test, we used a DBSCAN [6,7] cluster analysis to match craters between ground-truth [5], native L'LORRI, and deconvolved L'LORRI to determine matches. From those matches, we could determine true positives (craters found in L'LORRI that are also in the ground-truth), false negatives (craters missed in the L'LORRI data), and false positives (features identified as craters in L'LORRI data that do not have a matching counterpart in the ground-truth).

Ideally, rates would be 100%, 0%, and 0%, respectively. Due to resolution limitations, we would expect false negatives to grow as crater diameter shrinks, but still hope that false positives have a 0% rate regardless of size (*i.e.*, no "cratering by deconvolution").

Table 1 shows this analysis based on matching craters as a function of diameter; the matching was set to allow moderate deviations from the ground-truth catalog [5] that, if tightened, would increase the false positive rates, and if relaxed further, would lower them. The recovery rate (true positives) is very high for larger craters with a corresponding low false negative rate at large craters (bins with one or two craters notwithstanding). These decrease and grow, respectively, as one goes to smaller diameters. The table also shows that the recovery rate is consistently better when using deconvolved rather than native L'LORRI images. It is above 70% consistently for the diameter bin of ≥11.3 pix, whereas it is only above 80% for native L'LORRI for the ≥32 pix diameter bins. Similarly, the 50% detection level is one diameter bin better for craters on the deconvolved images as opposed to native.

Summary: At the time of this writing, analysis is ongoing, and these results are from one researcher's examination of the images. We have also found interesting trends with incidence angle that we will discuss at the 2023 LPSC meeting. However, there are three bottom-line conclusions based on the analysis so far. First, this sort of image processing *does* allow one to reliably recover more smaller features than are plainly visible in native pixel images. Second, deconvolution appears to produce completeness levels comparable to native pixel feature detection but to sizes smaller by ≈sqrt(2). Third, there appears to be minimum amounts of "cratering by deconvolution," but the unknown Trojan geology will require caution.

References: [1] Cheng et al. (2007). doi:10.1007/s11214-007-9271-6. [2] Robbins et al. (2017). doi:10.1016/j.icarus.2016.09.027. [3] Levison et al. (2021). doi:10.3847/PSJ/abf840. [4] Lauer (1999). doi: 10.1086/316319. [5] Robbins (2019). doi: 10.1029/2018JE005592. [6] Ester et al. (1996). [7] Robbins et al. (2014). doi: 10.1016/j.icarus.2014.02.022. [8] Robbins et al. (2018). doi: 10.1111/maps.12990.

Funding: This work was funded by NASA's *Lucy* mission.

Table 1: Summary of results for matching features. "N" and "P" are Native versus Processed L'LORRI images, respectively.

	True Positive		False Positive		False Negative	
D Range (px)	N	P	N	P	N	P
4–5.7	16%	47%	0%	0%	84%	**53%**
5.7–8	44%	**54%**	3%	41%	**56%**	46%
8–11.3	**52%**	56%	7%	37%	48%	44%
11.3–16	71%	76%	18%	12%	29%	24%
16–23	71%	71%	14%	14%	29%	29%
23–32	57%	71%	0%	0%	43%	29%
32–45	**80%**	**80%**	0%	0%	20%	20%
45–64	80%	100%	0%	0%	20%	0%
64–91	50%	50%	0%	0%	50%	50%
91–128	50%	100%	0%	0%	50%	0%

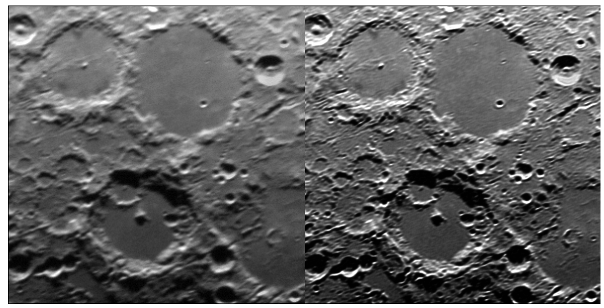

Figure 1: Sample native L'LORRI image (left) and deconvolved image (right).

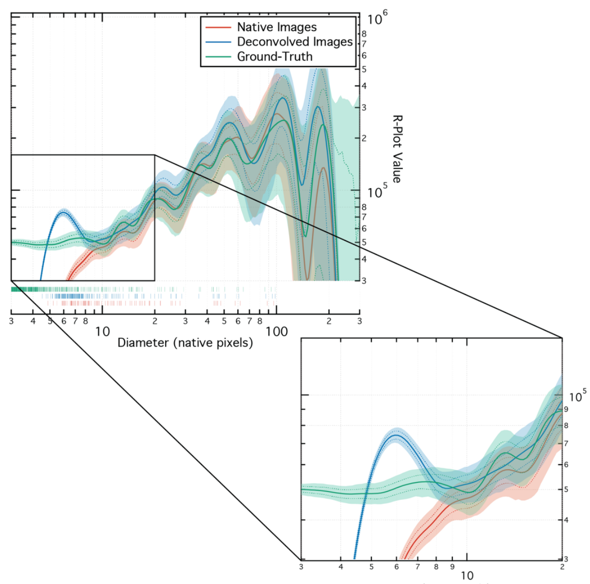

Figure 2: RSFD (arbitrary scale) following the method of [8] which has a rug plot on the bottom showing a mark for each original crater. The completeness-based deviation areas are expanded in panel at the bottom-right (note: 10 native = 20 deconvolved ≈ 3.3 resels). Shape deviation begins at ≈10 native pixels and ≈16 deconvolved pixels. 1σ deviations (short-dashed lines) begin at ≈9 native pixels and ≈15 deconvolved pixels. 2σ deviations (shaded bands) begin at ≈8 native pixels and ≈14 deconvolved pixels.