ACQUISITION AND PROCESSING OF X-RAY CT WHOLE-CORE DATA FOR APOLLO SAMPLES 73001 AND 73002. R. A. Ketcham[1] R. D. Hanna[1], D. R. Edey[1], R. A. Zeigler[2], S. A. Eckley[1,3], [1]Jackson School of Geosciences, University of Texas at Austin, Austin TX, [2]NASA, Johnson Space Center, Houston, TX, [3]Jacobs Technology, Johnson Space Center, Houston, TX.

Introduction: Prior to destructive sampling as part of the Apollo Next Generation Sample Analysis (ANGSA) program, paired Apollo 17 drive-tube cores 73001 and 73002 were brought to the University of Texas High-Resolution X-ray Computed Tomography (UTCT) Facility for high-resolution scanning. In addition to providing context for lithic fragments subsequently extracted from the cores for further study, these scans present a unique opportunity to study an intact lunar soil profile. Core 73002 was scanned in October 2019 [1], and 73001 in March 2022 [2].

Because of their importance and uniqueness, the cores were scanned at 12.9 µm resolution, an exceptional level for their size (~44 mm diameter and ~356 mm long), resulting in over 1.1 Tb of image data. Technical challenges were encountered with both scans, particularly that of 73001, which required adapting scanning conditions and considerable subsequent specialized processing of both the raw data prior to reconstruction and the reconstructed image data to maximize quality and fidelity. Due to the extent of these interventions, and their potential impact on any quantitative analysis of the image data, particularly in terms of effective relative X-ray attenuation of different phases and core sections, we here report the scanning and data processing in detail.

Raw Data Acquisition: Both cores were scanned in an instrument custom-designed by North Star Imaging (NSI), using a Feinfocus FXE 225.48 microfocal X-ray source and a 2048x2048 Perkin Elmer flat panel detector. To achieve maximum spatial resolution, we used the NSI Subpix™ capability, in which four overlapping data sets are gathered with half-pixel vertical and horizontal offsets of the detector, effectively doubling the detector size to 4096x4096. Data were acquired as a series of individual cone-beam volume scans, with overlap to aid in stitching them together to create a continuous data set for each core.

73002 scanning conditions. Curators removed the stainless-steel outer sleeve of core 73002 and triple-sealed the aluminum inner sleeve in teflon at Johnson Space Center. It was scanned mounted vertically in a plexiglass tube, with X-rays at 180 kV and 0.18 mA and pre-filtered with 0.72 mm Al. To complete scanning within time limits, each Subpix™ sub-acquisition was done with continuous rotation. A series of six volumes was acquired, with ~380 slices of overlap.

The continuous-rotation acquisition was slightly incompatible with the state of the Subpix™ software at that time, and the four data sets for each volume were rotationally mis-aligned from each other by up to 0.35°, resulting in a blurred reconstruction. Sharpness was recovered by manually re-aligning the raw projection images using bash scripts. A software beam-hardening correction was applied during reconstruction.

73001 scanning conditions. Pre-scanning of core 73001 at JSC revealed that the core was over-filled, resulting in poor seating of its inner aluminum seal when it was initially packaged on the Moon. It was thus decided to leave the core in its stainless-steel outer sleeve for scanning, necessitating a number of changes in scanning conditions. The core was positioned for scanning in a custom PVC tube mount. X-ray energy was increased to 190 kV, and no filter was used, in an attempt to compensate for the steel sleeve effectively serving as a more severe filter than aluminum. Gantry positions were adapted to allow the steel outer sleeve to be excluded from the field of view and achieve the same voxel size. For this scan non-continuous rotation was used, avoiding rotational mismatch issues. A series of 9 scan volumes was acquired along the length of the core. However, the configuration changes led to an under-estimation of the overlap required to avoid cone-beam artifacts at the top and bottom of each scan in the overlap regions. Additionally, a steel wire within the steel tube, twisting around the length of the core, cast a secondary beam hardening and scattering artifact that resulted in uneven brightness in the reconstructed data. This complicated estimating the optimal beam-hardening correction factor, so the value for the 73002 scan was re-used.

Other complications arose from the inner core sleeve being slightly tilted with respect to the outer sleeve, causing the core region of interest to migrate slowly in slice images from the top to the bottom of the drive tube, and the bottom of the inner sleeve including a stainless-steel cap that served as the drill bit on the Moon, but led to additional beam hardening and scattering artifacts.

Both scans were corrected for ring artifacts before further processing using methods created at UTCT [3].

Stitching-Related Corrections: During re-stitching of cone-beam image volumes for core 73002, we discovered a dimensional inaccuracy in the scan plane of 5-7 pixels between the top of one scan and the overlapping bottom of the next, probably owing to a slight miscalibration of the gantry and detector configuration. To address this, slice images in each volume were progressively isometrically rescaled in *X* and Y so all matched the mid-plane slice, using scripts in the IDL programming language. Each volume was also translated and rotated to match the prior one, utilizing the SIFT algorithm in ImageJ to find the transformation matrix. Finally, there was also a continuous change in image gray values from the top to the bottom of each cone-beam acquisition. This was corrected by rescaling using a second-degree polynomial, so that overlapping slices matched.

Core 73001 required the same geometric correction as 73002, but gray levels were not adjusted at this stage owing to complications stemming from other artifacts.

To improve data continuity between individual core volumes, a series of slices in the overlap regions were linearly averaged. Nine overlapping slices were used for 73002, and 80 for 73001 as a part of addressing the insufficient-cone-beam-overlap issue.

Grayscale Corrections: No further processing was done for the core 73002 data, but the remaining artifacts for 73001 required considerably more intrusive corrections. All corrections were first designed and calibrated using down-sampled versions of the data set, and then applied to the full-resolution data. All corrections were written as IDL functions.

The artifact from insufficient cone-beam overlap consists of progressive radial darkening, with some blurring, growing from the image edges toward the center as the bottom or top of a cone beam acquisition is approached. The artifact is centered in the scan field of view, but off-center with respect to the core material, due to the tilt of the inner sleeve. The radial progression and magnitude of the darkening was measured at each interface between cone-beam volumes. A functional form for the cone-beam artifact was found empirically as: $f_{CB}(r)=C_0 \tanh(C_1 (r\text{-}C_2))$, where C_0 is magnitude, C_1 radially scales the tanh function, and C_2 is the artifact inner radius. The artifact was modeled with the inner radius increasing linearly and magnitude decreasing linearly with vertical progression up and down from the center of overlap. Optimal values for all parameters were found by a combination of fits to the measured data and manual adjustment. This correction was applied to all interfaces prior to further processing.

Removing grayscale variations due to beam hardening and scattering was done by first precisely locating the center of the aluminum inner sleeve in each slice image, and then utilizing the innermost annulus of the sleeve as an effective attenuation standard to normalize gray levels both radially and along the core. The asymmetric effect of the steel wire between sleeves was characterized using the first three components of a Fourier expansion, $f_{ASYM}(\theta)=M_0 + M_1 \sin(\theta+A_1) + M_2 \sin(\theta+A_2) + M_3 \sin(\theta+A_3)$, where M and A are the magnitude and angular offset for each Fourier component. Values for these seven terms were fitted for the inner sleeve annulus each slice image, and they were used as the basis for a correction that scaled linearly from ~25% of the core radius to the outer portion of the aluminum sleeve. The sleeve could not be used for normalization at the steel-covered cap, and so the Fourier magnitudes were estimated based on linear extrapolation from the adjacent Al-enclosed section.

Removal of the asymmetric artifact revealed that the software beam-hardening correction applied during reconstruction had slightly over-corrected the data, making the core center brighter than its rim. This effect was fitted with a function of the form: $f_{BH}(r_c) = C_0(1\text{-}\exp(C_1\ r_c))$, where r_c is the radial distance from the center of the core, C_0 scales the magnitude, and C_1 scales the radial variation.

The stainless-steel cap caused severe beam-hardening and scattering artifacts that required another custom correction. The principal artifact was a steep rise in gray levels toward the steel rim, with an extent and severity that varied with steel thickness. The artifact was characterized by fitting another beam-hardening function $f_{\mathrm{BHS}} = C_0 \exp(C_1\ r_c\text{^}C_2)$ in two locations with different steel thicknesses, which were interpolated radially based on steel thickness.

The corrections f_{ASYM} and f_{BH} or f_{BHS} were combined into a single correction map for each slice, that was then subtracted from the data. Finally, a circular mask was used to remove everything more than a few voxels beyond the aluminum inner sleeve.

Outcomes: Based on comparisons along the core of void spaces and similar clast types, the corrections did an exceptional job of improving the consistency of meaning of the grayscale data along the cores. However, some imperfections and inconsistencies remain. The beam hardening correction for 73001 was more complete than for 73002, which could be improved using the method employed for 73001. There are scattering effects from the steel cap of 73001 that were not removed, and slightly contaminate data in that area, appearing as radially expanding and contracting areas of brightening or darkening. Nevertheless, even with these and other minor exceptions, the stage is set for quantitative investigation of the image data for these one-of-a-kind samples.

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References: [1] Zeigler R. A. et al. (2021) *LPSC 52*, #2632. [2] Zeigler R. A. et al. (2022) Annual Mtg. of the Meteoritical Society 85, #6504 [3] Ketcham R. A. (2006) *Proc. SPIE*, 63180O1-7.