INFERRED LUNAR BOULDER DISTRIBUTIONS AT DECIMETER SCALES. S. M. Baloga[1], L. S. Glaze[2], P.D. Spudis[3], [1]Proxemy Research (20528 Farcroft Lane, Laytonsville, MD 20882 steve@proxemy.com, [2]NASA Goddard Space Flight Center (Code 698, Greenbelt, MD 20771), [3] Lunar and Planetary Institute, Houston TX

Introduction: Block size distributions of impact deposits on the Moon are diagnostic of the impact process and environmental effects, such as target lithology and weathering. Block size distributions are also important factors in trafficability, habitability, and possibly the identification of indigenous resources. Lunar block sizes have been investigated for many years for many purposes [e.g., 1-3].

An unresolved issue is the extent to which lunar block size distributions can be extrapolated to scales smaller than limits of resolution of direct measurement. This would seem to be a straightforward statistical application, but it is complicated by two issues. First, the cumulative size frequency distribution of observable boulders 'rolls over' due to resolution limitations at the small end. Second, statistical regression provides the best fit only around the centroid of the data [4]. Confidence and prediction limits splay away from the best fit at the endpoints resulting in inferences in the boulder density at the CPR scale that can differ by many orders of magnitude [4]. These issues were originally investigated by *Cintala and McBride* [2] using Surveyor data.

The objective of this study was to determine whether the measured block size distributions from Lunar Reconnaissance Orbiter Camera – Narrow Angle Camera (LROC-NAC) images (m-scale resolution) can be used to infer the block size distribution at length scales comparable to Mini-RF Circular Polarization Ratio (CPR) scales, nominally taken as 10 cm. This would set the stage for assessing correlations of inferred block size distributions with CPR returns [6].

We have compiled block measurements for approximately two dozen fresh mid-latitude craters and various sites visited during the Apollo program. Two topics of analysis are presented here. First, the Surveyor III and VII data were reanalyzed to investigate whether the longstanding conclusions given in *Cintala and McBride* [2] are valid. The second topic was the crater Linné. Many tens of thousands of block sizes for the interior and exterior of the crater were obtained from NAC data. The statistical properties of these distributions are determined below as well as methods for extrapolating from NAC data down to scales relevant to CPR.

Surveyor Data Revisited. The Surveyor III block size data from *Cintala and McBride* [2] was trimmed below 1.8 m, the assumption being that the rollover in the distribution is caused by the limits of image resolution. Three statistical fitting models were investigated: power law, exponential and log-square-root (log sqrt). Both a power law and an exponential provide seemingly excellent fits with R^2 values of 93 and 95% respectively. However, when these fits are extrapolated to 10 cm, they both give implausible areal block densities that differ from each other by 3 orders of magnitude. These wildly varying extrapolations are caused by a small 'lack of fit' [4] for small boulder sizes.

A fitting function that mitigates this problem is the 'log sqrt model' available in the Statgraphics Centurion statistical software: $N = e^{(a+b\sqrt{diameter})}$. The fit (Fig. 1) gives an R^2 of 95% and a random residual pattern at the small end.

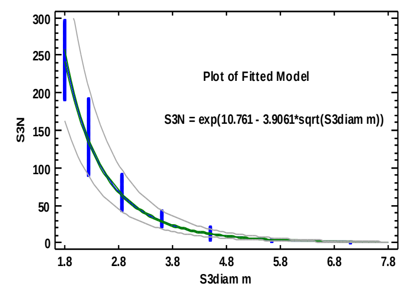

Fig. 1 log sqrt fit to Surveyor III data.

When this fit is extrapolated to 10 cm, the resulting estimated block density is 0.03/m^2, which is consistent with the values obtained using NAC data for Linné and numerous other craters. However, the distinction between the exponential and log sqrt forms is very difficult to rigorously delineate on the basis of statistics alone. This may be due to the use of the binned data given in *Cintala and McBride* [2] or post-impact modification of the block size distribution. Similarly the orbital data from Surveyor VII shown in *Cintala and McBride* [2] was reanalyzed. The distribution was trimmed below the resolution limit of 12.6 m, about an order of magnitude larger than the Surveyor III value. For this population of much larger boulders, the power law fit is significantly better than all the alternatives from all statistical perspectives (e.g R^2, mean absolute error, lack of fit). The extrapolated areal density at 10 cm, however, is again an unrealistic 602/m^2. The exponential and log sqrt models are inferior models and result in areal densities on the order of 10^{-5}/m^2 and 10^{-4}/m^2, respectively. The conclusion of this reanalysis is that the larger boulder population does indeed follow a power law distribution, but no model produces credible predictions of block densities at the 10 cm scale.

Analysis of Linné crater. More than 60,000 blocks were measured in the interior and exterior of the crater

Linné from NAC images. To avoid accumulating small errors, the first 5000 boulders were selected. A small block cutoff of 2 m was used to avoid resolution effects. The same three fitting models were again investigated. Three criteria were examined for each of these three distributions, R^2, the mean absolute error (MAE) of the fit, and the pattern of the residuals in the small diameter range.

Table 1.

Model	#/m2	R^2	MAE	Small Diam Fit
EXTERIOR				
log sqrt	0.113	99.25	0.057	Good
exp	0.015	96.17	0.093	Good
pwr	21.749	96.34	0.142	Poor
INTERIOR				
log sqrt	0.120	99.29	0.039	Good
exp fit	0.015	96.22	0.088	Good
pwr	40.527	96.80	0.124	Poor

The results for the crater exterior distribution are shown in Table 1. By all measures, the log sqrt function provides the best model (Fig. 2). The conventional power law would seem to be a reasonable fit. However, there is a poor fit at the small diameters. Any lack of fit in the small diameters leads to wildly varying predictions at the 10 cm scale. Also the power law extrapolation is 2-3 orders of magnitude higher than the other two preferred models. Similarly the exponential model does not suffer from a lack of fit for small diameters. The log sqrt model improves the R^2, but more importantly reduces the MAE by about a factor of two. This model provides the best estimate of the block density at the 10 cm scale (0.113/m^2).

The same forms were used to investigate block size distribution of the interior of Linné (See Table 1).

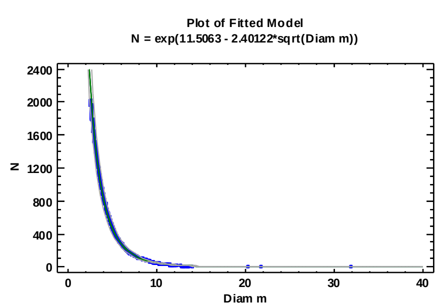

Fig. 2. log sqrt fit to Linne exterior.

The parameters of the fit and the inferred areal density of 10cm blocks (0.12) are indistinguishable for the interior and exterior of the crater. Moreover, there is no ambiguity about the statistical approach to extrapolating from NAC data down to scales relevant to CPR. The improved fit of the log sqrt at small diameters is illustrated by the pattern of the residuals (Fig. 3.)Even more compelling is the mean absolute error, which is approximately 3 times smaller for the log sqrt model. Of the various craters and areas investigated, Linné has the highest areal density of rocks at the decimeter scale. The model results show a significant departure from the power law anticipated from simple impact comminution [1, 2, 5] and other planetary studies.

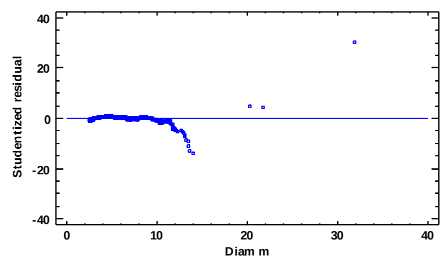

Fig. 3. Log sqrt residuals for Linne.

Conclusions: The power-law distribution of rock fragment sizes anticipated by conventional studies rarely provides the best statistical fit for boulder measurements based on NAC images. Exponentials, quartics, and more exotic models provide significantly better fits using standard statistical evaluation criteria. This suggests that the block size distributions of the fresh craters reflect complicated comminution processes or the influence of multiple processes, such as weathering or mass wasting subsequent to impact. Reanalysis of the Surveyor data shows that nonphysical block size distributions result from standard statistical extrapolations to CPR scales unless small-scale lack of fit criteria are additionally imposed. Analyses of interior and exterior block size distributions for Linné produce physically reasonable extrapolations of measured block sizes at the 10cm scale. The quality and defensibility of the extrapolated statistical fits provides a basis for determining whether CPR returns are correlated with surface roughness. Results from our initial studies of CPR and block size distributions suggest that a log sqrt extrapolation is generally appropriate to account for the range of CPR values that have been observed [6].

References: [1] Shoemaker G. et al (1968) NASA SP-180. [2] M. J. Cintala and K. M. McBride (1995) *NASA Technical Memorandum* **104804** [3] G. D. Bart and H.J. Melosh (2010) *Icarus* **209**, 337-357 [4] Draper and Smith, Applied regression analysis, Wiley, 1966 407pp. [5] Melosh H.J. (1989) Impact Cratering. Oxford Univ. Press, 245 pp. [6] Spudis P. *et al.*, this vol. (2012).