3D-LASER-SCANNING TECHNIQUE APPLIED TO BULK DENSITY MEASUREMENTS OF APOLLO LUNAR SAMPLES.

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Introduction: In order to better interpret gravimetric data from orbiters such as GRAIL and LRO to understand the subsurface composition and structure of the lunar crust, it is import to have a reliable database of the density and porosity of lunar materials. To this end, we have been surveying these physical properties in both lunar meteorites and Apollo lunar samples.

To measure porosity, both grain density and bulk density are required. For bulk density, our group has historically utilized sub-mm bead immersion techniques extensively [cf. 1,2], though several factors have made this technique problematic for our work with Apollo samples. Samples allocated for measurement are often smaller than optimal for the technique, leading to large error bars. Also, for some samples we were required to use pure alumina beads instead of our usual glass beads. The alumina beads were subject to undesirable static effects, producing unreliable results [3].

Other investigators have tested the use of 3d laser scanners on meteorites for measuring bulk volumes [cf. 4]. Early work, though promising, was plagued with difficulties including poor response on dark or reflective surfaces, difficulty reproducing sharp edges, and large processing time for producing shape models. Due to progress in technology, however, laser scanners have improved considerably in recent years.

We tested this technique on 27 lunar samples in the Apollo collection using a scanner at NASA Johnson Space Center. We found it to be reliable and more precise than beads, with the added benefit that it involves no direct contact with the sample, enabling the study of particularly friable samples for which bead immersion is not possible.

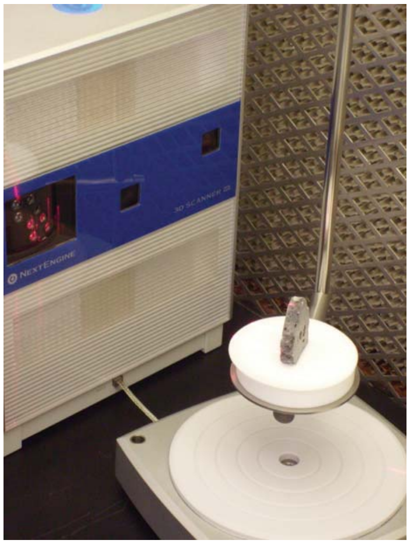

Figure 1: Laser scanner apparatus

Instrumentation and measurement: We utilized a NextEngine 3D Scanner HD model 2020i located on-site at NASA Johnson Space Center. This instrument was supplemented by ScanStudio HD Pro and the CAD Tools software. The scanner also comes with a rotating stage. Documentation for the scanner claims dimensional accuracy of 0.1 mm, with a capture density of 24,800 points cm^{-2} and a texture density of 62 dots cm^{-2}.

During measurement, the sample is placed on the rotating stage. 10 to 16 separate scans are produced with the stage rotated partially between each scan, producing a 360-degree partial model of the sides of the sample. To fill in the missing top and bottom portions, the sample is tilted and the scan is repeated. The entire process can take from 30 minutes for a low-resolution scan (suitable for larger samples with regular surfaces) to 90 minutes at high resolution (better for irregular surfaces or small samples).

Following measurement, the partial models must be processed to remove artifacts and then merged to form a complete shape model, from which volume is calculated. This generally takes less than an hour, but may be done after-the-fact. Thus, it need not interfere with productivity during the scanning process itself.

We found that the software had difficulty meshing scans of samples that had been cut into regular shapes such as cubes or parallelepipeds, producing a chaotic mess. Including external references in the scan window eliminated this problem, and since adopting this practice we have encountered no further difficulties.

Theoretical 1-σ uncertainties in volumetric measurements at high resolution are about 0.4% for a 1 cm^3 sample and decrease with sample size to 0.02% for samples above about 40 cm^3. We are still trying to confirm this experimentally, but the device appears to be capable of at least an order of magnitude improvement over the Archimedean glass bead method.

The scanner was tested using an arbitrary sample of low-grade high-carbon ferro-manganese alloy that resembled a meteorite in its exterior. This object’s low albedo and irregular shape with a specular feature would have been challenging for early laser scanners. It was scanned at three resolutions. High and medium resolution results agreed to within 0.001% at 21.1223 cm^3 and 21.1219 cm^3, respectively Low-resolution produced 21.1052 cm^3, or a difference of 0.08% from the other scans.

Results: We completed scans of 27 lunar samples over the course of 7 workdays in October. Many of these had been previously measured with alumina beads. While most of the alumina-bead results are within 2σ of the laser results, many fall outside that margin, with lower-mass samples having the greatest errors (Fig. 2). We attribute this to the unreliability of the bead technique for samples less than about 10 gm, coupled with the strong static response of the alumina beads.

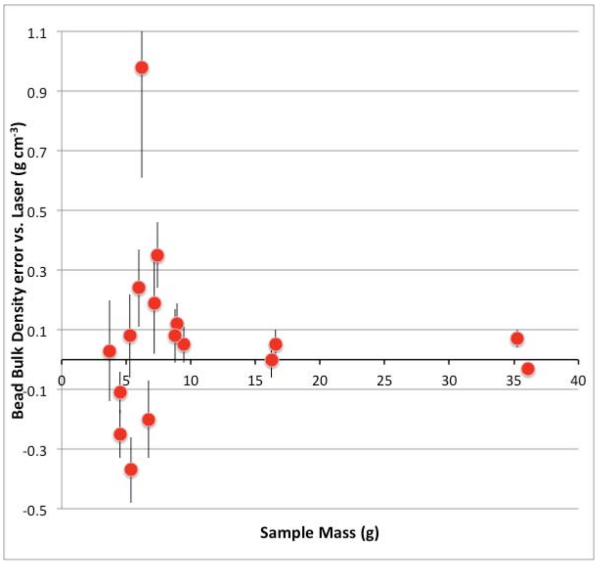

Figure 2: Difference between bulk densities measured with alumina beads vs. with laser, as a function of sample mass. Error bars are 1-σ based on bead data.

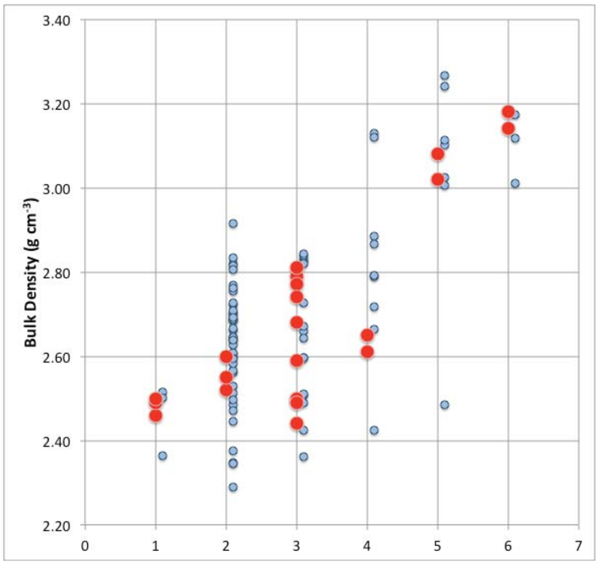

Figure 3: Bulk densities of all lunar samples (including meteorites) measured to date. Blue dots are glass-bead data, and red dots are laser data. Groups are: (1) Imbrium ejecta, (2) feldspathic, (3) impact-melt breccia, (4) other (regolith or polymict) breccia, (5) low-Ti basalt, (6) high-Ti basalt.

Figure 4: 14305,483 (wrapped in aluminum foil) in the larger pycnometer.

When compared with lunar samples and meteorites that had been measured with glass beads, there is good agreement in the data between the laser and the bead results for rocks of the same type (Fig. 3). Because only one glass-bead-measured sample was subsequently scanned (and it was only 4.5 gm), variation in results cannot *a priori* be attributed to either inhomogeneity among samples or measurement accuracy.

14305,483: A 156 gm slab of 14305, normally a display piece, was temporarily available for measurement. This piece of Imbrium ejecta from Fra Mauro was too large to fit in our bead container or our ideal-gas pycnometer (used for grain densities). This made it a good testbed for two new instruments: the laser scanner and a new larger pycnometer [5] (Fig. 4). Both instruments proved quite suitable for a sample of this size yielding a bulk density of 2.45 g cm^{-3}, a grain density of 3.10 g cm^{-3}, and a porosity of 21%.

Friable samples: The laser enabled measurement of several samples that due to friability had been excluded from use with beads. Among these was 14321,88, a 76 gm piece from the Fra Mauro formation which, along with 14305, helps constrain its properties. The two samples are in strong agreement in bulk and grain densities as well as porosities.

Ongoing work: We expect that 3D laser scanning is soon to replace the glass-bead method as the standard technique for bulk volume measurements. We have acquired an instrument for the Vatican Observatory, and are in the process of scanning much of the Vatican meteorite collection, focusing on those samples that had been too friable or fragile for bead work.

References: [1] Macke R. J. et al. (2011) *Meteorit. Planet. Sci.* 46, 311-326. [2] Kiefer W. S. et al. (2012) *Geophys. Res. Lett.* 39, L07201. [3] Macke R. J. et al. (2014) *LPSC XLV*, abstract #1949. [4] McCausland P. J. A. et al. (2007) *Meteorit. Planet. Sci. Suppl.* 42, A5066. [5] Macke R. J. et al. (2013) *LPSC XLIV*, abstract #1398.