MOONRAKER: PROMISE AND LIMITATIONS OF A CONCEPT FOR GRAIN-WISE MINERALOGICAL CHARACTERIZATION OF LUNAR REGOLITH USING RAMAN SPECTROSCOPY. M. D. Fries and A. Steele, Geophysical Laboratory, Carnegie Institution of Washington, 5251 Broad Branch Rd. NW, Washington, D.C. 20015, m.fries@gl.ciw.edu

Introduction: Lunar regolith is composed of a mixture of native and meteoritic materials that have accumulated since the formation of the solid lunar crust some 4.5 Ga ago. Along with native and meteoritic components, lunar regolith should contain a small fraction of material transported from the Earth's surface via impact throughout the history of the Earth-Moon system [1]. While high impact velocity [1] and subsequent impact gardening should have reduced most of this material to a fine powder, a fraction composed of small grains likely remains in the lunar regolith for collection and study. This paper explores the viability of using a roughly suitcase-sized instrument, here dubbed "Moonraker", for grain-by-grain regolith mineralogical analysis to isolate potential terrestrial grains and other important material utilizing Raman spectroscopy. This method can be used to sort through regolith for terrestrial material, for quantifying the volume and structure of condensed carbon in lunar regolith, for *in situ* regolith compositional measurements in support of stratographic analysis, for quantitative mineralogical analysis for *in situ* resource utilization and in general for any studies requiring an understanding of the mineralogical composition of lunar regolith. The comparatively slow pace of grain wise mineralogical identification optimizes this technique for sub-kg sample sizes, however, requiring that Raman analysis is preceded by some other bulk sorting technique if searching for terrestrial material.

Terrestrial Material: The transfer of material from the Earth to the moon is significant because it may preserve samples from the ancient Earth in an unweathered and non-metamorphosed state, although such material would certainly be affected by shock and heating during ejection and lunar impact, and by impact gardening on the lunar surface. It is reasonable to expect that the population of surviving particles would be dominated by sub-mm examples, and that the average size of the particle population would be inversely proportional to their lunar residency age.

Survival: While all terrestrial material transferred to the moon would be subjected to disruption and erosion by lunar impact and subsequent impact gardening the question of whether any material survives at all is addressed by meteorites returned from the lunar surface by Apollo astronauts. These meteorites were subject to the same minimum lunar impact velocity and gardening process as terrestrial material. Apollo meteorites include the Bench Crater carbonaceous chondrite, which is a CM-type meteorite returned to Earth by Apollo 12, the Hadley Rille EH chondrite collected by Apollo 15 and two probable iron meteorites. All of these meteorites measure in the millimeter(s) to 0.1 mm range. Surprisingly, Bench Crater not only survived lunar impact but also was found to contain hydrous clay minerals [2]. Similar clays, if transported from Earth, could contain isotopic and geochemical evidence of their pre-ejection chemical environment and possibly the remains of ancient terrestrial microbiota.

Identification: Raman spectroscopy is suitable for mineral phase analysis that could be accomplished in seconds. Identifying a particular grain as terrestrial is not conclusive by this method, but the goal instead is to triage bulk regolith down to a fraction of the starting material for transport to a laboratory setting. Mineral phases that are anomalous with regard to the general lunar mineralogy suite, such as quartz and any hydrous mineral, could be triaged out of the regolith bulk for sample return. Additionally, minerals useful for isotopic dating such as TiO_2 polymorphs and zircons would be separated for analysis.

Analysis: Investigations of early terrestrial material returned from the moon could cover a range of topics from atmospheric composition, characterization of potential biota remains, and in general the characterization of pre-impact chemical and environmental conditions preserved in terrestrial samples. Determining the age of returned grains would be of paramount importance in order to place other findings in context for these purposes. Small sample size is not necessarily prohibitive to these studies due to the sensitivity and resolving power of modern instrumentation. This fact is best demonstrated by the isotopic, chemical, structural and mineralogical analyses performed on micron-scale cometary particles returned to Earth by the Stardust sample return mission [3].

Other uses of the Moonraker instrument would be comparatively straightforward. Regolith mineralogical composition could be obtained as a function of depth to reveal stratigraphy, which may be useful for constraining the ages of major impact craters especially if coupled with grain size measurements. Isotopic dating of zircons [5] and other relatively impact-resistant mineral phases may assist in this endeavor by providing ages to individual strata.

Modal abundance measurements of condensed carbonaceous material in the lunar regolith would also be possible, since Raman spectrometry is very sensitive to the presence and structure of carbon [6]. This data may ultimately be used to determine the rate of carbonaceous material infall on inner solar system bodies over the course of their evolution. The non-destructive nature of Raman spectroscopy would also preserve carbonaceous and other samples for later examination using other analytical techniques.

It is also worth noting that the Moonraker concept would function equally as well as an instrument on a robotic mission or as a tool for scientist-astronauts performing the measurements described above.

The Moonraker Instrument Concept: The optimal approach for grain-wise analysis by Raman spectroscopy would utilize multiple excitation laser colors and confocal optics. This approach would minimize and possibly eliminate fluorescence as a problem in obtaining a usable Raman spectrum simply by collecting spectra from multiple regions of the visible light spectrum. Laser excitation would be staggered between red, green and blue laser excitation times of around 3s each, focused to a 1 μm spot. Given a typical laser power of 1mW at the focal plane with an attendant power density of 127kW cm^{-2}, total analysis would require ca. 10s per particle assuming a fast method of presenting the particle to the laser focal spot, perhaps in the form of rotating wheel fed by a sample hopper. Several commercial Raman instruments are both handheld and lightweight, illustrating that it is reasonable to expect that a three-color device and sample handing system could be approximately suitcase-sized before a stand and sample hopper are added. It is within reason to expect that customized software can identify the mineral phase of each grain from its unique Raman spectrum following rejection of any high-fluorescence spectra. If searching for terrestrial material, common lunar minerals such as silicate glass, olivine, pyroxenes and feldspar would be discarded while unusual grains would be separated and individually stored for laboratory analysis. Since the list of excluded minerals would include feldspars and glass, which could also be terrestrial in origin, the actual mass of retrieved terrestrial material may be less than the ca. 7 ppm predicted by Armstrong et al [1].

The sheer volume of material to be sorted requires that future work includes calculation of the best size fraction to search from based on expected age of terrestrial material with respect to the investment in time and instrumentation necessary to find a scientifically useful ensemble of terrestrial material. If, for example, particles of 50μm average diameter were examined, it would require 1404 years (and over 4.36 billion measurements) to examine 1 kg of material at 10s per particle with a single instrument. This calculation assumes an average regolith particle density of 3.5g cm^{-3} and spherical particles. Examining 1mm diameter particles, by contrast, would produce 1kg of examined material every 63 days (or 545,950 analyses) of constant analysis. If we apply Armstrong et al's estimation of ca. 7ppm terrestrial material resident in lunar regolith in terms of mass, this means that one Moonraker device will isolate ca. 3 terrestrial particles 1mm in diameter every 63 days, or one every three weeks. Additional laboratory time, not to mention a protocol for unambiguously identifying terrestrial particles, will be required to isolate the terrestrial material from the selection of anomalous particles isolated by Moonraker. While larger particles would take less time to triage, they would be very large compared to the 1μm laser spot size and the resulting spectrum may not truly represent the particle especially if it is an aggregate. It is also worth noting that many of the assumptions and calculations presented here are generally applicable to any grain-wise analytical technique, especially for measurement rate versus particle size considerations.

Additional work on developing this technique will also require empirical trials on measurement efficiency, sorting efficiency, and development of an efficient and reliable regolith sorting and handling system.

References: [1] Armstrong J., Wells L.E., Gonzalez G., (2002) Icarus 160, 183-196. [2] Zolensky M., (1997) MAPS 32, 15-18. [3] Brownlee D and 183 co-authors, (2006) Science 314, 1711-1716. [4] McSween H., (1976) EPSL 31,2 , 193-199. [5] Meyer C., Williams I.S., Compston W., (1996) MAPS 31, 370-387. [6] Tuinstra F., Koenig J. (1970), J. Chem. Phys. 53, 1126-1130