DISCOVERING THE NANO-MOON: LUNAR DUST AS A SCIENCE AND EXPLORATION OPPORTUNITY. J. B. Garvin[1] & J. S. Jones[2], [1]NASA Goddard *Chief Scientist*, 8800 Greenbelt Road, Greenbelt, MD 20771 (james.b.garvin@nasa.gov; CELL: 301-646-4369), [2]NASA Goddard *Subject Matter Expert for Non-Destructive Evaluation*, Code 541, Greenbelt MD 20771 USA (justin.s.jones@nasa.gov).

Summary: Lunar dust offers an opportunity to investigate a ubiquitous material within the lunar system using rapidly-advancing, quantitative characterization methods well-suited as tools in NASA's return to the lunar surface via *Artemis* (Space Policy Directive-1). Apollo samples of lunar dust and subsequent studies associated with crew safety, plasma dynamics, and micro-meteorite cratering [1-4] have painted a picture of an incompletely characterized "system" of particular importance as science investigations are integrated with human exploration and commercial activities over the next 5-10 years. *Non-destructive evaluation* (NDE) methods can now be used to evaluate lunar dust in the sub-micron size regime (nano-scale) [5-7,15,19], providing new engineering boundary conditions for programs such as *Artemis*, but also to enable a new spectrum of possibilities on the "**nano-moon**", including additive manufacturing (AM), astrobiology of lunar fine materials, and models of micro-cratering processes relevant across the solar system [6,8]. The "**nano-moon**" we define herein includes all of the lunar fine particles less than ~ 20 μm in diameter and embraces consideration of materials at the scale of the smallest biological entities (d < 1 μm) [**Fig. 1**] that may be part of the astrobiology of the Moon [1,3,4]. Advanced laser confocal microscopy (LCM), Scanning Electron Microscopy (SEM), and micro x-ray Computer Tomography (xCT), as well as other next-generation sensors (TEM, XPS), are now part of an arsenal of NDE capabilities that are poised to explore lunar dust in the era of *Artemis*, using the legacy of Apollo samples [5, 6, 15, 24-25] and extending to lunar materials sampled over the next decade by new partnerships in human spaceflight, commercial interests, and international players. The **nano-moon** we recognize today is minimally known, and yet poses engineering challenges recognized for decades by science pioneers such as Dave McKay, Larry Taylor, and many others [1-3, 9-21]. Understanding this **nano-moon** couples the physics of micro-cratering, space weathering, plasma dynamics, and geochemistry in an ensemble of processes that produce a myriad of fine-particle phenomena that vary on the Moon as a function of location, environment, and dynamics [12,18,19,21]. As *Artemis* moves forward, we recommend strong attention to creative application of NDE techniques for characterizing lunar dust down to the finest possible "nano-scales" [3,15,20,24] with potential measurement opportunities on the lunar surface, on the cis-lunar *Gateway*, and in laboratories and curation facilities on Earth (e.g., NASA JSC [5,12]). In particular, the combination of SEM/TEM imaging, LCM 3D characterization, and micro xCT volumetric measurements will address key variables and unknowns associated with lunar dust [1, 10,21,25] that represent aspects of multiple *strategic knowledge gaps (*SKG's) for the Moon [3]. Finally, crew-based measurements and experiments of **nano-moon** materials represent an opportunity for advancing understanding of deep space processes, environments, and engineering/safety challenges that will support the sustainability of human exploration at the Moon and eventually onto Mars. Thus, the **nano-moon** is countably infinite and nearly invisible, yet an essential element of the integrated lunar system awaiting our sustained human/robotic presence via *Artemis*.

INTRODUCTION and BACKGROUND

Lunar dust has long been recognized [1-4, 12, 18-21] as a critical component of the lunar sedimentary system with connections to the plasma environment, micro-meteorite cratering, space weathering, and other deep-space interactions that are absent on Earth. Here we define the "**nano-moon**" as that component of the integrated lunar system that includes all materials finer than about 20 μm (**Fig. 1**), with emphasis on those from 20 nm to 20 μm in diameter, both at the surface and within the exosphere to altitudes sampled by the recent LADEE mission [10,24].

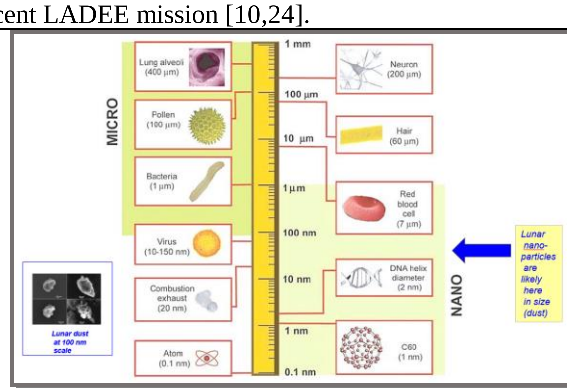

Figure 1: *The sizes of "things" including biological and manufactured materials. The "**nano-moon**" falls between the scale of the DNA helix and red blood cells, and includes the dominant "fine fraction" of particles in the lunar system [12, 18]*. Graphic modified/adapted from [1].

High precision measurements of the particle size distribution (PSD) [4, 21], shape, and composition [19] of **micron and smaller diameter lunar dust particles** are largely unavailable (i.e., only [4] have quantified such ultra-fine dust), and yet this aspect of the lunar surface environment, and its association with regolith formation and evolution [11], as well as future utilization of the Moon, presents a fundamental engineering boundary condition that connects science (from Apollo samples) to National Space Council policy objectives. The importance of ultra-fine-scale lunar dust has been emphasized in multiple science prioritization documents [e.g., *Visions and Voyages*, 2011 – NASEM Planetary Decadal Survey], as well as via investments extending from the LADEE mission [10], LRO, and also includes lunar simulants [2,3]. Here we suggest that *engineering-quality* measurements of Apollo samples with emphasis on sub-micron dust particles, small micro-craters (< 50 μm in diameter), and 3D volumetric analysis (dust, agglutinates, etc.), using available NASA *Non-Destructive Evaluation* (NDE) methods [5-7,25], in combination with advanced data analysis software (including Machine Learning and Neural Networks), is an amply warranted step forward to eliminate key unknowns as we return to the Moon via *Artemis*. Such integrated NDE-based measurements would serve as a pathfinder for studies of the origin, evolution, and significance of ultra-fine dust on the Moon [15] and on other solar system airless body surfaces, together with their connection to micro-cratering processes on such objects [8,11]. Results may also have a bearing on new samples soon to be returned from the asteroid *Bennu* by OSIRIS-REx [23], as well as for refining engineering solutions for upcoming human exploration activities at the lunar surface (*Artemis-3* and beyond, including VIPER and other landed systems).

The Apollo missions acquired samples that include varieties of the finest-scale lunar dust, as demonstrated in the published measurements [1-4,15,21]. However, current measurements do **not** include dust samples of the highlands from Apollo 16 landing site. Furthermore, geometric property measurements of the modal fraction of these nano-scale dust particles (i.e., with modes in the 100-300 nm range) have not been undertaken using newly-available laser confocal microscopes [6, 24,25]. Finally, the association of sub-micron diameter lunar dust with the smallest of the documented lunar micro-craters, such as those with diameters less than ~50 μm (and much smaller), has not been investigated using appropriately selected Apollo samples [8, 6, 11]. Via this invited paper, we recommend pathfinding and foundational measurements that will provide the lunar science and engineering community with quantitative knowledge that extend the existing (but limited) measurements in the *Lunar Sourcebook* [12,18] and other key references in support of *Artemis*. Using state-of-the-art NDE methods and newly-available segmentation and Machine Learning (ML) software for volumetric data analysis, we suggest that inventorying new aspects of this often-forgotten part of the Moon (literally, the **nano-moon**) will catalyze additional community-based investigations and more exhaustive measurements going forward that will contribute to AM, crew safety, sustainability, and potentially to astrobiology.

There is a scientific and engineering urgency to characterize the nano-scale properties of the Moon with emphasis on sub-micron diameter dust [4, 15], but also on micro-craters and other diagnostic features smaller than approximately 20 μm [8,19]. Recently, CAPTEM-approved analyses of a small number of Apollo 16 samples (**60095,36**; **65703,4**; **64803,23**) containing micro-craters has been undertaken using NDE methods at GSFC (via the Code 541 NDE facility [6]); **Figures 4-6** illustrate preliminary results relevant to the **nano-moon**. Connecting these new dust-related CAPTEM-approved surveys of the geometric properties of ultra-small lunar micro-craters to new measurements of sub-micron dust (**Fig. 2**) is another critical objective of the recommended **nano-moon** measurement campaign. Ultimately, community-based results could consist of new PSD, 3D shape (morphology), and chemistry data for highlands dust finer than 20 μm in diameter with comparisons to similar materials from Apollo's 15 and 17 mare site samples, all germane to the first women on the lunar highlands surface at the lunar South Pole via *Artemis-3*.

IMPACT OF APOLLO SAMPLES

Park and others [4] conducted pathfinding measurements of the finest size fraction of the lunar dust using samples from Apollo 11 and 17. We have recast their standard Particle Size Distribution (PSD) results using log-Hyperbolic Distribution (LHD) analysis [22] to isolate the critical sedimentary parameters of these particulates [21]]. **Figure 2** illustrates the separation of increasingly finer sub-populations of the Apollo 11 results published in [4] documenting the importance of an ultra-fine fraction < 500 nm. Such dust particles may represent the "loose" fraction that is in continuous production [11], in contrast with coarser agglutinates and other agglomerated materials, well recognized in the lunar regolith [12, 13, 18, 19].

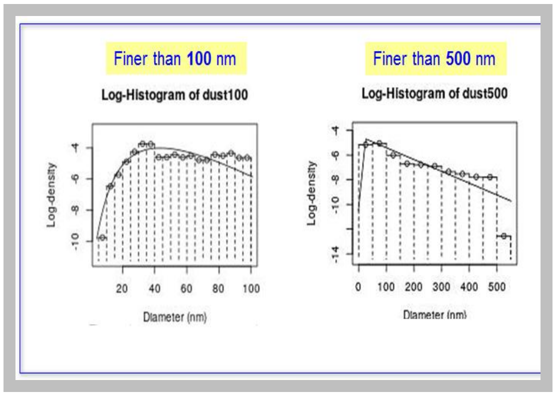

Figure 2: *Log Hyperbolic Distribution analysis of the Apollo 11 dust particle size measurements from [4]. Two size fractions are analyzed in order to isolate sub-populations and sorting effects. The strong isolation of 25-40 nm "ultra-fine" dust is evident in the left-most distribution, while the right plot illustrates the dominance of fine particles < 100 nm. While the overall modal value may be ~ 200-300 nm for many lunar soils, there is clearly a super-fine component in the 30-100 nm size range.* See text and [22] for details.

METHODS: NDE goes to the Moon

Circa 2020, a suite of NDE measurement capabilities are now well-established in NASA and industrial laboratories for materials sciences, engineering, and applied sciences [7]. These include Laser Confocal Microscopy (LCM) for defining 3D properties of materials down to tens of nanometers (vertical resolution), SEM/TEM imaging for morphologies down to < 10 nm, and micro x-ray Computer Tomography (xCT) for particles ~500 nm or larger. Application of these and other more "destructive" methods for characterizing lunar dust are now possible via facilities at NASA's JSC (Curatorial & Engineering, NASA GSFC (NDE Lab and 690 facilities), and at other NASA partners, including the Jet Propulsion Lab. Approaches for innovative handling of lunar dust to facilitate characterization at nano-scales are now possible, which can facilitate a new wave of *in situ* measurements starting with commercial landers (CLPS) and NASA precursor systems such as the VIPER rover. Recent experimental efforts at GSFC's NDE lab have focused on dust affixed to impact glass samples (e.g., **60095,36**) as well as that associated with highlands soil agglutinates (e.g., 64803,23). Landed NDE measurement systems, including proto xCT scanners for AM parts screening, safety, inspection, and sample triage (**Fig. 3**) have the potential to contribute to fundamental new measurements at the Moon, which themselves will inform future approaches as sustained human presence is established [6,7]. Efforts are underway at NASA to develop pathfinder instruments for some of these techniques (proto-xCT: **Fig. 3**) which may benefit from new analyses of Apollo soil samples over the next few years. For example, an integrated xCT, LCM examination of Apollo 16 highlands soils (**Figs. 4-6**) illustrates scales of features related to the sources and sinks of lunar dust at the finest scales, from micro-craters (**Fig. 6**) to dust affixed to lunar glasses and agglutinates (**Figs. 4-5**).

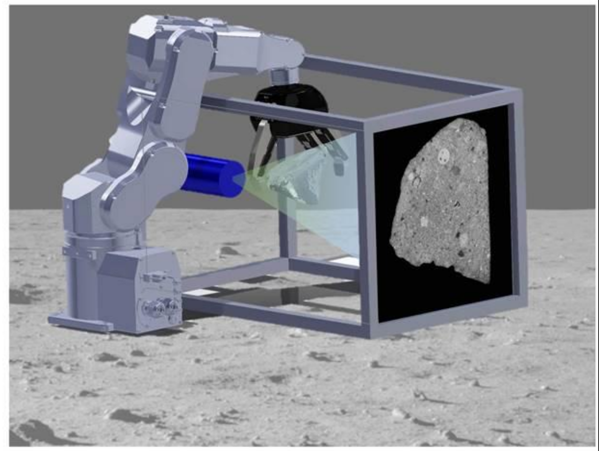

Figure 3: *Possible configuration concept for a proto-xCT scanner for the Moon under development at GSFC to support Artemis, Gateway etc. Such a 3D, volumetric scanning system would provide high-resolution non-destructive views of dust source materials [6].* Graphic adapted from Jones ECI efforts.

EXAMPLES OF OPPORTUNITIES

NASA's prime directive and the related *Artemis* program calls for aggressive return of human explorers (women & men) to the Moon in less than 5 years, with an armada of commercial, international, and NASA robotic precursors between 2020 and 2024. Commercial (CLPS) landers will carry a first-wave of payloads to evaluate the Moon including aspects of dust, and the proposed VIPER lunar resources rover may also address dust issues. When *Artemis-3* lands women on the Moon, it could be equipped with simple instrumentation for measuring (*in situ*) the finest fraction of dust, which is the most difficult to handle after return to Earth laboratories [4]. New technologies for dust characterization are now utilized via industrial laboratories and some of these approaches can readily be adapted for the Moon [5-7] (**Figs. 4-6**).

The **nano-moon** in general defines new opportunities for experimentation, building on the work by multiple NASA-funded virtual institute (SSERVI) teams over the past decade (e.g., DREAM-1, 2). One compelling concept involves the so-called astrobiology of the Moon and the consideration of agnostic life detection principles, as recently established by Professor Sarah Johnson's *Laboratory for Agnostic Bio-signatures* (LAB), which is a Research Coordination Network (RCN) within NASA's Astrobiology program. It is possible that microbiological experimentation on lunar dust can form the basis of a new line of research as biological systems are sent to the Moon for long-term, sustainable activities that include living systems at many scales. Other habitability-related aspects of lunar dust may also be relevant, as in [1].

RECOMMENDATIONS

The **nano-moon** presents a *scientific opportunity* that is associated with overarching safety and engineering considerations as human/robotic systems are established on the Moon in the near term [1-4]. The dust that is generally finer than ~20 µm, and as fine as ~ 10 nm [1,4], is pervasive, dynamic, and a part of the lunar environment that presents a materials science "frontier" [9,10,15]. While in many ways it must be mitigated as a hazard, it also must be evaluated as a long-standing part of the lunar environment [1,10] and regolith sedimentary system [11], with interactions that may relate to the lunar water cycle, dusty plasma dynamics, and space weathering [10,15,19, 21]. Characterization of this *almost invisible* **nano-moon** is nonetheless important and significant as science learns from the Moon in new ways in order to establish paradigms that are also relevant to asteroids and eventually to Mars. Applying NDE measurement systems to existing Apollo dust samples and extending them to new samples both on the Moon and those returned to Earth can be accomplished within the framework of safety, inspection, resources utilization, and applied science (geotechnical). Innovative development of *in space* xCT, LCM, and SEM systems may represent a key step, with benefits across multiple disciplines [5,7, 23].

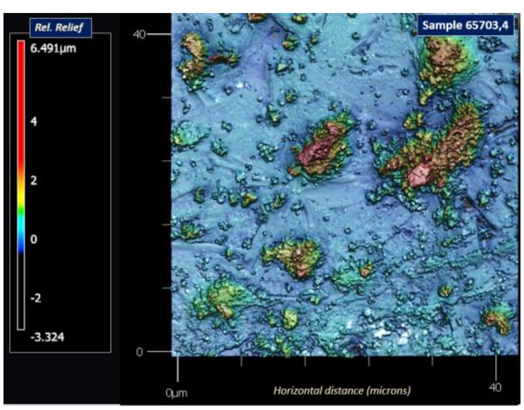

Figure 4: *LCM image of the surface of sample* ***65703,4*** *showing micron and smaller scale dust affixed to a glassy soil particle with measured topology.*

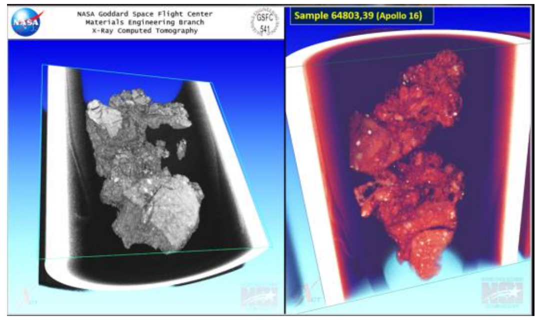

Figure 5: *Cross-sectional slices through a 3D micro-xCT scan (8 µm/voxel) of Apollo 16 agglutinate particles [sample* ***64803,39****] in a titanium tube, revealing features such as vesicles, metal-phase filled vugs, and suspected micro-craters (as source of the nano-scale dust).* Courtesy GSFC NDE facility [Jones].

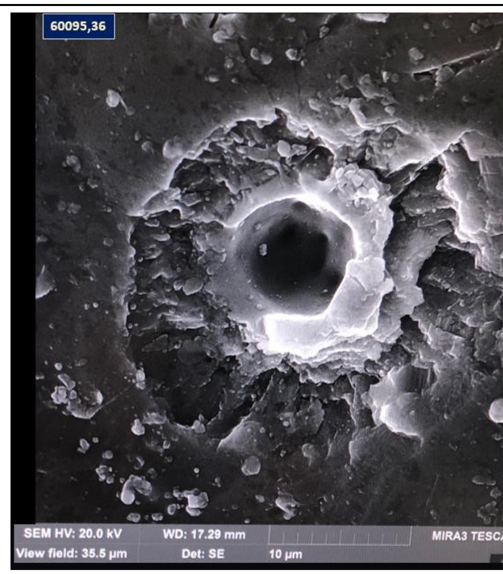

Figure 6: *SEM image of a ~ 8 µm diameter micro-crater on sample* ***60095,36*** *with a spallation zone outside of the inner cavity and small sub-micron particles (dust) affixed to the glassy surface, likely related to the cratering event. With SEM, LCM, and xCT, the story of the finest scale lunar dust (nano-moon) can be measured and evaluated in the context of Artemis for both science and applied engineering purposes [7].* SEM image courtesy R. Kent (GSFC NDE).

CONCLUSIONS

The **nano-moon** is real, and awaits our return to the lunar surface with robotic as well as human exploration systems. While viewed by many experts as an important issue [1-4] to circumvent, this nano-scale aspect of the lunar system offers a compelling set of opportunities for exploring the nearly invisible side of the lunar frontier, and one that is in a constant state of regeneration [9-12, 15, 19]. Today's NDE measurement systems and the highly-capable software (including Machine Learning) that are available for analysis makes the nano-scale fraction of the lunar dust an accessible problem, tied to fundamental solar system processes for which the Moon will always an ideal "natural laboratory" [2,3,10,12,15]. As such this **nano-moon** will be a constant part of our activities as we sustain a presence on the Moon as humanity's first deep-space outpost, and learn to explore this critical frontier.

Acknowledgments: We acknowledge the support of the lunar curator at JSC (Dr. Ryan Zeigler), CAPTEM, and the encouragement of GSFC senior leadership (Morrow, Johnson, Pittman, *et al*.). Special thanks to Ryan Kent (GSFC 541) and Dr. Jenny Seitins (US Army ARL) for their contributions, and to NRO Director (formerly of GSFC) Dr. C. Scolese. GSFC *Senior Fellows Innovation Challenge* (GFIC) supported early parts of this work, and current GSFC IRAD support is gratefully acknowledged (thanks to Drs. P. Hughes, M. Amato, *et al*.). Apollo lunar samples were provided by JSC after approval by CAPTEM for which we are grateful. We also acknowledge strong support for dust-related studies from the LRO Mission (***Appendix Fig. A***), and from the Mars Exploration Program.

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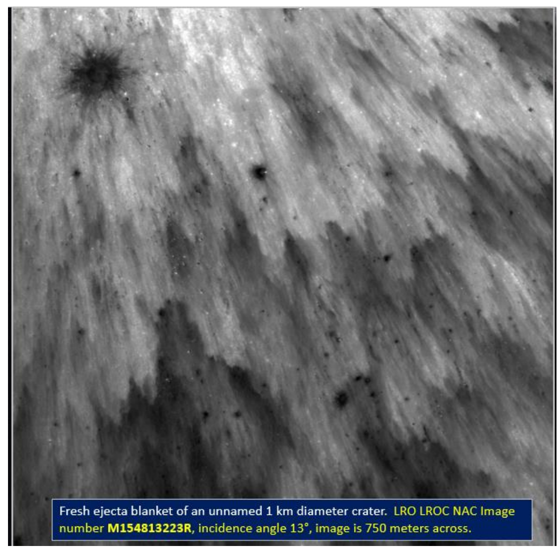

Appendix *Figure A*: *LRO LROC NAC view of unnamed fresh (simple) crater at "high sun" revealing the importance of ballistically emplaced lunar fines in ejecta curtains of recent impacts [8, 11]. The lunar dust cycle continuously produces dust at scales as fine as a few nanometers, providing a laboratory for fundamental research on such materials in deep space, with direct relevance to small airless bodies, heliophysics and even aspects of astrophysics. This* ***nano-moon*** *is an opportunity for science, engineering, technology, and human exploration to work together as Artemis unfolds as a program. Analysis of lunar dust will promote advancements in measurement technologies to catalyze understanding not possible before now.*