**The LUNAr Total Ice Concentration Survey (LUNATICS): A CUBESAT MISSION QUANTIFYING GLOBAL LUNAR WATER INVENTORIES ALSO CHALLENGES THE LATE HEAVY BOMBARDMENT.** N. M. Kerley[1] and B. R. Archer[1,2], J. Peloquin[3], N. Kendell[3], Z. Witte[3]. [1]University of Colorado Boulder-LASP, [2]National Aeronautics and Space Administration, [3]University of Colorado Boulder Aerospace Department

**Introduction:** We propose an ambitious and high-risk, economical year-long, high resolution CubeSat mission, the LUNAr Total Ice Concentration Survey (LUNATICS), to be placed in lunar orbit. We aim to quantify the total water content of the Moon by unambiguously determining if both a 3 µm and 6.1 µm Mid-wave and Long-wave Infrared (MLWIR) couplet bands exist[1], as would be expected for crystalline water. The payload will perform a statistically robust MLWIR survey for on-ejecta and off-ejecta orbital trajectories of lunar glass; with Tycho Basin (0.108 GYR)[2-4] and South Pole Aitken Basin (4 GYR)[5] as geochronological control points. Our detailed survey will be numerically modeled by blended mixing dynamics for a range of various particle sizes and simulated Tycho and South Pole Aitken Basin (SPA) impactors. These models will be extrapolated for the entire surface of the Moon; permitting a quantifiable water budget for this terrestrial body, and, surprisingly, lend insight into the thermal evolution of the solar system and terrestrial body habitability based upon total water budget.

**Scientific Justification:** We propose to analyze water content of the sunlit lunar regolith from lunar orbit in order to determine and model the distribution of water over the surface of the Moon and to what extent distribution of water within ejecta glasses or in pore space voids shelter ice from the harsh lunar environment. Previous work by the Moon Mineralogy Mapper ($M^3$) was only able to disambiguate hydroxyl (OH) stretch 3 µm bands. In order to model lunar water abundance, we must determine if findings of the SOFIA ice survey[1] reflect introduced terrestrial atmospheric false positives, or lunar water presence(Fig. 1); as well as the depth and location of ice embedded either within lunar regolith glass or interpore space.

This lunar ice survey has a valuable secondary scientific outcome for no additional cost; constraining current terrestrial geological isochrones, which define the timing of planetary evolution. Current geochronological models are poorly constrained, presenting a scenario termed the Late Heavy Bombardment (LHB) which is likely only an impactor overprint artifact[6-8] Mixing models defined by this survey will either support or refute the LHB with widespread implications for terrestrial planetary evolution for both our Solar System and that of exoplanets.

Figure 1.) 3 µm and 6.1 µm MLWIR Doublets May Detect Ice Water Outside of Lunar Poles (SOFIA)[1]

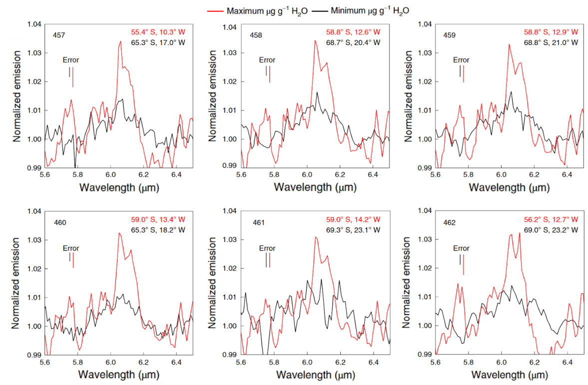


Fig. 1. (Modified from Honnibal et al. 2020)[1] 3 µm and 6.1 µm MLWIR doublets appear to successfully quantify crystalline water ice on sunlit regions of the Moon (red). This result, from SOFIA[1], is unexpected. These results may be confounded with terrestrial atmospheric water vapor overprint. Black transects are negative controls. LUNATICS will either confirm or refute SOFIA[1] findings for water outside of lunar poles.

Successful recovery of 3 µm and 6.1 µm MLWIR doublets for the southern hemisphere with a representative normal distribution of sampled ejecta (N Minimum = 56) will allow for testing of presence of water as well as maximizing signal/noise return. Our data captured from the Southern Hemisphere can be modeled and extended globally.

Such a detailed study is potentially high-risk and intensive, necessitating high resolution data capture. Such a high-risk study is inappropriate to a larger spacecraft but ideally suited to a CubeSat mission.

Calculating impact mixing of regolith can be numerically modeled by blending mixing scenarios (collision finite element methods, mass advection, compaction and ballistic) for particle size and distribution. This model will incorporate, as a first pass, a multivariate mass ejecta model ($M_{Total}$) incorporating hydrocode collision finite element methods (a*FE), mass advection (b*MA), compaction (c*C), and ballistic trajectory (d*BT), where:

Equation 1: Mass Ejecta Mixing Model

$Mix_{Total}=a*FE^{[9]}+b*MA^{[10]}+c*C^{[11]}+d*BT^{[10]}$; with a, b, c, and d are fractional impact indexes we hope to fit to our resultant models.

Again, LUNATICS modeling has an added potential benefit of clarifying to what extent regolith mixing affects LHB detection. Is it real, or is it artifact? Our term, $Mix_{total}$ plotted against high resolution cratering maps and, hopefully, SPA sample returns would constrain lunar isochrones, will help clarify planetary evolution timelines and processes.

**Methods:**

*Orbital Parameter* In order to ensure the success of the LUNATICS CubeSat, its orbit has been carefully designed in STK software[12] such that the periapsis will occur directly over the midpoint between Tycho crater and the South Polar region with a revisit time of 13 days at an altitude of 80km utilizing the MICROXCAM-384I-MLWIR's thermal imager in the 3-14 μm wavelength range[13]. This orbit results in altitude variation of 113.6 to 133.5 km over the Tycho Crater and 106.2 to 143.9 km over SPA. This trajectory allows that spacecraft altitudes above Tycho are comparable to that of the SPA.

Figure 2a,b. LUNATICS Polar Orbit Captures Global Water Inventories And Processes

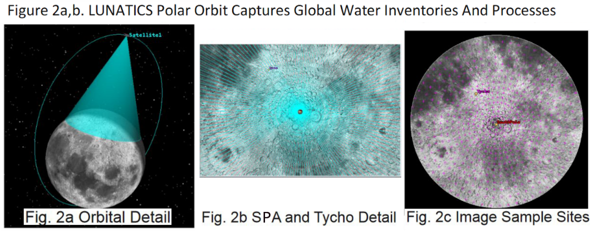


Fig. 2a. Global total orbital trajectory normal to lunar equator: Polar orbit periapsis altitude is 122.95 km while apoapsis is 2283.33 km. Targeted data capture is for the southern hemisphere only, up to the lunar equator. Total ice concentration inventory will be extrapolated from benchmark SPA and Tycho craters and anorthosite highland and basaltic marea (off ejecta ray trajectories) to compile a mean total ice concentration extrapolated to global scale as described in data analysis. Fig. 2b. Orbital detail for this mission allows for very fine resolution of water inventory by MLWIR, either refuting or supporting tentative 3.0 micron and 6.1 micron crystalline water IR couplets.

**Data Analysis:**

*Step 1* We will disambiguate crater ejecta rim overflight by building numerical models tracing continuous ejecta rays centered on both SPA and Tycho. Primary signal analysis will search for the 3.0 μm and 6.1μm water doublet over every orbital path. Data quality will be constrained by signal/noise ratios and will terminate at the lunar equator. Orbital path altitude and position will be determined to less than 20 meters by dead-reckoning against the Lunar Orbiter Laser Altimetry (LOLA)[14] database via ESRI ArcMap software[15]. ArcMap crater age date maps will be imported as secondary data layers. Estimates for absolute water concentration in $\mu g{*}g^{-1}$/km will be determined following the methods of Honnibal et al. (2020)[1] where the abundance of water ($Mass_{water}$):

$$Mass_{water} = 9,394 D^{2}_{band} + 9,594 D^{1}_{band}$$

where $D_{band}^{1}$ is the depth of the 6.1 μm band. $Mass_{water}$ values will be binned and optimized for Signal/Noise Ratio (SNR) for each MLWIR footprint every 13 days (N = 28 images/site) with a footprint resolution of 1.11 km ± 0.32 km. We will interpolate global water concentration point density maps which will be calculated with rolling average radii of 0.5 km to each nearest neighbor.

*Step 2 Domain Similarity Between Regolith Substrates*

We aim to correlate distinct age-crater domains and relationships via statistical cladistic domain analysis, and multivariate analysis. We will apply these techniques to bin and correlate relatedness between on-ray and off-ray populations. This will allow for correct modeling of ejecta formation by modifying the Housen et al.[16] crater ejecta scaling model for complex craters greater than 10 km; modified by smaller diameter processes captured in Equation 1 .

**Conclusions:** We expect that the results derived from this mission will be successful in determining quantitative water concentrations for the global lunar inventory for the lunar surface. Our model result will also constrain thermal history of the Moon and help to disambiguate regolith impact mixing. A successful survey of the Southern Hemisphere by the LUNATICS mission can be ground truthed by subsequent VIPER[17] surface missions. Finally determining the total lunar water inventory will shed light on terrestrial body evolution and habitability in our solar system and beyond.

**References:**

[1] Honniball, C. I et al. (2020) *Nat Astron* 5**,** 121–127 [2] Robinson et al., (2016) Icarus, 273, 121-134. [3] Bandfield et al., (2017) Icarus, 283, 282-299. [4] Paigeet al., (2018) LPSC, #2757. [5]Petro,N.E. (2004) JGR, 109.[6]Neukum, G., et al.(2001) Space Sci. Rev. 96, 55–86. [7]Bottke, W. F. et al. (2012) Nature 485, 78–81. [8]Bottke, W.F. and Norman M.D. (2017) Ann. Rev. Earth and Planet. Sci. 45, 619-647.[9]Caldwell, W.K. (2021) App. Sci. 11(6), 2504.[10]Kendall, J. D. (2016). (dissertation). ProQuest Dissertations & Theses, Ann Arbor.[11]Colwell, J. E. et al. (2007) Rev. of Geophys., 45(2). [12]Analytical Graphics, Inc., STK, http://www.agi.com [13]Ino. (n.d.). *MICROXCAM-384i-thz terahertz camera*. INO. [14]*Zuber, M. T.,et al.* (2009) Lunar Reconnaissance OrbiterMission,63–80.[15]*ArcGIS,http://www.esri.com* [16]Housen, KR et al. (1983) JGR, 88, B3 2485-2499. [17]Chen, R. (2020, June 4). *Viper: The Rover and its onboard toolkit*. NASA.