Characterizing Lunar Polar Volatiles at the Working Scale: Measurement Requirements and Demonstration.

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Introduction: The economic evaluation of natural resources depends on the accuracy of resource distribution estimates. On Earth such estimates, in the form of quantitative assessments, are necessary for informed decisions about investing in new or operating mines and other industrial efforts to extract a resource to produce a commodity. A frequently discussed lunar resource is water ice, however, we are only at the first stages of understanding its potential as a resource. In particular, we currently do not have a sufficient understanding of the areal distribution, depth, thickness, quality, and form at the scales it would be necessary to be extracted and processed, that is, the "working scale". Here the "working scale" is defined to be the processed volume required to meet some basic demand (for example, 100s of cubic meters of ice-laden regolith to produce 10s of tons of water) down to the scale of the anticipated heterogeneity in of the ice in the impact gardened regolith. We use a combination of Monte Carlo methods and classic geostatistical approaches to go from the exploration goal of "understand the distribution of water" to quantification of specific mission sampling requirements. We also demonstrate the value of this approach on data obtained during field testing of a neutron and NIR spectrometer as part of the Mojave Volatiles Prospector (MVP) effort in 2014 [1].

The Need for Mobility and Subsurface Access: A number of existing data sets suggest that water ice is heterogeneous at scales down to meters. For example, to reconcile the LCROSS observed water concentrations of ~5% [2] with the observations of neutron counts, the water would need to be either buried under a desiccated layer of regolith 20 to 50 cm deep and/or mixed laterally with an areal density of 20-40% [3]. The range of values for the lateral and vertical distributions are consistent with what one would expect due to the constant excavation/burial by impacts. A landed, mobile system is required to assess the water distribution across scales of 100s of meters with resolution of <10 meters. Additional modeling and geostatistical analyses are required to better quantify the areal extent and the minimum number of measurements required for making predictions away from the rover's path.

Geostatistics and Monte Carlo Modeling: The application of geostatistics in resource characterization dates back to the late 1970s and are useful for site assessment where data is collected spatially [4]. Typically a geostatistical study applies an iterative three-step approach involving exploratory data analysis, variogram modeling, and making predictions (kriging estimation and/or simulations). These same techniques can be applied to lunar spatial data sets and/or model predictions to evaluate the geospatial distribution of key physical parameters, including surface and subsurface temperatures, surface composition (e.g., from reflectance observations), bulk subsurface composition (e.g., from neutron or radar measurements), or discrete subsurface observations (e.g., drill sampling). By comparing variogram models of observed measurements to simulated data it may be possible to identify minimal rover-prospecting-path lengths required to validate model results. Furthermore the variogram results may be used to create predictive maps of the distribution of the observed parameter.

Variograms: Cryogenic subsurface temperatures appear to be a necessary requirement, but not the only determinant of volatile presence. We suggest it may represent one of the more heterogenous parameters that govern the distribution of water and thus it is useful to conduct a statistical study based on variations in temperature. To determine the possible predictive distance from measured values, variograms are used to calculate the 'Range' (i.e., the distance the variogram reaches the sill or the maximum variance) at which point there is no autocorrelation, the distance to predict.

Monte Carlo Modeling: In addition to geostatistical analysis, Monte Carlo modeling of rover traverses was conducted. These simulations aim to understand how much total distance and measurement density is required to achieve a specific uncertainty level in the overall characterization of an area/volume of regolith. By simulating multiple traverses it is possible to calculate a distribution of the areal density traversed and estimate the overall error in our estimate of the mean water concentration as a function of traverse distance and areal coverage.

Field Testing: These analytical approaches have been applied to data obtained during MVP testing in the Mojave. Both variogram and kriging analyses were conducted as a proof of concept for a polar volatiles rover mission.

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