National Aeronautics and Space Administration

Characterizing Lunar Polar Volatiles at the Working Scale: Going from Exploration Goals to Mission Requirements

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The Necessary Sampling to Characterize the Water Distribution

The mission must sufficiently characterize an area to evaluate the resource need or physical processes

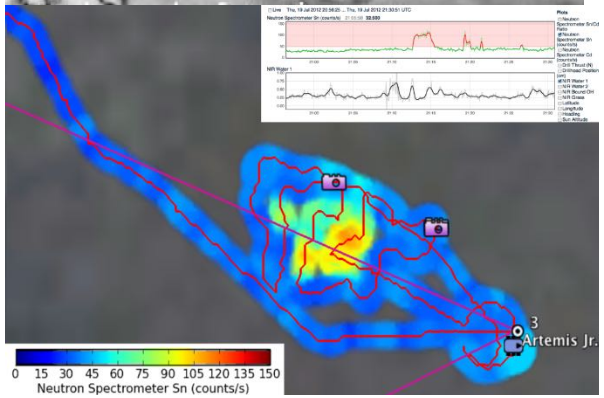
- Terrestrial mining companies have worked this problem for many years, developing "Mineral Models" for production evaluation
- Unfortunately the "Mineral Model" for lunar water is very uncertain, however many of the same techniques can be applied

To characterize an areas' water content for ISRU requires making spatially distributed point measurements

- Have built several Monte Carlo models and applied instrument models to simulate observations
- Applied various interpolation techniques to estimate total water from simulated instrument measurements

One method of "Prospecting" demonstrated in field testing

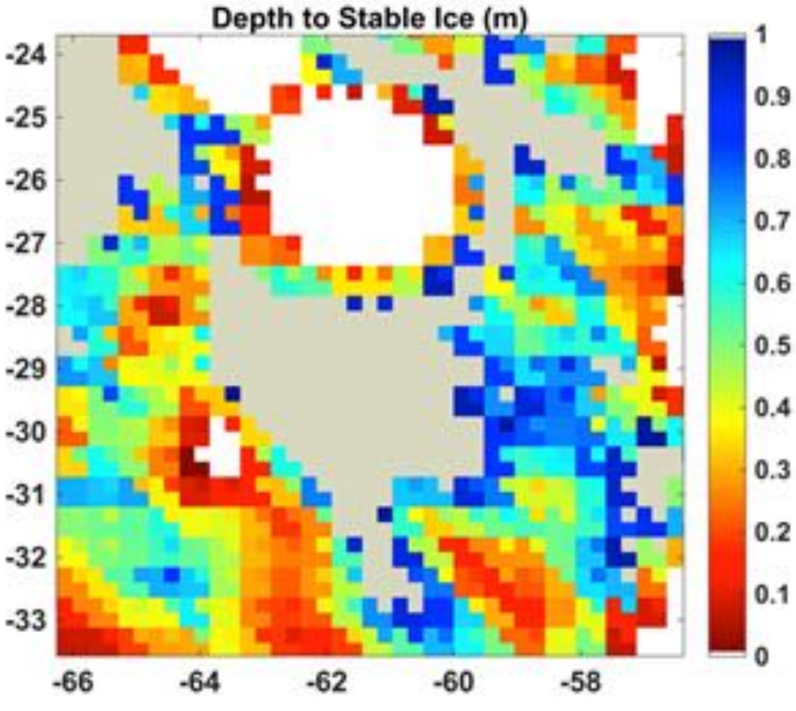
- Mojave Volatile Prospector (MVP) utilized the K-Rex rover, and versions of the Neutron spectrometer system (NSS) and Near InfraRed Volatiles Spectrometer System (NIRVSS)



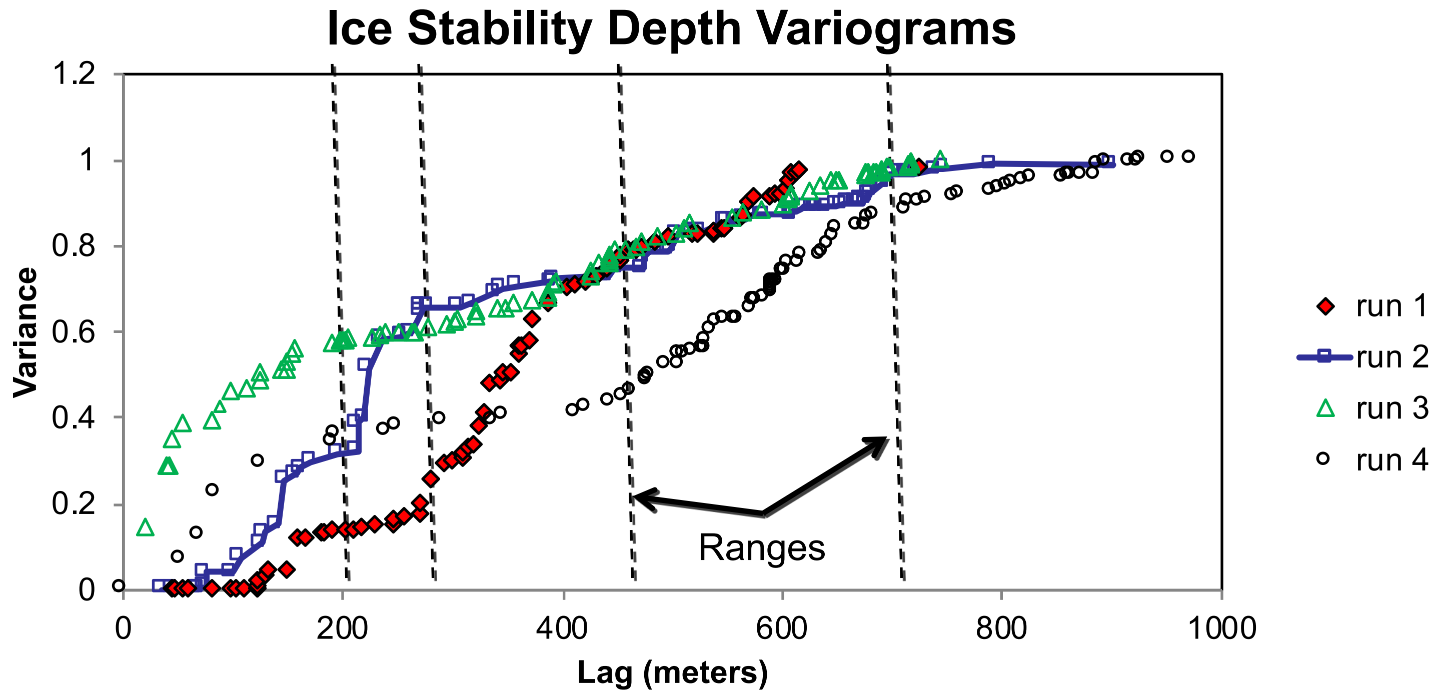
Spatial Scales of Ice Stability Depths

A possible determinant of spatial scales is the depth to water ice stability

- This is essentially a measure of the spatial scales at which temperatures vary (and hence potentially water)
- Gives an estimate of the distances over which measurements are necessary
- The four “runs” represent different origins from which the lag (distance between points) was calculated
- Several “Ranges” are clear, indicating several physical scales, with the largest being **>600meters**
- Demonstrates that **sampling across scales from 10s to 100s of meters is required**



Siegler and Paige (2017)



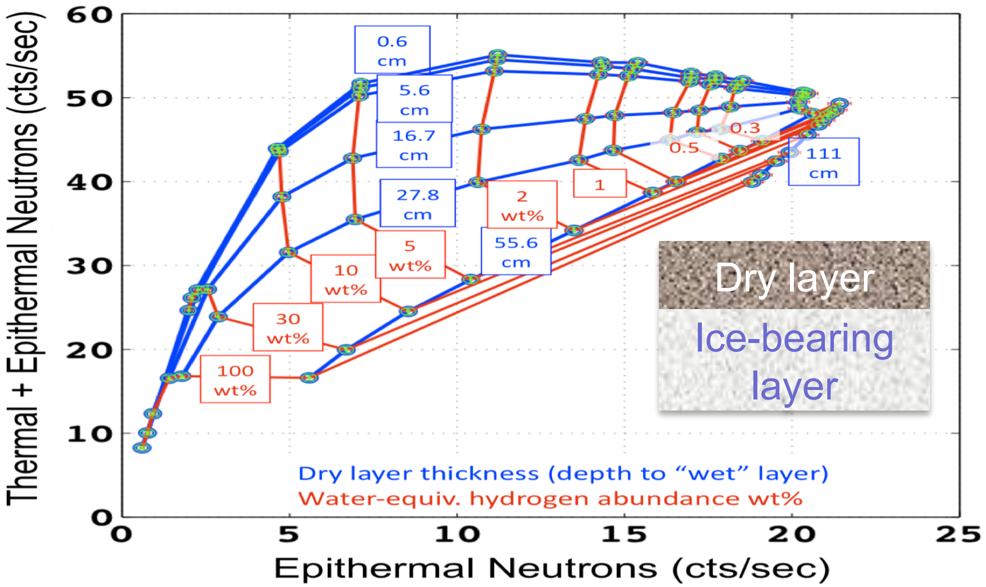
Prospecting for Water: From Requirements to Implementation

How to determine the distribution across a broad area with lengths scales >600m?

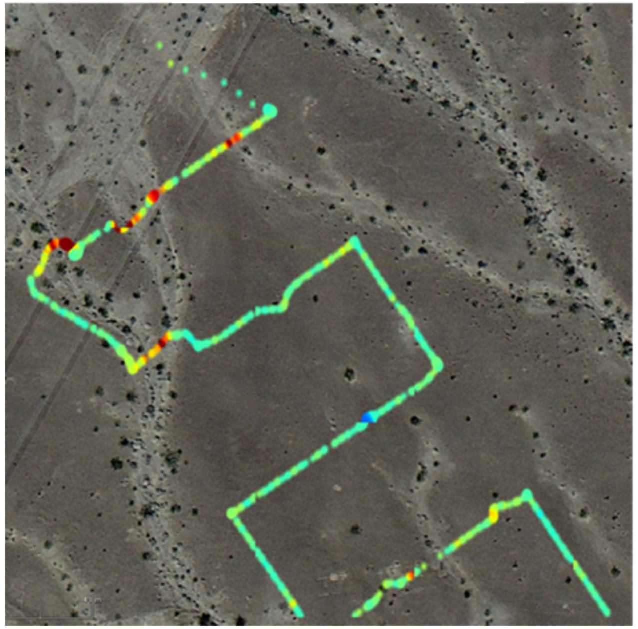
- Drilling alone would require an unreasonable number of drill sites and result in significant production uncertainty
- Measurements while moving give continuous sampling, however reflectance observations are only surficial, and neutron data can be ambiguous due to relation between neutron energy and flux with concentration and burial depth

Boreholes used to tie-down neutron observations by constraining vertical profile

- A combined Drill / NIR Spectrometer or Drill / Sample Analysis system can measure the vertical distribution of water constraining neutron modeling – provides the “tie point” for the prospecting data



NIR Reflectance



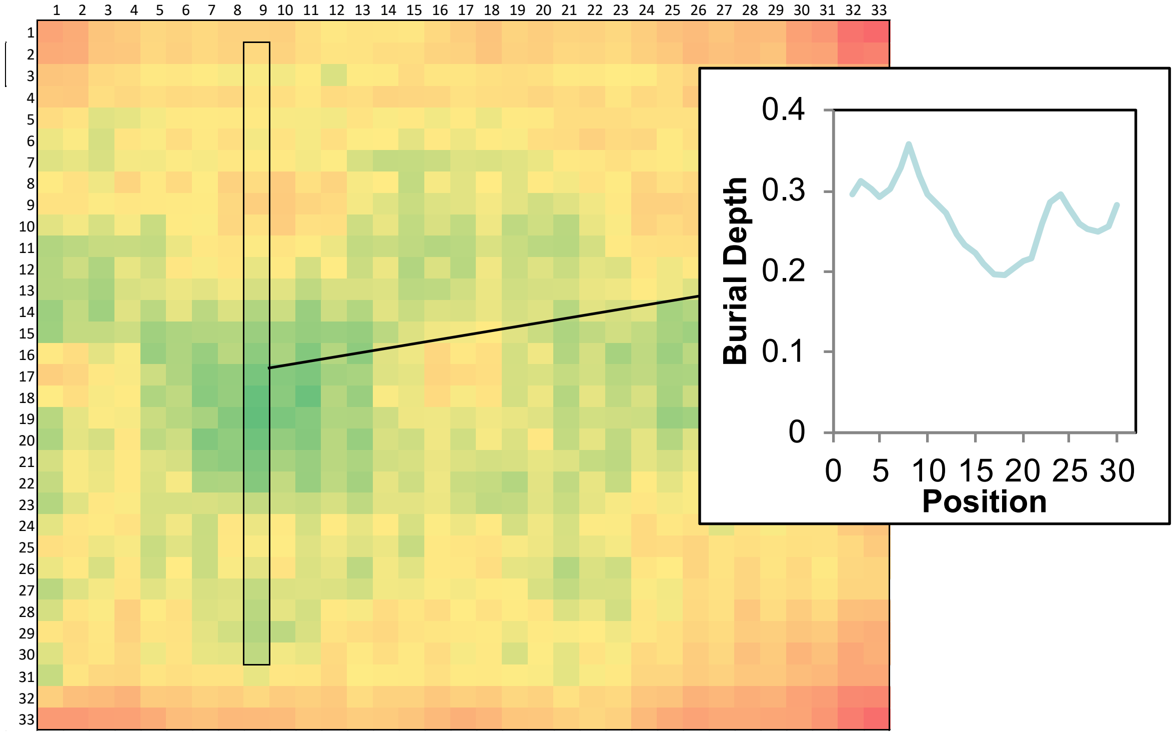
Neutron Flux

Monte Carlo Modeling

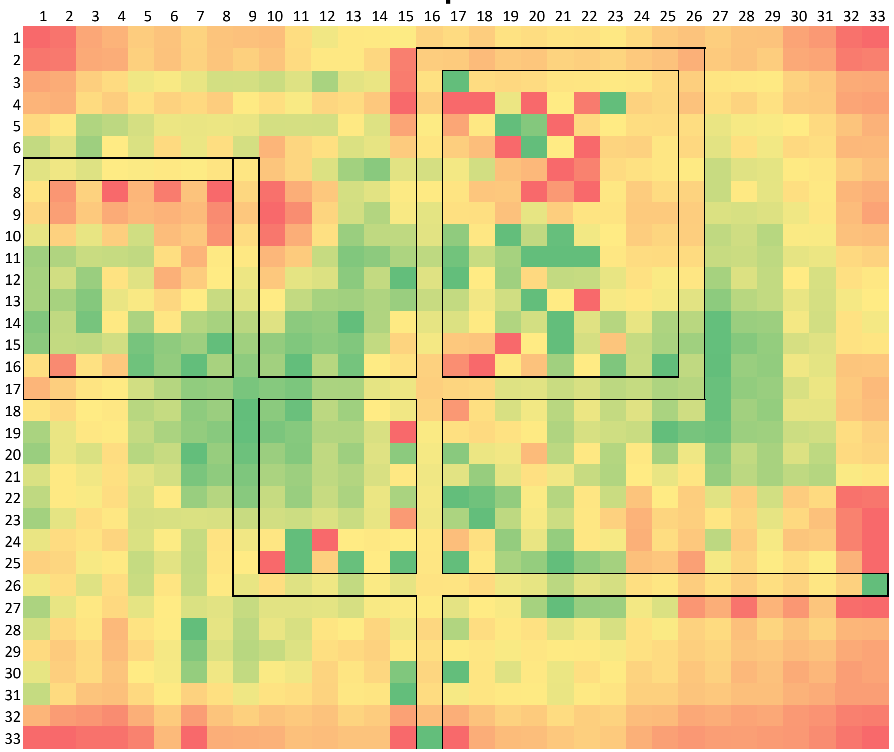
Simulations can put real numbers on how much prospecting and subsurface analysis is needed to meet measurement goals

- Example of simulations with random mixes of water
- Random concentrations and distributions (lateral and vertical) modeled and neutron observations modeled along arbitrary traverse

Water Column Concentration



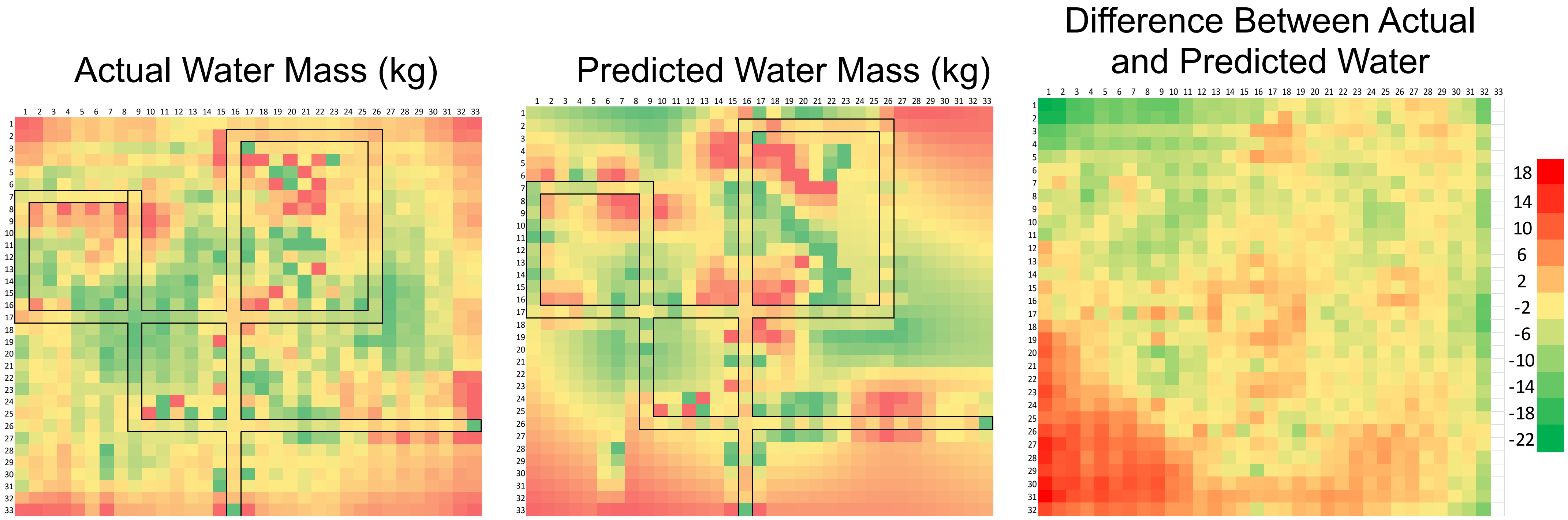
Water Column Integrated Mass (kg)
With Example Traverse



Spatial Weighted Modeling with Neutron Spectrometer Model

Interpolated total water from traverse measurements

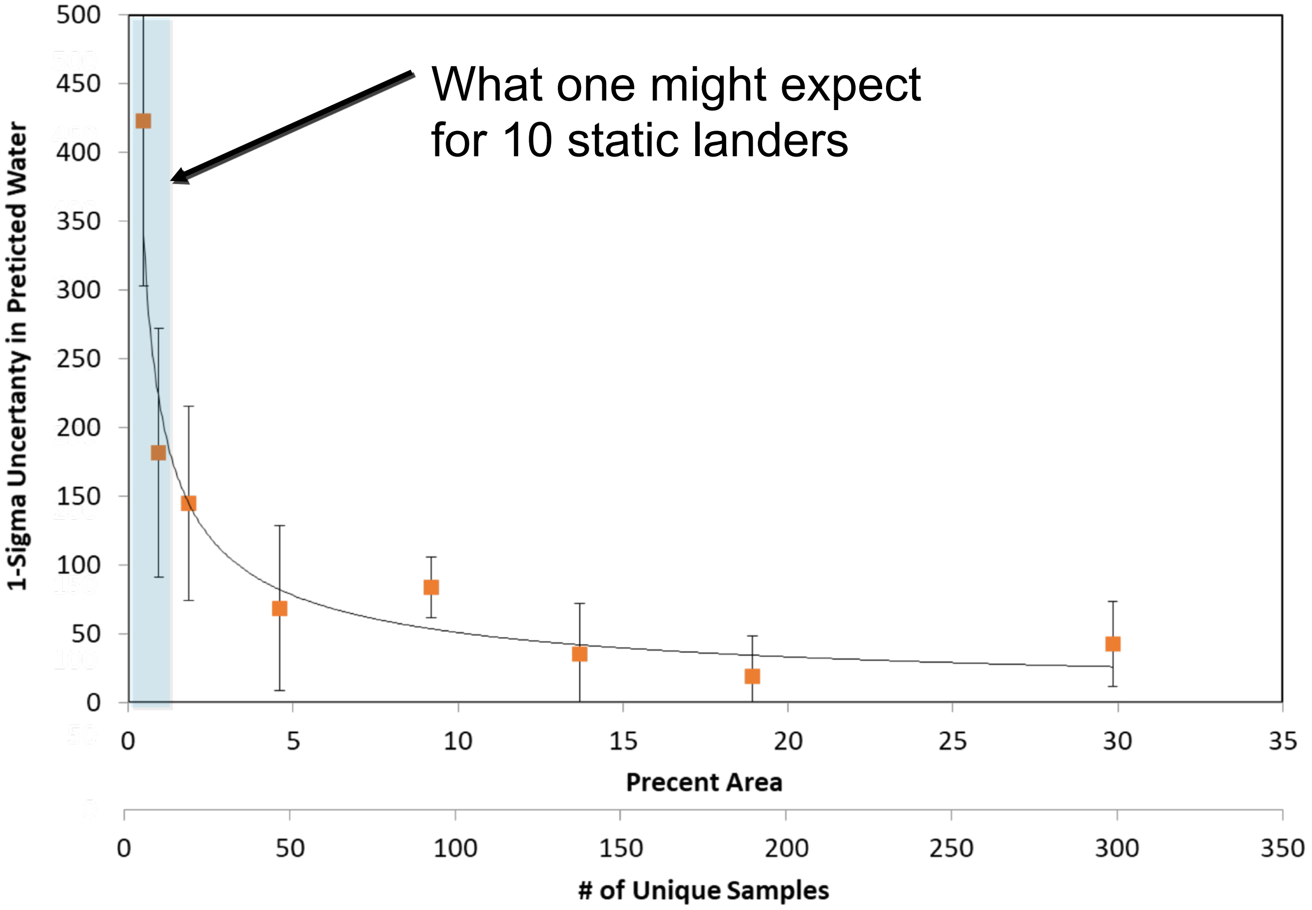
- Used predicted water along traverse based on neutron measurements
- Performed a Kriging (Gaussian process regression) interpolation across entire area
- Errors within/near the traverse area are typically <20%
- The error is a strong function of the number of unique sites sampled (the traverse path)



Uncertainty as a Function of Sample Number / Density

Interpolated total water from traverse measurements

- The error is a strong function of the number of unique sites sampled (the traverse path)
- Can estimate the total uncertainty in the total water estimated across model area (about 4300 m^2)



To characterize the total water in an area with an uncertainty of <50% must sample with a density of >15%

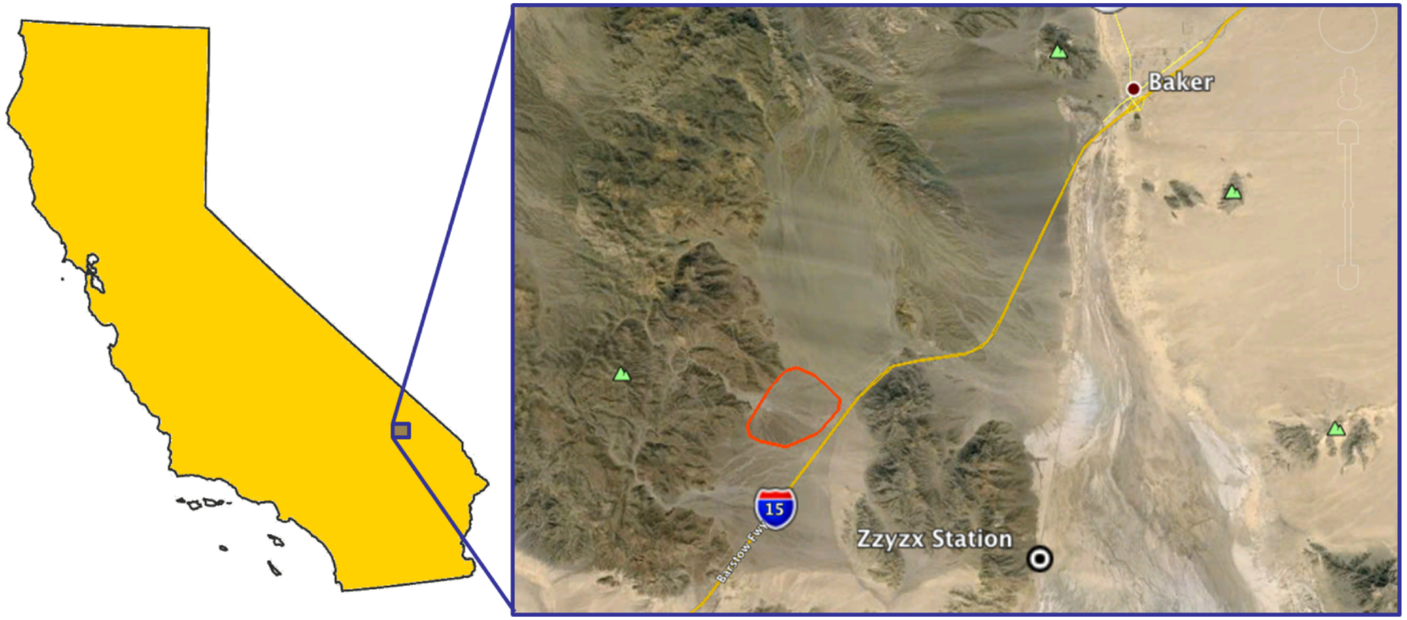
Additionally lateral/vertical physical scales show “ranges” (distinct changes in scale structure) at scales between 10s and 100s of meters

Mojave Volatiles Prospector (2014)

Goal 1: Prospecting. Mature prospecting ops concept for NIRVSS and NSS instruments in a lunar analog field test

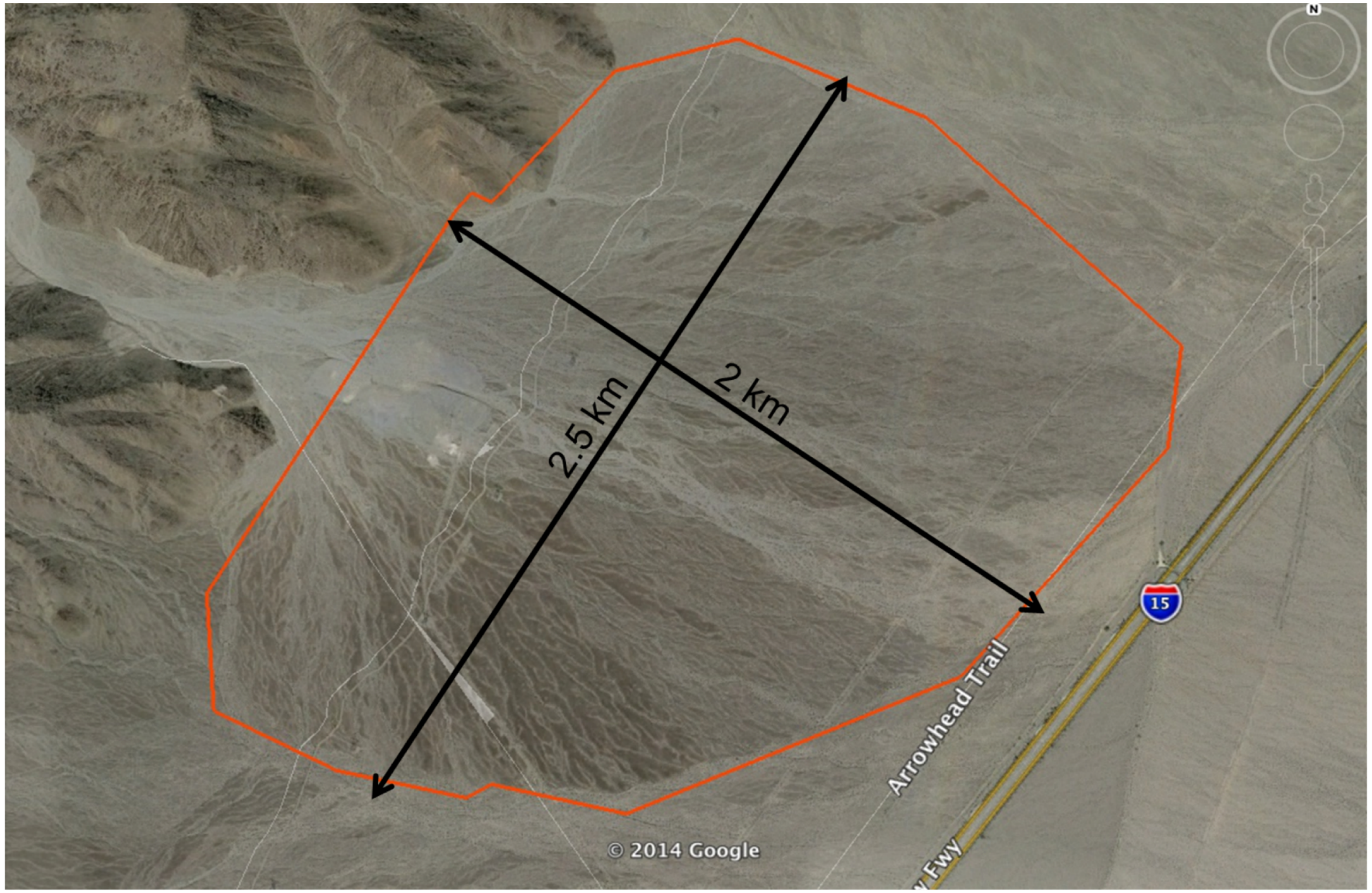
Goal 2: Real-Time Science Ops. Improve and mature xGDS real-time science tools by testing in a natural setting where the abundance and distribution of water is not known *a priori*

Goal 3: Science on Earth. Understand the emplacement and retention of water in the Mojave Desert by mapping water distribution / variability



Demonstration of Prospecting Method: MVP

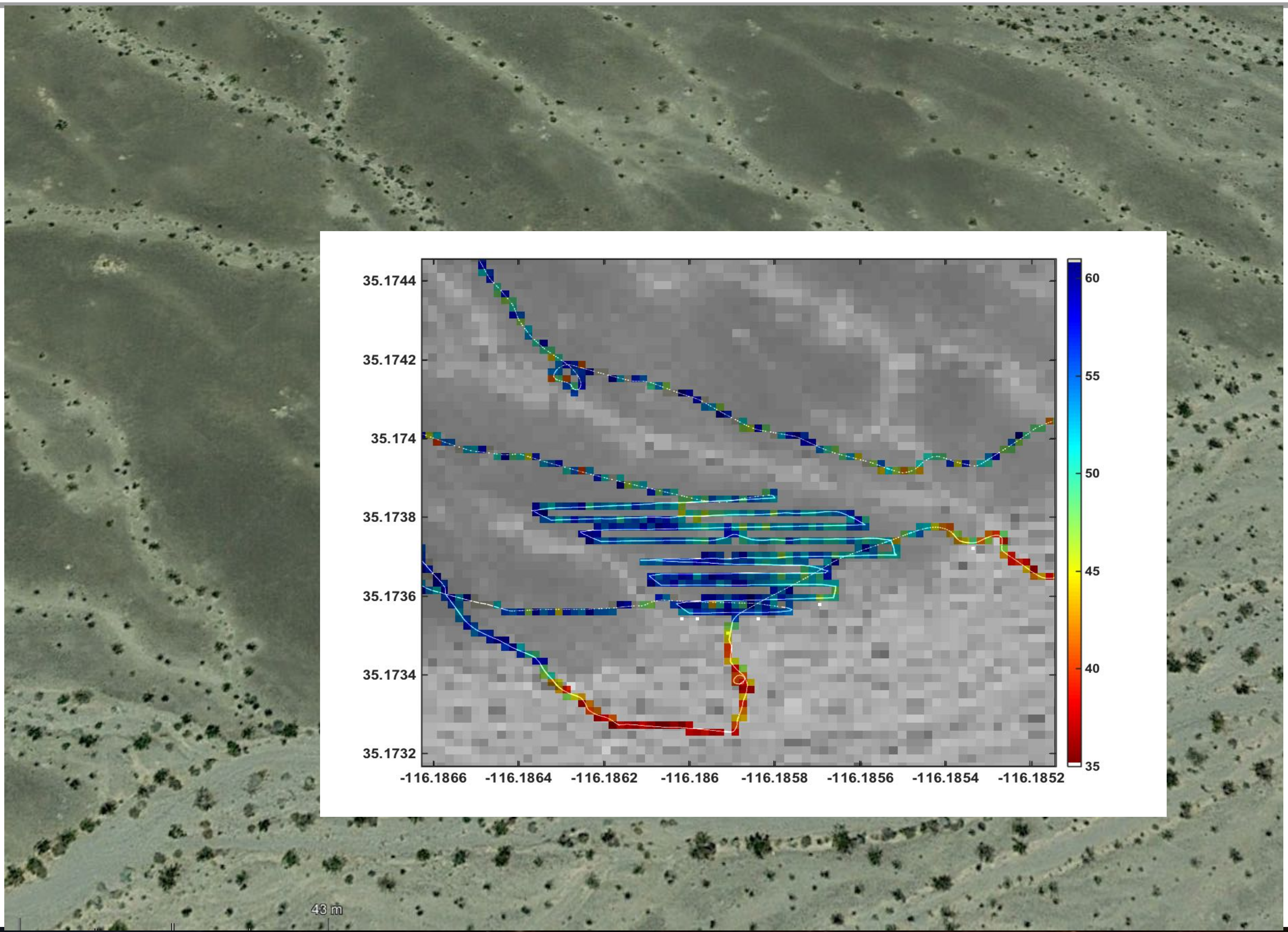
- Alluvial fan with regions covered with "desert pavements"
- Dissected with washes filled with eolian and alluvial fines
- MVP tested a range of operational concepts, and mapping traverses
- During traverses operated versions of Neutron Spectrometer System (NSS) and Near InfraRed Volatiles Spectrometer Systems (NIRVSS)



Mojave field site (N35.18° , W116.18°) – **Alluvial fan**

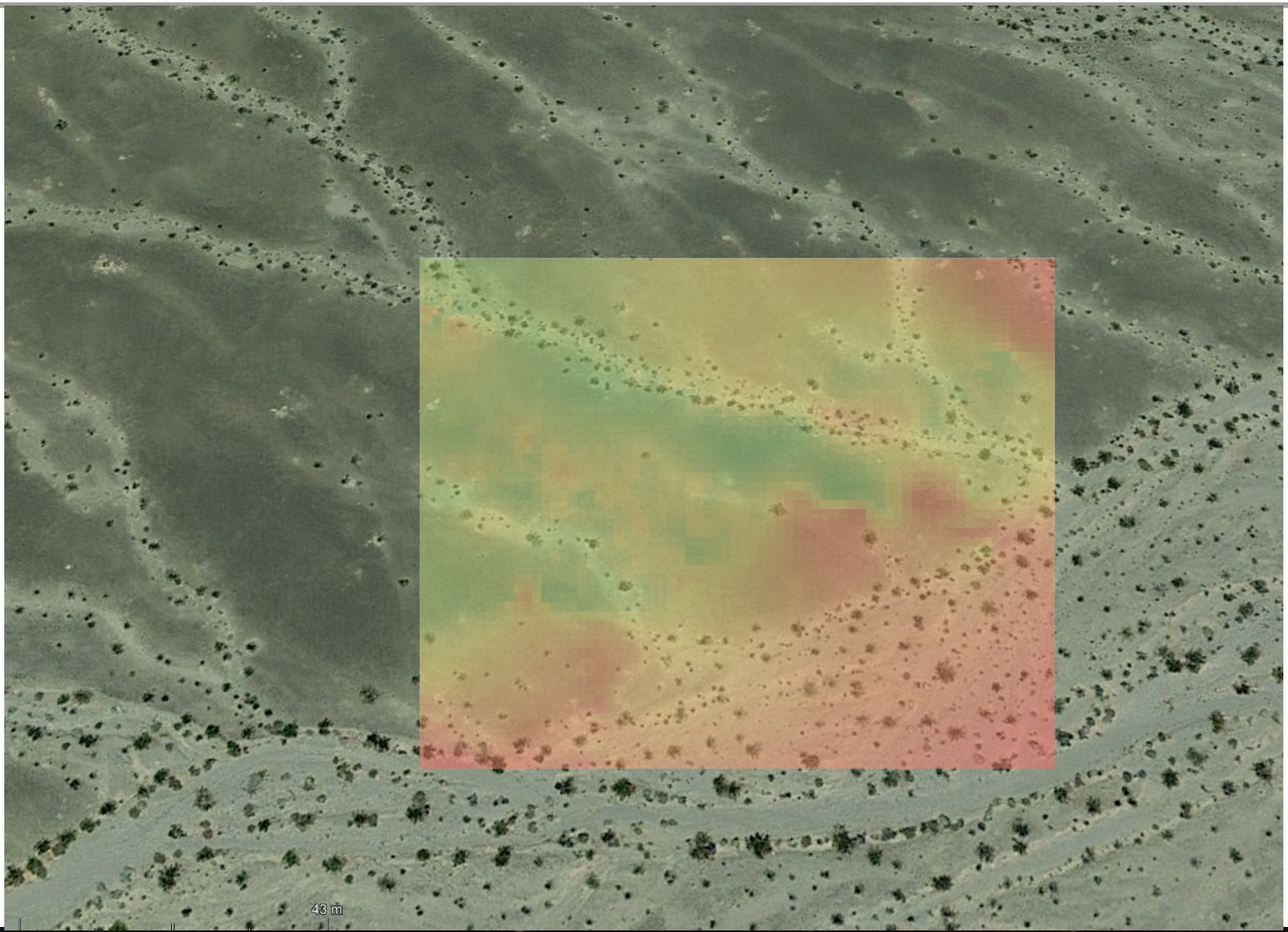
Demonstration of Prospecting Method: MVP

- Zoom in of fan showing dark surface pavements
- Inset shows NSS counts along the traverse
- Blues indicate higher hydration, apparently associated with surface pavements



Demonstration of Prospecting Method: MVP

- Kriging interpolation of NSS hydration signature
- From this we can make estimates of total hydration with a known confidence



Summary

A critical science and exploration goal is to understand the distribution of polar volatiles

- Lateral and vertical distributions at scales relevant to processes and ISRU
- Measurements at a range of scales from centimeters to kilometers on the lunar surface are needed
- A key question is how many and with what distribution are the measurements needed to be sufficient to understand process and resource potential; to build an adequate "mineral model"

Developed Monte Carlo models of water distributions to evaluate the overall uncertainty associated with a "prospecting rover" using a neutron spectrometer

- Integrates a neutron spectrometer instrument model with a Monte Carlo model of water distribution
- Using a weighted spatial interpolation (kriging) to predict (with an understood confidence) the area distribution of water
- For the random distributions of water (and burial depths) shown here need measurement densities of >10% to have reasonable confidence in total water predictions

The Mojave Volatiles Prospecting field test demonstrated the "Prospecting Method" proposed here

- Use NSS observations to build broad areal hydration maps
- With NIR surface and subsurface observations can develop a model for the distribution of hydration that allows further extrapolation to denser data sets (e.g., visible imagery)

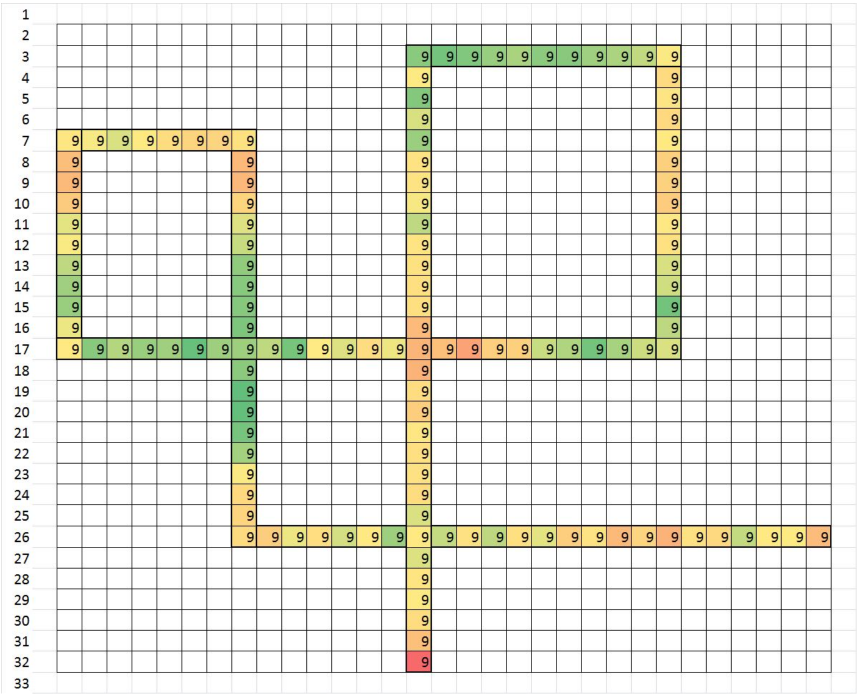
Thank You!

Spatial Weighted Modeling with Neutron Spectrometer Model

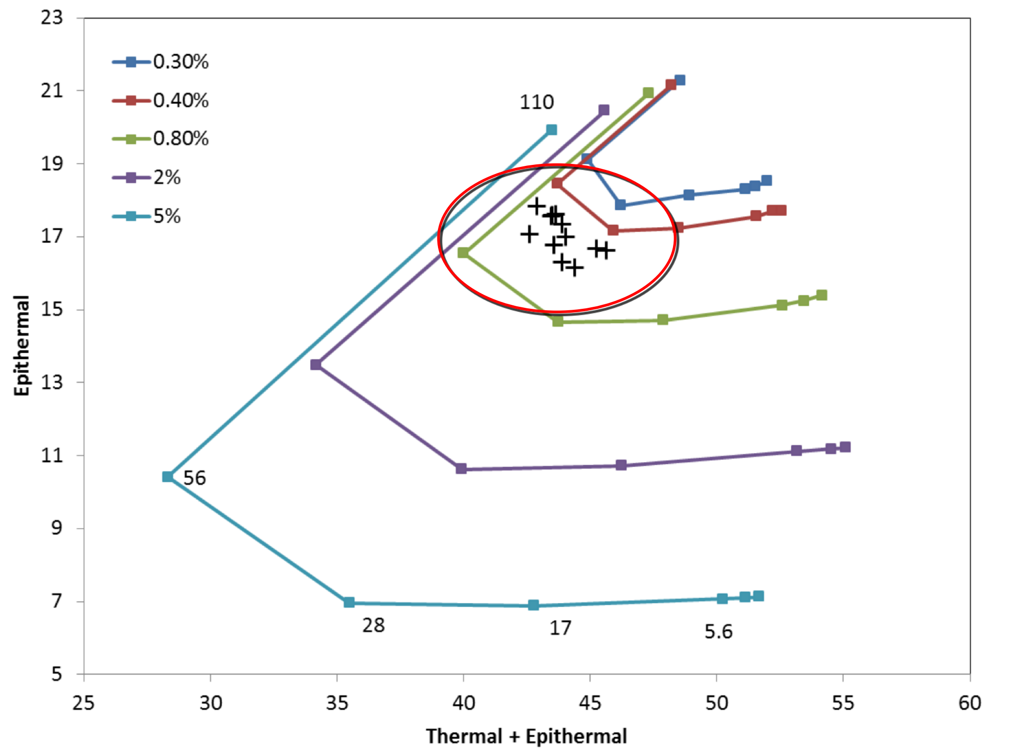
For any point along the traverse the Epi-Thermal and Epi-Thermal + Thermal neutron counts are "observed"

- These observations include instrument error, but not positon error
- The water equivalent hydrogen and burial depth is estimated along the traverse using an average of possible solutions of WEH & depth

Epi+Th Neutron Counts



Epi+Th vs Epi "Spider Chart"

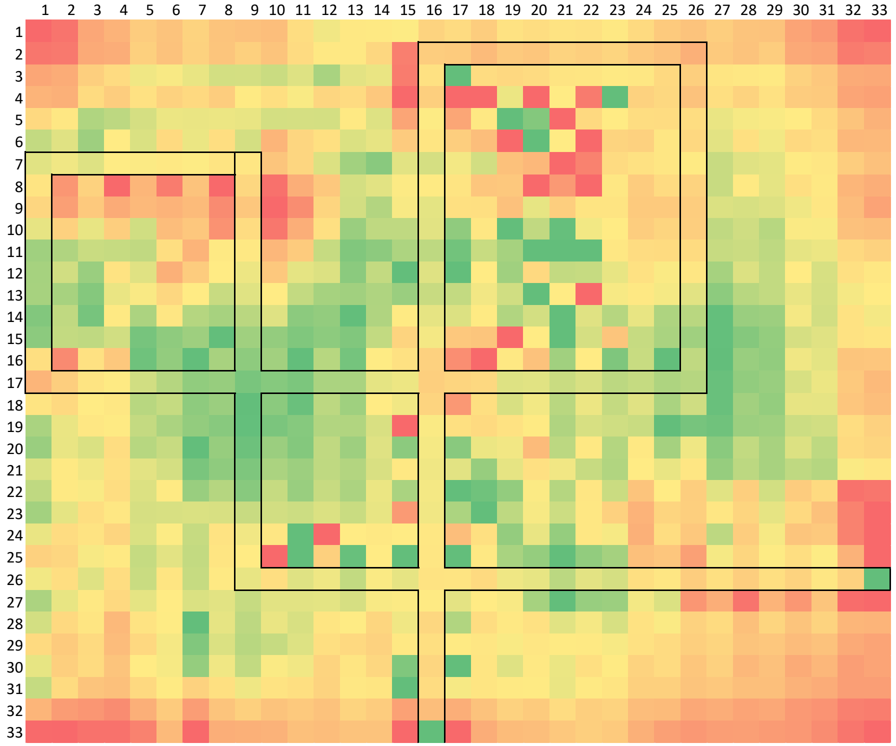


Spatial Weighted Modeling with Neutron Spectrometer Model

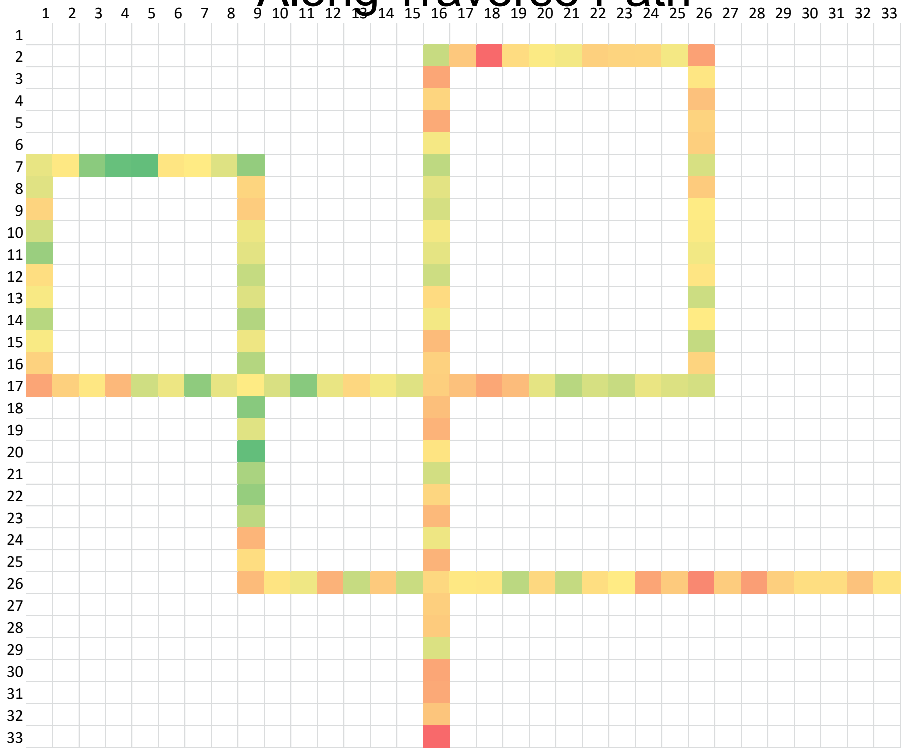
Simulations can put real numbers on how much prospecting and subsurface analysis is needed to meet measurement goals

- Example of simulations with random mixes of water (not binar)
- Random concentrations and distributions (lateral and vertical) modeled and neutron observations modeled along arbitrary traverse

Water Column Concentration



Estimated Water Column (from Neutron Measurements) Along Traverse Path



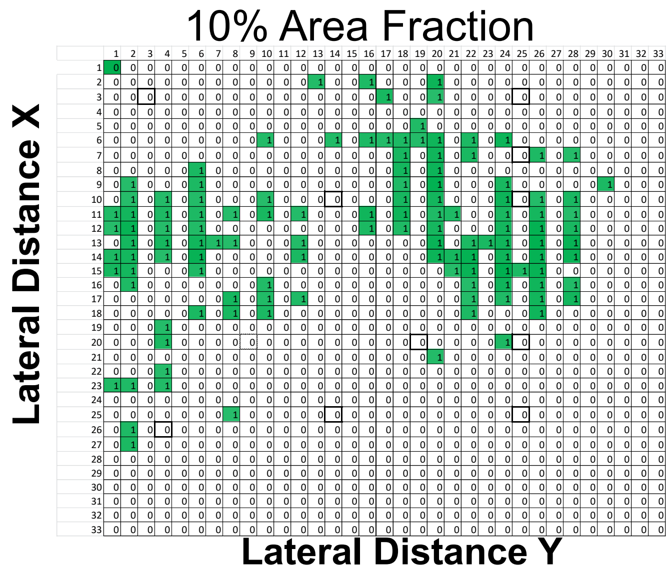
How Much Sampling is Necessary to Characterize an Area?

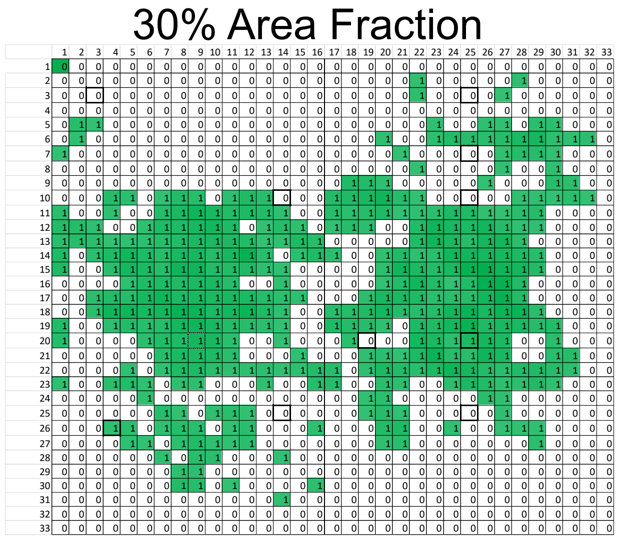
The mission must characterize an area sufficiently to evaluate the resource need

- Evaluated the required sampling using a series of Monte Carlo simulations with random distribution of water ice
- Sampled continuously along an arbitrary path, for example by a rover with a neutron spectrometer

Monte Carlo runs tested the uncertainty in sampling as a function of total distance or area coverage

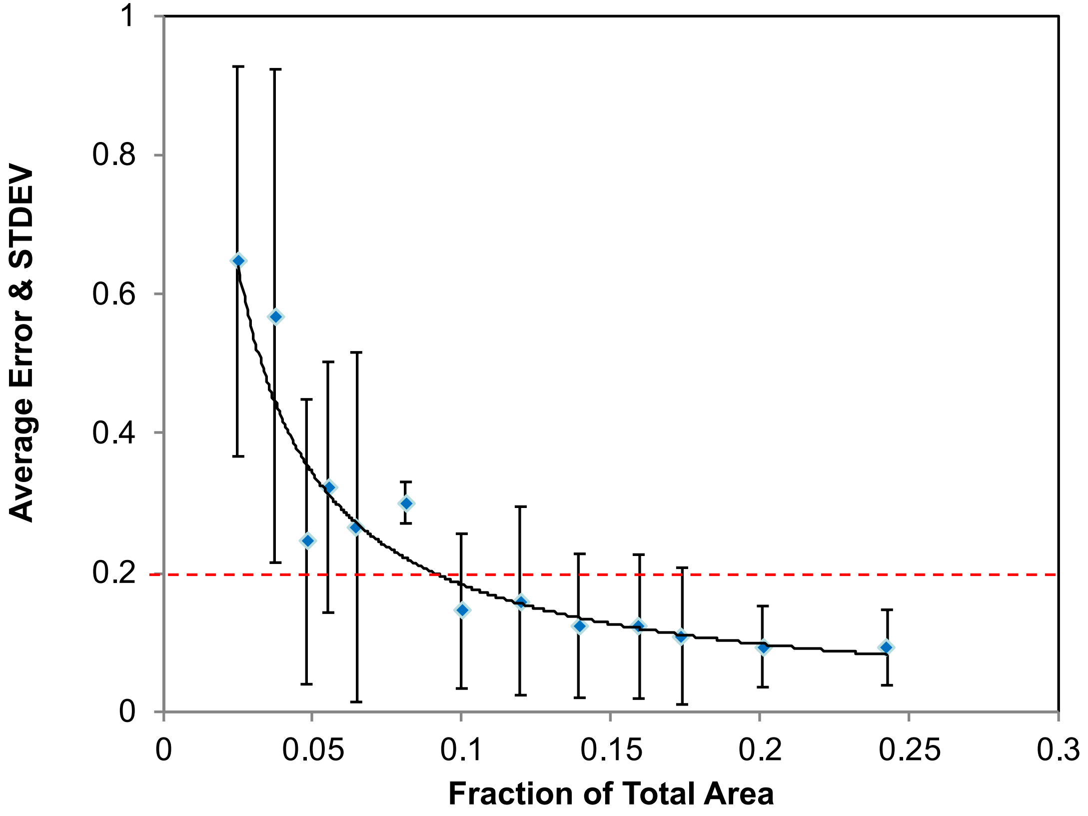
- Sampled concentration was compared to "True concentration", calculated for each run, and the error in sampling calculated (Error = [True – Sampled]/True)
- Distribution of Errors provides likely (mean and median) uncertainty in a sampled

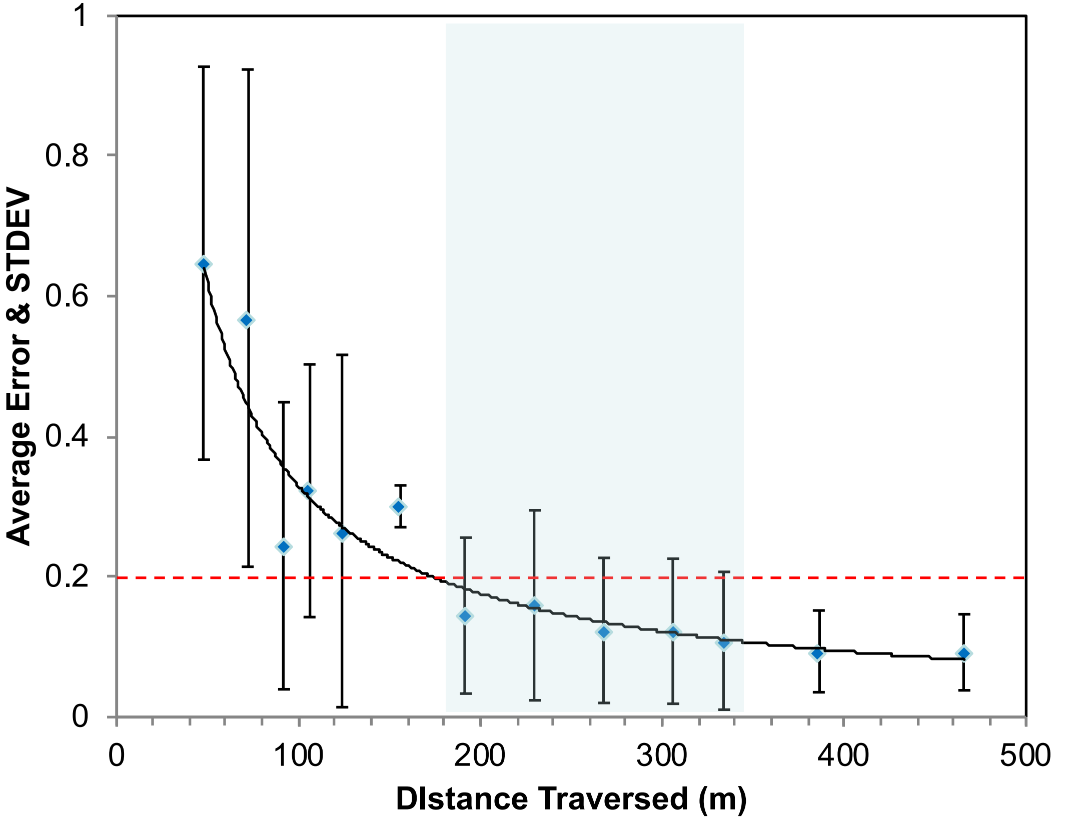




Required Prospecting Density/Distance

Monte Carlo Results for Assumed 30% Area Density of Water
No Measurement error (binary Water or No-water "observation")



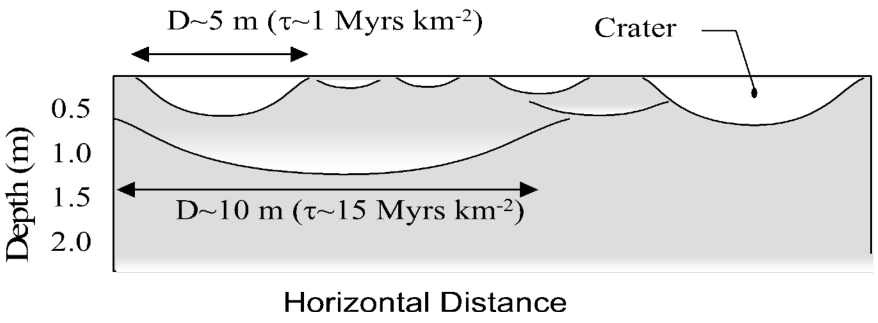


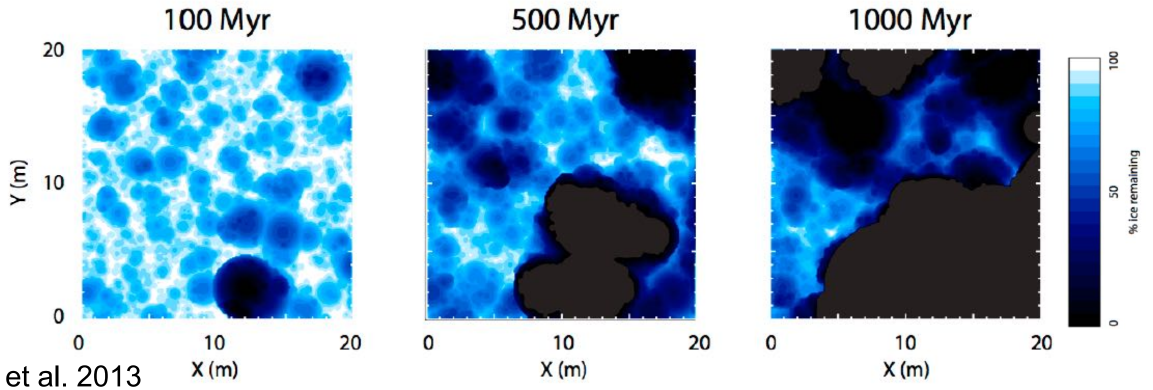
At a minimum need to traverse >180m with an area of 2500 m^2 to achieve a characterization uncertainty of <20%

Crater Mixing

- Dominant geological process affecting top meter of regolith is small impact cratering
- Distance between 10m wide craters (~1m deep) is ~50-150m
- ***Consequently top ~meter is likely to be patchy at scales of 10s-100s of meters***

Craters mix the top meters of regolith via excavation and burial





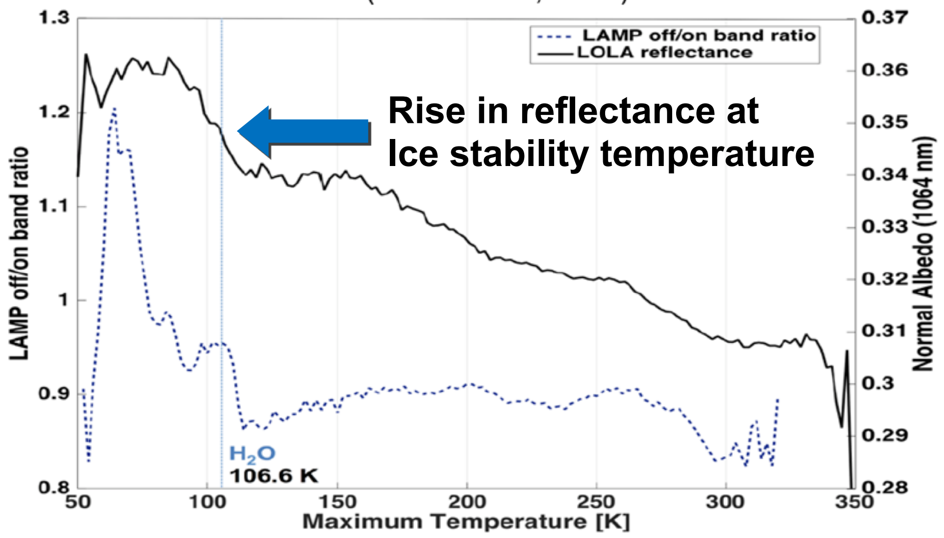
Hurley et al. 2013

Temperature Control

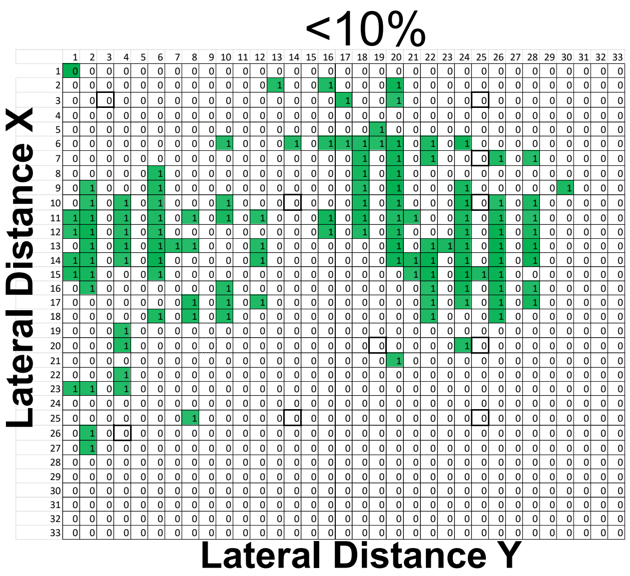
- Temperature appears to be a necessary requirement, but not the only determinant of volatile presence
- Thermal stability is defined as the temperature at which ice is stable in vacuum for geological periods of time (~Gyrs), or around <107K
- ***Temperature variations are largely determined by topography, thus temperature variations will be significant down to scales of <5 meters***

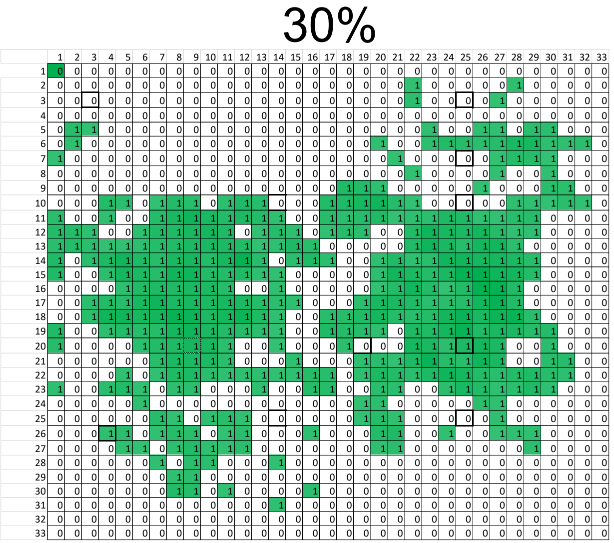
Surface Reflectance vs Temperature Indicative of Surface Frosts

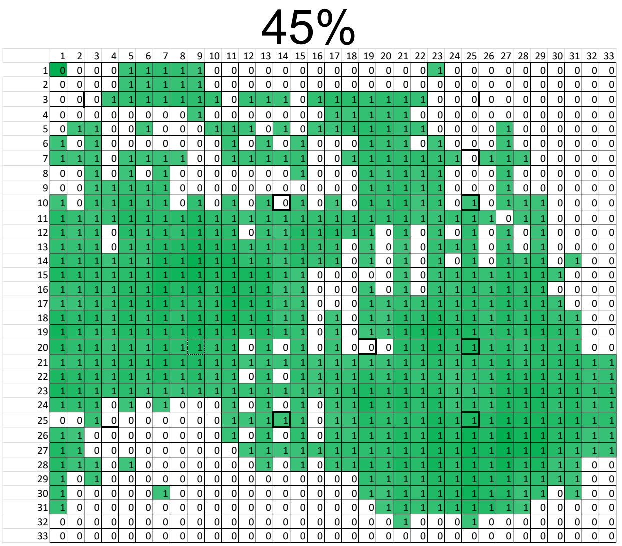
(Fisher et al., 2017)

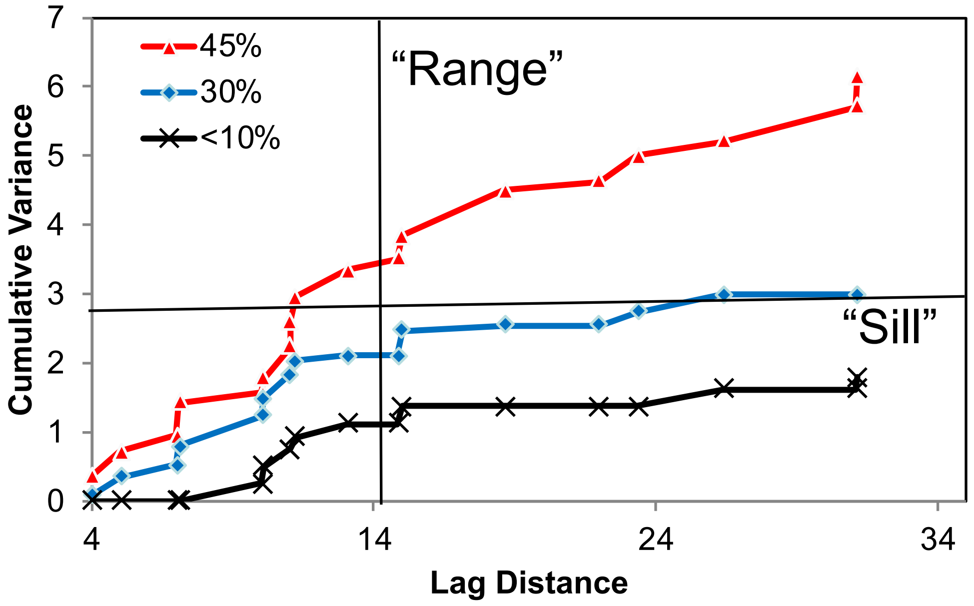


Variograms – Identifying Spatial Distribution Scales







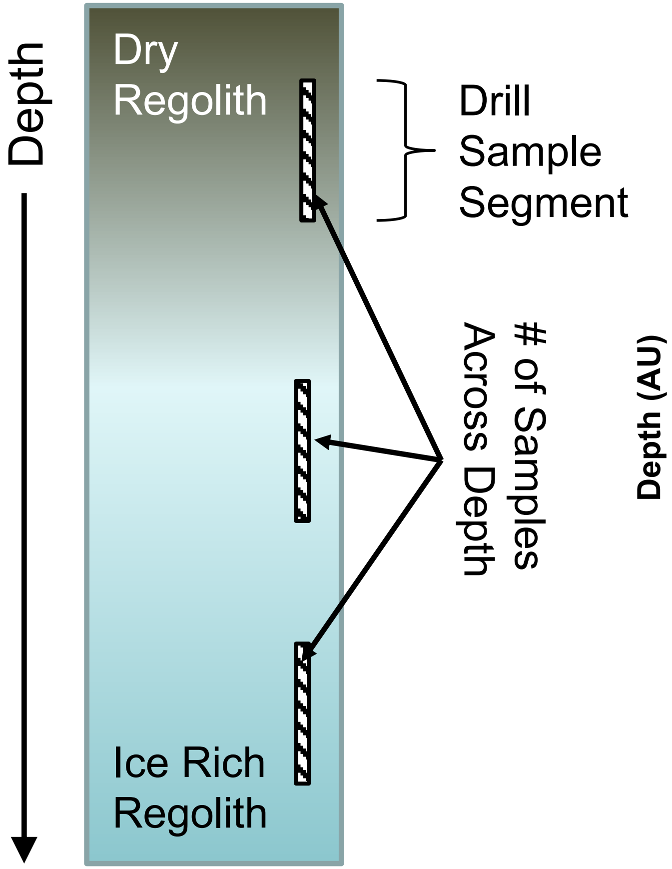


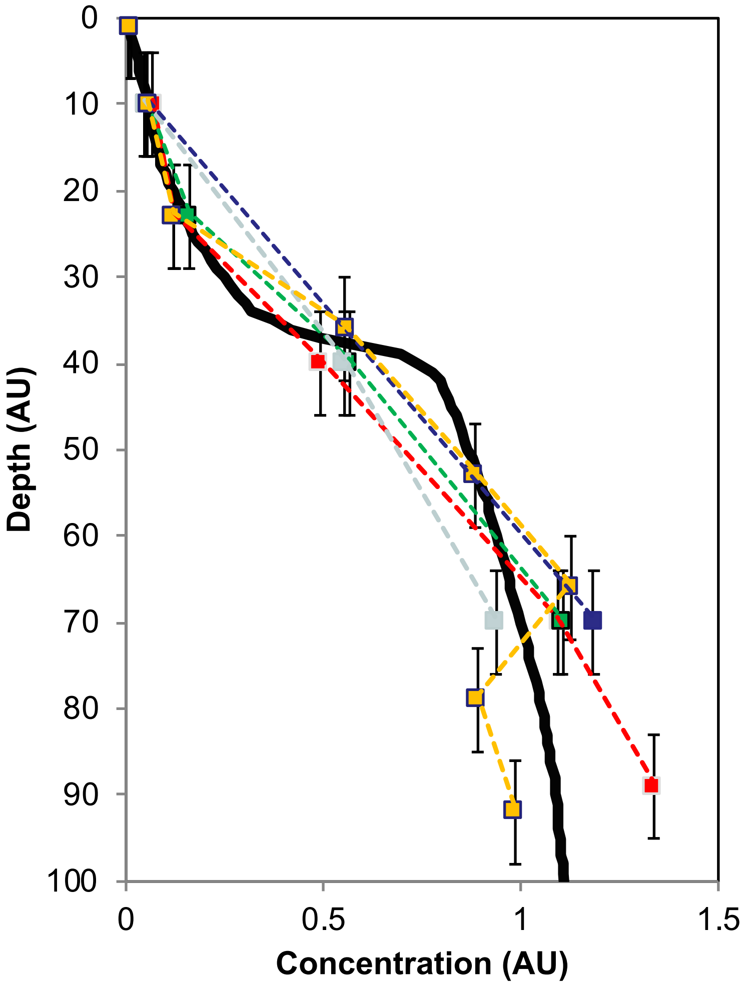
Measures spatial correlation: The geologic distance with respect to the Euclidian distance

- Beyond "Sill" lag value assume no autocorrelation (have extended beyond larges mixing scales)
- Different magnitudes of Sill indicate spatial structure scales
- Cratering model suggests **measurements across scales of at least ~25-30 units (or 50-60m) is necessary for 30% area fraction case**

Subsurface Sampling Requirements

- Need to resolve gradients in ice vertical distribution to inform neutron measurements (down to at least 50cm)
- Subsurface sampling can be defined in terms of both sample size (e.g., “Drill Sample Segment” length) and the number of these samples obtained across the column
- Conducted Monte Carlo simulations of various Sample Segment Lengths and Sample Numbers
- **Result: A Sample Length of >8cm and at least five samples per 80cm results in <10% integrated column uncertainty**





Demonstration of Prospecting Method: MVP

Reason for difference between NSS and NIRVSS

- Without pavement showed higher levels of hydration (spectra A)
- The desert pavement was protecting buried clays from dehydrating
- In light-tine washes, clays were more desiccated, but still had more water than the surface pavements
- From this data we can develop a model for hydration that is based on finer/ more complete data sets, such as albedo

Spectra from NIRVSS with and without surface pavement