Lunar Water ISRU Measurement Study (LWIMS): Establishing a Measurement Plan for Identification and Characterization of a Water Reserve

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Abstract

NASA's Artemis program aims to achieve a sustainable lunar presence by 2028. To carry out sustained crewed surface operations, In-Situ Resource Utilization (ISRU), which would use lunar resources (e.g., water) to produce mission consumables, will be critical. Water-bearing materials have been identified at both lunar poles, but the nature and extent of this resource is not well understood. Identification of the presence of water alone is not adequate for ISRU architecture planning and engineering design.

The Lunar Water ISRU Measurement Study (LWIMS) assessed and defined the type, amount, and fidelity of the information and measurements needed to select mining locations for lunar water ISRU and to define requirements for ISRU hardware and architecture development. Current ISRU requirements were used to define a water 'reserve' in this context. A measurement plan to achieve these goals includes three key elements; a predictive 'water favorability' model to identify and map potential deposits, continued assessment of orbital data, and three types of landed missions to make direct ground measurements. Corresponding mission scenarios and instrument suites will depend on risk posture and timelines for ISRU implementation.

Outline

Executive Summary

Lunar Polar Water ISRU Measurement Study (LWIMS)
Background and Problem Statements

EXPLORE
MOON to MARS

Background

Water identified in the permanently shadowed regions (PSRs) at the lunar poles can significantly enhance and enable lunar sustainability. But ISRU architectures (mining, conops, hardware design) requires knowledge of:

- Water content as a function of depth and area distribution (heterogeneity)
- Water form and energy to release from bound state
- The physical and mineral characteristics of the lunar regolith at mineable depths
- Topography and rock size distribution at potential mining infrastructure locations
- PSR environmental conditions

Problem Statements

1. Besides a single surface data point (LCROSS impact) there is significant uncertainty in the type, amount, physical parameters, and lateral/vertical distribution of water and volatiles in lunar PSRs
2. Before lunar ISRU water/volatile mining hardware and operations can even reach a preliminary design review, more 'ground truth' information on water/volatiles in PSRs is required.
3. While current and future lunar science instruments and missions can provide critical information, these science-focused efforts may not be sufficient for selecting mining locations, defining requirements for mining hardware designs, and planning mining operations

> Water has been identified as a **RESOURCE**, but its potential for ISRU requires identifying and locating a water **RESERVE**.

Lunar Polar Water: Current knowledge state

EXPLORE
MOON to MARS

Shallow bulk water is the target for ISRU.
- Potential lunar water sources include: surface frost, shallow bulk water, deep bulk water, and pyroclastic deposits
- There are 4 data sets for shallow bulk water (LCROSS, Chandrayaan-1, LRO, LP; see chart)
  - There are more data sets for surface frost detection (e.g., LAMP, LOLA and M3) than other data sets. While surface frost may be a geologic indicator of deeper water, there is currently no strong correlation between the two types of data sets (surface vs. buried reservoirs)

Water Equivalent Hydrogen (neutron spectroscopy) cannot give accurate concentration or depth distribution
- NS flux indicates there is hydrogen somewhere between the surface down to about 80 to 100 cm
- Conversion to WEH assumes uniform distribution laterally and with depth, and that all H is bound in water
- Is a function of assumptions regarding desiccated layer: concentration may be higher, but at depth

While regional distribution can be mapped from orbit significant local heterogeneity is expected
- Using Neutron Spectrometer: ~50 to 150 m (expected heterogeneity scale based on cratering statistics)

Radar data (CPR*) may suggest potential large volumes of water, but surface roughness can produce a similar signal.

Resolutions from current data sets are insufficient for Reserve definition.
- Reserve definition requires high resolution observation of a particular resource
- Current instruments and vantage points were designed with science objectives in mind.

Source	Sensing Depth	Resolution	Concentration	Extent	Comments
LCROSS	3 to 5 m	Single 50 m sample to 5 m deep	5.5 wt%, with other species	Single location	Consistent with the LP NS if distributed at 30% to 40% and/or buried under 10 to 30 cm desiccated layer
Chandrayaan-1 and LRO: RADAR CPR*	~1 to 2 m	150 m (baseline) up to 15 m (zoom-azimuth)	Wavelength scale ice blocks	Some PSRs	Source of high total volume estimates Could also be surface roughness
LP and LRO: Neutron count	0.8 to 1 m	LP: ~45 km at 30 km alt. LRO: ~75 km at 50 km alt. (STN) ~10 km at 50 km alt. (CSETN)-controversial	0.2 to several wt%	Poleward of 80°	Low resolution, deriving concentration depends on assumption of small scale and vertical distribution

*circular polarization ratio

Reserve Definition

Terrestrial Reserves

- Driven by **Economic** factors
  - Confidence in reserve is a cost trade:
    - Will a mine at the reserve site turn a profit?
    - Will a bank front the loan to start the mine?

- Exploration is known:
  - Geologic context is established
    - > Models exist to map/define reserve
    - > Measurements (model inputs) are defined
  - Measurement techniques (instruments, methods) are established and available
  - Exploration sites are (largely) accessible

- Exploration is an initial investment; consider cost benefit: confidence in profitability vs. up front cost
  - "Proven" Reserves vs. "Probable" reserves

Extraterrestrial reference Reserves

- Driven by **Mission Success** factors
  - Confidence in reserve impacts potential for mission success
    - Is engineering feasible and can the mission productivity goals be met?
    - Is production in critical path? (survival/productivity of crew, mission success)
    - Criteria for ISRU Reserve is listed on Slide 39
- Exploration is not established
  - Geologic context is not well understood
    - Models to predict or map/define reserve are in development
  - Measurement techniques are more restricted, potentially distinct from terrestrial options
  - Exploration sites are extremely difficult to access

- Exploration cost and timelines are much greater than terrestrial case.
  - Required confidence in reserve is therefore program dependent
  - Long term activity at extraterrestrial location will cause the terrestrial and extraterrestrial definitions to converge

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ISRU and Science: Commonalities and Differences

While Science and ISRU have common measurement needs that will support one another; distinct data sets are required for each.

- Science objectives are broad, with a wide variety of data required to build knowledge about natural processes.

ISRU Interest

Plan for interactions with engineered systems (physical properties) — Detect / locate water Reserves (mineable quantities) — Identify water, location, attributes and distribution — Predict potential Reserve locations

- ISRU objectives are targeted; focused on applied outcomes. There is an essential relationship to engineering.

Identify water, location, attributes and distribution — Understand history and origin of water — Understand Natural processes — Compare to other celestial objects

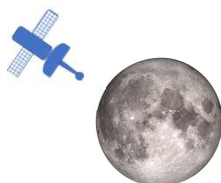**Science Interest**

Critical Commonalities

Measurement Plan Inputs

To achieve the measurements needed, 3 critical data inputs are required:

Predictive modeling capability

Analogous to terrestrial 'mineral favorability' models For lunar application this is a 'water favorability' predictive model to identify/map locations with water ice potential.

Orbital measurements

Provides information at the regional/global scale for the predictive model. Properly interpreting orbital data critical to identification of water-favorable sites.

Landed (surface) measurements

While this information can only be obtained locally (over a limited area) it is critical to proper interpretation of orbital data to identify water-favorable sites at the regional/global scale.

- 3 types of surface missions have been defined to achieve the fidelity of data needed

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Measurement Plan Structure

Orbital Measurements
New measurements or expanded interpretation of existing datasets

Predictive Model:
Water favorability map

ISRU pilot plant:
Land at a site, with a mapped reserve, that is matched to production engineering system: 2028

Type 1 Landed; Reconnaissance
Site selected for model validation. Multiple spatial measurements (mobility) preferred.

ISRU Demonstrations

Type 2 Landed; Focused exploratory
Site selected meets ISRU criteria according to model. Measurement(s) to validate/verify model water prediction only.

Type 3 Landed; Reserve mapping
Detailed mapping of selected ISRU Reserve site. Definition of the reserve and surface characteristics. Multiple spatial measurements (mobility) required.

Proposed Polar Resource Measurement Plan

EXPLORE MOON*to*MARS

The **GOAL** of a measurement plan is to **REDUCE RISK** for an ISRU pilot plant
Increase confidence in water reserve; reduce uncertainties
Decrease hardware operational risks: designed for conditions

Polar Resource Measurement Plan includes a framework with the following:

- A detailed list of measurements with target detection ranges and accuracies
- A list of potential instruments that could achieve measurements goals, depending on mission constraints
- An iterative approach to obtain and evaluate measurement data to achieve target goals, based on risk postures

Definition of a Measurement Plan requires the following Constraints
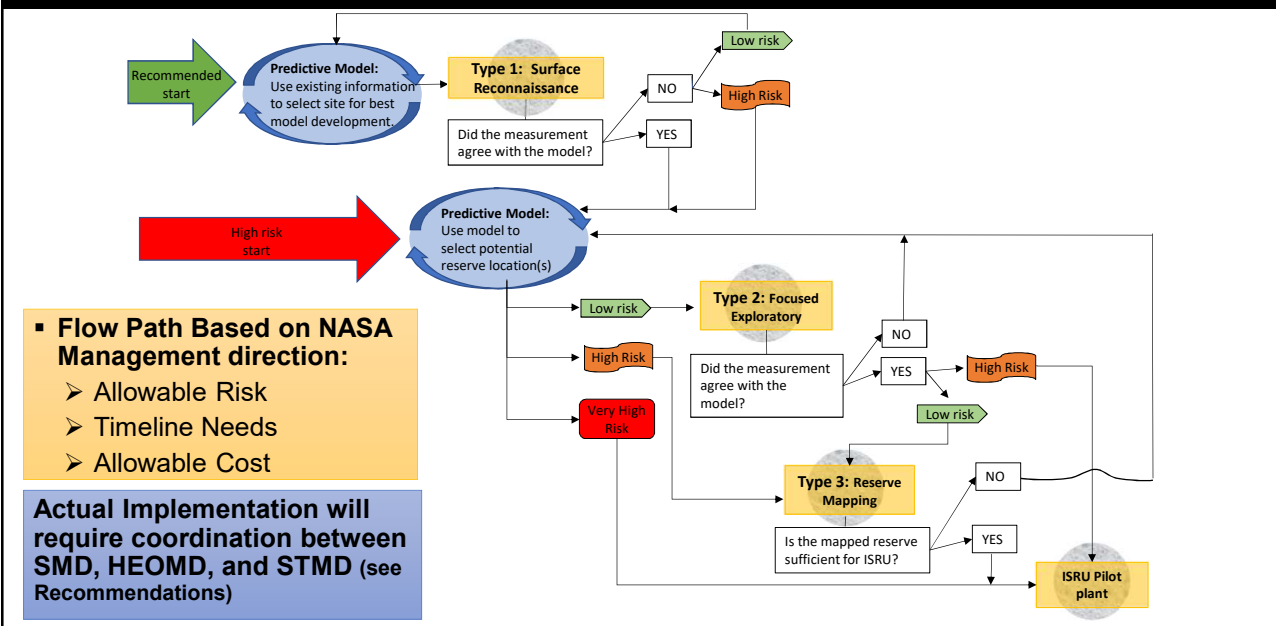
- **Timeline**
  - Need date for ISRU hardware (ISRU Pilot plant by 2028)
  - Instrument availability/development cycles
- **Mission opportunities**
  - CLPS payload selection and cadence of opportunities
- **Cost**
  - Instrument development and delivery (type/scale of missions)
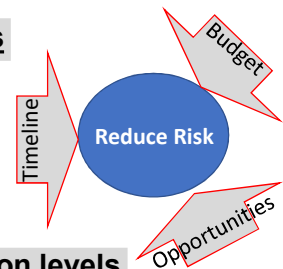
Strategic and Tactical planning required at programmatic and mission levels

- Coordinated selection of instruments, sites, operational concepts, etc.
- Consideration on impact to plan due to mission failure or null results

Budget / Timeline / Opportunities / Reduce Risk

Decisional Flow diagram

EXPLORE MOON*to*MARS

- **Flow Path Based on NASA Management direction:**
  - Allowable Risk
  - Timeline Needs
  - Allowable Cost

Actual Implementation will require coordination between SMD, HEOMD, and STMD (see Recommendations)
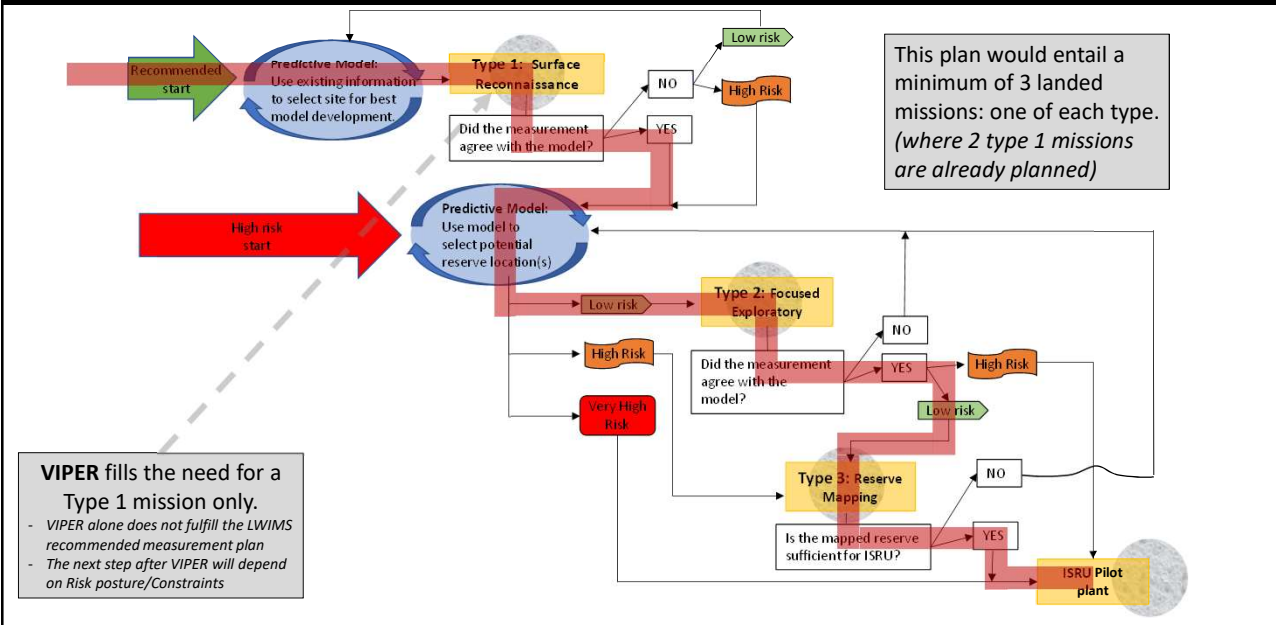
Findings

- **Current data sets are insufficient to define a reserve**
  - Identifying shallow bulk water can only be accomplished (currently) with NS (LRO,LP) and Radar (Chandrayaan-1 and LRO), but interpretation of data, particularly regarding distribution is inadequate
  - Coverage of this data at the Lunar poles and in PSRs is limited
  - LCROSS, while extremely valuable, was only a one point measurement

- **Schedule is a driver** (target: 2028 ISRU pilot plant), **which limits options** for instruments and implementation options.
  - May prefer reuse/re-flight of instruments hardware to reduce operational risk and improve data interpretation
  - Measurement plan (type and cadence) of missions must be reflective of Risk posture and results returned
  - Development of ISRU production systems have to occur in parallel with reserve identification to meet schedule; delaying measurements will result in less input to system design and result in higher hardware risk

- **Existing measurement techniques can achieve data needed, but must be adapted for lunar application**
  - Hardware (mobility, sampling, some instruments) must be adapted for operation in PSRs
  - Water quantification using heated sampling techniques, will likely provide highest accuracy, but are least developed for these applications

Recommendations

- **To meet aggressive schedule, a coordinated, focused effort must be implemented**
  - This impacts all Mission Directorate interests (STMD: ISRU hardware development, HEO: implementation of ISRU, SMD: volatiles measurements and overlap of science objectives)

- **Additional regional data sets (orbital)** including high spatial res Hydrogen maps, thermal, surface water detection **would be of high value to help reduce overall risk/uncertainty**
  - Missions (LunaH-map, Lunar Flashlight and the Lunar Trailblazer concept) should all go forward

- **Support ISRU relevant instruments in PRISM and LuSTR programs** (or similar) for advancement of ISRU technologies.

- **Recommend 'Best' Path based on Low to Moderate Risk is:**
  - Proceed with currently planned cubesat and smallsat missions to advance orbital/regional data sets
  - Support development of predicative model capability asap
  - Perform VIPER as planned for first Type 1 mission
  - Perform a minimum of 3 landed exploration missions: a Type 1, Type 2, and Type 3

Decisional Flow diagram: Recommended minimum Path

This plan would entail a minimum of 3 landed missions: one of each type. *(where 2 type 1 missions are already planned)*

VIPER fills the need for a Type 1 mission only.
- *VIPER alone does not fulfill the LWIMS recommended measurement plan*
- *The next step after VIPER will depend on Risk posture/Constraints*

Recommendations for Future Work

We recommend the **formation of a multi-disciplinary standing working group** with the following three responsibilities:

1. There are enough differences between how the term "reserve" is used on Earth, and how it might be used on the Moon (and on Mars) that a consensus definition should be developed.
   - *This is highly dependent on Risk tolerance for a given exploration program. This must be an on-going evaluation with inputs from all stakeholders to generate an appropriate (and evolving) measurement plan.*

2. Central to the scientific exploration process is the development of a "mineral model", or as referred to in this report, a "predictive model". This model needs to continuously incorporate new information as it becomes available, to monitor tests of model predictions, and to be updated in a timely way.

3. Coordination is needed between all Mission Directorates to ensure unified approach.
   - *Mission planning, CLPS usage, and investments should be coordinated for each MD portfolio to maximize investment and minimize overlap*
   - *Clear handoffs and roles between the MDs should be defined.*

- Composition should be similar make-up to existing LWIMS team including
  - Lunar Scientists
  - Measurement/Instrumentation specialists
  - ISRU engineers
- Core Team: NASA
  - A core team of NASA personnel should remain in place to gather information and serve as the conduit between the larger community and NASA management
  - Should include SMAs as listed above and key liaisons to each mission directorate
  - Recommend ~12 people at ~15% time (~2 FTE total)
- External Community engagement
  - Bi-Monthly (TBR) meetings to review current status and products
  - Will be engaged as expertise and feedback is required
  - Leverage the following groups:
    - LSIC
    - LEAG
    - SSERVI Nodes
    - Space Resources Roundtable
 - Standing group ~20 key people, voluntary basis?

Detailed Findings

Current knowledge state: Resources

Potential Water Sources

1. **Surface "frost":** Very low grade, but located exactly at the surface.
   - While easy to access, it likely does not meet ISRU criteria (production requirements)
   - However, knowledge of surficial water can be an indicator of shallow bulk water (may provide geologic context)

2. **Pyroclastic water deposits:** Low grade (max. 500 ppm), water bound in silicate glasses
   - Not of interest to ISRU, does not meet ISRU criteria (production requirements) and requires higher energy to extract (over ice)
   - However, these deposits exist at low latitude and could be relevant to other mission architectures

3. **Shallow bulk water:** moderate grade (up to 5 wt%) beneath 10 to 30 cm desiccated layer
   - *Highest ISRU potential*: meets ISRU criteria particularly in terms of production and accessibility requirements
   - Note that deposits may be irregularly distributed, occupying only 30% to 40% by area

4. **Deep bulk water:** Potentially high grade, at depths >1 m
   - Potential for ISRU, but does not meet current ISRU accessibility criteria:
     - Would require alternate technologies and grade must be substantial
   - No validated way of mapping/identifying deposits deeper than 1 m (possibly use seismic, GPR)
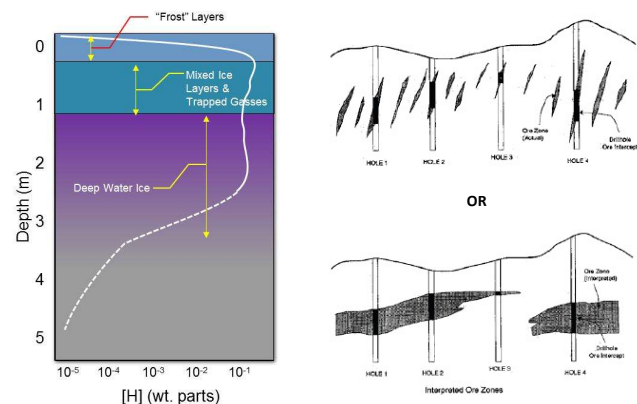
Current knowledge state: Data sets

Reservoir Type	Reservoir Depth	Dataset(s)	Concentration	Extent	Comments
Active Solar	Surface	Orbital NIR spectra	100 to 1000 ppm	Widespread	Current estimates of solar wind water production show very small amounts of water produced
Pyroclastic Deposits	Surface	M3	>300 ppm	None known near poles (present at low latitudes)	Water bound in silicate glasses
Frosts	Surface	LRO LAMP	1% to 2%, top 1 μm only	Some PSRs, patchy	Could be space weathering
Frosts	Surface	LRO LOLA	top 1 to 3 μm	Some PSRs, patchy	Debatable spatial correlation w/ LAMP
Frosts	Surface	M3	~2% to 30%	Widespread	1.1 μm water band only
Buried	Subsurface, down to 3 m to 5 m	LCROSS	5.5 wt%, other species too	Single location	Consistent with LPNS if distributed at 30% to 40% and/or buried under 10 to 30 cm desiccated layer
Buried	Surface and Subsurface, down to ~1 m to 2 m	RADAR CPR* (Chandrayaan-1, LRO)	Wavelength scale ice blocks	Some PSRs	Source of high total volume estimates; could be surface roughness
Buried	Subsurface, down to 0.8 m to 1 m	Neutron count (LP, LRO)	0.2 to several wt%	Poleward of 80°	Low resolution, deriving concentration depends on assumption of small scale and vertical distribution

Other datasets including international efforts, may provide additional information. The list here address primary data sets for the water sources.

*circular polarization ratio

Current knowledge state: Shallow Bulk Lunar Polar Water

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Neutron Spectrometer: WEH

**Going from Neutrons to Water Equivalent Hydrogen (WEH)**

- Neutron fluxes tell us there is hydrogen somewhere between the surface down to about 80 cm to 100 cm

- How this neutron flux translates to a Water Equivalent Hydrogen (basically how much water there is) depends on the sub-pixel mixing and burial stratigraphy

- Assuming uniform distribution laterally and with depth results in WEH of around 1% at Cabeus

- However, if the water is buried under a desiccated (dry) layer the water concentration may be higher

Lunar Prospector Neutron Spectrometer
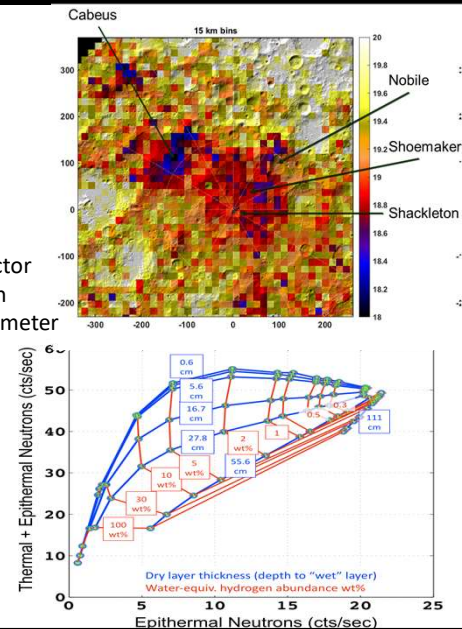
Neutron and LCROSS correlation

LCROSS NIR Camera Image of Impact Site

20% to 40% heterogeneity of "ice rich" region
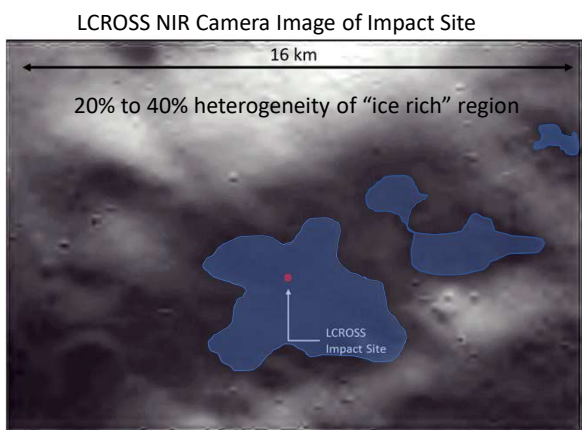
Blue areas are approximately "doubled shadowed"

A Model for the LCROSS Site

- LCROSS data reconciles with neutron data if ice is patchy and/or buried under a dry layer

- If the water is constrained to "protected" (coldest) double shadowed areas (figure at left), and has some amount of desiccated layer above it (10 to 30 cm), LCROSS water concentrations (5 wt%) are consistent with neutron measurements

- Within these areas of potentially enhanced water content, might expect mixing (due to impact and diffusion processes) at scales of 10s to 100s of meters, with variable depth (10 to 30 cm?)

Radar

- Radar on Chandrayaan-1 and LRO have made observations of the Circular Polarization Ratio (CPR) of the lunar surface

- Craters at the poles show two different characteristics:
    - Fresh craters show high CPR inside and outside of craters: fresh, blocky material
    - Some craters only show high CPR inside of crater and CPR is higher than most fresh craters

- This could suggest large volumes of water ice: Multiple blocks of ice approximately the same scales as the wavelength

- *Roughness can also produce high CPR*
    - *So while radar this may suggest ice, it must be interpreted with other data sets*
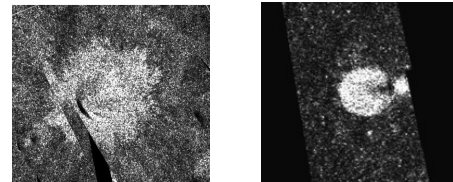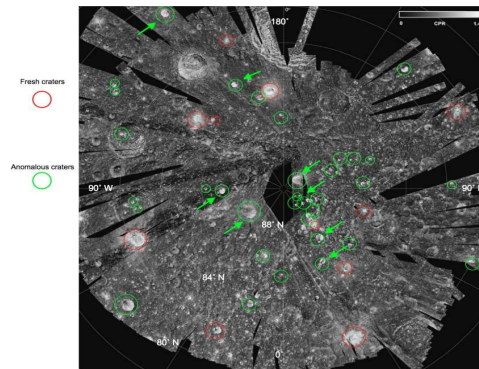
Spudis et al. 2010

Definition of a Water Reserve


"Reserve" definition

The study has involved much discussion regarding the definition of a reserve for extraterrestrial application and if/how it is unique from the terrestrial case. We would like to raise caution about using exact terrestrial definitions for extra-terrestrial situations, and we encourage further discussion.

- Part of the concept of "reserve" is that it can be presumed to lead to future success—in our usage we apply this context in both locations.

- On Earth, success is defined in financial terms—there is only one metric.

- However, on the Moon (and also on Mars/other), the situation is more nuanced.
  - There are other objectives than just making profit, such as keeping a crew of astronauts alive, or enabling the exploration of ever-more distant parts of the solar system. These have value that extends beyond money.
  - There are not consistent agreements on how to account for all of the costs that can or should go into the profit calculation for a lunar operation (an obvious example is exploration cost). By terrestrial definitions, if there is no profit, there is no reserve—we don't want this deteriorating into an exercise in creative accounting.
  - We note that circumstances change with time, and definitions that work on the Moon in the next few years may need to be replaced by more Earth-like definitions going forward.

Resource vs. Reserve

DEFINITIONS

- Resources:
  - Geological occurrences that have the potential for practical use, but for which viability has not yet been established

- Reserves
  - Resources which can be proven to exceed the threshold parameters (e.g., location, spatial extent, grade, chemistry) for at least one engineered system that can extract and process it to within a reasonable definition of success.
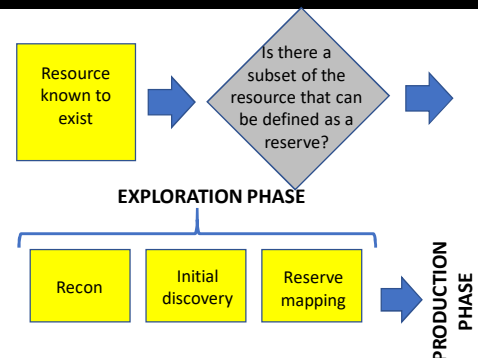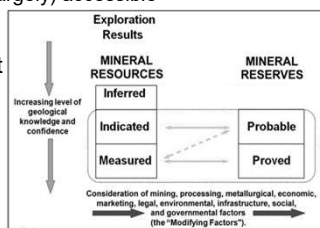

PROCESS FLOW

To convert resources into reserves requires two fundamental processes:

1. <u>Engineering work</u> to define a production/processing system that can convert raw material into commodities to meet an accepted (and mutually agreed) definition of success. The primary threshold parameters for reserve need to be defined by the engineered system.

2. <u>Exploration work</u> (in our case, missions and measurements) needs to define/locate at least one deposit of raw material that can be proven to exceed the primary threshold engineering parameters. Information informing secondary engineering parameters needs to be collected to ensure system operation.

Reserve Definition

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    - Will a bank front the loan to start the mine?

- Exploration is known:
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  - Measurement techniques (instruments, methods) are established and available
  - Exploration sites are (largely) accessible

- Exploration is an initial investment; consider cost benefit: confidence in profitability vs. up front cost
  - "Proven" Reserves vs. "Probable" reserves

Extraterrestrial Reference Reserves

- Driven by **Mission Success** factors
  - Confidence in reserve impacts potential for mission success
    - Is engineering feasible and can the mission productivity goals be met?
    - Is production in critical path? (survival/productivity of crew, mission success)
    - Criteria for ISRU Reserve is listed on Slide 39
- Exploration is not established
  - Geologic context is not well understood
    - Models to predict or map/define reserve are in development
  - Measurement techniques are more restricted, potentially distinct from terrestrial options
  - Exploration sites are extremely difficult to access

- Exploration cost and timelines are much greater than terrestrial case.
  - Required confidence in reserve is therefore program dependent
  - Long term activity at extraterrestrial location will cause the terrestrial and extraterrestrial definitions to converge

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Establishing a Reserve
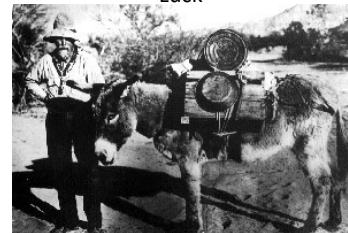## Mapping and Models

Mineral Favorability Models
- 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

Creating a "mineral" predictive model
1. Obtain empirical data about the reserve using an organized and focused exploratory campaign
2. Statistical analysis of resource distribution: Quantify the spatial variability (distribution)
   - Numerically reproduce the statistical properties of the variable depending on direction and distance
3. Create a predictive surface (map): cross validate with empirical data
4. Examine results in terms of geologic context: an understanding of the "how it got there" and "why it is still there" allows for the prediction of where the highest-grade resources may occur
   - Helps fill the gaps between empirical data points: higher confidence in predictive/inferred information

> *Exploration Science does not rely on luck!*

Luck

Applied Science
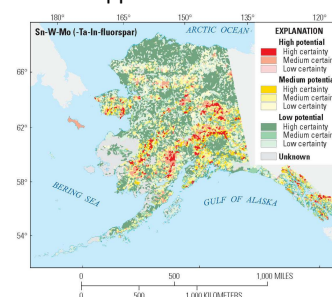
Establishing a Reserve
Predictive Models

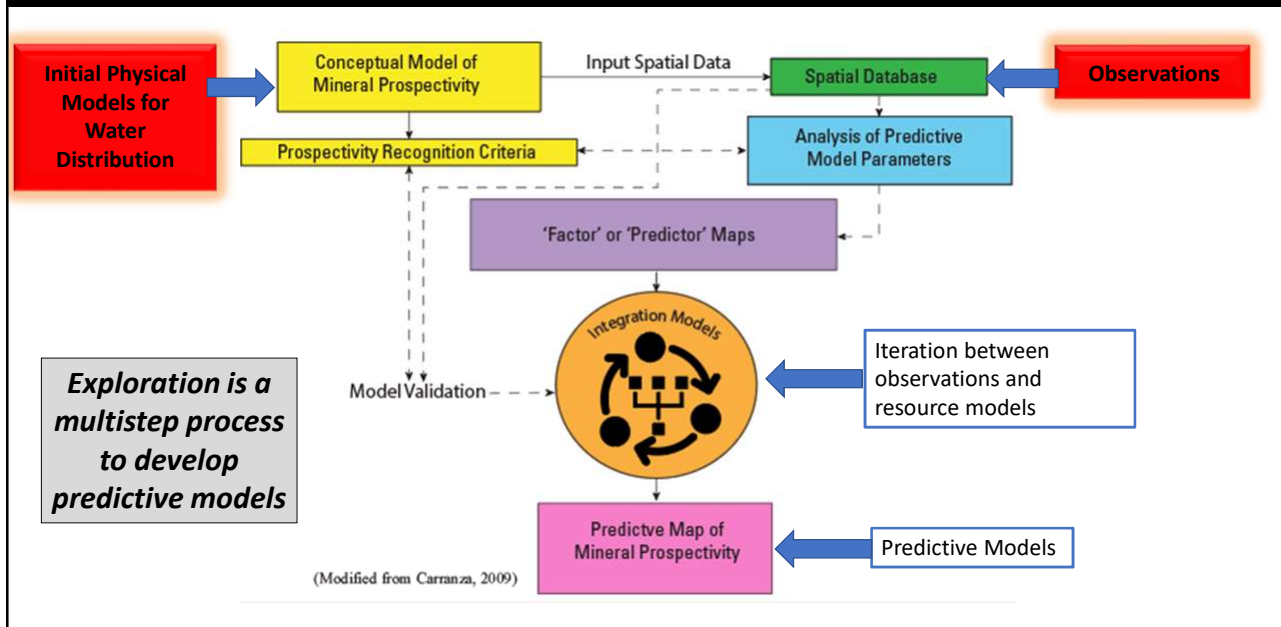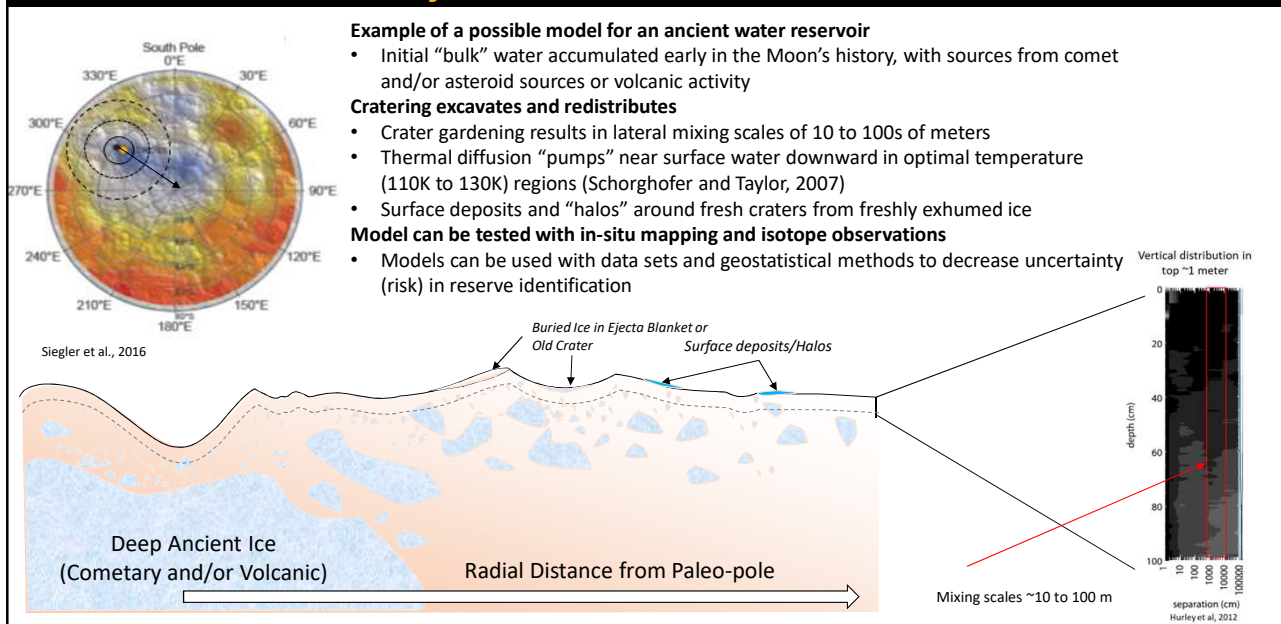Exploration is a multistep process to develop predictive models

Iteration between observations and resource models

Predictive Models

(Modified from Carranza, 2009)

Establishing a Reserve
Observations and Initial Physical Models for Water Distribution

Example of a possible model for an ancient water reservoir
- Initial "bulk" water accumulated early in the Moon's history, with sources from comet and/or asteroid sources or volcanic activity

Cratering excavates and redistributes
- Crater gardening results in lateral mixing scales of 10 to 100s of meters
- Thermal diffusion "pumps" near surface water downward in optimal temperature (110K to 130K) regions (Schorghofer and Taylor, 2007)
- Surface deposits and "halos" around fresh craters from freshly exhumed ice

Model can be tested with in-situ mapping and isotope observations
- Models can be used with data sets and geostatistical methods to decrease uncertainty (risk) in reserve identification

Siegler et al., 2016

Buried Ice in Ejecta Blanket or Old Crater

Surface deposits/Halos

Vertical distribution in top ~1 meter

Deep Ancient Ice (Cometary and/or Volcanic)

Radial Distance from Paleo-pole

Mixing scales ~10 to 100 m

Hurley et al, 2012

Establishing a Reserve
Progress toward a predictive map: unitless "Ice Favorability Index"
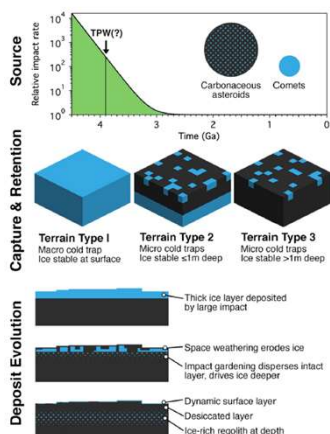
- Cannon et al. (2020) developed a system model for understanding polar ice deposits
- Model considers sources of water ice, capture, retention and redistribution (mainly as a result of impact gardening)
  - Model focuses on subsurface ice
- 3D impact simulations were used to test the model and investigate potential ice deposits over scales relevant to a mining outpost
- Results indicated that over time ice concentrations are lowered and increasingly homogenized at meter to hectare scales, high concentrations are randomly distributed, and best deposits are 10s of cm or greater depth

White box – Cabeus crater

Red box – Shackleton crater

Ice Favorability Index
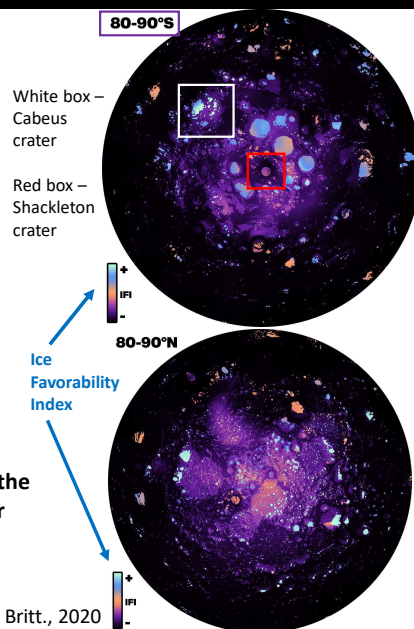
- **"Ice Favorability Index is a unitless measure meant to predict which locations at the lunar poles may be more or less favorable for deep, substantial deposits of water ice." (deep: <10s of cm to several meters)**
  - *Not intended to be a quantitative measure of ice, but can guide exploration efforts and additional site analysis.*

Cannon and Britt., 2020
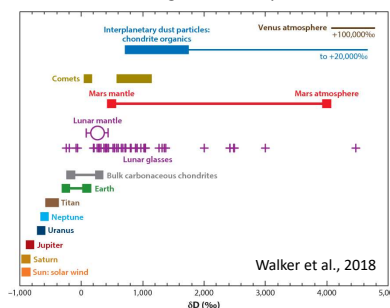

Establishing a Reserve
Predictive Models: Geologic Context

- Emplacement of shallow bulk water may have been through:
  - comet or asteroid delivery
  - early volcanic outgassing
  - production through solar wind interaction with lunar soils
- Observations of hydrogen/water distribution (e.g., association with craters of a certain age and size) and key isotopes can help constrain the initial origin of the water and hence its emplacement
- Current estimates of solar wind water production show very small amounts of water produced (Benna et al., 2019; Hendrix et al., 2019); no uniformity in surface "frosts" suggests production/loss are nearly equivalent or favor loss (Farrell et al., 2019)
- Hydrogen enhancements appear aligned to a potential paleo-pole (Siegler et al, 2016) with the ancient south pole very near where the LCROSS mission impacted
- **A potential source of shallow bulk water (of significant quality) is the excavation (via cratering) of deeper ancient ice which was emplaced prior to the polar wander**

The current "buried" distribution of water may be an ancient relic

Siegler et al., 2016
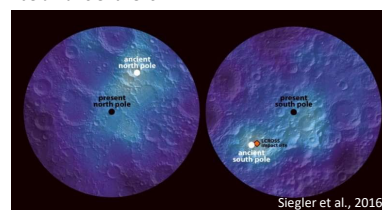
Isotopes from each reservoir may give clues to their origin and history

Walker et al., 2018

Establishing a Reserve
Predictive Models: Geologic Context

Origin	Distinct Attribute / Signature	Implications for Current Distribution
Comet / Asteroid	Isotope ratio (fractionation)	Paleo-emplacement; deeper reservoir centered on paleo-pole, being modified by subsequent processes
Volcanic Outgassing	Isotope ratio (fractionation); Sulfur compounds	
Processes		
Cratering - Excavation/Burial	Crater Age and Size (superposition)	Determines mixing scales (smaller impacts with higher rates)
Cratering - Heating leading to enhanced diffusion or chemistry	Crater Age and Size; Aqueous minerology	Possible enrichment/rarefaction associated with impact thermal profile
Molecular Diffusion / Thermal "pumping"	Regolith properties	"Blurring" of distributions via diffusion along temperature gradients; migration of water to depth (away from diurnal swing)
Surface sputtering /Far UV / Micro-meteoroid loss	Geochemistry, mineralogy	Creation of thin water "halos" around more recent excavated water
Other Environmental Controls		
Topography - Temperature	Subsurface temperatures; Paleo-temperatures	Poleward slopes having better water retention; Multi-shadowed craters having better water retention
Regolith properties (e.g., porosity)	Function of temperature, crater proximity	PSR near-surface regolith having higher porosity; Crater rims having higher porosity, Higher water storage/mobility
Surface Albedo - Temp control	Albedo variations (increases) from nominal regolith may be indicative of frosts	

LWIMS approach

LWIMS approach

Develop a **measurement plan needed to define a water 'reserve'** on the Lunar surface sufficient to meet ISRU requirements for a pilot scale production system

- Current State of Knowledge
  - We have already established that more than one kind of lunar water resource exists
  - We have reasonably refined ISRU engineering models, including working definitions of threshold "reserve" parameters that must be satisfied.
  - We do not know what fraction of the identified resources meet or exceed the threshold parameters; this could be anywhere from none to "reserves everywhere"

1. Define a Reserve, as distinct from a Resource, in terms of mission requirements and risk tolerance (recognizing that the risk cannot be quantified)
2. Assess current knowledge state by dividing into 3 subteams:
   - ISRU production criteria and measurement gaps needed to support an ISRU pilot scale plant at a given location
   - Resource/Reserve modeling and identification: What goes into reserve definition on the moon, as distinct from terrestrial, and what is needed to predict/map potential reserve sites.
   - Instrument State of the Art and options to fill knowledge gaps; including existing assets, planned missions, and development opportunities
3. Design a measurement strategy with goal to locate a reserve, with reasonable confidence, as quickly as possible
   - Approach measurement plan as a campaign of missions and/or suite of instruments, as needed
   - Multiple paths will be offered, the selection of which will depend on the agency's risk posture
     - Mission types will be defined by the type, quantity, and quality of measurements needed

Ground Rules and Assumptions

- Measurement plan must provide enough information to select a site and design hardware for an ISRU propellant pilot production plant (1 mT O_2 target) in 2028
  - Schedule is a driver, so reuse or adaptation of existing instruments/implementations is strongly preferred to reduce risk and facilitate timely data interpretation
  - Selected site must meet ISRU criteria, including ties to HLS/HEO needs
- Definition of the reserve is anchored to production need and risk tolerance; this drives measurement architecture
- Risk posture must be understood prior to pursuing a measurement plan
- PRIME-1, VIPER and CubeSats (orbital/Artemis 1) will occur as planned/scheduled
- Initial understanding of production systems, which are used to generate ISRU site criteria, are based on current models and technologies. These system models will continue to evolve with continued Research and Development and with advances in resource understanding.
- Predictive ("mineral"/water favorability) modeling/mapping capability is an integral and evolvable process to the measurement plan
  - Capability can be leveraged/brought on-line and supported in this timeline
- Reserve definition is an output of exploration process and directly feeds production process; this is a crucial interface
- Presence of a sufficient reserve is not assumed to exist (aka it is possible a sufficient reserve does not exist, or cannot be located, to pursue a water ice ISRU architecture on the moon.)
- Ground rules and assumptions are based on NASA architecture as understood Feb 4, 2020

Threshold Criteria for a Reserve

ISRU System

ISRU Requirement	Criteria
Water Concentration	≥2 wt% to a 1 wt% detection limit
Water Depth distribution	5 to 100 cm, ≤10 cm increments
Overburden depth	5 to 50 cm ≤10 cm increments
Lateral distribution	500 m radius
Target yield	15 tons water per lander

- Criteria according to current ISRU system models which use current technologies and architecture concepts (Kleinhenz and Paz, AIAA ASCEND 2020)
- Criteria are highly dependent on:
  - Amount of consumables needed
  - Timeline allotted for ISRU production
  - Architecture interface to HLS (location of produced consumables, power)
  - Assumptions about mobility options and capabilities including autonomy and operational life
- Consideration to Oxygen from Regolith (O2R) as the alternative to water from ice
  - When possible, identify breakpoints where O2R is clearly advantageous over water from ice
- Additional knowledge to design ISRU systems and architectures (next page)

Human Landing Systems

Lander Requirement	Initial	Sustained
Daylight Operations	continuous light	50 hours darkness (threshold) 191 hours (goal)
Surface Access	84° S to 90° S	global
Habitation Capability	two crew for 8 earth days	four crew lunar sortie with pre-emplaced surface infrastructure
EVA Excursion Duration	lasting a minimum of 4 hours	lasting a minimum of 8 hours
Landing Site Vertical Orientation	vertical orientation of 0 to 8° (threshold) and 0 to 5° (goal) from local vertical for surface operations.	
Landing Accuracy	landing within 100 m (3-sigma) of target landing site	
Surface Operations	operating on the lunar surface for a minimum of 6.5 Earth days	
EVA Excursions per Sortie	at least two (threshold) and five (goal) surface EVA excursions per sortie.	
Scientific Payload Return to Lunar Orbit	returning scientific payload of at least 35 kg and 0.07 m^3 volume (threshold) and 100 kg and 0.16 m^3 volume (goal)	

- For infusion of ISRU into Human campaign, the HLS site requirement must be considered
- ISRU reserves must have adequate proximity to HLS sites
- Information per HLS BAA Appendix H requirements

ISRU knowledge gaps

- The following information is required to design ISRU systems and architectures
- These parameters would not eliminate a site from consideration, but are key design parameters

Regolith reactivity

Required Input	Required Range (if applicable)
Water Release Temperature profile (Release Energy and Quantity)	≤~200°C
Volatiles released at temperature H_2S, SO_2, NH_3, Hg, HFl; CO_2, CO	≤~200°C

Geotechnical properties

Required Input	Required Range (if applicable)
Cohesive Strength (c)	0 to 100 kPa
Internal Friction Angle (Ø)	10° to 50°
Particle size distribution	1 to 1000 μm
Soil bulk density	0.5 to 2.5 g/cm³
Compressive Strength	1 to 100 MPa
Terrain features including rock abundance	

Measurement Plan Inputs

To achieve the measurements needed, 3 critical data inputs are required:

1. **Predictive modeling capability**
    - Analogous to terrestrial 'mineral favorability' models which are used to predict and map potential mineral deposits for the mining industry. For lunar application this is a 'water favorability' predictive model to identify locations with water ice potential
    - Leverage existing and new measurement data and models to build/refine models to locate water potential on the regional (if not global) scale
    - This capability is absolutely pivotal to selection of favorable ISRU sites
2. **Orbital measurements**
    - When considering input to the predictive model, orbital data provides information at the regional/global scale, while landed information will give point measurements. Properly integrating orbital data, including LCROSS, and anchoring to landed measurements is critical to identification of water-favorable sites.
3. **Landed (surface) measurements**
    - Direct, ground-based measurements are needed to develop the predictive model. While this information can only be obtained locally (over a limited area) it is critical to proper interpretation of orbital data to identify water-favorable sites at the regional/global scale.
    - Surface measurements are also needed to characterize the most promising water reserve sites in terms of higher resolution water distribution and water abundance information, as well as surface properties (geotechnical factors, dust, etc.). This information is key to ISRU hardware selection and con-ops.
    - 3 types of surface missions have been defined to achieve the fidelity of data needed

Definition of surface measurement types

- **Type 1:** Reconnaissance
    - Measurement requirement is to develop model and put orbital measurements in context
        - Model is key to understanding broad data sets and select target landing sites
        - Orbital measurements are critical to locate potential water on a regional scale
    - Landing site does not necessarily meet ISRU Reserve criteria. Selection based on:
        - Opportunities to obtain broader range of data to develop predictive model
   - Earliest landing site opportunities: start early

- **Type 2**: Focused exploratory
    - Measurement requirement is to validate water prediction only
    - Landing site meets ISRU Reserve criteria according to model predictions
    - Ideally performed at multiple sites
    - Options for Type 2 include:
        - Single point measurements (no mobility)
        - Multiple-point measurements (mobility, impactors)
        - Simple, low cost, quick turn-around landed instruments (potentially short life e.g., impactors)
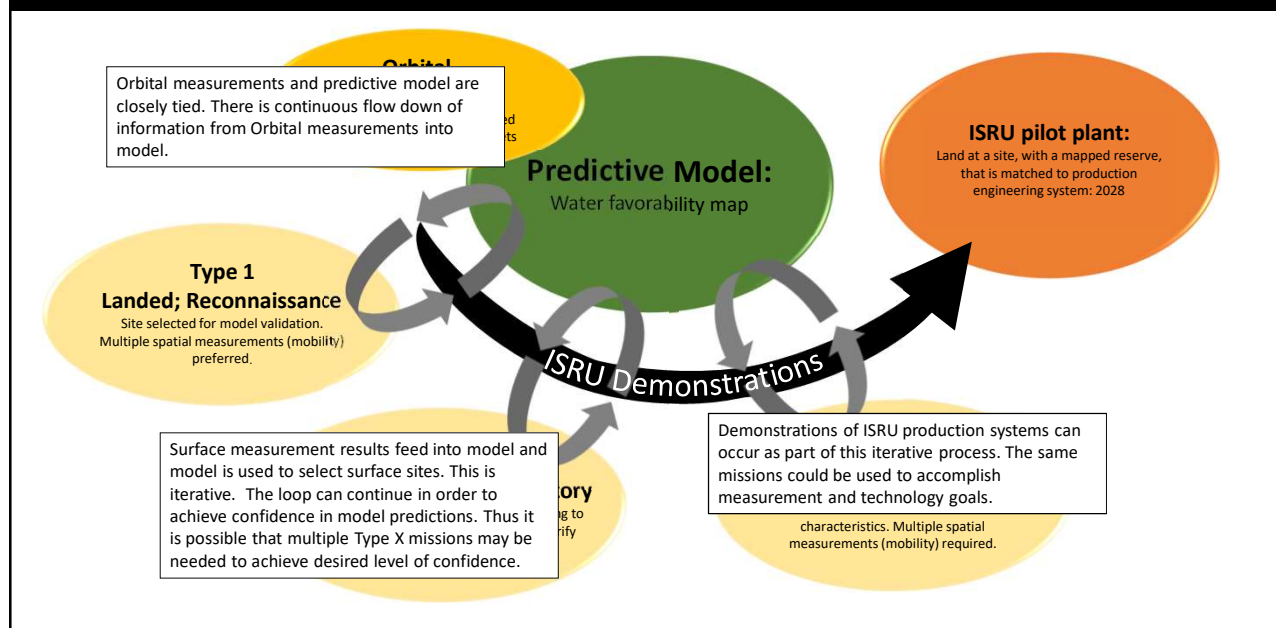
- **Type 3:** Detailed mapping of ISRU Reserve site
    - Measurement requirement is to obtain broader set of data needed to plan mining con-ops, hardware emplacement, etc.
    - Landing site has been accepted as likely ISRU Reserve location (based on Model and Type 2 validation)
    - Multiple types of measurements needed; not just water measurement
    - Mobility needed to obtain measurements to define lateral distribution
    - ISRU Reserve is likely in a PSR, so this asset must survive extended periods in this extreme environment. It is an opportunity to demonstrate technologies also needed for ISRU plant.
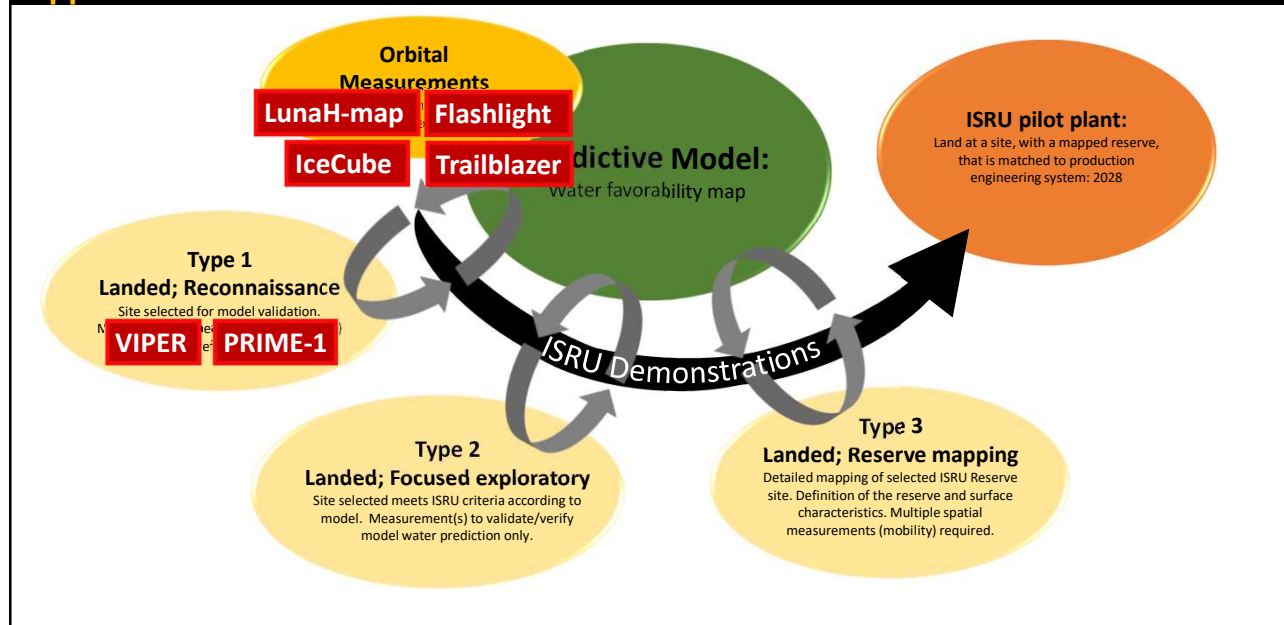
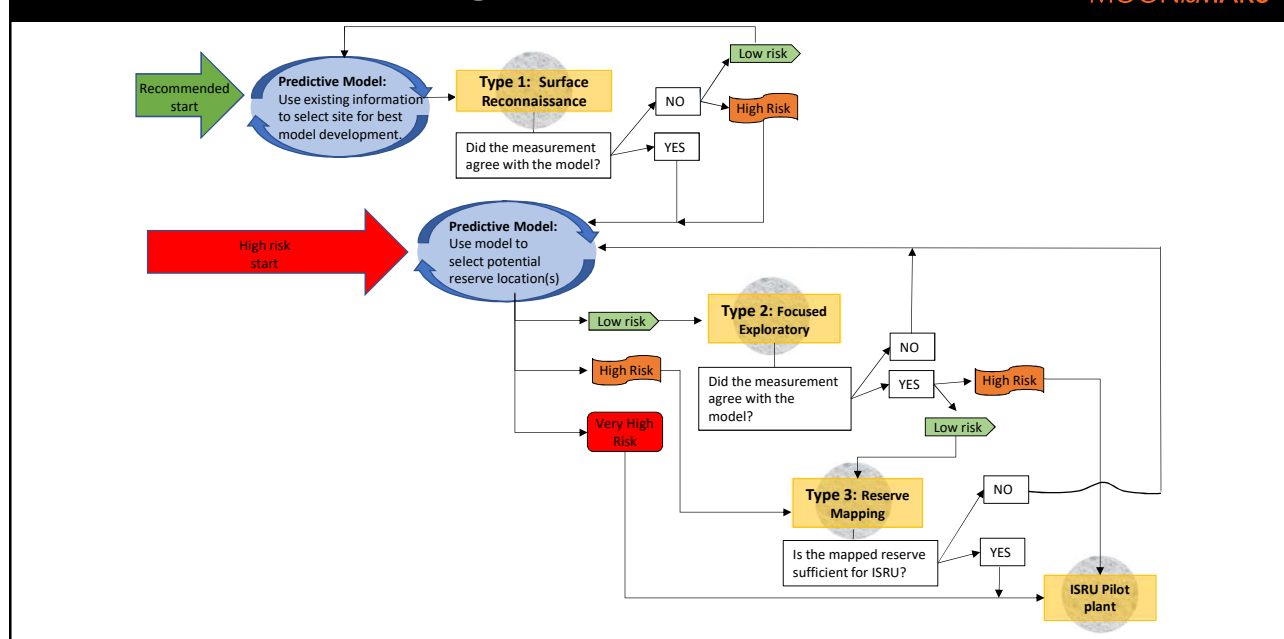# Measurement Plan Structure
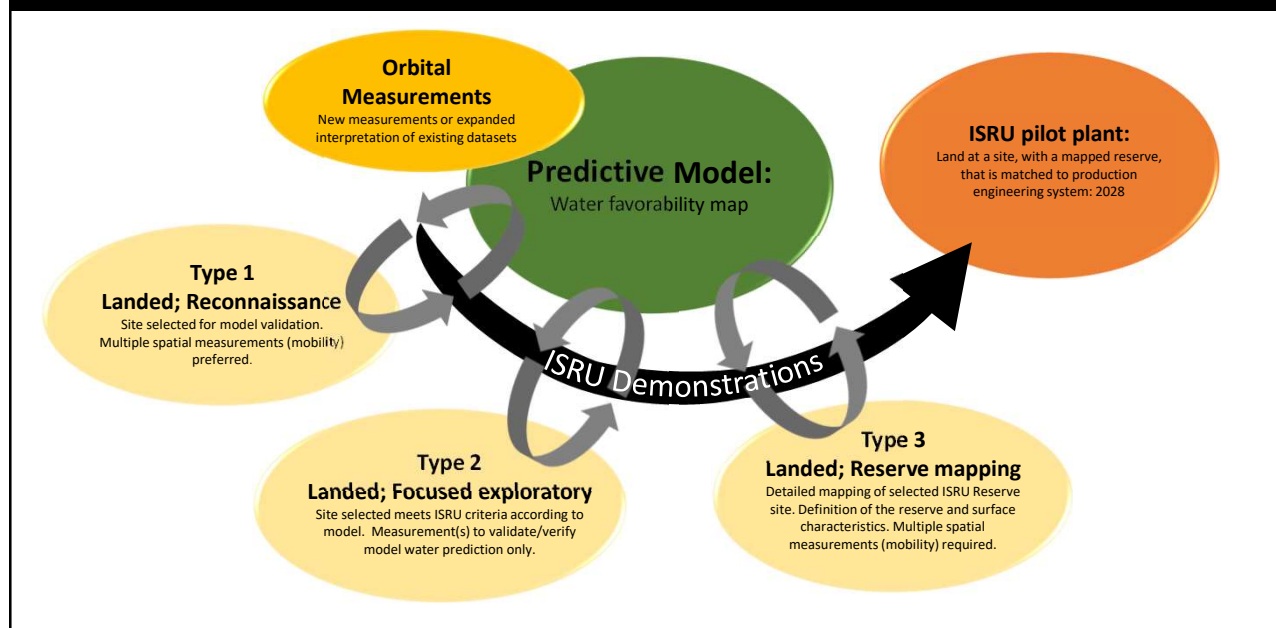
Measurement Plan Structure

Measurement Plan Structure: Applicable missions

Decisional Flow diagram

Decisional Flow diagram: Recommended minimum path

This plan would entail a minimum of 3 landed missions: one of each type.
(where 2 type 1 missions, VIPER and PRIME-1, are already planned)
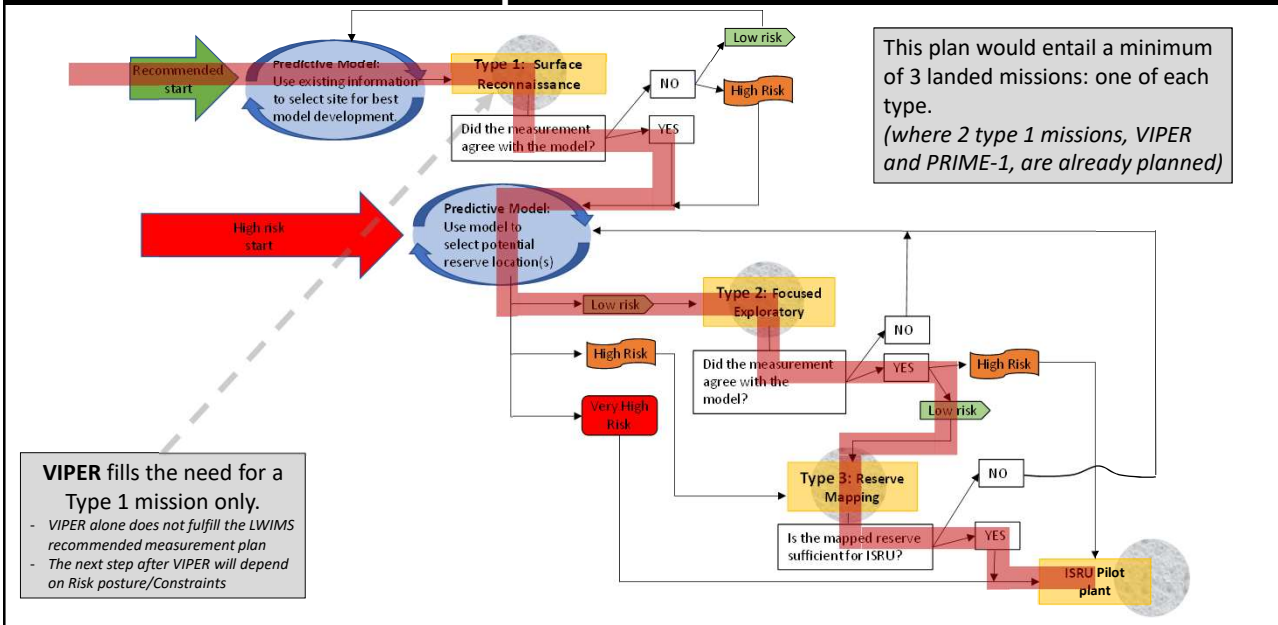
VIPER fills the need for a Type 1 mission only.
- *VIPER alone does not fulfill the LWIMS recommended measurement plan*
- *The next step after VIPER will depend on Risk posture/Constraints*

Science Linkage

ISRU and Science objectives: Linkages

EXPLORE MOONtoMARS

- ISRU criteria are targeted, focused on mission design. High fidelity is needed for key targets.
- Science objectives are broad, with a wide variety of data required to build knowledge about natural processes.

While distinct data sets required are for each, there are several commonalities. Below we trace criteria which will drive ISRU measurements to important examples of the science goals that can also benefit from those measurements.

ISRU Criteria		Science Goals which would benefit
Find a site that has:		
Water Concentration	≥2 wt% to a 1 wt% detection limit	4a, 4b, 4c
Target yield	15 tons water per lander	4a, 4b, 4c
And characterize:		
Water Depth distribution	5 to 100 cm, ≤10 cm increments	4a, 4b, 4c
Overburden depth	5 to 50 cm ≤10 cm increments	4a, 4c
Lateral Distribution	500 m radius	4a, 4b, 4c
Soil reactivity (volatile species and release energy)	≤~200°C	4a, 4b, 4c
Geotechnical properties	At PSR site, some properties to 1 m depth	4c, 4d

Science goals (NRC The Scientific Context for Exploration of the Moon, 2007)

4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.

Measure elemental and isotopic composition of gas evolved from regolith in permanent shade heated up to 700K, obtained from depths greater than 10 cm and up to a meter.

Determine the presence of refractory volatile-bearing species including water-bearing minerals, complex organics, and clathrates

Determine elemental composition, especially hydrogen, for immediate surroundings of sampling site

4b. Determine the source(s) for lunar polar volatiles.

4c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions.

4d. Understand the physical properties of the extremely cold (and possibly volatile rich) polar regolith.

ISRU to Lunar Science Linkages

EXPLORE MOONtoMARS

BOX 3.1
Linkages Between Lunar Resource Utilization, Science, and Human Exploration

Minimizing the costs of sustaining an outpost on the Moon requires the use of local resources. Interactions between the field of resource utilization and science lie in the following areas:

1. Exploration for resources based on chemical and mineralogical data employs the same data sets as those obtained for understanding the geochemical evolution of the Moon. The data in hand on the chemistry and mineralogy of the lunar regolith provide inputs to lunar resource process development as well as to the history of the regolith.
2. Extraction of lunar resources requires access to the subsurface (excavation, drilling). These techniques can be used to access lunar environments for scientific studies.
3. Development of products based on lunar resources will utilize special aspects of the lunar environment (particularly vacuum). Scientific understanding of the lunar atmosphere and the behavior of molecules on the lunar surface will be important in understanding the potential for lunar contamination from the resource extraction processes. In turn, the processes themselves may require the preservation of high-vacuum conditions.
4. New materials manufactured in the lunar surface environment (e.g., vacuum-coated surfaces) may lead to new types and applications of materials sciences.
5. Access to relatively inexpensive hydrogen and oxygen (less expensive than bringing them from Earth) may enable more intensive development of experimental biological systems and associated scientific studies.
6. Lunar resource development can enable new capabilities for science. Development of a propellant-chemical energy storage capability (e.g., regenerative fuel cells using lunar O_2 and H_2) may accelerate the potential to establish remote field camps away from the lunar outpost. Excavation technology and the extraction of large volumes of water could enable the emplacement of large subsurface cosmic-ray detectors. Metal and nonmetals extracted from the lunar regolith could enable the development of indigenous power (silicon for photovoltaic devices, metals for energy transmission), enabling an energy-rich environment for science. Some by-products of resource processing (e.g., noble gases) might become useful for the support of science experiments.

From The Scientific Context for Exploration of the Moon, NRC 2007

Table 1. Synergy of Exploration and Science Objectives in Lunar PSRs

Quantity	Exploration Objectives	Science Objectives
Composition	Available resource	Source of volatiles
Abundance	Value, Extraction technique	Source/loss rate
Depth Distribution	Extraction technique	Age of deposits
Heterogeneity	Mobility needs	Redistribution processes

From "Lunar Polar Volatiles: Assessment of Existing Observations for Exploration' white paper, Hurley et al., 2016

Detail of Measurement types

Orbital
Measurement Goals

- Goal: Global/regional area measurement for identification of potential reserve sites.
- Existing assets and datasets can and will be leveraged.
- Additional measurements and assets will help to reduce uncertainty significantly
  - There are some limitations on current dataset at the poles (LRO no longer observes the poles)
  - Existing neutron data from LRO and LP have larger footprints than the size of many PSRs and the expected mobility ranges of near-term landed missions.
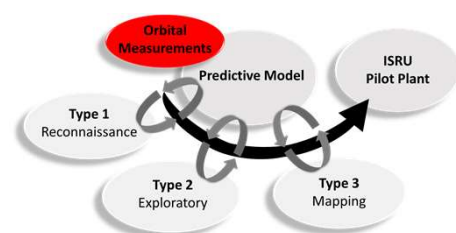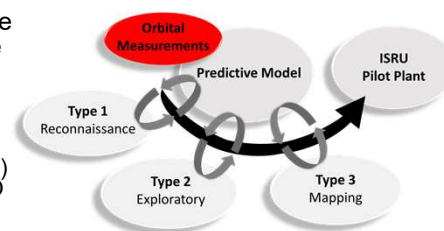
Orbital
Measurement Definition

Measurement *(Relative priority from top to bottom)*	Benefit and Rationale	Potential approach(es) /platform(s)	Target measurement parameters	*Example method(s)/instrument(s)*
Abundance and horizontal distribution of shallow bulk H_2O (shallow = in top 1 m)	Primary focus for finding/characterizing ISRU resource.	Cubesat (e.g., LunaH-Map)	H_2O spatial resolution at least 15 km (5 km preferred), to a depth of 1 m, coverage <6° from poles, sensitivity at least 1 wt%.	Low flying Neutron Spectrometer (NS)
Surficial water (OH, ice, adsorbed and bound water) distribution	Context for where to look for shallow bulk water. Provide basis of higher fidelity water distribution model with finer scale than subsurface shallow bulk measurements	Larger satellite (e.g., LRO) to provide more capable instrument and/or more delta V as these are unstable orbits	50 m spatial resolution at abundances >0.1%, polar coverage	Low flying surface reflectance VIS/NIR spectroscopy
Subsurface structure	Constrains degree of heterogeneity (e.g., ice deposits or sheets) in subsurface structure that can affect mining.	Larger satellite (e.g., LRO) *see comment above*	Assess top 2 m depth on spatial scale of <15 km (less than NS) with 10s of cm vertical resolution.	Low flying ground penetrating radar with large antenna
Thermal mapping	Can be used with surficial H_2O measurements as input to shallow bulk water distribution model	Larger satellite (e.g., LRO) *see comment above*	Temperatures on scale of <50 m spatial resolution (crater scales)	Low flying multispectral thermal imager

Orbital
Rationale for target parameters

Existing Orbital data will be leveraged, but additional measurements are recommended to reduce uncertainty. The below points describe the rationale for choosing the measurements and parameters listed on the previous slide which are recommended to significantly increase confidence for predictive model development targeting polar regions.

- Bulk shallow subsurface water
  - Higher spatial resolution (15 km) subsurface bulk water abundance (>1%) and vertical distribution (20 cm increments) is improved over LP and LRO LEND neutron data, and improved spatial and vertical distribution measurements are crucial to predictive model development
  - While 15 km spatial resolution is a significant improvement over current data and the near-term goal, 5 km spatial resolution is preferred as it can enable resolution of many PSRs and is closer to the expected mobility ranges of upcoming surface missions (LEAG VSAT).
- Surficial water
  - Higher spatial resolution (50 m) surface water (OH, ice, adsorbed and bound water) abundance (>0.1%) driven by viable cold trap (crater) size, improved over Chandrayaan M3
- Subsurface structure
  - Comparable/greater than the spatial and vertical resolution recommended for bulk shallow subsurface water measurement.
- Thermal mapping
  - 50 m scale thermal mapping is improved over LRO DIVINER and will assess crater scales
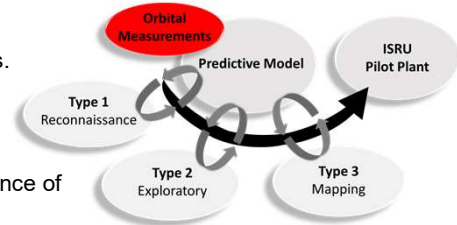
Orbital
Current or Planned Missions

- Lunar Flashlight
  - Measurement: Surface ice in PSRs within 10° of south pole
  - Method: Laser-induced reflectance at and near ice absorption features.
  - Performance: 1 km spatial resolution, 0.5 wt% detection limit
- LunaH-Map
  - Measurement: bulk water within 5° of south pole
  - Method: Neutron spectrometer thermal flux changes induced by presence of H+ (implying ice)
  - Performance: 15 km spatial resolution, <500 ppm detection limit, 0.5 m depth
- Lunar Trailblazer
  - Measurement: global surface water (OH (adsorbed and bound), ice) and major minerals and rock suites
  - Method: Near IR reflectance absorption features and thermal IR emission
  - Performance: 100 m spatial resolution, <0.1% detection limit
- Lunar Ice Cube:
  - Measurement: surface OH and various forms of water (adsorbed, bound, ice) as function of time of day and latitude by providing coverage of the same ground swaths from pole to pole at different times of day during consecutive diurnal cycles.
  - Method: IR reflectance absorption features from 1 to 3.5 μm
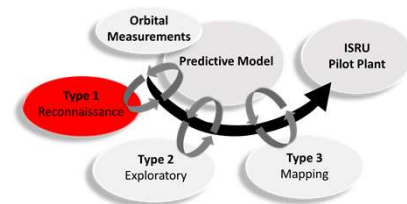 - Performance: 10 km footprints, 0.1% detection limit

Type 1: Surface Reconnaissance
Measurement Goals

- Direct, ground-based measurements at surface sites selected to develop model and put orbital measurements in context
  - e.g., Direct water measurement to translate/verify orbital WEH identification as water
- Selected site does not necessarily meet ISRU Reserve criteria. Instead, site selection based on:
  - Opportunities to obtain broader range of data to develop predictive model
  - Accessibility: Earliest landing site opportunities
- Measurement priorities primarily target model development needs, not reserve definition.

Type 1: Surface Reconnaissance
## *Measurement Definition*

Measurement (Relative priority from top to bottom)	Benefit	Potential approach(es) /platform(s)	Target measurement parameters	*Example* method(s)/ instrument(s)
Shallow (1 m) water horizontal and vertical distribution, abundance	Critical ISRU input. Even if not potential reserve site, data gained can be matched to orbital measurements for better interpretation and support of predictive modeling.	Active subsurface sampling from stationary or mobile platforms, with complementary sample analysis instruments.	Water abundance with vertical resolution <20 cm depth intervals to 1 m, 1% detection limit	Drill, scoop, or volatile drive off mechanism with attached analysis capability via Mass Spectrometer, Tunable Laser Spectrometer (TLS)
		In situ survey from network of small platforms equipped with cubesat-scale payloads, small mobile platforms, network of impactors, hoppers	Water abundance with vertical resolution <20 cm depth intervals to 1 m, horizontal resolution 50 m, to 1% detection limit	Miniaturized payloads (<10 kg) neutron spectrometer, ground penetrating radar, IR imager on mini-rovers
Potential ISRU contaminants (e.g., S compounds, HF, NH$_3$, Hg, organic compounds) in situ or in regolith	Neutrals and charged particles (generated from external or internal processes) could impact ISRU processing as an additional resource or a contaminant	Same as shallow water, active subsurface sampling with complementary payload or in situ survey	Element/compound identification (>1 to 100 Da or 150 Da baseline) and abundances (best effort)	mass spec, APXS/XRF (elements), LIBS (elements) for in situ analysis; mass spec with pyrolysis front end for analysis of sample; energetic neutral or charged particle analyzer

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Type 1: Surface Reconnaissance
Rationale for target parameters

Type 1 measurements are primarily driven by ISRU criteria to verify that the model water distribution predictions can detect needed site. Range of water levels preferred for model development. The points below describe the rationale for the measurements and parameters listed on the previous slide.

- Water subsurface distribution
  - 1 m depth target is estimated limit for ISRU systems. Greater depths do not trade well with current technology approaches
  - Vertical distribution resolution of 20 cm based on ISRU excavation techniques (e.g., overburden removal trades) and water distribution models requiring minimum of 4 measurements over depth
  - Water subsurface abundance >1 wt% detection limit: ISRU threshold criteria. Water abundances <2 wt% do not trade well for full scale ISRU systems with 1 wt% limit allowing for error.
- Possible ISRU contaminants
  - Example (not exhaustive) list of species to identify is based on potential contaminants to the ISRU system, to help plan filtration / clean-up systems and to choose appropriate materials.
  - Element/compound identification spanning a molar mass range from > 1 to 100 Da or 150 Da is based on a balance between range of expected compounds including organic compounds and cost vs. expected detection limits for very trace compounds. Additional mass range should be considered if cost allows.
  - Identification of compounds is priority, with quantification of compound abundances to best effort
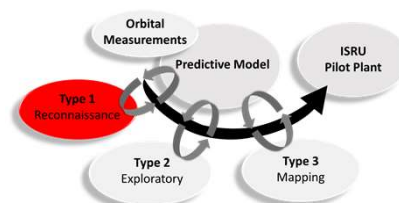
Type 1: Surface Reconnaissance
Current or Planned Missions

EXPL⚬RE
MOON*to*MARS

- PRIME-1
  - Measurement: Water abundance as function of depth in polar region at 1 location (stationary lander)
  - Method: Drill for samples and deposit on surface. Detection of sublimating volatiles using mass spectrometer
  - Performance:
    - Drill:
      - > 20 cm vertical resolution to depth of 60 cm
    - Mass Spectrometer:
      - > Detect water concentration as low as 0.5 wt%
      - > Relative concentrations of CO_2, CO, H_2, H_2S, NH_3, SO_2, CH_4 and C_2H_4, and other molecules in 0 to 100 amu mass range
      - > Isotope ratios for D/H and O^{18}/O^{16}
- VIPER
  - Measurement: Water abundance as function of depth in polar region at minimum of 50 unique locations (mobility)
  - Method: Drill for samples and deposit on surface. Detection of sublimating volatiles using mass spectrometer and NIR imaging. Scan subsurface with neutron spectrometer.
  - Performance:
    - Drill:
      - > 20 cm vertical resolution to depth of 1 meter
      - > Minimum of 50 unique holes to an average depth of 60 cm
    - Mass Spectrometer:
      - > Detect water concentration as low as 0.5 wt%
      - > Relative concentrations of CO_2, CO, H_2, H_2S, NH_3, SO_2, CH_4 and C_2H_4, and other molecules in 0 to 100 amu mass range
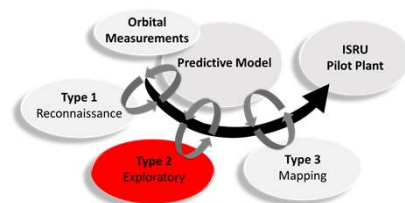   - > Isotope ratios for D/H and O^{18}/O^{16}
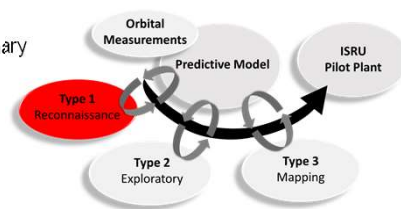
Type 2: Focused Exploratory
Measurement Goals

EXPL⚬RE
MOON*to*MARS

- Direct, ground-based measurements at landing site(s) that meets ISRU Reserve criteria according to model predictions

- Measurement requirement is to validate the model's water prediction only

- Ideally performed at multiple sites with reserve potential

- Flexible mission types; goal is to get a quick answer on model validation. Options could include:
  - Single point measurements (no mobility)
  - Multiple-point measurements (mobility/impactors)
  - Simple, low cost, short lived landed instruments (e.g., penetrators/impactors)

Type 2: Focused Exploratory
Measurement Definition

EXPLORE MOONtoMARS

Measurement (Relative priority from top to bottom)	Benefit	Potential approach(es) /platform(s)	Target measurement parameters	Example method(s)/ instrument(s)
Shallow (1 m) water horizontal and vertical distribution, abundance	Critical ISRU input. Direct measurement of water (not WEH). Validate model predictions and higher fidelity water information.	Minimum 1-point confirmation of model prediction (e.g., impactor mission), multiple landing site (e.g., network sensors) and/or multiple points at landing site reduces risk In situ surveys of the surface and subsurface using stationary or mobile landed asset(s) (e.g., small rovers, penetrators, hoppers, 'VIPER-2' or 'PRIME-2' like missions, others). Surveys can be used to choose subsurface sampling area and extrapolate sampling results to larger areas If sampling, collect subsurface samples at depths up to 1 m	Measure abundance of "mineable" water, at detection limit of at least 1 wt% to 50% accuracy or better, at depth intervals of 20 cm or less to 1 m depth	Neutron spectrometer for survey, drill or scoop for subsurface access and sampling, analysis of samples via pyrolysis-mass spec/thermogravimetry, pyrolysis-TLS)
(low priority: opportunistic) Initial geotechnical: strength, compressibility, particle shape and size distribution, electrostatic properties	Feeds into broader ISRU hardware design and architectures. Needed to understand options for mobility, hardware emplacement, and excavation.	As a secondary goal, the opportunity to obtain these measurements is wholly dependent on the approach. This could include instrumenting sampling hardware, taking high resolution images of manipulated soil, or including a small dedicated instrument as the platform (lander/rover) allows.	Measure particle size distribution to 100 µm , measure cohesive strength to 100 kPa, measure compressive strength to 100 MPa	Cone penetrometer, micro-imager, bevameter, electrometer

Type 2: Focused Exploratory
Rationale for target parameters

EXPLORE MOONtoMARS

Type 2 measurements are primarily driven by ISRU criteria to verify that the model has predicted a potential reserve site. The points below describe the rationale for the measurements and parameters listed on the previous slide.

- Water subsurface distribution
  - 1 m depth target is estimated limit for ISRU systems. Greater depths do not trade well with current technology approaches
  - Vertical distribution resolution of 20 cm based on ISRU excavation techniques (e.g., overburden removal trades) and water distribution models requiring 4 measurements over depth
  - Water subsurface abundance >1% detection limit: ISRU threshold criteria. Water abundances <2 wt% do not trade well for full scale ISRU systems with 1 wt% limit allowing for error.
  - Determination of water abundances at 50% accuracy or better is approximated based on the in situ pyrolysis-MS derived water measurements of geological materials made by the Mars Science Laboratory (MSL) Sample Analysis at Mars (SAM) instrument suite
    - These measurements are the basis for the target parameters but pyrolysis-MS measurements are not required components of Type 2 missions
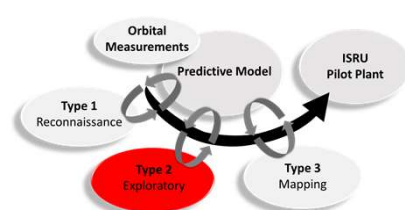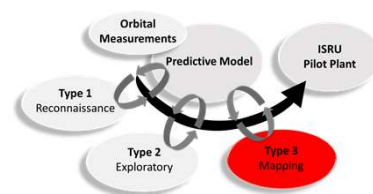
Type 3: Reserve Mapping
Measurement Goals

EXPLORE MOON*to*MARS

- ▪ Direct, ground-based measurements site that has been accepted as an ISRU Reserve
  - − Ideally: Model predictions at this site have been validated by Type 2
- ▪ Measurement requirement is to obtain broader set of data needed to plan mining con-ops, hardware emplacement, etc.
- ▪ Multiple types of measurements needed; not just water measurement
- ▪ Mobility needed to obtain measurements to define lateral distribution
- ▪ ISRU reserve is likely in a PSR, so this asset must survive extended periods in this extreme environment. It is an opportunity to demonstrate technologies also needed for ISRU plant.

Type 3: Reserve Mapping
Measurement Definition

EXPLORE MOON*to*MARS

| Measurement (Relative priority from top to bottom)	Benefit	Potential approach(es) /platform(s)	Target measurement parameters	Example method(s)/instrument(s)
Shallow (1 m) water horizontal and vertical distribution, abundance	Critical ISRU input. Higher fidelity information to plan processing rates, range required for excavation (extent of resource), and plan for con-ops of production systems.	• Multi-point analyses necessary (cover large spatial extent with high density of measurements) • In situ analyses from mobile landed asset(s) used to survey to choose subsurface sampling areas and extrapolate sampling results to larger areas • Collect subsurface samples at depths up to 1 m	Measure abundance of "mineable" water at detection limit of at least 1 wt% to 25% accuracy or better (absolute concentration) at depth intervals of at least 20 cm to 1 m depth	Neutron spectrometer for survey, drill or scoop for subsurface sampling, analysis of samples via pyrolysis-mass spec/thermogravimetry, pyrolysis-TLS)
Release energy/ temperature of H_2O from materials on heating (how H_2O/OH/H is bound)	Feeds into water extraction system design, primarily impacts extraction energy, thus power requirements.	• Multi-point analyses necessary • In situ analyses from mobile landed asset(s) used to survey to determine H speciation, choose subsurface sampling areas and extrapolate sampling results to larger areas • Collect subsurface samples at depths up to 1 m	Measure H_2O evolution temperatures to ± 50°C to temperatures of at least 200°C, measure energies required to release water within 200 J/g, mineralogy/context to best effort	NIR spectroscopy, Raman, XRD (in situ H speciation/mineralogy) (complementary to sample pyrolysis) AND pyrolysis-MS/TG/DSC, pyrolysis-TLS WITH detailed monitoring of input energy during heating
Contaminants (e.g., S compounds, HF, HCl, NH_3, Hg, organics) release w/ heating	Understand what type of water cleanup systems are needed for pilot plant.	Same as for shallow water measurement (row 1); should be measured at the same time as shallow bulk water.	Element/compound identification (1 amu to at least 200 amu), and abundances to 50% accuracy, during heating to 200°C	Pyrolysis-MS, pyrolysis-GCMS (choose GC column(s) to assess a range of expected organics, S compounds, etc.)

Type 3: Reserve Mapping
Measurement Definition (2)

EXPLORE MOONtoMARS

Measurement (Relative priority from top to bottom)	Benefit	Potential approach(es) /platform(s)	Target measurement parameters	*Example* method(s)/instrument(s)
Geotechnical: Cohesion and friction angle	Excavation hardware design, mobility, design of regolith processing and feed systems	• Mulitpoint analyses necessary (cover large spatial extent with high density of measurements). • In situ analyses from mobile asset(s) with instruments and/or ISRU excavation/mobility demonstration tech.	Measure cohesion of regolith to 100 kPa to account for unknown icy regolith properties. Measure friction angle from 10° to 50°	Cone penetrometer, bevameter
Geotechnical: Particle size distribution	Excavation hardware design, regolith processing and feed systems	Same as row 4.	Measure particle size distribution from 1 – 1000 μm	Micro imager, sieve screen, particle size analyzer
Geotechnical: Bulk density	Excavation hardware design, regolith processing and feed systems	Same as row 4.	Measure bulk density from 0.5 – 2.5 g/cm^3	Coring drill/tube
Geotechnical: Compressive strength	Excavation hardware design, regolith processing and feed systems	Same as row 4.	Measure compressive strength to 100 MPa to account for unknown icy regolith properties.	Drills/probes instrumented with force sensors.

Type 3: Reserve Mapping
Rationale for target parameters

Type 3 measurements are driven by ISRU criteria. Increased quantity of measurements to map area for con-ops planning. Broader range of measurement types, beyond just water, for more focused hardware development. The points below describe the rationale for the measurements and parameters listed on the previous slide.

- Water subsurface distribution
  - 1 m depth target is estimated limit for ISRU systems. Greater depths do not trade well with current technology approaches
  - Vertical distribution resolution of 20 cm based on ISRU excavation techniques (e.g., overburden removal trades) and water distribution models requiring 4 measurements over depth
  - Water subsurface abundance >1% detection limit: ISRU threshold criteria. Water abundances <2 wt% do not trade well for full scale ISRU systems with 1 wt% limit allowing for error.
  - Determination of water abundances at 25% accuracy or better is approximated based on improvements from recommended Type 2 measurements

- Release energy/ temperature of H_2O from materials on heating
  - Maximum pyrolysis temperature, temperature resolution, and energy measurement accuracy are driven by ISRU H_2O extraction requirements

- Contaminants (e.g., S compounds, HF, HCl, NH_3, Hg, organics) release w/ heating
  - Element/compound identification spanning a molar mass range from > 1 to 200 Da is based on improvements from recommended Type 1 reconnaissance mission measurements
  - Determination of element/compound abundances to 50% accuracy is based on improvements from the best effort abundance measurement target recommended for Type 1 reconnaissance missions, and is needed for more focused ISRU hardware development.
  - The measurement of contaminants during heating to 200°C requirement matches the requirement for H_2O releases; these compounds would be detected at the same time as evolved water
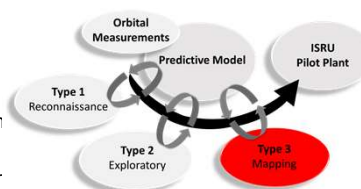
Type 3: Reserve Mapping
Rationale for target parameters (2)

- Cohesion and Friction angle
  - The cohesion and friction angle are fundamental geotechnical properties that are inputs to the design of excavation and processing equipment. The target measurement range for cohesion is expanded to 100 kPa and friction from 10° to 50° due to the unknown properties of the ice containing regolith.
- Particle size distribution
  - The particle size distribution will be used to design processing and handling geometries for proper flow in and out of systems. The dominant range of particle sizes is 1 to 1000 μm.
- Bulk density
  - The bulk density measurement range from 0.5 g/cm^3 to 2.5 g/cm^3 spans regolith with extremely low porosity up to fully dense regolith approaching grain densities.
- Compressive strength
  - The compressive strength target measurement ranges from 1 to 100 MPa. This range is intended to capture the strength of consolidated, possibly ice-cemented, regolith material. Below this range can be treated as unconsolidated and above will likely be too difficult to excavate.
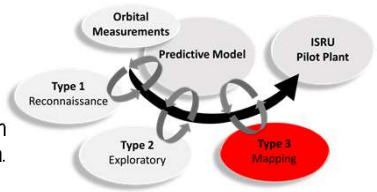

Predictive Models

Goal: Critical to prediction of 'Reserves' for ISRU; site selection.

Capabilities Needed

- Inputs: thermal maps, Vis/NIR spectral maps, neutron spectroscopy derived WEH maps, etc. (spatial proxies)
- Output: Water grade, depth, lateral distribution
- The model validation described in LWIMS recommendations refers to a "mineral model"
- For ISRU, map overlays are needed which include favorable "ice/mineral models" together with illumination, traffic-ability, etc.
  - These exist separately but need to be merged
    - Currently in work (adapting USGS mineral favorability to the Moon)
      - Worked by VIPER team and SSERVI (UCF node)- paper pending (ASCE Earth and Space Conference 2021)
    - *It is critical to make and continue to refine this data product based on new data but these efforts do not easily fit under an Research and Analysis program*
      - A funding source is needed (potentially SSERVI?)
  - Will be part of the VIPER Data Plan as a deliverable to NASA
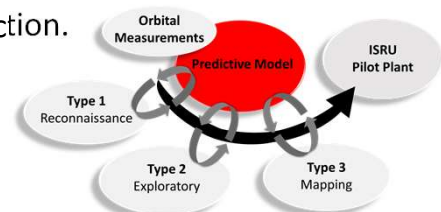
Summary: LWIMS Findings, Recommendations and References

Findings

- **Current data sets are insufficient to define a reserve**
  - Identifying shallow bulk water can only be accomplished (currently) with NS (LRO,LP) and Radar (Chandrayaan-1 and LRO), but interpretation of data, particularly regarding distribution is inadequate
  - Coverage of this data at the Lunar poles and in PSRs is limited
  - LCROSS, while extremely valuable, was only a one-point measurement

- **Schedule is a driver** (target: 2028 ISRU pilot plant), **which may limit options** for instruments and implementation options.
  - May prefer reuse/re-flight of instruments hardware to reduce operational risk and improve data interpretation
  - Measurement plan (type and cadence) of missions must be reflective of Risk posture and results returned
  - Development of ISRU production systems has to occur in parallel with reserve identification to meet schedule; delaying measurements will result in less input to system design and result in higher hardware risk

- **Existing measurement techniques can achieve data needed, but must be adapted for lunar application**
  - Hardware (mobility, sampling, some instruments) must be adapted for operation in PSRs
  - Water quantification, e.g., using heated sampling techniques, will likely provide highest accuracy, but are least developed for these applications

Recommendations

- **To meet aggressive schedule, a coordinated, focused effort must be implemented**
  - This impacts all Mission Directorate interests (STMD: ISRU hardware development, HEO: implementation of ISRU, SMD: volatiles measurements and overlap of science objectives)

- **Additional regional data sets (orbital)** including high spatial res hydrogen maps, thermal, surface water detection **would be of high value to help reduce overall risk/uncertainty**
  - Missions (LunaH-map, Lunar Flashlight and the Lunar Trailblazer concept) should all go forward

- **Support ISRU relevant instruments in PRISM and LuSTR programs** (or similar) for advancement of ISRU technologies.

- **Recommend 'Best' Path based on Low to Moderate Risk is:**
  - Proceed with currently planned cubesat and smallsat missions to advance orbital/regional data sets
  - Support development of predicative model capability asap
  - Perform VIPER as planned for first Type 1 mission
  - Perform a minimum of 3 landed exploration missions: a Type 1, Type 2, and Type 3

Recommendations for Future Work

We recommend the **formation of a multi-disciplinary standing working group** with the following three responsibilities:

1. There are enough differences between how the term "reserve" is used on Earth, and how it might be used on the Moon (and on Mars) that a consensus definition should be developed.
   - *This is highly dependent on Risk tolerance for a given exploration program. This must be an on-going evaluation with inputs from all stakeholders to generate an appropriate (and evolving) measurement plan.*

2. Central to the scientific exploration process is the development of a predictive model (analogous to a terrestrial mineral favorability model). This model needs to continuously incorporate new information as it becomes available, to monitor tests of model predictions, and to be updated in a timely way.

3. Coordination is needed between all Mission Directorates to ensure unified approach.
   - *Mission planning, CLPS usage, and investments should be coordinated for each MD portfolio to maximize investment and minimize overlap*
   - *Clear handoffs and roles between the MDs should be defined.*

LWIMS Standing Working Group

- Composition should be similar make-up to existing LWIMS team including
  - Lunar Scientists
  - Measurement/Instrumentation specialists
  - ISRU engineers
- Core Team: NASA
  - A core team of NASA personnel should remain in place to gather information and serve as the conduit between the larger community and NASA management
  - Should include SMAs as listed above and key liaisons to each mission directorate
  - Recommend ~12 people at ~15% time (~2 FTE total)
- External Community engagement
  - Bi-Monthly (TBR) meetings to review current status and products
  - Will be engaged as expertise and feedback is required
  - Leverage the following groups:
    - LSIC
    - LEAG
    - SSERVI Nodes
    - Space Resources Roundtable
  - Standing group ~20 key people, voluntary basis?

Supporting Work / References

- LEAG VSAT findings, 2014, 2017
  - Goal should be to develop a model, exceeding attainable spatial resolution of orbital measurements, that can guide future missions
  - Orbital data to resolve individual PSRs is the most important orbital measurement. Sufficient precision and resolution of <5 km, after signal averaging
  - New orbital methods can help characterize volatile distribution: namely surface frost and subsurface detection
  - Encouraged: LCROSS-like missions (simple, high return), near term landed measurement (any ground measurements of high value), polar rover development for PSR exploration
  - Set of missions at multiple sites, rather than focus solely on one site to assess resource potential
  - 2 Phase approach: Phase 1 is preliminary characterization of deposit (similar to LWIMS Type 1 and 2) and Phase 2 is comprehensive characterization of reserve (similar to LWIMS Type 3).
- LEAG Volatile Viability Measurement Special Action Team (VVM-SAT), 2019
  - Goals defined by the LEAG Advancing Science on the Moon (ASM-SAT) 2017 were adopted (these were derived from the SCEM 2007 report)
  - The SAT delineated individual measurements that would address each goal and defined how well each measurement would need to be made to "take the next significant step" in our scientific understanding.
  - The SAT also developed a list of instrument types that might be able to make each measurement, as well as the accuracy, cadence, or other measurement factors suggested to make the next step in addressing science goals.
    - LWIMS referenced this comprehensive list in considering measurements and possible instruments relevant to ISRU goals, as well as several other aspects of the LWIMS work
  - The VVM-SAT recommended a follow-up committee focused on defining the measurements required to plan and carry out in situ resource utilization (LWIMS products respond to this recommendation).

Supporting Work / References

- "Lunar Polar Volatiles: Assessment of Existing Observations for Exploration" white paper by Hurley et al., 2016
  - Suggested measurements:
    - Additional measurements that would improve the understanding of the composition of volatiles in the PSRs include active spectroscopy from orbit, which would provide spectral confirmation of the composition of the surface. In situ instrumentation on the surface using mass spectrometry, nuclear spectroscopy, LIBS, TLS, Raman, gas chromatography, or active optical spectroscopy would determine the composition of local samples.
    - Because heterogeneity persists down to the spatial resolution of existing measurements, new measurements with better spatial resolution would improve the understanding of the lateral distribution of volatiles.
    - Neutron spectroscopy provides the best integrated measure of the abundance of volatiles in lunar polar regions, albeit with ambiguity regarding the actual chemical composition.
    - Radar data would reveal if coherent, pure ice layers exist through the properties of the coherent backscatter.
  - A multi-faceted approach is necessary to effectively characterize the resource. Ground truth is essential to provide in situ confirmation of the composition and abundance. Subsurface access would resolve the depth distribution.
  - Observations both inside and outside of PSRs with lateral spatial resolution spanning 1 m – 100 m distance scales are most relevant.
  - Modeling that relates the existing water to its sources, the timing of its emplacement, and the processes maintaining and redistributing volatiles will enable us to integrate diverse and ancillary data to predict locations with enhanced water content.
    - Laboratory experiments are crucial for interpreting remote sensing data, understanding the interactions between volatiles and regolith, and illuminating the geotechnical properties of materials.

Nomenclature

APXS	Alpha Particle X-Ray Spectrometer		**M3**	Moon Mineralogy Mapper
Con ops	Concept of Operations		**MS or Mass Spec:**	Mass Spectrometer
CPR	Circular Polarization Ratio		**NIR**	Near Infrared
DSC	Differential scanning calorimetry		**NS**	Neutron Spectrometer
FTE	Full Year Equivelent		**O2R**	Oxygen from Regolith
GCMS	Gas Chromatograph Mass Spectrometer		**PRIME-1**	Polar Resources Ice. Mining Experiment
GPR	Ground Penetrating Radar		**PRISM**	Potential Lunar Surface Investigations
HEO	Human Exploration		**PSR**	Permanently Shadowed Region
HLS	Human Landing Systems		**SAT**	Special Action Team
IR	Infrared		**SMA**	Subject Matter Expert
ISRU	In-Situ Resource Utilization		**SMD**	Science Mission Directorate
LAMP	Lyman Alpha Mapping Project		**SSERVI**	Solar System Exploration Research Virtual Institute
LCROSS	Lunar Crater Observation and Sensing Satellite		**STMD**	Space Technology Mission Directorate
LEAG	Lunar Exploration Analysis Group		**TG ro TGA**	Thermogrameteric Analysis
LIBS	Laser-Induced Breakdown Spectroscopy		**TLS**	Tunable Laser Spectrometer
LOLA	Lunar Orbiter Laser Altimeter		**UV**	Ultra Violet
LP	Lunar Prospector		**VIPER**	Volatiles Investigating Polar Exploration Rover
LRO	Lunar Reconnaissance Orbiter		**Vis**	Visible Spectroscopy
LSIC	Lunar Surface Innovation Consortium		**VSAT**	Volatiles Special Action Team (under LEAG)
LUSTR	Lunar Surface Technology Research		**WEH**	Water Equivalent Hydrogen
LWIMS	Lunar Water ISRU Measurement Study		**XRD**	X-Ray Diffraction
			XRF	X-ray Fluorescence