An Overview of the Lunar Water ISRU Measurement Study (LWIMS)

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Note: The bulk of this presentation was also given at the Planetary and Terrestrial Mining Meeting /Space Resources Roundtable June 2021

Study Products

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- This presentation is a subset of information from the full LWIMS report
  - https://ntrs.nasa.gov/search?q=20205008626
    - Kleinhenz, J., A. McAdam, A. Colaprete, D. Beaty, B. Cohen, P. Clark, J. Gruener, J. Schuler, and K. Young, 2020, Lunar Water ISRU Measurement Study (LWIMS): Establishing a Measurement Plan for Identification and Characterization of a Water Reserve. NASA TM-2025008626

Lunar Polar Water ISRU Measurement Study (LWIMS)

Background and Problem Statements

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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

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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

ISRU and Science: Commonalities and Differences

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

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

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

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

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

Critical Commonalities

Science Interest

Reserve Definition

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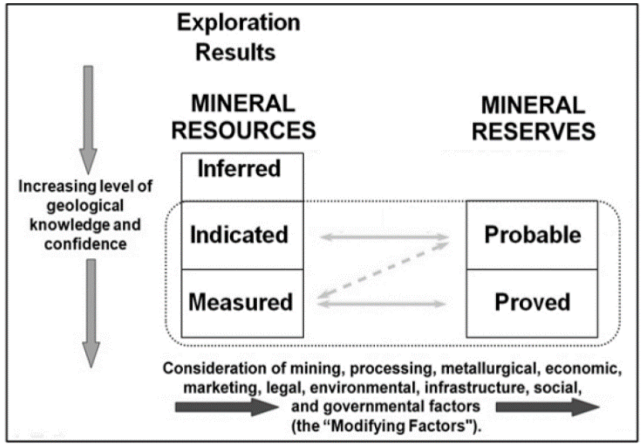
Terrestrial Reserves

- 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

Threshold Criteria for a Reserve

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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

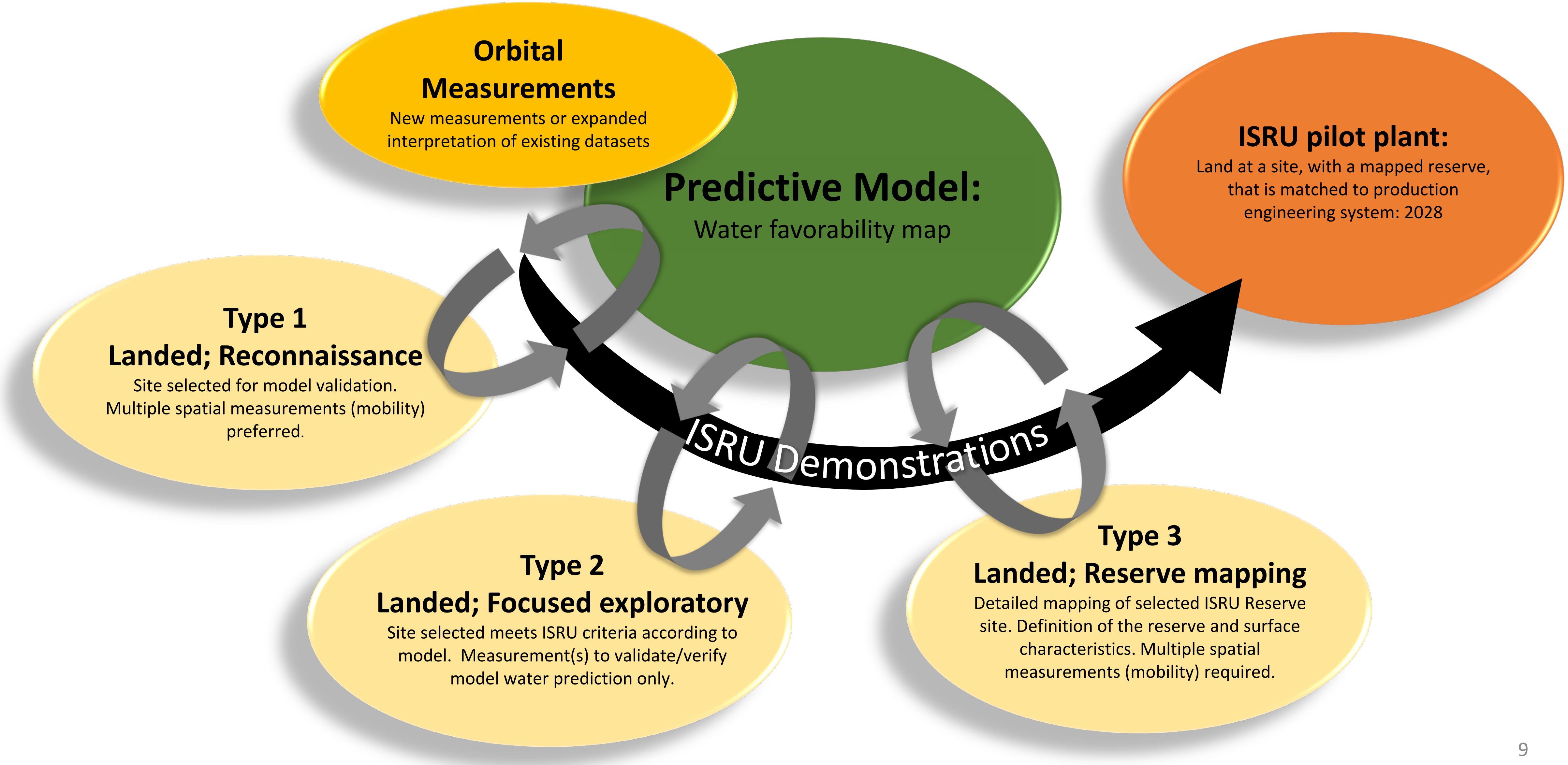
ISRU knowledge gaps

- 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/cm^3
Compressive Strength	1 to 100 MPa
Terrain features including rock abundance	

Measurement Plan Structure



Measurement Plan Structure

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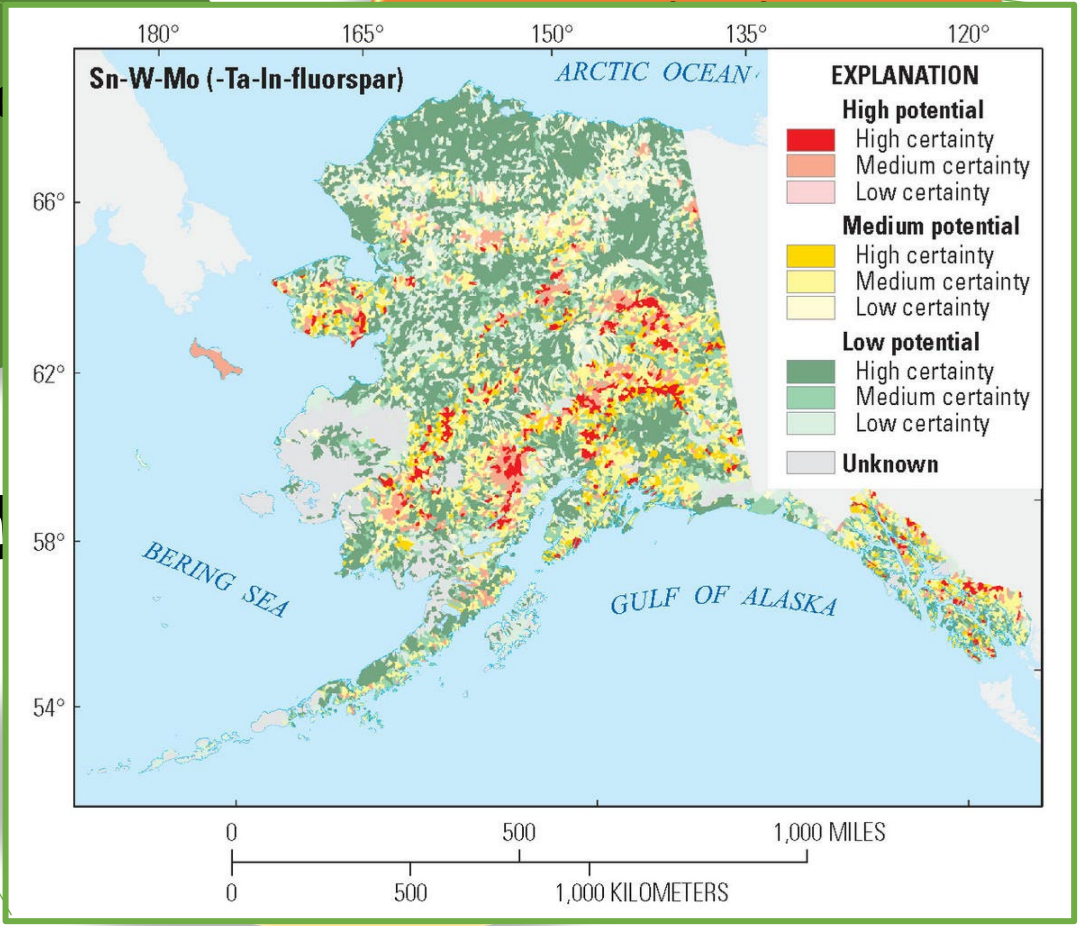
Orbital Measurements
New measurements or expanded interpretation of existing datasets

Predictive Mo
Water favorability

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

ISRU Demon

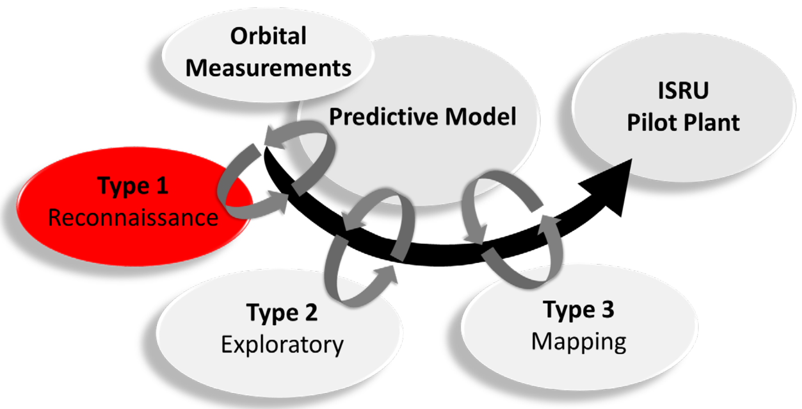
Type 2
Landed; Focused exploratory
Site selected meets ISRU criteria according to model. Measurement(s) to validate/verify model water prediction only.



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

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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

Proposed Polar Resource Measurement Plan

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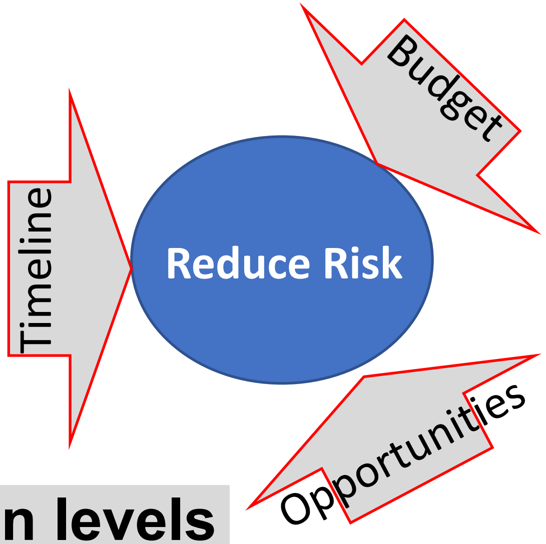
The **GOAL** of a measurement plan is to **REDUCE RISK** for an ISRU pilot plant
Increase confidence in water reserve; reduce uncertainties
Decrease hardware operational risks: designed for conditions

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

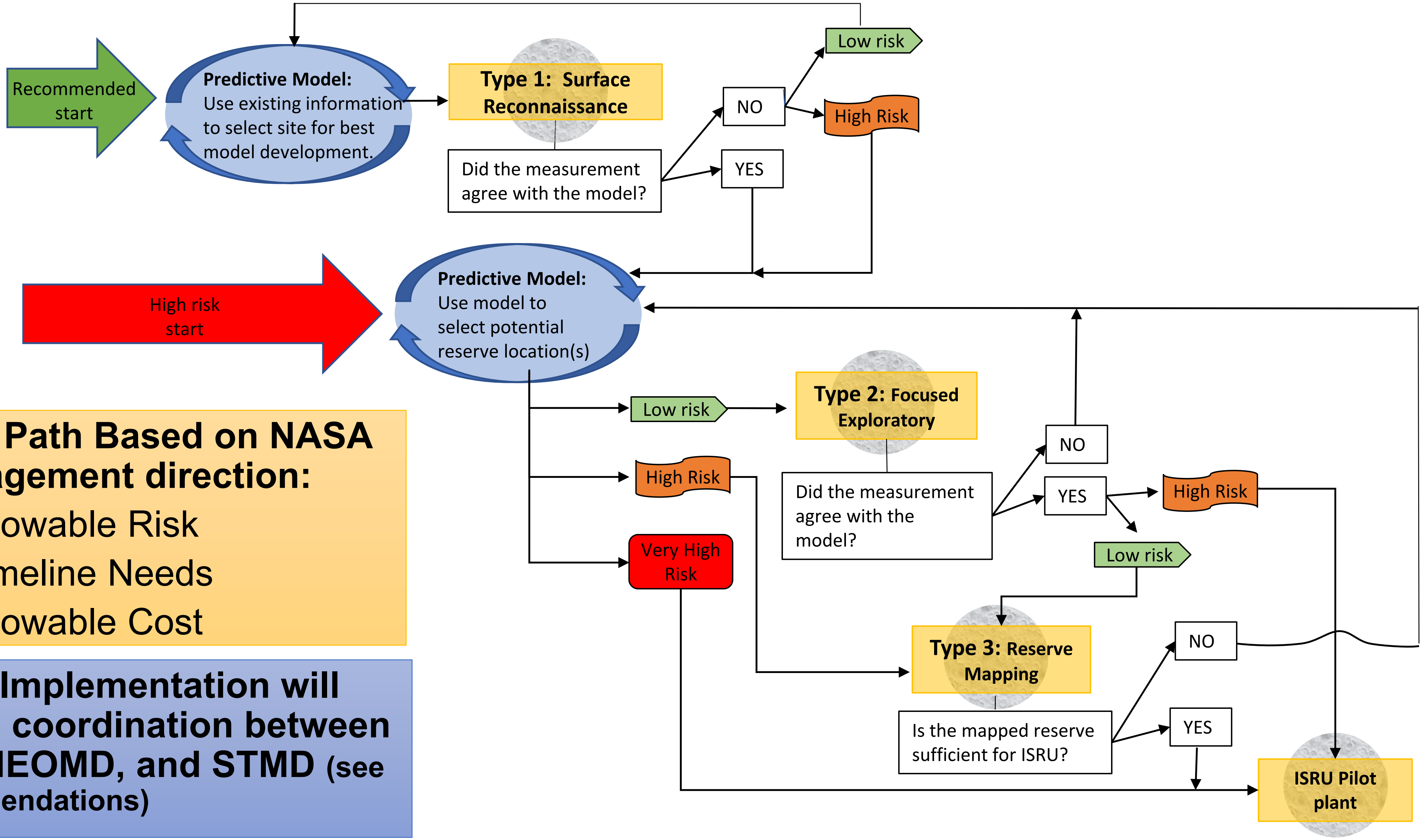
- **Timeline**
  - Need date for ISRU hardware (ISRU Pilot plant by 2028)
  - Instrument availability/development cycles
- **Mission opportunities**
  - CLPS payload selection and cadence of opportunities
- **Cost**
  - Instrument development and delivery (type/scale of missions)



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

Decisional Flow diagram



- **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

- **Future Work Recommendations**
  - Establish a multi-discipline standing group and follow-on activity(s) to support coordinated measurement strategy
    - Coordinate activities across NASA mission directorates with clear handoffs
    - Consensus on extraterrestrial "reserve' definition, evolving evaluation
    - Focused effort to develop and update predictive model capability