ISRU Evaluation of Artemis Campaign Sites: Considerations and Methodology

Lunar Surface Science Workshop (LSSW)

The First Steps in a Bold New Era of Human Discovery: Candidate Artemis III Landing Sites

April 4–5, 2023

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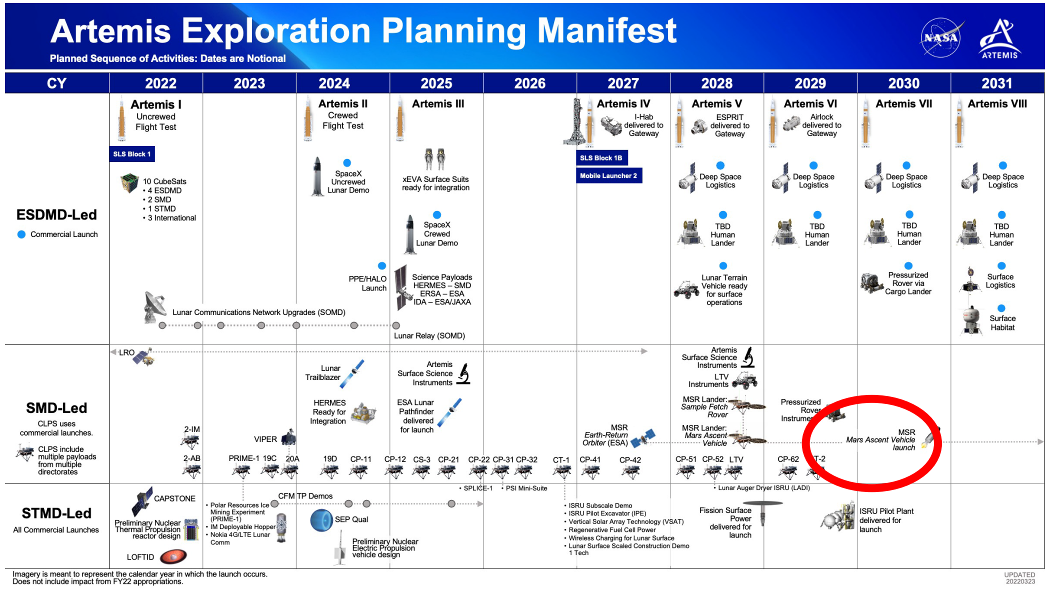
Context: Why are we talking ISRU now, for Artemis III?

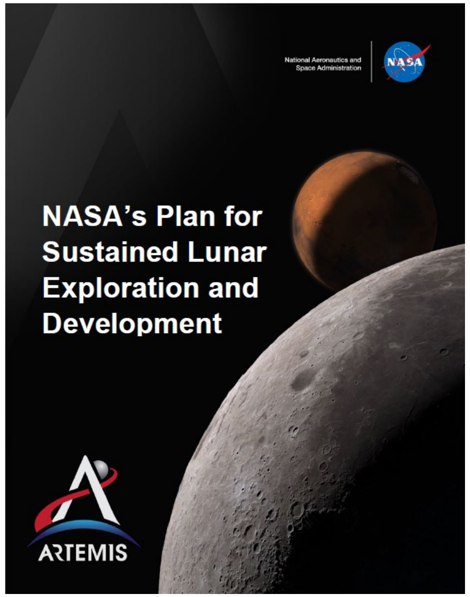
- NASA has stated intent to work toward ISRU on the lunar surface in long term Artemis objectives

LI-7[L]	Demonstrate **industrial scale ISRU** capabilities in support of continuous human lunar presence and a robust lunar economy.
AS-3[LM]	**Characterize accessible lunar and martian resources,** gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.
OP-3[LM]	**Characterize accessible resources,** gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable use of resources on successive missions.

- Early Artemis missions are key to ISRU technology development/demonstration and resource assessment
- The distribution of assets and long term utilization (reuse) is still in formulation
  - Considering ISRU from the beginning opens opportunities to better leverage these assets and ISRU products
  - This is a CAMPAIGN consideration

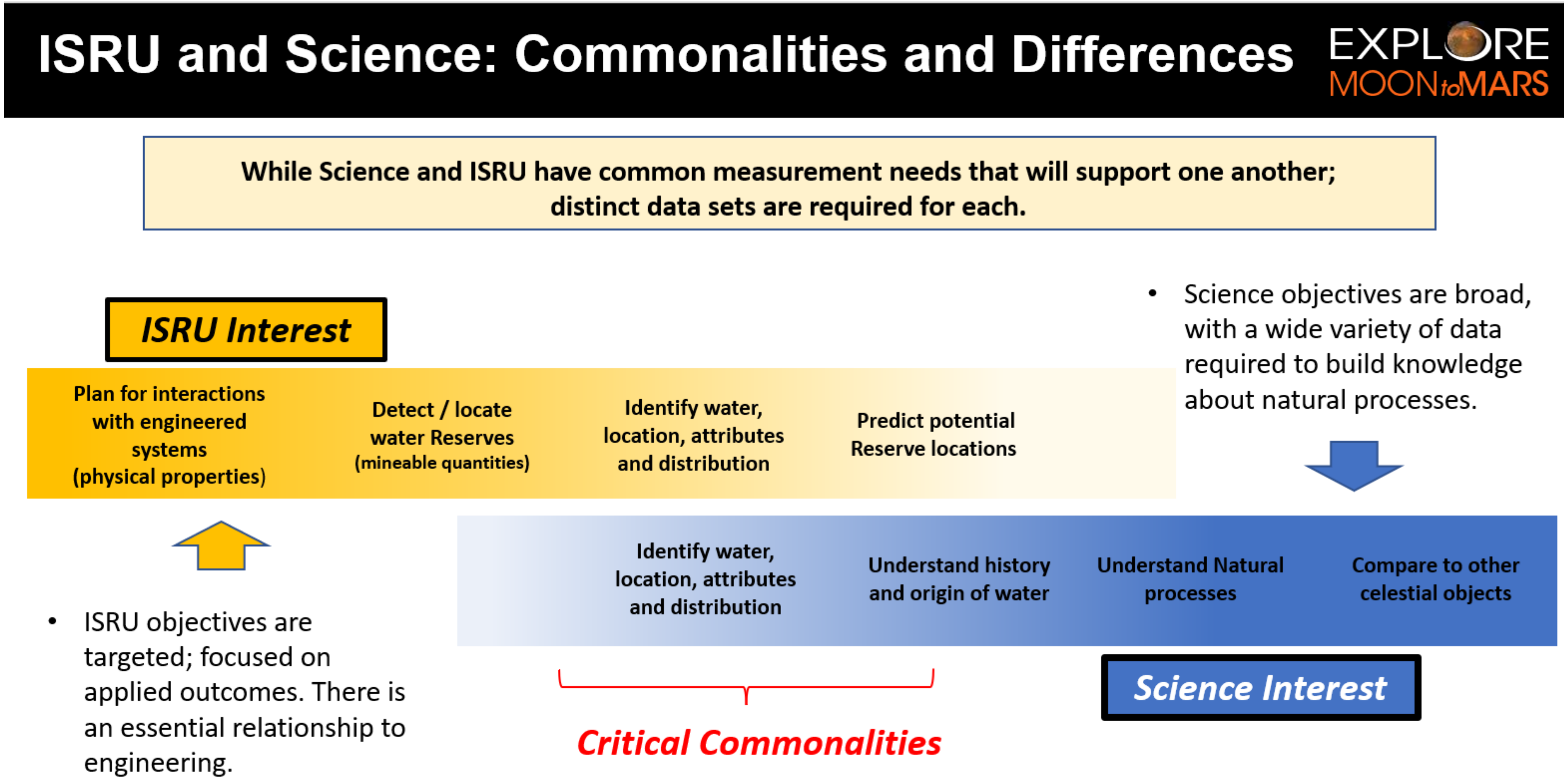


From the "Survive the Lunar Night" workshop Dec, 2022. Kearn, J.
https://www.hou.usra.edu/meetings/clps2022/pdf/clps2022_program.htm#sess101



Exploration ~~vs~~ & Science

- There is considerable overlap in ISRU resource assessment and science objects
- Locations can be mutually beneficial
  - Applied Science & Science
- Resource assessment benefits from all levels of mission (CLPS, orbital, etc) but for large asset placement it is even more benefit to choose regions that have viability to support ISRU architectures (that have reserve potential)



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
https://ntrs.nasa.gov/api/citations/20210016849/downloads/LWIMS_PTMSS2021_Kleinhenz.pdf

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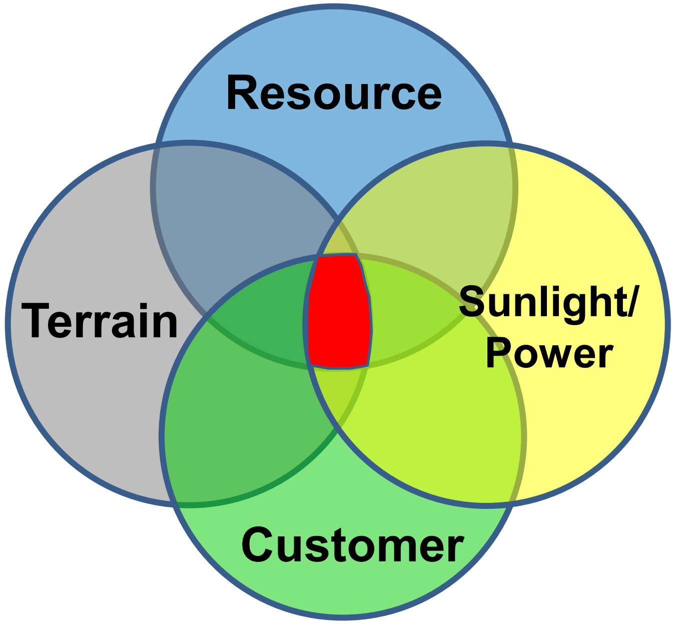
ISRU Considerations

- Early ISRU
  - Target production of large mission consumables (propellants: O2, H2)
    - Support for early mission needs (10s tons of propellant) and cadence
  - Limited infrastructure in terms of :
    - Limited/Standalone Power availability (no grid, no large reactors)
    - No/Limited Civil Engineering (roads, gondolas, pipes, etc)
    - Few support assets (robotic/human interaction, mobility)
      - > Mobility (distance) restricted
        - Resource/product transport



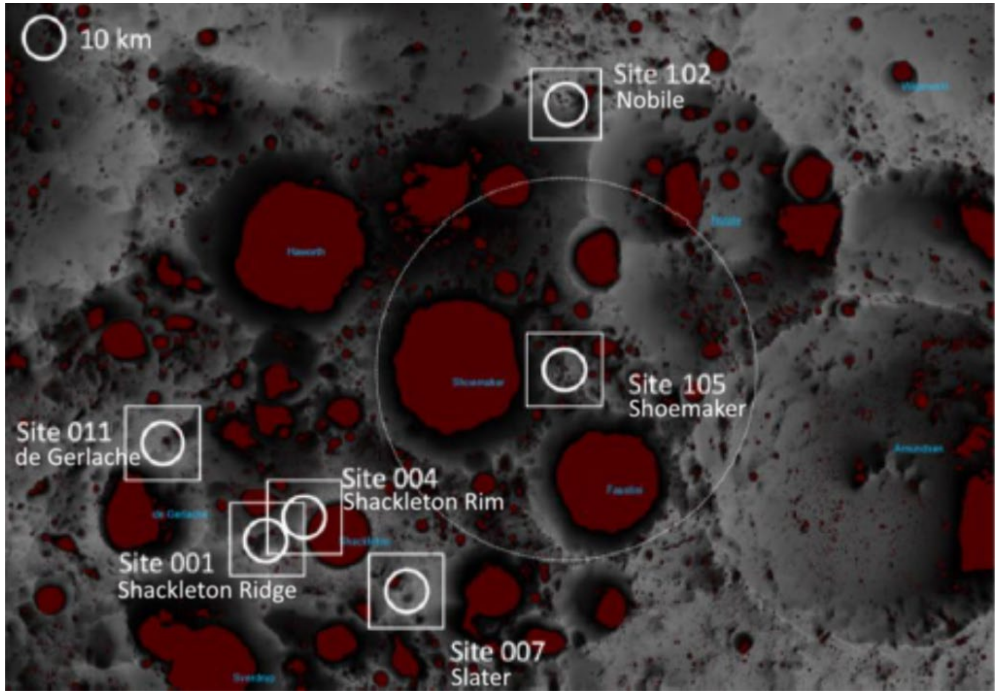
- Water ISRU
  - Note that oxygen from regolith (mineral extraction) is still a possibility for Oxygen-only consumable production. This is less dependent on location than water ISRU but does not close the loop for propellent fuel.
  - Focus on top 1m resource availability for early ISRU: PSRs

ISRU Considerations: Implications

Early ISRU	Assumption	Implication to evaluation
Production scale & cadence	10s ton of propellant in 1 year	**Tonnage** of smaller PSRs (few km) can be adequate : at ~3wt% bulk water concentration can support order of 1000 production cycles
Limited Infrastructure: Power	Solar power would be leverage for at least a portion of the ISRU system	**Illuminated** sites must be able to support solar power for at least some of the ISRU system within proximity. Customer will also favor illuminated regions, so this also impact **proximity** requirement
Limited Infrastructure: Mobility	Moving the ISRU feedstock and/or the product would occur through conventional surface mobility methods	**Proximity** between the ISRU water mine (PSR) and the customer is limited surface mobility platforms in terms of traverse distance (e.g. mass/power capacity) assuming an unprepared surface.
		Terrain: Traverse paths with acceptable slopes must be available between ISRU system and customer (while still meeting traverse distance criteria).

ISRU Initial Evaluation Case Study

- Initial effort to define evaluation criteria/method for Artemis regions of interest from an ISRU standpoint
  - Kleinhenz, J.E. and Sanders, G.B., Evaluation of the NASA Artemis Regions of Interest for ISRU Water Mine Potential, AIAA ASCEND, American Institute for Aeronautics and Astronautics, Oct. 24-26, 2022, AIAA-2022-4284
  - Evaluated the original 6 regions of interest in the Artemis Sustainability plan against a set of ISRU-centric criteria.
  - Study was to look at ISRU from an implementation perspective and include criteria:
    - Include criteria beyond water tonnage alone
    - Include criteria with anticipated early Artemis capabilities in mind
  - Case Study… expected to evolve:
    - ISRU architecture and infusion is still in formulation as are Artemis architecture and assets



NASA'S Plan For Sustained Lunar Exploration and Development. April 2020. https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf

- Other evaluations of this type have been done with different assumptions or viewpoints.
  - Most previous studies focused on large PSR regions which do not suite ground rules & assumptions for early Artemis
  - This study can be used to focus water reconnaissance efforts

ISRU Baseline Architecture

Customer

Transport of product to the customer is not explicitly covered by ISRU system. Though proximity estimates are included here.

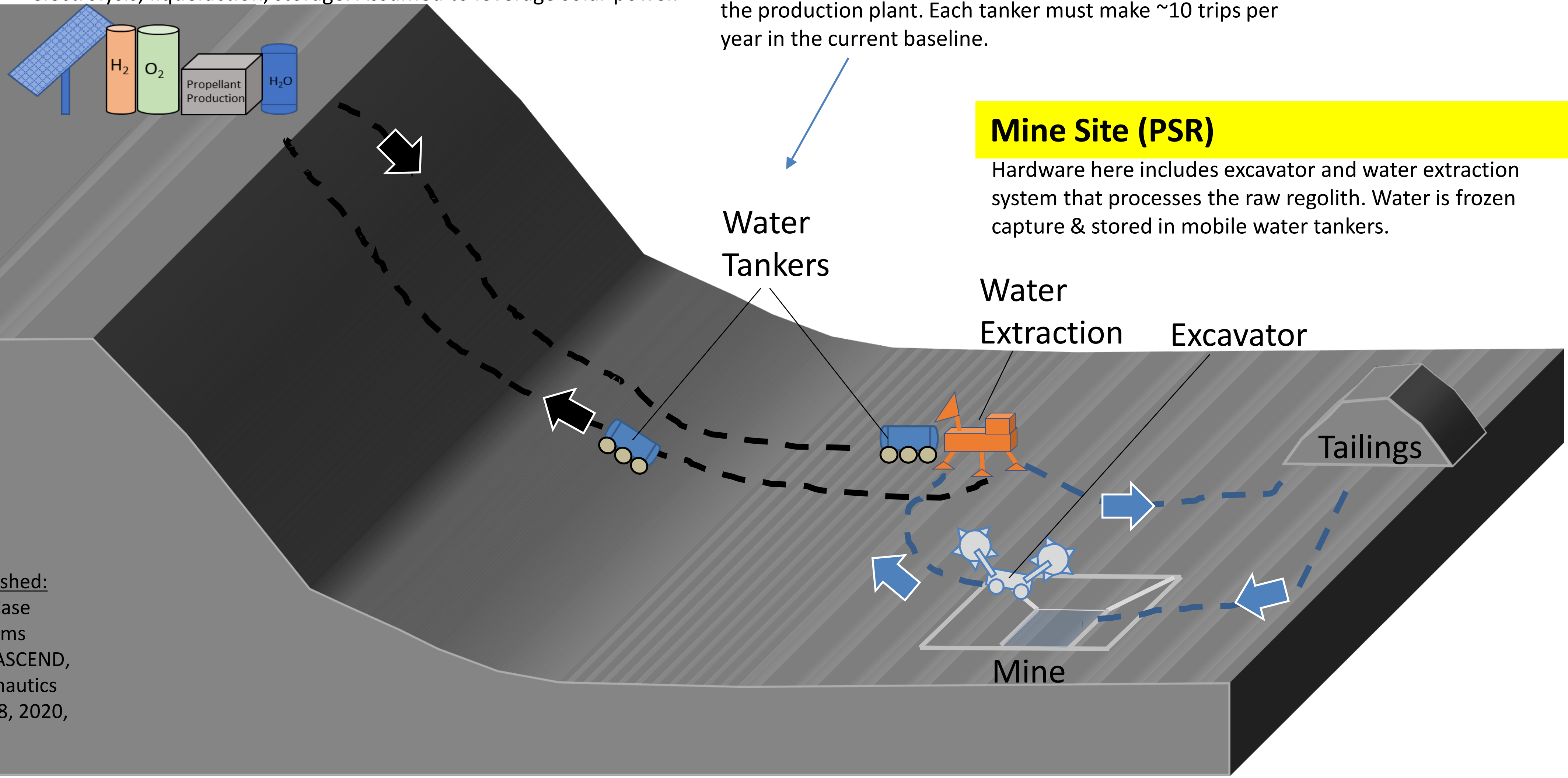
Propellant Production Plant (PPP) Site

Production plant hardware performs **water processing** coverts water, delivered by water tankers, into propellant: electrolysis, liquefaction, storage. Assumed to leverage solar power.

Two mobile water tankers transport water from the mine to the production plant. Each tanker must make ~10 trips per year in the current baseline.

Mine Site (PSR)

Hardware here includes excavator and water extraction system that processes the raw regolith. Water is frozen capture & stored in mobile water tankers.



Details of Architecture published:
Kleinhenz, J.E. and Paz, A., Case Studies for Lunar ISRU Systems Utilizing Polar Water, AIAA ASCEND, American Institute for Aeronautics and Astronautics, Nov. 16-18, 2020, AIAA-2020-4042

Ground Rules for Evaluation

ISRU is not a fixed design, the ground rules are best on notional capabilities of current technology baseline

- Results of site evaluation will change as criteria evolve
- Analyses of both locations was done with expanded criteria to see alternatives

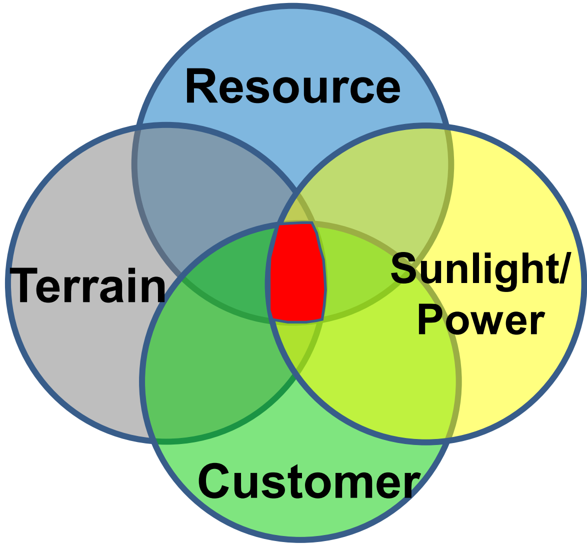
Parameter	Baseline	Expanded	Data product used
Traverse Leg 1 (Customer to PPP)	5 km (prefer >1km)	10 km	5m/pix High Res LOLA Topography LDEMs from https://pgda.gsfc.nasa.gov/products/78
Traverse Leg 2 (PPP to Mine)	5 km	10 km	
Traverse Total	10 km	20 km	
Slopes	≤ 20 deg		5m/pix High Res LOLA Topography Slope from https://pgda.gsfc.nasa.gov/products/78
PSR/Mine Size	≥ 1 km equivalent diameter (multiple pixels in the 240mpp ice stability product)		Diviner: Current Ice Stability layer from LROC Quickmap: based on Siegler 2017: 240mpp https://quickmap.lroc.asu.edu/
PSR Ice Stability (mine)	Surface ice stability corresponding to PSR region		
Sun Visibility (PPP)	> 75% visibility		LOLA 60m/pix Sun Visibility LROC Quickmap https://quickmap.lroc.asu.edu/: Percentage of timestamps when any fraction of solar disc is visible using Mazarico 2011 methodology [5].

Kleinhenz, J.E. and Sanders, G.B., Evaluation of the NASA Artemis Regions of Interest for ISRU Water Mine Potential, AIAA ASCEND, American Institute for Aeronautics and Astronautics, Oct. 24-26, 2022, AIAA-2022-4284

ISRU Considerations

The ISRU Analysis considered the following factors to develop ground rules and perform the evaluation

Factor	Criteria	Reasoning
Customer	Fixed location	The highest ranked surface illuminated site in area from Mazarico et al 2011*)
Propellant Production plant (PPP)	Illumination (sun visibility)	**Located** in a highly illuminated region to leverage solar power and be more accessible to customer. Exact illumination needs will depend on ISRU technology used and power architecture.
	NOT co-located with Customer	Avoid interference with other customer activities and to provide better proximity to the mine site
Mine Site	Ice Stability	Permanently shadowed regions (PSRs) that offer surface ice stability
	PSR/Mine Size	Tonnage to support multiple years production cycles (>10mT production) for initial Artemis needs
Traverses between locations	Distances	Based on no path preparation and projected capabilities of mobility assets. Options were scored and ranked to assist with evaluation
	Slopes	



*Mazarico, E., Neumann, G.A., Smith, D.E., Zuber, M.T., and Torrence, M.H., Illumination conditions of the lunar polar regions using LOLA topography. Icarus. 211, 2011, 1066-1081.

Summary 1/3

001: Shackleton Connecting Ridge:

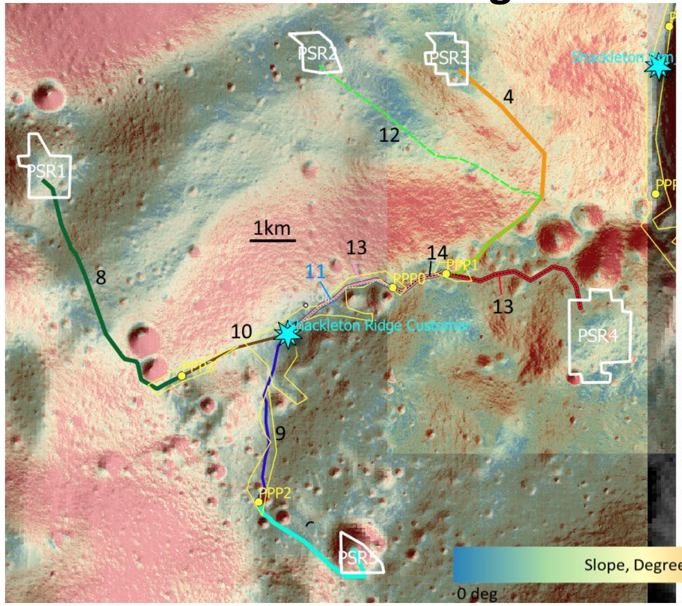
- There are 4 viable PSRs within expanded criteria, the most of any of the evaluated regions.
- Some features in the area have high slopes but generally there are passes available between features to enable path finding. There is one clear best traverse (and PSR) solution which was used in the architecture study AIAA-2020-4042
- The high illumination in the region opens up flexibility in PPP locations, which is part of the reason so many PSRs are accessible.

004: Shackleton Rim:

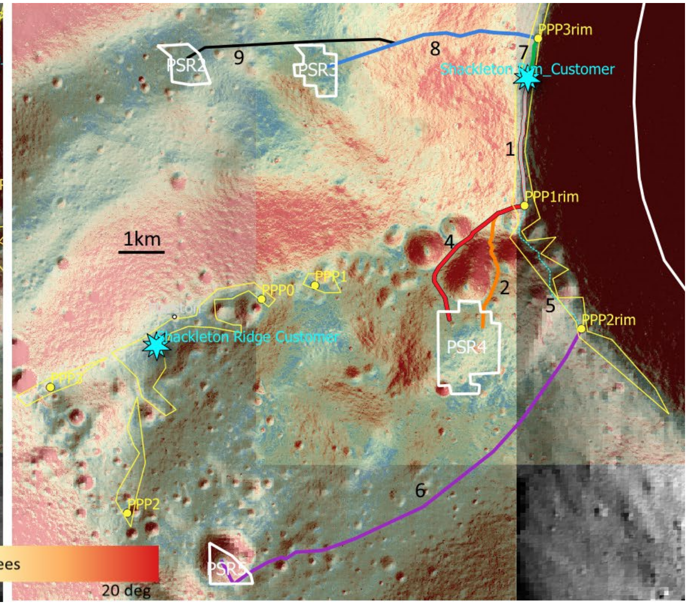
- The available PSRs are all common with 001; no new PSRs are in range due to the dominance of Shackleton crater itself (which is not accessible due to slopes). The best PSR solution is the same as that of Shackleton Ridge.
- Most area of any region for PPP locations; but these areas are on a restricted path (the rim itself) with limited off-ramps due to high slope, so traverse paths are limited.

	# of traverses mapped	Best Traverse Path Score	Mine size for Best Traverse, km (equivalent diameter)	Best mine size in expanded criteria, km (equivalent diameter)	# PSRs accessible in Baseline criteria	# PSRs accessible in Expanded criteria	Available PPP size, km (equivalent diameter)
001 Shackleton Ridge	6	1.05	1.47	1.47	1	4	2.18
004 Shackleton Rim	6	1.08	1.47	1.47	2	3	2.37
007 Slater	5	1.10	2.62	2.62	1	1	0.52
011 de Gerlache	5	1.02	1.06	1.06	0	1	0.76
102 Nobile	5	1.12	0.65	1.33	1	3	0.85
105 Shoemaker	3	1.23	0.89	1.16	2	3	0.22

001 Shackleton Ridge



004 Shackleton Rim



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Summary 2/3

007: Slater:

- Fewest PSRs available. Expanding to 10 km per travel leg does not add much value; the criteria would need to go to 15 km reach the other PSR.
- Only one traverse solution meets all baseline criteria, though it is one of the best options in terms of path score and PSR/mine size.
- Slopes in regions are favorable, so some traverses even come close to meeting a <15deg path criteria.
- Limited flexibility both in terms of PSRs and PPP areas.

011: De Gerlache:

- Only one accessible PSR in the region just meets the 1 km size target. While the outskirts of de Gerlache itself can be reached with traverses >12 km, these paths all exceed slope criteria.
- No options fully meet the baseline criteria. Slopes in the region tend to necessitate longer traverses for pathfinding
- There are several smaller PPP areas spread out along the ridgeline, which would offer options in PPP placement if the PSRs could be accessed.

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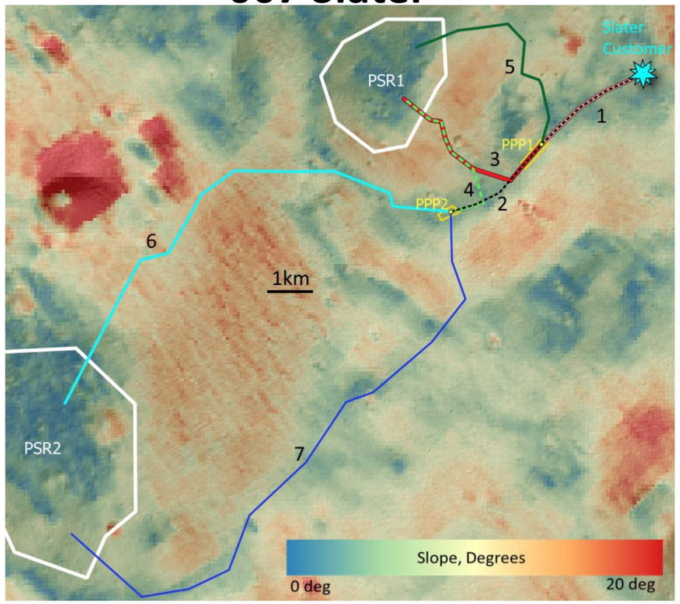
007 Slater



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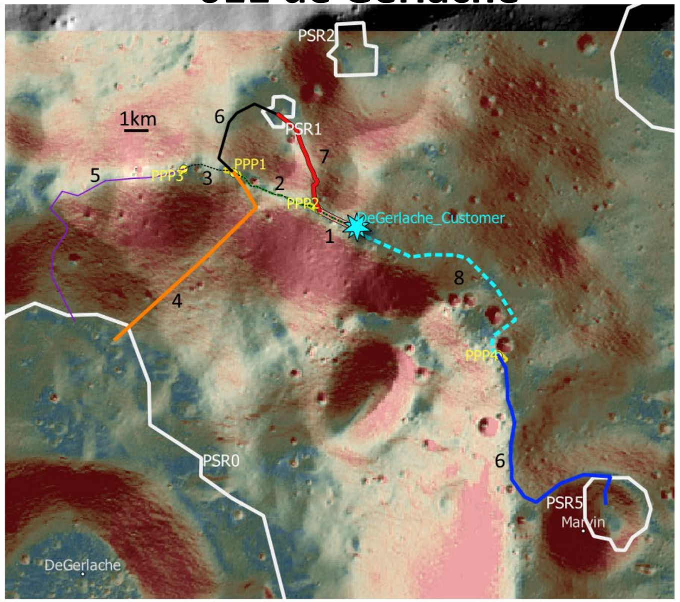

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Summary 3/3

102 Nobile:

- Region is broken up by high slope features, with the customer site located in a difficult position among them.
- While there are several PPP areas are available, many are in the opposite direction of the PSRs, so getting to them require some amount of backtracking from the customer site.
- One PSR meets baseline criterion but is small (<1 km) with limited mineable area. The expanded distance criteria does open up two more PSRs, one fully meets size criteria

105: Shoemaker:

- Of all the regions, this is the most favorable in terms of slopes for the traverse paths.
- While quite a few PSRs in the region of appropriate size, but the high slopes into these PSRs restricts mineable area (such that only one PSR has acceptable mine area) and either limits or eliminates traverses into the PSR.
- The challenge is the illumination potential, where there are very few options for PPP locations. The confidence of these areas is low, & is the only region where the customer site was not ranked in Mazarico et all 2011
- However, it should be noted that practically the entire region is an ISR.

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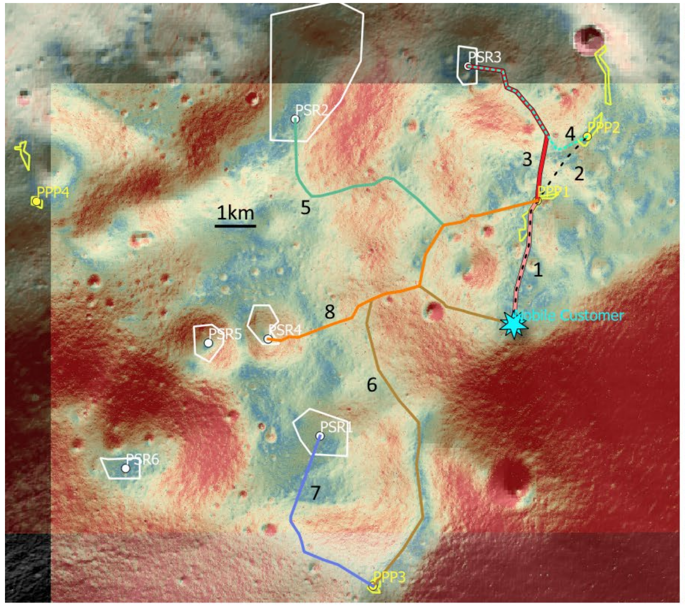
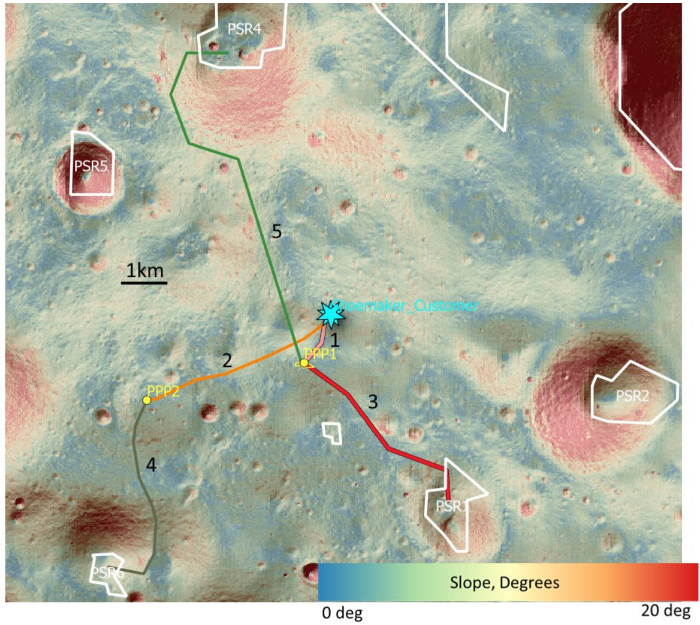


105 Shoemaker



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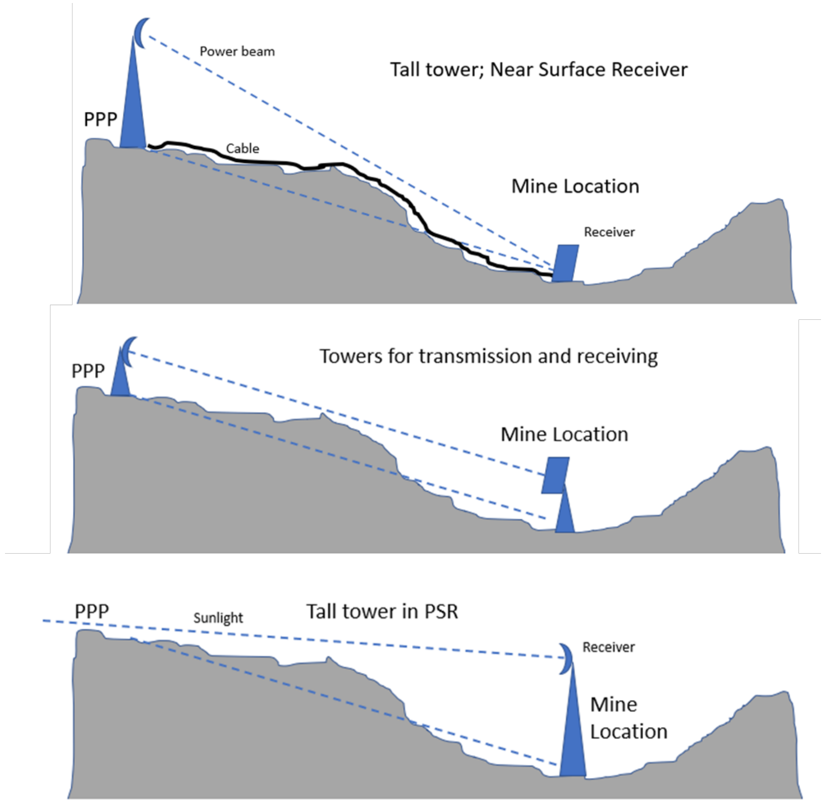
BACK UP

Things NOT considered (that may impact criteria)

- Power options for the PSR
  - The power source for both the PSR and PPP may impact the criteria. However: the PSR in presents a challenge. For example:
    - Beaming: Line of site to either a ridge transmitter or the sun itself may pose elevation requirements for PSR (relative to ridge)
    - Cable: The length of the cable to an unspecified source would add an additional/different proximity requirement

- Path preparation
  - For initial (early) mining ISRU assumes minimal infrastructure, so path planning assumes simple/direct traverses over unprepared ground. The following examples would alter assumptions and may open up options as an outpost is established
    - Roads/pipes/gondolas: more deliveries possible. ISRU system itself may be more flexible (e.g. faster production over less time = less sun needed for PPP)
    - Switchbacks: adding switchbacks into steeper craters may increase the maximum slope criteria.

- Exact placement and fine-tuned traverses (Disclaimer)
  - Locations of PPP and mine sites are notional in this analysis. Traverse paths were not fine tuned for smaller scale slope hazards. While reported results were held strictly to criteria, it may be possible to adjust path and placements to improve.



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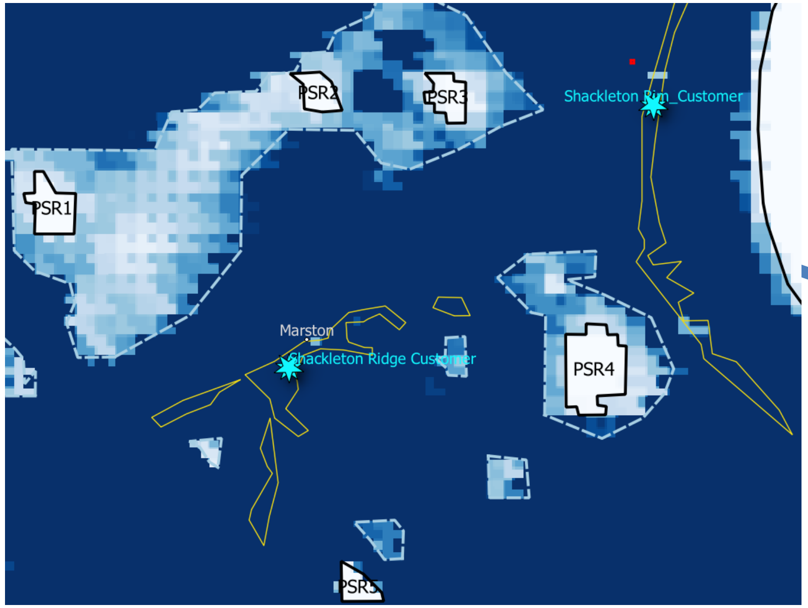
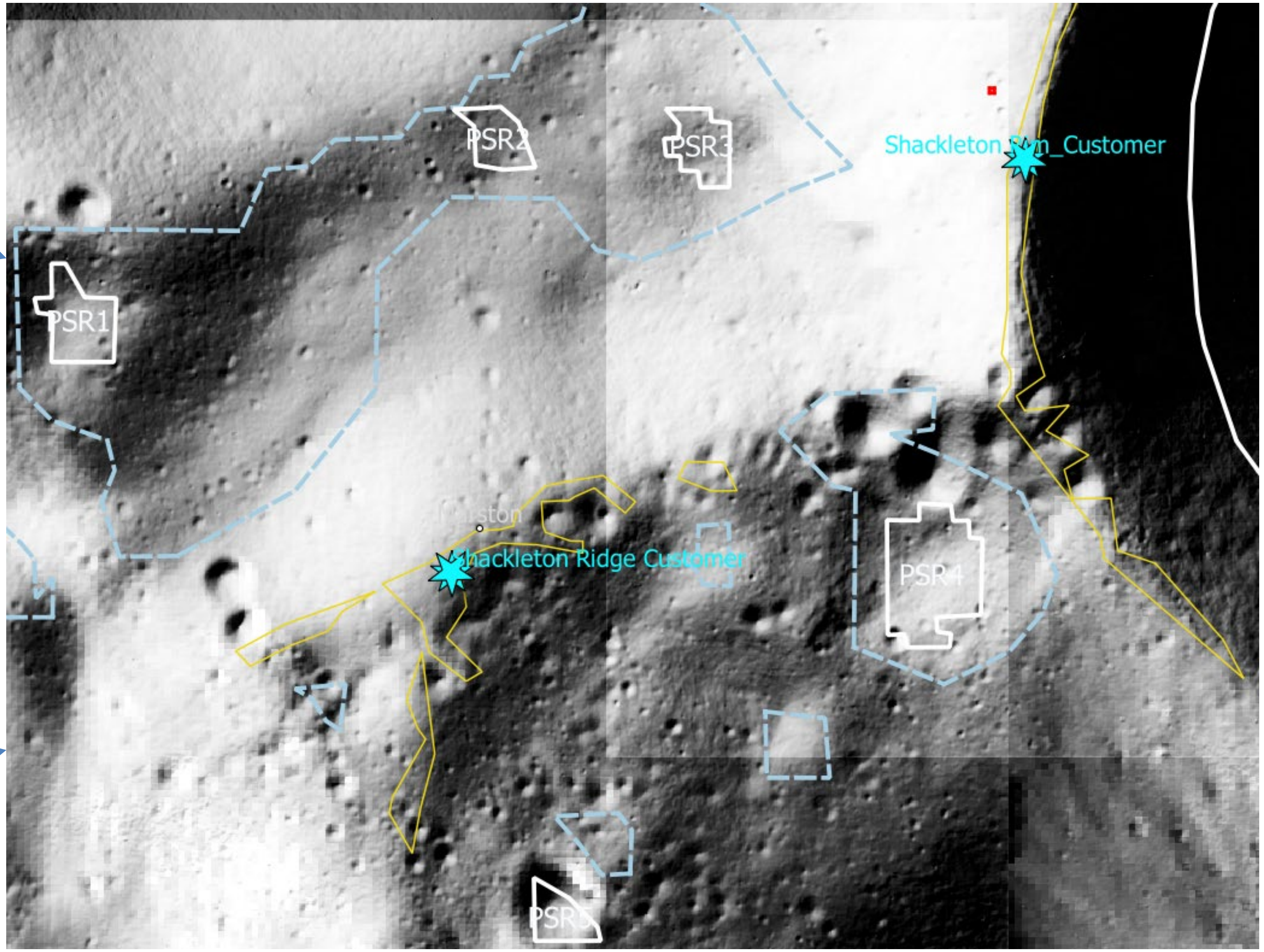
EXAMPLE:
001 Shackleton Ridge

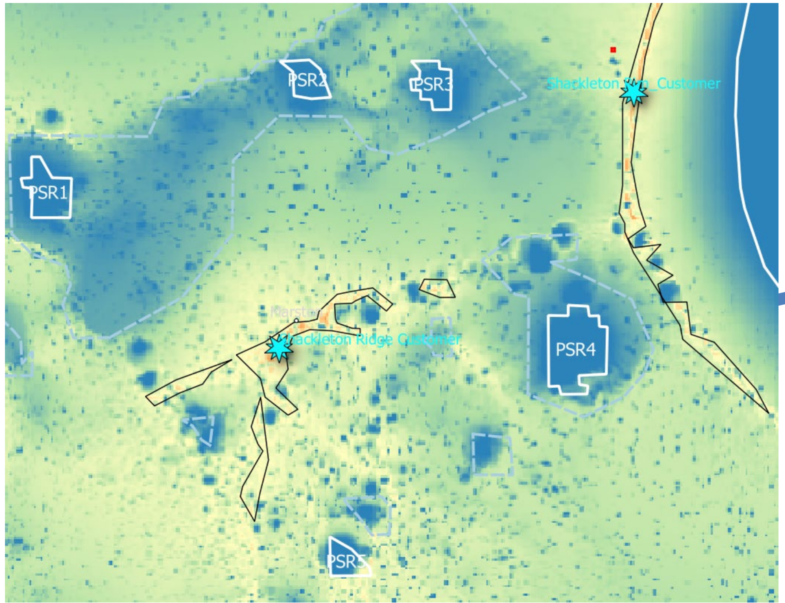
Map Orientation



Ice stability depth

0m 1m





0% Sun Visibility 100%

% of timesteps any fraction of sun disc is visible

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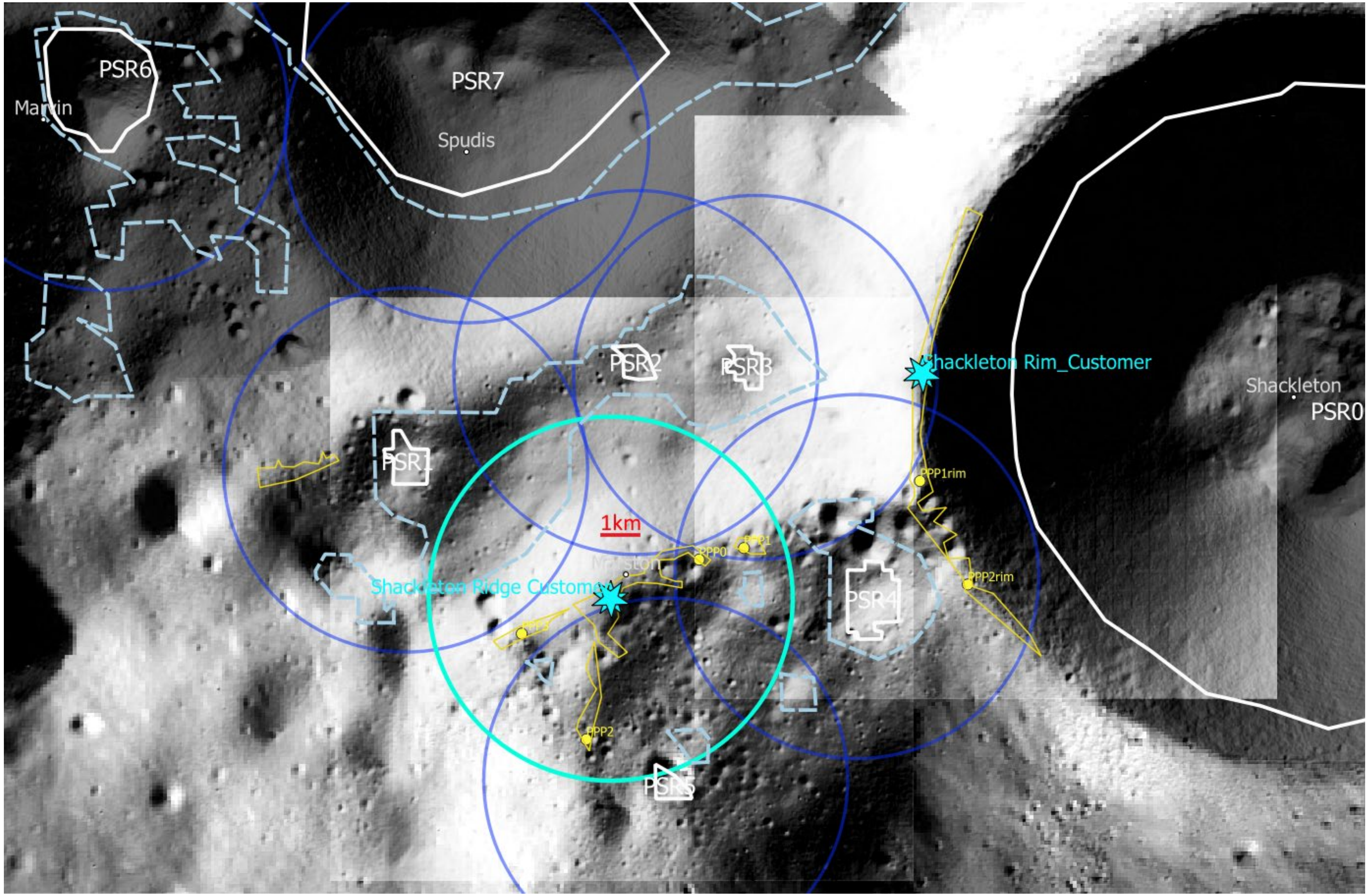
001 Shackleton Ridge: ISRU Regions Of Interest



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Customer site

5km radius around Customer

Mine sites

PSR = Shallow ice stability = deep crater

ISR = 'Deeper' ice stability (50 to 100 cm) = shallow crater

5km radius around mine

Production sites

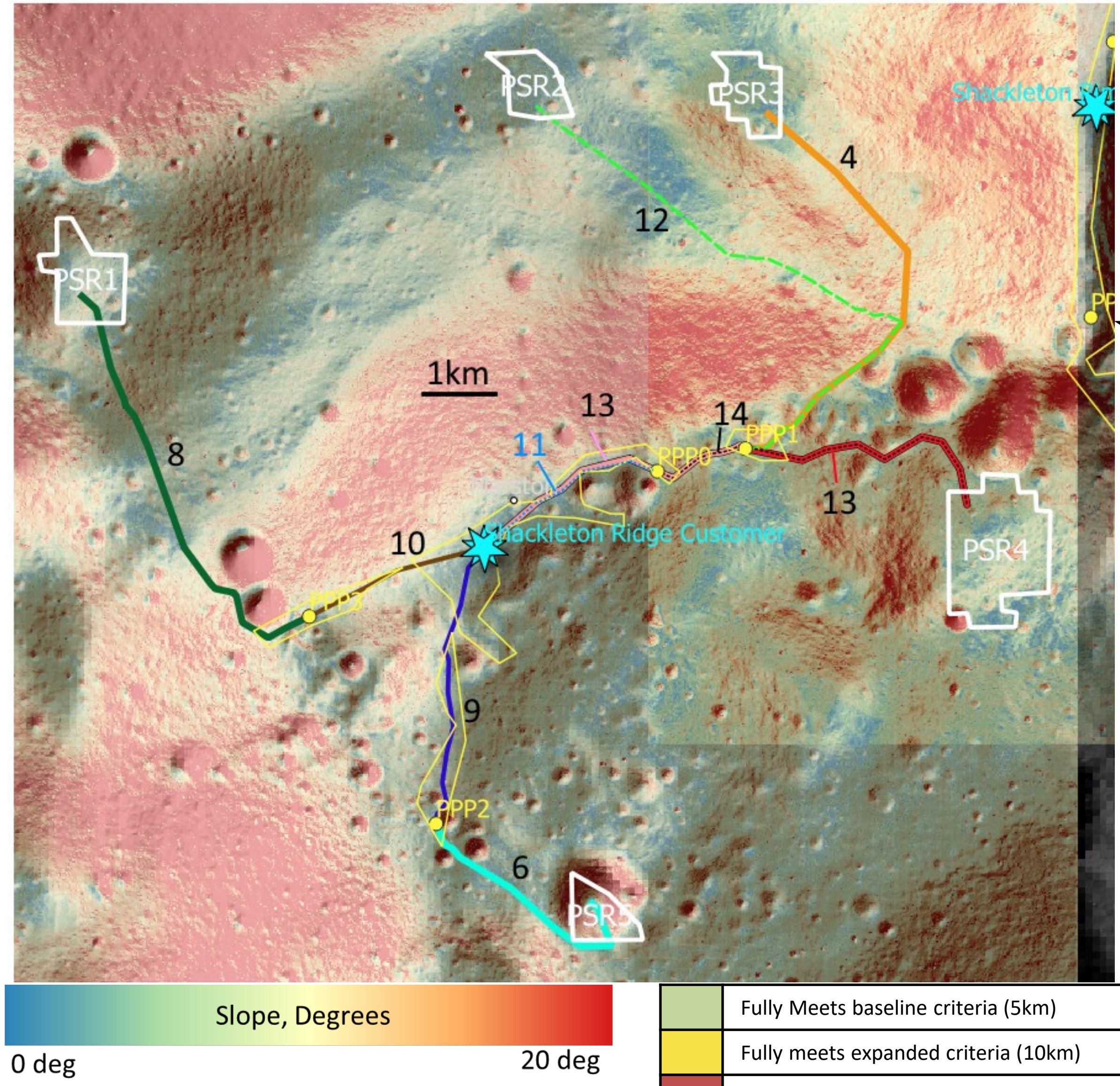
PPP = ISRU propellent production plant @ illuminated site

Analysis:

Valid sites should have a PPP options where light and blue circles overlap

- PSR3, 4, and 5 are possible, with PSR2 just barely outside range
- Note that the large PSRs typically discussed in this region (Spudis, Shackleton) are not in range

001 Shackleton Ridge : Traverse Options



	Fully Meets baseline criteria (5km)
	Fully meets expanded criteria (10km)
	Fails all proximity and/or slope criteria

Data
High Res LOLA Topography DEMs from PGDA: Site 01. https://pgda.gsfc.nasa.gov/products/78

Option	Score	Rank	Path #	From - To	Length: leg (total) km	Slope Max, °	Slope >20°% (m)	Slope Avg, °
A	1.00	10	11	Customer – PPP0	2.9	12.2	0% (0m)	5.3
			14	PPP0 – PSR4	5.3 (8.2)	19.0	0% (0m)	8.4
B	1.05	6	13	Customer – PPP1	4.2	14.9	0% (0m)	6.3
			2	PPP1 – PSR4	3.9 (8.1)	19.0	0% (0m)	8.4
C	0.89	20	13	Customer – PPP1	4.2	14.9	0% (0m)	6.3
			4	PPP1 – PSR3	6.6 (10.8)	18.7	0% (0m)	10.2
D	0.82	23	9	Customer – PPP2	4.1	17.9	0% (0m)	6.8
			6	PPP2 – PSR5	3.8 (7.9)	20.8	1% (41m)	6.9
E	0.94	14	10	Customer – PPP3	2.6	17.2	0% (0m)	7.6
			8	PPP3 – PSR1	6.3 (8.9)	19.8	0% (0m)	8.0
F	0.86	21	13	Customer – PPP1	4.2	14.9	0% (0m)	6.3
			12	PPP1 – PSR2	9.0 (13.2)	18.2	0% (0m)	8.4

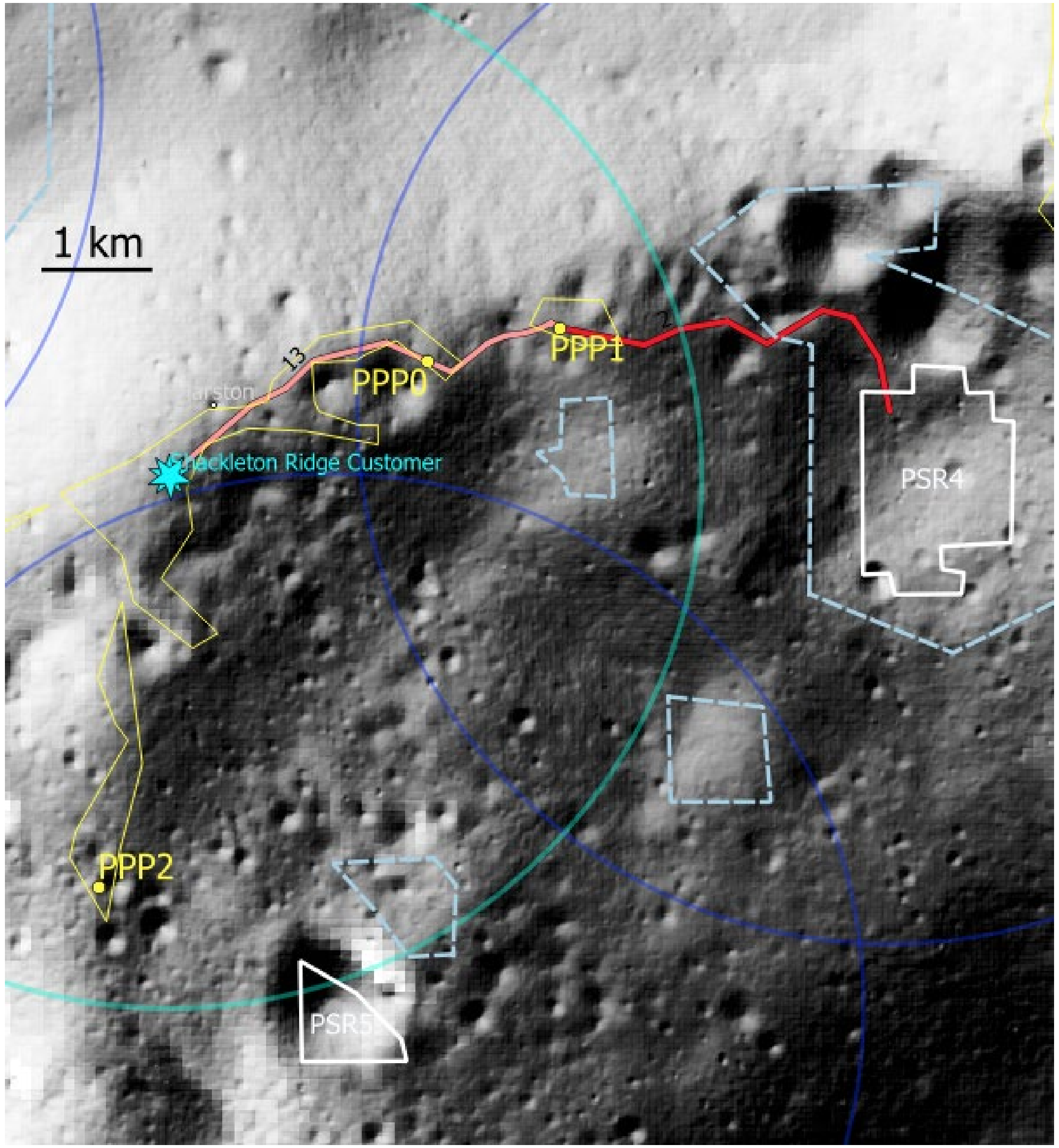
- Option A and B are the same path but if PPP1 is used all criteria are met. PPP0 would put the mine slightly out of the 5km range
  - Option A was used in AIAA-2020-4042

Kleinhenz, J.E. and Sanders, G.B., Evaluation of the NASA Artemis Regions of Interest for ISRU Water Mine Potential, AIAA ASCEND, American Institute for Aeronautics and Astronautics, Oct. 24-26, 2022, AIAA-2022-4284

001 Shackleton Ridge: PSR Summary

	5km Range	10km Range	Slope	PSR Size equivalent diameter, km	Mine size, equivalent diameter, km
PSR1	Acceptable traverse path exceeds distance (by ~1km)	PPP options in range	Paths available	1.20	1.04
PSR2	Acceptable traverse path exceeds distance	PPP options in range	Paths available	0.94	0.88
PSR3	Acceptable traverse path exceeds distance (by ~1.5km)	PPP options in range	Paths available, but high average slopes	1.03	0.94
PSR4	PPP options in range	PPP options in range	Paths available	1.75	1.47
PSR5	PPP options in range	PPP options in range	Slopes into PSR exceed 20deg in all directions	0.87	0.19

- One best option that meets all existing criteria. This was the baseline for the architecture study in 2020.
- Adding 1-2km to distance criteria would put all 5 in bounds.
- Of all the regions of interest, this region provides the most flexibility.



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