ISRU Potential Water Mine Sites; Preliminary Evaluation for NASA Artemis Campaign

Space Resources Roundtable

June 7-10,2022

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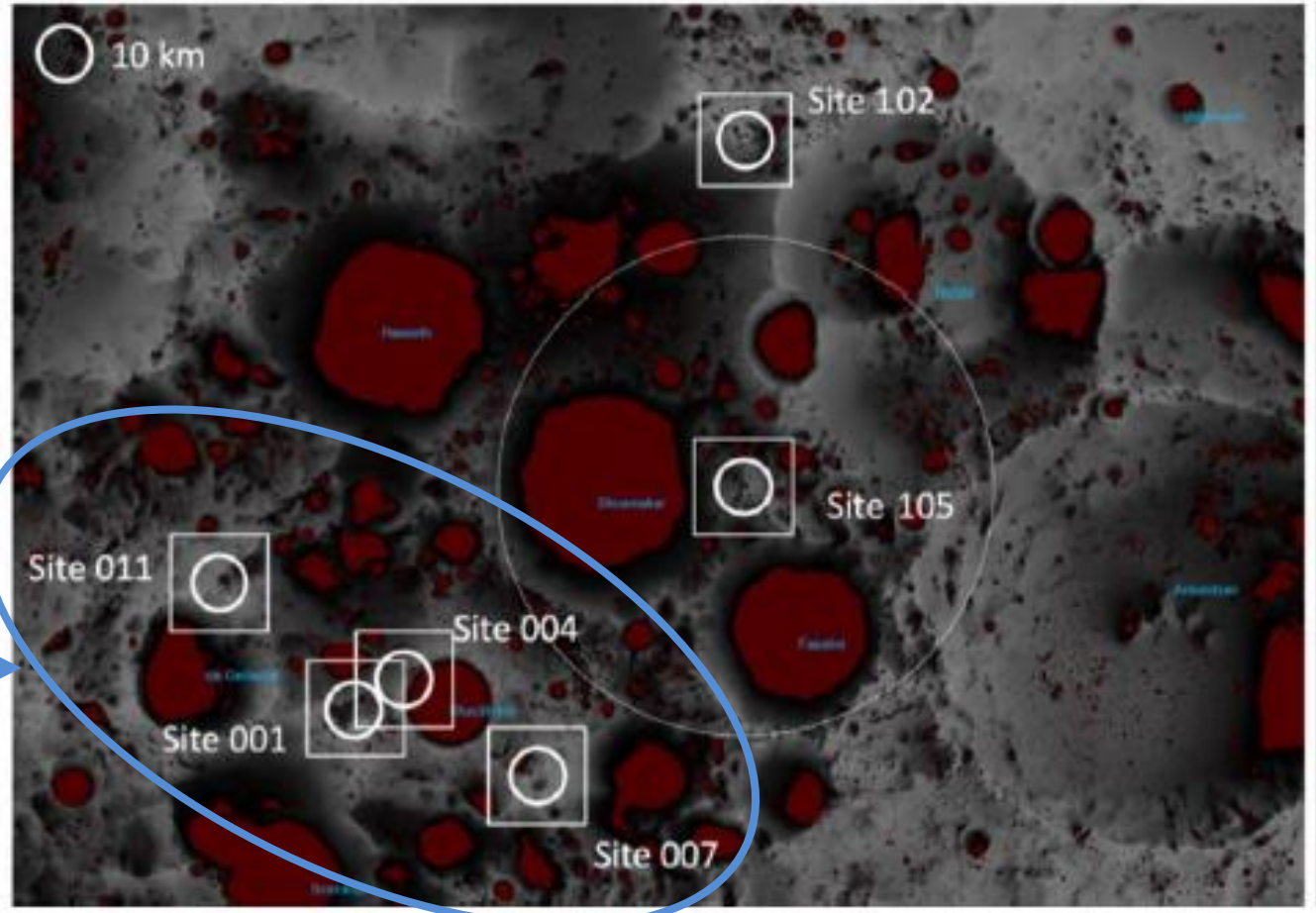
Background

- Evaluate the Regions of Interest (ROIs) for the Artemis Campaign in terms of potential for ISRU water mining
- Ground rules have been defined based on
  - Anticipated customer needs
  - Projected lunar surface hardware capabilities
  - Limited infrastructure (early missions)
  - Lunar environmental & terrain data
- Preliminary analysis, will evolve
- To date preliminary analysis has been done on the “western’ cluster of ROIs
  - Full set should be ready for AIAA ASCEND conference in October 2022
- 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



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

ISRU Baseline Architecture

Customer

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

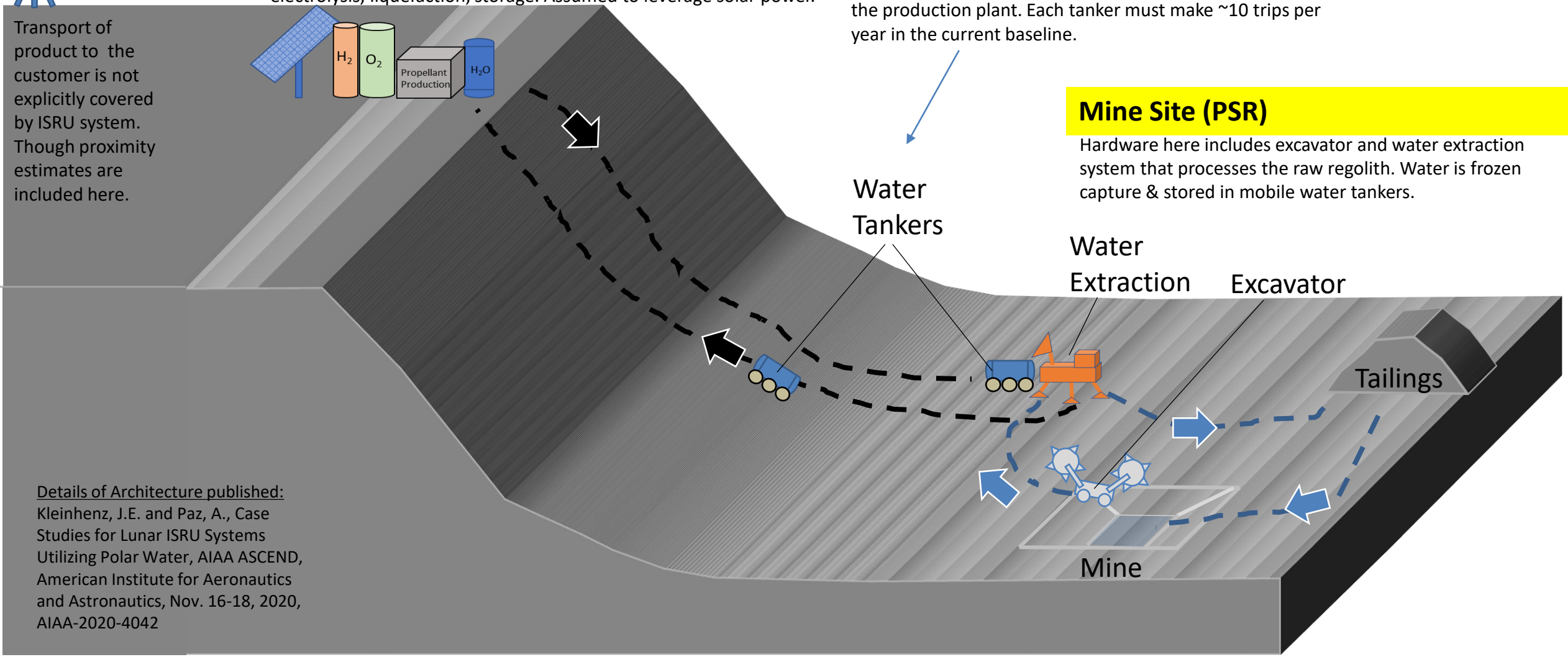
Propellant Production Plant (PPP) Site

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)

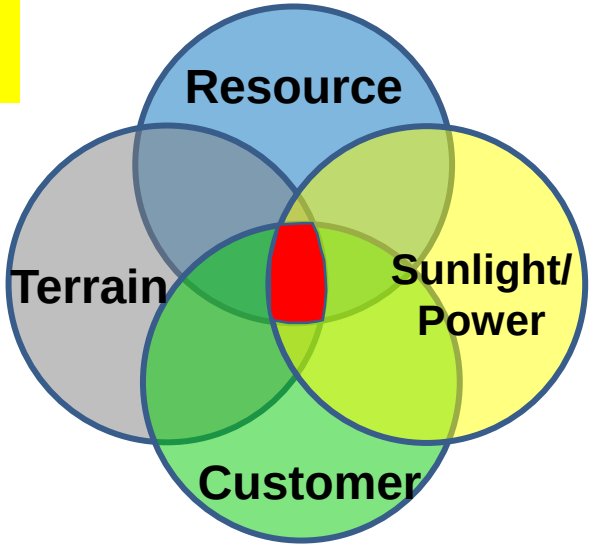
Hardware here includes excavator and water extraction system that processes the raw regolith. Water is frozen capture & stored in mobile water tankers.



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

Approach

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



The ISRU Analysis considered

- **Proximity distances** between 3 sites:
  - Customer (The highest ranked surface illuminated site in area from Mazarico et al 2011*)
  - ISRU propellant production site (PPP) (water processing, H2/O2 liquefaction and storage site based on sun visibility)
  - Water mining site (PSR) (water extraction location based on ice stability maps)
- ❖ *Note: PSR-PPP path distance is more critical since more frequent traverses in/out of PSR are needed*
- ❖ *The PPP is NOT co-located with Customer*
- **Slopes:** traverse paths that offered slopes at or below the ground rule value
- **Ice stability**: the mine sites considered were all permanently shadowed regions that offer shallow ice stability
  - Deeper Ice stability regions were identified, but not evaluated. Alternative ISRU technologies would be needed. These also carry more risk for ice-mining ISRU (lower confidence).
- **Size of ice stability region**: Ice stability maps are 240mpp, so regions had show shallow stability over a cluster of pixels
  - If region had ~3% bulk water content, each production cycle (13mT of O2) would need to excavate a 30m square to 0.3m depth. So a 1 km mine could support 1000 production cycles.
- **Sun Visibility:** The propellant production plant should be located in an illuminated region- currently solar power is anticipated for baseline technology. The duration/amount is currently a parameter of consideration (e.g. not set); The locations specified here are notional based on Sun visibility maps, but actual locations can be worked to fit with the traverse identified.
  - Original analysis done considering 200+ days of contiguous exposure.
  - Non-continuous can be considered, but its likely that periods < 5-10days (TBR) are not as useful.
  - Sun availability over a year should be >150days (TBR), preferably 200+

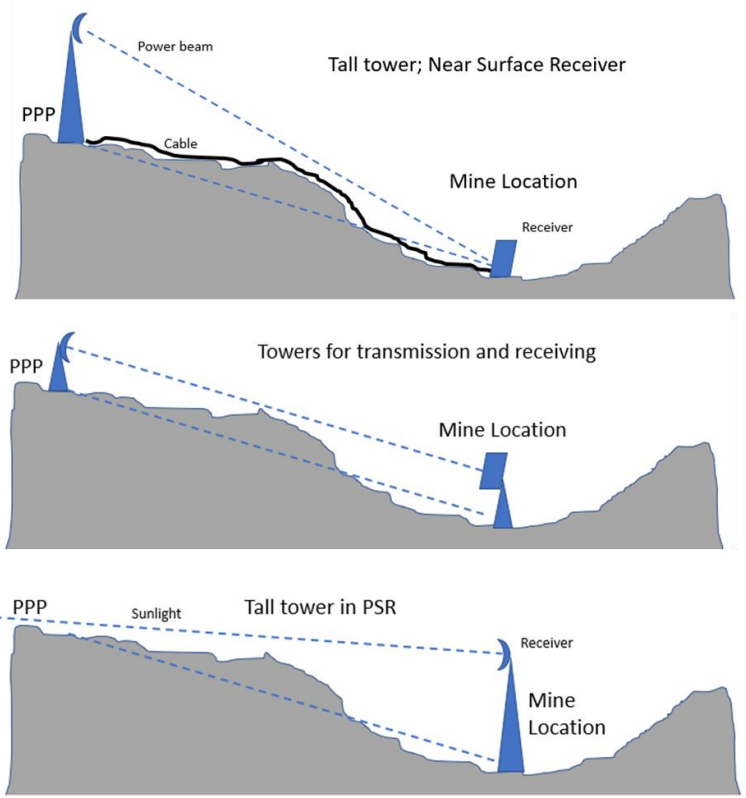
*Mazarico, E., Neumann, G.A., Smith, D.E., Zuber, M.T., and Torrence, M.H., Illumination conditions of the lunar polar regions using LOLA topography. Icarus. 211, 2011, 1066-1081.

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.

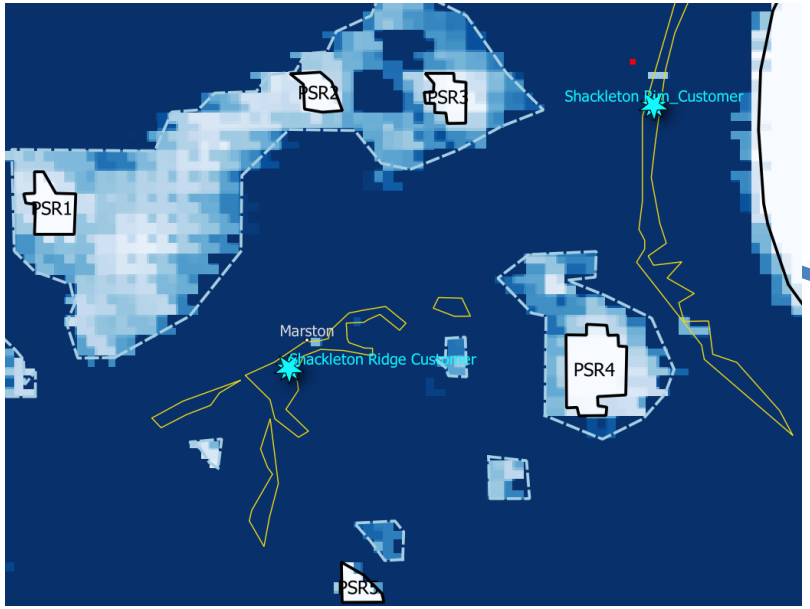
- Exact placement and fine-tuned traverses (Disclaimer)
  - Locations of PPP and mine sites are notional in this analysis. Traverse paths were not fine tuned for smaller scale slope hazards. While reported results were held strictly to criteria, it may be possible to adjust path and placements to improve.



Ground Rules for Site Analysis - summary

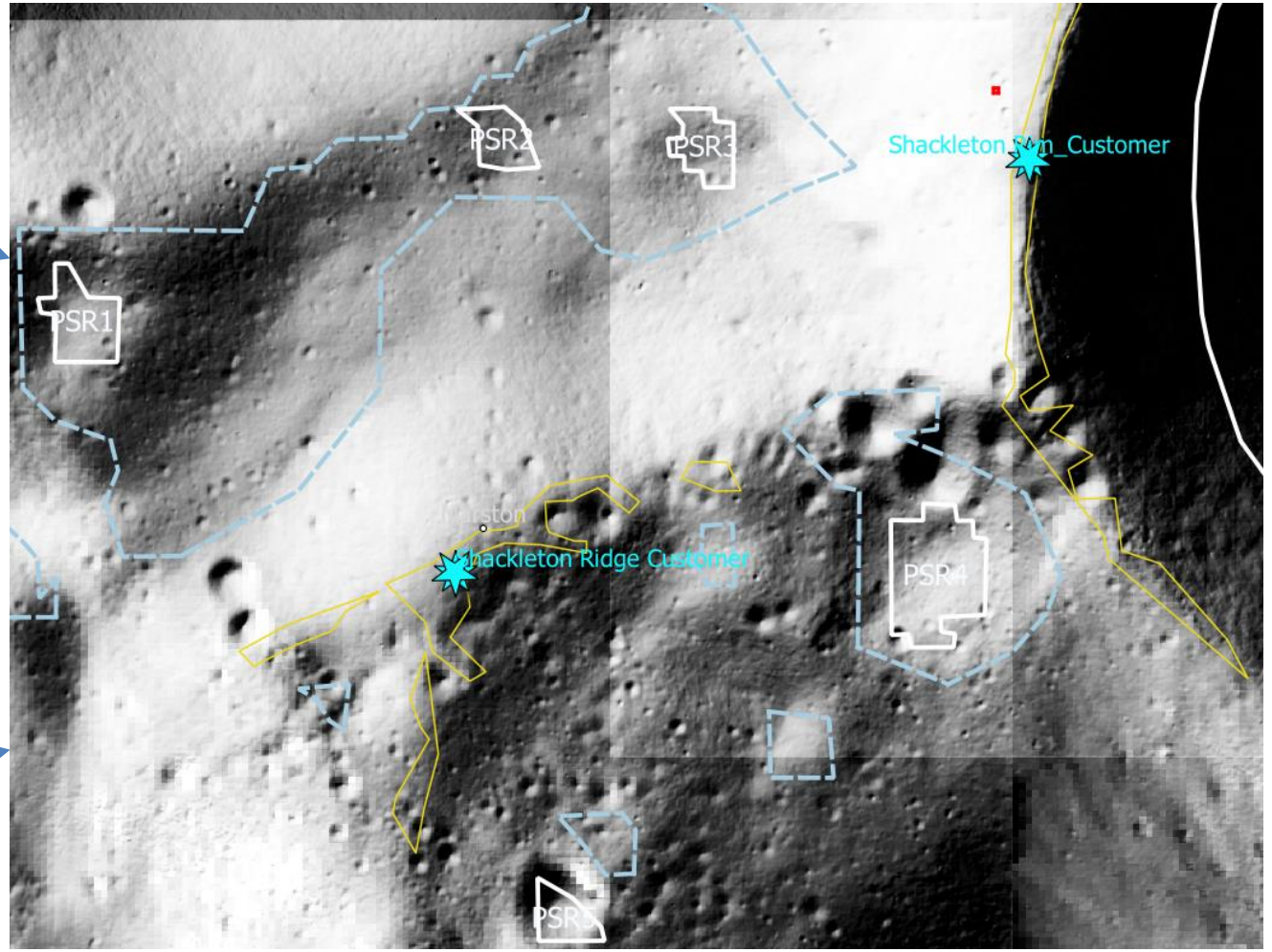
Parameter	Relevant path/location	Ground rule Value	Note
Proximity Distance	Customer to PPP	5 km	10km 'expanded criteria' analysis also performed
	PPP to Mine	5 km	10km 'expanded criteria' analysis also performed
	Total	10 km	20km 'expanded criteria' analysis also performed
Slopes	Any path	<= 20deg	
PSR size	Mine site	~ >1 km equivalent diameter	Multiple pixels on the 240mpp map
Ice Stability	Mine site	Surface ice corresponding to PSR	ISRU requires ice <=1m depth, and there are ice stability regions that are not PSRs that do not indicate surface ice. However, with lack of prospecting data only PSRs are considered for more confidence in the ice deposit.
Sun Visibility	PPP (Propellant Production Site)	~ > 75% visibility using LOLA Sun Visibility 60m	LOLA 60m/pix Sun Visibility, Percentage of timestamps when any fraction of solar disc is visible using Mazarico 2011 methodology. Exported from Quickmaps

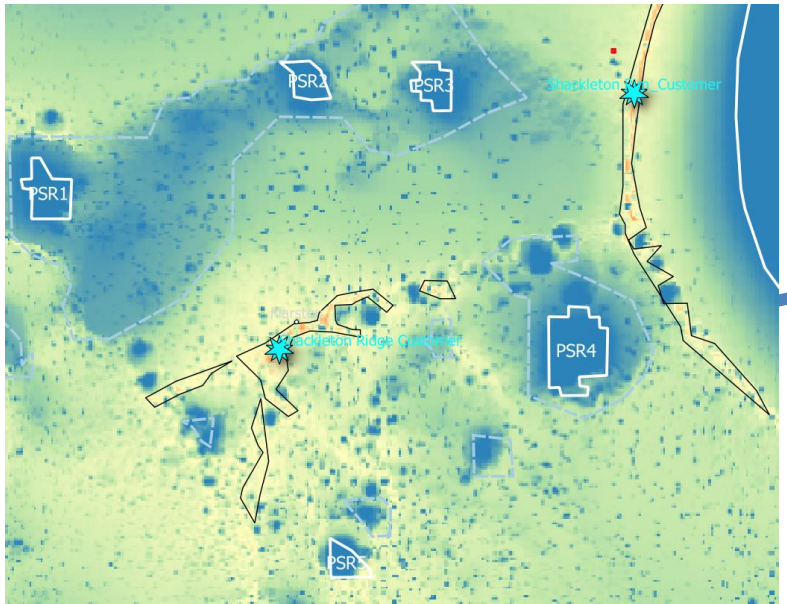
Map Orientation



Ice stability depth

0m 1m

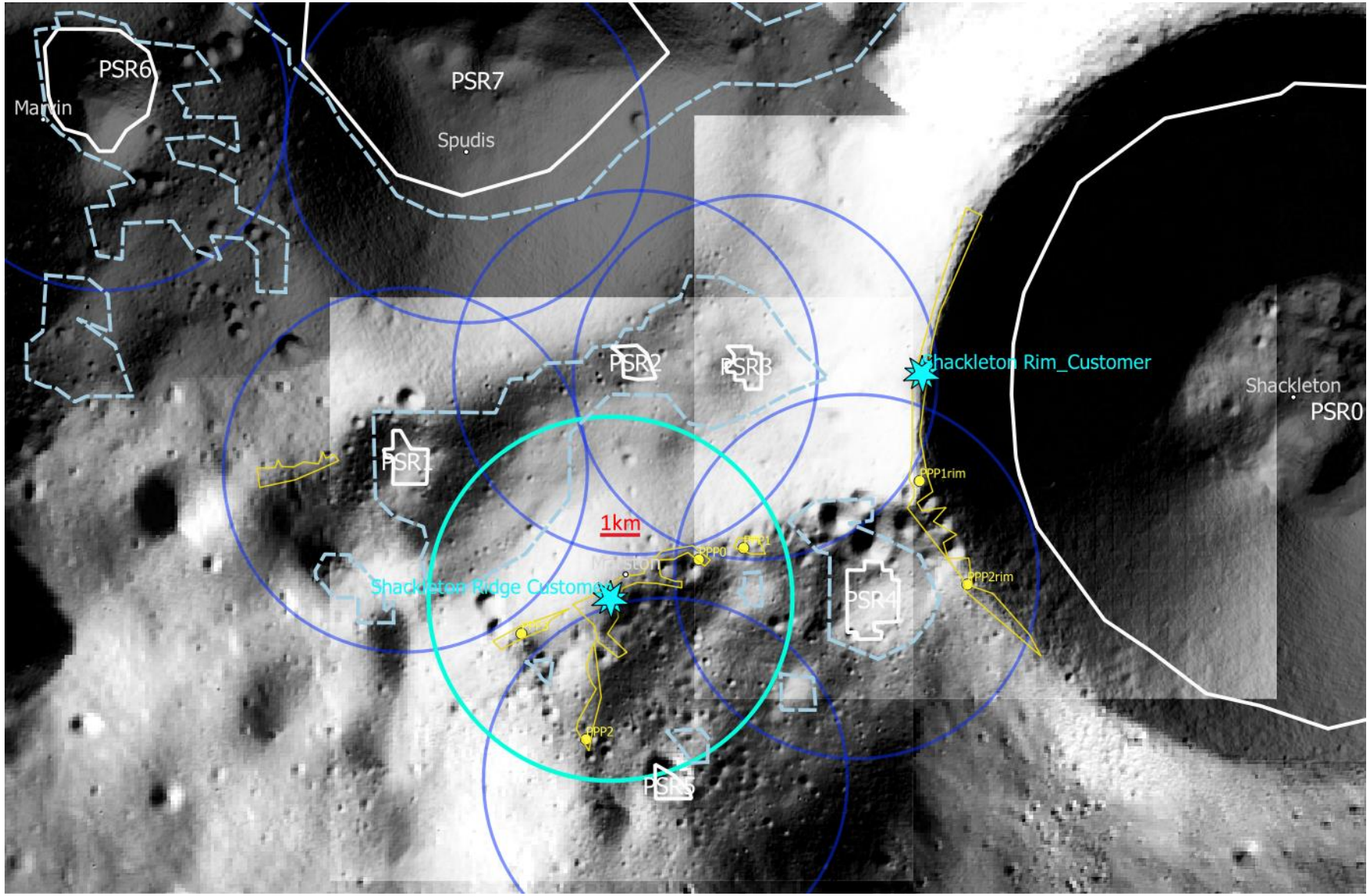




0% Sun Visibility 100%

% of timesteps any fraction of sun disc is visible

001 Shackleton Ridge: ISRU Regions Of Interest



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

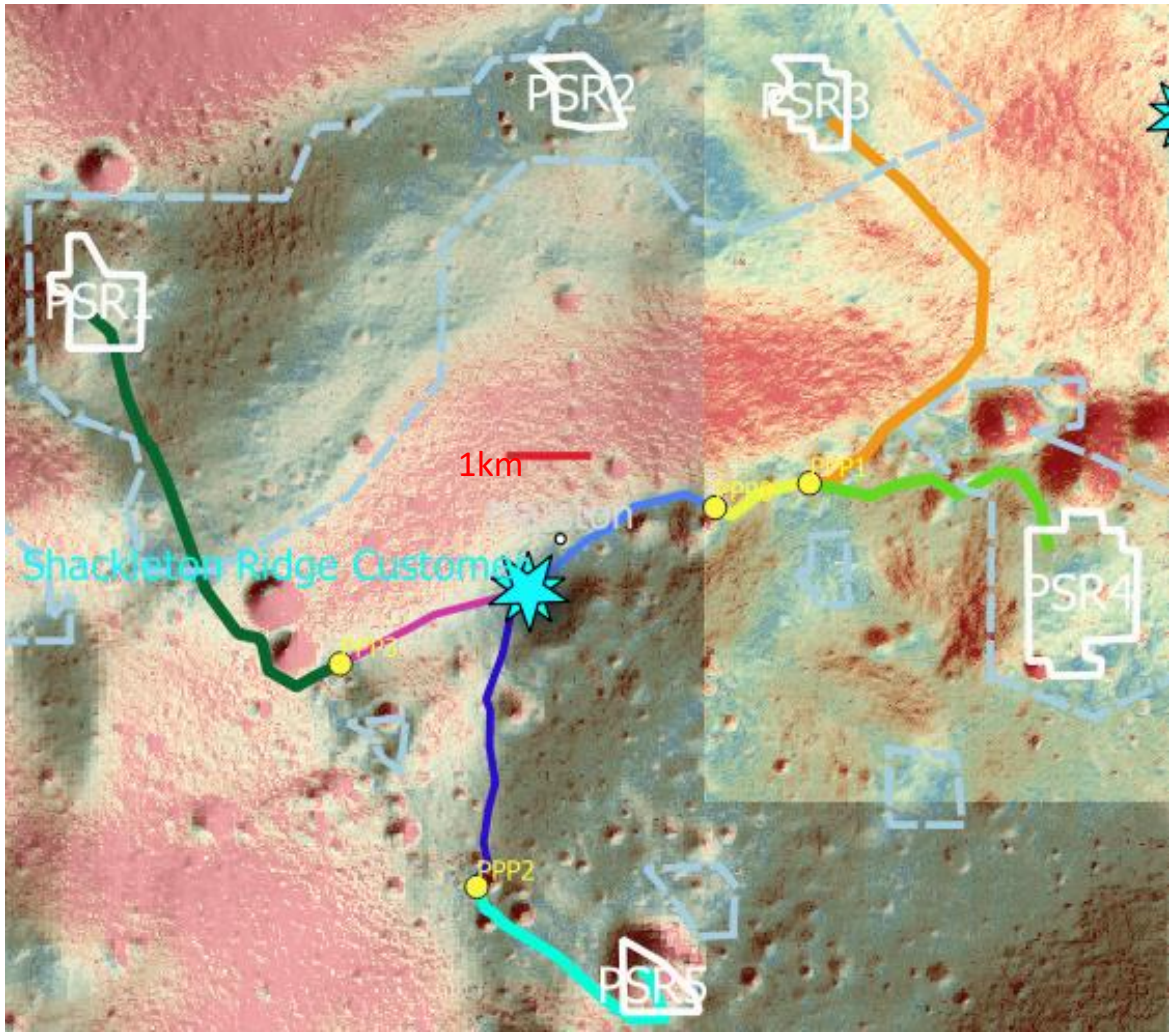
PPP = ISRU propellent production plant @ illuminated site

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



Slope, Degrees

0 deg 20 deg

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

Option	Path #	From - To	Length: leg (total) km	Slope		
				Max, °	>20°% (m)	Avg, °
A	1	Customer – PPP0	2.9	12.2	0% (0m)	5.3
	2-3	PPP0 – PSR4	5.32 (8.2)	19.0	0% (0m)	8.4
B	1-2	Customer – PPP1	4.2	14.9	0% (0m)	6.3
	3	PPP1 – PSR4	3.9 (8.1)	19.0	0% (0m)	8.4
C	1-2	Customer – PPP1	4.2	14.9	0% (0m)	6.3
	4	PPP1 – PSR3	6.1 (10.3)	19.7	0% (0m)	10.2
D	5	Customer – PPP2	4.1	17.9	0% (0m)	6.8
	6	PPP2 – PSR5	3.8 (7.9)	20.8	1% (41m)	6.9
E	7	Customer – PPP3	2.6	17.2	0% (0m)	7.6
	8	PPP3 – PSR1	6.3 (8.9)	19.8	0% (0m)	8.0

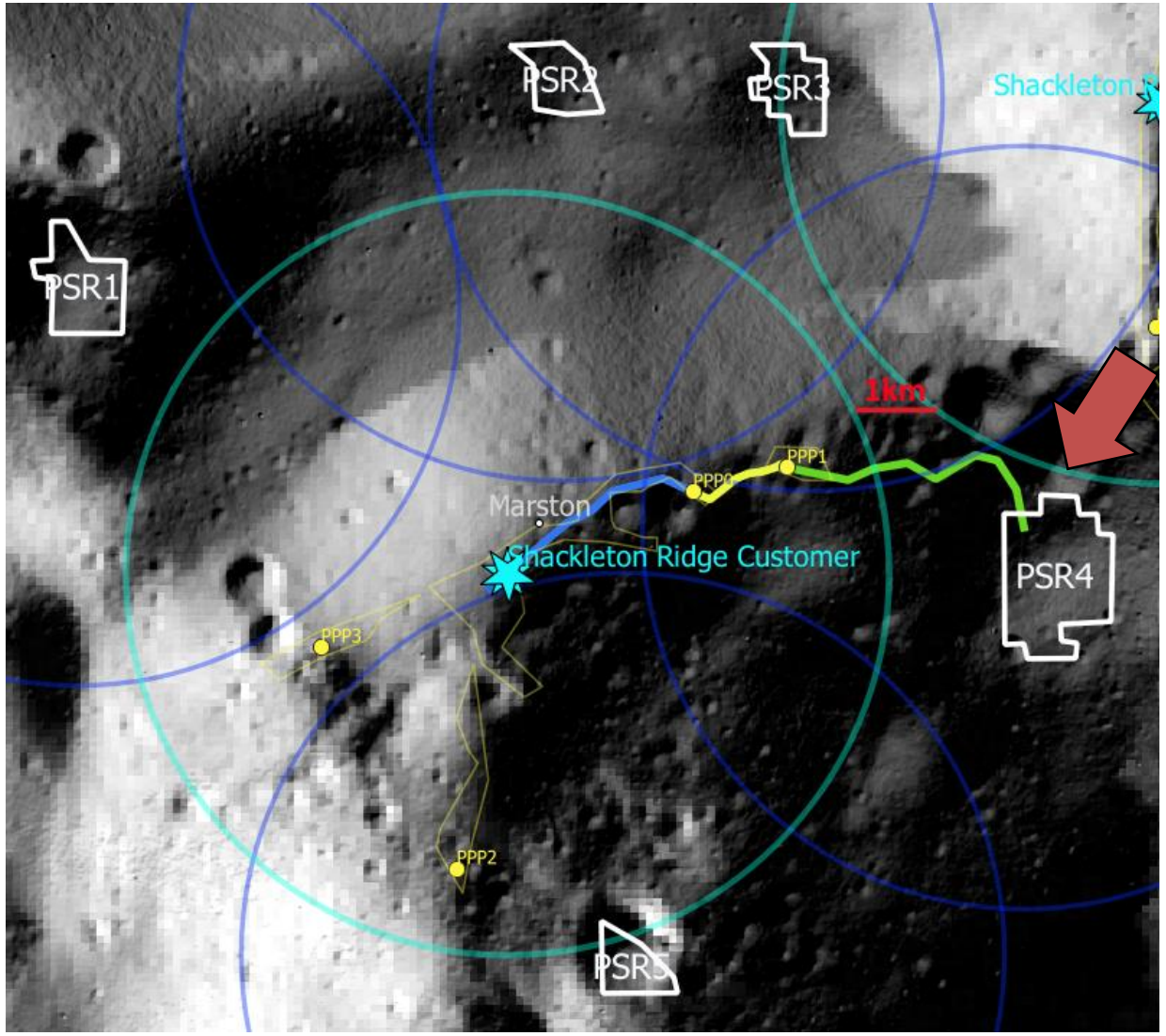
- Option A and B are the same path but if PPP1 is used all criteria are met. PPP0 would put the mine slightly out of the 5km range
  - Option A was used in AIAA-2020-4042
- Option D into PSR5 is ruled out because the slopes into the PSR are high. This accounts for a small portion of the total traverse but will nevertheless be difficult to avoid even with detailed pathfinding.

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

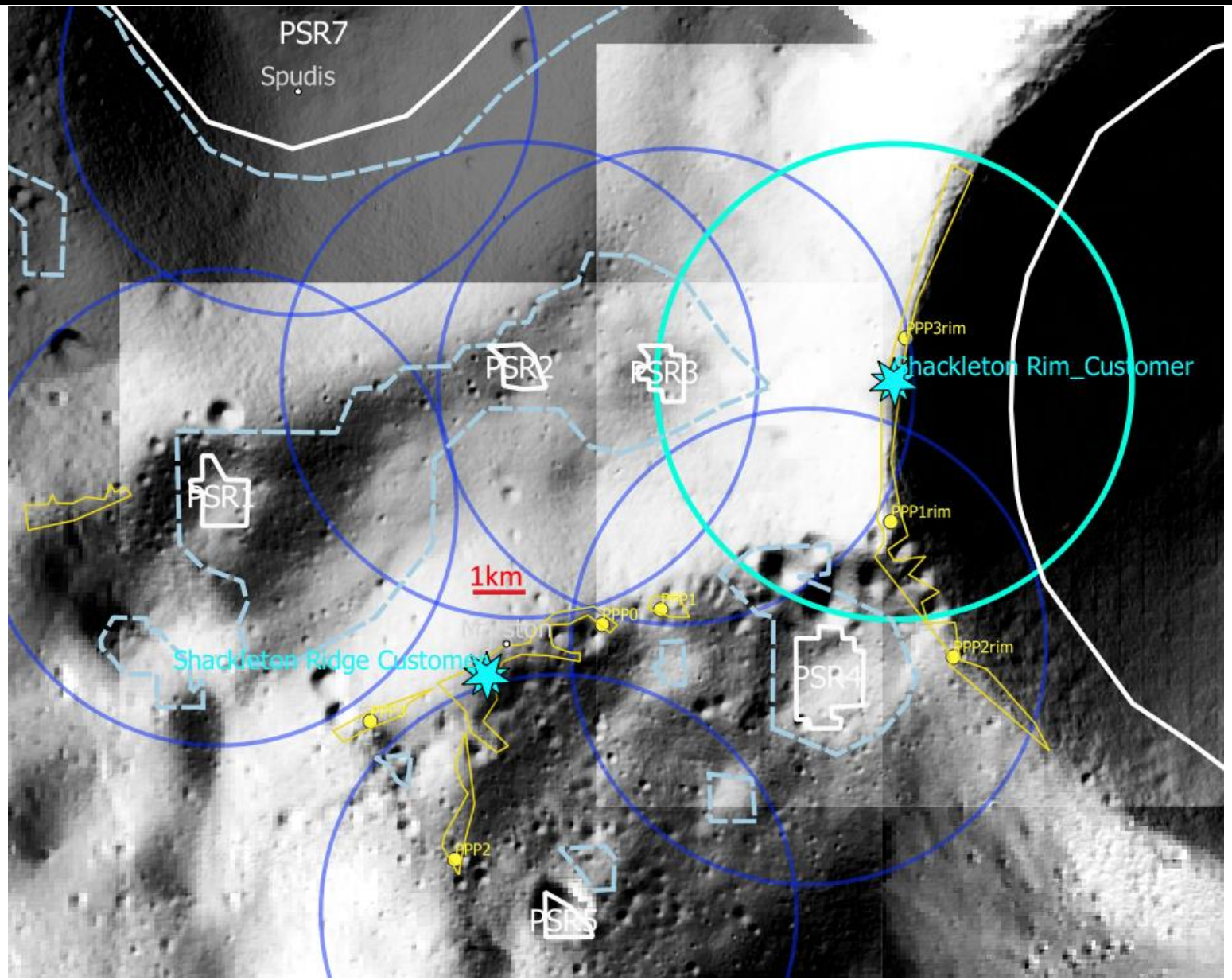
001 Shackleton Ridge: Summary

	5km ranges	10km Range	Slope
PSR1	PPP options in radii, but acceptable traverse path exceeds distances (by ~1km)	PPP options in range	Paths available
PSR2	PPP options in radii, but acceptable traverse path exceeds distances	PPP options in range	Path available, but not direct. Paths would go right past other viable PSRs
PSR3	PPP options in radii, but acceptable traverse path exceeds distances (by ~1.5km)	PPP options in range	Paths available
PSR4	PPP options in range	PPP options in range	Paths available
PSR5	PPP options in range	PPP options in range	Slopes into PSR exceed 20deg in all directions

- One best option that meets all existing criteria. This was the baseline AIAA-2020-4042
- Multiple PPP and PSRs are nearby and either meet criteria or come very close.
  - Adding1-2km to distance criteria would put all 5 in bounds)
- Of all the regions of interest, this region provides the most flexibility.



004 Shackleton Rim: ISRU Regions Of Interest



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

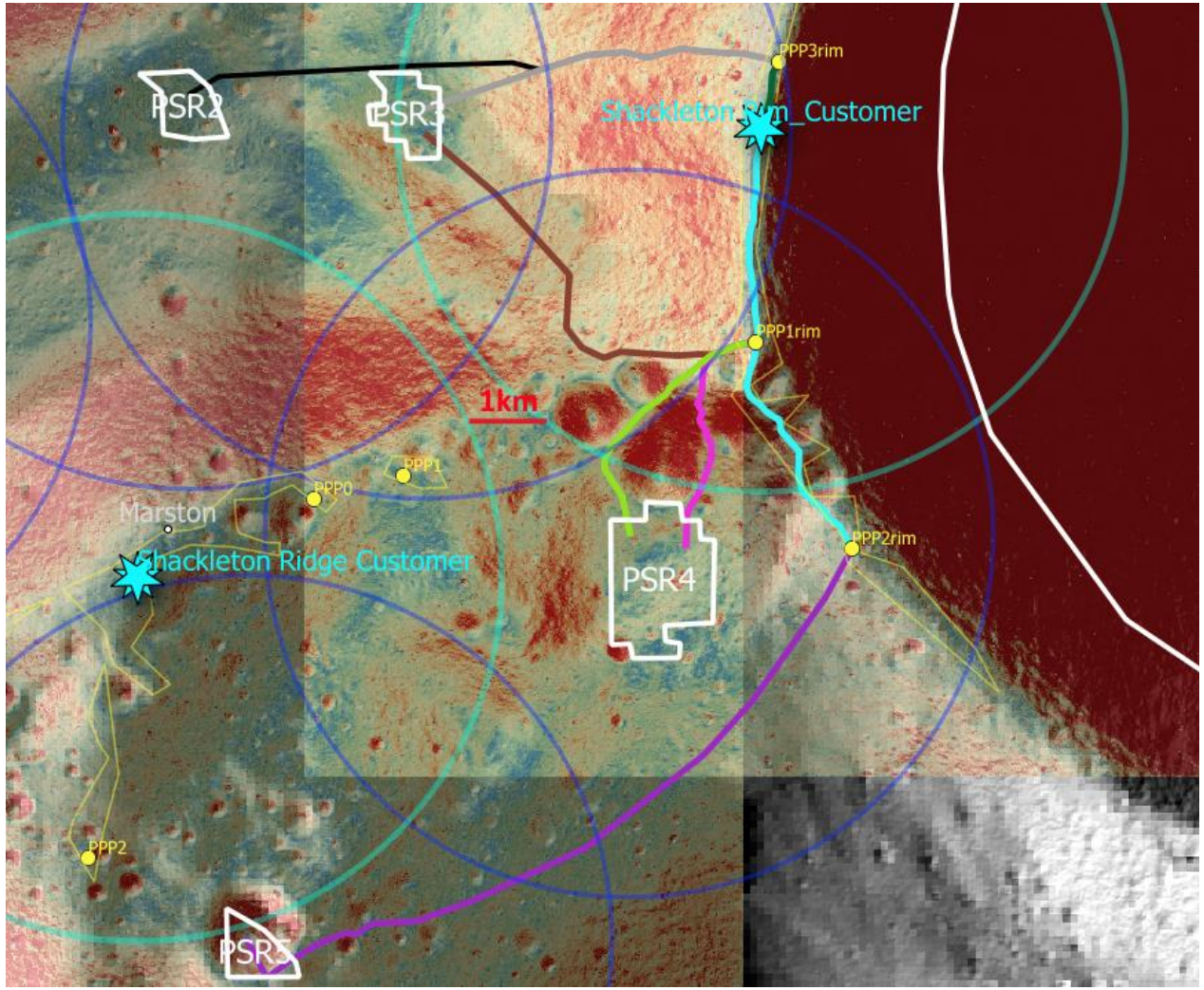
- **PPP** = ISRU propellent production plant @ illuminated site

Analysis:

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

- All PSRs are same as those from Site 001
- PSR3 has limited PPP options that are all very near customer
- PSR4 was the best option for Site 001 Shackleton Ridge

004 Shackleton Rim: Traverse Options



Slope, Degrees

0 deg — 20 deg

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

option	Path #	From - To	Length (total), km	Slope		
				Max, °	>20° % (m)	Avg, °
A	1	Customer – PPP1r	2.98	15.8	0% (0m)	5.56
	3	PPP1r – PSR3	6.3 (9.28)	18.8	0% (0m)	10.9
B	1	Customer – PPP1r	2.98	15.8	0% (0m)	5.56
	4	PPP1r – PSR4	3.8 (6.8)	18.9	0% (0m)	9.36
C	1	Customer – PPP1r	2.98	15.8	0% (0m)	5.56
	2	PPP1r –PSR4e	3.4 (6.42)	19.9	0% (0m)	11.3
D	7	Customer – PPP3r	0.96	15.1	0% (0m)	5.8
	8	PPP3r – PSR3	5.0	20.1	0.1% (5m)	13.0
E	7	Customer –PPP3r	0.96	15.1	0% (0m)	5.8
	9	PPP3r – PSR2	8.2 (9.2)	20.0	0.1% (5m)	9.6
F	5	Customer – PPP2r	6.43	19.8	0% (0m)	7.09
	6	PPP2r – PSR5	10.9 (9.3)	22.1	0.3% (29m)	7.69

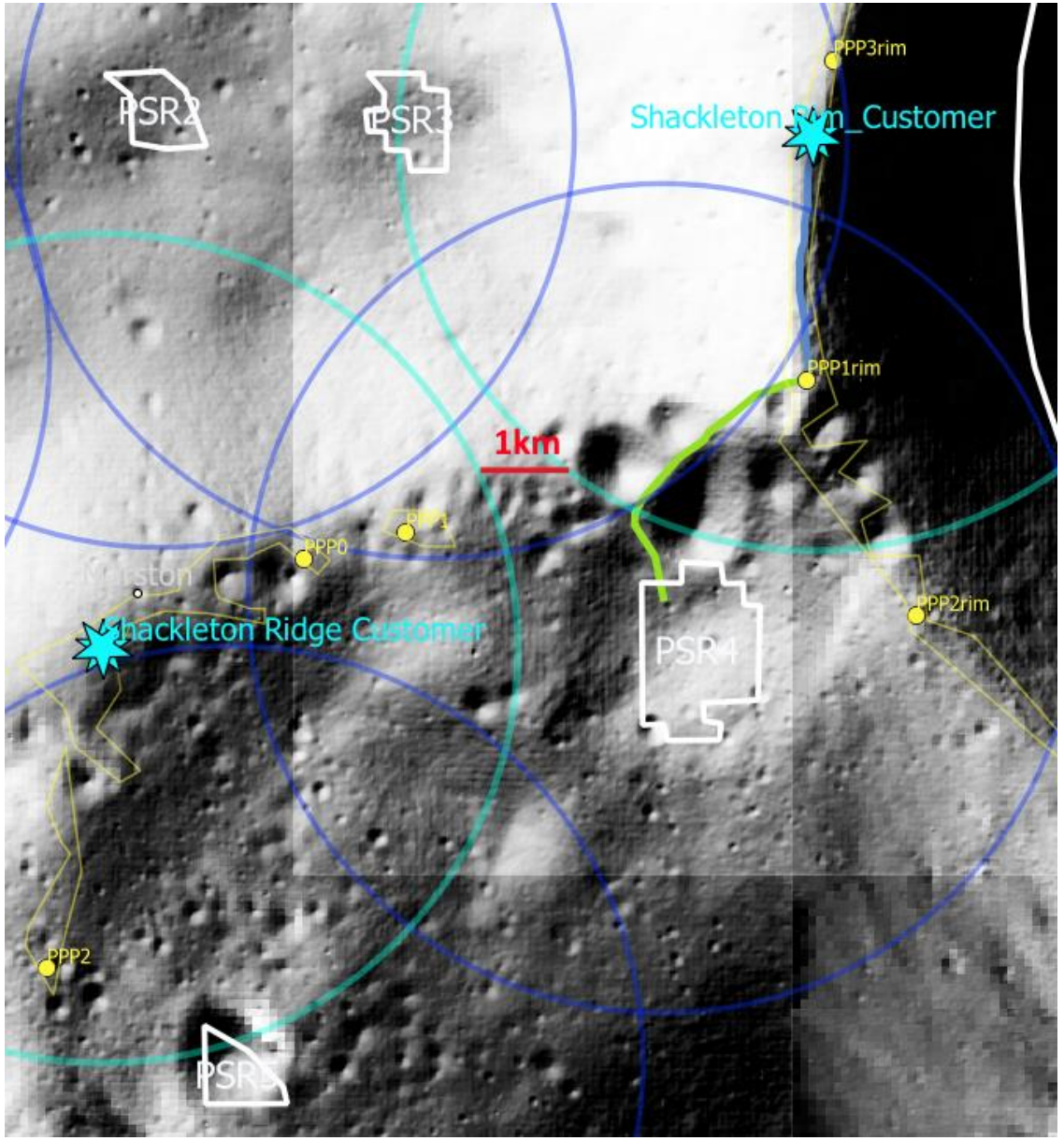
- All options have high average slopes
- PSR4, is best option, the same as site001, and can be done from 2 different paths (B and C) though both have high average

Data
High Res LOLA Topography DEMs from PGDA: Site 04. https://pgda.gsfc.nasa.gov/products/78

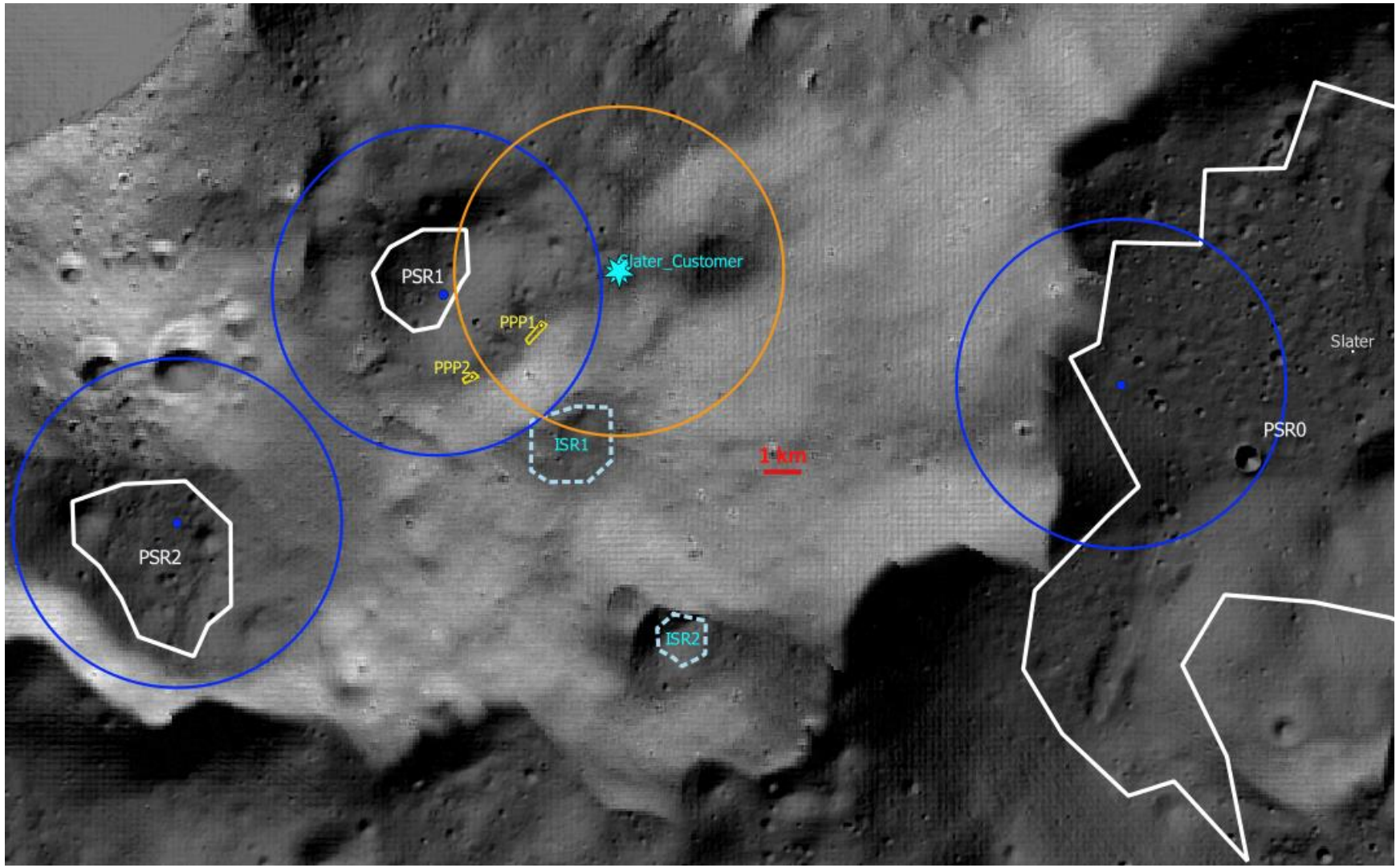
004 Shackleton Rim: Summary

	5km ranges	10km Range	Slope
PSR2	Out of range	PPP options in range	Paths available, but high average slopes
PSR3	PPP options in range but very close (1km) to customer	PPP options in range but very close (1km) to customer	Paths available, but high average slopes
PSR4	PPP options in range	PPP options in range	Paths available
PSR5	Out of range	PPP options in range	Slopes into PSR exceed 20deg in all directions

- One best PSR that meets all existing criteria, and is the same PSR that worked for 001 Shackleton Ridge
- PSR3 is also an option, but requires PPP very close to customer and has high average slopes off the rim
- Expanded proximity criteria opens up PSR2, though since PSR3 is along the traverse route, there is limited value
  - PSR5 is in proximity, but traverse paths are >10km and slopes into crater are too high



007 Slater: ISRU Regions Of Interest



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

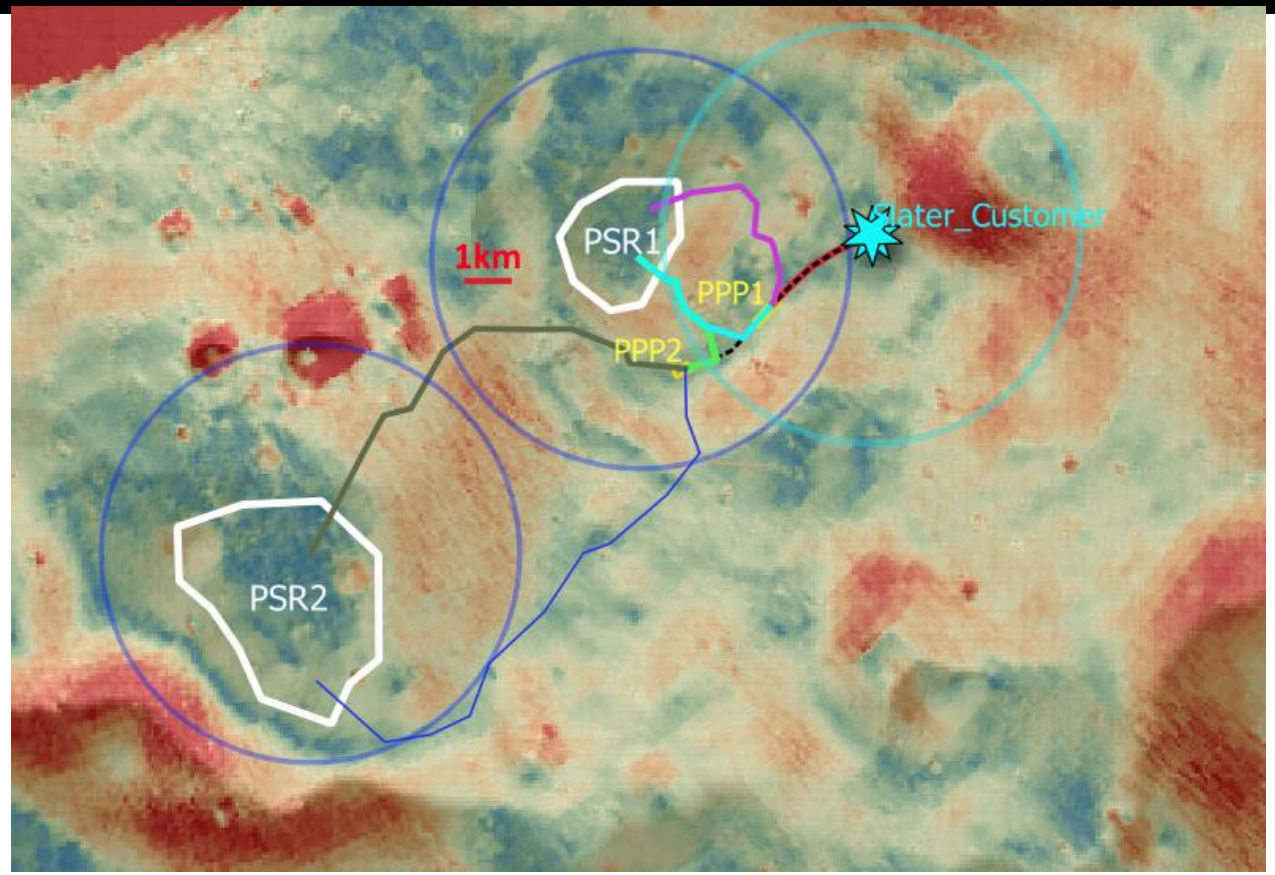
PPP = ISRU propellent production plant @ illuminated site

Analysis:

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

- To meet the 5km travel limits only 1 PSR is viable for ISRU mining

007 Slater: Traverse Options



Option	Path #	From - To	Length: leg (total) km	Slope		
				Max, °	>20° % (m)	Avg, °
A	1	Customer - PPP1	2.91	14.5	0% (0m)	5.5
	3	PPP1 – PSR1	4.4 (3.9)	16.4	0% (0m)	8.2
B	1	Customer - PPP1	2.91	14.5	0% (0m)	5.5
	5	PPP1 – PSR1N	5.5 (8.41)	15.4	0% (0m)	6.8
C	2	Customer – PPP2	5.62	17.6	0% (0m)	5.0
	4	PPP2 – PSR1	4.05 (9.67)	16.2	0% (0m)	7.7
D	2	Customer – PPP2	5.62	17.6	0% (0m)	5.0
	6	PPP2 – PSR2	12.2 (17.8)	34.9	3.3% (401m)	8.6
E	2	Customer – PPP2	5.62	17.6	0% (0m)	5.0
	7	PPP2 – PSR2s	14.9 (20.5)	26.5*	0.3% (47m)	6.5

Slope, Degrees

0 deg 20 deg

Data

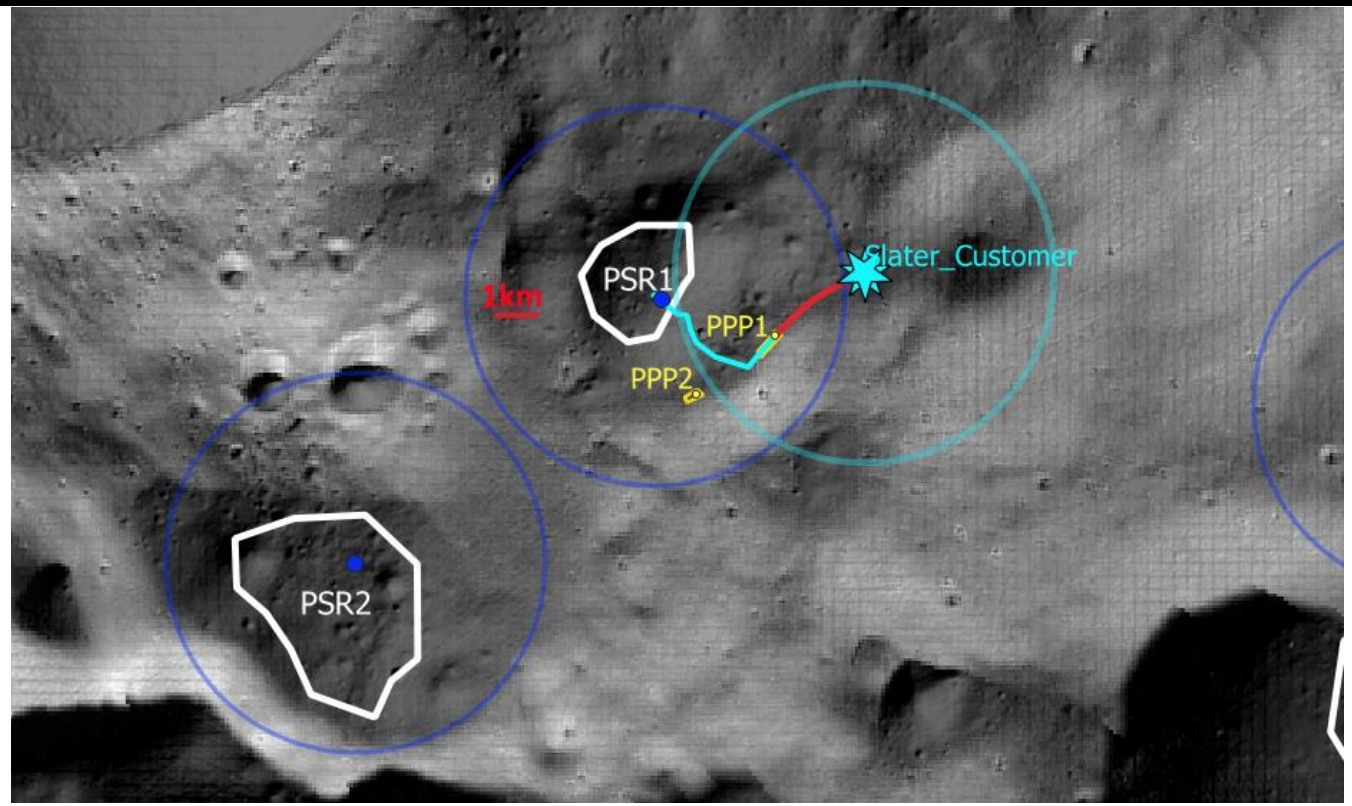
High Res LOLA Topography DEMs from PGDA: Site 07.
https://pgda.gsfc.nasa.gov/products/78

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

- Customer paths follow same ridgeline path then deviate to access PSR
- There is a clear optimal slope path (a ‘pass’) into PSR from the South (path 3 & 4 use this)
- Expanding criteria opens up an additional PPP location and an additional path into PSR1
- To get to another PSR, proximity criteria would have to increase to 15km, where more detailed pathfinding around high slopes is needed

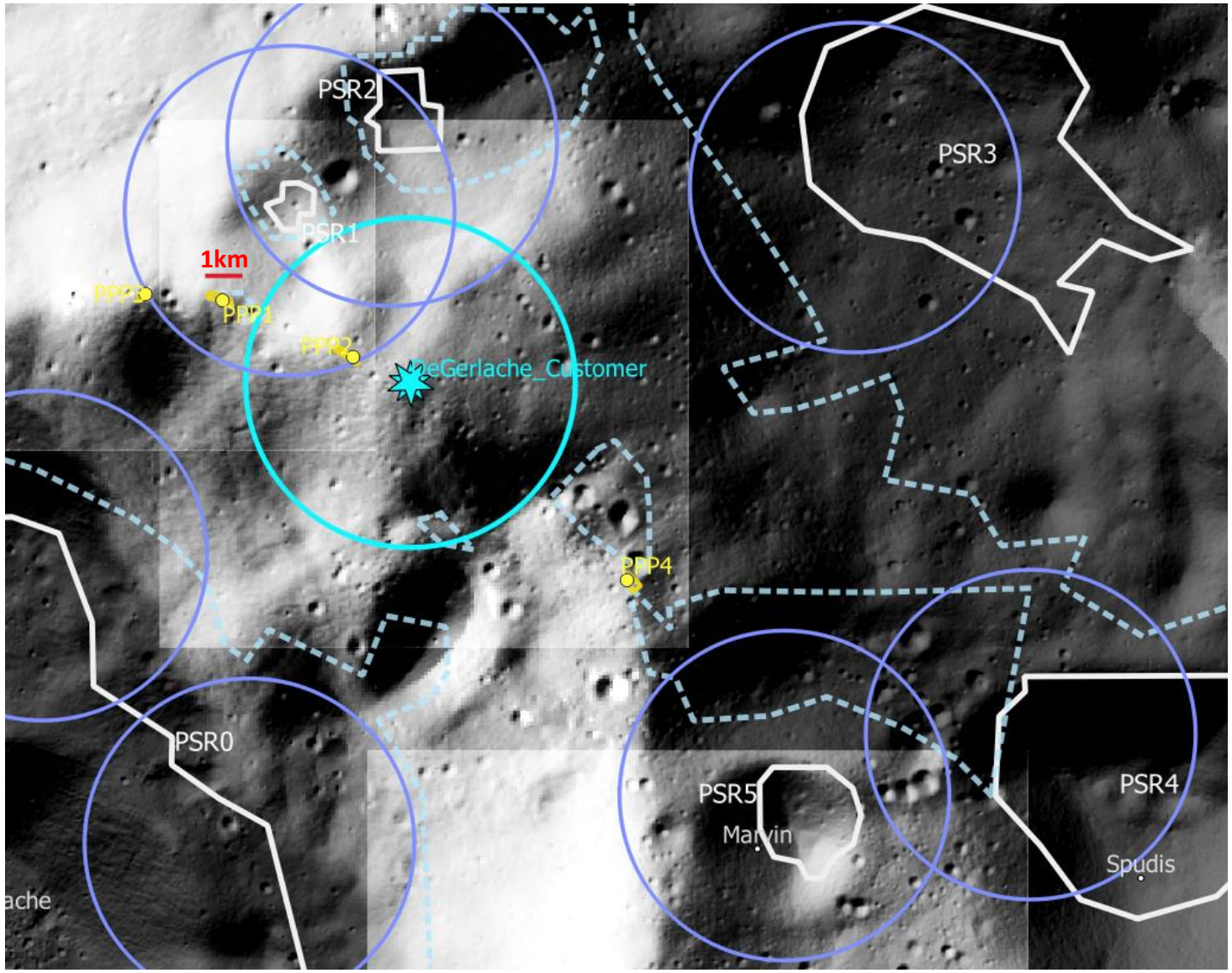
007 Slater: Summary

	5km ranges	10km Range	Slope
PSR0 (Slater)	Out of range	No PPP options in range	Path available
PSR1	PPP options in range	PPP options in range	Paths Available : clear best path
PSR2	Out of range	PPP option in range	Slopes favorable to SE, but requires longer traverses (~15 km)



- There is a best option for ISRU that meets ground rule criteria
  - 1 PSR (mine) and PPP area are accessible, meets criteria, from both slope and distance standpoint
- Other options would require expanded criteria
  - For the same PSR, there are is an additional PPP region that only requires an additional 0.5 km
  - Expanding proximity criteria to 10km for each leg puts PSR2 in range, but path finding would cause traverses to exceed 10km by 5km

011 De Gerlache: ISRU Regions Of Interest



Customer site

5km radius around Customer

Mine sites

PSR = Shallow ice stability = deep crater

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5km radius around mine

Production sites

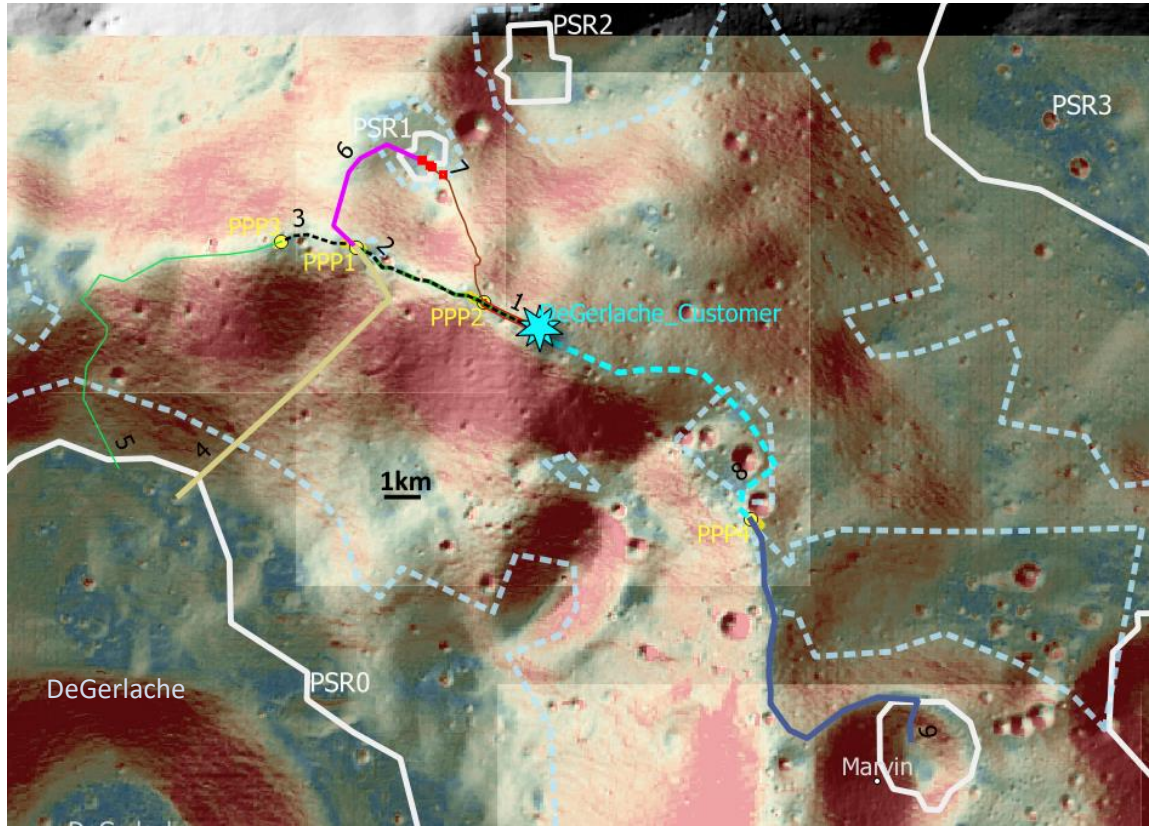
PPP = ISRU propellent production plant @ illuminated site

Analysis:

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

- Only one PSR (PSR1) and one PPP area (PPP2) is in proximity range

011 De Gerlache: Traverse Options



	Path #	From - To	Length (total), km	Slope		
				Max, °	>20° % (m)	Avg, °
A	1	Customer – PPP2	1.96	11.1	0% (0m)	4.4
	7	PPP2 – PSR1	5.2 (7.2)	19.7	0% (0m)	11.1
B	2	Customer – PPP1	6.39	12.7	0% (0m)	5.7
	6	PPP1 – PSR1	5.44 (11.8)	19.8	0% (0m)	8.8
C	3	Customer – PPP3	8.85	14.8	0% (0m)	5.6
	5	PPP3 – PSR0	12.8 (21.7)	31.9	2% (238m)	11.3
D	2	Customer – PPP1	6.39	12.7	0% (0m)	5.7
	4	PPP1 – PSR0	10.9 (17.3)	30.6	12% (1314m)	13.7
E	8	Customer – PPP4	11.5	19.6	0% (0m)	9.2
	9	PPP4 - PSR4	12.6 (24.1)	21.5	0.3% (38m)	8.3

Slope, Degrees

0 deg — 20 deg

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

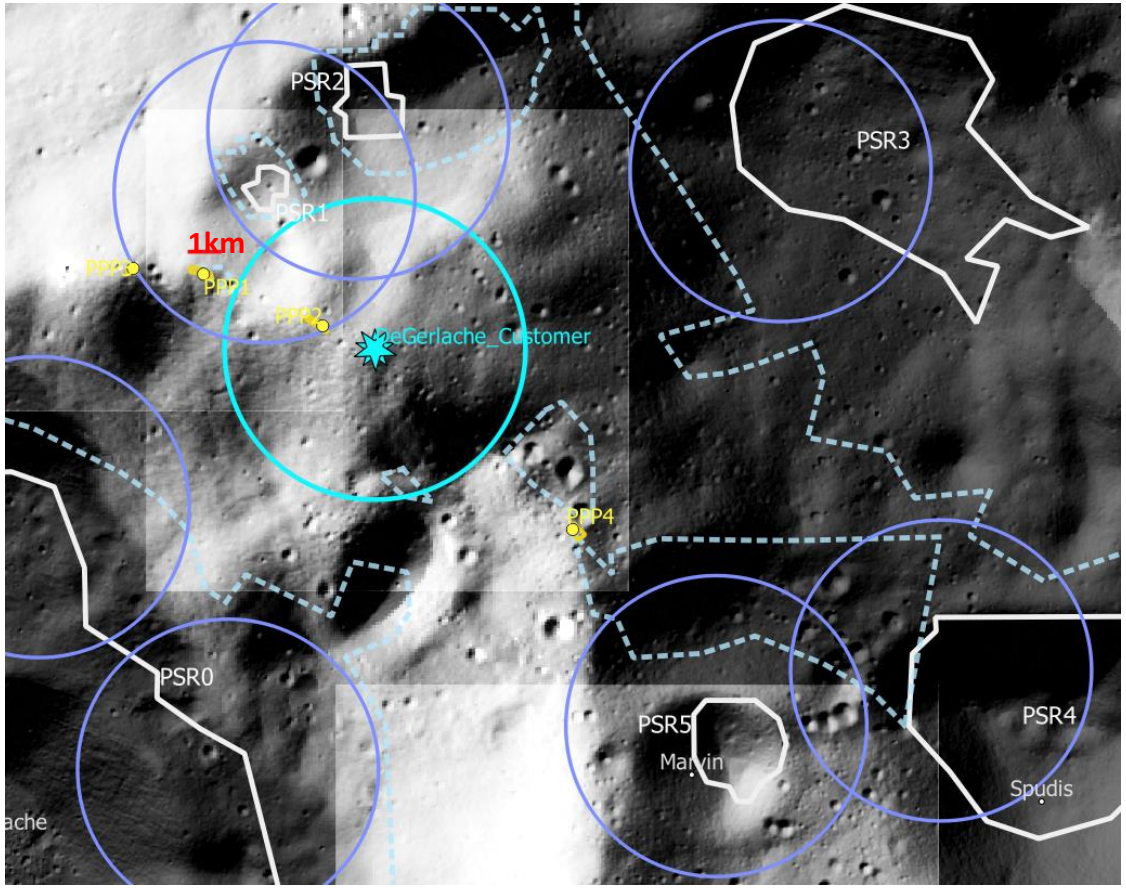
- No path fully meet baseline criteria - All paths exceed proximity requirement (though B only by 200m)
- Option A and B are possible with only an addition 1-2km proximity criteria
- All other options exceed expanded criteria somewhat due to pathfinding around high slopes and all exceed Slope criteria
  - Option C is can be within slope criteria with detailed path finding
  - Option D has Slope exceedances are unlikely to be solved by detailed pathfinding
  - Option E is has high slopes into PSR4 (Marvin), which makes this a poor PSR option (even though rest of path slopes are in bounds)

Data

High Res LOLA Topography DEMs from PGDA: Site 11, SL2, SL3 .
https://pgda.gsfc.nasa.gov/products/78.
PDS data from Polar Stereographic GDR, 5mpp, latitude 87.5 deg,
http://imbrium.mit.edu/BROWSE/LOLA_GDR/POLAR/SOUTH_POLE/

011 De Gerlache: Summary

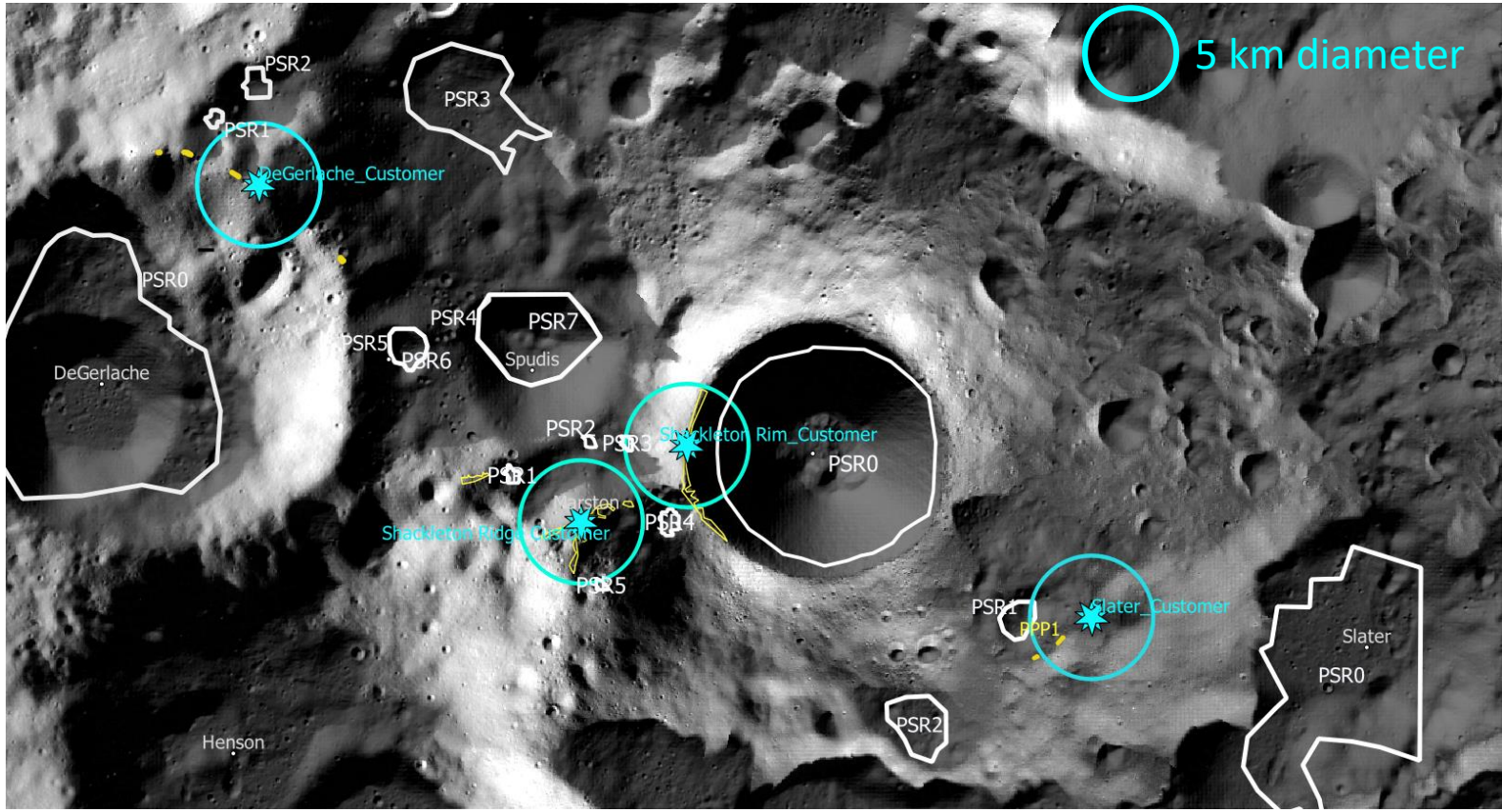
	5km ranges	10km Range	Slope
PSR0 (DeGerlache)	Out of range	PPP options in range	Path exceeds slope but only over 2% of distance, high average slopes
PSR0a (DeGerlache East)	Out of range	No PPP options in range	Paths available
PSR1	PPP options in range, but detail pathfinding needed (exceeds by 0.2km)	PPP options in range	Path for 5km has high average slopes Paths available for 10km
PSR2	PPP options in range	PPP options in range	Not evaluated because of PSR1 is comparable
PSR3	Out of range	No PPP options in range	Options are on Northwest side, would require longer traverses
PSR4 (Spudis)	Out of range	Out of range	No <20deg paths
PSR5 (Marvin)	Out of range	PPP options in radii, but acceptable traverse path exceeds distances (by <5km)	Paths available on far (east) side of crater, but surrounding slopes high



- No options fully meet baseline, but PSR1 has one option that is only 0.2km exceedance
- Larger PSR access requires expanded ground rule requirements: one path option for DeGerlache (PSR0)
- Several ISRs (deeper ice) available in area, some even are along ridge. This would require other ISRU methods to make use of.

Summary

- **001: Shackleton Connecting Ridge**: *Most flexibility: Multiple PPP and PSR options with reasonable slope paths*
  - There are 4 viable PSRs within baseline criteria, though several require expanded distance criteria (by 1-2 km) for traverse pathfinding which is the is a result of the high slopes to get off the connecting ridge to the 'north'. There is one clear best solution which was used in the case study AIAA-2020-4042.
- **004: Shackleton Rim**: *Moderate: a few PSRs, ample PPP along restricted path*
  - The available PSRs are all common with site 001, with the best solution being the same PSR as 001. While plentiful PPP sites are available along the ridge, they are on a restricted path with limited off-ramps.



- **007: Slater:** *'Easier' paths but fewer PSR options*
  - Only one solution meets all baseline criteria, but there are limited alternative options mostly due to distance to/number of PSRs. Slopes in regions are favorable, can come close to meeting a <15deg path criteria. Expanding to 10km per travel leg does not add much value… would need to go to 15km at least for one leg to reach another PSR.
- **011: De Gerlache:** *Difficult slopes, expanded proximity criteria needed*
  - Several PSR options are in the area and quite a few ISRs (some very near PPP locations). However, slopes in the region tend to require longer traverses for pathfinding and generally all PSR paths have relatively high average slopes and would hit 20deg at least for a portion of travel. No options fully meet baseline criteria.