DETERMINING TECHNOLOGY PRIORITIES TO ENHANCE LUNAR SURFACE SCIENCE MISSION PRODUCTIVITY

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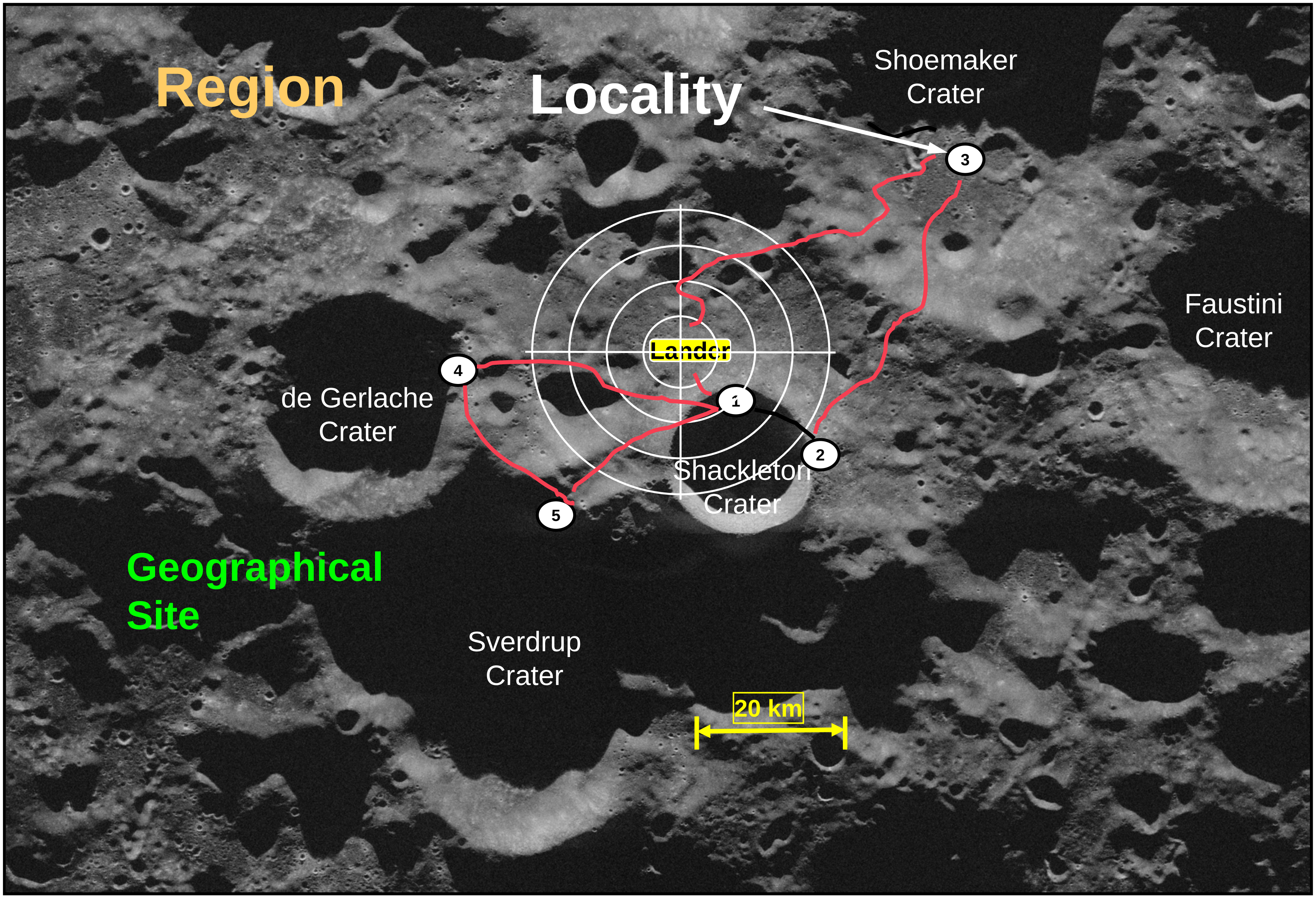
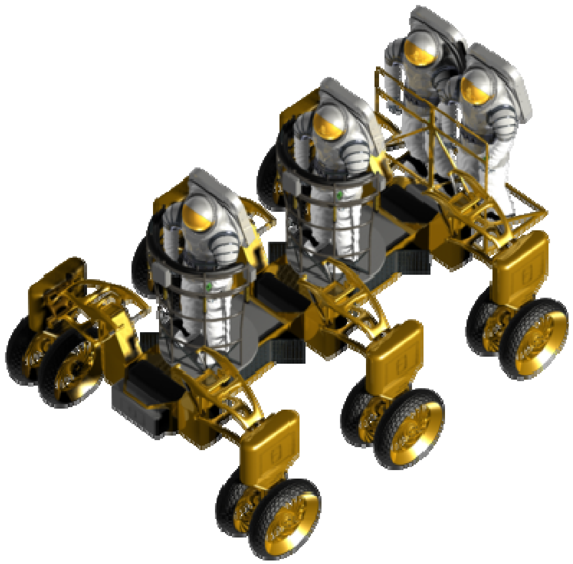
Site Geometry (4 Sites; 5 localities)



Lunar Vehicles



Unpressurized Traverses

Very Apollo-like (i.e., lunar roving vehicle)

Astronauts wear space suits

Limited to local traverses (10-20 km from outpost site) and short periods of time (<8 hours)

Pressurized Traverses

Similar to current undersea exploration (i.e., pressurized submersibles)

Astronauts inside in 'shirt-sleeve' environment

Designed for long-duration traverses (i.e., many tens of km to low hundreds of km), and many days away from an outpost site

Two Scenarios Compared

- Full Goal: Visit 5 Localities and complete 37 science activities at each during 14 day lunar mission.
- Scenario 1: 4 Astronauts with 2 SPRs

  vs

- Scenario 2: 4 Astronauts with 2 UPRs

Key Assumptions

- Science Task Assumptions
  - Astronauts do all Rock, Trench, Regolith and Drive Tube Sampling
  - UPR's / SPR's performing raking, drilling, and rock coring; monitored from the ground or in-situ
  - Assumed all localities have equal importance
- Scenario Assumptions
  - All agents (astronauts and robots) must stay together
  - Astronauts EVA limit = 8 hours/astronaut/day
  - Astronauts awake 16 hours/day
  - UPR/SPR charge limit = 72 hours
    - UPR/SPR and astronauts need 2 days "rest/recharge" period at Habitat/Lander after every 3 days.
  - Traverses include 20% margin for obstacle avoidance; 10 km/hr
  - 8 days * 4 astronauts * 8 hrs/day = potential of 256 total EVA hrs (64 hours per crew member)
  - Review data table on slide 6

Estimated Times for Science Activities

Science Activities	Mission goal (# of samples)	Mass Per Sample (kg)	Astronaut EVA time required (hrs/sample)	Rover time required (hrs/sample)
Rock sampling	35 (25 basalt, 10 breccia)	Basalt: 0.5 Breccia: 5.0	0.39 each sample	n/a
Regolith sampling	35	2	0.39 each sample	n/a
Shallow trench sample	35	1	0.39 each sample	n/a
Drive tube sample	35	0.7	0.39 each sample	n/a
Soil core drilling	5	0.9	n/a	3.9
Rock coring	5	0.5	n/a	2.3
Raking	35	0.5	n/a	0.63
Lunar Environmental Monitoring Station	1	n/a	3.1 hours/2 astronauts	n/a

- **Mission sample collections are spread over scenario localities**
- **Activity times include time to identify and select sample**
- **Activity times include engineering and documentation margins**
- **Global geologic survey subsumes and integrates all the above tasks**
- **EVA time estimates provided by Dean Eppler and Andrew Abercromby**

Recent Additions

- New assumptions for these runs:
  - 25% Documentation margin added to all science activities
  - 25% Engineering margin added to:
    - All science activities
    - All drive times
    - Egress and Ingress times
    - Not added to: Sleep, “unplanned” times, idle times
- Includes deposition of Lunar Environmental Monitoring Station

Estimate of Relative Measurement Priorities
(to be confirmed and tested via sensitivity analysis)

Measurement Type	Relative Priority
Subsurface characterization	**(8)**

Includes drive tube; drill/core tube; trench sample acquisition

Surface sample collection/characterization	**(10)**

Includes site 'outcrop' hand (rock) specimen; site 'Statistical' collection (rake sample); Regolith bag sample; characterization activity - composition (in situ geochemical measurements); physical, electromagnetic properties (in situ geotechnical measurements); visual

Deploy Science Station (local)	**(10)**

Includes Environmental (atmosphere, radiation, particles, fields)

•Subsurface characterization and Surface sample collection/characterization include time for site analyses such as camera/video acquisition; structural analysis; compositional (geochemical); Physical (electromagnetic properties) (geotechnical measurements)

Productivity Definition

Operational Productivity

= Outputs/Inputs

= Benefits/Costs of surface activities

= Value of Activities performed /Cost of completing those activities

= V / C

where

Value, V = Weighted sum of activities completed

Cost, C = Estimated marginal cost of completing the activities

Value Definition

For *N* locations and *M* measurement types:

$$\text{Science Value} = \sum_{i=0}^{N} V_i \cdot w_i$$

$$V_i = \sum_{j=1}^{M} k_j v_{ij} = \text{value of activities at location i}$$

$w_n =$ importance of location i

$v_j =$ fraction of required measurement type j completed at location i

$k_j =$ importance of measurement type j

Cost Definition

$$\mathrm{C}(n) = \alpha \cdot Total\ EVA + \beta \cdot Total\ IVA \quad + \gamma \cdot Total\ IVR_{Local} + \varepsilon \cdot Total\ IVR_{Ground}$$

where

$C(n) =$ Total estimated operations cost for agents to complete task n

Total EVA $=$ Total astronaut work hours of extravehicular activity

Total IVA $=$ Total astronaut work hours of intravehicular activity

Total $\mathrm{IVR}_{\mathrm{Local}}$ $=$ Total robot system operating hours by astronauts

Total $\mathrm{IVR}_{\mathrm{Ground}}$ $=$ Total robot system operating hours by ground personnel

$\alpha, \beta, \gamma, \varepsilon =$ estimated hourly marginal cost weights $(\alpha + \beta + \gamma + \varepsilon = 1)$

e.g., if EVA costs were equal to IVA costs, then $\alpha = \beta$, but cost weights are influenced by a variety of factors…

Cost Definition

- Parametric Values for example

Cost Factor	If no cost difference	Cost weights[a]
α (EVA)	0.25	0.54
β (IVA)	0.25	0.14
γ (IVR_{Local})	0.25	0.15
ε (IVR_{Ground})	0.25	0.17[b]

[a] Derived from Space Station marginal cost estimates, 1990 escalated to 2007 dollars: MRC/Doane, L., “Standard Resource Marginal Costs, Version 90-1 (September 14, 1990)," NASA Memorandum MSR (OHM:cs 90-082), September 17, 1990.

[b] assumed 20% > IVR_{Local} due to added infrastructure (communications) and ground team costs.

HURON Optimization

Maximize {Completion of all required activities}

Maximize {Productivity of sites and activities selected}

Subject to:

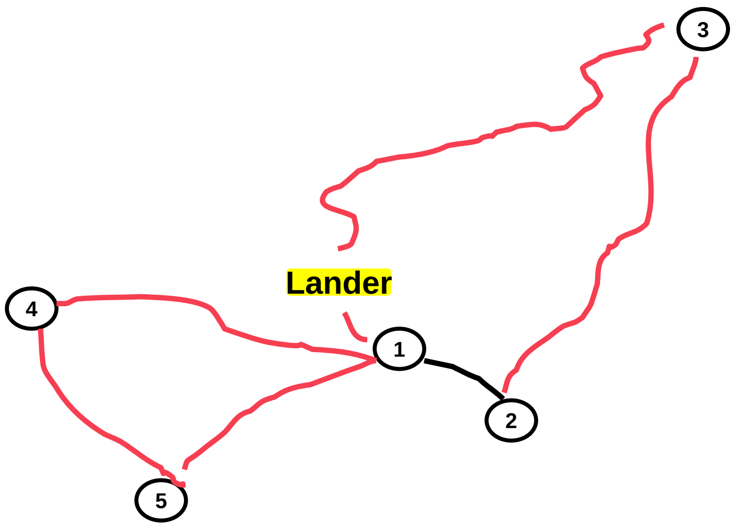
EVA and Vehicle performance specifications

Maximum EVA per day = 8 hours

End state = all astronauts in habitat module

Two Cases

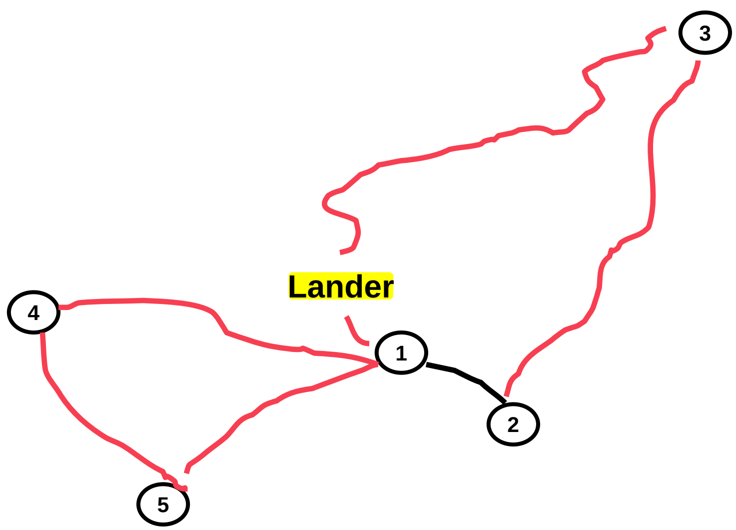
- I: 4A 2SPR (The “SPR case”)
- II: 4A 2UPR (The “UPR case”)



- Upfront Conclusions:
  - The elements in the UPR case do not visit localities 3, 4 and 5.
    - Also, unable to complete certain activities at locality 2
  - The elements in the SPR case are able to visit all localities and complete all science activities

Two Cases – Schedule Summaries

- SPR
  - Travels to locality 1, then 2, then returns to lander for 2 day recharge
  - Travels to localities 5, 4 then 3 before returning to lander



- UPR
  - UPR team completes ~1/2 tasks at locality 1 in 1 day
  - Next day finishes locality 1
  - Locality 2, team able to do 2 of 7 collection sites in 1 day, but there after only has time to complete 1 collection site per day due to EVA limit

Summary Results: UPR x SPR

	UPR		SPR	
		Comments		Comments
Number activity sites visited	**14**	**Locality 2: Drill core, rock core, and 1 rake could not be completed**	**35**	**All 5 localities at all 4 geographical sites**
Mass samples collected (kg)	84	Not enough mass to require triage	215	May require triage if mass exceeds
Vehicle distance traveled (km)	707	Many commutes to and from the lander	497	Round trip w/ only 1 pit stop at lander
Total time required for mission completion	15 days, 8 hrs	Includes three 2-day rest periods. Including 1 Day set up and 1 day tear down > 14 day limit	8 days, 5 hrs	Includes 2-day rest period. No “filler” work. Includes 1 day set up and 1 day tear down
EVA time (hrs.)	218	All time with UPR is EVA, including driving	81	Only time spent doing science.
Relative Mission Productivity	1.86	8 hour/day EVA limits the UPR from reaching the 3 furthest localities. Valuable EVA time spent driving	11.4	Completes all science tasks at all localities with only one pit stop at the lander

Potential Next Steps

- Additions to Current Scenario
  - New Experiments (from Moses Lake Trials)
    - Microscopic Imaging
    - Lidar Imaging
    - Ground Penetrating Radar
  - Astronaut “Free Time” – unplanned exploration
- New Scenarios
  - With Guidance from OSEWG

Range of Changes in Performance Parameters

- Productivity = Value / Cost
  - Productivity is generally not a linear function of performance parameters.

- What Δ performance parameter to use?
  - Method 1:
    - Use fixed percent change for ranking based on impact separate from the cost to achieve improved performance.
  - Method 2:
    - Delta from State of Art (SOA) performance level.
    - Threshold or goal performance from project plans.

$$\text{Impact} = \frac{\Delta \text{ productivity / productivity}}{\Delta \text{ performance parameter / performance parameter}}$$

Impacts for two cases

Activity Name	Agent Type	Units	Nominal Value	Impact in two UPR case	Impact in two SPR case
Drive UPR	eva astronaut	km/hr	10	100.0	n/a
Drive SPR	astronaut	km/hr	10	n/a	100.0
DriveTube	eva astronaut	hr	0.25	6.7	72.2
Regolith	eva astronaut	hr	0.25	6.7	72.2
Rock	eva astronaut	hr	0.25	6.7	72.2
Trench	eva astronaut	hr	0.25	6.7	72.2
Rake	teleop	hr	0.4	4.6	49.0
DrillCore	teleop	hr	2.5	4.0	43.2
RockCore	teleop	hr	1.5	2.4	25.2
DrillCore	eva astronaut	hr	1.75	n/a	n/a
DriveTube	teleop	hr	0.4	n/a	n/a
Rake	eva astronaut	hr	0.25	n/a	n/a
Regolith	teleop	hr	0.3	n/a	n/a
Rock	teleop	hr	0.75	n/a	n/a
RockCore	eva astronaut	hr	1	n/a	n/a
Trench	teleop	hr	0.6	n/a	n/a

- In UPR case the increased task times caused increase in driving's impact because of the need for more round trips.
- In the SPR case the increased task times caused their relative impact to approach driving's impact.
- Used 10% improvement in parameter performance.

✓ One decimal place for impact columns.

✓ Yellow rows do not have impact because analysis precluded those agents performing those activities in the scenarios included.

Illustrative Capabilities Not Currently Under Development ?

- Geological context survey metrics
  - Number of sources for data fusion, percent reduction in logging time
- Instrument packages for triage of collected samples
  - Mass of instrument; specificity of geochemical interest for return
- Robotic sample acquisition and handling metrics
  - Pickup specified rocks of potentially arbitrary shape within available timeline

Application of HURON Might Assist Constellation in Planning Lunar Surface System Development and Operations

Our planning software approach is **independent of the specific problem being solved**

• The software **gives the user freedom to specify agents, actions, resources, parameters, constraints, start and goal states, and the objective function to be optimized**

•This methodology can be applied to **different mission architectures from the point of view of mission efficiency**

• The system description used (agents, resources, actions, start/goal states, etc.) corresponds to **-level behavioral mission model**. This means that our approach can also be applied to **mission/technology planning**

Applications have already provided interesting observations and quantification.