Low-Latency Teleoperations for Human Exploration & Evolvable Mars Campaign

** Notional analysis – does not reflect NASA approved missions*

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Overview

- Key areas for feedback
- Low-Latency Teleops (LLT) Goals & Objectives
- Mission / Task Concepts
  - Human-Assisted Sample Return
  - LLT In-situ Resource Utilization (ISRU) & Maintenance tasks
  - Mars System LLT
- Preliminary Implications & Summary

Summary of Ops Areas for Feedback

1. **Crew Ops**: Can small crew execute LLT activities effectively and efficiently?
2. **Time:** How do we reduce time and other resources needed for LLT activities?
3. **Reconnaissance**: Pre- and post-landing site recon requirements, including sub-surface.
4. **Assets**: Will we have surface assets available to conduct LLT tasks properly"?
5. **Cross-contamination**: How do we address contamination from one area to another?
6. **Life-detection**: If we find life via LLT from orbit and/or while on surface, what then?
7. **ISS Testing**: LLT science? How do we increase ops testing fidelity?
8. **Lunar Testing**: LLT PP activities at the Moon? E.g. return sample from far side?
9. **Environmental Impacts**: Assess broader environmental impact considerations
10. **Mars orbit "campaign"**: Multiple Mars orbit missions before landing crew?
11. …

Potential Objectives & Activities: Telerobotics - General

TG.1 Test basic LLT operation

TG.1.1 Assess Human factors

TG.1.2 Measure overall system performance

TG.2 Test LLT communication and data infrastructure

TG.2.1 Test interfaces

TG.3 Test/Demonstrate LLT maintenance and repair of assets

TG.3.1 Conduct LLT maintenance and repair tasks on in-space systems

TG.3.2 Conduct LLT maintenance and repair tasks on lunar surface system

TG.4 Demonstrate ops coordination between EVA crew, IVA LLT crew, and ground control team

TG.4.1 Conduct scenarios with significant participation from EVA crew, IVA crew, and ground control team

TG.5 Demonstrate parallel, high-latency telerobotics for public outreach and "participatory exploration"

Potential Objectives & Activities: Lunar

L.TSR.1 Explore lunar surface via LLT (emphasis on lunar farside and poles)
- L.TSR.1.1 Teleoperate surface mobility system with TBD range from lunar vicinity (e.g. LDRO or L2)
- L.TSR.1.2 Analyze samples in-situ on lunar surface

L.TSR.2 Collect lunar surface samples via LLT
- L.TSR.2.1 Acquire samples of TBD type from TBD location(s) and TBD depth
- L.TSR.2.2 Collect and store samples to prevent sample contamination, demonstrating systems needed for sample containment in Mars Sample Return missions
- L.TSR.2.3 Store sample cache in ascent vehicle

L.SR.3 Return lunar samples to crew vehicle(s) and back to earth
- L.SR.3.1 Launch sample cache to rendezvous location (e.g. lunar orbit, L2)
- L.SR.3.2 Maintain environment for sample cache, demonstrating systems needed for sample containment in Mars Sample Return missions
- L.SR.3.3 Rendezvous with crew vehicle (TBD level of autonomy, passive/active, etc.)
- L.SR.3.4 Transfer sample cache to crew vehicle
- L.SR.3.5 Return sample cache to Earth with crew

L.SR.4 Perform TBD sample analysis with crew – STRETCH OBJECTIVE TBD

L.T.5 Test/Demonstrate LLT lunar ISRU prospecting and operations – STRETCH OBJ
- L.T.5.1 Teleoperate mobile lunar asset to prospect for key resources such as water
- L.T.5.2 Teleoperate mobile lunar ISRU asset to test ISRU device operations and product generation

Potential Objectives & Activities: Asteroid

A.T.1 Test/Demonstrate LLT micro-g proximity operations at asteroid

- A.T.1.1 Explore high risk sites via LLT "stand off" ops
- A.T.1.2 Conduct LLT science investigations
- A.T.1.3 Conduct high-resolution LLT survey and compare with autonomous/robotic and/or ground-controlled operations

A.T.2 Test/Demonstrate LLT micro-g sample acquisition at asteroid

- A.T.2.1 Return asteroid samples to crew vehicle(s) and back to earth, demonstrating systems needed for sample containment in Mars Sample Return missions

A.T.3 Perform TBD sample analysis with crew – STRETCH OBJECTIVE

A.T.4 Test/Demonstrate LLT asteroid ISRU operations – STRETCH OBJECTIVE

- A.T.4.1 Test/Demonstrate LLT asteroid ISRU prospecting for key resources such as water
- A.T.4.2 Test/Demonstrate LLT asteroid ISRU device and generate product

A.T.5 Test/demonstrate LLT deployment of planetary defense related assets – STRETCH OBJECTIVE

A.T.6 Conduct LLT deployment of services and/or infrastructure to support TBD asteroid exploration and utilization – STRETCH OBJECTIVE

- A.T.6.1 Deploy surface navigation assets

Potential Objectives & Activities: Mars

M.SR.1 Return Mars sample safely to Earth

M.SR.1.1 Transfer Mars sample to translunar asset (e.g. Orion or EAM)
M.SR.1.2 Ensure/verify sample containment is safe for earth return
M.SR.1.3 Return Mars sample from TBD translunar location to Earth with crew

M.SR.2 Perform basic TBD analysis on Mars sample prior to earth return – STRETCH OBJECTIVE - TBD

M.T.3 Perform LLT from Mars Orbit to Mars Surface

Details under development…

M.T.4 Perform LLT from Mars Surface to another remote Mars Surface location

Details under development…

Objectives, Activities, Success Criteria Traceability

NASA Goals & Objectives

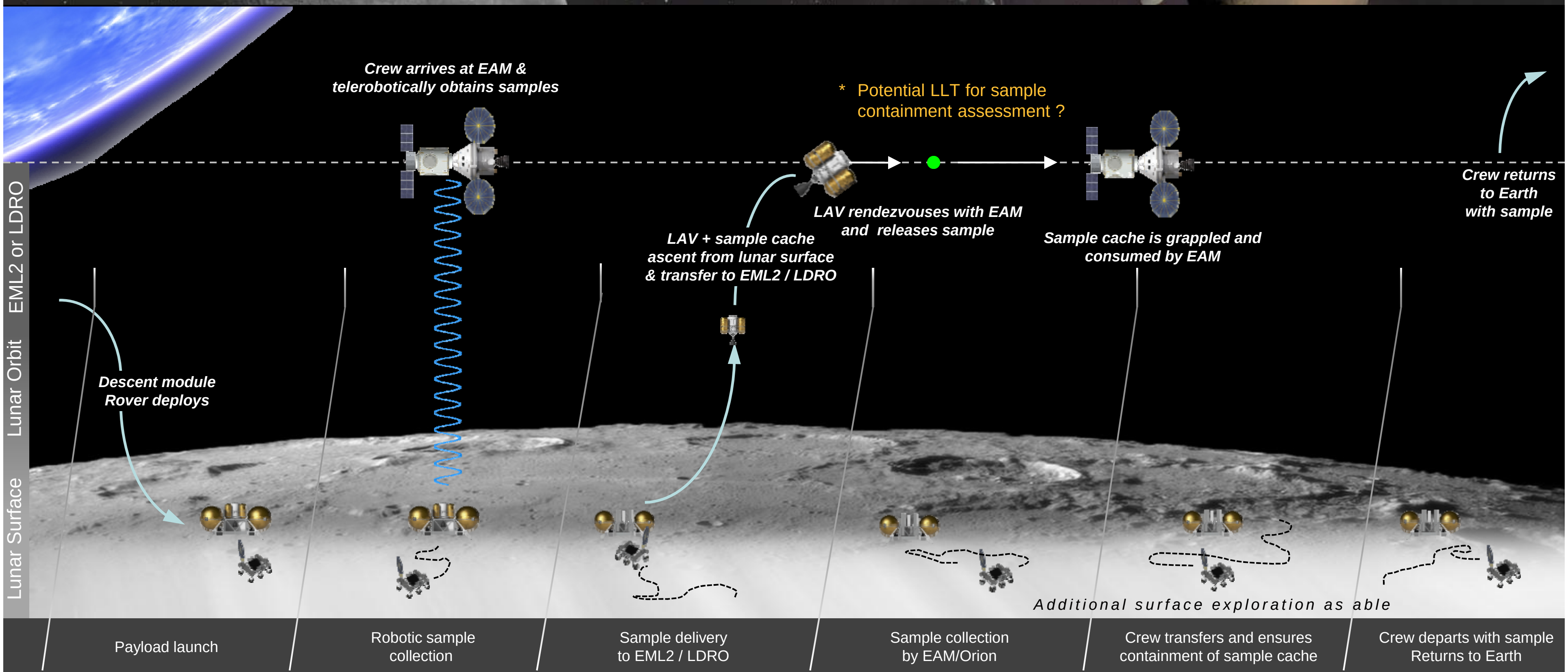
Mission Objectives, Activities, Success Criteria

Area	Goal ID	Goals	Objective ID	Program Objectives	SKGs	Obj ID	High Level Mission Objectives	Translunar Activities	Success Criteria
	G1	Expand Human Presence	G1.1	Explore new destinations			L.TSR.1 Explore lunar surface via LLT (emphasis on lunar farside and poles) L.TSR.2 Collect lunar surface samples via LLT L.SR.3 Return lunar samples to crew vehicle(s) and back to earth L.SR.4 Perform TBD sample analysis with crew – STRETCH OBJECTIVE	L.TSR.1.1 Teleoperate surface mobility system with TBD range from lunar orbit (e.g. LDRO) or L2 L.TSR.1.2 Analyze samples in-situ on lunar surface L.TSR.2.1 Acquire samples of TBD type from TBD location(s) and TBD depth L.TSR.2.2 Collect and store samples to prevent sample contamination L.TSR.2.3 Store sample cache in ascent vehicle L.SR.3.1 Launch sample cache to rendezvous location (e.g. lunar orbit, L2) L.SR.3.2 Maintain environment for sample cache L.SR.3.3 Rendezvous with crew vehicle (TBD level of autonomy, passive/active, etc.) L.SR.3.4 Transfer sample cache to crew vehicle L.SR.3.5 Return sample cache to Earth with crew Simulate anticipated Mars teleoperations on ISS and at Moon	L.TSR.1.1 Cover TBD area/ range L.TSR.1.2 Obtain quality samples via TBD measurments and analysis L.TSR.2.1 Obtain 75% of TBD desired type and quanitity of samples L.TSR.2.2 Sample integrity is preserve during collection process. L.SR.3 Successful launch of sample to orbit and return to earth with negible sample enviornment degradation and containment breaches.
							A.T.1 Test/Demonstrate LLT micro-g proximity operations at asteroid A.T.2 Test/Demonstrate LLT micro-g sample acquisition at asteroid A.T.3 Perform TBD sample analysis with crew – STRETCH OBJECTIVE	A.T.1.1 Explore high risk sites via LLT "stand off" ops A.T.1.2 Conduct LLT science investigations A.T.1.3 Conduct high-resolution LLT survey and compare with autonomous/robotic and/or ground-controlled operations A.T.2.1 Return asteroid samples to crew vehicle(s) and back to earth Simulate anticipated Mars teleoperations on ISS and at Moon	A.T.1.1 Throughly characterize high risk site and avoid hazardous events for crew A.T.1.2 Collect TBD samples of TBD kind A.T.1.3 Obtain data on the differences of the various operations modes and learn optimal approaches A.T.2.1 Rreturn sample to earth with minimal sample enviornment degradation and no containment breaches.
							M.SR.1 Acquire Mars sample(s) and return safely to Earth M.SR.2 Perform basic TBD analysis on Mars sample prior to earth return – STRETCH OBJECTIVE	M.SR.1.1 Transfer Mars sample to translunar asset (e.g. Orion or EAM) M.SR.1.2 Ensure/verify sample containment is safe for earth return M.SR.1.3 Return Mars sample from TBD translunar location to Earth with crew Simulate anticipated Mars teleoperations on ISS and at Moon	M.SR.1 Return TBD amount of preserved and partially analyzed uncontaminated sample to earth
			G1.2	Lengthen human duration in space					
			G1.3	Expand the quantity of humans in space					
			G1.4	Increase the self-sufficiency of humans in space			LT.5 Test/Demonstrate LLT lunar ISRU prospecting and operations - STRETCH OBJECTIVE A.T.4 Test/Demonstrate LLT asteroid ISRU operations – STRETCH OBJECTIVE A.T.6 Conduct LLT deployment of services and/or infrastructure to support TBD asteroid exploration and utilization – STRETCH OBJECTIVE	LT.5.1 Teleoperate mobile lunar asset to prospect for key resources such as water LT.5.2 Teleoperate mobile lunar ISRU asset to test ISRU device operations and product generation A.T.4.1 Test/Demonstrate LLT asteroid ISRU prospecting for key resources such as water A.T.4.2 Test/Demonstrate LLT asteroid ISRU device and generate product A.T.6 Conduct LLT deployment of services and/or infrastructure to support TBD asteroid exploration and utilization	LT.5.1 Demonstrate LLT for mobile lunar asset over TBD area to find key resources such as water LT.5.2 Demonstrate LLT for ISRU device and generate a test resource product A.T.4.1 Demonstrate LLT asteroid ISRU prospecting for key resources such as water A.T.4.2 Demonstrate LLT asteroid ISRU device and generate test product A.T.6 Use LLT to deploy a testable asset for asteroid-related activities (e.g. a navigation device)

Mars Pulls for Lunar Human Assisted Sample Return

- Telerobotic mobility range for landing site recon and prep and/or sampling
- Telerobotic sample acquisition and analysis on surface. Need better understanding of LLT ops and LLT science ops (e.g. difficulty and time of tasks, “science cognition loop”, etc.)
- Mars sample acquisition from cis-lunar space
- Mars sample acquisition from Mars orbit
- Sample containment, including verification methods, time needed, etc.
- Contamination control & planetary protection

Lunar Human-Assisted Sample Return Lunar Vicinity Ops Con: Passive Exploration Augmentation Module (EAM)



Mission Summary

- Total mission duration ~ 60 daysAfter landing at the South Pole/Aitken Basin, the rover is deployed
- The rover identifies, collects, and stores a sample (semi-autonomously or via tele-operations)
- Sample cache transferred to Lunar Ascent Vehicle (LAV)
- The LAV delivers sample canister to EML2 (Earth-Moon Libration Point 2) or LDRO (Lunar Distant Retrograde Orbit) and rendezvouses with EAM
- LAV releases passive sample cache
- The sample cache is grappled by EAM and placed in sample airlock
- Sample stored in Orion and returned to Earth with crew

Elements

- Payloads:
  - Descent and ascent modules, rover, sample canister
- Orion + Crew
- EAM

Mission Value

- South Pole/Aitken Basin sample addresses HEOMD Goals & Strategic Knowledge Gaps (SKGs)
- Low-latency telerobotic sample acquisition enables Mars forward activities such as Phobos mission and Mars surface missions.
- Planetary Protection feeds forward to Mars missions
- Sample analysis capabilities may also feed forward to Mars missions - TBD

Surface Teleoperations Ops Con

	2 hrs	2 hrs	2 hrs	2 hrs
Day 11	System Checkout			
Day 12	Drive to Site 1	Analyze Environ.	Drill and Collect Sample	
Day 13	Drill and Collect Sample			
Day 14	Analyze Sample			
Day 15	Drive to Site 2	Analyze Environ.	Drill and Collect Sample	
Day 16	Drill and Collect Sample			
Day 17	Analyze Sample			
Day 18	LLT Maintenance			
Day 19	LLT Maintenance			
Day 20	LLT Maintenance			
Day 21	Drive to Site 3	Analyze Environ.	Drill and Collect Sample	
Day 22	Drill and Collect Sample			
Day 23	Analyze Sample			
Day 24	Drive to Site 4	Analyze Environ.	Drill and Collect Sample	
Day 25	Drill and Collect Sample			
Day 26	Analyze Sample			
Day 27	Store Sample			
Day 28	Drive to ISRU plant	Transfer Sample to ISRU plant		
Day 29	Transfer Sample to ISRU plant			
Day 30	ISRU Demonstration			
Day 31	ISRU Demonstration			
Day 32	ISRU Demonstration			
Day 33	Transfer ISRU products to LAV			
Day 34	LAV Ascent Checkout			

Assumptions:

2.5 km/hr drive speed

5 km x 5 km search area

4 sites visited

12 hrs to drill and collect sample

8 hrs to analyze sample

3 days of LLT maintenance

3 days for ISRU production

Descope Options:

Reduce number of sites

Eliminate sample return

Eliminate ISRU demonstration

Eliminate LLT maintenance

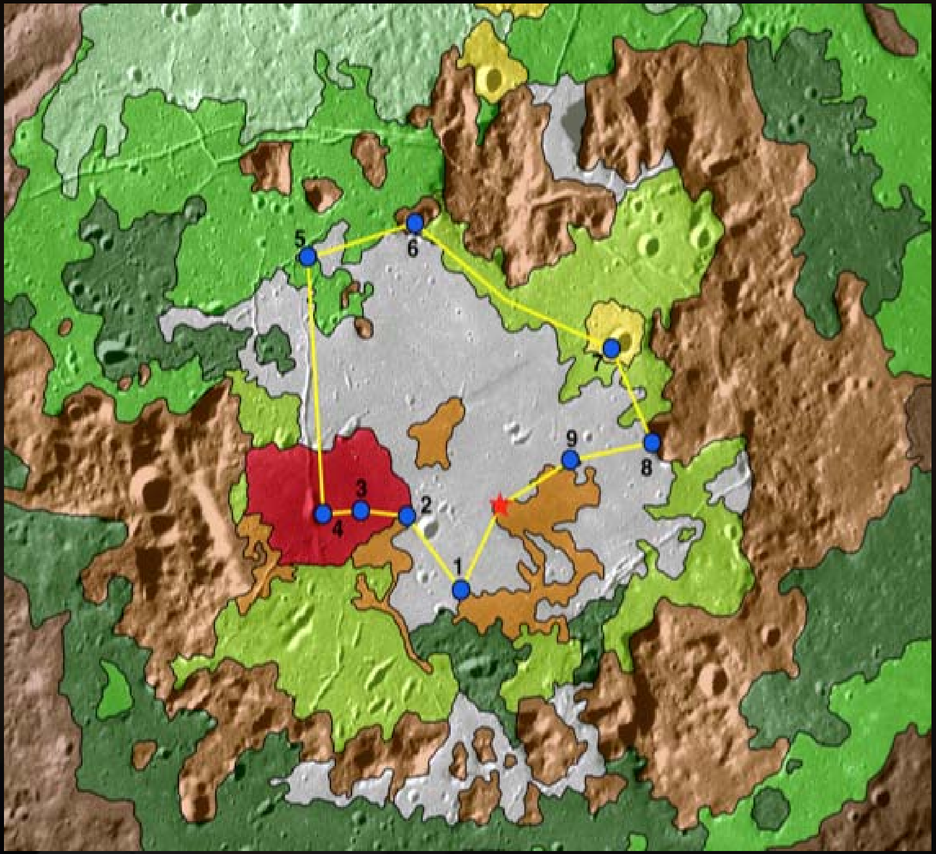
Mission Phase	Days
Transfer to EML2/LDRO	9
Arrival Operations	1
EAM Teleoperations	24
LAV Transfer from surface	4
Sample Collection in EAM	1
Sample Containment Analysis	3
Other EAM Operations	5
Sample Transfer to Orion	1
Departure Operations	1
Transfer to Earth	11
Total	60
Total in EAM	39
Total in Orion	21

Color Code:

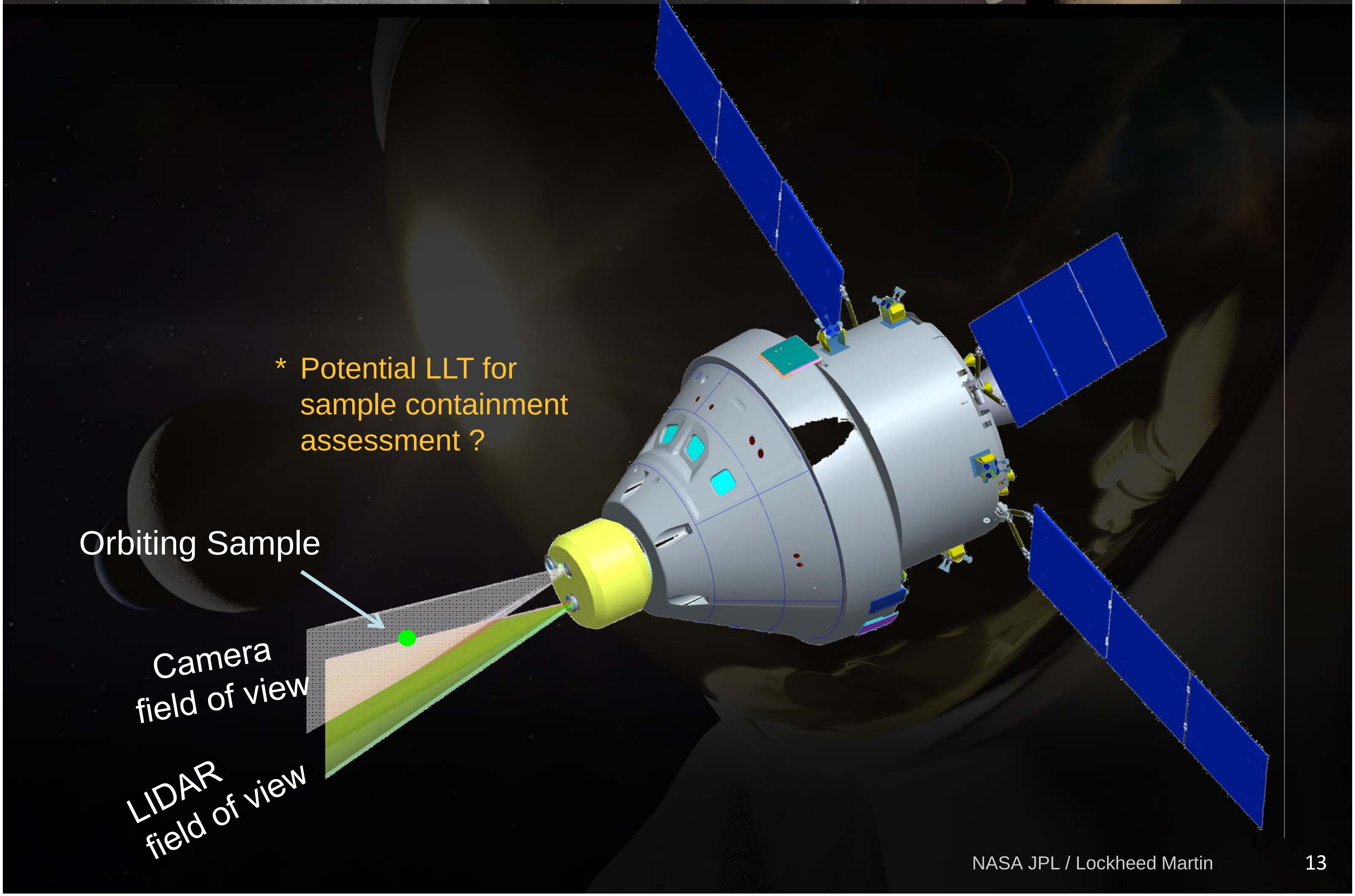
Sample Handling
Driving
Vehicle/System Ops
Analyze Environment

Schrödinger basin traverse

Site Number	Description	Distance (km)
Landing Site (red star)	Located on contact between upper smooth plains (very light green; mare or impact melt) and dark plains units (orange; young mare).	
Stop 1:	Contact between upper smooth plains and dark plains unit.	**22**
Stop 2:	Contact between upper smooth plains, dark plains unit along fissure, and edge of dark mantle deposit (red), interpreted to be pyroclastic deposit.	**22**
Stop 3:	Dark mantle deposit midway between contact and source vent; could attempt to dig into subsurface to estimate thickness of deposit and look at history of eruptive events.	**12**
Stop 4:	Source vent for dark mantle material.	**10**
Stop 5;	Contact between hummocky plains (medium green; early-stage impact melt) and upper smooth plains. This leg of the traverse follows a fracture in the plains, which could allow for a few quick stops for sampling or pictures.	**53**
Stop 6:	Exposure of peak ring material (brown; lower crustal material brought to the surface during the Schrödinger impact event) showing possible exposures of olivine-bearing material.	**28**
Stop 7:	Rim and ejecta blanket (yellow) of impact crater; will contain material excavated from subsurface, including upper and lower smooth plains materials (very light and light green, respectively; late-stage impact melt or older mare).	**54**
Stop 8:	Contact between upper smooth plains and peak ring showing possible exposures of anorthosite.	**22**
Stop 9:	Contact between upper smooth plains and dark plains unit.	**23**
Back to Landing Site.		**18**



Sample Capture with Orion



Human-Assisted Sample Return Comparisons

* Assessments assume Schrodinger crater as lunar surface location and redirected asteroid brought to LDRO

Configuration		From Earth	Orion Only		Orion + EAM	
Location		N/A	LDRO	EM L2	LDRO	EM L2
COMMUNICATIONS w/ Assets at Schrodinger location (RTE=Relay to Earth; RTS=Relay to Schrodinger)						
Bandwidth (Mbps)		8 Mbps	<1, but can still do mission		Large potential: large dish, optical, etc.	
Coverage with *n* Relays (%). (* Relays not needed at EM-L2 for Schrodinger crater coverage)	0	0 %	10%	98%	10%	98%
	1	89%$_{RTE}$ 70%$_{RTS}$	70%	98%	70%	98%
	2	96%$_{RTE}$ /97%$_{RTS}$	92%	98%	92%	98%
Latency (sec., two way comm)		~ 2 – 2.5	~.5 - 1	~.5	~ .5 - 1	~.5
IN-SPACE SAMPLE CAPTURE/ACQUISITION						
Crew Exposure to Sample Cont.		–			Better isolate from crew?	
Available Capture Time		–	~ 1-2 days	~ 1-2 days	10 days	
ACS (Attitude Control System)		–	Already has	Already has	ARV/Orion	EAM need if separates from Orion
Augmented Capture		–	Limited capability	Limited capability	Added capability	Added capability
Sample containment assessment		–	Limited capability	Limited capability	Added capability	Added capability
Propulsion		–	Already has	Already has		EAM would need if separates from Orion
SURFACE OPS						
Teleops Time			5-10 days		~ 14 days	~ 25 days
Teleops efficiency			Orion capabilities limited (e.g. comm)			
FEED FORWARD						
Asteroid (e.g. ARM alignment)						
Moon						
Mars (e.g. PP, Mars orbital mission)					Closer to Mars orbital mission than L2?	
COST					1 comm aset	Add Prop Go direct

Possible Telerobotics Maintenance Tasks

Tasks / Approach:	Autono-mous	HLT	MLT	LLT	Co-EVA	Crew as B/U
Electrical power system (EPS) battery replacement				✓		✓
EPS solar panel cleaning (esp. at remote locations)	✓	✓	✓	✓	✓	✓
ISRU resource acquisition system refurbishment				✓	✓	✓
ISRU processing system servicing/refurbishment				✓	✓	✓
Reconnaissance/sampling rover sample offload	✓	✓	✓	✓		✓
Co-robotic refurbishment, rescue (e.g, tow-out)				✓	✓	✓
Core sample/collection system refurb/cleaning				✓		✓
Fission power system (FPS) servicing				✓		✓
Prop depot refueling with ISRU products	✓		✓	✓		✓
Hab external logistics stores (e.g., spares, clothing)			✓	✓	✓	✓
Sample return system maintenance	✓	✓	✓	✓	✓	✓
Radiation protection bunker maintenance/contruction			✓	✓	✓	✓
SEP system maintenance/repair (esp. electronics)				✓	✓	✓
SEP or upper stage servicing, top-off	✓		✓	✓		✓
Surface hab maintenance/repair while unoccupied		✓	✓	✓		
Rover battery recharge	✓		✓	✓		✓
Scientific instrument servicing/repair			✓	✓	✓	✓

HLT is high latency: greater than earth-moon distance. MLT is medium latency: between .5 and ~ 3 seconds. LLT is ~ .5 seconds or less.
Co-EVA suggests crew on EVA while conducting activity. Crew as B/U is crew as back-up.

Notional Timeline: LLT Solar-Electric Propulsion Refueling

* Prox ops, docking and undocking not included

(purple)	= Telecommand/telemetry to/from ISRU surface asset (ISRU)
(green)	= Robotic operation of Telerobotic Servicing Robot (TSR)

Shift 1	Time >	15m	30m	45m	1h	15m	30m	45m	2h	15m	30m	45m	3h	15m	30m	45m	4h	15m	30m	45m	5h	15m	30m	45m	6h
	Sub Task	Deactivate power to ARRMV SEP system		Connect common ground line between ARRMV and TSV				Secure ARRMV prop feed valve		Remove and temporarily stow MLI covering ARRMV fill/drain (F/D) valve												Cut ARRMV F/D valve actuation nut (AN) cap and wires			

Shift 1 (cont'd)	Time >	15m	30m	45m	7h	15m	30m	45m	8h	15m	30m	45m	9h	15m	30m	45m	10h	15m	30m	45m	11h	15m	30m	45m	12h
	Sub Task	Cut ARRMV F/D valve AN cap and wires (cont'd)				Remove and stow ARRMV F/D valve AN cap, wires, and seals							Verify PTS fill hose ready & valve closed	Position TSV PTS fill hose at ARRMV F/D interface		Connect PTS fill hose QD to F/D intfc	Perform PTS gas system leak check		Verify hose at vac & gas/fuel system isolation	Prime PTS up to F/D valve AN with xenon	Open PTS Xe outlet valve & balance press.	Open ARRMV F/D valve AN (monitor pressure change)		Open PTS valve and pump Xe into ARRMV tanks (monitor pressure & temperatures)	

Shift 2	Time >	15m	30m	45m	13h	15m	30m	45m	14h	15m	30m	45m	15h	15m	30m	45m	16h	15m	30m	45m	17h	15m	30m	45m	18h
	Sub Task	Continue pumping Xe (monitor pressures and temperatures)																							

Shift 2 (cont'd)	Time >	15m	30m	45m	19h	15m	30m	45m	20h	15m	30m	45m	21h	15m	30m	45m	22h	15m	30m	45m	23h	15m	30m	45m	24h
	Sub Task	Continue pumping Xe (monitor pressures and temperatures)																							

Shift 3	Time >	15m	30m	45m	25h	15m	30m	45m	26h	15m	30m	45m	27h	15m	30m	45m	28h	15m	30m	45m	29h	15m	30m	45m	30h
	Sub Task	Stop Xe pump and close PTS valve	Verify final Xe mass transfer	Close ARRMV F/D valve AN		Verify no external leakage from ARRMV F/D valve		Lower hose press. via tank vent & close valve	Pressu-rize volume b'tween PTS & F/D vlv	Verify no internal leakage from ARRMV F/D valve (monitor pressure)		Demate TSV PTS fill hose QD from ARRMV F/D interface & stow		Visually inspect ARRMV F/D valve	Reinstall ARRMV F/D valve AN seals, cap, and wires							Reinstall MLI over ARRMV F/D valve			

Shift 3 (cont'd)	Time >	15m	30m	45m	31h	15m	30m	45m	32h	15m	30m	45m	33h	15m	30m	45m	34h	15m	30m	45m	35h	15m	30m	45m	36h
	Sub Task	Reinstall MLI over ARRMV F/D valve (cont'd)								Open ARRMV prop feed valve		Disconnect common ground line between ARRMV and TSV				Reactivate power to ARRMV SEP system		Perform ARRMV SEP system functional test							

Timeline Example: ISRU Plant Battery Replacement

Shift 1	Time >	15m	30m	45m	1h	15m	30m	45m	2h	15m	30m	45m	3h	15m	30m	45m	4h	15m	30m	45m	5h	15m	30m	45m	6h
	Sub Task	Disable ISRU battery in/out & heater power	Connect common ground line between ISRU and TSR				Remove and stow MLI from ISRU battery access panel								Remove access panel fasteners				Open battery access panel	Demate battery electrical connectors				Retrieve/connect battery discharge resistors	

Shift 1 (cont'd)	Time >	15m	30m	45m	7h	15m	30m	45m	8h	15m	30m	45m	9h	15m	30m	45m	10h	15m	30m	45m	11h	15m	30m	45m	12h
	Sub Task	Retrieve/connect battery discharge resistors (cont'd)		Discharge battery		Remove discharge resistors and stow				Remove battery mechanical fasteners				Remove original battery and stow		Retrieve/install new battery		Install battery mechanical fasteners				Secure battery fasteners			

Shift 2	Time >	15m	30m	45m	13h	15m	30m	45m	14h	15m	30m	45m	15h	15m	30m	45m	16h	15m	30m	45m	17h	15m	30m	45m	18h
	Sub Task	Mate battery electrical connectors				Secure battery electrical connectors				Close battery access panel	Install battery access panel fasteners						Secure battery access panel fasteners						Reinstall MLI over battery access panel		

Shift 2 (cont'd)	Time >	15m	30m	45m	19h	15m	30m	45m	20h	15m	30m	45m	21h	15m	30m	45m	22h	15m	30m	45m	23h	15m	30m	45m	24h
	Sub Task	Reinstall MLI over battery access panel (cont'd)									Disconnect common ground line and stow				Enable battery in/out & heater power	Begin battery charging and verify voltage		Peform ISRU/battery functional test							

= Telecommand/telemetry to/from ISRU surface asset (ISRU)

= Robotic operation of Telerobotic Servicing Robot (TSR)

Timeline Example: Drill Bit Replacement

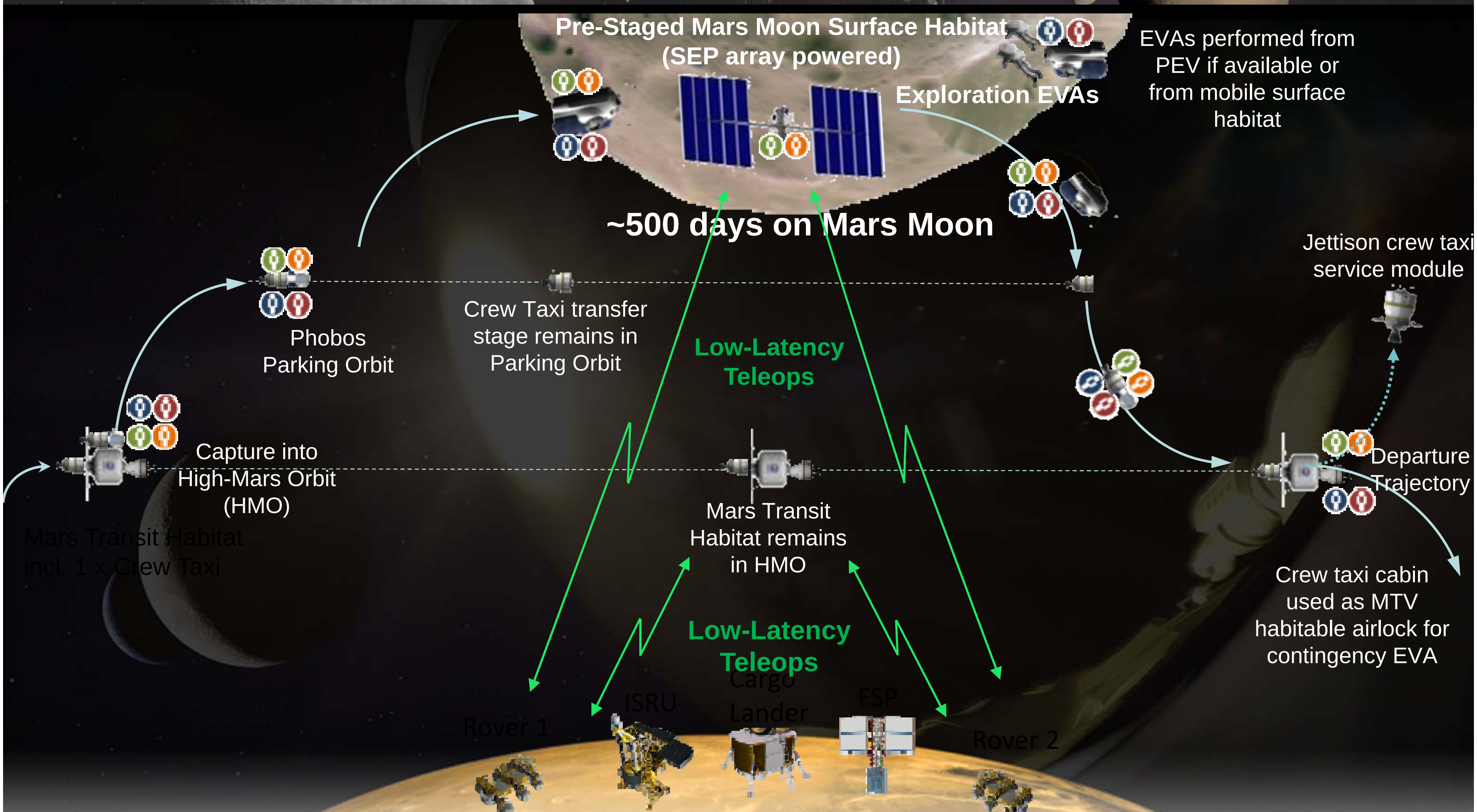
Shift 1	Time >	15m	30m	45m	1h	15m	30m	45m	2h	15m	30m	45m	3h	15m	30m	45m	4h	15m	30m	45m	5h	15m	30m	45m	6h
	Sub Task	Disable ISRU drill system power	Connect common ground line between ISRU and TSR				Position drill head for replacement		Clean drill head/bit (as necessary)		Remove drill bit fasteners and stow				Remove used bit & stow			Retrieve & install new bit				Install bit fasteners & secure			

Shift 1 (cont'd)	Time >	15m	30m	45m	7h	15m	30m	45m	8h	15m	30m	45m	9h	15m	30m	45m
	Sub Task	Reposition drill head for operation		Disconnect and stow ground line				Re-enable system power	Peform ISRU drill functional test							

= Telecommand/telemetry to/from ISRU surface asset (ISRU)

= Robotic operation of Telerobotic Servicing Robot (TSR)

Phobos Mission Concept



Notes:
1. Surface Habitat(s) delivered in advance by SEP.
2. Habitat may be fixed or mobile on Phobos surface.
3. PEV may also be pre-staged by SEP.
4. EVAs performed from PEV (if available) or Mobile Hab

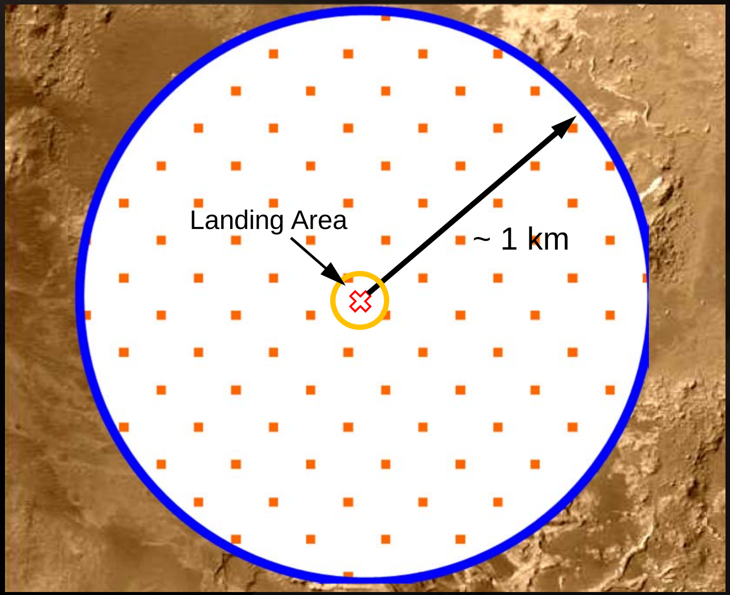
Low-Latency Tele-operation Tasks:
1. Scouting and preparation of landing sites for human landers
2. Deployment, maintenance, repair of ISRU & FSP
3. Demonstration & testing of surface mobility systems
4. Scientific exploration (on Mars surface and Mars Moons)

Low-Latency Teleops (LLT) to Mars Surface from Phobos: Task categorization

1. **Landing site recon**: recon and hazard assessment
2. **Landing site prep**: asset positioning, leveling, site construction,
3. **Offloading**: surface asset/cargo offloading from lander
4. **ISRU**: site recon, operations, MAV fuel, maintenance
5. **Science**: site recon, sample acquisition and analysis

Landing Site Hazard Assessment

- **Assumptions:**
  - Assets ready on surface to support
  - Survey area limited to small radius from planned landing site (e.g., ~ 1 km: TBD for future analysis).
  - Average unencumbered “baseline” rover travel speed ~ 3-5 km/hr (teleoperated – could be significantly improved - TBD)
- **Challenges:**
  - If large number of locations are desired, could be something like 95 sampling locations (if 100 m apart)
  - Drill cleaning and reusability (bit is limited-life item)



**** 1 km assumed for present timelines, but distance and sampling needs are remaining questions***

Notional Landing Site Hazard Assessment Timeline

<table>
<tr><td rowspan="2">Shift 1</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>1h</td><td>15m</td><td>30m</td><td>45m</td><td>2h</td><td>15m</td><td>30m</td><td>45m</td><td>3h</td><td>15m</td><td>30m</td><td>45m</td><td>4h</td><td>15m</td><td>30m</td><td>45m</td><td>5h</td><td>15m</td><td>30m</td><td>45m</td><td>6h</td></tr>
<tr><td>Task</td><td>Relo-cate rover & secure on-station</td><td>Activate survey camera</td><td colspan="2">Perform 360-degree panorama survey (auto)</td><td colspan="10">Proximity surface photo survey</td><td>Deacti-vate survey camera</td><td>Position shovel at selected dig location</td><td>Place rover in standby mode</td><td colspan="7">LOS</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 1 (cont'd)</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>7h</td><td>15m</td><td>30m</td><td>45m</td><td>8h</td><td>15m</td><td>30m</td><td>45m</td><td>9h</td><td>15m</td><td>30m</td><td>45m</td><td>10h</td><td>15m</td><td>30m</td><td>45m</td><td>11h</td><td>15m</td><td>30m</td><td>45m</td><td>12h</td></tr>
<tr><td>Task</td><td colspan="21">LOS</td><td colspan="2">Perform shallow dig</td><td>Place sample into analytic lab</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 2</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>13h</td><td>15m</td><td>30m</td><td>45m</td><td>14h</td><td>15m</td><td>30m</td><td>45m</td><td>15h</td><td>15m</td><td>30m</td><td>45m</td><td>16h</td><td>15m</td><td>30m</td><td>45m</td><td>17h</td><td>15m</td><td>30m</td><td>45m</td><td>18h</td></tr>
<tr><td>Task</td><td colspan="2">Take closeup photos of dig location</td><td colspan="5">Clean shovel for subsequent sample</td><td colspan="5">Deploy vibro-acoustic stimulation and measurement instruments</td><td colspan="2">Generate vibro-acoustic input, measure response</td><td colspan="10">LOS - Auto-analyze surface sample (density, firmness, composition)</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 2 (cont'd)</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>19h</td><td>15m</td><td>30m</td><td>45m</td><td>20h</td><td>15m</td><td>30m</td><td>45m</td><td>21h</td><td>15m</td><td>30m</td><td>45m</td><td>22h</td><td>15m</td><td>30m</td><td>45m</td><td>23h</td><td>15m</td><td>30m</td><td>45m</td><td>24h</td></tr>
<tr><td>Task</td><td colspan="18">LOS - Auto-analyze surface sample (cont'd)</td><td colspan="2">Position drill at sample site</td><td colspan="4">Drill into surface</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 3</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>25h</td><td>15m</td><td>30m</td><td>45m</td><td>26h</td><td>15m</td><td>30m</td><td>45m</td><td>27h</td><td>15m</td><td>30m</td><td>45m</td><td>28h</td><td>15m</td><td>30m</td><td>45m</td><td>29h</td><td>15m</td><td>30m</td><td>45m</td><td>30h</td></tr>
<tr><td>Task</td><td colspan="5">Remove drill and sample</td><td>Place sample into analytic lab</td><td colspan="5">Clean bit for subsequent sample</td><td colspan="13">LOS - Auto-analyze drill sample (density, firmness, composition)</td></tr>
</table>

* Recon details (e.g. specific measurements such as biohazard assessment & number of sample sites) need to be further evaluated. Also need to evaluate implications of larger recon area.

LLT Activity

Loss of Signal

Cargo Offloading from Lander

Offload Item	Mass (kg)	Offload Method	Timeline No.	Duration (hrs)	Latency Sensitivity
Offload Ramp (offload preps) – use is TBD		Crane/hoist	0	18	1
Mobility for Payload Positioning (MoPP)	1000	Self roll-off	1	18	3
Pressurized Rover	5562	Self roll-off	2	18	2
Robotic Rovers (2 ea)	500 x 2	Self roll-off	3	38.25	3
Small Unpressurized Rover (SUpR)	300	Self roll-off	4	14.5	2
Reconfigurable Science Lab	3000	Crane/hoist	5	48	2
Science Payload	1000	Crane/hoist	6	42	2
EVA Suit & PLSS	169	Crane/hoist	7	20.5	3
Sample Return System (SRS)	100	Crane/hoist	8	13.25	3
LEA Suit	26	Crane/hoist	9	20.25	3
Habitat Consumables Pallet (HCP)	Flexible	Crane/hoist	10	13.25	3
Habitat Spares & Logistics Pallet (HSLP)	Flexible	Crane/hoist	11	20.5	3
EVA Logistics Pallet (ELP)	Flexible	Crane/hoist	12	13.25	3
Mobility Spares & Logistics Pallet (MSLP)	Flexible	Crane/hoist	13	20.5	3
Kilopower Portable Utility Pallets (4 + spare)	1500 x 5	Crane/hoist	14	115.5	4

These could be combined into 1 offload (container concept is TBD)

Overall Sequence Duration: 434 hrs
18 dys

Latency/LOS Sensitivity Key
0: No sensitivity
1: Slight sensitivity
2: Low-Medium sensitivity
3: Medium sensitivity
4: Med-high sensitivity
5: High sensitivity

Notional Timeline for Robotic Rovers Offload

Shift 0*

Time > 45 | 30m | 15m | 5h | 45m | 30m | 15m | -4h | 45m | 3(| 15m | -3h | 45m | 30m | 15m | -2h | 45m | 30m | 15m | -1h | 45m | 30m | 15m | 0h

Task: LOS | Open Robotic Rover #1 access panel (close others as req'd) | Remove & stow Robotic Rover #1 fasteners & restraints | te Robotic Rover #1 (verify brakes on)

* "Leftover" shift time from previous timeline, assuming continous operations

Shift 1

Time > 15m | 30m | 45 | 1h | 15m | 30m | 45m | 2h | 15m | 30m | 45m | 3h | 15m | 30m | 45m | 4h | 15m | 30m | 45m | 5h | 15m | 30m | 45m | 6h

Task: vate Robotic Rover 1, verify brakes (cont'd) | e Robotic Rover #1 | LOS

Shift 1 (cont'd)

Time > 15m | 30m | 45m | 7h | 15m | 30m | 45m | 8h | 15m | 30m | 45m | 9h | 15m | 30m | 45m | 10h | 15m | 30m | 45m | 1 | 15m | 30m | 45m | 12h

Task: LOS | Activate Robotic Rover #1 | Perform Robotic Rover #1 short-form functional check | Roll-off Robotic Rover #1 via ramp | Move Robotic Rover #1 to staging/dwell area | De-activate Robotic Rover #1 | Open Robotic Rover #2 access panel (close others as req'd) | ntin-gency/ Wait Time | LOS

Shift 2

Time > 15m | 30m | 45m | 13h | 15m | 30m | 45m | 14h | 15m | 30m | 45m | 15h | 15m | 30m | 45m | 16h | 15m | 30m | 45m | 17h | 15m | 30m | 45m | 18h

Task: LOS

Shift 2 (cont'd)

Time > 15m | 30m | 45m | 19h | 15m | 30m | 45m | 0h | 15m | 30m | 45m | 1h | 15m | 30m | 45m | 22h | 15m | 30m | 45m | 3h | 15m | 30m | 45m | 24h

Task: LOS | Remove & stow Robotic Rover #2 fasteners & restraints | Activate Robotic Rover #2 (verify brakes on) | Perform Robotic Rover #2 short-form functional check | e Robotic Rover #2 | LOS

Shift 3

Time > 15m | 30m | 45m | 5h | 15m | 30m | 45m | 26h | 15m | 30m | 45m | 27h | 15m | 30m | 45m | 28h | 15m | 30m | 45m | 29h | 15m | 30m | 45m | 30h

Task: LOS

Shift 3 (cont'd)

Time > 15m | 30m | 45m | 1h | 15m | 30m | 45m | 2h | 15m

Task: Activate Robotic Rover #2 | Roll-off Robotic Rover #2 via ramp | Move Robotic Rover #2 to staging/dwell area | De-activate Robotic Rover #2

LLT Activity

Contingency Wait Time

Loss of Signal

Mars LLT Task Summary

(to date – many tasks not included – e.g. science)

LLT Sequence	Approx. Duration w/ LOS (days)	Approx. Duration w/out LOS (days)	Latency Sensitivity
1. Landing Site Recon & Hazard Assessment	119	91	2
2. Offloading	18	7	3
3. Power Cable Deploy w/o trenching & burying	5	5	1
4. Power Cable Deploy with trenching & burying	138	53	4
5. O2 Production	2	2	2
6. MAV Fuel	3	1.5	2
TOTAL without burying power cable	147	107 *	
TOTAL w burying power cable	280	155 **	

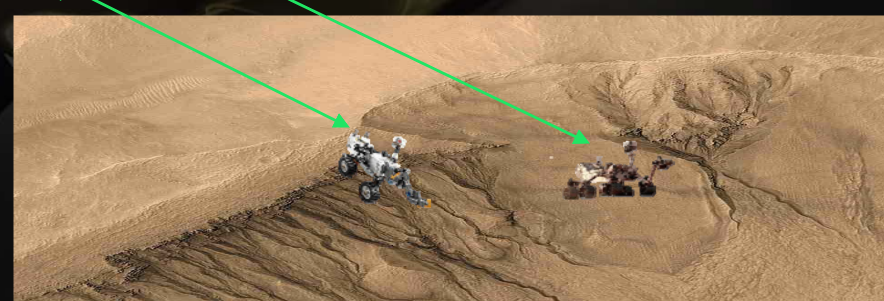
* Indicates ~ 28% less time for LLT ops if continuous comm available – e.g. comm relay(s).
** Indicates cable burying time could be reduced almost by half if continuous comm is available.

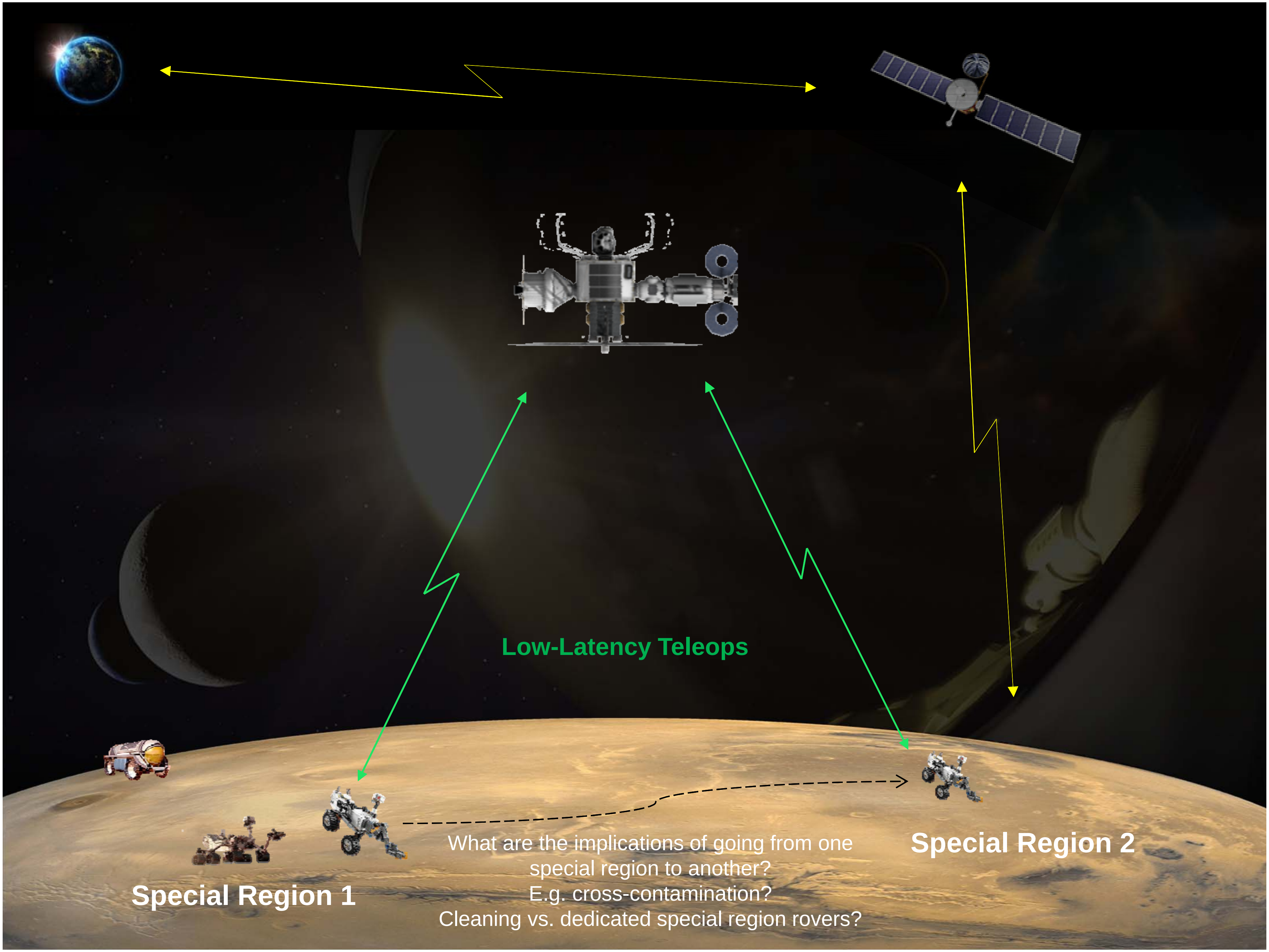
Special Regions Teleops & Potential Sample Return from Mars Moons, Mars Orbit

LLT from Mars moons and Mars orbit to Mars surface can be used to find and operate within special regions on Mars surface.

- Partially address environmental, contamination and planetary protection concerns until it is thought to be safe to land crew.
- Practice for doing LLT special region exploration when crew is on surface.

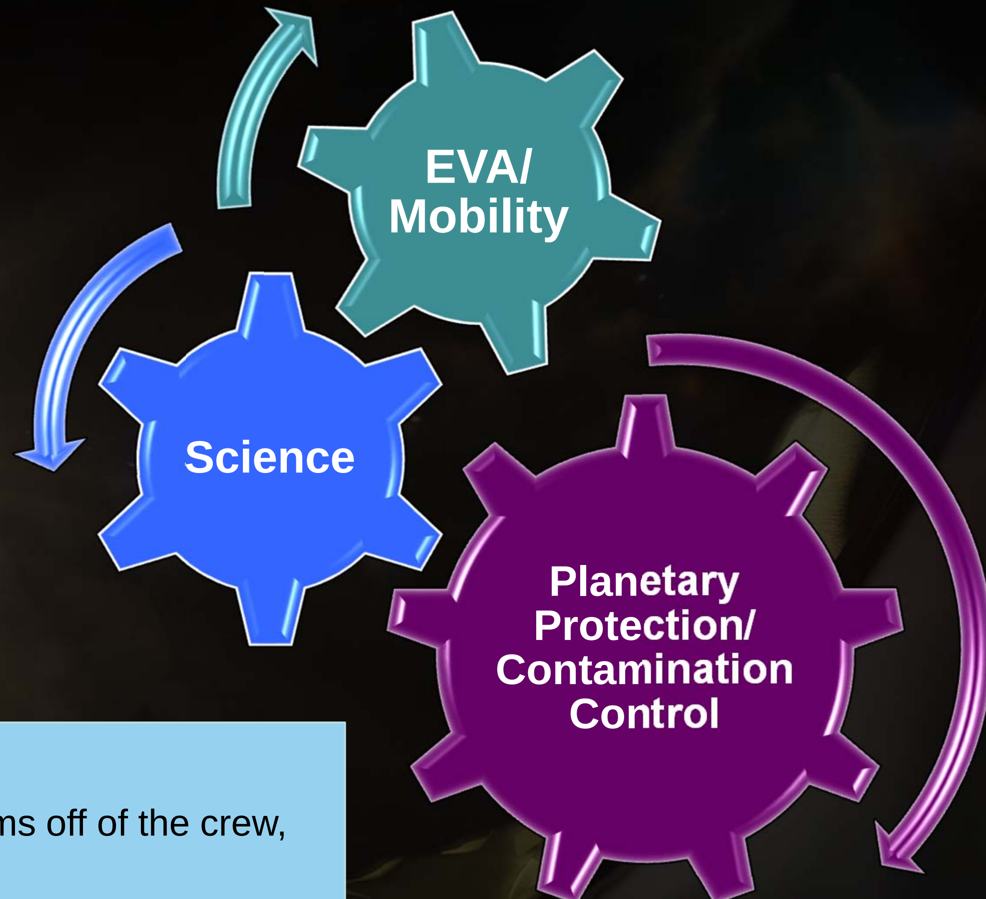
Special Region




Low-Latency Teleops
Special Region 1
Special Region 2
What are the implications of going from one
special region to another?
E.g. cross-contamination?
Cleaning vs. dedicated special region rovers?

Planetary Protection Influences Functional Decomposition & Con Ops

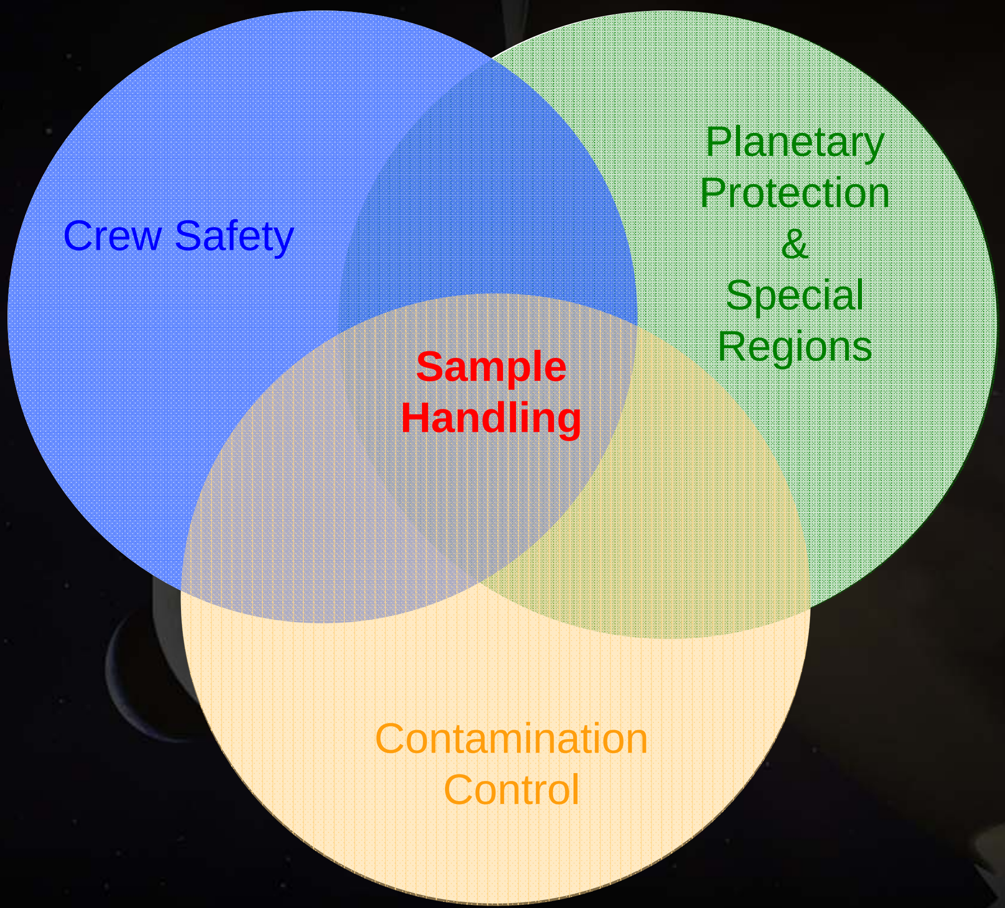
- Can only take Functional Decomposition so far without knowing more about Planetary Protection-Crew Safety-Contamination Control ops con
  - Impacts *how* we do Science
  - Which in turn impacts our EVA and Mobility Strategies and architectures
  - All of which impacts Habitat design and drives overall mission mass



Three related but distinct issues:

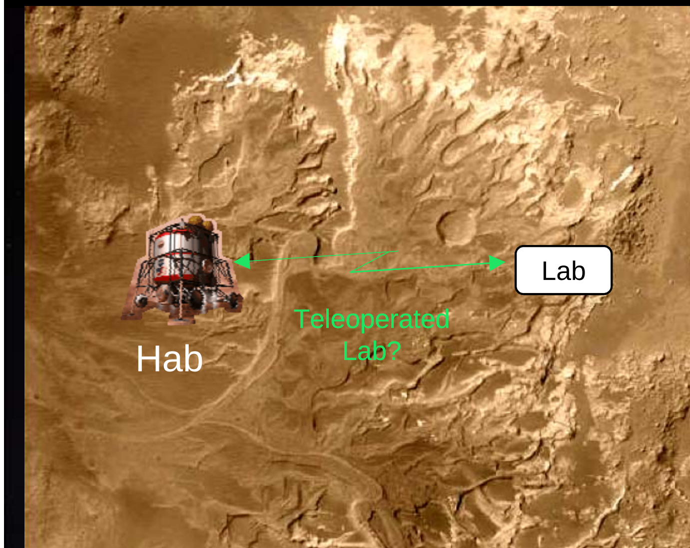
1) **Planetary Protection**: Keeping Mars organisms off of the crew, and vice versa
2) **Crew Safety**: Keeping toxic dust out of the Habitat/out of EVA suits (regardless of whether there are “bugs” in the dust)
3) **Good Science**: Keeping crew/equipment contamination off of Mars science samples

Sample Handling



- Sample handling includes: acquisition, containment, transport & delivery, and analysis, all of which are affected by contamination control, planetary protection, and crew safety.
- If a sample is not from a potential special region, it may be possible send humans into the area to collect the samples.
- Otherwise, alternative methods (e.g., real-time telerobotic sample acquisition and analysis) may be required to avoid the threat of introducing terrestrial biota into the special region.
- Or, if contamination can be sufficiently controlled, crew may be able to enter sensitive areas to acquire samples directly?

Mars Laboratory & Sample Handling



Technical Challenges

- Mars Samples
  - How to collect & contain?
  - How to handle & how to transport?
  - How & what to analyze?
  - Sample curation needs?

- Mars Analytical Laboratories
  - Types?
  - Located where?
  - How do labs fit into science strategy?
  - Lab outfitting?
  - Special Issues: e.g., maintain contamination control, manipulate samples

- **Samples are required across science disciplines**
  - Geology requires surface and shallow subsurface samples
  - Atmospheric & Climate Science requires atmosphere & surface samples
  - Astrobiology has most difficult sampling requirements: 250 – 300 m subsurface (requires drilling) to subsurface aquifer (potential for Mars extant life)
  - Geophysics requires emplacement of instrumentation & data returned

- **Representative instrumentation was identified**
  - Some sensors and analytical instrumentation development may be required
  - Microminiaturized analytical instrumentation from biotechnology industry may be leveraged

- **Distributed analytical capability required in rover, downhole during drilling, at habitat area, and "glove-size" for EVA crew**
  - Small analytical laboratory in rover, used during traverses
  - Downhole sensors required for data collection during drilling for subsurface samples
  - Small handheld instruments by EVA-suited crew
  - More capable analytical capability at habitat area: *Separate astrobiology lab for analyzing Mars subsurface samples probably required*

- **Issues to be addressed**
  - Sample handling: collection, containment, transport, analysis, curation
  - Contamination control: specifications & protocols required; in-situ cleaning
  - Planetary Protection & Special Regions operations: Leakage, transport, inducing special regions
  - Crew Safety: protocols required, impact on surface element design.

Follow-On Mars Surface Ops Con Focused Studies

1. Mars Drilling (shallow and deep) operations and options
2. Sample Strategy / In situ sample analysis requirements
3. TBD Contingency Operations
4. Quarantine Protocols
5. "Special Regions" strategy
6. Crew Waste Management
7. Mars Precursor Missions
   - Precursor knowledge is important for human Mars missions. NASA has identified a number of "Strategic Knowledge Gaps" to address prior to a crewed Mars mission.
   - NRC recommends "conducting a precursor in situ experiment at a location as reasonably close to the human mission landing sites as possible to determine if organic carbon is present."
   - Pre-delivered cargo assets (such as robotic assets/rovers) could be used to conduct sample analysis prior to human landing. *If there is concern about the environment after the crew lands, then initial crew surface operations might be conducted via IVA telerobotics from hab.* This could be done during a planned period of crew acclimation that is already accounted for in our present ConOps.

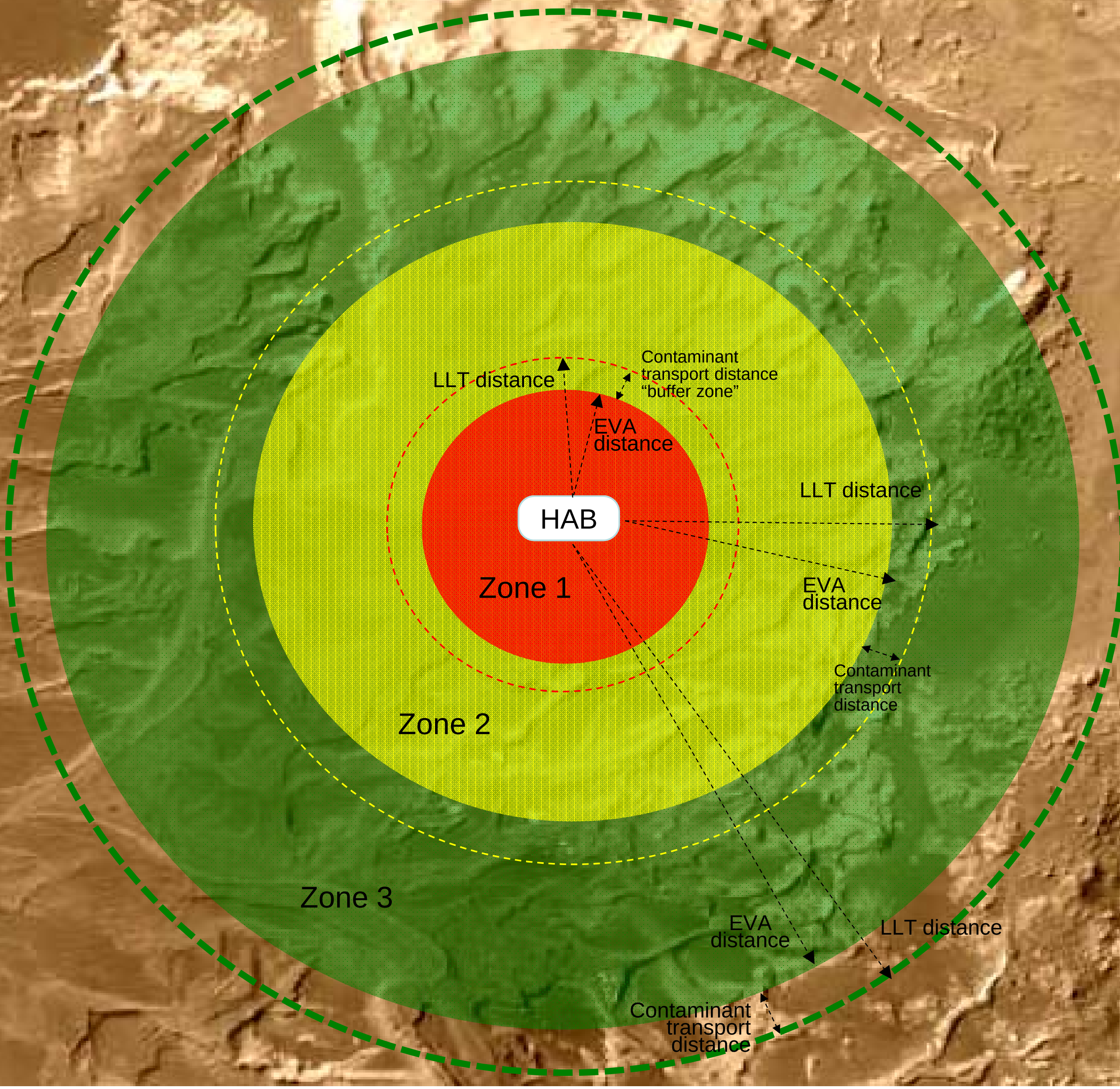
INCREMENTAL "NESTED EVA"

A habitat will likely create a zone of contamination that should be understood prior to landing.

If the area beyond that initial contamination zone needs to be understood better after landing, the low-latency telerobotic (LLT) exploration can be conducted from hab to determine safe zones prior to EVA .

The LLT characterization distance and any EVA safe zone distance could take into account potential contamination transport distance so that any subsequent EVA will not contaminate past a zone that has been properly characterized first via LLT.

Distances and zones could vary significantly as new information is obtained by crew and other



Preliminary Implications

Preliminary Implications

Key General Activities Enabled or Enhanced by LLT

- Observation and response to transient phenomena: e.g., dust devils on Mars, boundary layer dynamics, subsurface aquifers, life.
- Operations that benefit from real-time communication:
  - Drilling, brushing, coring, digging
  - Exploration of extreme terrain: e.g., lava tubes, cliff walls
  - Using unconventional robotic platforms: e.g., aerial vehicles & cliff climbers

Preliminary Implications for Lunar and Cislunar LLT

- LLT feed-forward: Testing LLT activites at Moon, in cislunar, and at retrieved asteroid could ensure effectiveness of similar tasks for future missions – e.g. Mars landing site recon & prep, human-assisted sample return, etc.
- Stand off prox ops: LLT could be used for “stand-off” ops of first exposure to asteroid and help with Phbos/Deimos exploration.
- Re-use: Existing surface assets could be “re-used” (e.g. RPM/RESOLVE if technically feasible, commercial assets, etc.)
- ISRU: Lunar and asteroid ISRU LLT could be an effective ISRU testing and operational strategy to leverage lunar and asteroid resources, and possibly Phobos/Deimos resources for future Mars missions.
- ISS LLT science tests will help with lunar and Mars surface applications. LLT “science cognition loop” needs to be tested and practiced with higher fidelity of ISS testing.

Preliminary Capabilities & Functions for LLT Assets

- Mobility speed: ~ 5-20+ km/hr (TBD, depends on range needed and Mars feed forward needs)
- Mobility range: TBD, depends on lunar sample needs and Mars feed forward needs. Could be hundreds of kms.
- Analysis: Analyze environment and identify quality samples: TBD instruments
- Sample collection: sample core, scoop, etc. (TBD) Number of Samples >= 3
- Sample containment: Not strict for lunar samples, but very strict for Mars feed forward tests and Mars samples; Asteroid TBD
- Lunar night ops: Rover will need to operate (or at least stay alive) during lunar night to take advantage of total duration that EAM enables.

LLT Maintenance Key Commonalities, Challenges, Systemic Issues

- **Commonalities:**
  - ESD control/grounding
  - Electrical connector mate/demate
  - Fastener removal/installation
  - MLI handling

- **Key Challenges:**
  - Manipulating small components that have distinctly different geometries
  - Ensuring fluid system integrity – for mate-demate during resource transfer
  - Hardware alignment following replacement (bits, wheels, etc.)
  - Ensuring purity of refill fluids or calibration samples

Systemic Issues:

- Contamination control of assets
- Accessibility of item requiring maintenance

Phobos to Mars Surface LLT Preliminary Implications

- **Time:**
  - *Tasks looked at so far could take significant time: e.g. ~ 30% to 60% of 500 day mission*
  - Total TBD LLT activities (e.g. adding outpost prep, science, etc.) could take entire 500 day mission
  - Additional contingency time may be required

- **Recon:**
  - *Recon needs could have significant impact on surface assets and possibly campaign*
  - Hazard assessment area/volume drives time
  - Sampling density and kind drives surface asset payloads and time

- **Surface Assets:**
  - Diversity and difficulties of potential LLT activities suggests multi-purpose surface asset(s) and/or multiple assets with distributed functionality
  - Fast integration instruments for surface and subsurface, including life detection

- **Common Challenges:**
  - Manipulation of heavy or delicate equipment (e.g., drill heads) within close quarters
  - Ensuring critical ops (e.g., lifts, drilling) are handled properly prior to loss-of-signal
  - Anomalies or unexpected delays in completing critical tasks prior to LOS may require unplanned safing
  - Need effective mobility, e.g. including speed for rapid recon and covering large distances quickly

Phobos to Mars Surface LLT Preliminary Implications

- **Autonomy:**
  - Common tasks that could be optimized through autonomy
    - Functional tests of surface assets (self-tests)
    - Standard soil analyses that can be performed during no-comm periods
    - Long-distance roving with autonomous positioning/guidance and hazard avoidance
    - Laying cable once sequence is started
  - Supervised autonomy with real-time intervention control can be a guiding paradigm – *with possible exception of certain science tasks and other highly complex tasks*
  - Goal-based operations: e.g. goal-based commanding, including via voice

- **Communications:**
  - 7:4.25 ratio of LOS-to-AOS durations for Phobos mission makes orbiting comm/relay a potentially important architecture implication for completing tasks.
  - Deimos comparison could be useful, but 72-hour LOS may significantly reduce value of LLT.

- **Contamination Control & Planetary Protection:**
  - LLT keeps human contamination out but real-time human cognition in
  - Landing site recon and sampling can be performed prior to crew landing
  - LLT can be used for in-situ analysis as well as lab analysis
  - Special regions can be found and explored prior to landing crew – helps address PP concerns
  - Going from one special region to another may raise cross-contamination concerns
  - LLT can be used for cleaning assets
  - Burying cable potentially has additional planetary protection considerations

What Crew Complement is needed?

Performing in-system teleoperation doesn't replace the "backroom" in Mission Control.

Even with 2 to 4 highly skilled scientist astronauts, there are still backroom activities that would be useful to perform.

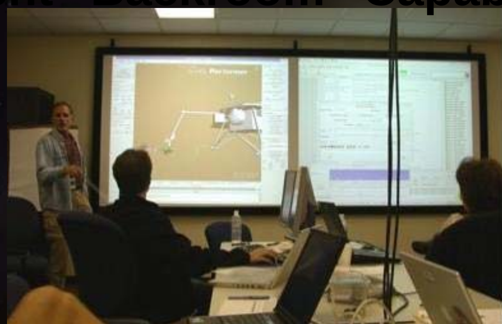
However, ability of crew and robots to do more autonomously needs to be pursued, including dynamic science decision-making, implying significant training and advanced information systems.

The backroom performs enabling activities, to include defining daily scientific objectives, monitoring robotic assets performance, processing of instrument data, and detailed engineering (thermal, power, data) analysis.

Moving Expertise & Capabilities In-System

Number of skills & capabilities need to be moved "in-system"

Backroom	**Crew**
Current "Backroom" Capabilities	Capabilities to Move In-System



Extensive Science Knowledge - - - - - - - - - -> Excellent Science Knowledge

Thermal, Power, Data Analysis - - - - - - - - → Thermal, Power, Data Analysis

Model Updates Based on Actuals

Remote Sensing Data Processing - - - - - - - > Remote Sensing Data Processing

In-Situ Instrument Data Processing

Instrument Sequencing & Validation - - - - → Instrument Sequencing and Validation

S/C Sequencing, Integration, and Validation → S/C Sequencing, Integration, and Validation

Radiation Analysis

Testbeds

Candidate Teleoperated Platforms

Platform	Mission/Capabilities
Lander	Mars – includes ascent vehicle for sample return?
Rover	Mars – Sample gathering for return to lander ascent vehicle?
Hopper	Deployed to an initial location and moved to another location(s) during the mission to scout areas of interest for investigation by future robotic landers/rovers
Gecko / Cliff Climber	Deployed to extreme terrain on Martian surface
Penetrator	Deployed into the moons or the Martian surface at locations of interest (greater deployment accuracy by a crew vs autonomous deployment?)
Atmospheric Sample Return	Deployed into Mars' upper atmosphere to collect dust particles and atmospheric gas
Aerial Vehicle	Take atmospheric measurements at varying altitudes on Mars. Local teleoperation may increase the viability of aerial vehicle concepts.
Hybrid Vehicle	For example, an aerobot with deployable mini-rovers

Summary Ops Areas for Future Assesment

1. **Crop Ops**: Can small crew effectively execute LLT activities?
   - Remote science and in-situ sample analysis, science lab ops, asset cleaning and deep drilling?
   - Automation/LLT balance?
   - Robotic manipulation of delicate and/or heavy equipment?
   - What kind of training?
2. **Time:** How much time there will be for LLT activities prior to crew landing. How do we reduce time and other resources needed for LLT activities?
3. **Recon rqmts**: Pre- and post-landing site recon requirements, including sub-surface. E.g. may need fast rovers and fast integration instruments for surface and subsurface, including life detection. May need to cover large area quickly.
4. **Assets**: Will we have surface assets available to conduct tasks properly over a potentially long time prior to crew landing. Can just a few LLT surface assets "do it all"?
5. **Cross-contamination**: How do we address cross-contamination when moving a rover from one area to another? E.g. Trade in-situ cleaning vs. dedicated special region assets?
6. **Life-detection**: If we find life via LLT from orbit and/or while on surface, what then? Develop tentative guidelines sooner than later?
7. **ISS Testing**: More ISS LLT testing – e.g. LLT science
8. **Lunar Testing**: LLT PP activities at the Moon? E.g. return sample from far side?
9. **Environmental Impacts**: Assess broader environmental impact considerations
10. **Mars orbit "campaign"**: Multiple Mars orbit missions before landing crew?
11. …

Backup

Mars Surface Operations Timeline Considerations

- **Estimated timelines based on:**
  - Historical as-executed durations from Apollo EVA's, HST-SM's, RRM, etc.
  - Telerobotics project "Fastnet" mission simulation with ISS (Fong, et al., 2014)
  - Visibility/communication with LLT command base
  - Input from discipline experts, e.g., Tasks 3.2 and 7, ISRU ConOps
- **For ISS mission sim, overhead time assessed**
  - Accounts for response time, admin (e.g., logs), etc.
  - Time when both rover and operator are "waiting"
  - Overhead time ranged from 30% to 40%
- **Loss-of-signal (LOS) for command base at Phobos or Deimos**
  - Assumes no orbiting comm relay
  - Phobos: period = 7:39, visible for 4.2 hrs every 11.1 hrs; LOS lasts about 6.9 hrs
    - > Preferable for short tasks or long sequences that can be distributed over days
  - Deimos: period = 30:12, visible for 59.6 hrs; LOS lasts 71.8 hrs (Hopkins & Pratt, 2011)
    - > Preferable for sequences of less than 2 sols 10 hrs that require continuous ops
- **Phobos LLT command base assumed for representative timelines**
  - Phobos is primary candidate for human exploration
  - 4.2 hrs comm duration is approx.1/3 shift: serves as good point for crew break period
- **Other timeline considerations**
  - Average overhead time of about 1/3 time added to each task (per ISS sims)
  - Contingency/wait time added when appropriate or necessary for imminent LOS
  - Some shifts are contiguous across timelines (to take advantage of AOS times)
  - "Leftover" shift time at end of a timeline utilized for subsequent timeline ("Shift 0")

Decision tree for mitigating adverse effects to possible indigenous Martian biota from a human mission