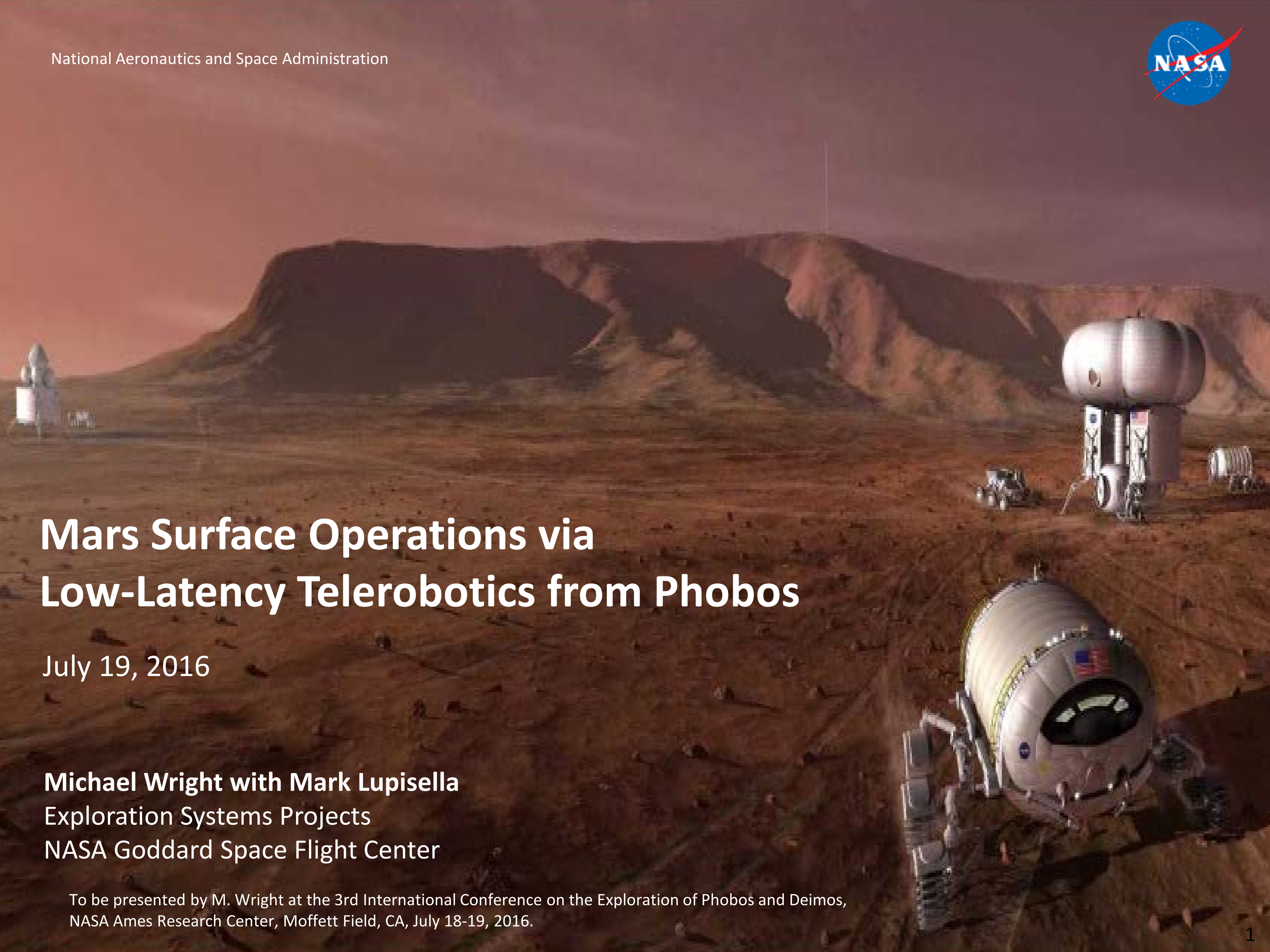

Mars Surface Operations via Low-Latency Telerobotics from Phobos

July 19, 2016

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Exploration Systems Projects
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To be presented by M. Wright at the 3rd International Conference on the Exploration of Phobos and Deimos, NASA Ames Research Center, Moffett Field, CA, July 18-19, 2016.

Unique Acronyms and Abbreviations

ALHAT	Auto. Landing & Hazard Avoidance Technology
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
AN	Actuation Nut
AOS	Acquisition-of-Signal
C&DH	Command & Data Handling
CB	Converter Box
Cmd	Command
CM	Centauri Montes
CMS	Cargo Mobility System
CS	Crew Support (rover)
D	Deimos, Dozer (rover)
ECLSS	Environmental Control & Life Support System
ELIB	Electrical Loads Integration Box
ELP	EVA Logistics Pallet
EMC	Evolvable Mars Campaign
EVA	Extravehicular Activity
F/D	Fill and Drain
GNC	Guidance, Navigation & Control
H	Hopper (rover)
Hab	Habitat
HAT	Human spaceflight Architecture Team
HCP	Habitat Consummables Pallet
HEM-SAG	Human Explorat'n of Mars Science Analysis Group
HLT	High-Latency Telerobotics
HSLP	Habitat Spares & Logistics Pallet
HST	Hubble Space Telescope
I&T	Integration & Test
IGOR	Instrumental Ground Operations Rover
ISRU	In-Situ Resource Utilization
ISS	International Space Station
KPU	Kilopower Unit
KPUP	Kilopower Portable Utility Pallet
LEA	Launch, Entry, and Abort
LIDAR	Light Detection And Ranging
LLT	Low-Latency Telerobotics
LOS	Loss-of-Signal
LSMS	Lunar Surface Manipulator System
MADD	Mars/Actic Deep Drill
MARTE	Mars Astrobiology Research & Technology Experiment
MAT	Metabolic Activity Test
MAV	Mars Ascent Vehicle
MoPP	Mobility for Payload Positioning
MPS	Martian Positioning System
MSL	Mars Science Laboratory
MSLP	Mobility Spares & Logistics Pallet
OH	Overhead
OT	Overhead Time
P/L	Payload
PLSS	Portable Life Support System
RRM	Robotic Refueling Mission
SEM	Scanning Electron Microscope
SM	Servicing Mission
SOE	Solid Oxide Electrolyzer
SPR	Small Pressurized Rover
SR	Special Region (rover)
SRS	Sample Return System
SRU	Surface Replaceable Unit
SUR	Small Unpressurized Rover
TCS	Thermal Control Subsystem
Tlm	Telemetry

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Mars LLT Operations from Phobos – Concept Description

- **Purpose: To conduct Mars surface operations prior to crew landing via low-latency telerobotics (LLT) from a telecommand base in Mars orbit, such as on Phobos**
- **Considers surface activities and tasks that may be prime candidates for conducting via LLT by a crew in Mars orbit**
  - Primarily repetitive tasks best performed with human interaction, vs. autonomous or high-latency telerobotics (HLT)
  - Assumes LLT comm time/latency less than approx. 500 msec
  - For purposes of LLT assessment, most tasks assumed non-autonomous and non-HLT
- **Includes pre-crewed missions to deploy surface outpost assets, e.g., power system, science lab, logistics, etc.**
- **Manifests based on Evolvable Mars Campaign (EMC) Task 7 Case 1 for 27t lander (7/22/15)**
  - Case affords expedited manifesting and outpost establishment with realistic flight rate
- **Includes analysis of LLT activities and tasks**
  - Considers those of potential value to campaign
  - Reflects some filtering and prioritization
  - Factors: task risk, criticality, latency sensitivity, etc.

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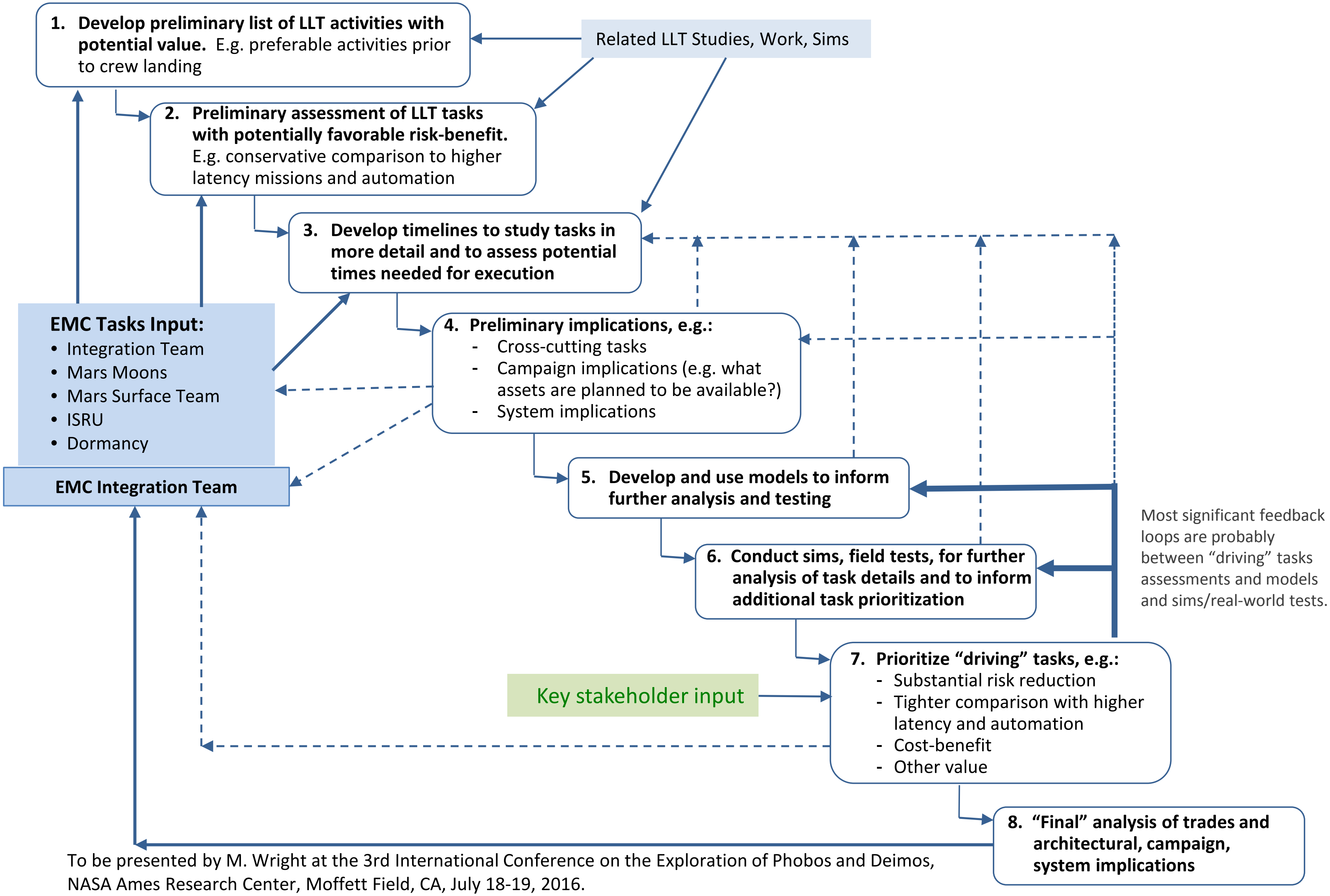
High Level Process for Mars Vicinity LLT



1. **Develop preliminary list of LLT activities with potential value.** E.g. preferable activities prior to crew landing

Related LLT Studies, Work, Sims

2. **Preliminary assessment of LLT tasks with potentially favorable risk-benefit.** E.g. conservative comparison to higher latency missions and automation

3. **Develop timelines to study tasks in more detail and to assess potential times needed for execution**

EMC Tasks Input:
- Integration Team
- Mars Moons
- Mars Surface Team
- ISRU
- Dormancy

EMC Integration Team

4. **Preliminary implications, e.g.:**
   - Cross-cutting tasks
   - Campaign implications (e.g. what assets are planned to be available?)
   - System implications

5. **Develop and use models to inform further analysis and testing**

6. **Conduct sims, field tests, for further analysis of task details and to inform additional task prioritization**

Most significant feedback loops are probably between "driving" tasks assessments and models and sims/real-world tests.

Key stakeholder input

7. **Prioritize "driving" tasks, e.g.:**
   - Substantial risk reduction
   - Tighter comparison with higher latency and automation
   - Cost-benefit
   - Other value

8. **"Final" analysis of trades and architectural, campaign, system implications**

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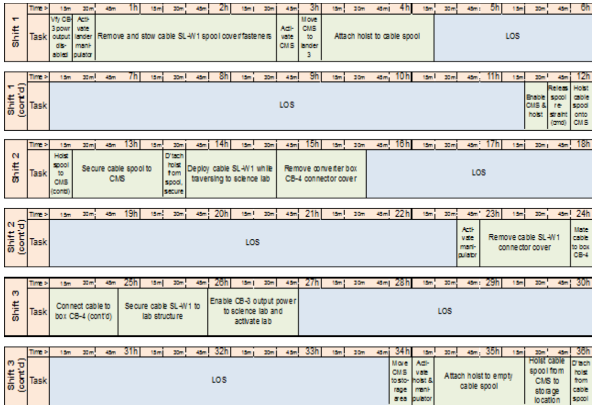
Mars Ops via LLT from Phobos: Some General Assumptions

- **Telerobotic assets assumed already deployed on surface**
  - Stationary equipment such as hoists/cranes, video monitors, etc.
  - Mobile systems such as ATHLETE, teleoperated service and science rovers
  - Manipulators on landers and mobile systems w/ mate/demate capability
- **Systems designed for LLT operations**
  - Tools and equipment can be grappled with precision manipulators
  - Robust motion control (e.g., joystick vs. discrete commanding)
  - Relatively high positioning tolerance (order of cm vs. mm) for rover, tools, etc.
  - Ability to recover from unexpected occurances (e.g., stuck drill bit)
  - High-bandwidth, dedicated channels for cmd/tlm & enhanced telerobotics capabilities
  - Emergency backup/redundancy required
- **Control/monitoring of surface assets by orbiting crew**
  - Minimum 2 crew members in Mars orbit to support 12-hour shifts (4 crew proposed)
  - Goal-based commanding, with predetermined or “learned” sequences
  - Possible haptics, audio (e.g., for possible voice commanding)

Mars Ops via LLT from Phobos: Timeline Assumptions

- **No orbiting comm relay assumed; loss-of-signal (LOS) lasts about 6.9 hours**
  - Phobos period = 7:39, line-of-site to surface lasts 4.2 hrs every 11.1 hrs
  - 4.2 hrs comm duration is approx.1/3 shift (serves as good point for crew break period)
  - Unless otherwise noted as autonomous, LOS is a no-op period (task is latency-sensitive)
  - Lengthy tasks that can be performed autonomously scheduled during LOS
  - Contingency/wait time added when appropriate or necessary for imminent LOS
  - Support equipment goes to standby upon LOS or after some predefined no-op time
- **Estimated task durations based on:**
  - Historical as-executed durations from HST-SM's, RRM, flight systems I&T, etc.
  - ISS-ground telerobotics mission simulations
  - Input from discipline experts
- **Overhead time included in durations based on ISS demo/sims**
  - Accounts for response time, admin (e.g., logs), etc.
  - Time when both rover and operator are "waiting"
  - Overhead time ranged from 30% to 40%
- **Timeline sequences assumed non-contiguous to each other**
  - Each timeline begins w/ AOS period
  - Allows modifying sequence of performance
  - Task durations rounded to nearest 15-min increments



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
	Task	Vfy CB-3 powr output disabled	Activate lander manipulator	Remove and stow cable SL-W1 spool cover/fasteners								Activate CMS	Move CMS to lander 3	Attach hoist to cable spool					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	11h	15m	30m	45m	12h
	Task	LOS																					Enable CMS & hoist	Release spool restraint (cmd)	Hoist cable spool onto CMS

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	Hoist spool to CMS (contd)	Secure cable spool to CMS				D'tach hoist from spool, secure	Deploy cable SL-W1 while traversing to science lab				Remove converter box CB-4 connector cover				LOS									

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
	Task	LOS																		Activate manipulator	Remove cable SL-W1 connector cover				Mate cable to box CB-4

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
	Task	Connect cable to box CB-4 (cont'd)			Secure cable SL-W1 to lab structure				Enable CB-3 output power to science lab and activate lab				LOS												

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
	Task	LOS															Move CMS to storage area	Activate hoist & manipulator	Attach hoist to empty cable spool				Hoist cable spool from CMS to storage location		D'tach hoist from cable spool

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Mars Operations via LLT – LLT Latency/LOS Sensitivity

- **Latency/LOS “sensitivity” values roughly assessed for LLT op sequences**
- **Values based on task criticality/susceptibility due to:**
  - Immediately preceding LOS (e.g., within a half-hour)
  - High risk of anomaly (e.g., misalignment on offload ramp)
  - No tolerance for latency > approx.1 sec (e.g., lifts, mates)
- **Scale range:**
  - **0**: Latency or LOS have no effect on operations
  - **5**: Latency or LOS can significantly impact ops

Sensitivity
0: None
1: Slight
2: Low-Medium
3: Medium
4: Medium-high
5: High

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Mars Operations via LLT – LLT Latency Sensitivity

- **Surface preparation sequence is low-medium (2) sensitivity:**
  - Rationale: No latency-critical operations; repetitive tasks can be done autonomously or HLT; however, tasks are extensive and long-duration, with high risk of unexpected obstructions during excavation/leveling operations
- **Offload sequences are either low-med (2) or medium (3) sensitivity:**
  - Rationale: Some latency-sensitive ops (e.g., lifts); roll-offs can be self-manuevering
- **Power farm prep & KPU deploy sequence has med-high (4) sensitivity:**
  - Rationale: Excavation required, KPU handling/deployment is critical
- **General power cabling sequences have low-medium (2) sensitivity:**
  - Rationale: No time-critical ops, connector mates are latency-sensitive
- **Science recon, sampling, & analyses are medium (3):**
  - Rationale: Traversing and very long analyses can be auto; but drill prep, and drilling/handling of critical samples required
- **Core sample transport is medium-high (4) sensitivity:**
  - Rationale: Traversing can be autonomous; but handling of critical samples required

Sensitivity
0: None
1: Slight
2: Low-Medium
3: Medium
4: Medium-high
5: High

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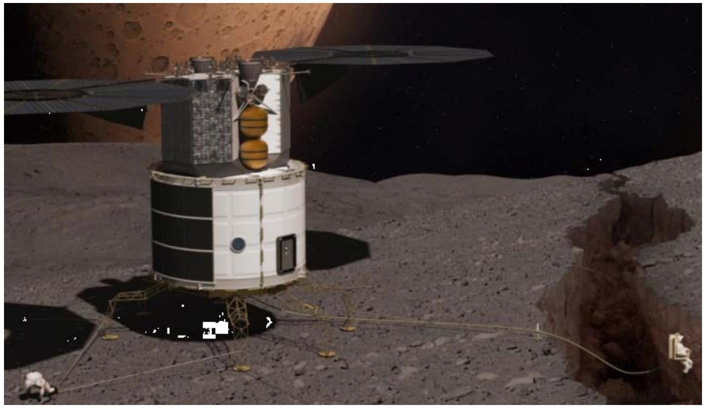
Mars LLT Operations – Summary of Surface Operations via LLT

- **Assess and prepare outpost area (pre-lander "Mission 0")**
- **Offload assets from lander and deploy**
- **Connect assets to power systems**
- **Commence ISRU production of MAV fuel**
- **Stage logistics, spares, consummables**
- **Deploy science lab module**
- **Deploy mobility and payloads**
- **Science reconnaissance, sampling, and analysis ("Mission S")**



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Outpost Area Assessment and Preparation

Outpost Area Hazard Assessment – Description

- **Description: Assess potential hazards at outpost area, incl. landing site**
    - Perform visual/photo survey
    - Perform laser topographical survey
    - Perform shallow digging and drilling
    - Conduct vibro-acoustic measurements
    - Conduct chemical and biological measurements
- **Tasks for hazard assessment representative sequence:**
    - Position teleoperated rover at selected areas: relocate rover, secure on-station
    - Conduct visual survey: 360º panorama, prox surface photos (e.g., tracks)
    - Conduct laser survey: 360º detailed topo/elevation survey (autonomous during LOS)
    - Shallow digging: position rover, dig, photograph
    - Analyze sample - can be done autonomously during LOS: density, firmness, composition; identify any ice (potential diurnal or seasonal risk)
    - Vibro-acoustics: deploy stimulator, position detector, generate input, measure response
    - Shallow drilling: position drill, perform drilling, remove, measure density/firmness, clean
    - Analyze sample: chemical, biological, organics; can be done autonomously during LOS
- **Latency/LOS sensitivity for sequence:**
    - Assessed latency/LOS sensitivity: **1**
    - Rationale: Although no latency-critical operations and automated tasks during LOS, no contingency time prior to LOS

Outpost Site Hazard Assessment Timeline

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
	Task	Reloc. rover, secure on-station	Activate survey cam	Perform 360° survey (auto)		Proximity surface photo survey										Deactivate survey cam	Deploy LIDAR survey scanner	Start LIDAR 360° auto-survey	LOS - LIDAR auto-survey						

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
	Task	LOS - Laser auto-survey (cont'd)																					Verify LIDAR survey complete	Position shovel at dig loc.	Perform shallow dig

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	Perform shallow dig (contd)	Place sample in analytic lab	Take closeup photos of dig location		Clean shovel for subsequent sample					Deploy vibro-acoustic stimulation and measurement instruments					LOS - Auto-analyze surface sample (density, firmness, composition)									

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
	Task	LOS - Auto-analyze surface sample (cont'd)																		Generate vibro-acoustic input, measure		Position drill at sample site		Drill into surface	

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
	Task	Drill into surface (cont'd)		Remove drill and sample					Place sample in analytic lab	Clean bit for subsequent sample (continue after LOS, if necessary)			LOS - Auto-analyze surface sample												

(Repeated for each sample site)

🟩 = LLT Operations

🟦 = Loss Of Signal (LOS)

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Outpost Area Surface Preparation (Mission 0) – Description

- **Description: Preparation of outpost hab area, landing site, & power farm**
  - Perform gross leveling of any higher mounds
  - Perform final surface leveling of entire area
  - Landing site area includes blast berm buildup
- **Assumes a pre-lander mission that precedes the EMC/HAT proposed missions (i.e., “Mission 0”)**
  - Would include one or more excavation LLT rovers to perform pre-lander preps
- **Tasks for surface preparation representative sequence:**
  - Peform gross leveling of mounds within outpost base area (300m diam)
  - Perform final leveling of outpost hab area
  - Perform leveling of power farm area (10m x 10m)
  - Peform gross leveling of mounds within landing site (100m diam)
  - Relocate spoil to perimeter for blast berm buildup
  - Perform final leveling of landing site

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Outpost Site Surface Preparation 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>Sub Task</td><td>Move rover to out-post center</td><td colspan="4">Perform gross leveling of base mound sites 1-9</td><td colspan="4">Perform gross leveling of base mound sites 10-18</td><td colspan="4">Perform gross leveling of base mound sites 19-27</td><td colspan="4">Perform gross leveling of base mound sites 28-36</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>Sub Task</td><td colspan="21">LOS</td><td colspan="3">Perform gross leveling of base mound sites 37-45</td></tr>
</table>

(Continue gross leveling for approx. next 141 hours)

<table>
<tr><td rowspan="2">Shift 25</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>289h</td><td>15m</td><td>30m</td><td>45m</td><td>290h</td><td>15m</td><td>30m</td><td>45m</td><td>291h</td><td>15m</td><td>30m</td><td>45m</td><td>292h</td><td>15m</td><td>30m</td><td>45m</td><td>293h</td><td>15m</td><td>30m</td><td>45m</td><td>294h</td></tr>
<tr><td>Sub Task</td><td colspan="14">Perform final leveling of entire outpost base area</td><td colspan="10">LOS</td></tr>
</table>

(Continue final leveling for approx. next 36 hours)

<table>
<tr><td rowspan="2">Shift 28 (cont'd)</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>331h</td><td>15m</td><td>30m</td><td>45m</td><td>332h</td><td>15m</td><td>30m</td><td>45m</td><td>333h</td><td>15m</td><td>30m</td><td>45m</td><td>334h</td><td>15m</td><td>30m</td><td>45m</td><td>335h</td><td>15m</td><td>30m</td><td>45m</td><td>336h</td></tr>
<tr><td>Sub Task</td><td colspan="9">LOS</td><td colspan="12">Complete final leveling of entire outpost base area (cont'd)</td><td>Move to power farm area</td><td>Gross & final level'g, power area</td><td>Move to landing area</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 29</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>337h</td><td>15m</td><td>30m</td><td>45m</td><td>338h</td><td>15m</td><td>30m</td><td>45m</td><td>339h</td><td>15m</td><td>30m</td><td>45m</td><td>340h</td><td>15m</td><td>30m</td><td>45m</td><td>341h</td><td>15m</td><td>30m</td><td>45m</td><td>342h</td></tr>
<tr><td>Sub Task</td><td colspan="2">Gross leveling of landing area mound sites 1-4</td><td colspan="22">LOS</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 29 (cont'd)</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>343h</td><td>15m</td><td>30m</td><td>45m</td><td>344h</td><td>15m</td><td>30m</td><td>45m</td><td>345h</td><td>15m</td><td>30m</td><td>45m</td><td>346h</td><td>15m</td><td>30m</td><td>45m</td><td>347h</td><td>15m</td><td>30m</td><td>45m</td><td>348h</td></tr>
<tr><td>Sub Task</td><td colspan="6">LOS</td><td colspan="4">Perform gross leveling of landing area mound sites 5-13</td><td colspan="4">Perform gross leveling of landing area mound sites 14-22</td><td colspan="4">Perform gross leveling of landing area mound sites 23-31</td><td colspan="4">Perform gross leveling of landing area mound sites 32-40</td><td>Gross level'g, mound sites 41-42</td><td>LOS</td></tr>
</table>

<table>
<tr><td rowspan="2">Shift 30</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>349h</td><td>15m</td><td>30m</td><td>45m</td><td>350h</td><td>15m</td><td>30m</td><td>45m</td><td>351h</td><td>15m</td><td>30m</td><td>45m</td><td>352h</td><td>15m</td><td>30m</td><td>45m</td><td>353h</td><td>15m</td><td>30m</td><td>45m</td><td>354h</td></tr>
<tr><td>Task</td><td colspan="24">LOS</td></tr>
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<table>
<tr><td rowspan="2">Shift 30 (cont'd)</td><td>Time ></td><td>15m</td><td>30m</td><td>45m</td><td>355h</td><td>15m</td><td>30m</td><td>45m</td><td>356h</td><td>15m</td><td>30m</td><td>45m</td><td>357h</td><td>15m</td><td>30m</td><td>45m</td></tr>
<tr><td>Task</td><td colspan="3">LOS</td><td colspan="4">Perform gross leveling of landing area mound sites 43-50</td><td colspan="8">Perform final leveling of entire landing site area</td></tr>
</table>

🟩 = LLT Operations

🟦 = Loss Of Signal (LOS)

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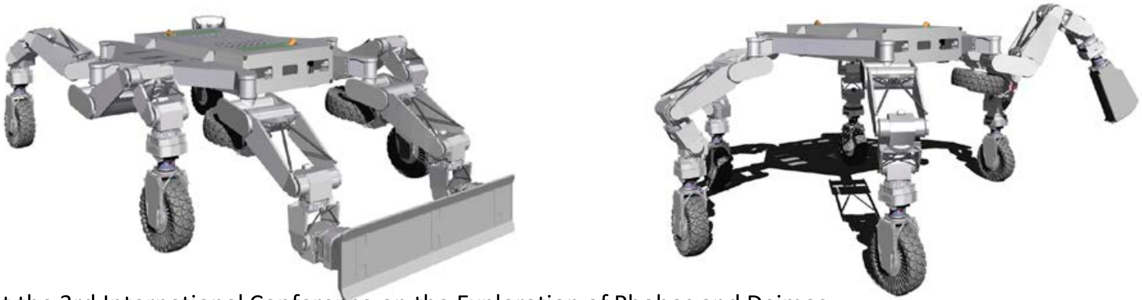
Outpost Setup and Integration

Outpost Mobility Assumptions

- **Cargo Mobility System (CMS)**
  - Can be ATHLETE or similar teleoperable roving vehicle
- **Equipped with:**
  - Hoist for offload following arrival at asset deployment location
  - Manipulator to assist with asset handling
  - Ability to deploy cables via preloaded spool during traverse
- **CMS traverse/operation rates:**
  - Loaded traverse: 10 km/hr
  - Empty traverse: 20 km/hr
  - Traverse w/ cable deployment: 1 km/hr
  - Assumes constant running velocity for timeline estimates (i.e., no accel/decel times)
- **Excavation for site preparation, as needed**
  - Can be effected by one or more vehicles already manifested (rover, “mobility,” etc.)
  - Excavation tools available (e.g., blade, backhoe, hopper)



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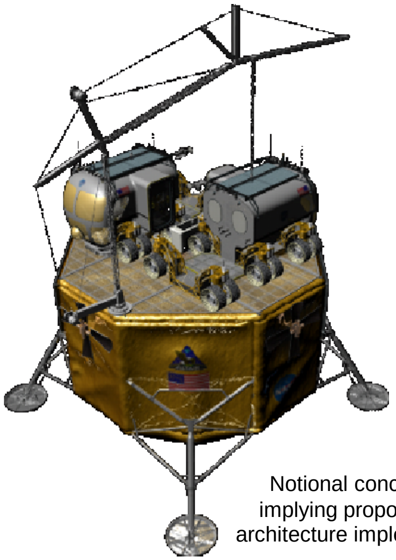
Cargo Offloading From Lander – Description

- **Description: Offload assets from lander to staging area on surface**
  - By asset category, i.e., independent of Mission 1-3 manifests
  - Prepare handling and accessibility equipment (hoist, ramps, etc.)
  - Move cargo from lander to surface and/or transport vehicle
- **Tasks for each asset/item offload for cargo offloading sequence:**
  - Position handling equipment adjacent to lander
  - Open cargo access panels
  - Remove cargo fasteners/restraints
  - Grapple and position item for lift, if required
  - Attach crane to item for lift, or self roll-off
  - Lift item via crane, or roll-off via ramp
  - Secure item to transport, and/or move to staging/dwell area
  - Disengage handling equipment, as required
  - Repeat for each item to be offloaded
- **Latency/LOS sensitivity for sequence:**
  - Assessed overall latency/LOS sensitivity: **3**
  - Rationale: Some time- or latency-critical operations (lifts, roll-offs), some lack of contingency time prior to LOS's



Notional concept not implying proposed LLT architecture implementation

Note: For this sequence, "Mobility for Payload Positioning" (MoPP) is same as the previously referenced "Cargo Mobility System" (CMS)

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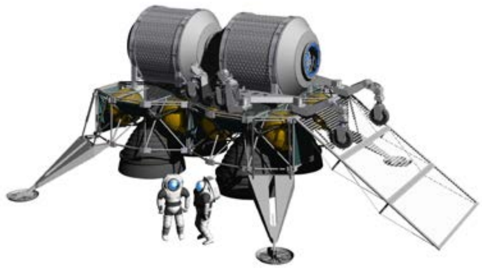
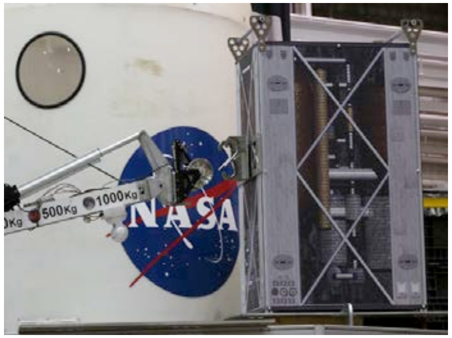
Lander Offloading Assumptions

- **Logistics, small cargo, consummables, and spares stowed on pallets**
- **Protective flight covers on some hardware require removal prior to offload**
- **Flight restraints for hardware released via command (vs. manipulated)**
  - Necessitated, regardless of LLT or not
  - Since not time-critical, can rely on non-pyro mechanisms (e.g., frangibolts)
- **Cargo offload capability is LSMS-type hoist**
  - Relocatable between landers, if necessary (but see implications later)
- **Offload sequence dependent on:**
  - Self-rolloff capability; "get out of the way" as soon as possible
  - Most critical operationally (e.g., KPU-1)
  - Asset location on lander deck which depends on volume and mass, based on results of lander tip-over analysis



- **Self-roll assets have positioning capability (e.g., IR sensors) for safe roll-off**
- **Stationary assets are offloaded to either surface or CMS**
  - Area adjacent to lander available for staging/dwell
- **Ramp is assumed included in manifests**
  - Used to offload items that have mobility (e.g., rovers, CMS)
  - Enables effective access to each lander deck following offload for future utilization
  - Ramp manifest trade pending



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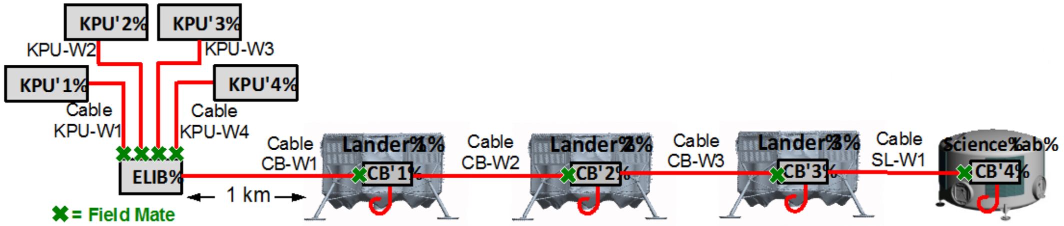
Outpost Power Interconnect Assumptions

- **Power cable deployment assumptions:**
  - Power farm located 1 km from lander to afford minimum distance for radiation protection
  - Cable routed between power farm and Lander 1 along pretermined, unobstructed route
  - Cable layed on surface (not buried), with spool mounted to mobility vehicle (rover, CMS)
- **Kilopower units (KPU's) for power generation**
  - KPU-1 preconnected to lander for ISRU and lander keep-alive power
  - KPU-1 subsequently relocated to permanent location at power farm
  - KPU's positioned within individual "power pits" to afford below-grade radiation protection
    - Reduces safe distance req'd between farm and outpost base, and cable length/mass
  - KPU's interconnected to Electrical Loads Integration Box (ELIB) in field
- **Electrical Loads Integration Box (ELIB) & power Converter Boxes (CB's)**
  - CB's distribute power between KPU's and landers
  - ELIB located at power farm (i.e., in proximity to KPU's)
  - Hardwired cables from KPU outputs mated to ELIB in field
  - Each CB is mounted to structure of respective lander
- **Hardwired connections minimizes field connections and cables/mass**
  - Assumed secure and tested; no LLT required for these interfaces for nominal ops



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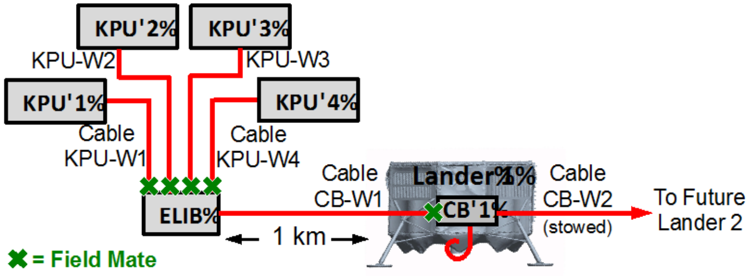
Outpost Integration – 27t Lander Mission 1

- **Pre-crew Mission 1 outpost integration covers manifest for only 27t Lander 1**
  - Mars Ascent Vehicle (MAV) (not offloaded)
  - In-Situ Resource Utilization (ISRU) plant (not offloaded)
  - Cargo offload hoist and ramp (assumed)
  - KiloPower Unit (KPU) x 4
  - Power cables (hardwired to KPU’s)
  - Electrical Loads Integration Box (ELIB) w/ hardwired output cable
  - Special region (SR) and crew support (CS) rovers
  - Cargo Mobility System (CMS)
  - Allocated payload
- **Task timelines for Mission 1 outpost integration sequence:**
  1. Deploy offloading hoist/crane and ramp
  2. Offload KPU-1 and activate (for lander keep-alive and ISRU production)
  3. Commence O_2 production and MAV prop loading
  4. Offload SR/CS rovers and CMS
  5. Prepare power farm for KPU deployment (includes leveling, excavating “power pits”)
  6. Offload remaining KPU’s (x 3) and EPIB
  7. Deactivate and disconnect KPU-1 from lander/ISRU
  8. Deploy KPU’s (x4) and ELIB, and connect
  9. Connect power cable to Lander 1 and activate KPU’s
  10. Offload allocated payload and deploy at science station

Outpost Integration – Mission 1 Assumptions

- **Power farm area requires surface preparation prior to KPU deployment**
  - Leveling of area (10m x 10m assumed)
  - Excavation of 4 power pits (1m x 1m, ≤ 1m deep)
  - Spoil deposited as berms (≤ 1-m high) on hab-facing side of pits
  - Time to dig and level 1 power pit takes 2 hours (incl. berm construction, overhead)
- **KPU-1 offload and activation is priority, then relocated**
  - To provide lander keep-alive power and start ISRU production asap
  - KPU-1 and ISRU preconnected to lander/MAV prior to launch, to provide lander keep-alive power and commence O_2 production immediately after KPU-1 activation
  - Relocation of KPU-1 necessitates deactivation, cooling, and disconnection from lander
  - Power cable hardwired to KPU output minimizes connector demates and cable quantity
- **Only the following cable connections are required in field:**
  - KPU power output cables to ELIB power interfaces (4 ea.)
  - ELIB power output cable to Lander 1 converter box CB-1
  - Note: Lander 2 power cable (between CB-1/CB-2) hardwired at CB-1 and left stowed



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Outpost Integration – Mission 1 Assumptions

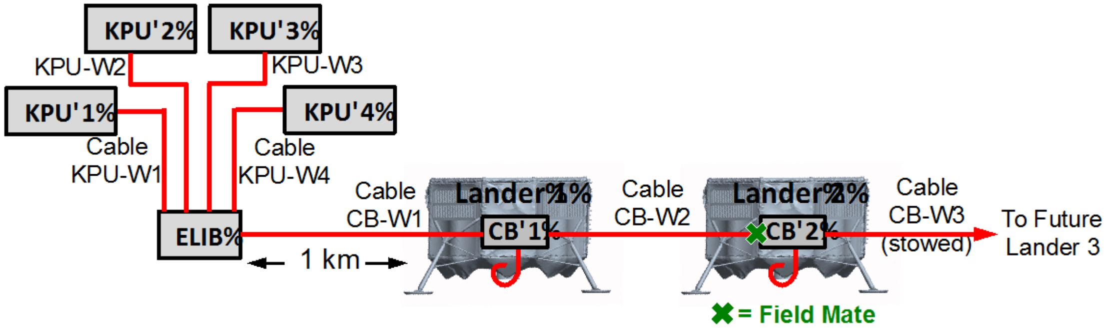
- **KPU’s positioned within pits to afford below-grade radiation protection**
  - Covered within pits to afford protection and hab shielding
  - Burying performed after radiator deployment to ensure proper clearance (2 hrs duration)
- **ELIB is designed for surface deployment**
  - No surface prep, accommodation, or support hardware required
  - However, integral with spool for hardwired cable CB-W1 (power to lander)
- **Distance assumptions:**
  - KPU's deployed at power farm 1km from lander
  - Science station is approx. 1 km from lander
  - Other assets in proximity to lander
- **SR & CS rovers offloaded following start of ISRU ops to clear lander area**
- **"Allocated payload" offloaded via hoist as one unit**

Outpost Integration – 27t Lander Mission 2

- **Pre-crew Mission 2 outpost integration covers manifest for only 27t Lander 2**
  - Power cable/spool (for future Lander 3)
  - Offload ramp (assumed); no hoist on this lander
  - Small Pressurized Rover (SPR)
  - Small Unpressurized Rover (SUR)
  - Logistics module
  - EVA logistics
  - Small cargo
  - Consummables and spares
- **Task timelines for Mission 2 outpost integration sequence:**
  1. Deploy/connect power cable from Lander 1 CB-1 to Lander 2 CB-2
  2. Relocate offloading hoist/crane from Lander 1 to Lander 2, and deploy ramp
  3. Offload SPR and SUR
  4. Offload/stow logistics modules (x 2)
  5. Offload/stow EVA logistics (pallet)
  6. Offload/stow small cargo (pallet), consummables and spares (pallet)

Outpost Integration – Mission 2 Assumptions

- **Cargo offloading hoist has capability to be relocated via LLT**
  - Can be relocated from Lander 1 to Lander 2 via CMS
  - Hoist has remotely controllable base attachment/interface
- **Power cable manifested w/ Lander 2 is actually for Lander 3 (Lab)**
  - Hardwired to Lander 2 CB-2 box, but left unused pending Lander 3 arrival
- **Only one cable connection required in field:**
  - Lander 1 power output cable to Lander 2 converter box CB-2



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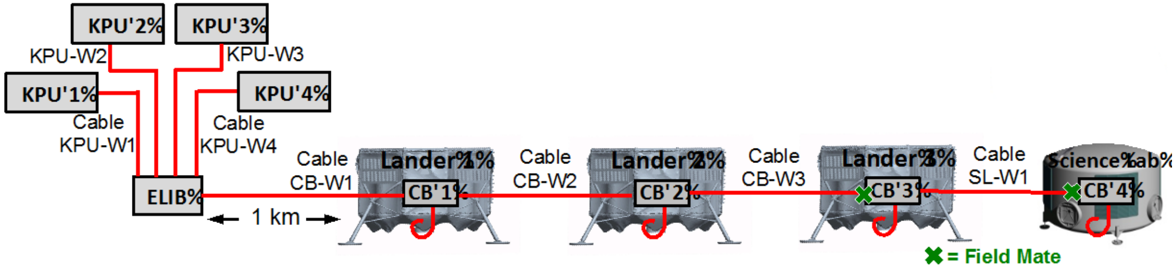
Outpost Integration – 27t Lander Mission 3

- **Pre-crew Mission 3 outpost integration covers manifest for only 27t Lander 3**
  - Power cable/spool (for Mission 3 Science Lab)
  - Cargo offload hoist and ramp (assumed)
  - Small Pressurized Rover (SPR)
  - Cargo Mobility System (CMS)
  - Science Facility (Lab)
  - Logistics module
  - Small cargo
  - Consummables

- **Task timelines for Mission 3 outpost integration sequence:**
  1. Deploy/connect power cable from Lander 2 CB-2 to Lander 3 CB-3
  2. Deploy offloading hoist/crane and ramp
  3. Offload SPR and CMS (w/ Science Lab)
  4. Deploy/connect power cable from Lander 3 CB-3 to Science Lab
  5. Offload/stow logistics module
  6. Offload/stow small cargo (pallet) and consummables (pallet)

Outpost Integration – Mission 3 Assumptions

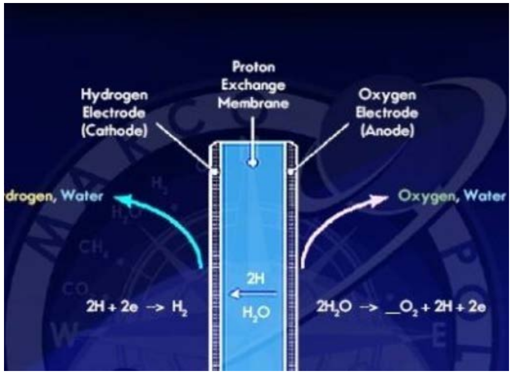
- **Science Lab is flown mounted to cargo mobility chassis for ease of offload**
- **Cargo Mobility System (CMS) could be ATHLETE/Tri-ATHLETE for Mission 3**
  - ATHLETE is better suited for transporting the Science Lab, esp. if already mounted
  - Tri-ATHLETE's autonomously place Lab after traverse to science station, then auto-dock
- **Power cable manifested on Lander 3 is for Science Facility (Lab)**
  - Hardwired to Lander 3 converter box (CB-3) and connected to Lab following deployment
- **Only two cable connections required in field:**
  - Lander 2 CB-W3 cable to Lander 3 converter box CB-3
  - Lander 3 SL-W1 cable to Science Lab interface



ISRU O_2 Production & MAV Fueling Sequence – Description

(For case where ISRU plant is isolated from Lander/MAV)

- **Description: O_2 production from atmospheric CO_2 and transfer to MAV tank**
  - Oxygen plant configuration #1 checkout and start of production operations
  - ISRU systems pressurization and reactor activation
  - Carbon dioxide acquisition and Solid Oxide Electrolyzer (SOE) processing
  - Oxygen collection, liquefaction, and characterization
  - Begin transfer of liquid oxygen to MAV storage tank
- **Assumptions:**
  - ISRU plant not preconnected to MAV on lander, as in the case of Mission 1 (shown earlier)
  - Robotic rover has fine manipulation capability (e.g., for valves, QD's)
  - Most ISRU ops can be automated and continued through LOS periods
  - Overall production sequence continues automated through LOS
  - Task with no durations identified by task estimated at 3 hours each
  - Fuel transfer a separate sequence, since may not be immediately after O_2 liquefaction
  - MAV tank loading not good candidate for autonomous ops during LOS periods
    - > LLT recommended for near real-time control/monitoring
  - MAV tank loading can be completed within approx. 4 hours, with interruptions acceptable during LOS periods
- **Latency/LOS sensitivity for ISRU sequence:**
  - Assessed latency/LOS sensitivity: **2**
  - Rationale: Although O_2 production tasks are generally automated, MAV tank transfer ops necessitate near real-time LLT (15-30 min safing time)



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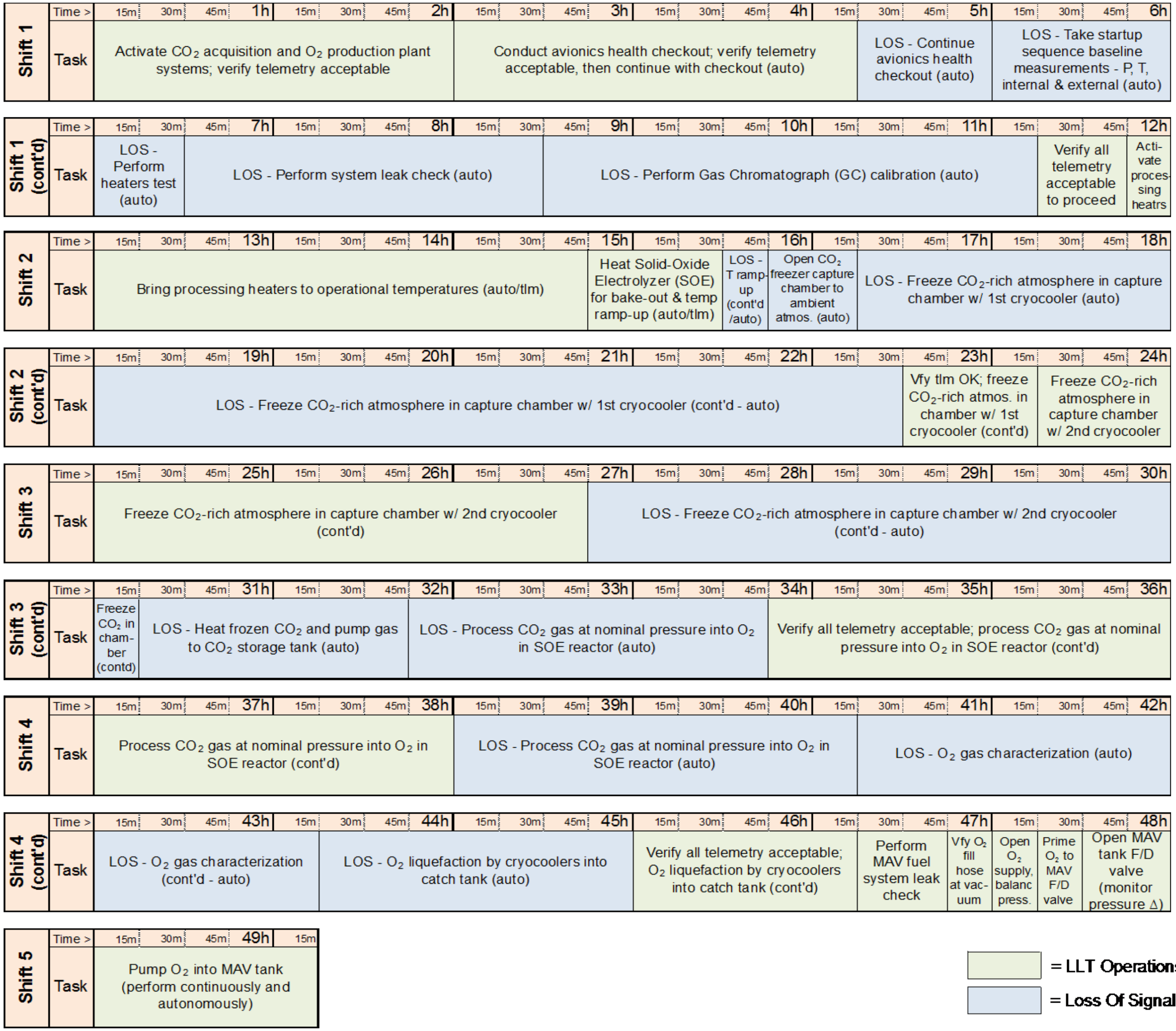
Outpost Integration – Representative Timeline

ISRU Oxygen Production and MAV Fueling Startup



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
	Task	Activate CO_2 acquisition and O_2 production plant systems; verify telemetry acceptable								Conduct avionics health checkout; verify telemetry acceptable, then continue with checkout (auto)									LOS - Continue avionics health checkout (auto)			LOS - Take startup sequence baseline measurements - P, T, internal & external (auto)			

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
	Task	LOS - Perform heaters test (auto)		LOS - Perform system leak check (auto)								LOS - Perform Gas Chromatograph (GC) calibration (auto)											Verify all telemetry acceptable to proceed		Activate processing heatrs

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	Bring processing heaters to operational temperatures (auto/tlm)											Heat Solid-Oxide Electrolyzer (SOE) for bake-out & temp ramp-up (auto/tlm)			LOS - T ramp-up (cont'd /auto)	Open CO_2 freezer capture chamber to ambient atmos. (auto)		LOS - Freeze CO_2-rich atmosphere in capture chamber w/ 1st cryocooler (auto)						

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
	Task	LOS - Freeze CO_2-rich atmosphere in capture chamber w/ 1st cryocooler (cont'd - auto)																		Vfy tlm OK; freeze CO_2-rich atmos. in chamber w/ 1st cryocooler (cont'd)			Freeze CO_2-rich atmosphere in capture chamber w/ 2nd cryocooler		

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
	Task	Freeze CO_2-rich atmosphere in capture chamber w/ 2nd cryocooler (cont'd)											LOS - Freeze CO_2-rich atmosphere in capture chamber w/ 2nd cryocooler (cont'd - auto)												

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
	Task	Freeze CO_2 in chamber (contd)	LOS - Heat frozen CO_2 and pump gas to CO_2 storage tank (auto)						LOS - Process CO_2 gas at nominal pressure into O_2 in SOE reactor (auto)								Verify all telemetry acceptable; process CO_2 gas at nominal pressure into O_2 in SOE reactor (cont'd)								

Shift 4	Time >	15m	30m	45m	37h	15m	30m	45m	38h	15m	30m	45m	39h	15m	30m	45m	40h	15m	30m	45m	41h	15m	30m	45m	42h
	Task	Process CO_2 gas at nominal pressure into O_2 in SOE reactor (cont'd)								LOS - Process CO_2 gas at nominal pressure into O_2 in SOE reactor (auto)									LOS - O_2 gas characterization (auto)						

Shift 4 (cont'd)	Time >	15m	30m	45m	43h	15m	30m	45m	44h	15m	30m	45m	45h	15m	30m	45m	46h	15m	30m	45m	47h	15m	30m	45m	48h
	Task	LOS - O_2 gas characterization (cont'd - auto)					LOS - O_2 liquefaction by cryocoolers into catch tank (auto)							Verify all telemetry acceptable; O_2 liquefaction by cryocoolers into catch tank (cont'd)					Perform MAV fuel system leak check		Vfy O_2 fill hose at vacuum	Open O_2 supply, balanc press.	Prime O_2 to MAV F/D valve	Open MAV tank F/D valve (monitor pressure Δ)	

Shift 5	Time >	15m	30m	45m	49h	15m
	Task	Pump O_2 into MAV tank (perform continuously and autonomously)				

🟩 = LLT Operations

🟦 = Loss Of Signal (LOS)

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Mars Operations via Low-Latency Telerobotics

Science Operations

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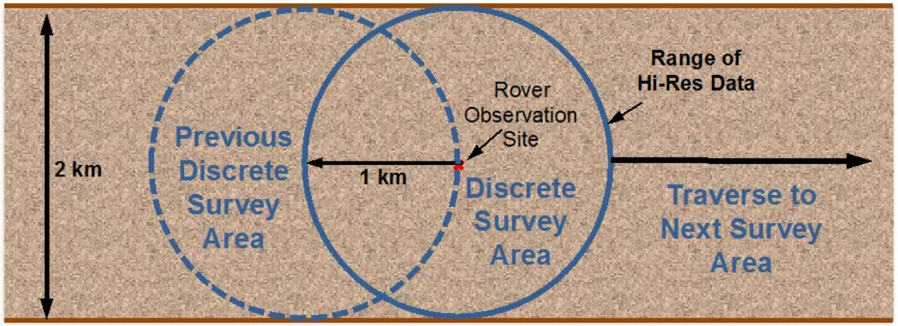
Outpost Science via LLT (Mission S) - Overview

- **Proposed search for extant life on Mars**
  - Relies on companion rovers using both LLT (proximity comm) and HLT (earth comm)
  - Designed to enable pre-landing ops by crew in Mars system, or from earth following departure
  - LLT ops possible during subsequent crewed missions
  - HLT used for functional testing and other latency-independent task
  - A "Mission S" that is either supplemental or in parallel with manifested missions
- **LLT/HLT rovers**
  - Recon rover ("Lewis"): for site reconnaissance and sample transport
  - Sampling rover ("Clarke"): for sample acquisition, analysis, and prep for transport
  - Instrumental Ground Operations Rover ("IGOR") introduced for consideration:
    - To reduce potential cross-contamination by performing sample retrieval
    - To "trail blaze" path from outcrop site to science lab, to facility traverse by Lewis
    - To serve as a companion rover for maintenance or upgrade to other rovers
  - All would benefit from modularity for component/instrument upgrades or maintenance
- **Surface assets required already included in EMC mission manifests**
  - Two rovers, crew support (CS) and special region (SR): can be equipped as Lewis & Clarke
  - "Allocated payload": can serve as supplemental science support or third rover
  - Science facility/lab: can serve for detailed and on-going sample analysis
- **Scientific data collection**
  - Multispectral survey (visible, IR, etc.)
  - LIDAR scans (1 km radius)
  - Surface samples at outcrops
  - Core samples (2- to 3-meter depth)

Outpost Science via LLT – Reconnaissance Rover "Lewis"

- **Purposes**
  - Locate, validate, and evaluate outcrops of potential scientific significance
  - Assess trafficability of terrain to/from science sites, including mapping for hazards
  - Serve to highgrade station locations for the larger science rover (Clarke)
- **Features/capabilities**
  - No direct contact with surface/outcrop, i.e., no arm/manipulator
  - Characterized as "punctuated fast" LLT rover, traversing several km/day (max. 10 km/hr)
  - Autonavigation capability (i.e., prox sensors, maps, etc.)
  - Imaging of geologic structure, texture, morphology; ability to "see through" dust
  - Capable of detailed imaging/LIDARing to approx. 1-km radius from observation point
  - Therefore: 2-km swaths of precise topographic data, incl. outcrop locations & trafficability
  - Storage for transporting cores retrieved by Clarke to science lab for detailed analysis
- **Equipped with LLT instruments having quick-return data capability**
  - LIDAR scans of high-elevation terrain adjacent to landing site, up to 3 km distance
  - Cameras: visible, multispectral
  - Remote-sensing chemical/mineral spectrometer



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Outpost Science via LLT – Sampling Rover "Clarke"

- **Purposes**
  - Detailed science survey and data collection at previously identified high-interest sites
  - Sample acquisition for detailed analysis, including excavation and coring
  - On-board highgrading assessment of samples for transport to science lab
- **Features/capabilities**
  - Larger, more capable science
  - Direct contact with surface/outcrop: arm/manipulator, drill/core sampler
  - Autonavigation capability (i.e., prox sensors, maps, etc.)
  - Slower, more deliberate manuevering than Lewis (est. 1 km/hr max.)
  - Chemistry & mineralogy measurement (H_2O, trace, etc.)
- **Equipped w/ LLT instruments for sample acq./analysis**
  - Visible cameras
  - High-def imager to help assess site as candidate for coring
  - Onboard sample analysis lab (chemistry, minerology)
  - Excavator for sampling regolith of interest
  - 2-cm core sample system with 2-3 meter depth capability
  - Core assessment system: chemical examination, weighing
  - Manipulator to handle, store, and transfer samples to Lewis
  - Surface brush

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Outpost Science via LLT – Recon & Sampling Operations

- **Reconnaissance**
  - Lewis traverses through compelling science regions in 1-km overlapping areas
  - Lewis surveys for candidate science collection sites; transmits data to local (LLT) crew
  - Crew analyzes data to determine surface conditions of path to outcrops, to ensure safe traverse of heavier Clarke rover
  - If no safe path is found, then site is deselected for investigation
  - Recon continues throughout campaign, in parallel with Clarke science data gathering
  - Proposed third rover (IGOR) could be utilized to conduct LiDAR/vis recon of path to lab
- **Science survey and sample acquisition**
  - Clarke science rover traverses to selected science site
  - Outcrop at site is evaluated, crew determines if/where the site should be cored
  - Collected core is analyzed by Clarke to determine if sample return to lab is required
  - Exposed core is discarded at a proximal location
  - If lab analysis is indicated, then two new cores are collected
- **Sample collection and transport**
  - Clarke returns to best site to retrieve core samples; est.10 km
  - Lewis ceases recon; rendezvouses with Clarke at retrieval site
  - Clarke uses manipulator to transfer core samples to Lewis
  - Lewis rapidly traverses w/ cores from site to lab; est. 50 km

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Outpost Science – Representative Timeline

Sample 1 Acquisition & Analysis (Each Outcrop Site)

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
	Task	Clarke rover returns to best outcrop site for sampling (auto)																	LOS - Clarke traverse continues (auto)						

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
	Task	LOS - Clarke traverse continues (auto)																LOS (cont'd)					Prepare drill for core sampling (e.g., prep/setup drill, unstow/install bit)		

(Drill prep continues for next 66 hours)

Shift 7 (cont'd)	Time >	15m	30m	45m	79h	15m	30m	45m	80h	15m	30m	45m	81h	15m	30m	45m	82h	15m	30m	45m	83h	15m	30m	45m	84h
	Task	LOS			Prepare drill for core sampling (cont'd)						Position drill at first core location				Contingency/wait time							LOS			

Shift 8	Time >	15m	30m	45m	85h	15m	30m	45m	86h	15m	30m	45m	87h	15m	30m	45m	88h	15m	30m	45m	89h	15m	30m	45m	90h
	Task	LOS																							

Shift 8 (cont'd)	Time >	15m	30m	45m	91h	15m	30m	45m	92h	15m	30m	45m	93h	15m	30m	45m	94h	15m	30m	45m	95h	15m	30m	45m	96h
	Task	Drill first core sample												Remove first core sample					LOS						

Shift 9	Time >	15m	30m	45m	97h	15m	30m	45m	98h	15m	30m	45m	99h	15m	30m	45m	100h	15m	30m	45m	101h	15m	30m	45m	102h
	Task	LOS																					Remove first core sample (cont'd)		

Shift 9 (cont'd)	Time >	15m	30m	45m	103h	15m	30m	45m	104h	15m	30m	45m	105h	15m	30m
	Task	Prepare first sample for on-site analysis								Begin core sample analysis (auto)					

(Sample analysis continues autonomously for next 9-10 days)

🟩 = LLT Operation of Clarke Science Rover

🟪 = Wait/Contingency Time

🟦 = Loss Of Signal (LOS)

"Auto" = Can be performed autonomously

To be presented by M. Wright at the 3rd International Conference on the Exploration of Phobos and Deimos, NASA Ames Research Center, Moffett Field, CA, July 18-19, 2016.

Notional Dual Science Rover Traverses at *Centauri-Montes*

LLT Dual Science Rover Mission Overview

- **Focus of research at region of scientific interest: To determine if life ever existed on Mars**
  - Characterize complex organics
  - Characterize spatial distribution of chemical and/or isotopic signatures
  - Characterize morphology or morphological distribution of mineralogical signatures
  - Identify temporal chemical variations requiring life
- **Proposed traverses include four routes covering 50-km radial distance from landing site/base**
  - Base is on edge of Penticton crater having active gully
  - 50 km mobility offers adequate diversity of samples
  - Preferred landing site located central to the four routes
- **Dual science rover operations concept (ops con)**
  - Faster-moving reconnaissance rover conducts preliminary site data gathering; identifies sites for sample rover
  - Slower-moving sampling rover collects and analyzes samples at sites of interest

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LLT Reconnaissance Rover Capabilities and Instruments

- **Purposes**
  - Locate, validate, and evaluate areas of potential scientific significance
  - Assess trafficability of terrain to/from science sites, including mapping for hazards
  - Serve to high-grade station locations for the slower sampling rover
- **Features/capabilities**
  - No direct contact with surface/outcrop, i.e., no arm/manipulator
  - Characterized as “punctuated fast” LLT rover, traversing several km/day (avg. 5 km/hr) but stopping periodically for relatively quick investigation
  - Auto-navigation capability (i.e., prox sensors, maps, etc.)
  - Imaging of geologic structure, texture, morphology; ability to “see through” dust
- **Equipped with LLT instruments having quick-return data capability**
  - Panorama/stereo cameras: visible, multispectral
  - LIDAR
  - Magnetometer
  - Meteorology and dust environment
  - Neutron/gamma-ray spectrometer
  - Quadrapole mass spectrometer (atmospheric)
  - Raman/Laser-Induced Breakdown Spectroscopy (LIBS) / X-ray fluorescence spectrometer
  - Tunable laser spectrometer (atmospheric)
  - Remote-sensing chemical/mineral spectrometer
  - Voltameter
- **Instrument resource requirements:**
  - Total instrument mass: 48 kg
  - Total power (all-on average): 146 W op, 155 W peak

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LLT Sampling Rover Capabilities and Instruments

- **Purposes**
  - Detailed science survey and data collection at previously identified high-interest sites
  - Sample acquisition for detailed analysis, including scooping and drilling
  - On-board sample analysis and science return/assessment
- **Features/capabilities**
  - Science sample acquisition and detailed analysis
  - Direct contact with surface/outcrop: arm/manipulator, drilling sampler
  - Auto-navigation capability (i.e., proximity sensors, maps, etc.)
  - Slower, more deliberate manuevering than reconn rover (est. 1 km/hr)
  - Chemistry and mineralogy measurement (H_2O, trace, etc.)
  - Signs of life (SoL) detection (TBD)
- **Equipped w/ LLT instruments for sample acquisition/analysis**
  - Visible cameras: fine imagery (hand-lens scale)
  - Pyrolysis gas chromatograph mass spectrometer (GCMS)
  - Rock abrasion/drilling tool
  - Rock dust removal tool
  - Sample acquisition and handling (surface, subsurface)
  - Signs of life detector
  - X-ray diffraction/fluorescence spectrometer (XRD/F)
  - Satellite geophysics station (deployable)
- **Instrument resource requirements:**
  - Total instrument mass: 69 kg (not incl. geophysics station)
  - Total power (all-on average): 175 W op, 420 W peak

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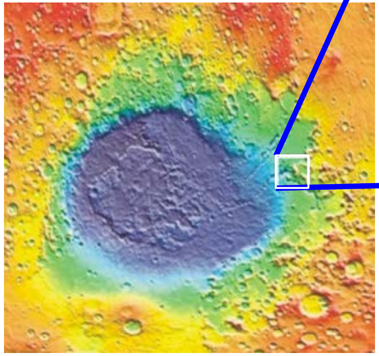
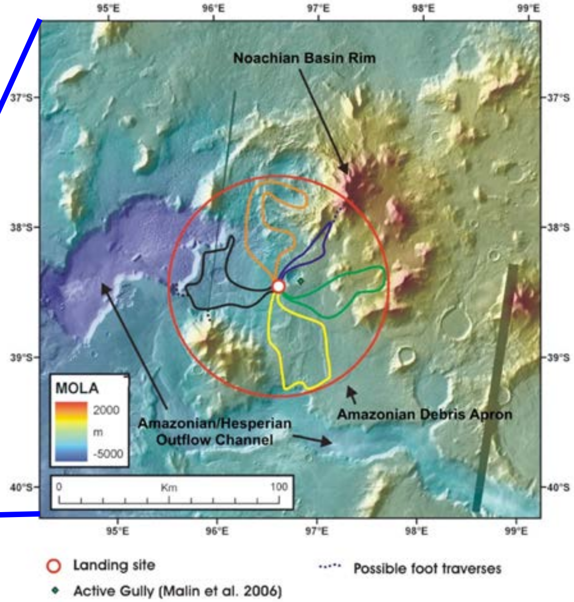
Candidate Traverse Region: Centauri Montes (CM)

- **Based on candidate Mars traverses for scientific exploration**
  - Proposed by the Mars Exploration Program Analysis Group (MEPAG) Human Exploration of Mars Science Analysis Group (HEM-SAG), 2008
  - Centauri Montes (CM) located on rim of Hellas Basin characterized by remnant massifs
- **Focus of research at CM region: to determine if life ever existed on Mars**
  - Characterize complex organics
  - Characterize spatial distribution of chemical and/or isotopic signatures
  - Characterize morphology or morphological distribution of mineralogical signatures
  - Identify temporal chemical variations requiring life
- **Proposed traverses include four routes covering 50-km radial distance from landing site/base**
  - Base on edge of Penticton crater having active gully
  - 50 km mobility offers adequate diversity of samples
  - Preferred landing site located central to the 4 routes
  - Distance affords sufficient safety



MOLA Image of Hellas Basin

showing location of CM region (white square)



CM Region

with traverses identified

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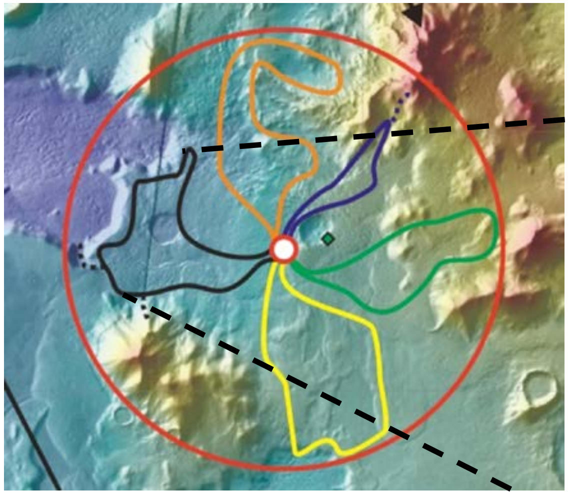
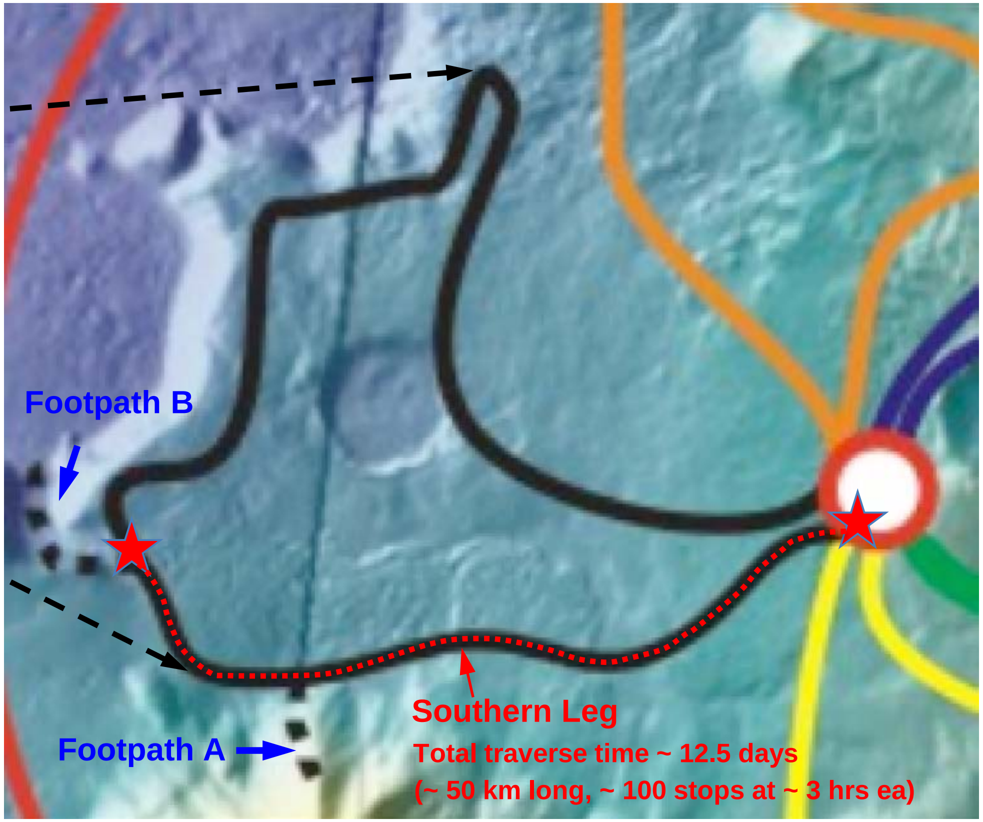
Representative CM Traverse Route

- **Black (38.5S/96E) traverse loop selected for representative CM traverse**
  - Estimated black route length to/from landing site/base: 150 km
- **Southern leg of loop shown (red dotted line) is approx. 50 km long**
  - Between base and farthest of two “footpath” excursion/spur traverse routes
  - Science recon stops proposed every 500 m (reasonable distance given overall duration)
  - Total of 100 stops along leg (red dots)
  - Two footpaths identified (by HEM-SAG): mid-route and end of leg (blue arrows)



CM Region
with traverses identified
(50 km radius)



Total traverse time ~ 12.5 days
(~ 50 km long, ~ 100 stops at ~ 3 hrs ea)

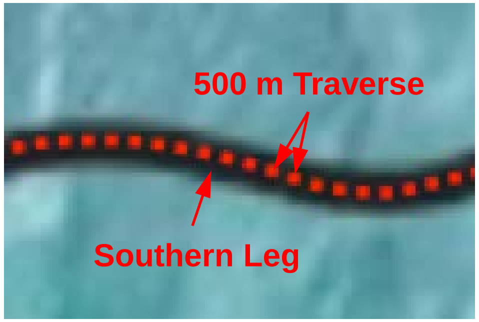
Black Traverse Loop
with southern leg and
footpaths identified

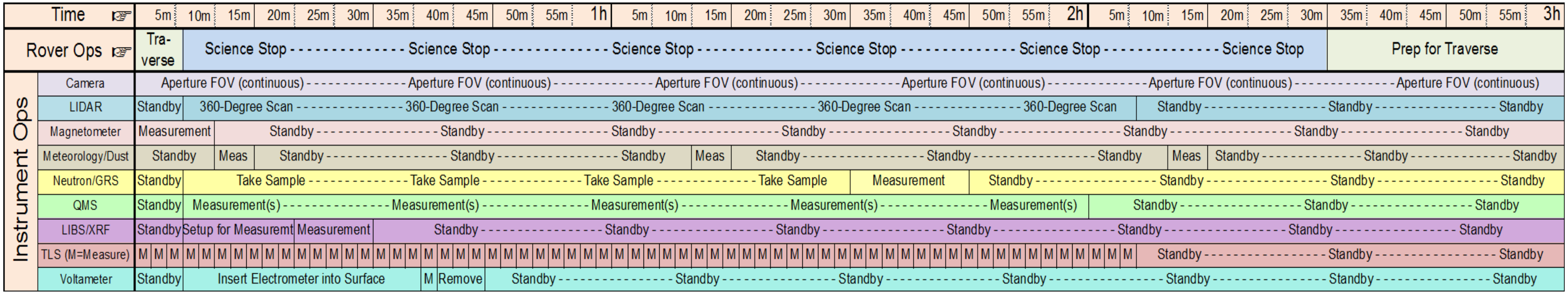
LLT Constraints and Assumptions

- **General LLT Constraints**
  - 300 msec maximum latency for operator comfort (per Redenbo, et al., Caterpillar, 2013)
  - Discrete tasks are macro-controlled (vs. joystick)
- **Assumptions**
  - No loss-of-signal (LOS) periods assumed in timelines, i.e., continuous comm coverage
  - Power system sufficient to enable traverses, climbs, and instrument ops as described
  - Soil/dust samples assumed to be auto-transferred to analytic lab following collection
  - Drill bit replacement (if necessary) can be performed in parallel with sample analyses
  - 25% of reconn rover stops are selected for detailed science data/sample collection by sampling rover
  - No unusually complex tasks not already within the rover’s capabilities
  - No extensive time required to deploy geophysics stations
  - No sampling on footpath upon return to trailhead (although opportunistic stops possible)

Southern Leg 500 m Traverse/Stop Timeline (Reconn Rover)

- **Timeline covers one 500m traverse and science stop**
  - On black loop route map, distance between each red dot on southern leg
  - At average 5 km/hr, point-point traverse time: 6 min
  - Remaining time is predominately science data collection
  - Overall allocated duration: 3 hours
- **Rover takes science data both enroute and while stationary**
  - Data taken while traversing: imaging, B field, TLS (atmosphere)
  - Data taken at science stops: imaging, meteorology/dust, B field neutron/GRS, QMS, LIBS/XRF, TLS, voltameter
- **Timeline repeated for each of the 100 sites**
  - Total traverse time along southern leg (incl. stops): 12.5 days





Time ☞		5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	1h	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	2h	5m	10m	15m	20m	25m	30m	35m	40m	45m	50m	55m	3h
Rover Ops ☞		Traverse	Science Stop - - -					Science Stop - - -					Science Stop - - -						Science Stop - - -					Science Stop - - -					Science Stop			Prep for Traverse					
Instrument Ops	Camera	Aperture FOV (continuous) - - -						Aperture FOV (continuous) - - -							Aperture FOV (continuous) - - -						Aperture FOV (continuous) - - -						Aperture FOV (continuous) - - -						Aperture FOV (continuous)				
	LIDAR	Standby	360-Degree Scan - - -					360-Degree Scan - - -					360-Degree Scan - - -						360-Degree Scan - - -					360-Degree Scan			Standby - - -					Standby - - -				Standby	
	Magnetometer	Measurement			Standby - - -				Standby - - -				Standby - - -					Standby - - -				Standby - - -				Standby - - -					Standby - - -				Standby		
	Meteorology/Dust	Standby		Meas	Standby - - -				Standby - - -					Standby		Meas	Standby - - -				Standby - - -					Standby		Meas	Standby - - -			Standby - - -				Standby	
	Neutron/GRS	Standby		Take Sample - - -				Take Sample - - -					Take Sample - - -				Take Sample			Measurement			Standby - - -				Standby - - -					Standby - - -				Standby	
	QMS	Standby	Measurement(s) - - -					Measurement(s) - - -					Measurement(s) - - -					Measurement(s) - - -					Measurement(s)				Standby - - -				Standby - - -				Standby		
	LIBS/XRF	Standby	Setup for Measuremt			Measurement			Standby - - -				Standby - - -					Standby - - -				Standby - - -				Standby - - -				Standby - - -					Standby		
	TLS (M=Measure)	M M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	M M M	M M	Standby - - -					Standby - - -				Standby	
	Voltameter	Standby	Insert Electrometer into Surface						M Remove		Standby - - -				Standby - - -				Standby - - -				Standby - - -				Standby - - -					Standby - - -				Standby	

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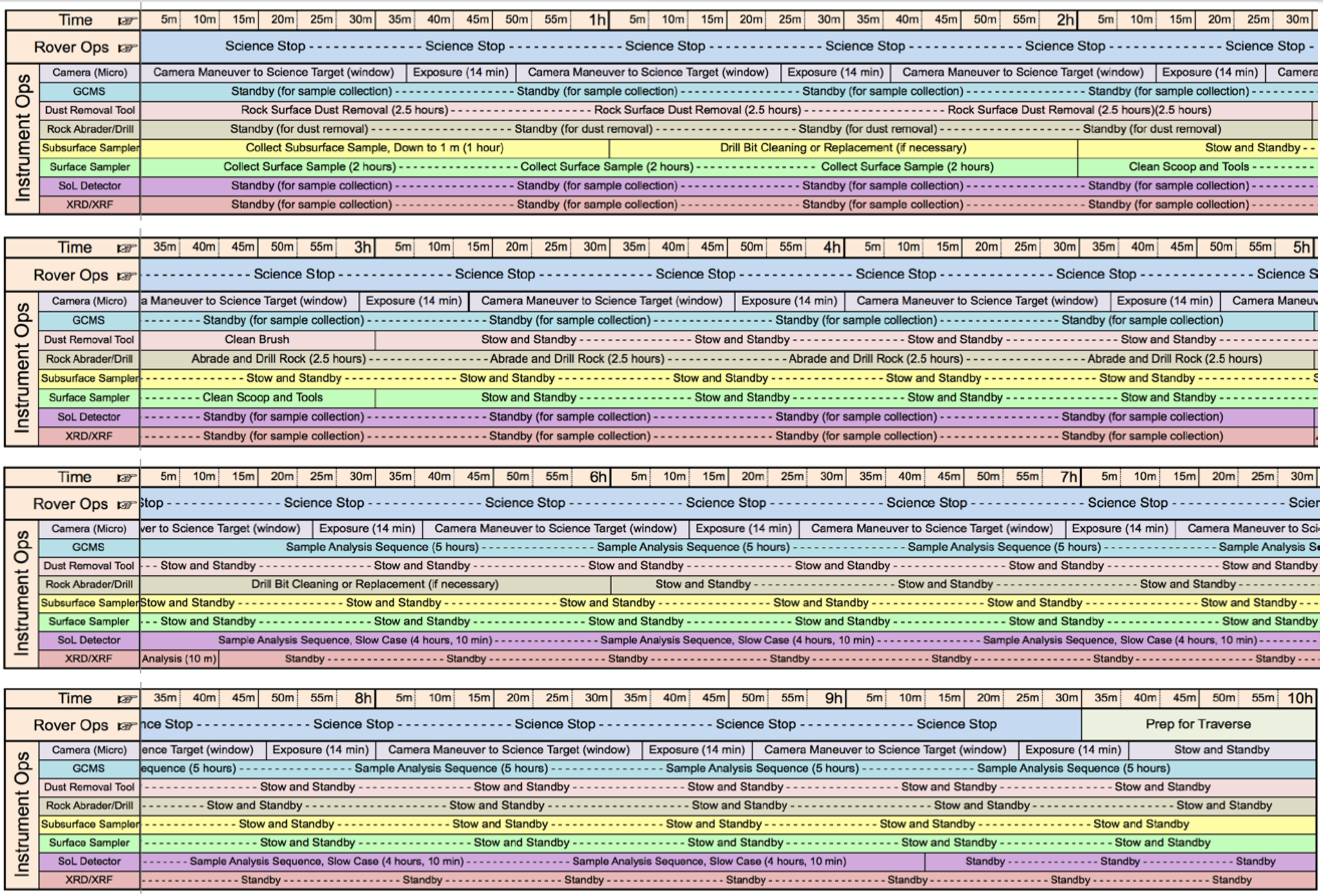
Southern Leg Sampling Stop Timeline (Sampling Rover)

- **Timeline covers one science sampling stop**
  - Traverse time not included, since will vary depending on distance to selected site
  - Only one solid sample (i.e., rock dust, soil, drill) taken per 10-hour stop assumed
- **Rover collects and analyses samples while stationary**
  - Data sampling at stops: imaging, rock abrasion/drilling/dust removal, subsurface drilling, and scooping with observation tray
  - Soil/dust samples assumed auto-transferred to analytic lab following collection (few min)
  - Sample analysis during stops: GCMS, Signs of Life (SoL), XRD/XRF
- **Timeline drivers are rock surface sampling and analyses**
  - Dust removal: 2.5 hours
  - Drilling and abrading: 1-4 hours, or avg. 2.5 hours
  - Analysis of collected samples: 4-6 hours, or avg. 5 hours
  - Icebreaker-3 type drill assumed for subsurface sampling: 1 hour
  - Drill bit replacement (if necessary), in parallel with sample analyses: 1 hour (each)
  - Total average duration of one science stop: 10 hours
- **Timeline repeated for each sample stop**
  - Since slower sampling rover relies on faster reconn rover to identify sampling site, some lag time associated with reaching sample site following identification
  - Assuming 25% of reconn rover stops are selected for sampling (25), total traverse time for sampler along southern leg at 1 km/hr (including stops): 12.5 days
  - Note that if rover were faster (e.g., 5 km/hr), total time would be 10.8 days

Southern Leg Sampling Stop Timeline (Sampling Rover)



Time		5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 1h 5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 2h 5m 10m 15m 20m 25m 30m
Rover Ops		Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop -
Instrument Ops	Camera (Micro)	Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera
	GCMS	Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - -
	Dust Removal Tool	Rock Surface Dust Removal (2.5 hours) - - - - - - - - - - - - - - - - - - - Rock Surface Dust Removal (2.5 hours) - - - - - - - - - - - - - - - - - - - Rock Surface Dust Removal (2.5 hours)(2.5 hours)
	Rock Abrader/Drill	Standby (for dust removal) - - - - - - - - - - - - - - - - - - - Standby (for dust removal) - - - - - - - - - - - - - - - - - - - Standby (for dust removal) - - - - - - - - - - - - - - - - - - - Standby (for dust removal)
	Subsurface Sampler	Collect Subsurface Sample, Down to 1 m (1 hour) | Drill Bit Cleaning or Replacement (if necessary) | Stow and Standby - -
	Surface Sampler	Collect Surface Sample (2 hours) - - - - - - - - - - - - - - - - Collect Surface Sample (2 hours) - - - - - - - - - - - - - - - - Collect Surface Sample (2 hours) | Clean Scoop and Tools - - - - - - - -
	SoL Detector	Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - -
	XRD/XRF	Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - -

Time		35m 40m 45m 50m 55m 3h 5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 4h 5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 5h
Rover Ops		- - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science S
Instrument Ops	Camera (Micro)	a Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuv
	GCMS	- - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection)
	Dust Removal Tool	Clean Brush | Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - -
	Rock Abrader/Drill	Abrade and Drill Rock (2.5 hours) - - - - - - - - - - - - - - - - - Abrade and Drill Rock (2.5 hours) - - - - - - - - - - - - - - - - - Abrade and Drill Rock (2.5 hours) - - - - - - - - - - - - - - - - - Abrade and Drill Rock (2.5 hours)
	Subsurface Sampler	- - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - S
	Surface Sampler	- - - - - - - - Clean Scoop and Tools | Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - -
	SoL Detector	- - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection)
	XRD/XRF	- - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection) - - - - - - - - - - - - - - - - Standby (for sample collection)

Time		5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 6h 5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 7h 5m 10m 15m 20m 25m 30m
Rover Ops		top - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Scier
Instrument Ops	Camera (Micro)	ver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Sci
	GCMS	Sample Analysis Sequence (5 hours) - - - - - - - - - - - - - - - Sample Analysis Sequence (5 hours) - - - - - - - - - - - - - - - Sample Analysis Sequence (5 hours) - - - - - - - - - - - - - - - Sample Analysis Se
	Dust Removal Tool	- - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby
	Rock Abrader/Drill	Drill Bit Cleaning or Replacement (if necessary) | Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - -
	Subsurface Sampler	Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - -
	Surface Sampler	- - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby
	SoL Detector	Sample Analysis Sequence, Slow Case (4 hours, 10 min) - - - - - - - - - - - - - - - Sample Analysis Sequence, Slow Case (4 hours, 10 min) - - - - - - - - - - - - - - - Sample Analysis Sequence, Slow Case (4 hours, 10 min) - - - - - - - -
	XRD/XRF	Analysis (10 m) | Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - -

Time		35m 40m 45m 50m 55m 8h 5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 9h 5m 10m 15m 20m 25m 30m 35m 40m 45m 50m 55m 10h
Rover Ops		nce Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop - - - - - - - - - - - - - - Science Stop | Prep for Traverse
Instrument Ops	Camera (Micro)	ence Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Camera Maneuver to Science Target (window) | Exposure (14 min) | Stow and Standby
	GCMS	equence (5 hours) - - - - - - - - - - - - - - - Sample Analysis Sequence (5 hours) - - - - - - - - - - - - - - - Sample Analysis Sequence (5 hours) - - - - - - - - - - - - - - - Sample Analysis Sequence (5 hours)
	Dust Removal Tool	- - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby
	Rock Abrader/Drill	- - - - - - - - Stow and Standby - - - - - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - - - - - Stow and Standby
	Subsurface Sampler	- - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby
	Surface Sampler	- - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby - - - - - - - - - - - - - - - Stow and Standby
	SoL Detector	- - - - - - Sample Analysis Sequence, Slow Case (4 hours, 10 min) - - - - - - - - - - - - - - - Sample Analysis Sequence, Slow Case (4 hours, 10 min) | Standby - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - Standby
	XRD/XRF	- - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby - - - - - - - - - - - - - - - - - Standby

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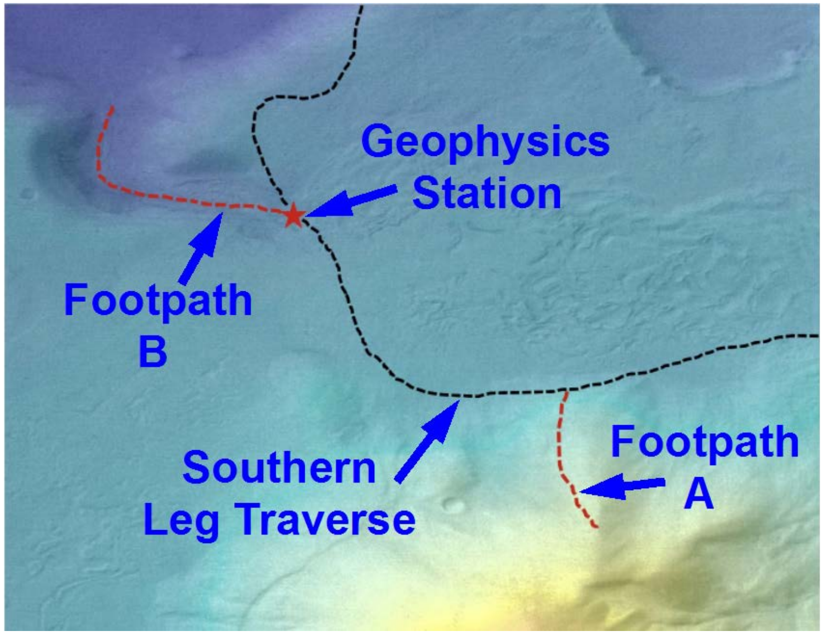
Southern Leg "Footpath" Routes (Sampling Rover)

- **Two locations identified (by HEM-SAG) along southern leg traverse route where spur trails intersect southern leg route**
  - Footpath A: approx. 35 km from base, up northern rim of Centauri Montes (to south)
  - Footpath B: west end of 50 km leg, down toward Amazonian/Hesperian outflow channel
- **More frequent stops than for southern leg traverse**
  - Approx. every 100 m along estimated 10 km-long footpaths, i.e., 100 science sites
  - Can do more dense sampling in areas of compelling science (e.g., significant outcrops)
  - Affords greater science resolution and opportunity to collect more samples at outcrops
  - Close up imagery as well as samples taken at each stop, esp. in areas of potentially significant scientific interest
- **Geophysics station deployed at Footpath B trailhead**
  - West end of southern leg traverse route
  - No unusually complex tasks or rover capabilities required



Overview of Footpaths A&B

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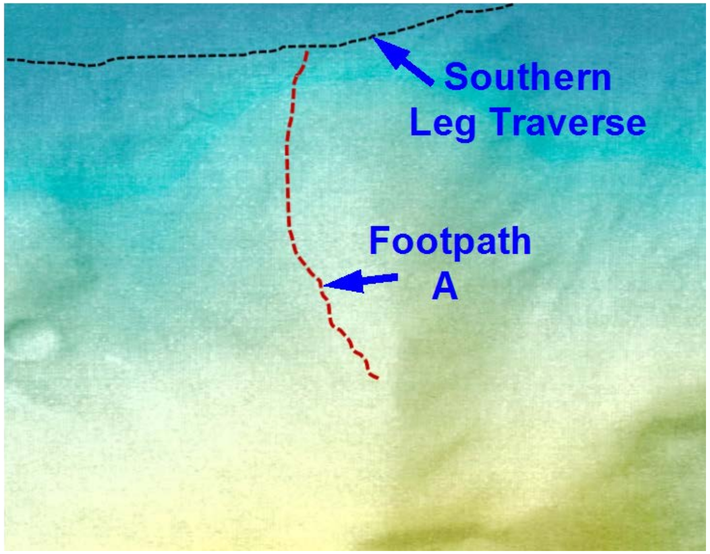
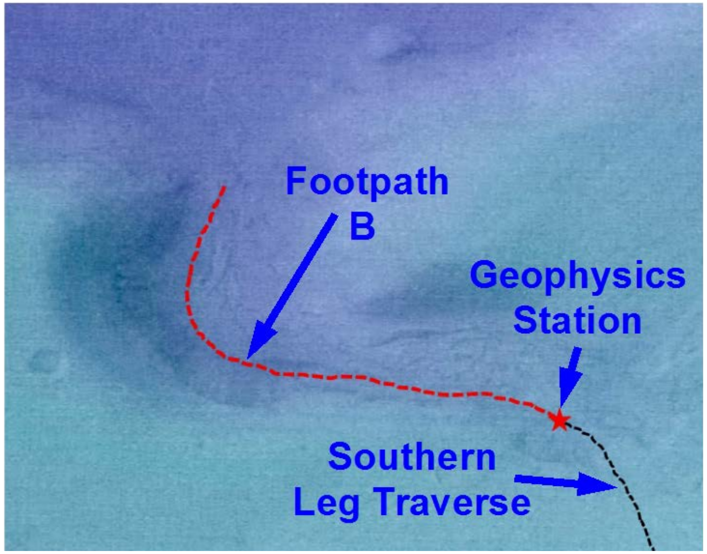
Footpath Traverses and Science Stops (Sampling Rover)

- **100 incremental 100-meter traverse/stop lengths along a given footpath**
  - Footpath traverses taken by sample rover (more deliberate, equipped for sampling)
  - At 1 km/hr, point-point traverse time for each 100 m traverse: 6 min
- **Traverse increments along footpath are predefined and short-distance**
  - Unlike for samples along southern leg, where sites are identified by reconn rover
  - Footpath science stop timeline same as traverse science stop: 10 hrs
- **Timeline repeated for each of the 100 science sites**
  - Science stops on outbound trip along footpath
  - Continuous traverse on return, although opportunistic science stops possible
  - Total round-trip time along one 10-km footpath (including stops): 42 days



Footpath A Detail



Footpath B Detail

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LLT Science Ops Considerations and Implications

- **Footpath Traverse Considerations**
  - In high incline areas, rover stability during sample acquisition needs to be considered
  - Obviously, significantly more power required for uphill traversing, so if solar/battery then more frequent recharging required
  - During footpath ops of sampling rover, parallel ops for reconn rover are TBD; may include continuing along black loop or standing by at trailhead if, e.g., sampling rover rescue or other servicing is required
- **Potential Issues/Implications**
  - Supply of replacement drill bits and tools is limited, so may be unable to take samples at all planned science stops
  - Extensive number of science stops w/ identical ops suggests automated sequences
  - But...science site high-grading and sample assessment benefits from crew involvement
  - Significant science “backroom” analysis on earth can inform Mars crew LLT activities
  - Traditional HLT science ops can be performed in parallel or interleaved with LLT ops
- **Value for Science Community**
  - The assumptions made here for these timelines provide a tool from which the science community can assess stops based on science prioritization
  - An alternative scheme would be to define a traverse of *X* distance that lasts *Y* number of days, that will enable *Z* number of stops within this assumed architecture

Science Planning Value of Timeline Analysis

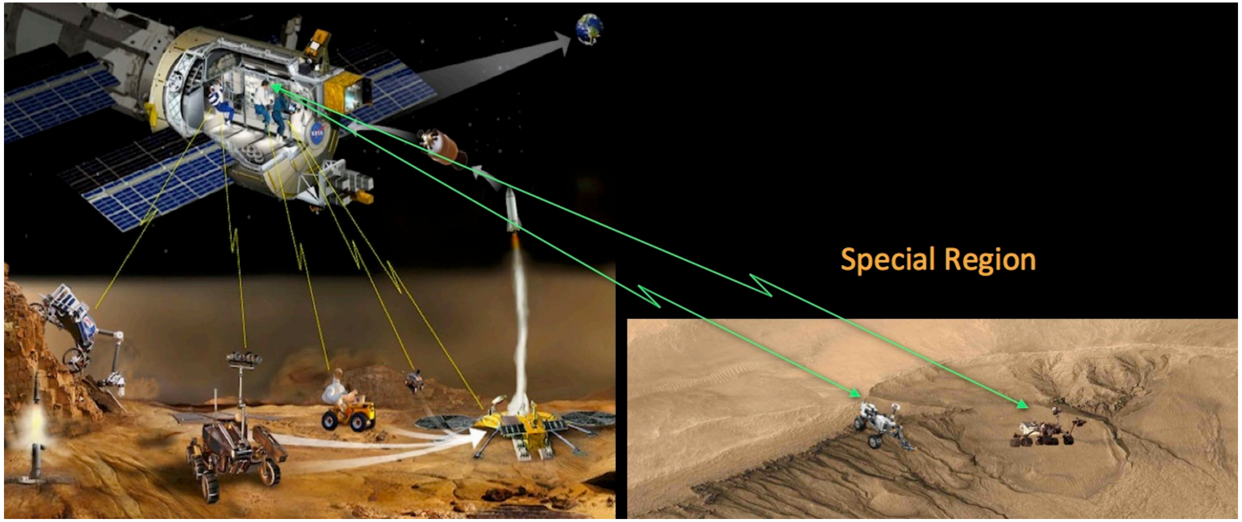
- **The science community's basis for approaching a traverse will always be based on a real-time evaluation of prioritizing science stops**
- **To a scientist, a traverse is a process of balancing how often you can stop within the time allotted vs. how important a given stop is**
  - Changes in real time based on your last measurement
  - Leverages advantage of LLT for scientific exploration
  - We make assumptions about a certain number of stops per distance only to initiate the timeline analysis
- **The result for the science community is an ability to:**
  - Gauge downstream impacts on the timeline
  - Understand the trade space based on science-motivated decisions to stop with either rover, or if drive times take longer than anticipated
- **This provides an ability to constrain technology development related to all aspects of mission design**
  - Drive speed, instrument measurement times, ability to co-operate (change-out bits while instrument measurements occur)
  - Ultimately influences instrument suite selection

Mars Operations via Low-Latency Telerobotics

Summary

Benefits of LLT to Mars Surface Exploration

- **LLT can be implemented with assets already in manifest (rovers, mobility)**
- **Surface prep via LLT can include features otherwise not possible**
  - Power pits, e.g., afford greater protection from KPU's while reducing mass for shielding
  - Reduced distance required from base also translates to reduced cable mass and deploy time, and less overall outpost area required
- **Environmental, contamination, and planetary protection concerns can be addressed and mitigated via LLT**
  - Partially addresses environmental, contamination, and planetary protection concerns by deferring crew landing until sufficient confidence is obtained
  - Special regions can be found and explored prior to landing crew and allow practice while crew is there
  - LLT could mitigate special region cross-contamination (caused by traversing between regions) by permitting more efficient remote cleaning by crew as needed



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Mars Operations via LLT – Observations & Implications

- **Many common tasks may be candidates for autonomy or supervised autonomy, with contingency intervention if necessary:**
  - Functional tests of surface assets (self-tests)
  - Standard soil analyses that can be performed during no-comm periods
  - Rover and CMS operations with autonomous positioning/guidance, hazard avoidance
  - Cable deployment once sequence is started, since basically a point-A to point-B traverse
  - However: Incorporating autonomous mechanisms (e.g., moving platforms, doors/latches, auto-nav systems) adds mass and some level of reliability risk
- **Robust surface asset functionality needed to optimize LLT effectiveness**
  - Diversity and difficulties of candidate LLT activities suggest multi-purpose assets
  - "Companion" assets (e.g., rovers) with distributed functionality
  - Manipulators are convenient enough tool to be included on multiple assets (lander, CMS)
- **Although Lander 1 offload hoist is assumed to be relocatable, there are benefits of having additional hoists on Lander 2 as well as the CMS's:**
  - Obviates need to relocate hardware from Lander 1 to Lander 2
  - Advantageous for post-offload utilization of all lander decks
  - Ensures hoist base structural interface integrity
  - Reduces risk to hoist and interface (damage, wear, contamination, etc.)

Mars Operations via LLT – Observations & Implications (cont'd)

- **Despite overhead (approx. 1/3 time) added per task and optimization of AOS utilization, additional contingency time may be required**
- **The high LOS-to-AOS ratio (for Phobos base) makes an orbiting comm/relay a potentially important asset to support LLT ops within a 500-day mission**
  - LOS periods typically more than double overall time to complete activity sequences
  - Depends on degree of autonomy and criticality of LLT for pre/post-landing ops
  - Can compare w/ Deimos LLT base, but 72-hour LOS period may reduce value of LLT
- **Lunar demonstration of LLT tasks could be beneficial to long-term Mars mission planning**
- **Value of telerobotic assets on Mars makes their functionality and operational life imperative**
  - Redundancy of capabilities required
  - Points to potential value of multiple smaller rovers that can perform only 1-2 types of tasks (vs. all-powerful "deluxe" rovers like MSL)
  - Each would backup/overlap capabilities of another
  - Rover-to-rover maintenance capability would be another valuable capability

Mars Operations via LLT – Some Challenges

- **Schedule constraints will likely necessitate more continuous ops**
  - More automation may be needed to fully utilize LOS periods
  - "Choreography" & planning across shifts and timelines with due respect to LOS periods
- **Choreography also required between LLT surface & concurrent orbit base ops**
  - E.g., moon science, housekeeping, crew, personal time/rest, etc.
  - Timelines based on 12-hour shifts, so only 12 hours of non-LLT time available (plus LOS)
- **Effective task/timeline execution when LOS is imminent**
  - Critical ops (e.g., lifts, drilling) must be completed or handled properly prior to LOS
  - Anomalies or other unexpected delays in completing critical tasks may require safing
- **Deploying cable during traverses involves some risk**
  - Necessitates slower traverse speeds, esp. in case of potential uncharted obstructions
  - Rover auto-detection of cable binding (e.g., tensiometer) may be required
- **Lander keep-alive power not established for a minimum of 27 hours**
  - At least 38 hours for Lander 1
  - Assumes individual offload timelines commence immediately after landing
  - Assumes tasks proceed continuously (excluding LOS periods)
- **Offloading requires some level of near-realtime control/monitoring**
  - Necessitated for safe operations: grappling, lifting, CG-awareness
  - Avoidance of other items or critical components during handling
- **Core drilling is tedious and may be op w/ highest probability of anomalies**
  - Binding/choking, heating, bit failure, etc.

Mars Operations via LLT – High-Level Considerations

- Telerobotics and automation will not be as simple for Mars exploration as on earth
- Terrestrial applications of robotics and telerobotics (e.g., automotive, mining, oceanographic) have benefited from decades of human experience (and in 1 g)
- Critical, high-cost, one-of-a-kind assets that take months/years to deploy and maintain on Mars warrant robust self-sufficiency
- Analysis is suggested regarding how LLT can impact Mars operations and assets, both positively and negatively
- More mechanisms and support equipment required for telerobotics require more mass (e.g., for mechanisms) and energy, offset by fewer ECLSS resources that would have been required for crew on surface
- Unexpected contingencies (i.e., “we don’t know what we don’t know”) suggest need for direct human interaction and intuition
- Science operations can be complex and unpredictable and warrant careful analysis, combined with extensive testing and training to assess how LLT may enhance or diminish science return
  - Much science may be better served by taking the time needed for proper scientific deliberation with “backroom” scientists on earth
  - Certain dynamic science phenomena may benefit from quick crew reaction and science judgment
  - Science return efficiency (e.g., science return per unit time) could go up significantly with real-time crew control of robotic and other science analysis assets

Mars Operations via LLT – Future Work

- Reprioritize tasks w/ input from broader community and “drill down” where needed
- Identify tasks that do not strictly require LLT (e.g., functionals); reserve for auto/HLT
- Revisit latency/LOS sensitivity assessment, consider input from sims
- Asset & architecture implications, e.g., lander classes, manifests, mission timeline,
- Discuss w/ broader community details of proposed offload sequences, cable interconnects, excavation requirements (incl. KPU power pits), flight covers & restraints, durations, etc.
- Crew implications: e.g., 4 vs. 2, dedicated crew on-task times for activities
- Human factors implications (e.g., effects of continuous 12-hr shifts)
- Assess differences in durations between LLT, HLT, and autononous ops
- Revisit task durations for higher fidelity timelines in light of data from demos (e.g., analogs, ISS) and statistical analyses (e.g. @risk)
- More effectively utilize LOS for tasks that could possibly be automated
- Study details of additional science measurements, such as: ISRU volatile detection, EM fields, meteorology, soil toxicity, biohazards
- Develop surface-to-surface LLT ops cons for post-crew missions
- Utilize tool or model for timeline generation (e.g., DSCOVR Timeline Mgmt Tool)
- Consider Lewis traverse times in light of unknowns from outcrop sites to science lab, and potential benefit of proposed IGOR rover as trail-blazer
- Compare Phobos ops cons and timelines with Deimos or orbiting crew station

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Mars Operations via Low-Latency Telerobotics

Backup
Material

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Mars Outpost Pre-Crew Mission Manifests – 27t Lander

Manifested Asset	Mission 1	Mission 2	Mission 3
Mars Ascent Vehicle (MAV)	1		
In-Situ Resource Utilization (ISRU)	1		
KiloPower Unit (KPU)	4		
Power Cable (on spool)	2	1	1
Special Region (SR) Rover	1		
Crew Support (CS) Rover	1		
Small Unpressurized Rover (SUR)		1	
Small Pressurized Rover (SPR)		1	1
Cargo Offload System (i.e., hoist)	1		1
Cargo Mobility System (CMS)	1		1
Logistics Module		2	1
Consummables (pallet)		1	1
Spares (pallet)		1	
EVA Logistics (pallet)		1	
Allocated Payload	1		
Small Cargo (pallet)		1	1
Science Facility (Lab)			1

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Cargo Offloading From Lander – Summary

- Common elements to be offloaded* included in task timelines:

Offload Item	Mass (kg)	Offload Method	Timeline No.	Duration (hrs)	Latency Sensitivity
Offload Ramp (Offload Preps)		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	33.5	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	103.75	4

Overall Sequence Duration: 417 hrs
17.4 days

* Per Hoffman/Watts, JSC-YX

Latency/LOS Sensitivity Key:

0: No sensitivity
1: Slight sensitivity
2: Low-Medium sensitivity
3: Medium sensitivity
4: Med-high sensitivity
5: High sensitivity

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Sequence 2: Cargo Offloading From Lander – LLT Sensitivities

Offload Item	Time-line #	Sensi-tivity	Rationale for Latency/LOS Sensitivity Value
Offload Ramp (Offload Preps)	0	1	No critical ops, sufficient contingency prior to LOS; ramp positioning is latency-sensitive
Mobility for Payload Positioning (MoPP)	1	3	Functional may take longer; no contingency prior to LOS; roll-off is time-critical
Pressurized Rover	2	2	Although functional may take longer, contingency time is available; rolloff is time-critical
Robotic Rovers (2 ea)	3	3	Functional may take longer; no contingency prior to LOS; roll-off is time-critical
Small Unpressurized Rover (SUpR)	4	2	Although functional may take longer, some time available prior to LOS; rolloff is time-critical
Reconfigurable Science Lab	5	2	Lift is time-critical and latency-sensitive; but cotingency time available prior to LOS
Science Payload	6	2	Lift is time-critical and latency-sensitive; but some contingency available prior to LOS
EVA Suit & PLSS	7	3	Lift is time-critical and latency-sensitive; no contingency prior to LOS or next timeline
Sample Return System (SRS)	8	3	Lift is time-critical and latency-sensitive; no contingency prior to LOS or next timeline
LEA Suit	9	3	Lift is time-critical and latency-sensitive; no contingency prior to LOS or next timeline
Habitat Consumables Pallet (HCP)	10	3	Lift is time-critical and latency-sensitive; no contingency prior to LOS or next timeline
Habitat Spares & Logistics Pallet (HSLP)	11	3	Lift is time-critical and latency-sensitive; no contingency prior to next timeline
EVA Logistics Pallet (ELP)	12	3	Lift is time-critical and latency-sensitive; no contingency prior to LOS or next timeline
Mobility Spares & Logistics Pallet (MSLP)	13	3	Lift is time-critical and latency-sensitive; no contingency prior to next timeline
Kilopower Portable Utility Pallets (KPUP)	14	4	Lifting operations are time-critical, latency-sensitive; although contingency time available, overall extent of timeline (4.3 days w/ 5 lifts) introduces additional risk

Latency/LOS Sensitivity Key:

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2: Low-Medium sensitivity
3: Medium sensitivity
4: Med-high sensitivity
5: High sensitivity

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Cargo Offloading From Lander – Assumptions & Challenges

- **Assumptions:**
  - Surface assets designed for LLT handling/grappling
  - Access panels for smaller assets (≤ 1,500 kg)
  - Grapple or similar capability to position assets on lander for offload
  - Self-roll assets have some positioning capability (e.g., IR sensors) for safe roll-off
  - Mobility for Payload Positioning (MoPP) chassis offloaded first to relocate larger assets
  - Other self-roll assets offloaded next, in order to clear lander deck for handling stationary items and allow ramp removal for more area on surface
  - Stationary assets are offloaded (via predeployed crane) to either surface or MoPP
  - Lander and MoPP have crane/hoist w/ min. 6000 kg capacity
  - MoPP has max. loaded speed of at least 3.5 km/hr (teleoperated)
  - Adjacent staging/dwell area on surface available for assets (Note: relocation to final emplacement is outside scope of offloading sequence)
  - Smaller identical items (e.g., EVA suits) stowed as one offloadable package/pallet
  - Lengthy tasks that can be performed autonomously can be scheduled for LOS periods
  - KPUP's transported on MoPP as a set of 5 (4 + spare); offloaded last due to time required to relocate to remote permanent location
- **Challenges:**
  - Ensuring safe operations: lifting, roll-off, CG-awareness
  - Avoidance of other items or critical components during handling
  - Access to all items and positioning for offload
  - Choreography between shifts and sequences/timelines, w/ due consideration to LOS
  - Long continuous sequence required to maximize AOS times (interspersed with LOS)

ISRU O_2 Production & MAV Fueling – Assumptions, Challenges

- **Assumptions:**
  - ISRU plant and power systems already deployed
  - MAV storage tank in proximity to O_2 production plant
  - Robotic rover with manipulation capability and fine articulation (e.g., valves)
  - Most ISRU ops can be automated and continued through LOS periods
  - Overall production sequence continues automated through LOS, with telemetry verification upon AOS
  - Task with no durations identified by task estimated at 3 hours each
  - Transfer to MAV tank considered a separate sequence, since might not be performed immediately after O_2 liquefaction into catch tank
  - MAV tank loading not considered good candidate for autonomous ops during LOS periods; LLT recommended for near real-time control and monitoring
  - MAV tank loading can be completed within approx. 4 hours, with interruptions acceptable during LOS periods
- **Challenges:**
  - Cryogenic operations
  - Secure connectors and valve actuation
  - Ensure no leakage

Outpost Science – Sample Analysis at Lab (SAL) Operations

- **Detailed SAL Operations**
  - Mostly automated, with crew assistance/refinement as needed
  - Inside the lab, one sample is analyzed via crew, LLT, and/or HLT
  - All analysis conducted on each sample from a sample group
  - Due to potential for extant life to change following exposure, prompt performance of analyses is necessary
  - First containment analysis for preliminary risk mitigation
  - If no recognized hazards, detailed survey and cellular analysis performed
- **Containment analysis for preliminary risk mitigation (high-grading)**
  - Gas analysis from sample container (automated)
  - Core removal and analysis
  - Metabolic activity test (MAT) and analysis
  - Nucleobase sequencing, incl. sample prep/analysis (automated, concurrent w/ MAT)
  - Biohazards, cellular membrane lipids analysis (concurrent w/ MAT)
  - Perchlorate analysis (concurrent w/ MAT)
- **Detailed survey and cellular analysis**
  - Detailed survey (visible, spectral)
  - Cellular analysis (microscopy, SEM)
  - Crew on-site analysis

Mars Surface Operations via LLT – Summary Assessment

Mission	LLT Operation/Activity	Approx. Duration w/ LOS (hours)	Approx. Duration w/out LOS (hours)	Assessed Latency Sensitivity
0	Surface preparation (leveling)	358	134	2
1	Initial offloads, incl. temporary KPU-1 placement/activation	37	18	3
	Offload of remaining assets (rovers, mobility, payload)	37	15	2
	Power farm site prep & KPU deploy/connection/activation	268	126	4
2	Initial offloads, incl. power cable connection	62	26	3
	Offload of remaining assets (rovers, logistics, consummables)	73	36	3
3	Initial offloads, incl. power cable connection	49	20	3
	Science lab power cable offload/connection	36	14	2
	Offload of remaining assets (rover, lab, logistics, consumables)	61	26	2
S	Science reconnaissance, 3 sites (outcrop investigation)	36	36	3
	Sample acquisition & analysis, 3 sites (avg. analyses = 6.5 days)	1,338	849	3
	Sample loading and transport, 3 sites	36	24	4

Note: With exception of science (due to analysis), **LOS periods may double** overall durations.
Durations do not specify dedicated crew time, but overall activity time with/without LOS.

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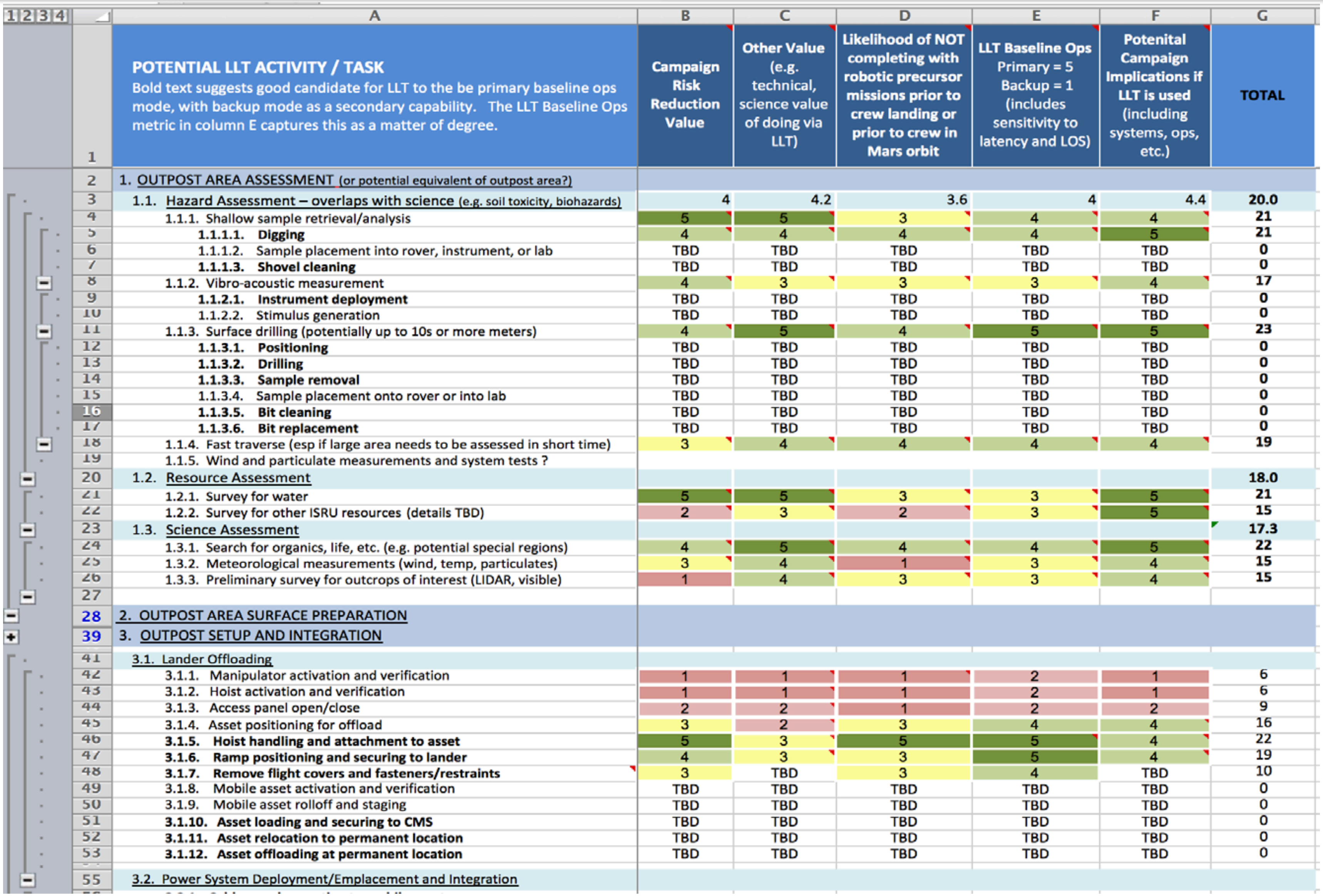
Excerpt of Draft LLT Value Assessment Spreadsheet



	A	B	C	D	E	F	G
1	**POTENTIAL LLT ACTIVITY / TASK** Bold text suggests good candidate for LLT to the be primary baseline ops mode, with backup mode as a secondary capability. The LLT Baseline Ops metric in column E captures this as a matter of degree.	**Campaign Risk Reduction Value**	**Other Value (e.g. technical, science value of doing via LLT)**	**Likelihood of NOT completing with robotic precursor missions prior to crew landing or prior to crew in Mars orbit**	**LLT Baseline Ops Primary = 5 Backup = 1 (includes sensitivity to latency and LOS)**	**Potential Campaign Implications if LLT is used (including systems, ops, etc.)**	**TOTAL**
2	1. OUTPOST AREA ASSESSMENT (or potential equivalent of outpost area?)						
3	1.1. Hazard Assessment – overlaps with science (e.g. soil toxicity, biohazards)	4	4.2	3.6	4	4.4	**20.0**
4	1.1.1. Shallow sample retrieval/analysis	5	5	3	4	4	**21**
5	**1.1.1.1. Digging**	4	4	4	4	5	**21**
6	1.1.1.2. Sample placement into rover, instrument, or lab	TBD	TBD	TBD	TBD	TBD	**0**
7	**1.1.1.3. Shovel cleaning**	TBD	TBD	TBD	TBD	TBD	**0**
8	1.1.2. Vibro-acoustic measurement	4	3	3	3	4	**17**
9	**1.1.2.1. Instrument deployment**	TBD	TBD	TBD	TBD	TBD	**0**
10	1.1.2.2. Stimulus generation	TBD	TBD	TBD	TBD	TBD	**0**
11	1.1.3. Surface drilling (potentially up to 10s or more meters)	4	5	4	5	5	**23**
12	**1.1.3.1. Positioning**	TBD	TBD	TBD	TBD	TBD	**0**
13	**1.1.3.2. Drilling**	TBD	TBD	TBD	TBD	TBD	**0**
14	**1.1.3.3. Sample removal**	TBD	TBD	TBD	TBD	TBD	**0**
15	1.1.3.4. Sample placement onto rover or into lab	TBD	TBD	TBD	TBD	TBD	**0**
16	**1.1.3.5. Bit cleaning**	TBD	TBD	TBD	TBD	TBD	**0**
17	**1.1.3.6. Bit replacement**	TBD	TBD	TBD	TBD	TBD	**0**
18	1.1.4. Fast traverse (esp if large area needs to be assessed in short time)	3	4	4	4	4	**19**
19	1.1.5. Wind and particulate measurements and system tests ?						
20	1.2. Resource Assessment						**18.0**
21	1.2.1. Survey for water	5	5	3	3	5	**21**
22	1.2.2. Survey for other ISRU resources (details TBD)	2	3	2	3	5	**15**
23	1.3. Science Assessment						**17.3**
24	1.3.1. Search for organics, life, etc. (e.g. potential special regions)	4	5	4	4	5	**22**
25	1.3.2. Meteorological measurements (wind, temp, particulates)	3	4	1	3	4	**15**
26	1.3.3. Preliminary survey for outcrops of interest (LIDAR, visible)	1	4	3	3	4	**15**
27							
28	2. OUTPOST AREA SURFACE PREPARATION						
39	3. OUTPOST SETUP AND INTEGRATION						
41	3.1. Lander Offloading						
42	3.1.1. Manipulator activation and verification	1	1	1	2	1	6
43	3.1.2. Hoist activation and verification	1	1	1	2	1	6
44	3.1.3. Access panel open/close	2	2	1	2	2	9
45	3.1.4. Asset positioning for offload	3	2	3	4	4	16
46	**3.1.5. Hoist handling and attachment to asset**	5	3	5	5	4	22
47	**3.1.6. Ramp positioning and securing to lander**	4	3	3	5	4	19
48	**3.1.7. Remove flight covers and fasteners/restraints**	3	TBD	3	4	TBD	10
49	3.1.8. Mobile asset activation and verification	TBD	TBD	TBD	TBD	TBD	0
50	3.1.9. Mobile asset rolloff and staging	TBD	TBD	TBD	TBD	TBD	0
51	**3.1.10. Asset loading and securing to CMS**	TBD	TBD	TBD	TBD	TBD	0
52	**3.1.11. Asset relocation to permanent location**	TBD	TBD	TBD	TBD	TBD	0
53	**3.1.12. Asset offloading at permanent location**	TBD	TBD	TBD	TBD	TBD	0
55	3.2. Power System Deployment/Emplacement and Integration						

To be presented by M. Wright at the 3rd International Conference on the Exploration of Phobos and Deimos,
NASA Ames Research Center, Moffett Field, CA, July 18-19, 2016.

Scientific Basis for Selection of CM Traverse for LLT Scenario

- **Based on candidate Mars traverses for scientific exploration**
  - Proposed by the Mars Exploration Program Analysis Group (MEPAG) Human Exploration of Mars Science Analysis Group (HEM-SAG)
  - Garvin, et al., *Planning for the Scientific Exploration of Mars by Humans*, Jan. 31, 2008
- **Centauri Montes (CM) region is one of 4 candidate sites recommended by the HEM-SAG for human exploration of Mars**
  - Located on rim of Hellas Basin characterized by remnant massifs
  - Stands out due to active gully observed by MGS (blue diamond in center of map)

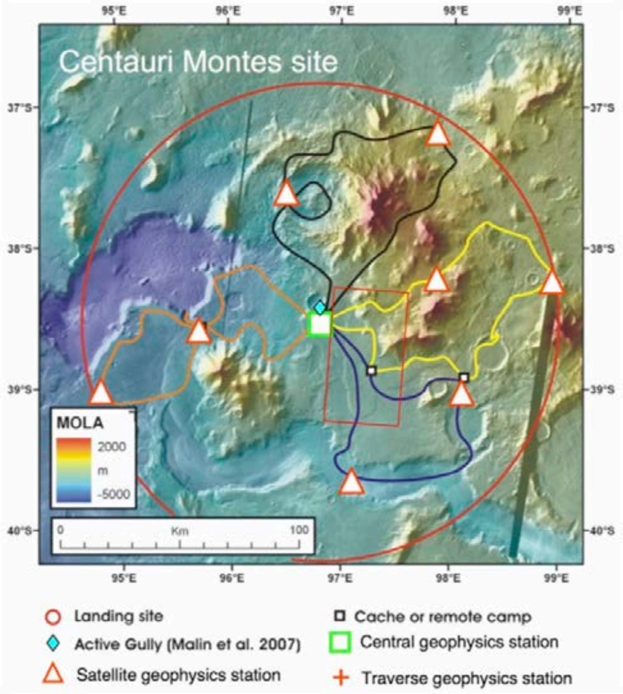


Figure 11. Centauri Montes mission landing site and traverses.

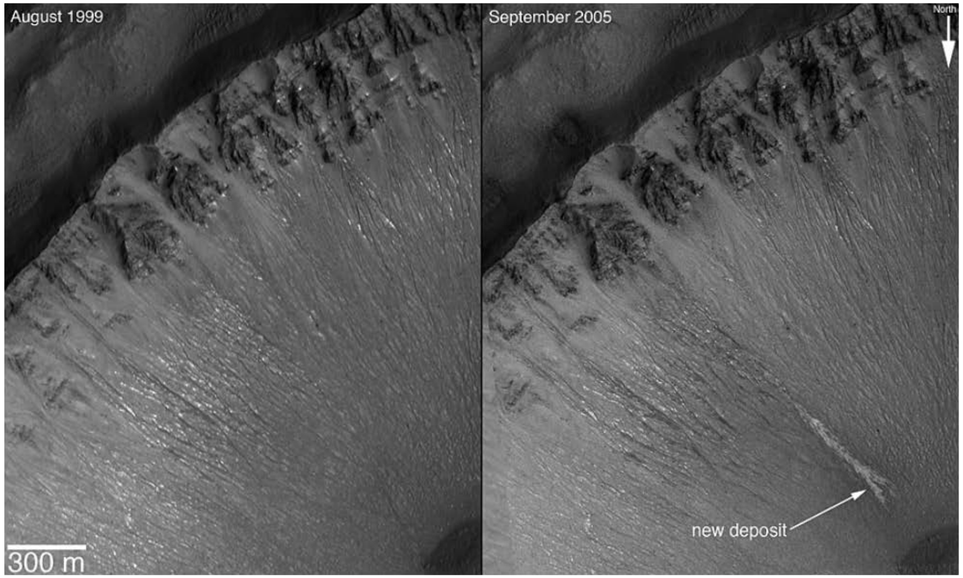


Figure 20. Southeast wall of an unnamed crater in the Centauri Montes region, as it appeared in August 1999, and later in September 2005 (MGS MOC Release No. MOC2-1619, 6 December 2006).

References (LLT Task Duration Estimates)

- **Power System and Avionics:**
  - Connector mates: HST-SM & RRM ops as-runs; servicing con ops drafts; G.Coll/GSFC
  - KPU operations: D.Palac/GRC, 7/15
  - Power system configuration: M.Rucker/JSC, 7/15 – 8/15
  - Functional tests: Flight systems integration & test as-runs, M Wright/GSFC
- **Science Reconnaissance and Sampling:**
  - Sampling and analysis: J.Bleacher/GSFC, “HAT LLT Science Scenario,” 5/1/15
  - Core drill setup: K.Zacny, Honeybee Robotics, personal correspondence, 8/31/15
  - Core drilling: K.Zacny, et al., “Icebreaker Drill,” Astrobiology, 2013
- **LLT and ISRU Operations:**
  - Phobos LOS/AOS periods: J.Hopkins and W.Pratt, “Comparison of Deimos and Phobos as Destinations for Human Exploration,” AIAA Space 2011, 9/27/11
  - LLT ops times and overhead: Fong, et al., “Testing Astronaut Controlled Telerobotics Operation of Rovers from the ISS,” IAC, Toronto, 9/30/14
  - ISRU ops: Task 11A ISRU team, G.Sanders/JSC, R.Mueller/KSC
- **Offloading:**
  - Cover removal: comparitive estimate based on HST/RRM operations
  - Hoist preps: operational capability estimate, M.Wright/GSFC
  - Lifts: operational capability estimates, M.Wright/GSFC
  - Hoist attachment: comparitive estimate based on HST/RRM operations
  - Rover traverses: capability estimates, M.Lupisella/M.Wright/J.Bleacher/GSFC
- **Site Preparation:**
  - LIDAR scans: D.A. Hoffman, professional surveyor, 2/27/15
  - Site prep excavation: C. Hinson, professional excavator, 6/2/15
- **EMC architecture, manifesting, and conops:**
  - Manifest: 7/22/15, file "field station v10_072215”
  - Consultation: K.Watts/JSC, L.Toups/JSC, S.Howe/JPL, S.Wall/JPL, S.Hoffman/JSC, G.Merrill/LaRC

References (Centauri-Montes Traverse)

Garvin, et al. “Planning for the Scientific Exploration of Mars by Humans,” MEPAG Human Exploration of Mars Science Analysis Group, Jan. 31, 2008 (Review Copy)

Redenbo, et al., “Long Range Latency and the Effects on Operator Performance,” Caterpillar Corp, Aug. 19, 2013.