Mars Surface Operations via Low-Latency Telerobotics from Phobos

July 19, 2016

Michael Wright with Mark Lupisella
Exploration Systems Projects
NASA Goddard Space Flight Center

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

Table of Contents

• Overview and Assumptions
• Outpost Area Assessment and Preparation
• Outpost Setup and Integration
• Science Operations
• Notional Science Rover Traverses
• Summary
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.

---

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

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

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

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

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

EMC Integration Team

Key stakeholder input

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

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 occurrences (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
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
• **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
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”)

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: 360° panorama, prox surface photos (e.g., tracks)
  - Conduct laser survey: 360° 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


<table>
<thead>
<tr>
<th>Shift 1</th>
<th>Task</th>
<th>Time &gt;</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>2h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>3h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>4h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>5h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>6h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reloc. rover, secure on-station</td>
<td>Perform 360° survey (auto)</td>
<td>Proximity surface photo survey</td>
<td>Deactivate survey cam</td>
<td>Deploy LIDAR survey scanner</td>
<td>Start LIDAR 360° auto-survey</td>
<td>LOS - LIDAR auto-survey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 1 (cont'd)</th>
<th>Task</th>
<th>Time &gt;</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>8h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>9h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>10h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>11h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>12h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOS - Laser auto-survey (cont'd)</td>
<td>Verify LIDAR survey complete</td>
<td>Position shovel at dig loc.</td>
<td>Perform shallow dig</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 2</th>
<th>Task</th>
<th>Time &gt;</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>13h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>14h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>15h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>16h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>17h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>18h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Perform shallow dig (cont'd)</td>
<td>Place sample in analytic lab</td>
<td>Take closeup photos of dig location</td>
<td>Clean shovel for subsequent sample</td>
<td>Deploy vibro-acoustic stimulation and measurement instruments</td>
<td>LOS - Auto-analyze surface sample (density, firmness, composition)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 2 (cont'd)</th>
<th>Task</th>
<th>Time &gt;</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>19h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>20h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>21h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>22h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>23h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>24h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LOS - Auto-analyze surface sample (cont'd)</td>
<td>Generate vibro-acoustic input, measure</td>
<td>Position drill at sample site</td>
<td>Drill into surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 3</th>
<th>Task</th>
<th>Time &gt;</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>25h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>26h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>27h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>28h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>29h</th>
<th>15m</th>
<th>30m</th>
<th>45m</th>
<th>30h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drill into surface (cont'd)</td>
<td>Remove drill and sample</td>
<td>Place sample in analytic lab</td>
<td>Clean bit for subsequent sample (continue after LOS, if necessary)</td>
<td>LOS - Auto-analyze surface sample</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Repeated for each sample site)

- **LLT Operations**
- **Loss Of Signal (LOS)**

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:
  - Perform 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)
  - Perform gross leveling of mounds within landing site (100m diam)
  - Relocate spoil to perimeter for blast berm buildup
  - Perform final leveling of landing site
# Outpost Site Surface Preparation Timeline


## Shift 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0h</td>
<td>Move rover to outpost center</td>
</tr>
<tr>
<td>1m</td>
<td>Perform gross leveling of base mound sites 1-9</td>
</tr>
<tr>
<td>2h</td>
<td>Perform gross leveling of base mound sites 10-18</td>
</tr>
<tr>
<td>3h</td>
<td>Perform gross leveling of base mound sites 19-27</td>
</tr>
<tr>
<td>4h</td>
<td>Perform gross leveling of base mound sites 28-36</td>
</tr>
<tr>
<td>6h</td>
<td>LOS</td>
</tr>
</tbody>
</table>

(Continue gross leveling for approx. next 141 hours)

## Shift 25

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>289h</td>
<td>Perform final leveling of entire outpost base area</td>
</tr>
<tr>
<td>290h</td>
<td>LOS</td>
</tr>
<tr>
<td>(Continue final leveling for approx. next 36 hours)</td>
<td></td>
</tr>
</tbody>
</table>

## Shift 28 (cont'd)

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>331h</td>
<td>Complete final leveling of entire outpost base area (cont'd)</td>
</tr>
<tr>
<td>332h</td>
<td>LOS</td>
</tr>
</tbody>
</table>

## Shift 29 (cont'd)

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>337h</td>
<td>Gross leveling of landing area mound sites 1-4</td>
</tr>
<tr>
<td>338h</td>
<td>LOS</td>
</tr>
</tbody>
</table>

## Shift 29

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>343h</td>
<td>Perform gross leveling of landing area mound sites 5-13</td>
</tr>
<tr>
<td>344h</td>
<td>Perform gross leveling of landing area mound sites 14-22</td>
</tr>
<tr>
<td>345h</td>
<td>Perform gross leveling of landing area mound sites 23-31</td>
</tr>
<tr>
<td>346h</td>
<td>Perform gross leveling of landing area mound sites 32-40</td>
</tr>
<tr>
<td>347h</td>
<td>Gross leveling of landing area mound sites 41-42</td>
</tr>
<tr>
<td>348h</td>
<td>LOS</td>
</tr>
</tbody>
</table>

## Shift 30 (cont'd)

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>349h</td>
<td>LOS</td>
</tr>
</tbody>
</table>

## Shift 30

<table>
<thead>
<tr>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>355h</td>
<td>Perform gross leveling of landing area mound sites 43-50</td>
</tr>
<tr>
<td>356h</td>
<td>Perform final leveling of entire landing site area</td>
</tr>
<tr>
<td>357h</td>
<td>LOS</td>
</tr>
</tbody>
</table>

Legend:

- **= LLT Operations**
- **= Loss Of Signal (LOS)**
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)
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

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

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

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

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 O₂ 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 O₂ 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
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

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 O₂ Production & MAV Fueling Sequence – Description**
*(For case where ISRU plant is isolated from Lander/MAV)*

**Description:** O₂ production from atmospheric CO₂ 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 O₂ 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 O₂ production tasks are generally automated, MAV tank transfer ops necessitate near real-time LLT (15-30 min safing time)

### Outpost Integration – Representative Timeline

**ISRU Oxygen Production and MAV Fueling Startup**


<table>
<thead>
<tr>
<th>Shift 1</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15min</td>
<td>15m</td>
<td>Activate CO₂ acquisition and O₂ production plant systems, verify telemetry acceptable</td>
</tr>
<tr>
<td>30min</td>
<td>30m</td>
<td>Conduct avionics health checkout, verify telemetry acceptable, then continue with checkout (auto)</td>
</tr>
<tr>
<td>45min</td>
<td>45m</td>
<td>LOS - Continue avionics health checkout (auto)</td>
</tr>
<tr>
<td>1h</td>
<td>1h</td>
<td>LOS - Take startup sequence baseline measurements - P, T, internal &amp; external (auto)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 1 (cont'd)</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7h</td>
<td>7h</td>
<td>LOS - Perform system leak check (auto)</td>
</tr>
<tr>
<td>1h</td>
<td>1h</td>
<td>LOS - Perform Gas Chromatograph (GC) calibration (auto)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 2</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>15m</td>
<td>15m</td>
<td>Bring processing heaters to operational temperatures (auto/lim)</td>
</tr>
<tr>
<td>30m</td>
<td>30m</td>
<td>Heat Solid-Oxide Electrolyzer (SOE) for bake-out &amp; temp ramp-up (auto/lim)</td>
</tr>
<tr>
<td>45m</td>
<td>45m</td>
<td>LOS - Freeze CO₂ capture chamber to ambient atmos. (auto)</td>
</tr>
<tr>
<td>1h</td>
<td>1h</td>
<td>LOS - Freeze CO₂-rich atmosphere in capture chamber w/1st cryocooler (auto)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 2 (cont'd)</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>13h</td>
<td>13h</td>
<td>LOS - Freeze CO₂-rich atmosphere in capture chamber w/1st cryocooler (cont’d - auto)</td>
</tr>
<tr>
<td>14h</td>
<td>14h</td>
<td>Vv filt OK, freeze CO₂-rich atmos. in chamber w/1st cryocooler (cont’d)</td>
</tr>
<tr>
<td>16h</td>
<td>16h</td>
<td>Freeze CO₂-rich atmosphere in capture chamber w/2nd cryocooler</td>
</tr>
<tr>
<td>20h</td>
<td>20h</td>
<td>Freeze CO₂-rich atmosphere in capture chamber w/2nd cryocooler (cont’d - auto)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 3</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>25h</td>
<td>25h</td>
<td>Freeze CO₂-rich atmosphere in capture chamber w/2nd cryocooler (cont’d)</td>
</tr>
<tr>
<td>26h</td>
<td>26h</td>
<td>LOS - Freeze CO₂-rich atmosphere in capture chamber w/2nd cryocooler (cont’d - auto)</td>
</tr>
<tr>
<td>28h</td>
<td>28h</td>
<td>LOS - Heat frozen CO₂ and pump gas to CO₂ storage tank (auto)</td>
</tr>
<tr>
<td>28h</td>
<td>28h</td>
<td>LOS - Process CO₂ gas at nominal pressure into O₂ in SOE reactor (auto)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 3 (cont’d)</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31h</td>
<td>31h</td>
<td>Verify all telemetry acceptable, process CO₂ gas at nominal pressure into O₂ in SOE reactor (cont’d)</td>
</tr>
<tr>
<td>32h</td>
<td>32h</td>
<td>33h</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 4</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>37h</td>
<td>37h</td>
<td>Process CO₂ gas at nominal pressure into O₂ in SOE reactor (cont’d)</td>
</tr>
<tr>
<td>38h</td>
<td>38h</td>
<td>LOS - Process CO₂ gas at nominal pressure into O₂ in SOE reactor (auto)</td>
</tr>
<tr>
<td>39h</td>
<td>39h</td>
<td>LOS - O₂ gas characterization (auto)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 4 (cont’d)</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>43h</td>
<td>43h</td>
<td>LOS - O₂ gas characterization (cont’d - auto)</td>
</tr>
<tr>
<td>44h</td>
<td>44h</td>
<td>LOS - O₂ liquefaction by cryocoolers into catch tank (cont’d)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shift 5</th>
<th>Time</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>49h</td>
<td>49h</td>
<td>Pump O₂ into MAV tank (perform continuously and autonomously)</td>
</tr>
</tbody>
</table>

Legend:
- LLT Operations
- Loss Of Signal (LOS)
Science Operations
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

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 maneuvering than Lewis (est. 1 km/hr max.)
  - Chemistry & mineralogy measurement (H₂O, 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, mineralogy)
  - 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

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

## Outpost Science – Representative Timeline

### Sample 1 Acquisition & Analysis (Each Outcrop Site)

<table>
<thead>
<tr>
<th>Shift 1</th>
<th>Time</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1h</td>
<td>Clarke rover returns to best outcrop site for sampling (auto)</td>
</tr>
<tr>
<td></td>
<td>2h</td>
<td>LOS - Clarke traverse continues (auto)</td>
</tr>
<tr>
<td></td>
<td>3h</td>
<td>LOS - Clarke traverse continues (auto)</td>
</tr>
<tr>
<td></td>
<td>4h</td>
<td>Prepare drill for core sampling (e.g., prep/setup drill, unstow/install bit)</td>
</tr>
<tr>
<td>Shift 1 (cont'd)</td>
<td>5h</td>
<td>LOS (cont'd)</td>
</tr>
<tr>
<td></td>
<td>6h</td>
<td>Prepare drill for core sampling (e.g., prep/setup drill, unstow/install bit)</td>
</tr>
<tr>
<td></td>
<td>7h</td>
<td>Position drill at first core location</td>
</tr>
<tr>
<td></td>
<td>8h</td>
<td>Contingency/wait time</td>
</tr>
<tr>
<td></td>
<td>9h</td>
<td>LOS</td>
</tr>
<tr>
<td>Shift 7 (cont'd)</td>
<td>10h</td>
<td>Contingency/wait time</td>
</tr>
<tr>
<td></td>
<td>11h</td>
<td>LOS</td>
</tr>
<tr>
<td></td>
<td>12h</td>
<td>LOS</td>
</tr>
<tr>
<td></td>
<td>13h</td>
<td>Drill first core sample</td>
</tr>
<tr>
<td></td>
<td>14h</td>
<td>Remove first core sample</td>
</tr>
<tr>
<td>Shift 8 (cont'd)</td>
<td>15h</td>
<td>LOS</td>
</tr>
<tr>
<td></td>
<td>16h</td>
<td>Remove first core sample (cont'd)</td>
</tr>
<tr>
<td></td>
<td>17h</td>
<td>Begin core sample analysis (auto)</td>
</tr>
</tbody>
</table>

*Auto* = Can be performed autonomously

---

Mars Operations via Low-Latency Telerobotics

Notional Dual Science Rover Traverses at Centauri-Montes

• 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
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
  - Voltmeter

• Instrument resource requirements:
  - Total instrument mass: 48 kg
  - Total power (all-on average): 146 W op, 155 W peak

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 maneuvering than reconn rover (est. 1 km/hr)
  - Chemistry and mineralogy measurement (H₂O, 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

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

• 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)
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

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)

<table>
<thead>
<tr>
<th>Time (hr)</th>
<th>Rover Ops</th>
<th>Instrument Ops</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 1</td>
<td>Science Stop</td>
<td>Camera Maneuver to Science Target (window)</td>
</tr>
<tr>
<td>1 - 3</td>
<td>Stop</td>
<td>Clean Brush</td>
</tr>
<tr>
<td>3 - 5</td>
<td>Prep for Traverse</td>
<td>Sample Analysis Sequence (5 hours)</td>
</tr>
</tbody>
</table>

**Rover Ops**
- **Camera**
  - Maneuver to Science Target (window) (14 min)
  - Dust Removal Tool (2.5 hours)
  - Rock Abrader/Diagnostic Tool
- **GCMS**
  - Sequence (5 hours)
  - Sample Analysis Sequence (5 hours)
- **Sol Detector**
  - Sample Analysis Sequence, Slow Case (4 hours, 10 min)
- **XRD/XRF**
  - Analysis (10 min)

**Instrument Ops**
- **Sample Analysis Sequence**
  - Slow and Standby
  - Slow and Standby
  - Slow and Standby
  - Slow and Standby
  - Slow and Standby
- **GCMS**
  - Sequence (5 hours)
  - Sample Analysis Sequence (5 hours)
- **Sol Detector**
  - Sample Analysis Sequence, Slow Case (4 hours, 10 min)
- **XRD/XRF**
  - Analysis (10 min)

---

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
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

**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.
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.
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

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.)
• 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 with 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 with 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 autonomous 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

Acknowledgements

The authors would like to thank the following individuals for their contributions to this effort:

**NASA:**

P. Abell, JSC/NASA  
A. Abercromby, JSC/Wyle  
A. Andrews, JSC/SaIC  
J. Bleacher, GSFC/NASA  
M. Bobskill, LaRC/NASA  
S. Chappell, JSC/Wyle  
G. Coll, GSFC/OSC  
S. Cornford/JPL  
Z. Crues/JSC  
J. Eigenbrode/GSFC  
T. Fong/ARC  
B. Garry/GSFC  
M. Gernhardt/JSC  
S. Hoffman, JSC/SaIC  
A. S. Howe, JPL  
J. Johnson/JSC  
R. Lewis/GSFC  
G. Merrill/LaRC  
R. Mueller/KSC  
D. Palac/GRC  
M. Rucker/JSC  
G. Sanders/JSC  
L. Sibille/KSC  
L. Toups/JSC  
S. Wall, JPL  
K. Watts/JSC  
B. Wilcox/JPL

**Other Organizations:**

C. Hinson, professional excavator  
D. Hoffman, D. A. Hoffman Surveying  
J. Hopkins, LMCO  
W. Pratt, LMCO  
M. Race, SETI Institute  
K. Zacny, Honeybee Robotics

Backup Material
# Mars Outpost Pre-Crew Mission Manifests – 27t Lander

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

### Cargo Offloading From Lander – Summary

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

<table>
<thead>
<tr>
<th>Offload Item</th>
<th>Mass (kg)</th>
<th>Offload Method</th>
<th>Timeline No.</th>
<th>Duration (hrs)</th>
<th>Latency Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offload Ramp (Offload Preps)</td>
<td></td>
<td>Crane/hoist</td>
<td>0</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>Mobility for Payload Positioning (MoPP)</td>
<td>1000</td>
<td>Self roll-off</td>
<td>1</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>Pressurized Rover</td>
<td>5562</td>
<td>Self roll-off</td>
<td>2</td>
<td>18</td>
<td>2</td>
</tr>
<tr>
<td>Robotic Rovers (2 ea)</td>
<td>500 x 2</td>
<td>Self roll-off</td>
<td>3</td>
<td>33.5</td>
<td>3</td>
</tr>
<tr>
<td>Small Unpressurized Rover (SUuR)</td>
<td>300</td>
<td>Self roll-off</td>
<td>4</td>
<td>14.5</td>
<td>2</td>
</tr>
<tr>
<td>Reconfigurable Science Lab</td>
<td>3000</td>
<td>Crane/hoist</td>
<td>5</td>
<td>48</td>
<td>2</td>
</tr>
<tr>
<td>Science Payload</td>
<td>1000</td>
<td>Crane/hoist</td>
<td>6</td>
<td>42</td>
<td>2</td>
</tr>
<tr>
<td>EVA Suit &amp; PLSS</td>
<td>169</td>
<td>Crane/hoist</td>
<td>7</td>
<td>20.5</td>
<td>3</td>
</tr>
<tr>
<td>Sample Return System (SRS)</td>
<td>100</td>
<td>Crane/hoist</td>
<td>8</td>
<td>13.25</td>
<td>3</td>
</tr>
<tr>
<td>LEA Suit</td>
<td>26</td>
<td>Crane/hoist</td>
<td>9</td>
<td>20.25</td>
<td>3</td>
</tr>
<tr>
<td>Habitat Consumables Pallet (HCP)</td>
<td></td>
<td>Crane/hoist</td>
<td>10</td>
<td>13.25</td>
<td>3</td>
</tr>
<tr>
<td>Habitat Spares &amp; Logistics Pallet (HSLP)</td>
<td></td>
<td>Crane/hoist</td>
<td>11</td>
<td>20.5</td>
<td>3</td>
</tr>
<tr>
<td>EVA Logistics Pallet (ELP)</td>
<td></td>
<td>Crane/hoist</td>
<td>12</td>
<td>13.25</td>
<td>3</td>
</tr>
<tr>
<td>Mobility Spares &amp; Logistics Pallet (MSLP)</td>
<td></td>
<td>Crane/hoist</td>
<td>13</td>
<td>20.5</td>
<td>3</td>
</tr>
<tr>
<td>Kilopower Portable Utility Pallets (4 + spare)</td>
<td>1500 x 5</td>
<td>Crane/hoist</td>
<td>14</td>
<td>103.75</td>
<td>4</td>
</tr>
</tbody>
</table>

* Per Hoffman/Watts, JSC-YX

Overall Sequence Duration: 417 hrs
17.4 days

Latency/LOS Sensitivity Key:

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

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

Latency/LOS Sensitivity Key:

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

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)

• 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

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

**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.

Excerpt of Draft LLT Value Assessment Spreadsheet

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)
- 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

• LLT and ISRU Operations:
  - 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: comparative estimate based on HST/RRM operations
  - Hoist preps: operational capability estimate, M.Wright/GSFC
  - Lifts: operational capability estimates, M.Wright/GSFC
  - Hoist attachment: comparative 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"

References (Centauri-Montes Traverse)