CARLO GAVAZZI SPACE SpA

Sustained Moon Surface Operations

Automated Surface Infrastructure Elements

CGS

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Main Requirements for Automated Moon Surface Exploration

Geology

- **In-situ analysis of lunar terrain at sites of special geological interest**
    - Far side / Aitken basin
    - Perpetually shadowed craters
        - *Exploration of the Shackleton Crater on the South Pole*
        - *Evaluation of the presence of volatiles*
- **Crater and lava flow sample collection**
- **Deep Drilling**
    - Bedrock sample collection, temperature measurement

Moon Observatories

- **Deployment of an interferometric array of dipole detectors for $\lambda > 10$ m**
    - Operates on the Far Side

Manned Exploration Support

- **Demonstration of ISRU processes for the Lunar Surface Base**
- **Selection and exploration of landing place**
- **Lunar Surface Base: electrical power provision, element and material transport / positioning, ISRU production**

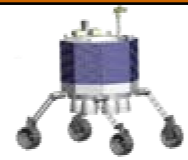
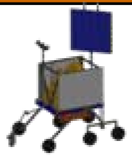
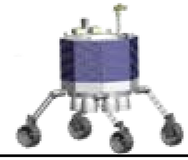
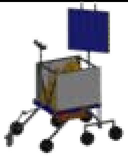
Mapping of Functionalities vs. Automated Elements

Main Functionalities

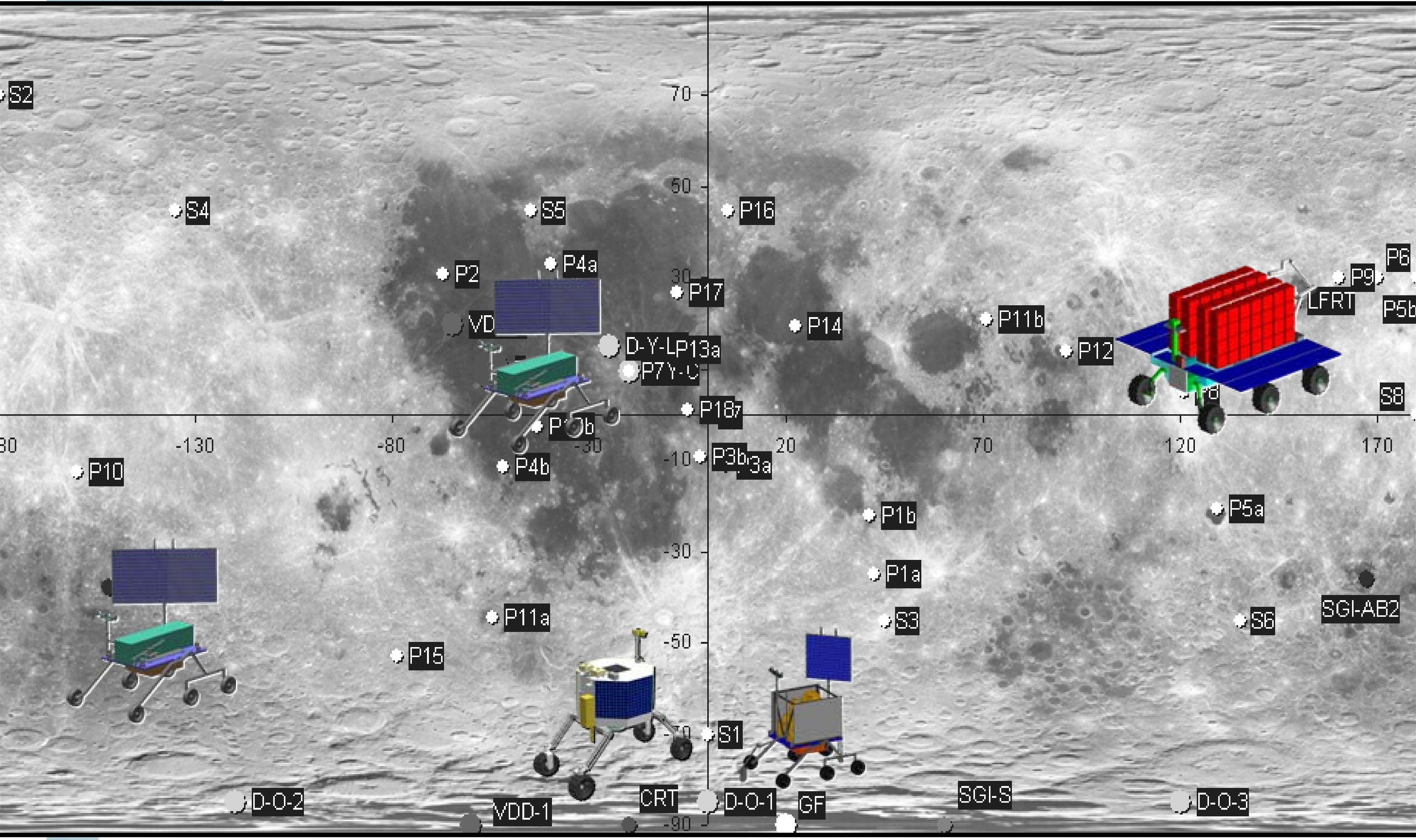
The Main Functionalities required to the Automated Surface Elements of the Phase I and Phase II are:

- Scientific In-Situ Analysis
- Robotic Exploration
- Deep Drilling

Functionalities vs. Elements Mapping

Element / *Functionality*	Exploration Hopper	ISRU Demo Rover	Deep Drilling Rover	LF Telescope Deployer
Scientific In-Situ Analysis				
Robotic Exploration				
Deep Drilling				

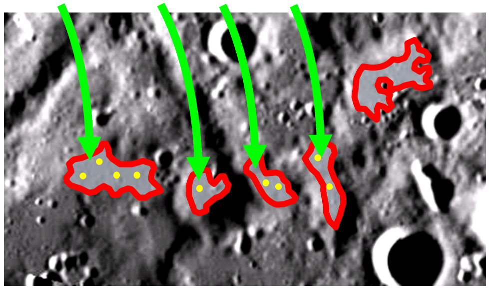
Trade-off: Positioning of Automated Surface Elements



Trade-off: Exploration Hopper vs. Rovers

- Science targets: points (yellow dots) inside traversable zones (red borders)
- Trade-off: choice of the exploration scenario: A, B, or C, shown below:

A

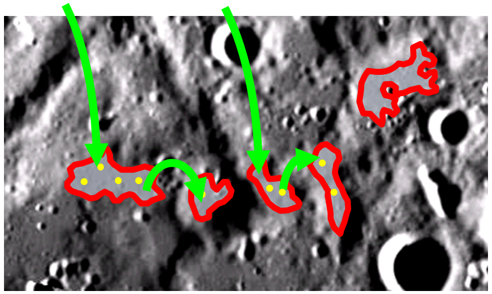


- Rover on a lander
- Multiple landings

B

- Hopper on a lander
- Single landing

C

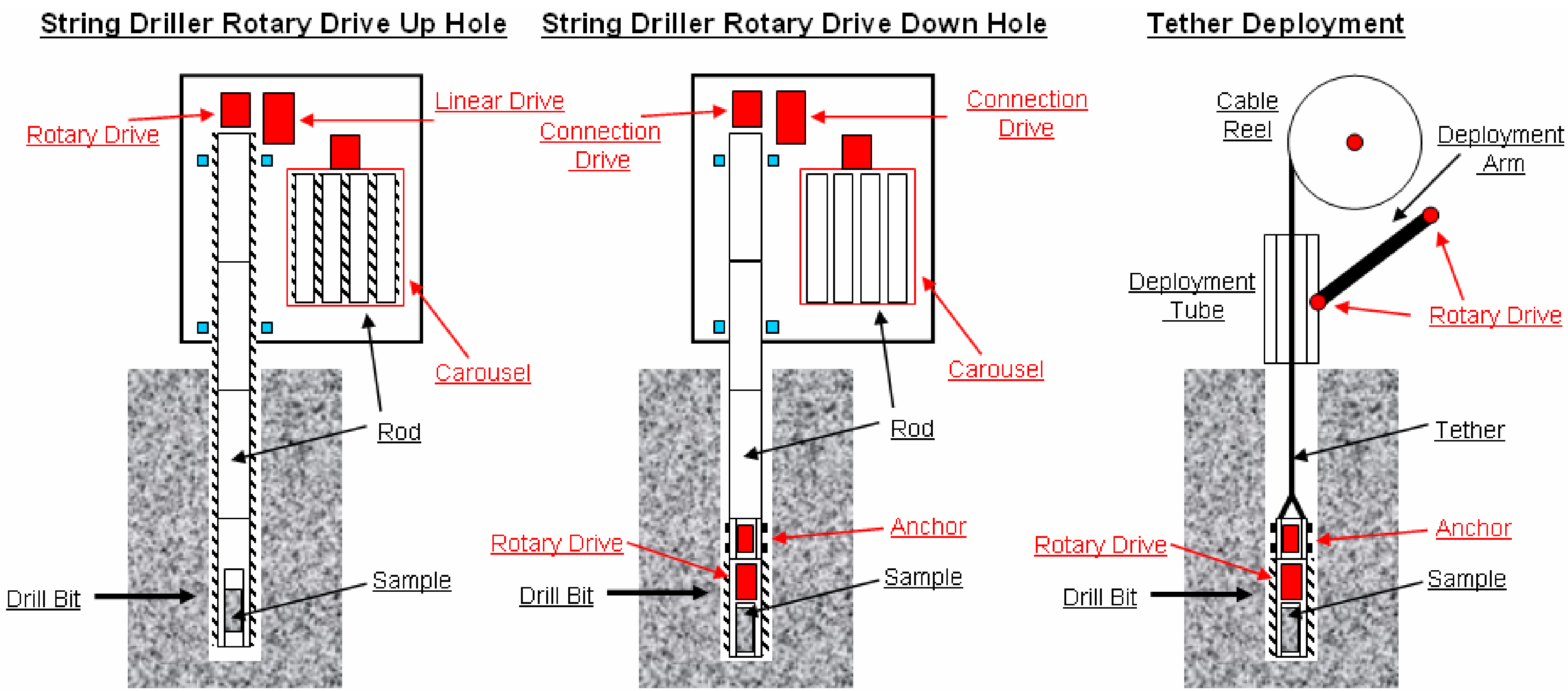


- Hopper on a lander
- Double landing

	M (number of zones)						
H (jump length, km)	2	6	10	14	18	22	26
2	B	B	B	B	B	C	C
4	B	B	B	B	C	C	C
8	B	B	B	C	C	C	C
16	B	B	B	C	C	C	C
32	B	B	C	C	C	C	C
64	B	C	C	C	C	A	A
128	B	C	C	A	A	A	A
256	B	C	A	A	A	A	A

- Trade-off outcome
  - Hopper preferred in case of:
    - ✓ "low" number of "near" zones: B
    - ✓ "intermediate" situation: C
  - Rovers preferred in case of:
    - ✓ "high" number, or "distant" zones: A
- There are other (different) scenarios where the use of an Exploration Hopper is advantageous, e.g. exploration of lunar permanently shadowed polar craters

Trade-off: Driller Architecture

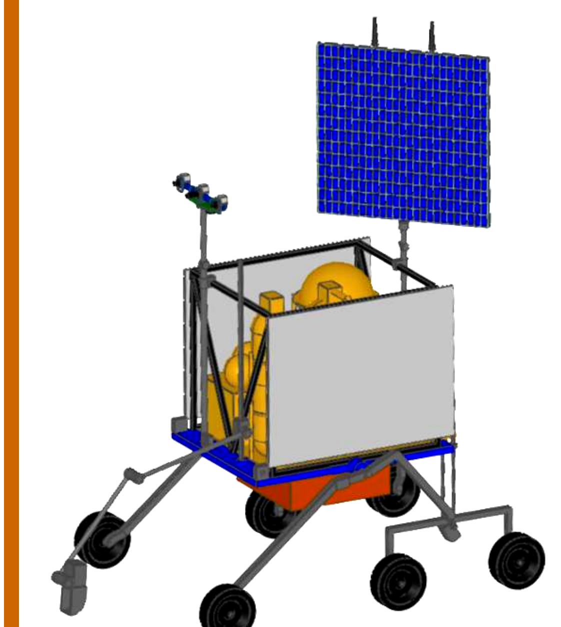


	Power Required	Mass	Operational Time	Bore-hole Stability	Extension Complexity	
String Driller Rotary Drive Up Hole	High	Medium	Low	High	High	
String Driller Rotary Drive Down Hole	Medium	Medium	Medium	High	High	✓
Tether Deployment	Medium	Low	High	None	Low	

Phase I and II Automated Elements

ISRU Demonstration Rover

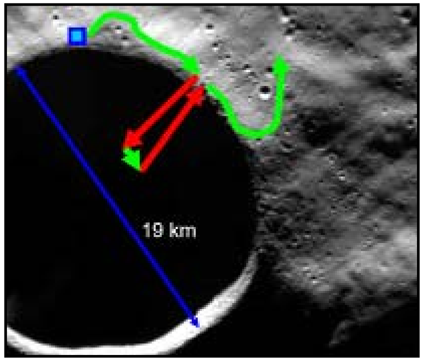
- **What is it:** a rover platform with an In-Situ Resource Utilization (ISRU) Payload
- **Payload:**
  - **Demonstrator for a full-scale ISRU Plant**, using the Carbothermal Reduction Process in the South Pole area
  - **Input**: regolith + CH_4 feedstock
  - **Output**: oxygen + waste slags
- **Rover platform (adaptable for other P/Ls)**
  - **Payload support robotics,** for delivering regolith to the plant and removing waste
  - **Mobility** for accessing different sites
- **Mission: 3 months (15 kg O_2 production)**
  - Main modes: travelling, process, night
  - **Overlapping 12h Processing Cycles** (2 parallel activities executed)



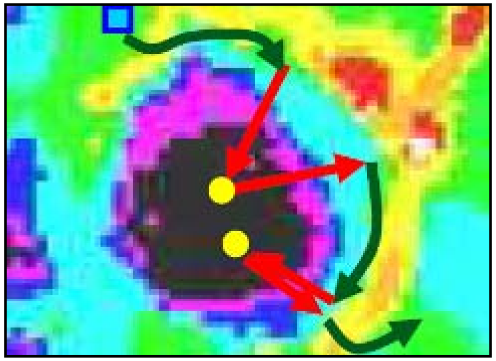
Activity #1	Beneficiation + Excavation		Heating		Furn. Reduct.	Catalytic Reduction				Electrolysis			
Activity #2	Catalytic Reduction		Electrolysis				Beneficiation + Excavation		Heating		Furn. Reduct.	Cataly. Reduct.	
Timeline	0h	2h	4h	6h	8h	10h	12h	14h	16h	18h	20h	22h	24h

Exploration Hopper

- **What is it**: can be seen as a rover to which a propulsion subsystem has been added, enabling "hops" across the lunar surface
- **Standard operation**: rover-like:
  - **movement** (4 wheels), night survival
  - **science**: robotic manipulator, 2-m driller, payload (microscope, APXS, Raman, IR, Mössbauer and mass spectrometers)
- **Hopping**: also to overcome obstacles, but: the primary application is cold trap sampling for volatiles
  - **reference mission**: exploring Shackleton crater (S Pole), alternative option: Peary (N)



Shackleton crater mission



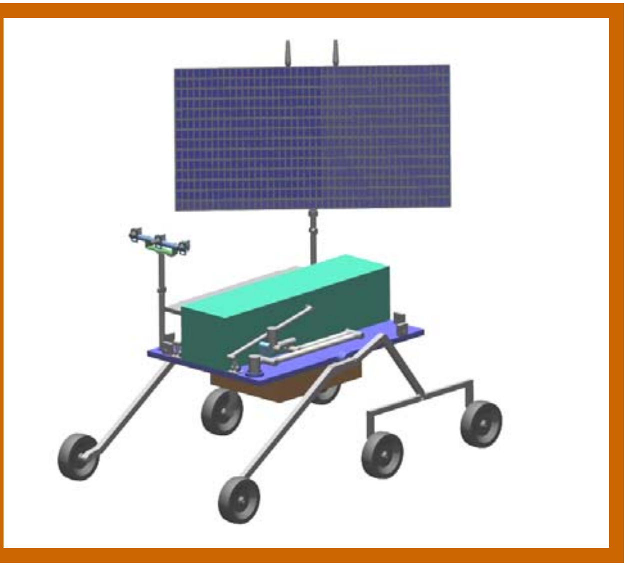
Peary crater mission

Obstacle example: Hadley Rille

Phase I and II Automated Elements

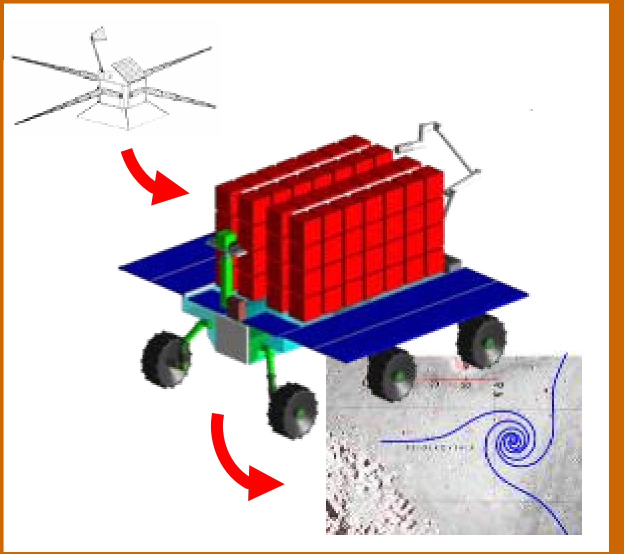
Deep Driller Rover

- **What is it:** a **rover platform** with a **Deep Driller Main Payload**
- **Main Payload:** 40 m max depth
  - **String Driller** (ensures bore-hole stability)
  - **Down Hole Drive** (rotating part: deep)
- **Additional Payload Features:**
  - **Robotic subsystem** for driller sample management, and surface scooping



LF Radiotelescope Deployer

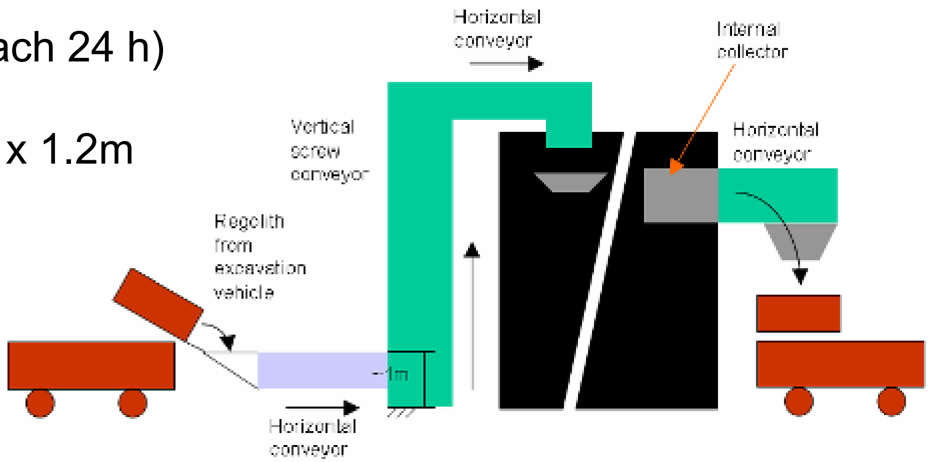
- **What is it:** a **specialized vehicle** for carrying and deploying the components of the <u>Low Frequency Radiotelescope</u>: a set of <u>dipole antenna units</u> (0.25 m^3 cubes when stowed) to be placed in a spiral Y on the lunar far side
- Sized for transporting 100 antennas at a time; deployment performed with a specialized robotic manipulator



Lunar Surface Base - Automated Support Elements

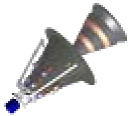
ISRU Plant

- **What is it:** a **full scale plant** using the process demonstrated by the ISRU Demo Rover (**Carbothermal Reduction**)
- Sizing criteria: on a single Medium Lander
- Production per year: ~**470kg of O_2**, inputs: ~5850kg of regolith and ~170kg of CH_4 (conservative)
- Positioned on the surface using the Element Transport Vehicle
- Mass break-even time: **~58 months**
- Interfaces with other elements:
  - Power plant: provision of ~1 KW
  - Tanker: brings CH_4, takes O_2 (each 24 h)
  - Terrain Management Vehicle
- m = 322kg, V_{stowed} = 1.3m x 2.5m x 1.2m
- Scalable design; with a yearly O_2 need of ~**1416 kg**, the mass break-even time is reduced to **18 months**



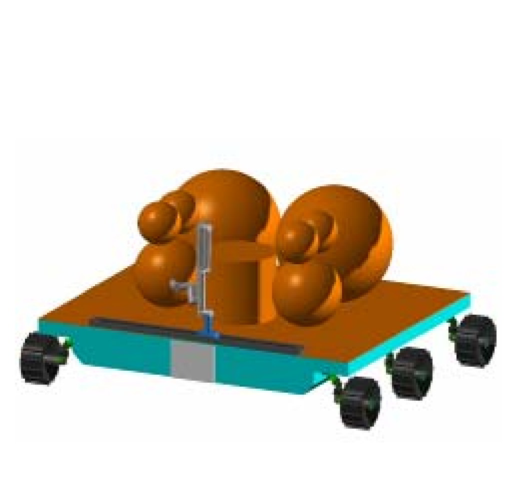
Lunar Surface Base - Automated Support Elements

Tanker & Service Vehicle



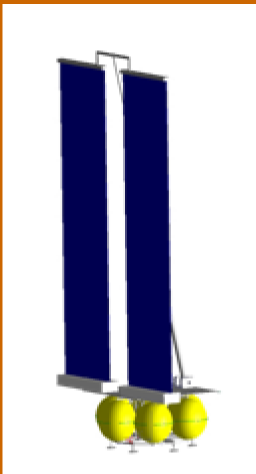
- **What is it:** a **multi-purpose vehicle** that is used for servicing and transporting:
  - up to **420 kg** of O_2 (ISRU → Base / Lander)
  - up to **150 kg** of CH_4 (Logistics → ISRU)
  - up to **350 kg** of H_2O (Logistics → Base, ...)

- Auxiliary pressurant - avoids pump cavitation
- m_{dry} = 1164 kg, m_{full} = 2084 kg, V = 3.6x3x2 m^3



Power Plant

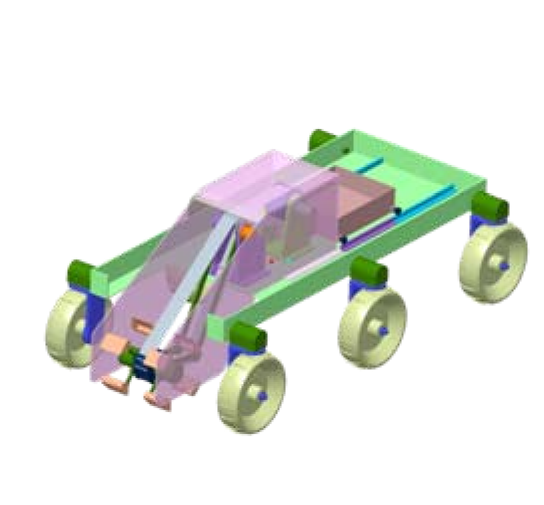
- **What is it:** a **steerable array of triple-junction photovoltaic cells** + **regenerative fuel cells (used during night / shadow)**
- Scalable design; **two considered configurations**:
  - **Medium Power Plant**: 4 kW (day) / 2 kW (night), m = 845 kg
    V = 2.7x2.7x2.7/21.7 (stored/deployed) m^3
  - **Large Power Plant**: 10 kW (day) / 3 kW (night), m = 1534 kg
    V = 3.5x3.5x3/32 (stored/deployed) m^3
    (main "building block" for power provision)



Lunar Surface Base - Automated Support Elements

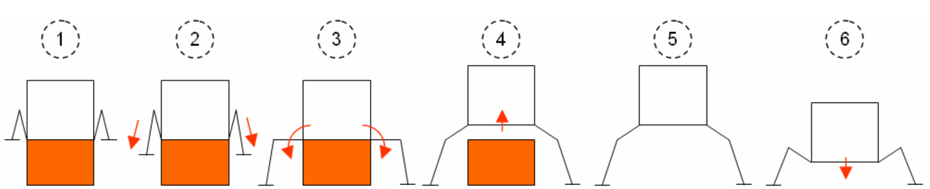
Terrain Management Vehicle

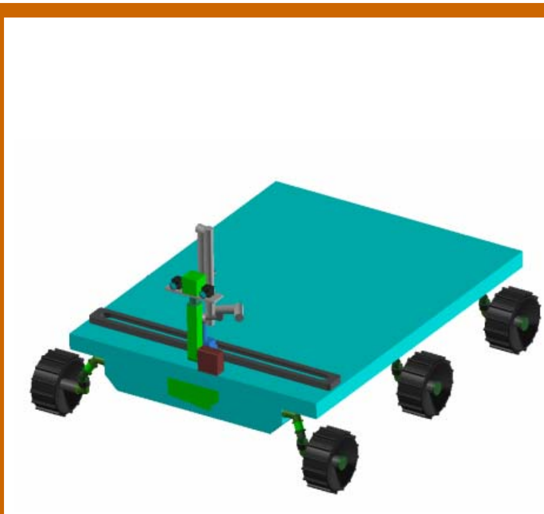
- **What is it:** an **automated vehicle** able to:
- **collect and transport regolith** to ISRU plant
- **transport ISRU waste slags** to deposit
- Collection concept: **Bucket Wheel Excavator** (placed at the rear of the vehicle)
- Other key components of the element: material container, conveyor belt, guide rail
- m = 442 kg, V = 2.5x1x1.8 m, P = 137 W



Element Transport Vehicle

- **What is it:** an **automated vehicle able of transporting elements** that are delivered to the lunar surface using a Medium Lander
- Positioning: 4 robotic "legs" on each element

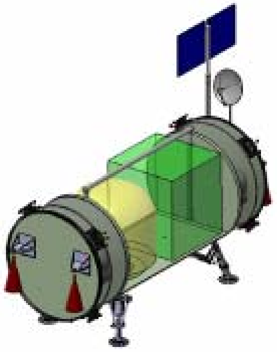




Interfaces with other Segments

Transportation Segment

- **For all the considered Automated Surface Elements, the same interface with the transportation segment has been assumed:**
  - Utilization of the "Medium (Cargo) Lander"
  - Main characteristics:
    - *Max payload mass: 1700 kg*
    - *Max payload envelope: 3.9 x 5.7 x 3.2 m*
    - *Unloading system: on the lander, using a crane*
  - No further support from lander assumed after deployment
  - Multiple surface elements can be placed on a single lander
  - Also used for providing consumables for the Automated Elements that are used at the Lunar Surface Base: these are collected using the Tanker and Service Vehicle

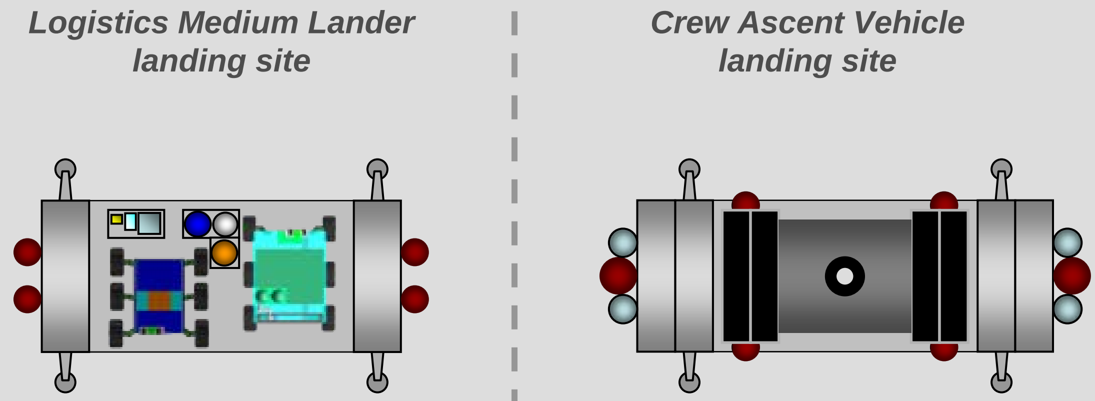


In-Space Segment

- **Communication Support**
  - Assumed availability of communication satellites
    - *Telemetry: max data rate: 200 Kb/s*
    - *Telecommand: max data rate: 20 Kb/s*
- **Navigation Support:** reducing the criticality of onboard navigation systems

Phase II Interfaces / Human-Robotic Partnership

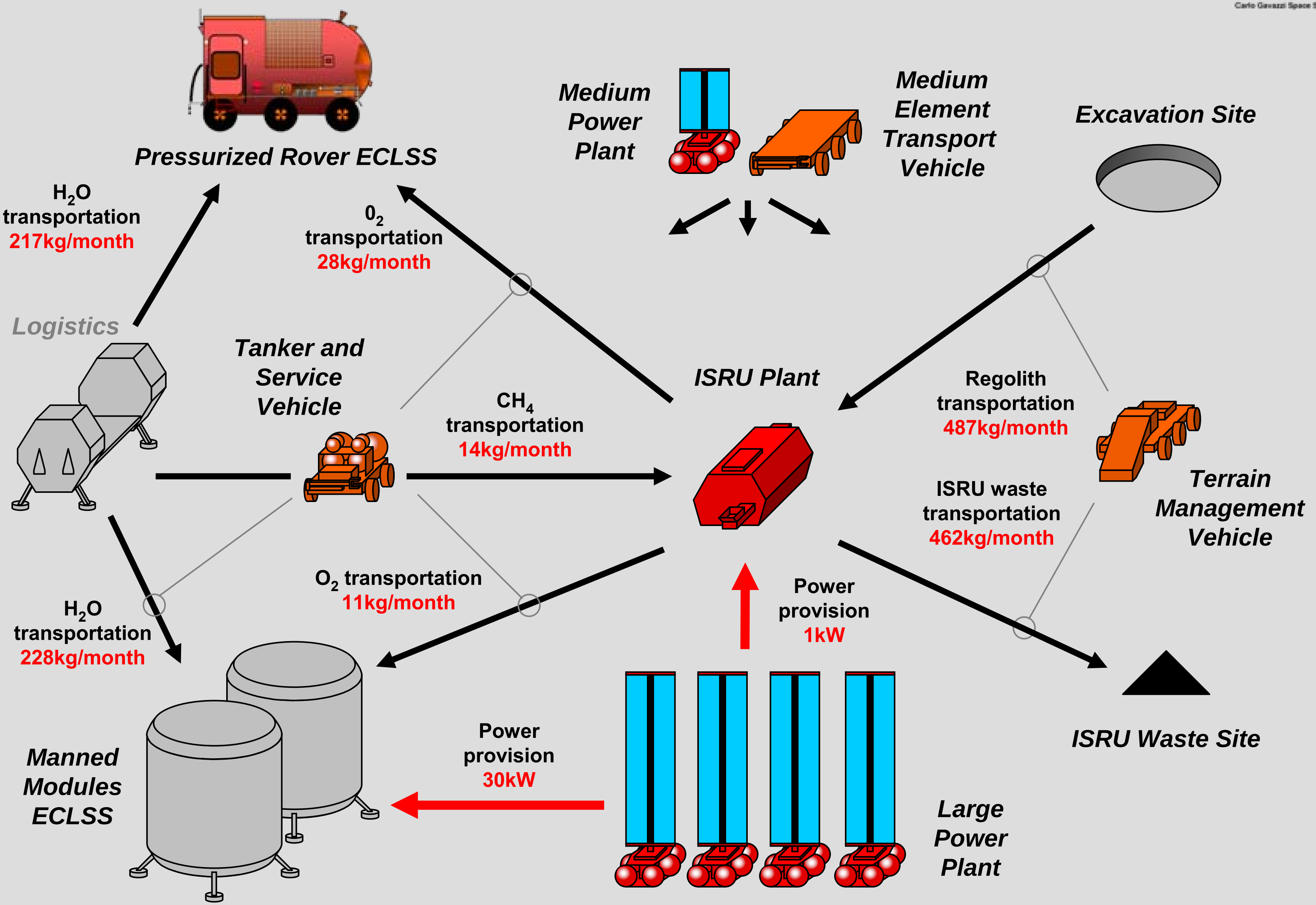
Sortie missions



Sequence of activities

1) Arrival of the Pressurized Rover (PR)
2) Arrival of the second Medium Lander (ML), carrying the consumables for the second Sortie Mission (SM), the Deep Driller Rover and the ISRU Demo Rover
3) Start of the Deep Driller and ISRU Demo missions
4) Unmanned refurbishment of the PR with the ML via the PR robotic manipulator, and arrival of the SM crew
5) Interaction of the crew with the Deep Driller and ISRU Demo rovers
6) Transfer of the crew to the PR, and of the O_2 produced by the ISRU Demo Rover
7) Realization of the second SM
8) Return of the crew to the Ascent Vehicle
9) Unmanned unloading of PR waste water to the ML
10) Transfer of the PR to the site of the Lunar Surface Base

Phase III Interfaces - Lunar Surface Base

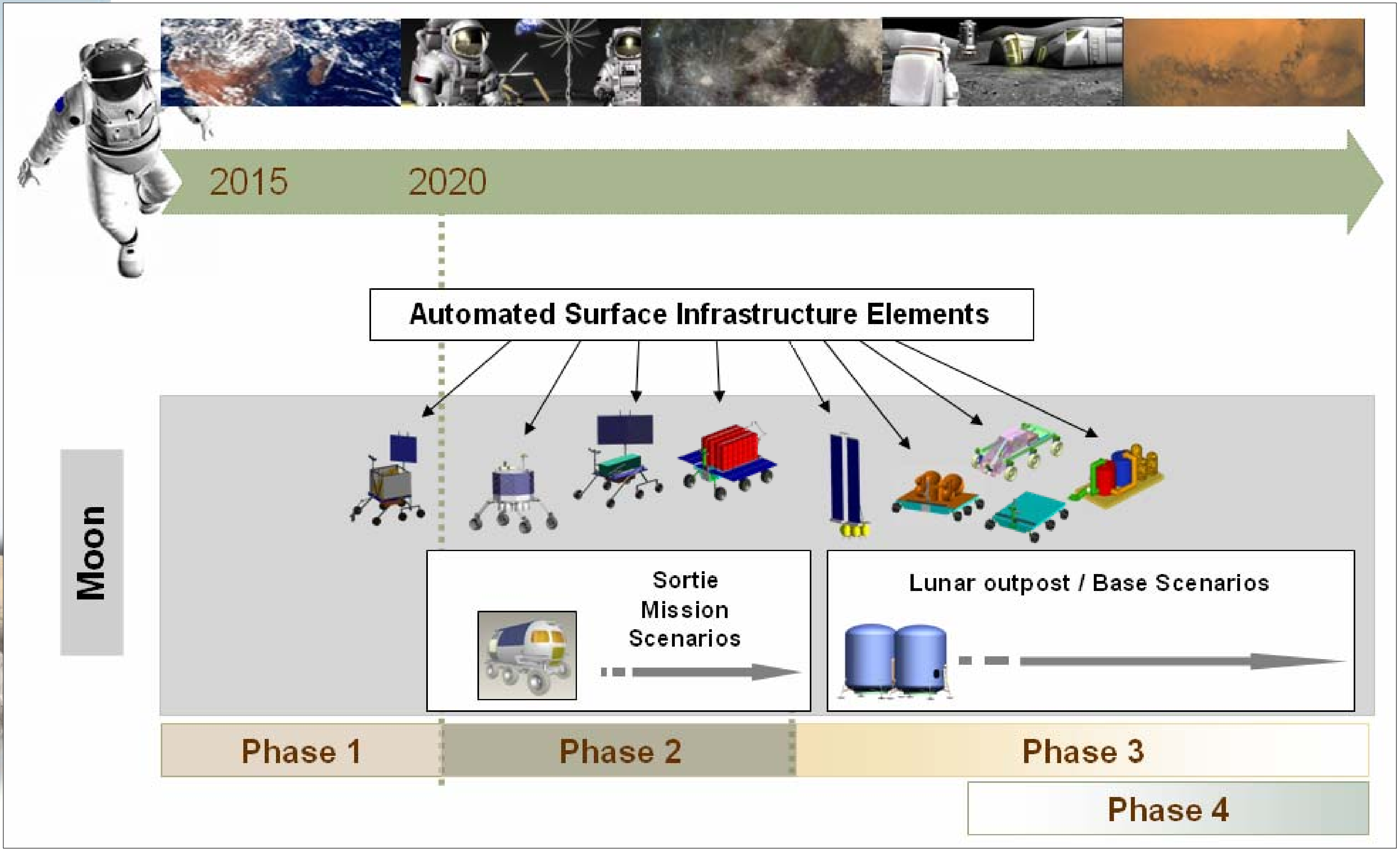


Capability Requirements

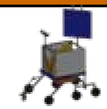
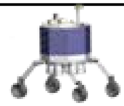
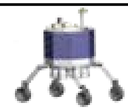
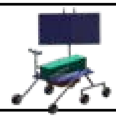
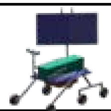
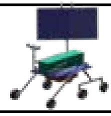
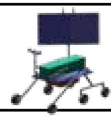
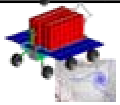
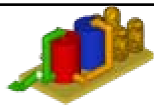
- The main identified Capabilities / Technologies requiring a predevelopment phase are the following:

  - **Propulsion**
    - Propulsion subsystem for hopping (Exploration Hopper)
  - **Energy Management**
    - Solar Cells (Solar Power Plant)
    - Fuel Cells (Solar Power Plant)
  - **Servicing**
    - Terrain Manipulation Robotics (Terrain Management Vehicle)
  - **Surface Mobility**
    - Wheels and Chassis Configuration (Exploration Hopper, Terrain Management Vehicle, Tanker, Element Transport Vehicle)
  - **Drilling**
    - Driller Payload (Exploration Hopper, Deep Driller Rover)
  - **In-Situ Resource Utilization**
    - ISRU lunar processes (ISRU Demo Rover, ISRU Plant)
  - **Guidance, Navigation and Control**
    - GNC subsystem for hopping/roving (Exploration Hopper, Rovers)

Link to Scenarios



Link to Scenarios

Scenarios / Elements	Sortie	Super-Sortie	Man-Tended Outpost	Polar Outpost
ISRU Demo Rover				
Exploration Hopper				
Deep Drilling Rover				
LF Telescope Deployer				
ISRU Plant				
Tanker & Service Vehicle				
Power Plants				
Terrain Management Vehicle				
Element Transport Vehicle