Lunar Exploration Initiative

Briefing Topic:

Lunar Mobility Review

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Lunar Mobility

- **Robotic Vehicles**
  - Lunokhod 1 (Luna 17)
  - Lunokhod 2 (Luna 21)

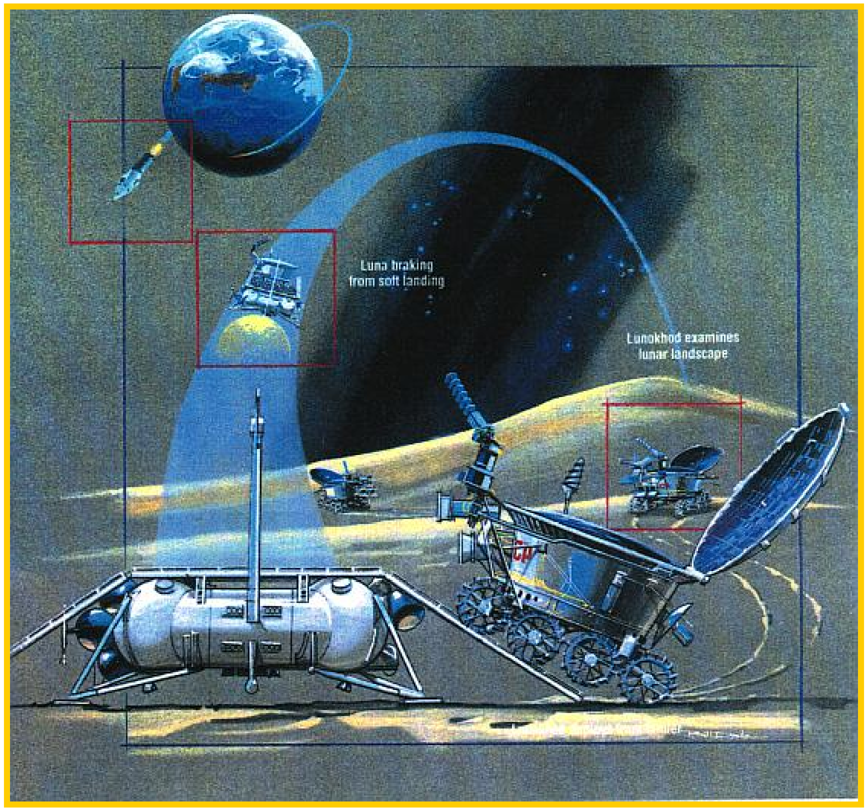
- **Human Exploration Vehicles**
  - MET (Apollo 14)
  - LRV (Apollo 15, 16, and 17)
  - Lunar Motorcycle (for Apollo 15, but not flown)

Lunar Robotic Vehicles

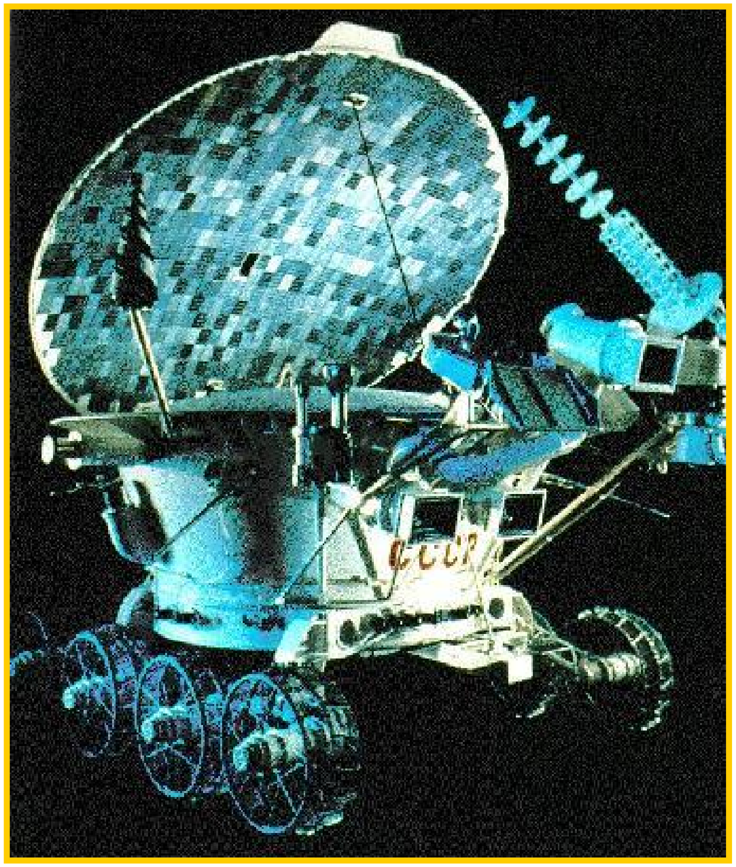
- Robotic Rovers
  - Lunokhod 1 (Luna 17, Nov 1970)
    - Explored Mare Imbrium
    - 756 kg
    - Rover had 1.7 m wheelbase and was ~1 m wide
    - Driven by 8 rigid spoked wheels with a wire mesh rim connected to three hoops
    - Wheel diameter ~51 cm and width ~20 cm
    - Operated on slopes up to 32°
    - 212-220 day lifetime (~7 lunar days) per Petrov (USSR, 1972) or 322 day lifetime (~11 lunar days) per National Space Science Data Center
    - Traversed 10.54 km
  - Lunokhod 2 (Luna 21, Jan 1973)
    - Explored Mare Serenitatis
    - 840 kg (1814 kg with lander)
    - 170 cm long, 160 cm wide, 135 cm high
    - Two-speeds: ~1 km/hr and ~2 km/hr
    - 139 day lifetime (~5 lunar days)
    - Traversed 37 km

NSSDC 1970-095A; 1973-001A

Lunokhod 2



Carried 3 TV cameras, one of which was high on rover for navigation, allowing real-time driving by 5-man team in USSR



Powered by batteries that were recharged by a solar panel on lid of payload bay & a Polonium-210 radiogenic heat source

Lunokhod 2 Mission Profile

- Earth parking orbit
- Translunar injection
- 90 x 100 km parking orbit around Moon
- Perilune lowered to 16 km and stabilized for 40 orbits
- Braking rocket puts lander in free fall
- Main thrusters fire 750 m above surface
- Main thrusters shut down 22 m above surface and secondary thrusters ignited
- Secondary thrusters shut down 1.5 m above surface
- Landing occurs from a free fall height of 1.5 m

- Surface operations
  - Dual-ramp roll-off
  - Navigated while on battery
  - Stopped occasionally to recharge battery with solar panel
  - Hibernated during lunar night, remaining warm with radiogenic heater

Lunokhod 2 Science

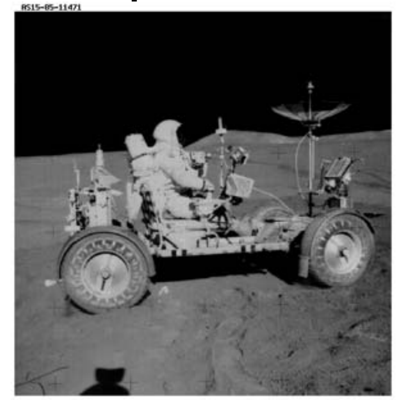
- **Science Goals**
  - Image lunar surface
  - Examine ambient light levels to assess suitability for astronomical observations
  - Perform laser ranging experiments from Earth
  - Observe solar x-rays
  - Measure local magnetic fields
  - Study mechanical properties of lunar surface materials

- **Instruments**
  - 4 panoramic cameras
  - Astrophotometer for VIS and UV light
  - Radiometer
  - Rubin-1 photodetector for laser detection & French-supplied laser corner-reflector
  - Solar X-ray detector
  - Magnetometer (at end of 2.5 m boom)
  - Soil mechanics device (penetrometer)

Human Exploration Vehicles

- **Modular Equipment Transporter (MET) for Human Exploration**
  - **Apollo 14 (Jan-Feb 1971)**
    - **75 kg (with instruments and samples)**
    - **Hand-drawn**
    - **2 pneumatic tires**
    - **40 cm diameter tires, width of 10 cm**

- **Apollo Lunar Roving Vehicle (LRV) for Human Exploration**
  - **Apollo 15 (July-Aug 1971), Apollo 16 (April 1972), Apollo 17 (Dec 1972)**
    - **708 kg (with astronauts, equipment, and samples; more than half of this mass was the astronauts and their life support systems)**
    - **4 wheels composed of a flexible mesh of woven zinc-coated piano wire and chevron-shaped titanium treads**
    - **82 cm wheel diameter and 23 cm width**
    - **Battery-powered**



- **Lunar Motorcycle**
  - **Designed for, but not flown on, Apollo 15**
    - **2 pneumatic tires**

Apollo LRV

Empty mass	218 kg
Payload mass	490 kg
Two astronauts	363 kg
Experiments, tools, & samples	127 kg
Gross Mass	790 kg
Dimensions	
Length	310 cm
Wheelbase	229 cm
Overall width	206 cm
Height	114 cm
Power supply	2 parallel, non-rechargable Ag-Zn batteries (36 V)
Drive	Independent motors on each wheel
Steering	Front and rear independent steering
Minimum turning radius	305 cm
Wheels	Woven Zn-coated piano wire with Ti-treads in chevron pattern (50% coverage)
Maximum speed	13 km/hr
Normal cruise speed	6 to 7 km/hr
Maximum slope	19 to 23 deg
Energy consumption	35 to 56 W-hr/km 0.05 to 0.08 W-hr/km/kg

Mobility

- **Wheeled vehicles**
  - **Based on Apollo and Lunokhod mission results**
  - **Vehicles with round wheels work well on lunar surface if ground contact pressure does not exceed 7 to 10 kPa**
  - **Overcoming surface roughness and soil compaction consumes the energy equivalent to a 1 ½ degree climb up a smooth, rigid slope**
  - **Surface roughness, in a relatively low gravity situation, limits surface speed (otherwise, one bounces out of control)**
    - **The LRV was limited to 6-7 km/hr**
    - **Faster speeds require larger wheels, larger wheel base, greater mass, and/or softer suspension**

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Mobility

- **Soft soils**
  - **The Apollo 15 LRV spun its wheels (and got stuck) in soft soil**
  - **The empty LRV weighed only 38 kg in lunar gravity, so the astronauts moved it to solve the problem. This solution is not possible in a completely robotic mission.**
  - **Lunokhod 2 encountered soft soils on the inside walls of craters; the soil was particularly soft at the base of slopes**
    - **Normal wheel sinkage was 2 cm**
    - **Wheel sinkage was >20 cm near impact craters**

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Maneuvering

- **Cohesion varies as a function of geologic terrain**
  - **Cohesion on interior crater rims is less than that in intercrater areas**
  - **Cohesion in intercrater areas is less than that on crater rims**

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Slope Requirements

- **LExSWG (1995) findings for rover mobility**
  - **Impact-cratered terrains**
    - **Old 100 m diameter crater (a common feature) has maximum slopes of 5 to 10°**
    - **Somewhat fresher craters have interior slopes of 15 to 20°**
    - **A very fresh crater, 500 m diameter South Ray Crater, has ejecta blanket and rim slopes of 7° or less; interior crater wall slopes can be as high as 35°, but routes to crater floors with slopes of 17 to 26° exist**
    - **Even large craters with diameters >10 km have average crater wall slopes <30°**
    - **Conclusion: capability to ascend and descend slopes of ~25° is sufficient**

Slope Requirements

- **LExSWG (1995) findings**
  - **Volcanic terrains**
    - **Near vertical walls will occur near rilles, but less steep routes to rille floors exist**
    - **Topographic study of Rima Prinz and Rima Mozart reveal numerous routes to rille floors with slopes of 15 to 20°; routes with slopes <15° also exist**
    - **Conclusion: capability to ascend and descend slopes of ~25° is sufficient**

Trafficability

- Empirical equations for the slope-climbing ability and energy consumed by a wheeled vehicle moving through lunar soil were determined for Apollo's LRV (Bekker, 1969):
  - Wheel sinkage
  - Soil compaction resistance per wheel
  - Gross pull per wheel
  - Maximum trafficable slope
- These equations failed, however, to represent the trafficability of small rovers in lunar soils, as simulated in 1/6 G conditions on NASA 930 (KC-135A) flights (Carrier, 1994, summarizing Scott)
- A computational method (WHEEL-E) was developed to evaluate small rover wheel performance in lunar soils (Carrier, 1995). These solutions are for flexible, elastic wheels on a flexible, elastic surface, so they may potentially be modified to assess the trafficability of tracks.

Summary

- Human and robotic rovers operated on the lunar surface in the past.
- The latter operated for several lunar days & nights, enduring cold conditions without solar power.
- The lunar surface is covered with a soft soil that varies in depth and cohesion; a wheeled vehicle has been stuck in this soil.
- LExSWG (1995) recommended future rovers have the ability to climb slopes up to 25° for operations in both impact-cratered and volcanic terrains.

References

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