A ROBOTIC PROSPECTING ARCHITECTURE FOR THE MOON

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Lunar Exploration Analysis Group Meeting

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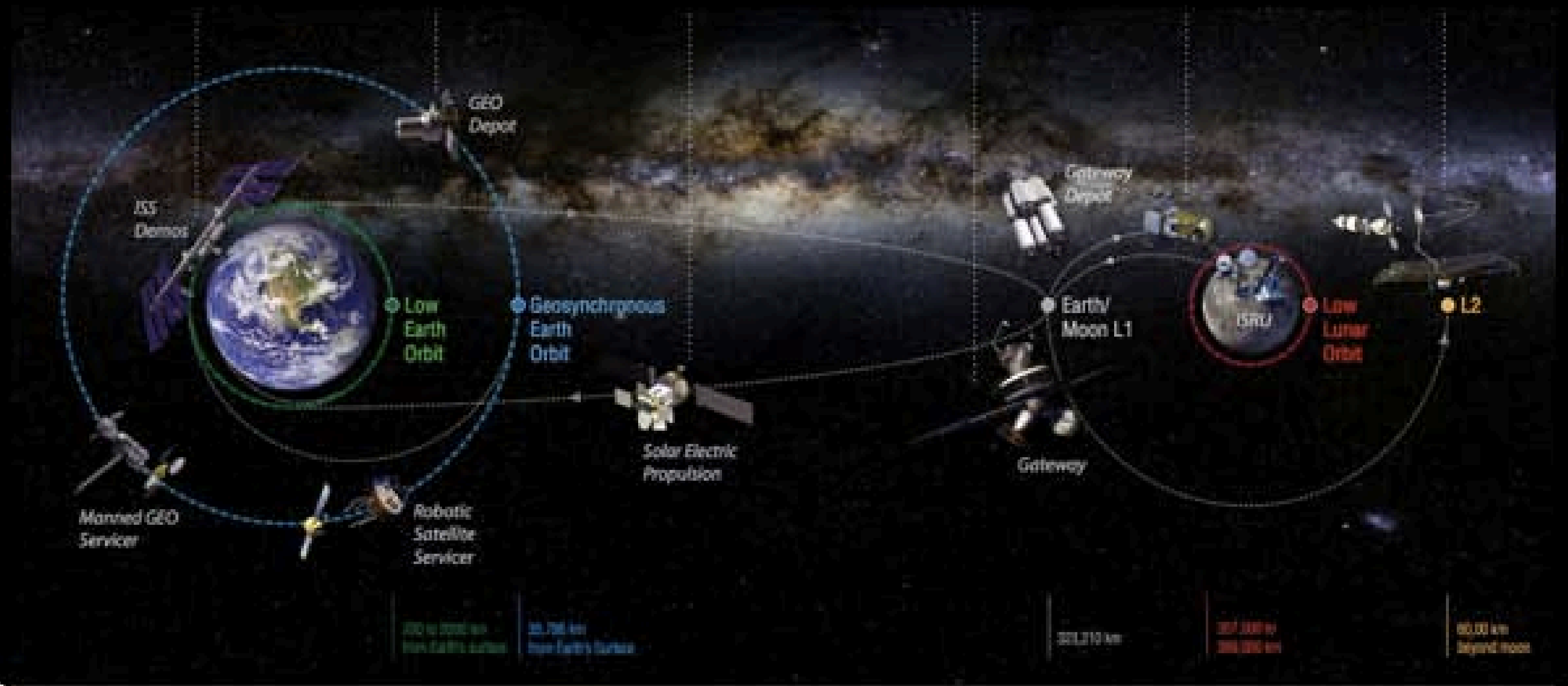
What are we trying to do?

The Vision

Expand human reach* to cislunar and beyond



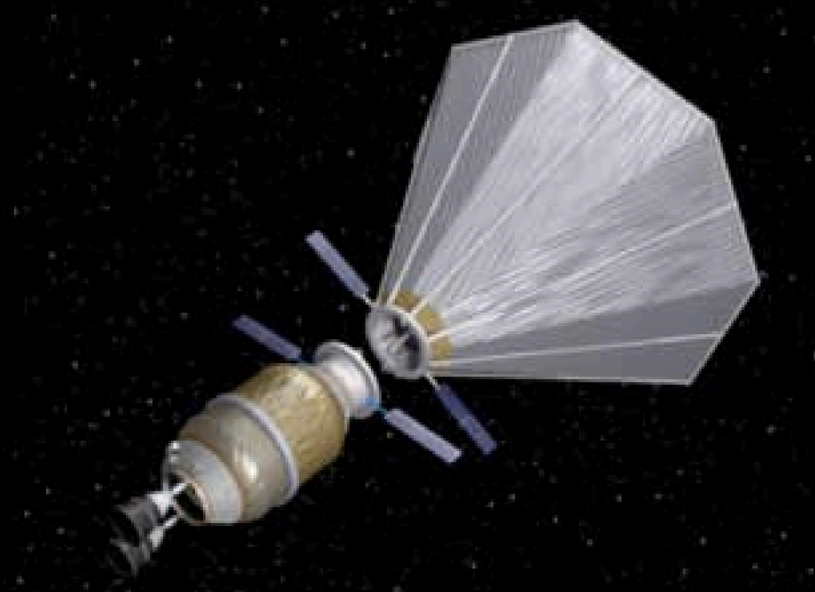
The Mission

Establish a robotic and human presence on the Moon (as the closest planetary body) to learn how to use local resources of material and energy in order to live affordably off-planet and, in so doing, create new space faring capabilities

*reach = the ability to send people and machines to any point within a given volume of space to perform whatever tasks are envisioned

Goals and Principles

- Extend human reach beyond LEO by creating a permanent, extensible space faring infrastructure
- Use the material and energy resources of the Moon to create this system
- Lunar return by small, incremental, cumulative steps
- Proximity of Moon permits progress prior to human arrival via robotic teleoperations
- Innovative space systems: fuel depots, robotics, ISRU, reusable spacecraft, staging nodes
- Fit under anticipated budget curve
- Schedule is free variable; constant, steady progress but no deadlines



A Lunar Return Architecture

P.D. Spudis and A.R. Lavoie (2011) Using the Resources of the Moon to Create a Permanent Cislunar Space Faring System. Space 2011 Conf, Long Beach CA, AIAA 2011-7185, 24 pp.

Mission

- Create a permanent human-tended lunar outpost to harvest water and make propellant

Approach

- Small, incremental, cumulative steps
- Robotic assets first to document resources, demonstrate production methods
- Teleoperation of robotic mining equipment from Earth. Emplace and build outpost assets remotely
- Use existing LV, HLV if it becomes available

Schedule

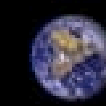
- Resource processing outpost operational halfway through program (after 18 missions); end stage after 30 missions: 150 mT water/year production

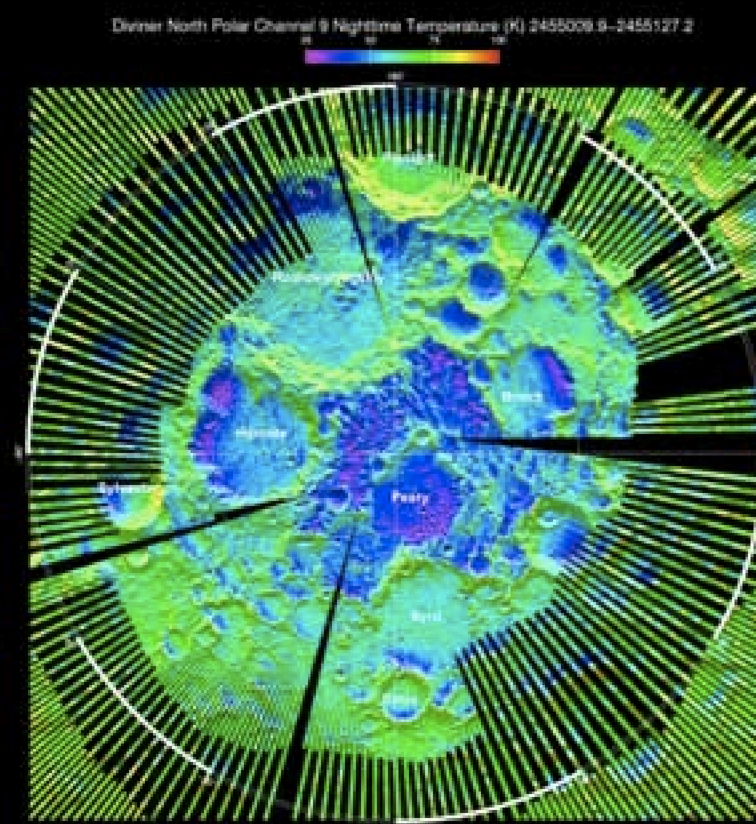
Benefits

- Permanent space transportation system
- Routine access to all cislunar space by people and machines
- Experience living and working on another world

The Lunar Poles

What we know





Environment

Polar terrain is mature highlands; typical slopes 5°-15°, some steep slopes in crater walls (~35°)

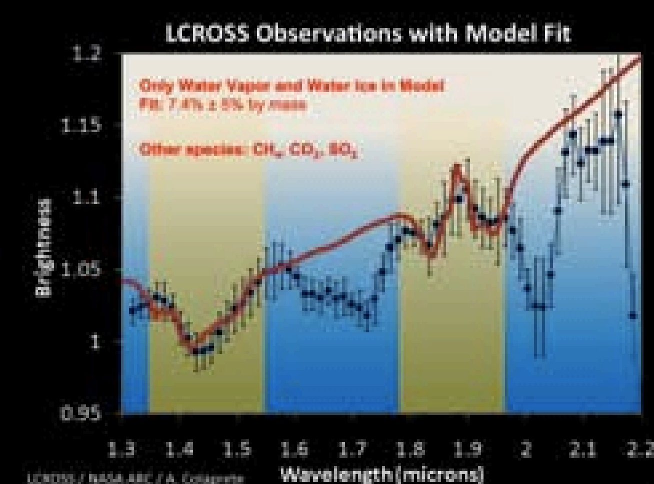
Receives oblique solar illumination; sunlit surface temperatures hover around 220 K

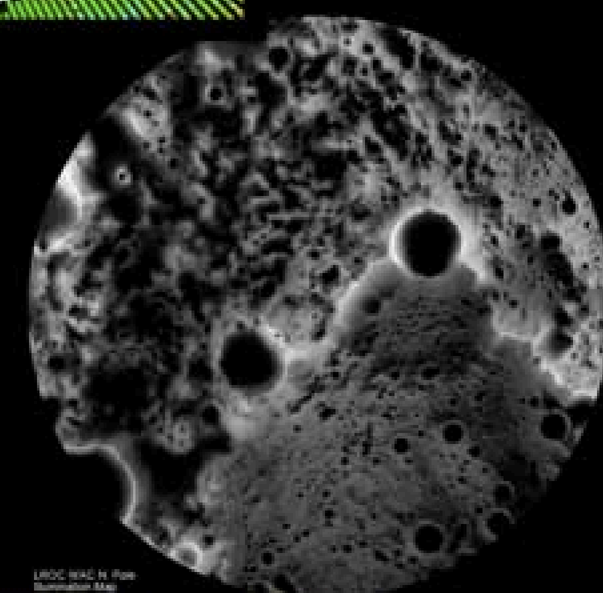
Dark areas (cold traps) as cold as 25 K; typically, 30-70 K

Energy

No permanent sunlit areas, but several regions are sunlit 100% of day in local summer and over 90% illuminated over course of year

High sunlight areas (at least four at each pole) are hundreds of meters in dimension



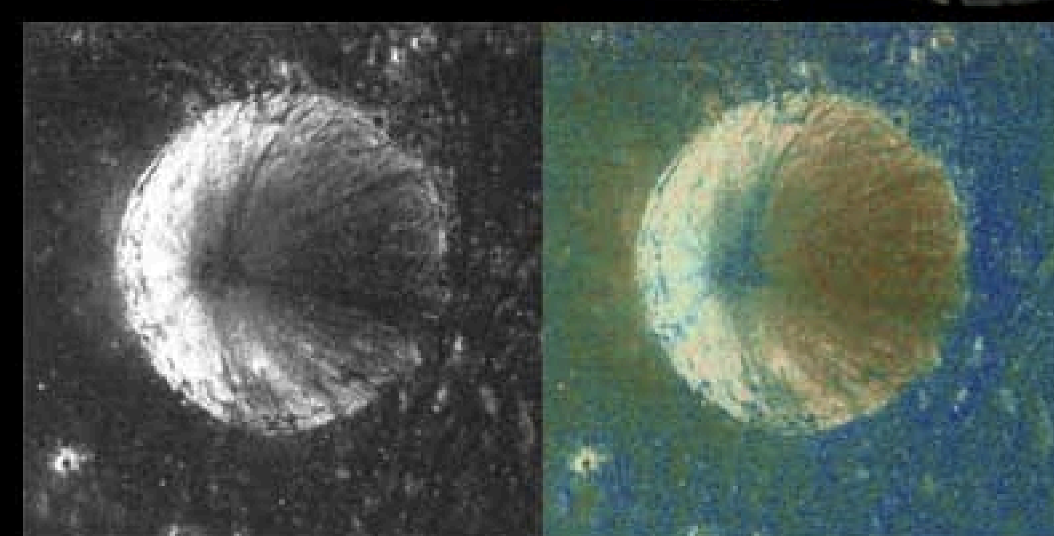


Materials

Water is present in quantity; admixed into polar regolith (5-10 wt.%) over wide areas

Nearly pure water ice in some small (4-12 km) craters near poles; at least 2-3 m thick

Preliminary estimates suggest more than 10 billion metric tons of water at each pole



Prospecting vs. Science

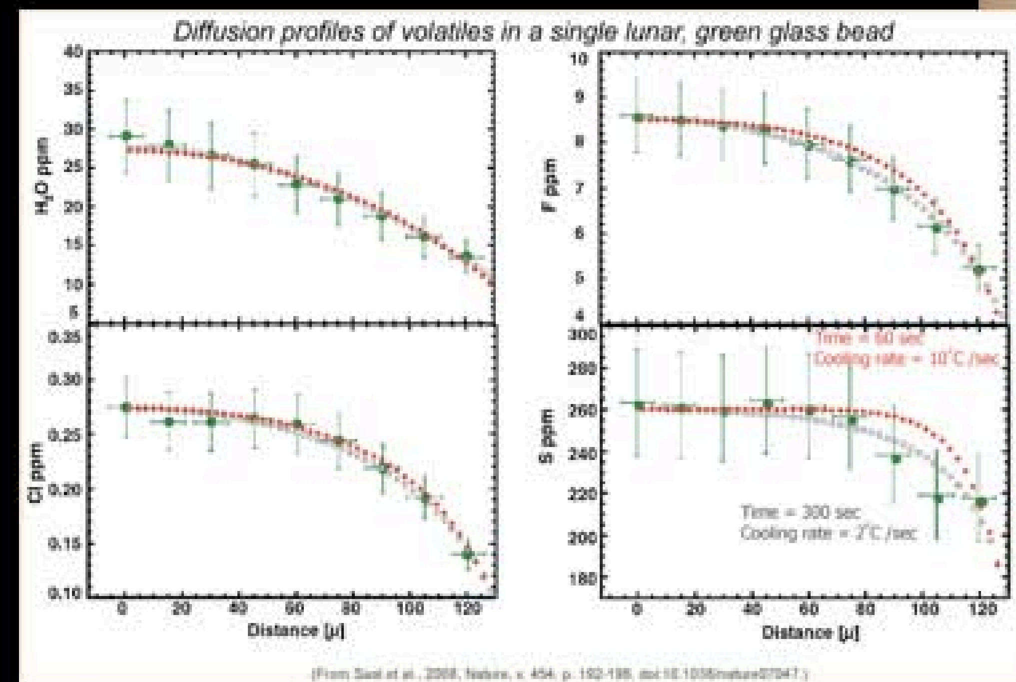
What's the difference?

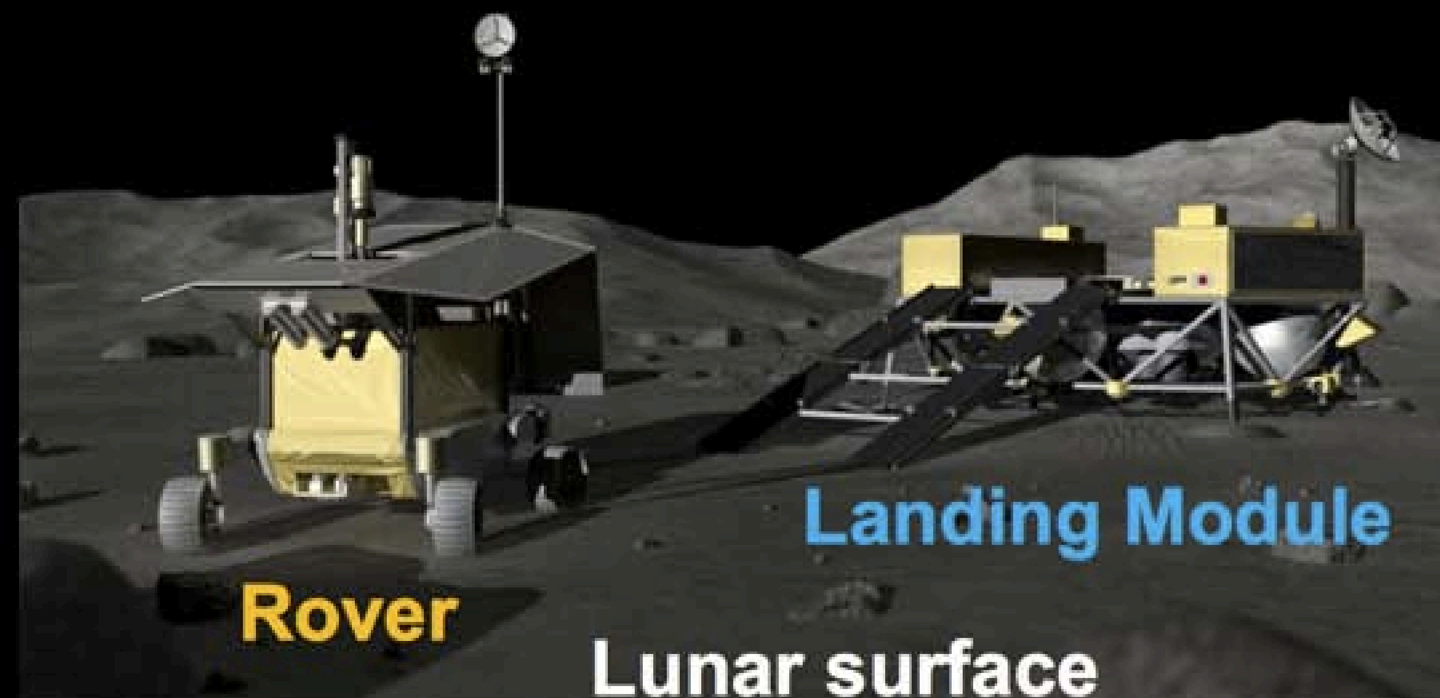
Science

- Emphasis on processes, history, origin(s)
- Broad regional characterization, intense local characterization at as many sites as possible

Prospecting

- Emphasis on distribution at km-, m- and cm-scales
- Most promising sites identified at regional scales, detailed characterization only of chosen prospects

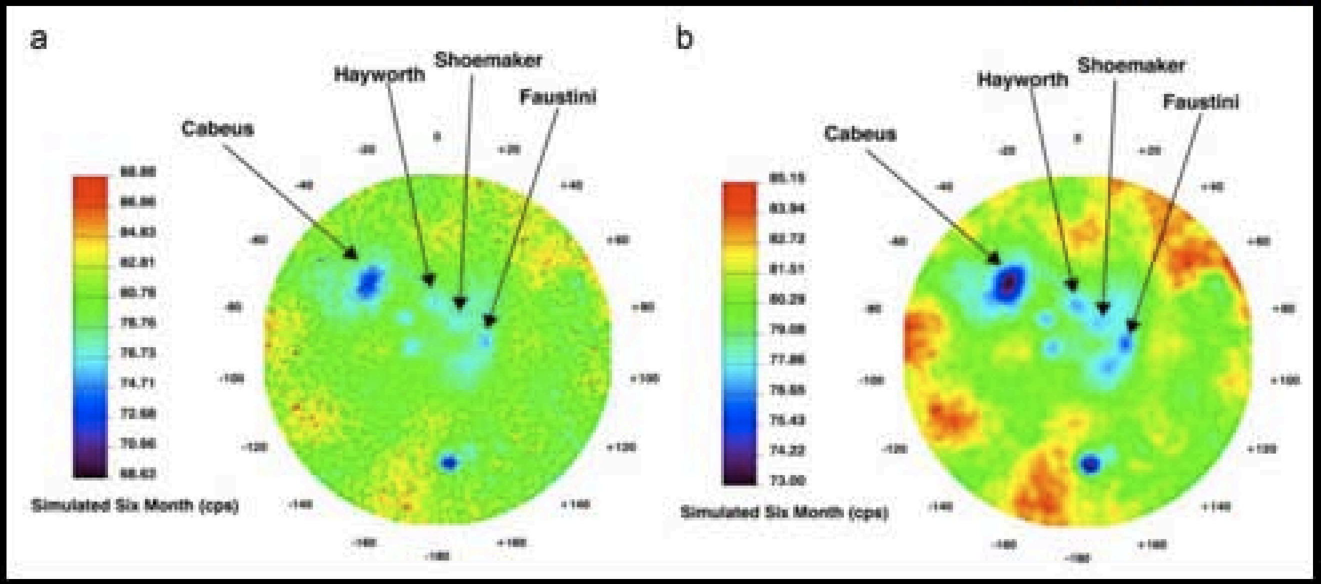


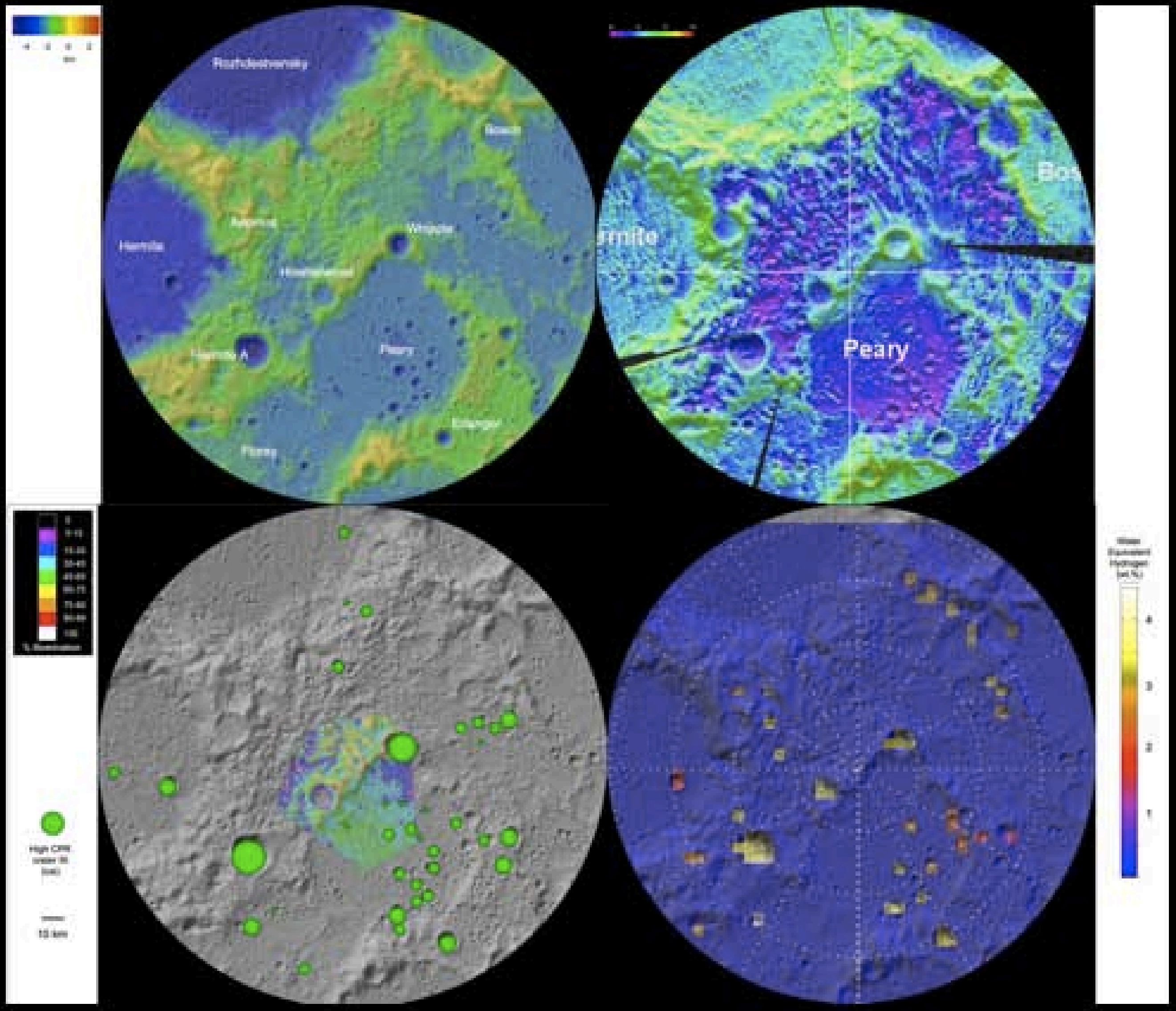


Knowledge Needs

- Water ice and hydrogen concentrations at km-scale
  - Locate best prospects for mining
- Physical properties of polar sunlit and shadowed regolith, volatile deposits (density, cohesiveness, trafficability, compressibility, etc.)
- Composition of water ice; ice/soil ratios
- Other volatile species and their abundances
- Variations in concentration on meter-to-tens of meter scales
- Lateral and vertical extent of volatile deposits

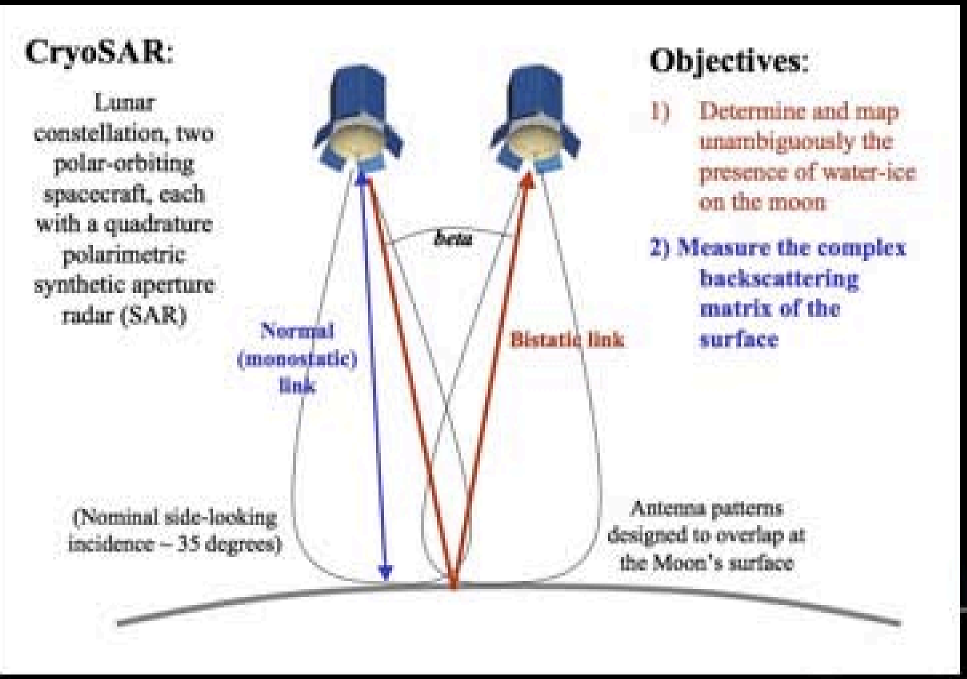
Lawrence *et al.* 2015

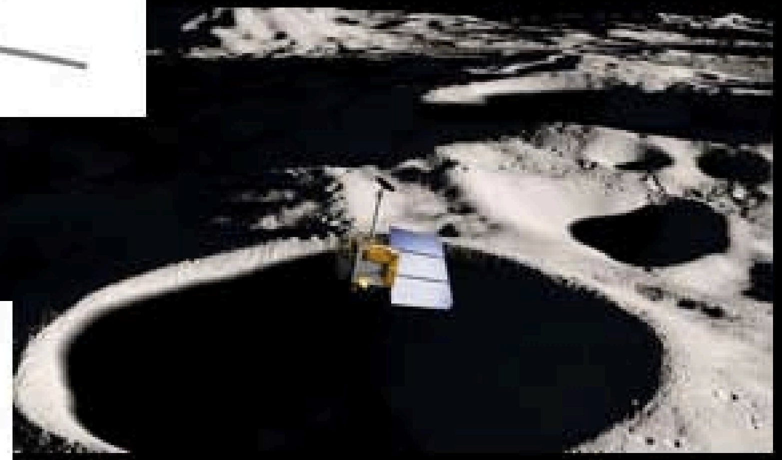


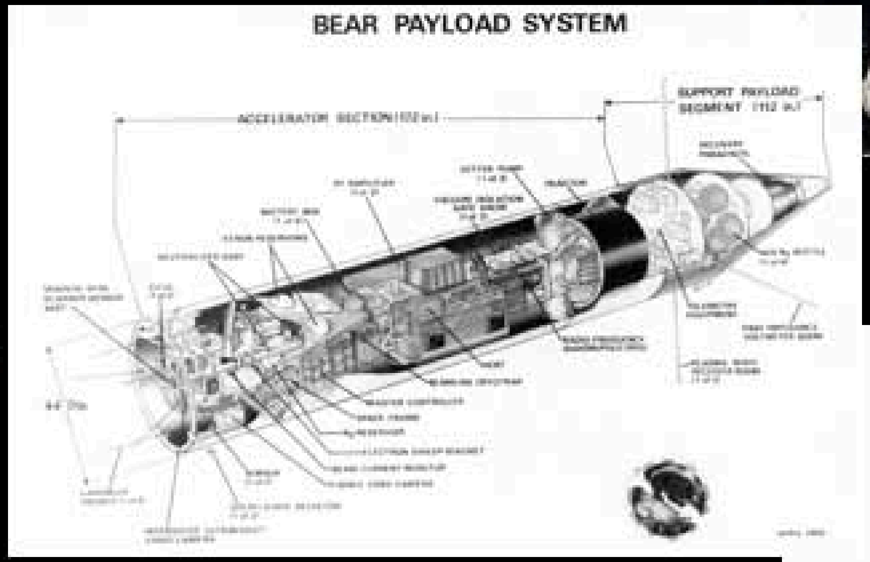


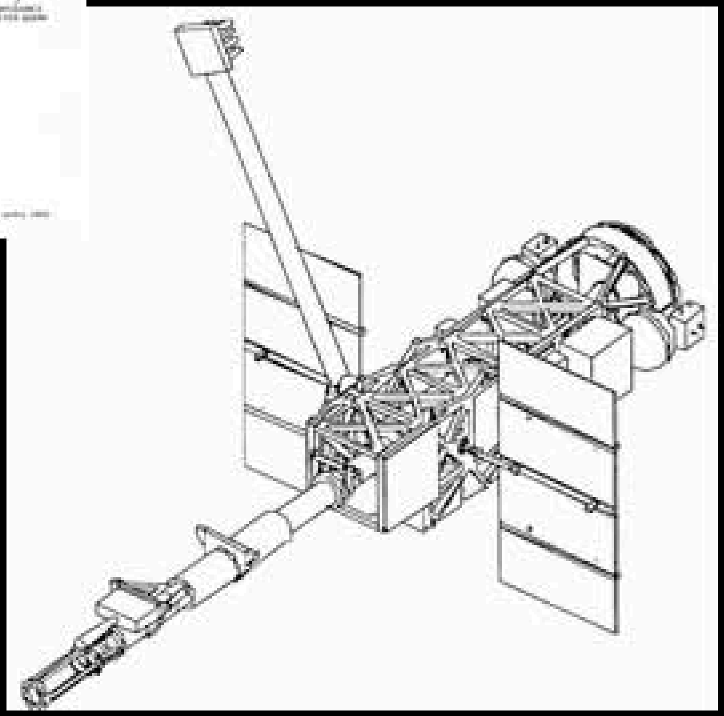
Orbital Missions

- Bistatic imaging radar
  - Dual identical spacecraft
  - Docked together at start; after 1st mapping cycle, separate and fly in formation
  - Each equipped with SAR
  - High (84°) inclination orbit; complete polar map in one month
  - Repeat for increasing β angles
- Double Eagle
  - Active neutron sensing
  - Originally conceived to space test TOPAZ reactor
  - Particle accelerator powered by solar arrays (~12 kW)
  - 100 m spot on surface
  - Detailed analysis of chemical composition of PSR, sunlit areas





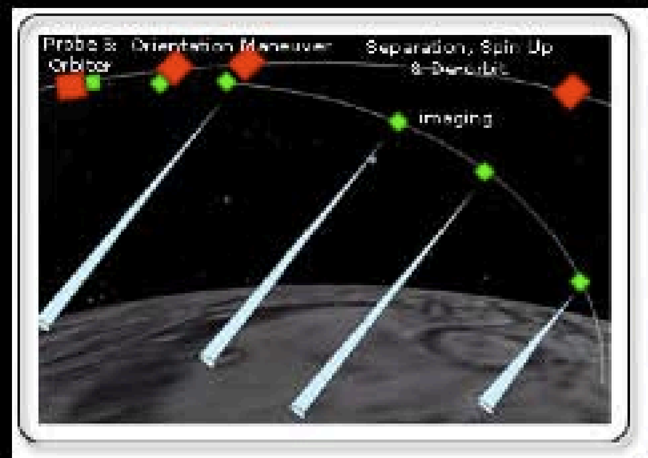


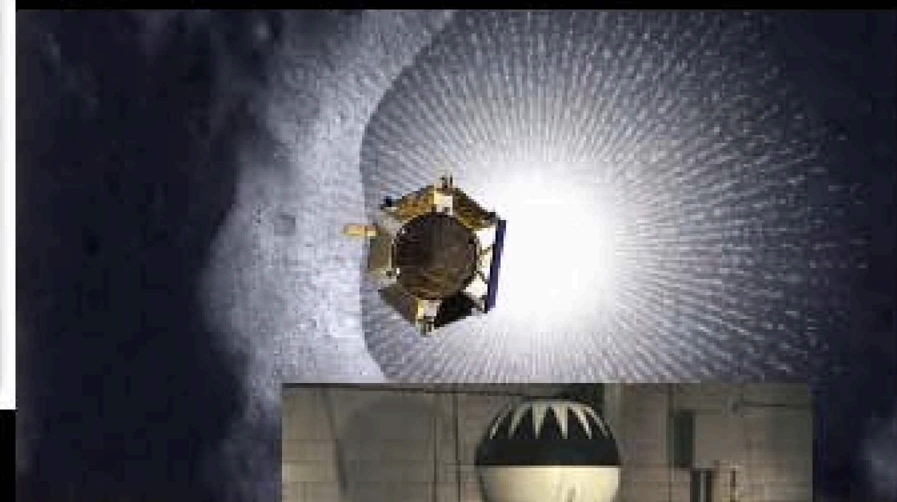
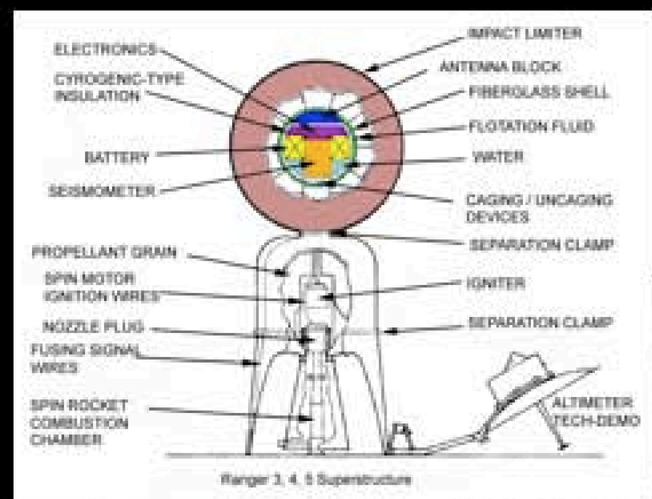


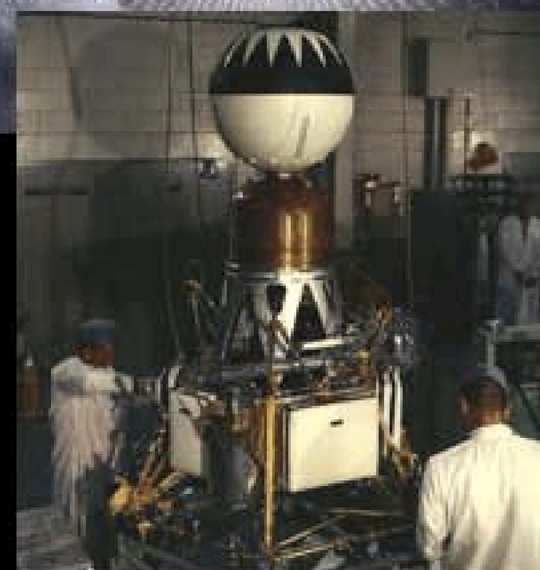
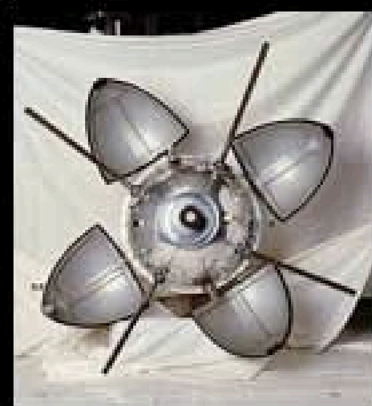
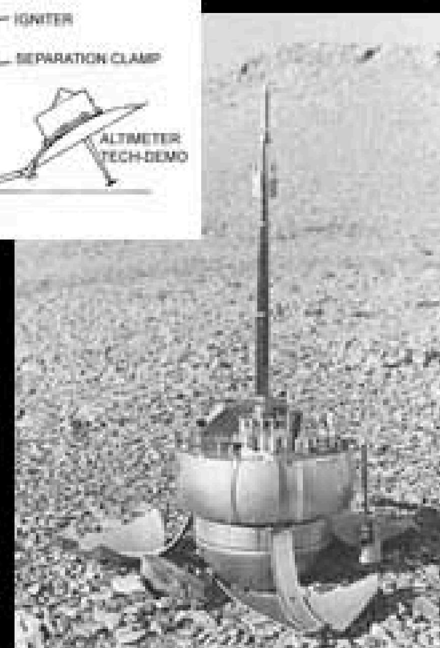
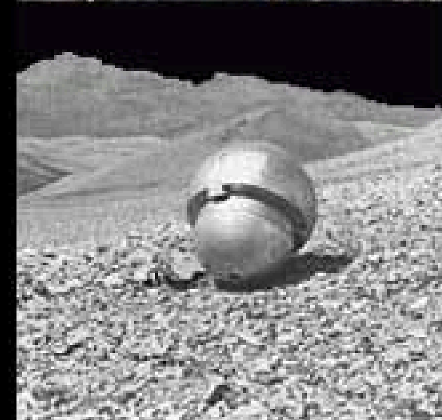
Hard Lander Missions

- LCROSS-type hard impactors
  - Die on impact; kick up ejecta
  - Following and/or orbital asset to watch ejecta plume
  - Use to test make up of promising areas
- Survivable hard landers
  - Encase instruments in crushable material (e.g., Al foam)
  - Pallet of 12-20 probes
  - De-orbit with solid at 10 km perilune, free-fall to surface (90 seconds; impact velocity ~100-200 m/s)
  - Spherical shape with offset CG (assumes correct orientation)
  - Collect data, radio results to orbiter, die (mission duration ~few hrs)
  - Map point analyses; ground truth orbital data



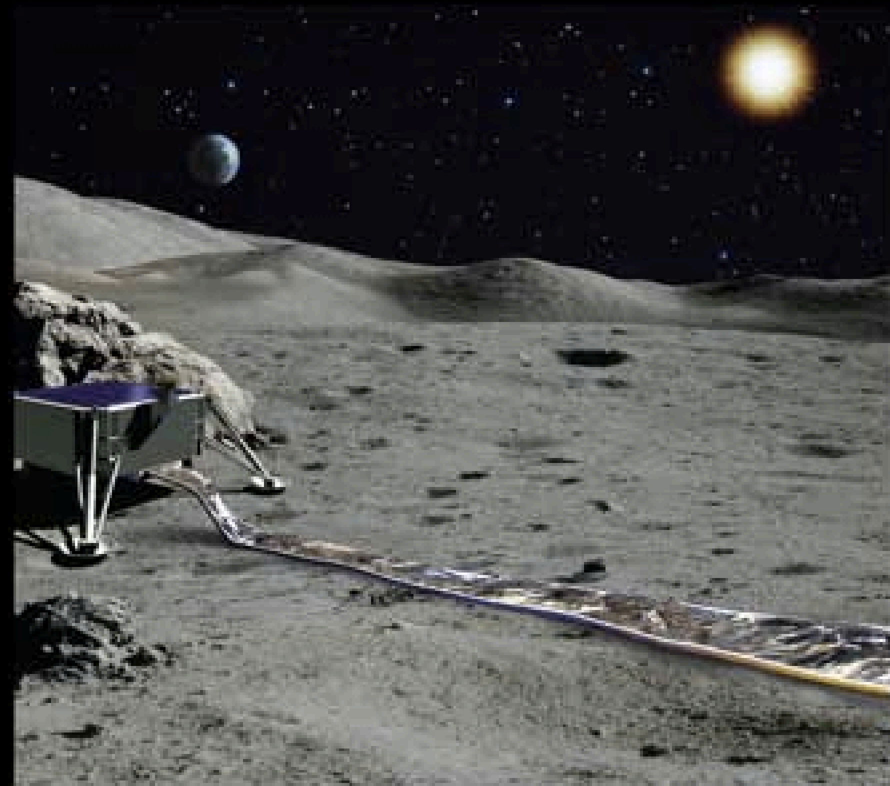


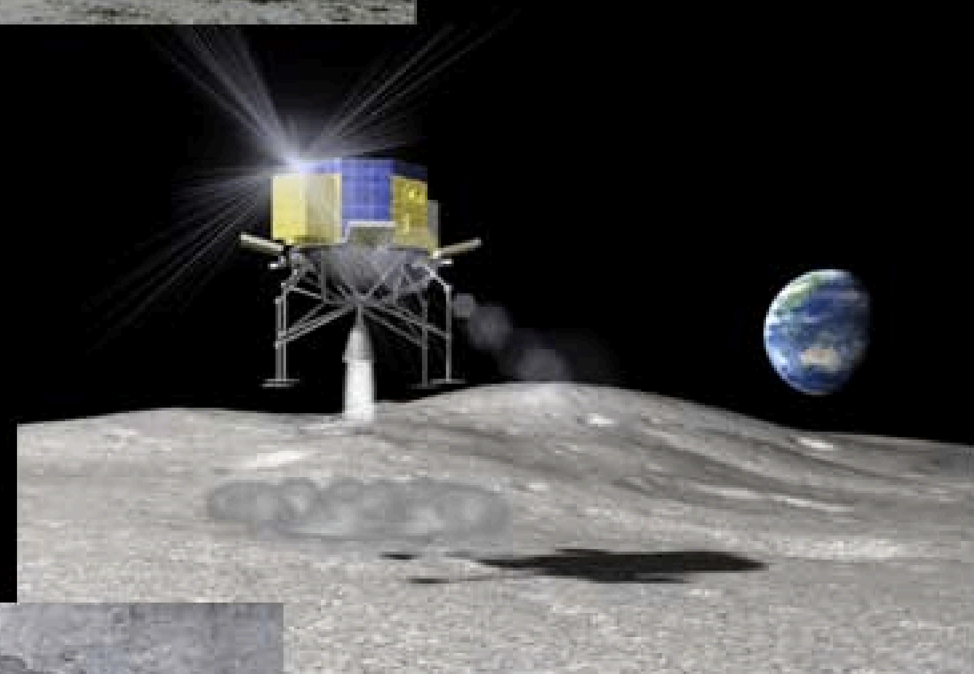



Soft Lander Missions

- Need for long-lived fixed surface landers to monitor thermal and electrical environment over time
- Sunlight lander (one year lifetime)
  - Solar powered
  - Measure plasmas, dust, electrical charging, physical properties of regolith, volatiles in flight and on surface (if any)
  - Send to possible future outpost sites
- Dark lander (multi-month lifetime)
  - RTG powered
  - Measure physical properties of regolith, electrical environment
  - Volatile content, chemical and isotopic analysis
  - Send to possible future mining site





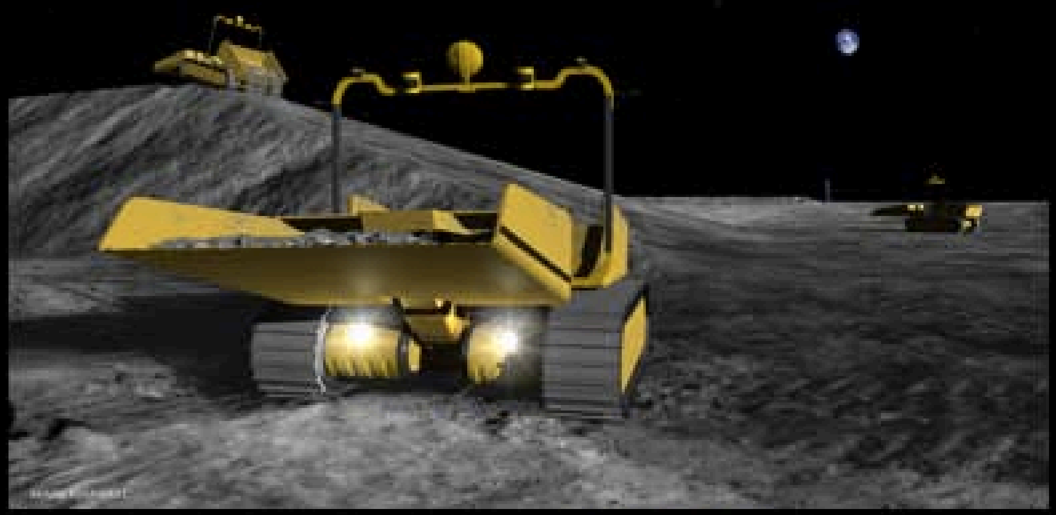
Roving Missions

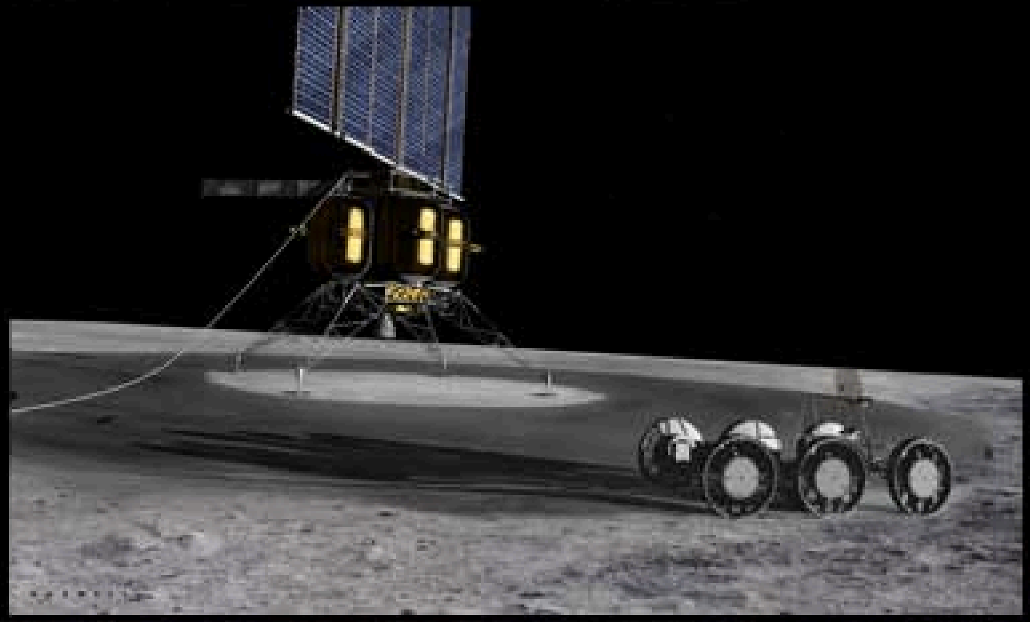
- Need mobile assets to characterize volatile deposits on km, decameter and meter scales
- Hoppers
  - Soft-landers with fuel reserve can lift-off Moon and re-land nearby
  - Typically capable of only a few hops post-landing
  - Configure with instruments to measure chemical and physical properties of ice and regolith
  - Best used once preliminary decision (short list) has been made on mining sites
- Rovers
  - Long-life is desirable (rechargable batteries + solar, RFC, RTG)
  - Traverse into and out of cold traps; need to negotiate steep slopes (~30°)
  - Configured to measure chemical and physical properties
  - Best used for detailed characterization of final mining site(s)

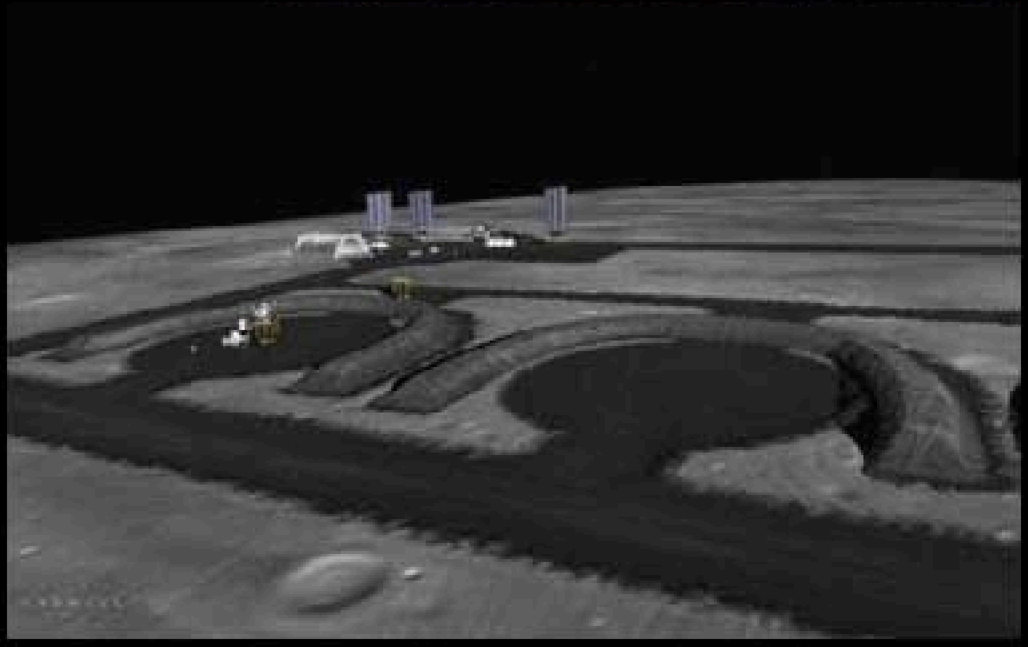



Excavation and Processing Demos

- Do not know best methods to extract, process water ice
  - Excavate feedstock or extract *in situ*?
  - Batch vs. continuous processing
- Practice dozing, hauling, loading with different techniques
  - Bladed vehicles, haul buckets, drag lines, backhoes
  - Maximum distances between mining and processing sites?
  - Thermal management and heat piping
- Determine optimum processing streams and methods
  - Distances of mine sites to sunlit areas
  - Regolith sintering, construction, paving
  - Purification and storage of products
  - By-product handling







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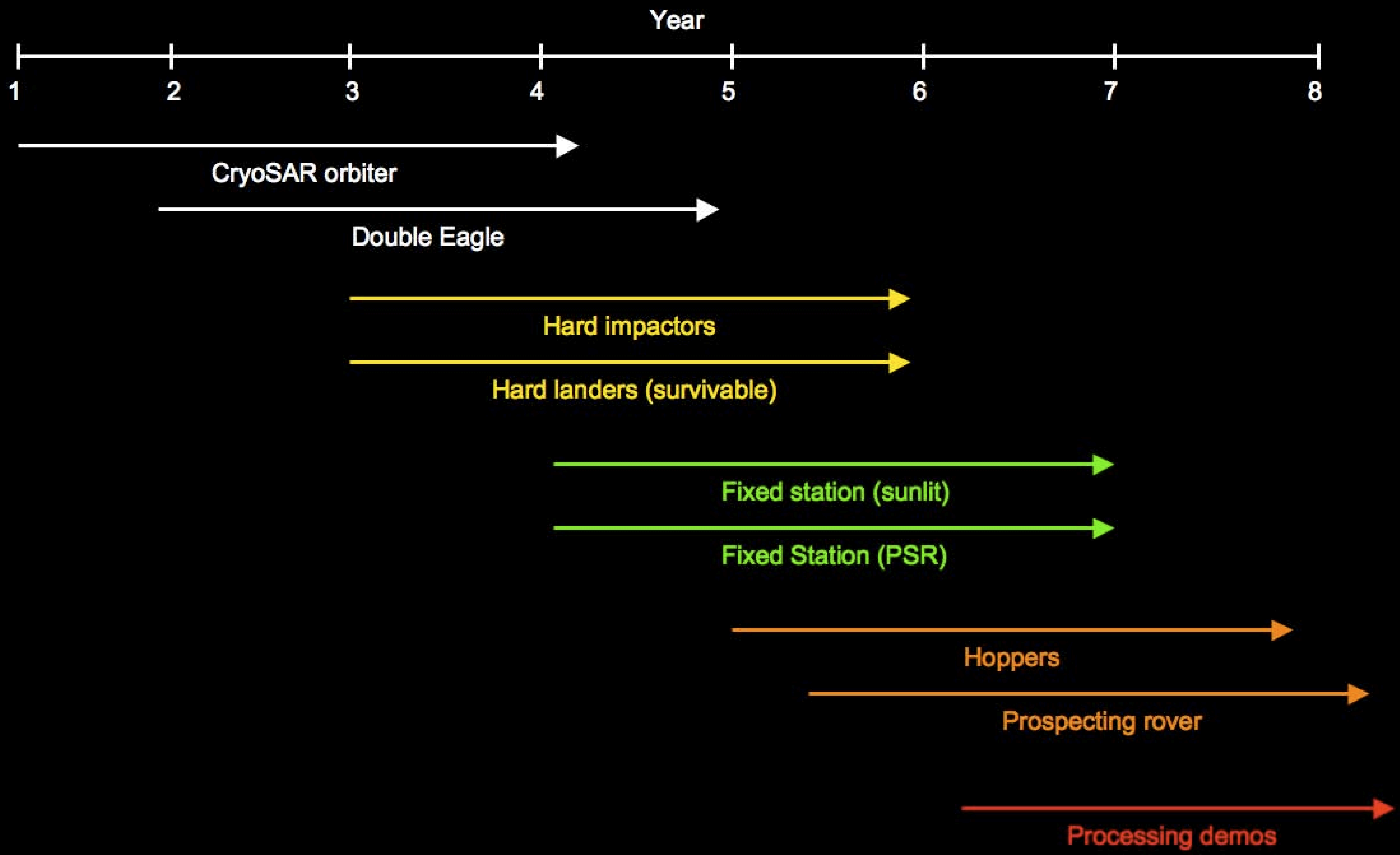

Year
1
2
3
4
5
6
7
8
CryoSAR orbiter
Double Eagle
Hard impactors
Hard landers (survivable)
Fixed station (sunlit)
Fixed Station (PSR)
Hoppers
Prospecting rover
Processing demos

Conclusions

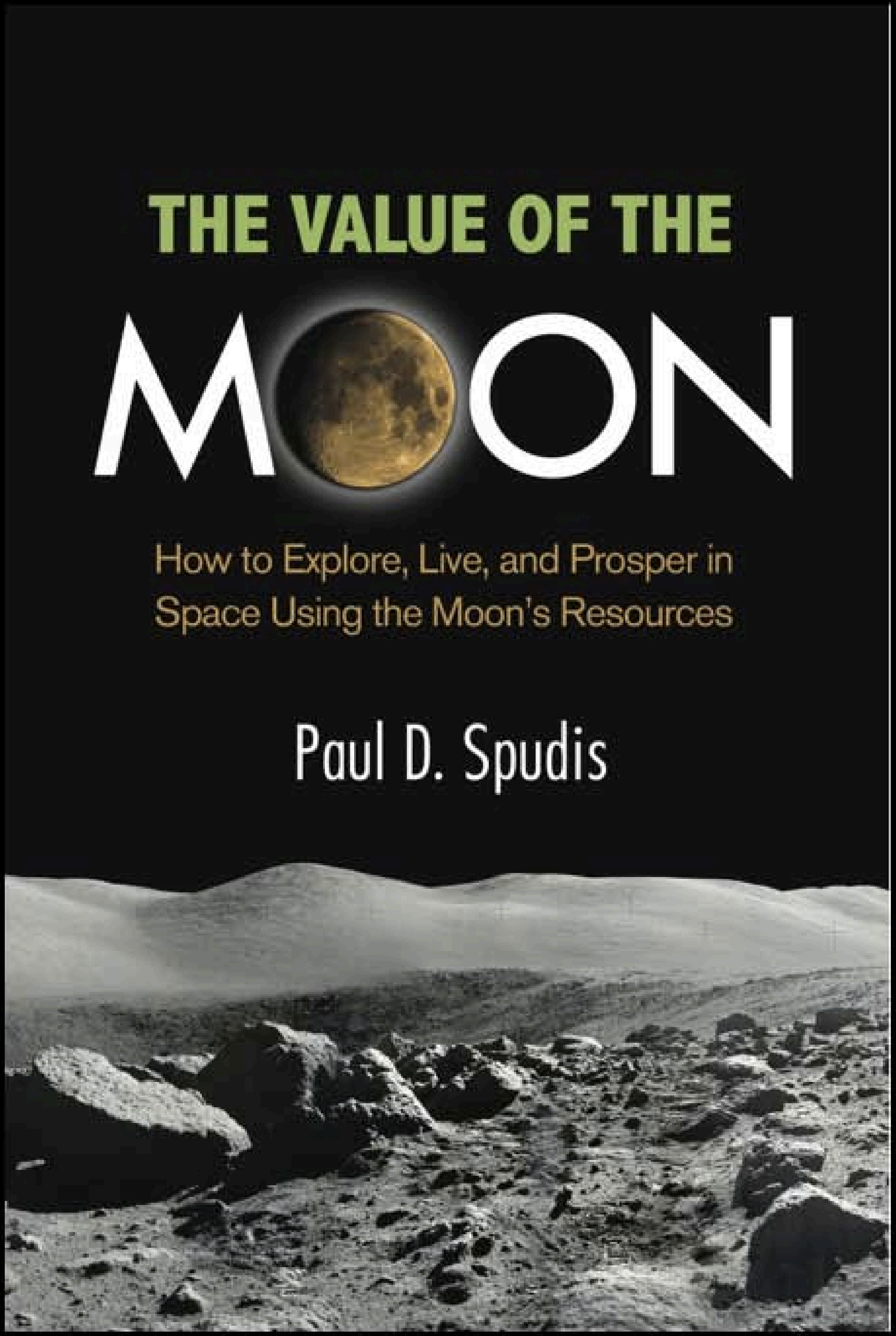
The next steps in lunar exploration depend upon the ***mission*** of lunar return

That mission should be to develop the resources of the Moon to create a permanent, cislunar spacefaring system

Such an objective requires the establishment of a resource-processing outpost at a lunar pole

We do not now possess the critical data needed to make many key strategic decisions (best prospects, proximity to sunlight, ease of surface operations)

A robust and recurring robotic flight program using orbital, hard and soft fixed landing spacecraft, and surface rovers is needed to gather this critical information



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