National Aeronautics and Space Administration

PNT as an Enabling Capability for Artemis

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Moon to Mars Top-Level Goals

SCIENCE

Lunar/Planetary Science (LPS) Goal: Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, aided by surface and orbiting robotic systems.

Heliophysics Science (HS) Goal: Address high priority heliophysics science and space weather questions that are best accomplished using a combination of human explorers and robotic systems at the Moon, at Mars, and in deep space.

Human and Biological Science (HBS) Goal: *Advance understanding of how biology responds to the environments of the Moon, Mars, and deep space to advance fundamental knowledge, support safe, productive human space missions and reduce risks for future exploration.*

Physics and Physical Science (PPS) Goal*:* Address high priority physics and physical science questions that are best accomplished by using unique attributes of the lunar environment.

Science-Enabling (SE) Goal: *Develop integrated human and robotic methods and advanced techniques that enable high-priority scientific questions to be addressed around and on the Moon and Mars.*

Applied Science (AS) Goal: *Conduct science on the Moon, in cislunar space, and around and on Mars using integrated human and robotic methods and advanced techniques, to inform design and development of exploration systems and enable safe operations.*

INFRA

Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

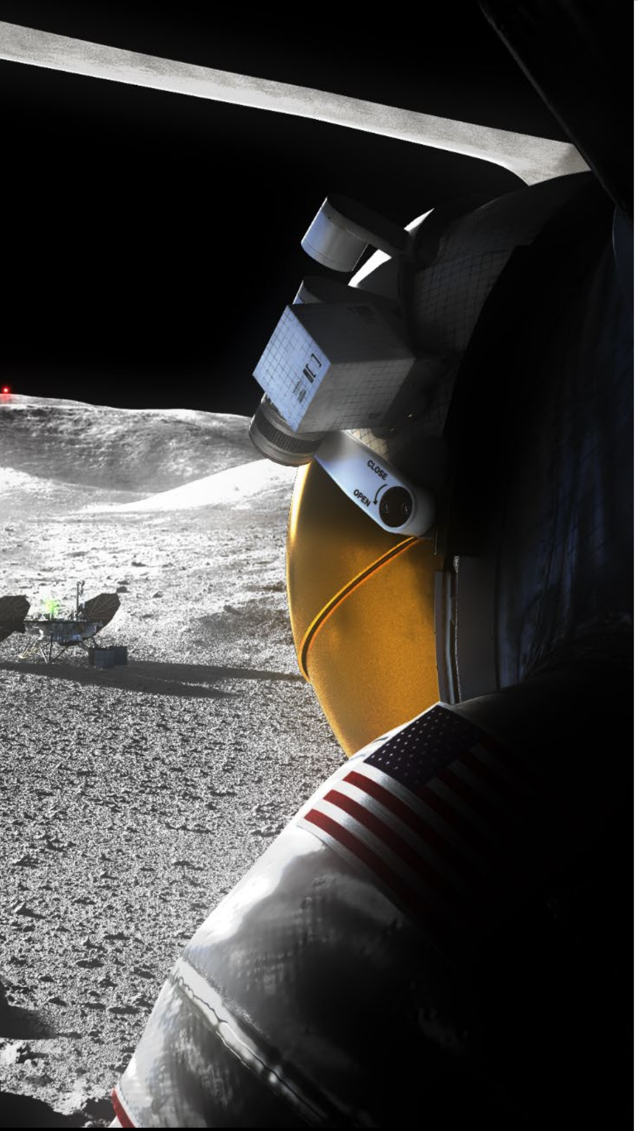
Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.

T&H

Transportation and Habitation Goal: Develop and demonstrate an integrated system of systems to conduct a campaign of human exploration missions to the Moon and Mars, while living and working on the lunar and Martian surface, with safe return to Earth.

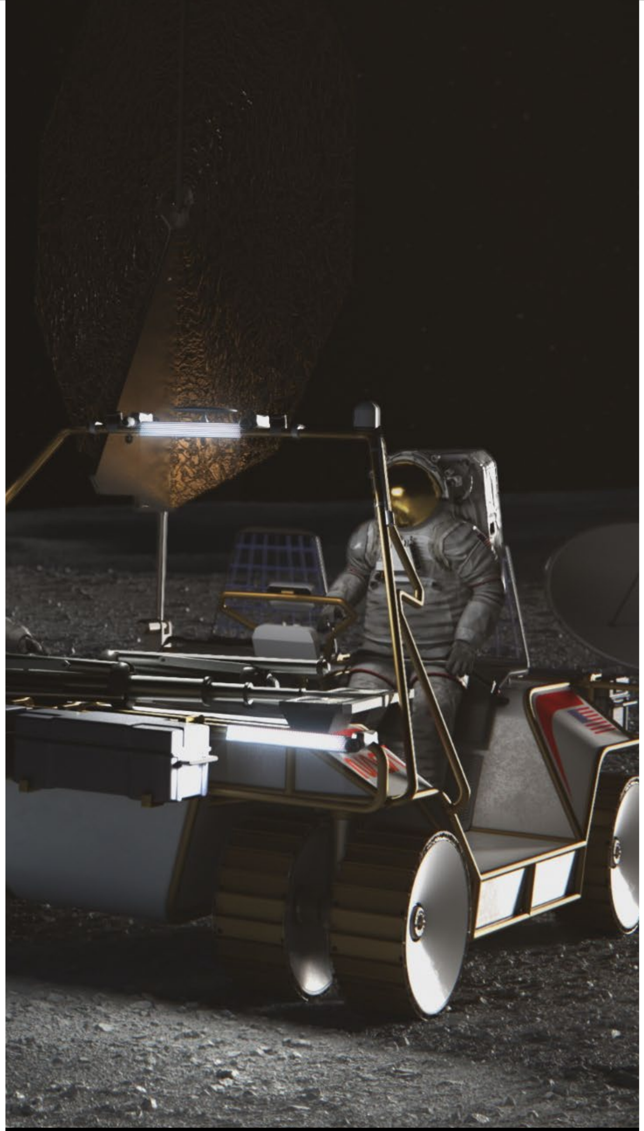
OPS

Operations Goal: Conduct human missions on the surface and around the Moon followed by missions to Mars. Using a gradual build-up approach, these missions will demonstrate technologies and operations to live and work on a planetary surface other than Earth, with a safe return to Earth at the completion of the missions.



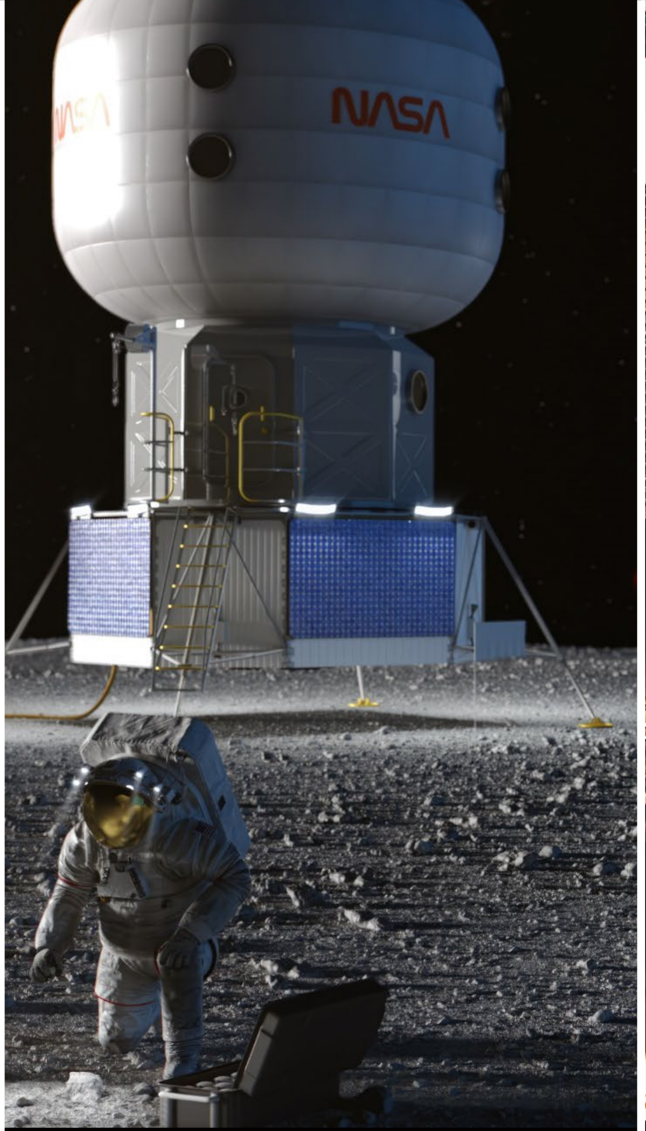
Human Lunar Return

Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization (e.g., science) on and around the Moon.



Foundational Exploration

Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.



Sustained Lunar Evolution

Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

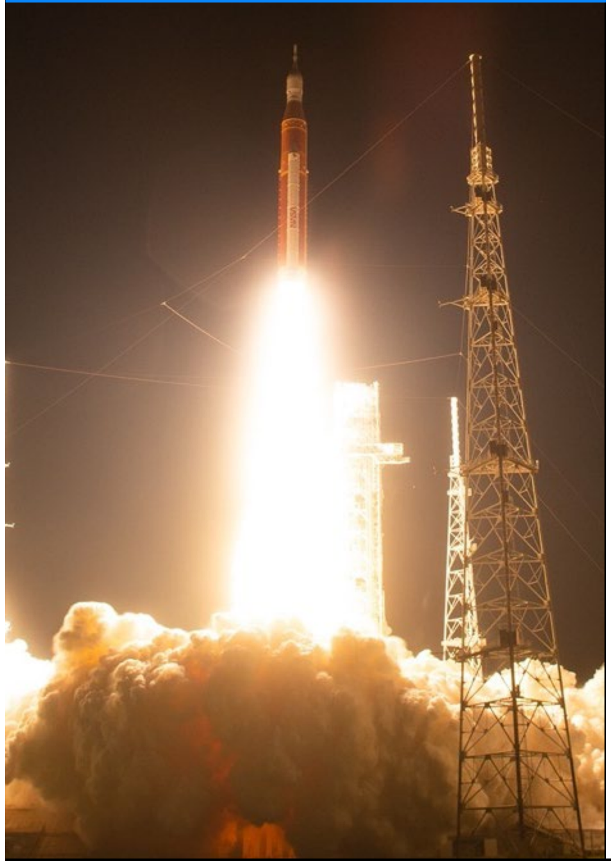
Humans to Mars

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

ARTEMIS I

First mission
(uncrewed flight test)

COMPLETE



ARTEMIS II

First crew

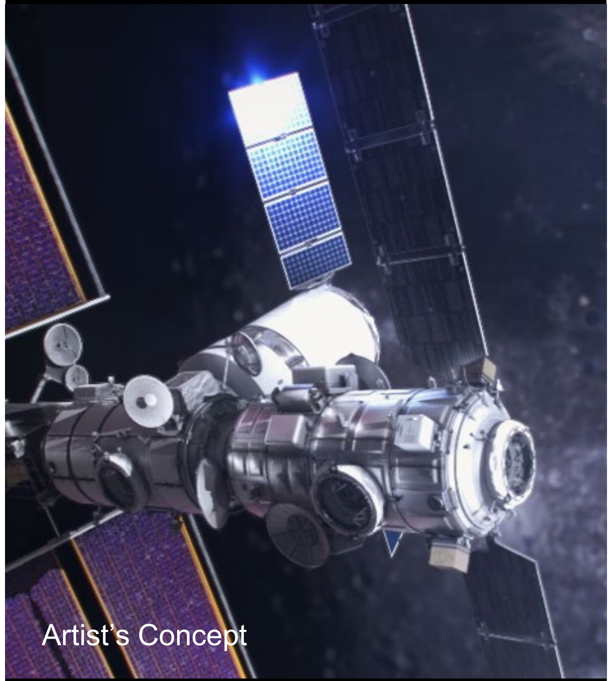
CREW SELECTED

ARTEMIS III

First human
surface landing

ARTEMIS IV

First lunar space station
assembly mission



Gateway space station

Human landing system, spacesuits

Crew

Space Launch System rocket, Orion crew spacecraft, Exploration Ground Systems

Conducting science and demonstrating technology in orbit and on the surface

Human Lunar Return Segment

EXPLORATION GROUND SYSTEMS

ORION SPACECRAFT

SPACE LAUNCH SYSTEM

GATEWAY

DEEP SPACE LOGISTICS

xEVA Systems

HUMAN LANDING SYSTEM

COMM, POSITIONING, NAV, TIMING (CPNT)

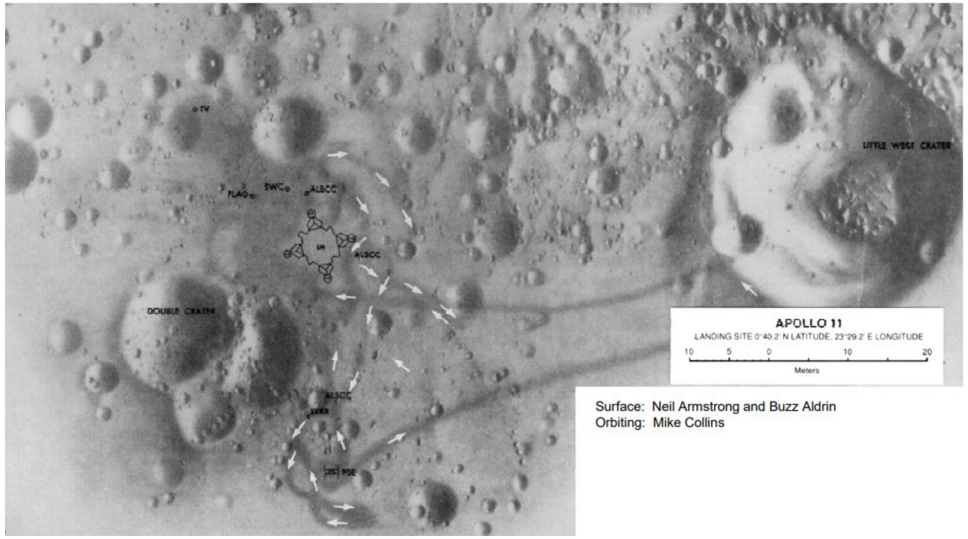
COMMERCIAL LUNAR PAYLOAD SERVICES

Apollo History and Approach (Missions with no Rover)

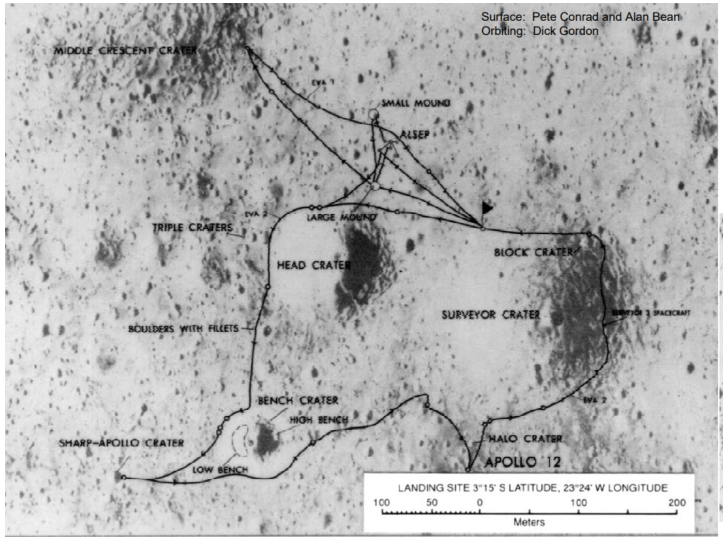
- **Apollo 11 - 14: walking range between 55 m to 1.3 km on ~6 hr supply**
- **Crews navigated via orienteering to surface features**
  - Used scale ruler, solar compass
  - Apollo 14 came within 20 m of Cone Crater but missed
  - Astronauts identified difficulties in navigation due to lunar environment
    - Difficulty in judging distances
    - Nearer than expected horizon
    - Stark lighting and lack of atmosphere (no haze)
- **Crew timelines had to balance science objectives, public outreach events, instrument deployments & set-up, and reasonable walking pace**

Apollo crew distances were limited due to time constraints and navigation methods.

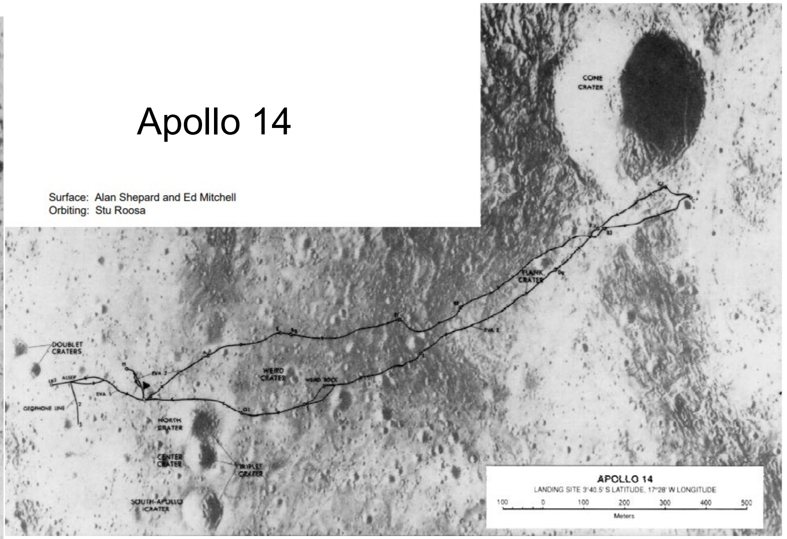
Apollo 11

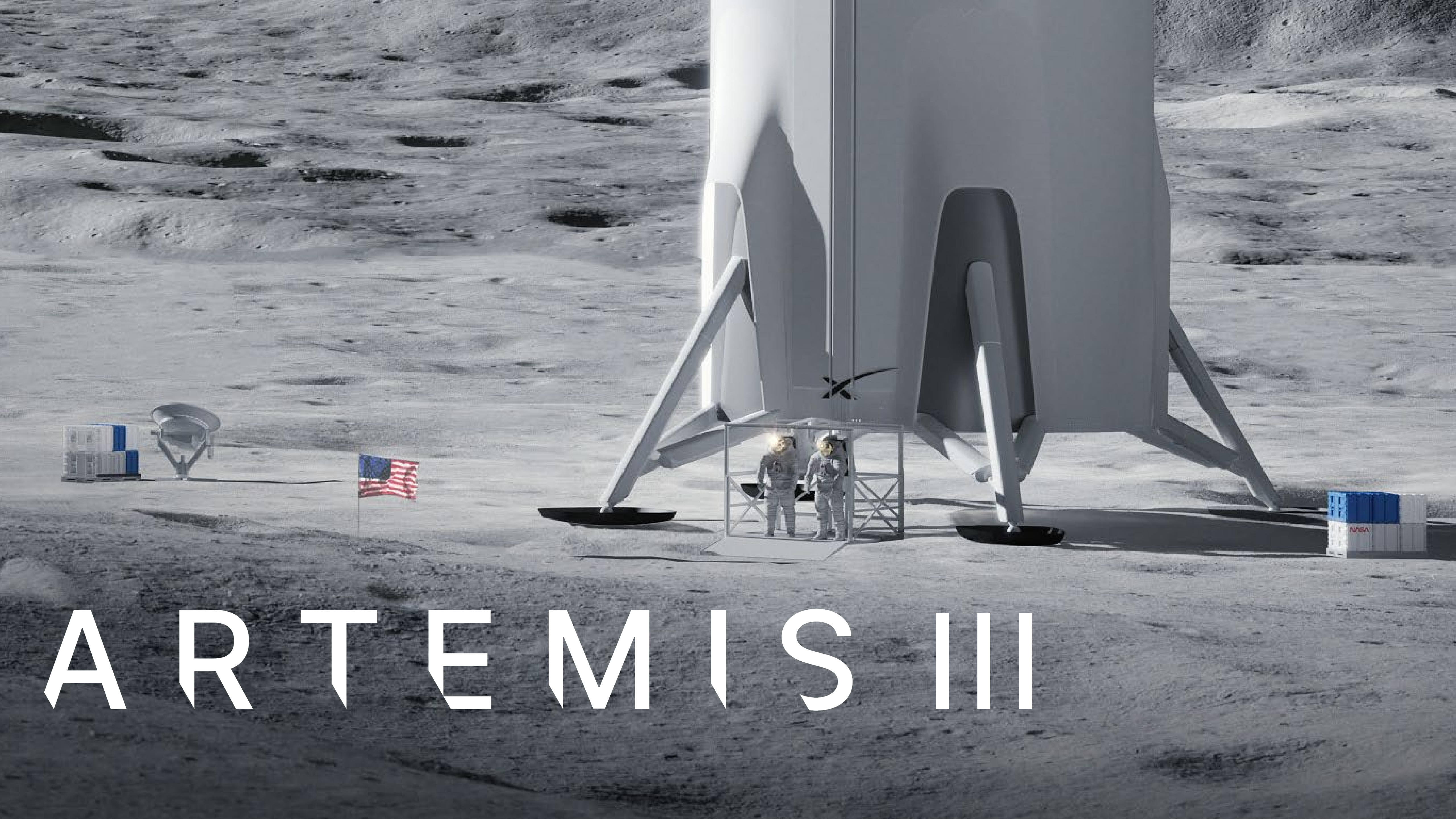


Apollo 12



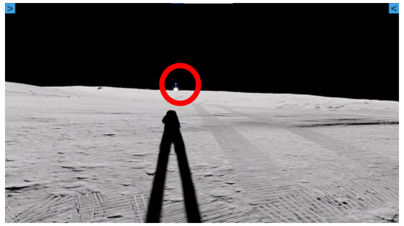
Apollo 14

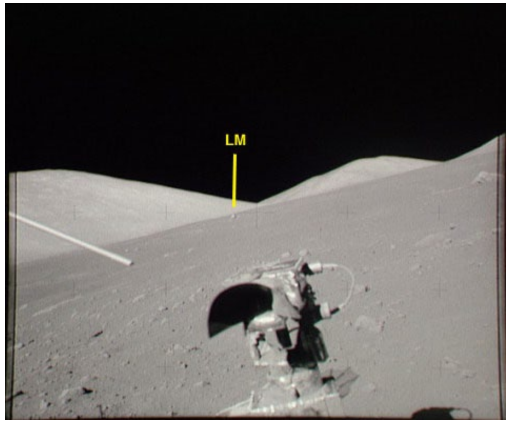



ARTEMIS III

Differences between Apollo and Artemis South Pole

- **Artemis III and IV requirements are to be capable of up to 2km walking distance.**
- **Lighting, environments, terrain, objectives (PSRs, ranges, utilization), provide addition challenges beyond Apollo conditions**
  - Navigate without impacting science (minimize contamination)
  - High intensity low-sun angles: visibility of landmarks (landers, craters, outcroppings, and other work-sites) beyond the reach of artificial lighting very difficult
  - Long shadows with high contrast: very misleading in terms of distance and topographic features (is that a small crater, boulder, or just shadow?)
  - Terrain conditions will limit line of sight to lander; while strict constraints on landing areas, South Pole terrain more rugged
- **Artemis III Geology Team identifying science objectives and science stations**
  - More interesting science farther from safe landing areas





LM@750 m – Apollo17

Apollo 14 Conditions will be a “best case day” for Artemis

Artemis is more challenging from lighting, environment, and desirements perspective, but objectives remain flexible on a per-mission basis.

Lunar Navigation From An Apollo Crew Perspective

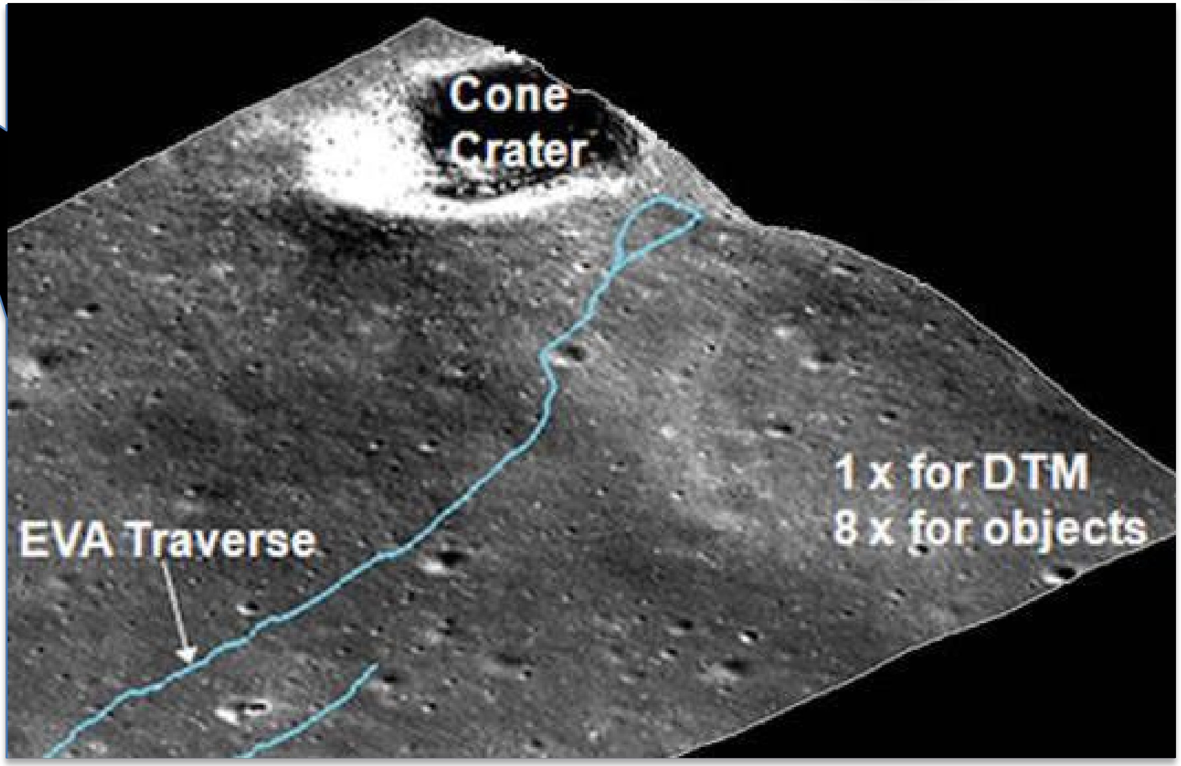
"Maps are primarily only useful for large surface features"

"Even when the crewmen climbed to a ridge, the landmark often was not clearly in sight."

"Craters were hidden behind other craters, ridges, and old worn-down mounds"

"Distances are deceiving"

"It is, however, potentially dangerous to proceed on the assumption that no navigation aids are needed and to discover in the middle of a mission that 'seat of the pants' navigation is inadequate"

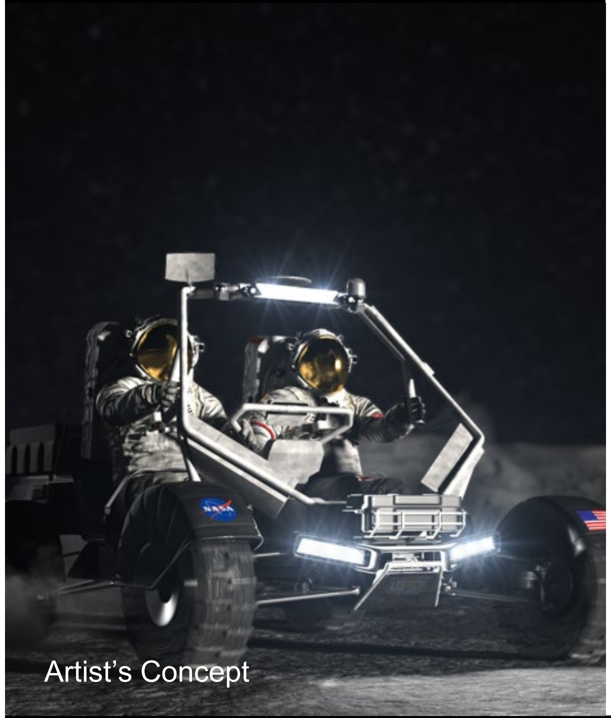


Apollo 14 Crew Came within 20 m of Cone Crater objective without realizing It

"Navigation is more difficult with so much dark terrain and crude nav aids" – DRATS 2021 Summary

ARTEMIS V

First unpressurized rover



ARTEMIS VI

Gateway assembly complete

ARTEMIS VII AND BEYOND

Longer missions = preparation for human Mars missions

Access to more of the Moon = new scientific discoveries

Pressurized rover, surface habitat, and other new elements

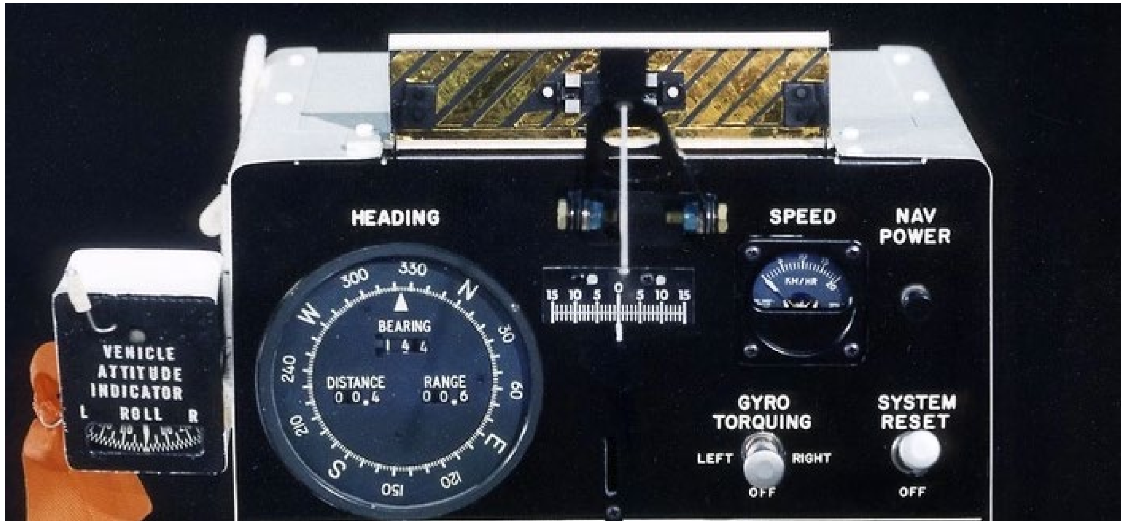
Gateway airlock module

Lunar terrain vehicle; Gateway refueling and robotics

Crew conducting science and demonstrating technology in orbit and on the surface;
Space Launch System rocket; Orion crew spacecraft; Exploration Ground Systems; Gateway space station

Apollo Roving Vehicle History compared to Artemis Operations

- **Apollo 15 – 17: driving range between 5 to 7 km with ~8 hr supply**
- **Navigation for Lunar Roving Vehicle (LRV)**
  - Dead reckoning via odometer and gyroscope
  - No telemetry or external commanding
  - Initialization required manual observation of solar heading and pendulum inclination
    - MCC calculated heading and crew commanded
    - System could be realigned in mission (rarely used)
    - Took ~5-10 minutes to perform initialization
  - Performance on order of ~100 m



- **Artemis V+ Long-term goals going well beyond Apollo operations**
  - Multiple vehicles operating in tandem (Lunar Terrain Vehicle and Pressurized Rover)
  - Traverse from 10 km to 20km from lander via rovers
  - Expanded operations into large shadowed regions
  - Transport of mobile assets between landing zones over long periods
  - Uncrewed Tele-robotic Operations throughout the year
  - Surviving the lunar night

Apollo demonstrated benefits of Coarse Navigation Capability from Lunar Roving Vehicle (~100 m). Artemis goals require more PNT Capability.

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Artemis Requirements Drivers

Requirements – Derived based on Safe Return in Contingencies

- **Nominal Scenarios**
  - Walk-back from 2 KM
  - Drive-back from 10KM
  - Walk-back to LTV from 500m

- **Contingency Scenarios**
  - Return to HLS from 2KM on-foot due to EVAS Contingency
  - Return to HLS from 10KM driving due to EVAS Contingency
  - Return to HLS from 10KM walking due to LTV contingency

- **In all cases, factor in supply times, max walking speeds, egress and ingress times, and detection time of failure**

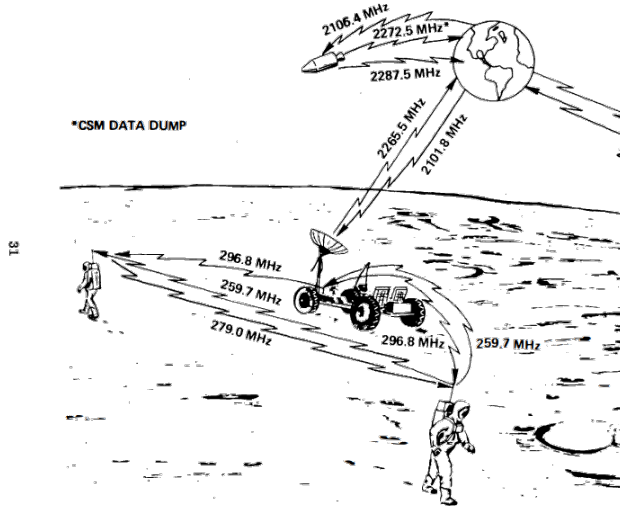


Figure 1-3. LCRU in Fixed Base Operation or

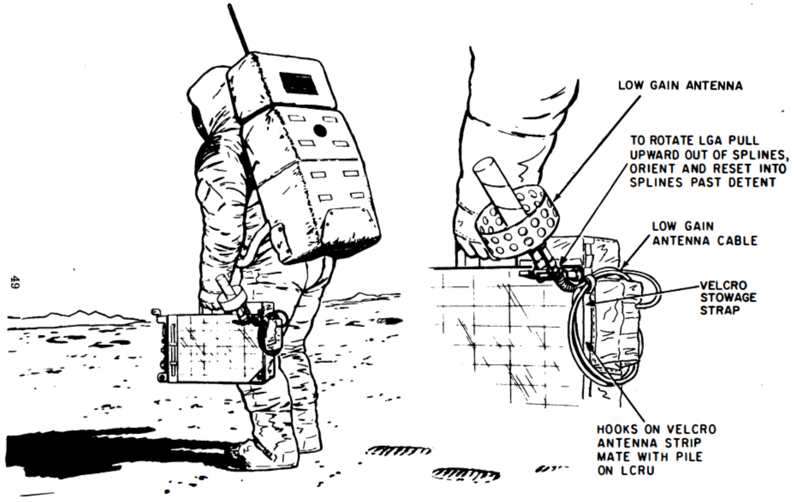
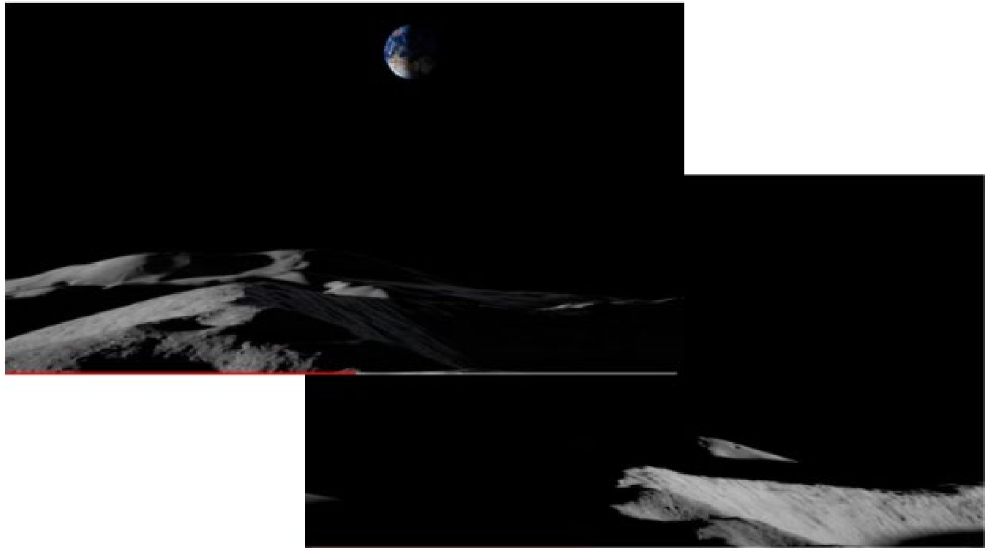


Figure 4-16. LCRU Hand Carry Mode

Requirements – Derived from Discussions with Science

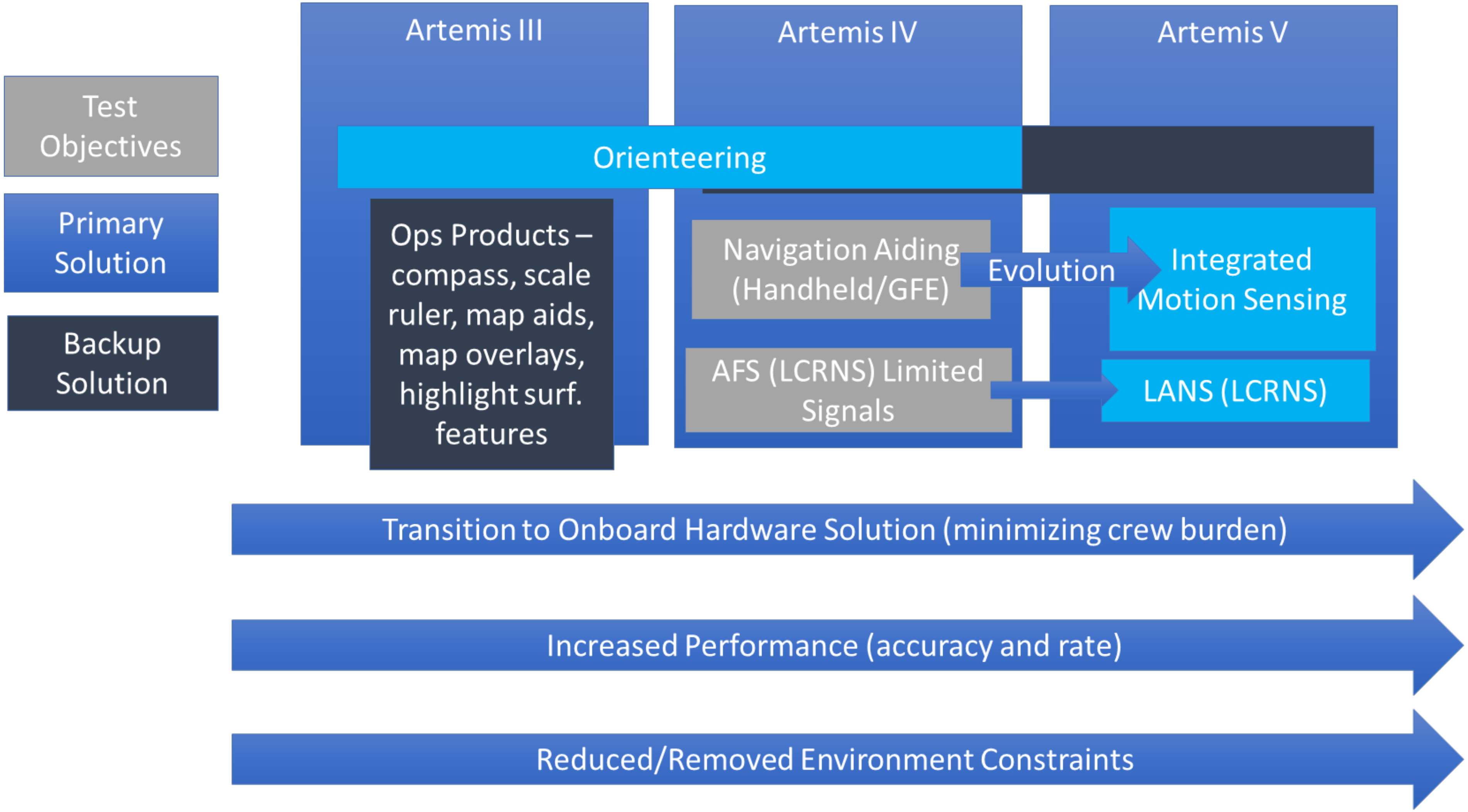
- **Desire to reach specific areas of interest**
  - Large boulders
  - Small boulders
  - Small craters
  - Larger craters
  - Rolling surface feature
  - Radial sampling from crater
- **Desire to resample a specific site**
- **Traverse Reconstruction**
- **Exploration into shadowed regions**
- **Desire to sample along less defined, older craters, requires ~10m navigation accuracy due to gentle sloping nature of crater (hard to differentiate crater from rolling hill)**

Artemis - Low Sun and low Earth



Unique science objectives and hazards drive accuracy and time to solve requirements to not exceed available EVA time.

Artemis driving PNT as an enabling & evolving capability



Artemis at Lunar South Pole presents more stressing distance, lighting, earth availability, and navigation challenges than previous Lunar and Mars programs driving an evolutionary approach.

We came in peace.

We return for all humanity.

Image credit: Andrew McCarthy