Blast Off into the Future of Autonomy in Space

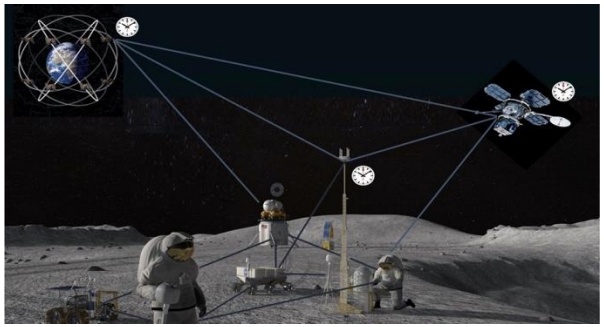
Prof. Grace X. Gao

New Era for Exploring the Moon

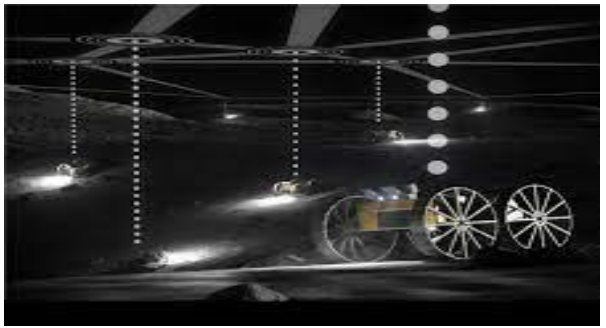
Blast Off into the Future of Autonomy in Space: Technical Trends

- Building infrastructure (e.g. WiFi, GPS, power plant, base station)
- Collaborative intelligence (e.g. swarm robots, satellite swarms)
- Long-range autonomy
- AI for space

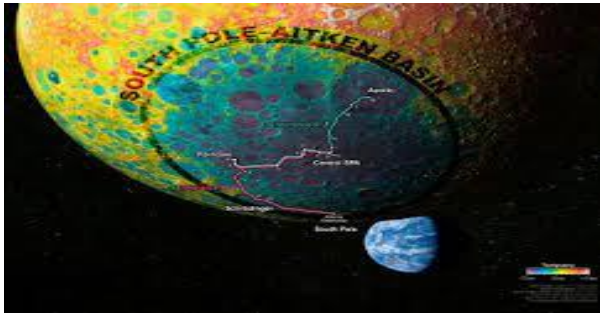
Example Projects in the Stanford NAV Lab



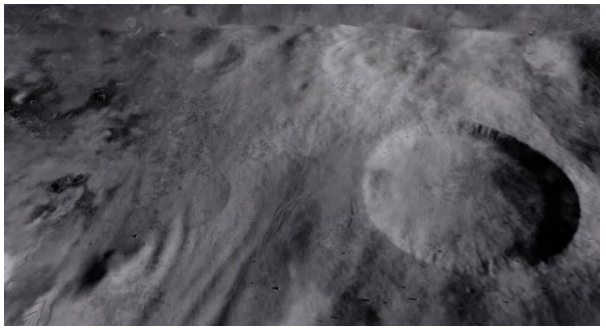
"GPS" for the Moon



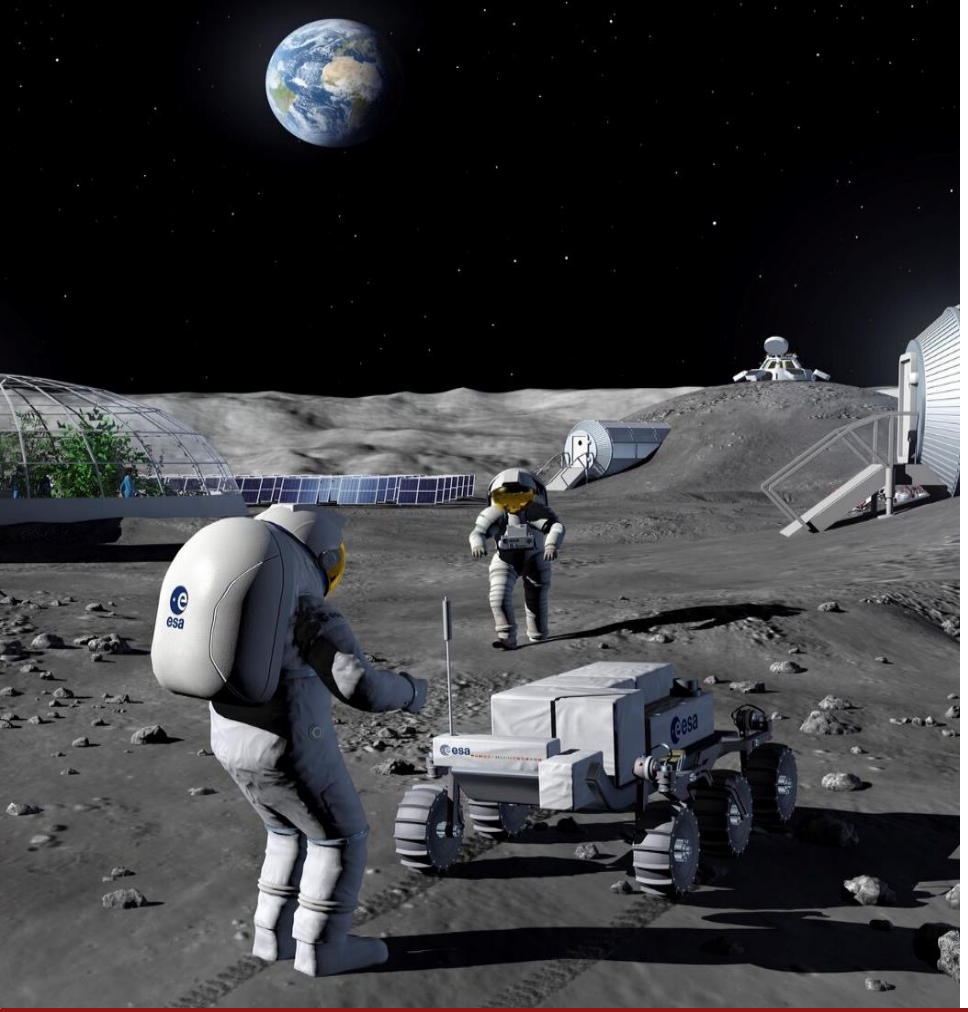
Moon Rover Swarm: CADRE Mission



Long-Range Moon Rover:
Endurance Mission Concept



Neural Moon Surface Maps








“GPS” for the Moon

LunaNet

- Satellite network around the moon for navigation and communication
- Joint effort by
  - US NASA
  - European ESA
  - Japanese JAXA
  - + Korea
  - + India

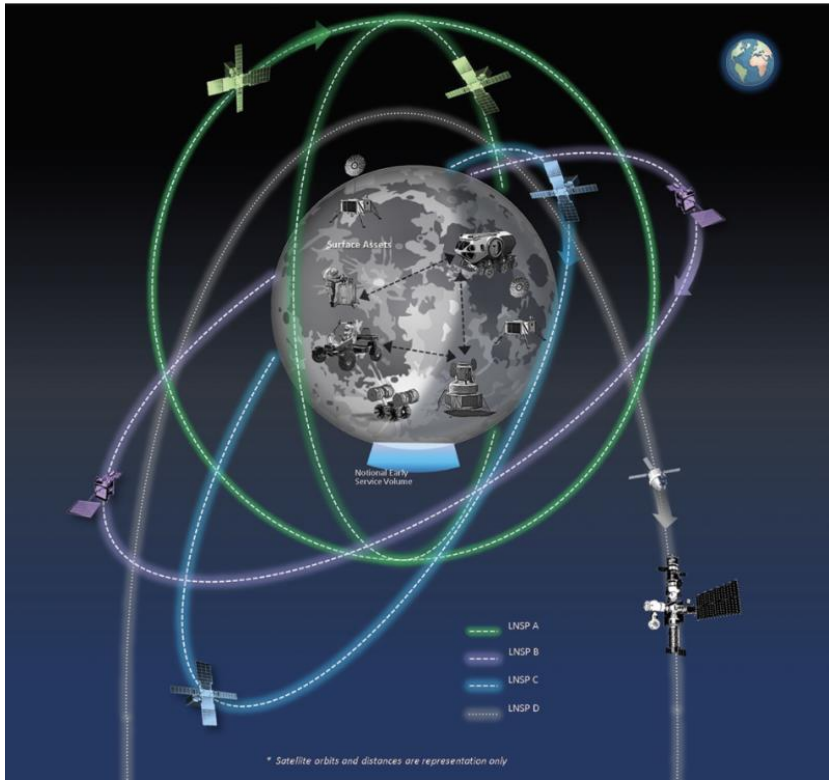
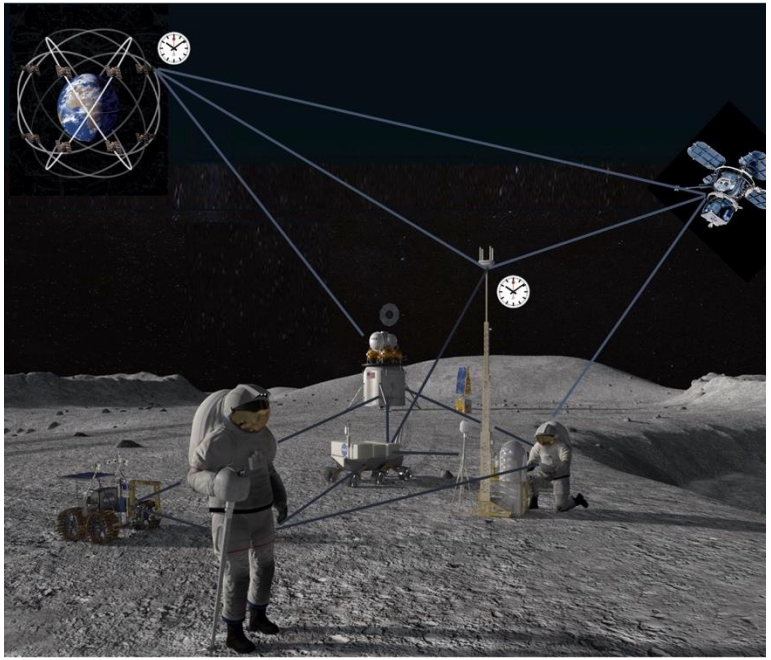


Image courtesy of InsideGNSS

Can we have a GPS-like system for the Moon, but with a much lower cost?

Lunar Navigation Satellite System

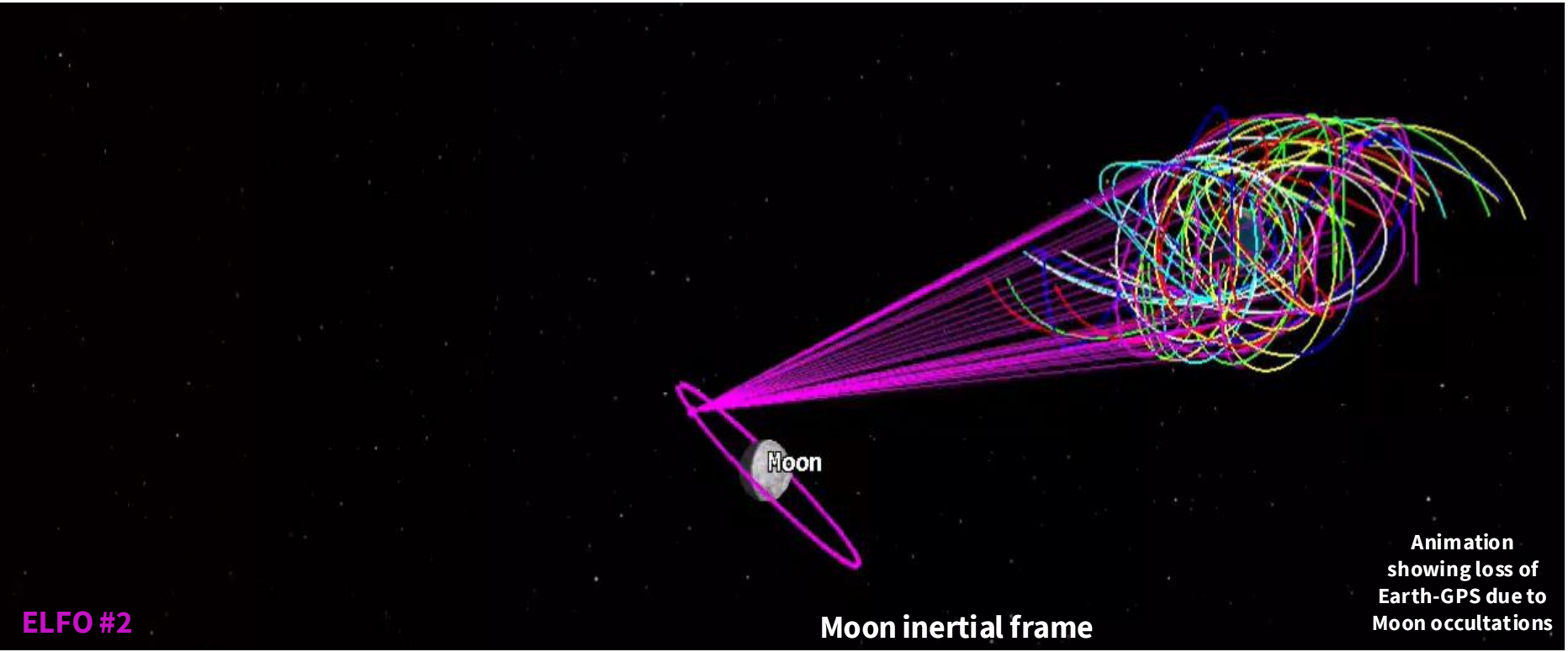
- Smaller satellites
  - as small as a shoe box
  - vs. terrestrial GPS satellites: as large as a truck
- Cheaper clocks
  - a thousand times cheaper than the atomic clocks on today's GPS satellites



Key idea: Use terrestrial GPS for lunar navigation satellite clock and ephemeris corrections

Bhamidipati, Mina and Gao, ION GNSS+ 2021
Bhamidipati, Mina and Gao, ION ITM 2022
Cortinovis, Iiyama and Gao, ION GNSS+ 2023
Bhamidipati, Mina, Sanchez and Gao, ION GNSS+ 2022
Iiyama, Bhamidipati, and Gao, ION ITM 2023
Iiyama and Gao, ION GNSS+ 2023

Loss of Earth-GPS due to Occultation



Animation showing loss of Earth-GPS due to Moon occultations

LuGRE: Lunar GNSS Receiver Experiment

- **LuGRE:** a payload onboard Firefly Aerospace Blue Ghost Mission 1, launched on **Jan 15, 2025**.
  - Collaboration among NASA, ASI, and Qascom SRL
- Catches GPS Signal From 205,674 miles (331,000 km) Away, sets distance record.
- Demonstrated the feasibility of using Earth GNSS signals

Image courtesy of NASA

Moonshot 2.0: Blast Off into the Future of Autonomy in Space

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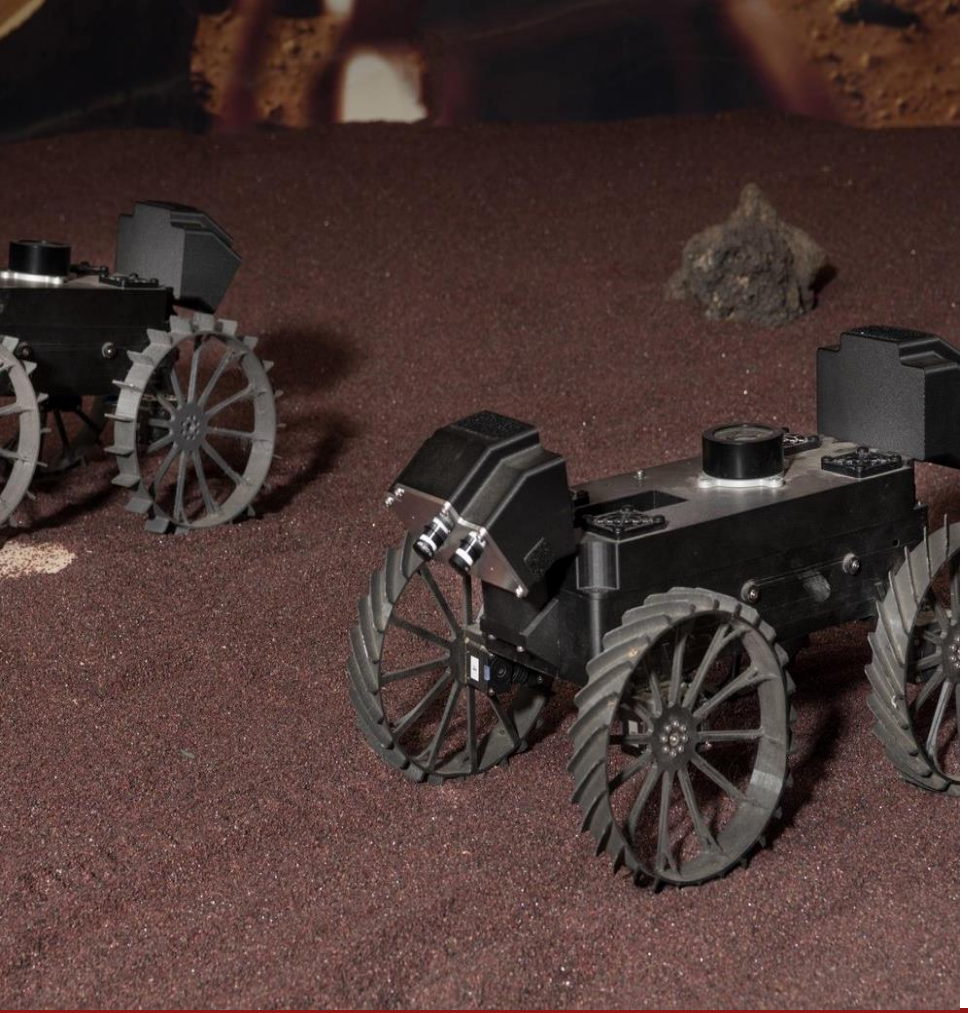




Moon Rover Swarm: CADRE Mission


CADRE
Cooperative Autonomous Distributed Robotic Exploration
NASA

Robot Swarm Navigation




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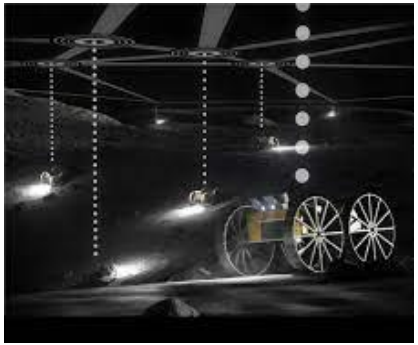

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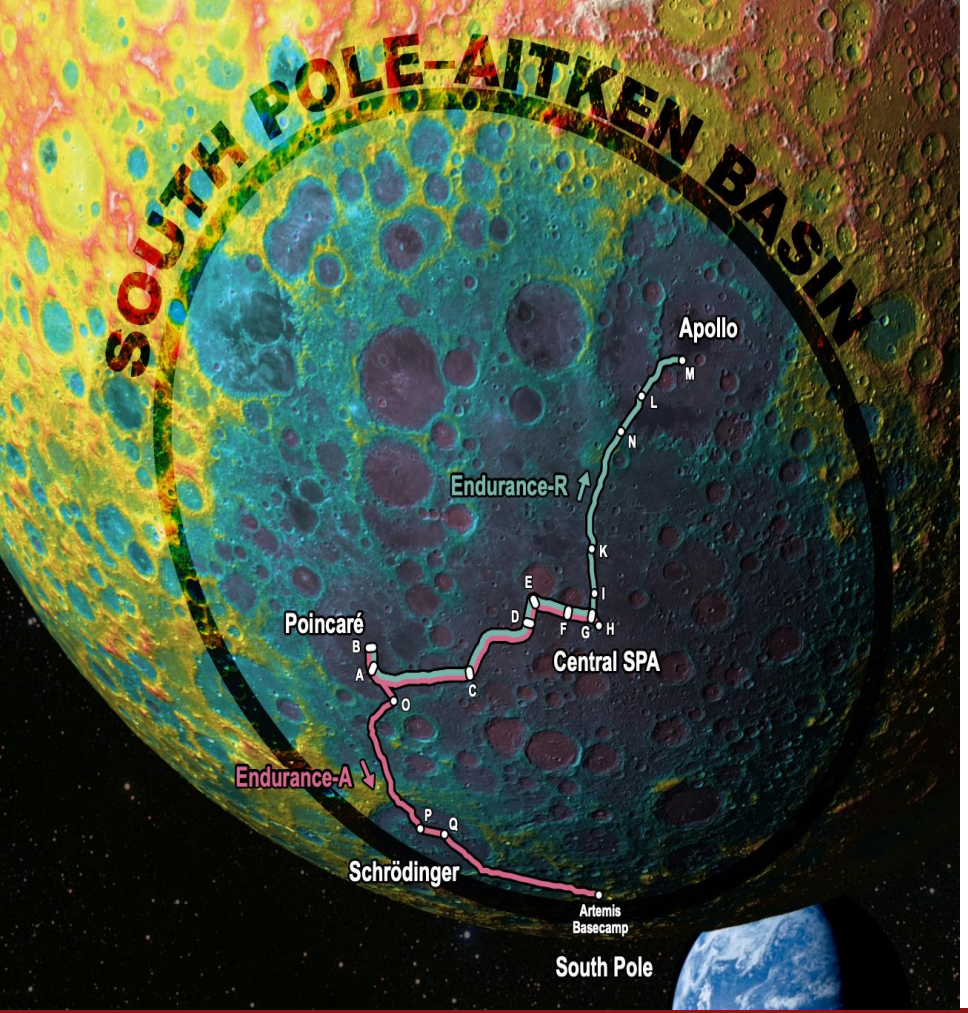
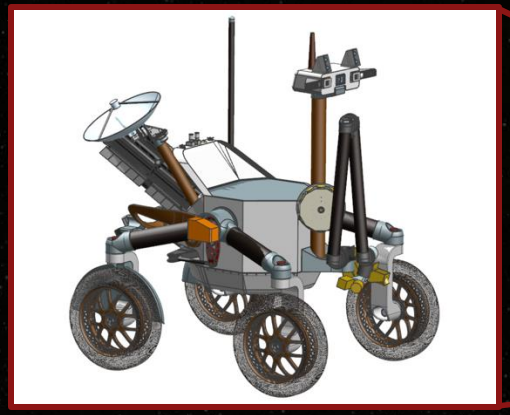


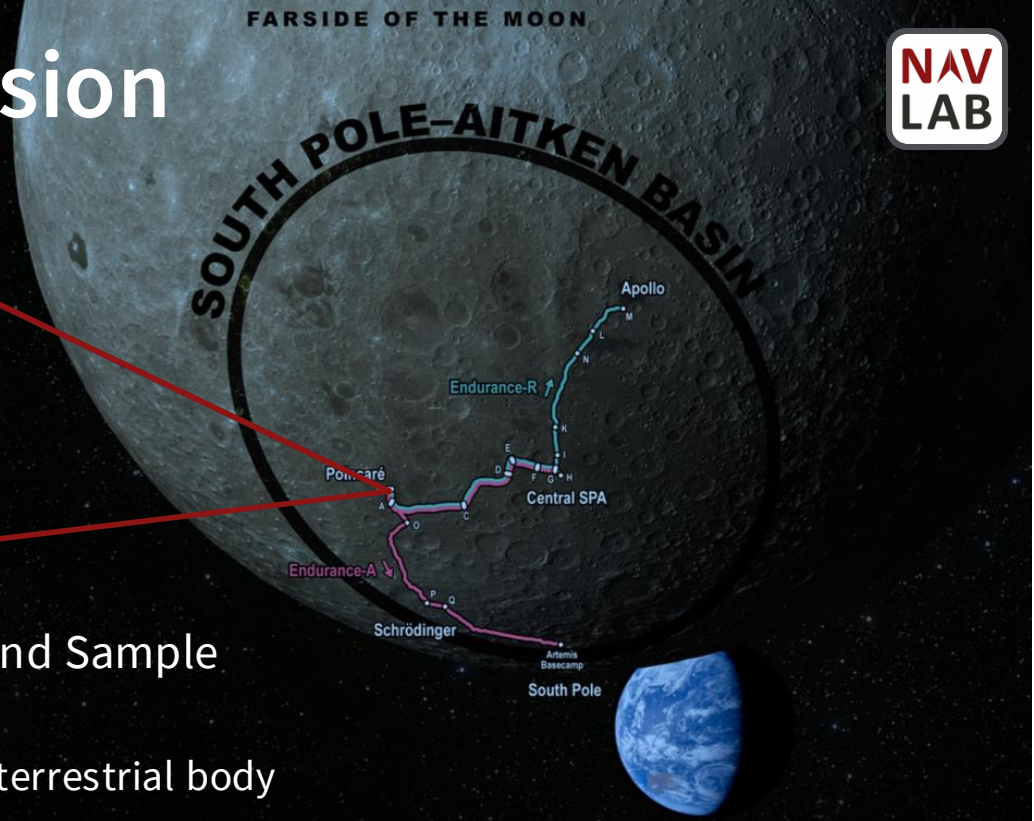


Long-Range Moon Rover: Endurance Mission Concept

Cortinovis and Gao, IEEE Aerospace Conf. 2025
Coimbra, Cortinovis, Mina and Gao, ION GNSS+ 2024
Cortinovis, Mina and Gao, IEEE Aerospace Conf. 2024

NASA Endurance Mission



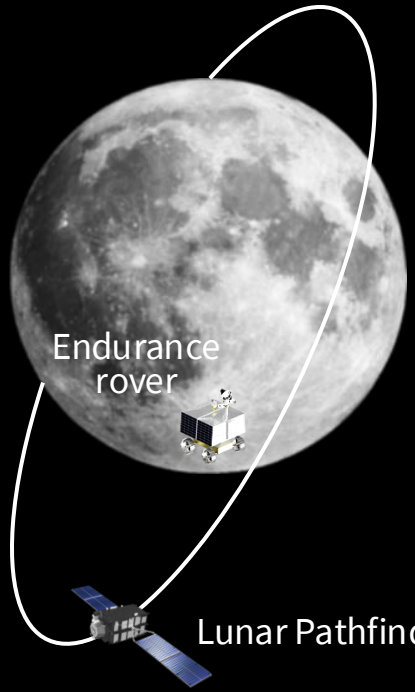


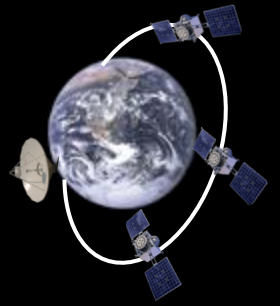
Lunar South Pole-Aitken Basin Traverse and Sample Return Rover

- First rover to traverse 2000 km on an extraterrestrial body
- *Launch*: ~2030s
- *Mission*: Collect 12 samples along its traverse and return samples to Artemis astronauts

Earth image: Apollo 11 / NASA / JSC.
Moon topography: LRO LOLA.
Moon image mosaic: LRO WAC / LRO LOLA / NASA's Scientific Visualization Studio.
Sky: Taurus / NSF NOIRLab / Akira Fujii.
Composited by James Tuttle Keane.

The Existing Lunar Landscape



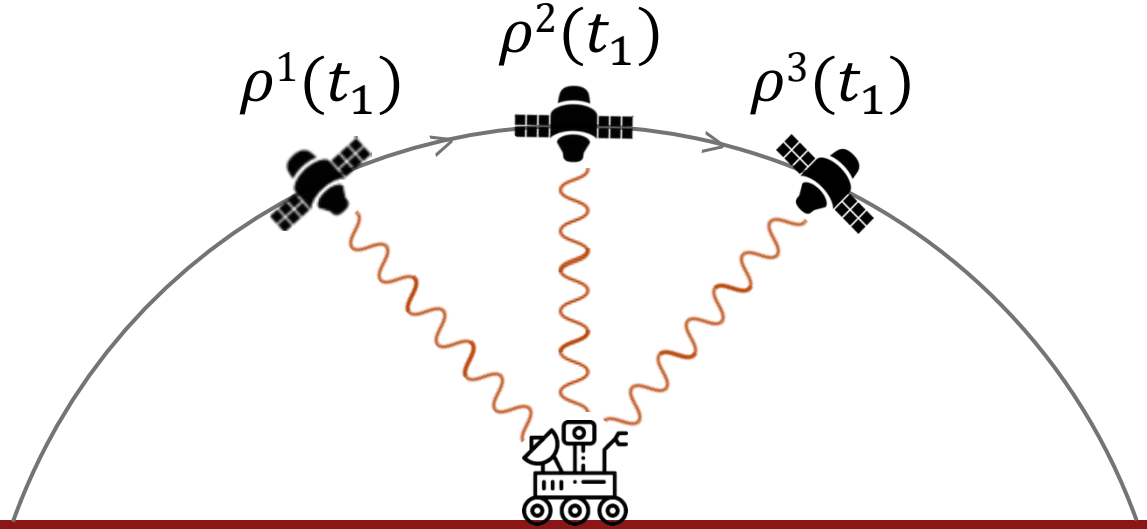


Lunar Pathfinder Satellite

- Data Relay Satellite
- in elliptical lunar frozen orbit (ELFO)
- *Service*: ~2025 - 2033

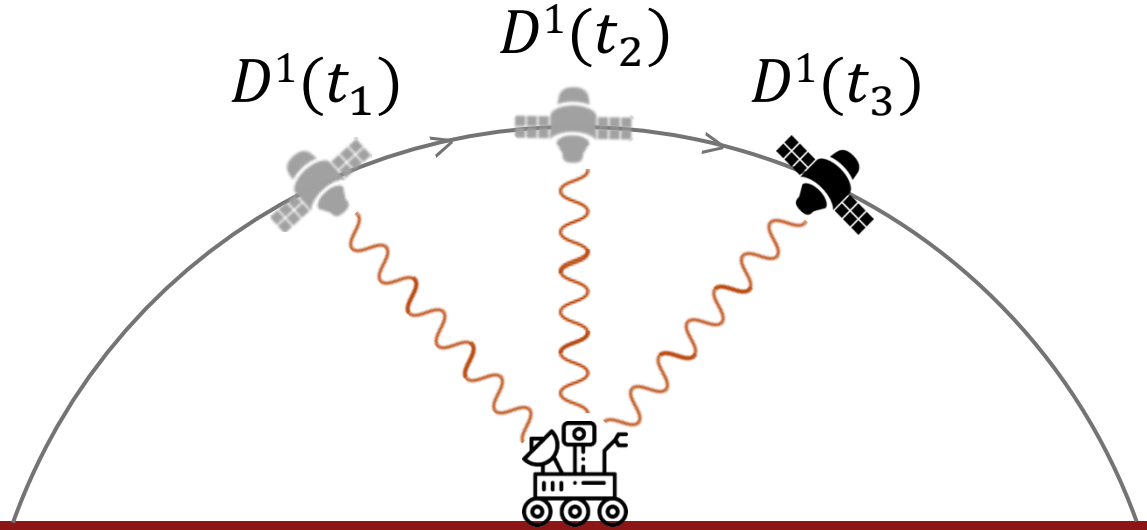
Desired and Traditional Scenario

- ***Multiple satellites*** – instantaneous localization (with at least 4 satellites)
- ***Navigation payload*** – obtain pseudorange measurements for trilateration



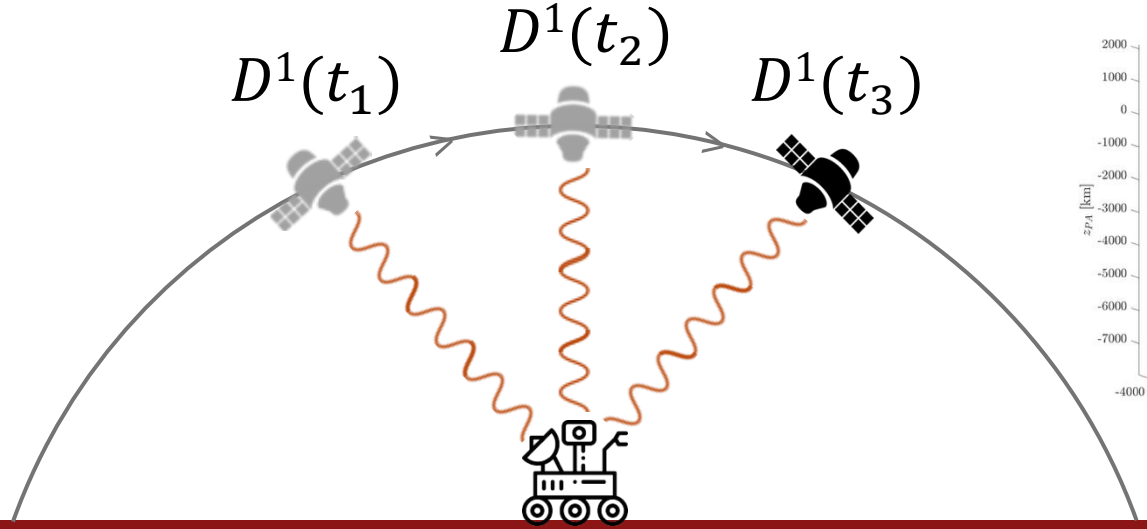
Our Scenario

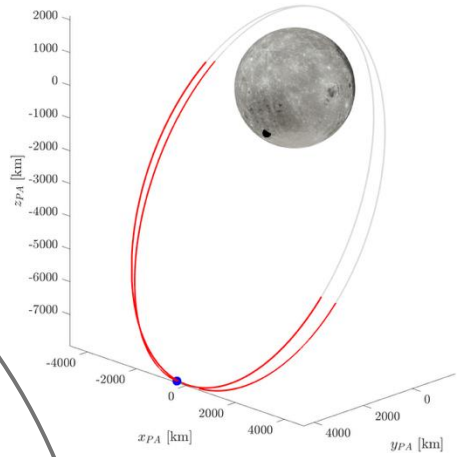
- ***Single satellite***
- ***No navigation payload***



Key Ideas

- ***Single satellite*** – measurements over time -> multiple virtual satellites
- ***No navigation payload*** – use Doppler shift observables to obtain pseudorange rate measurements





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Neural Map for the Moon

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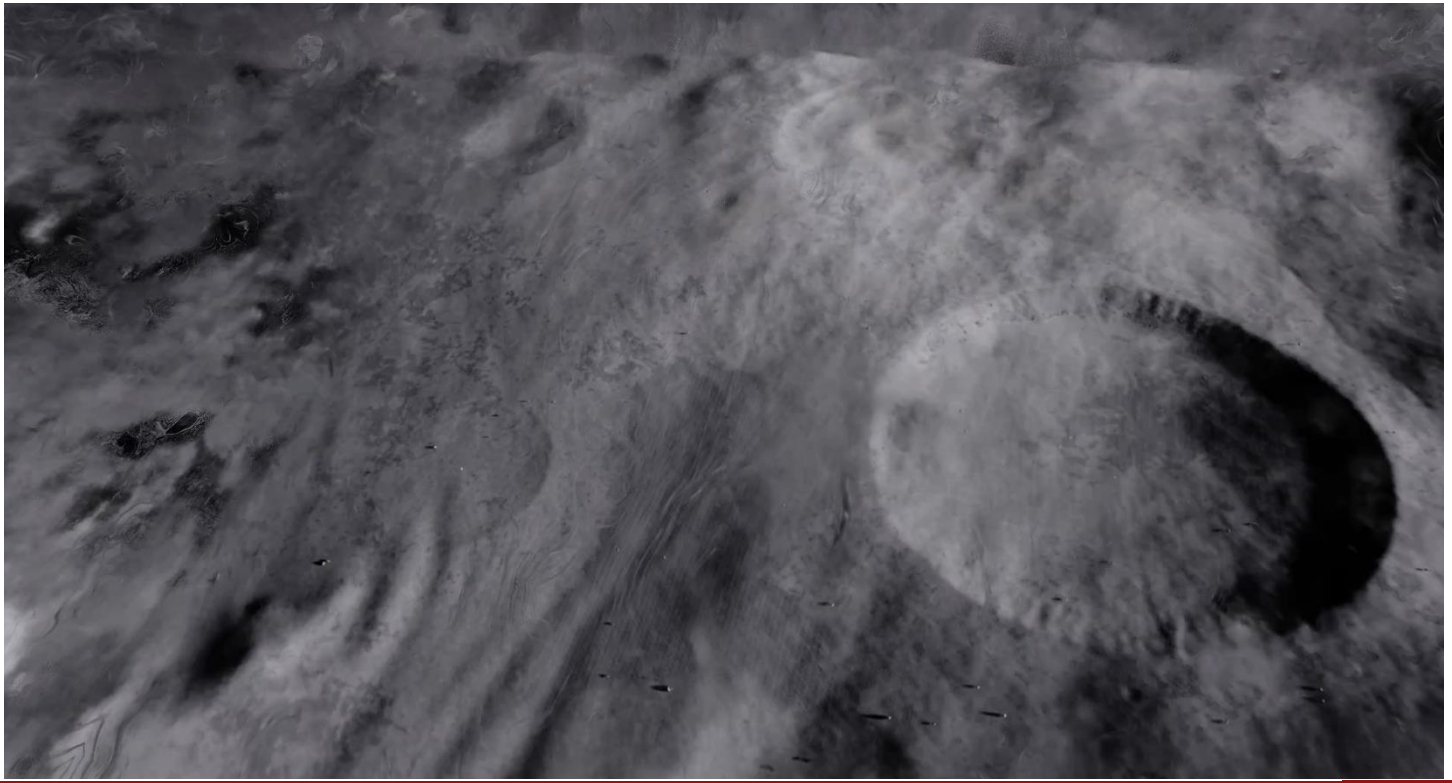
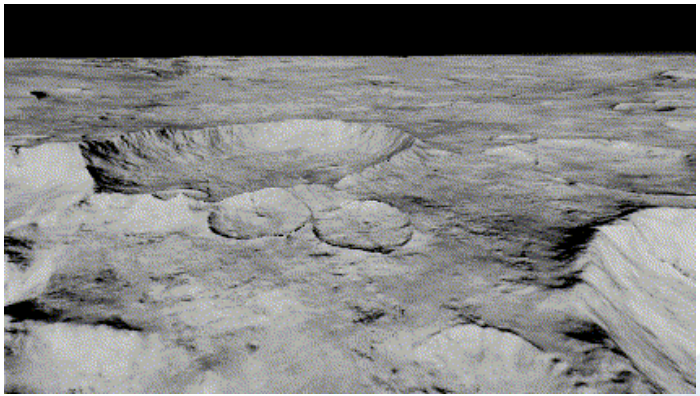
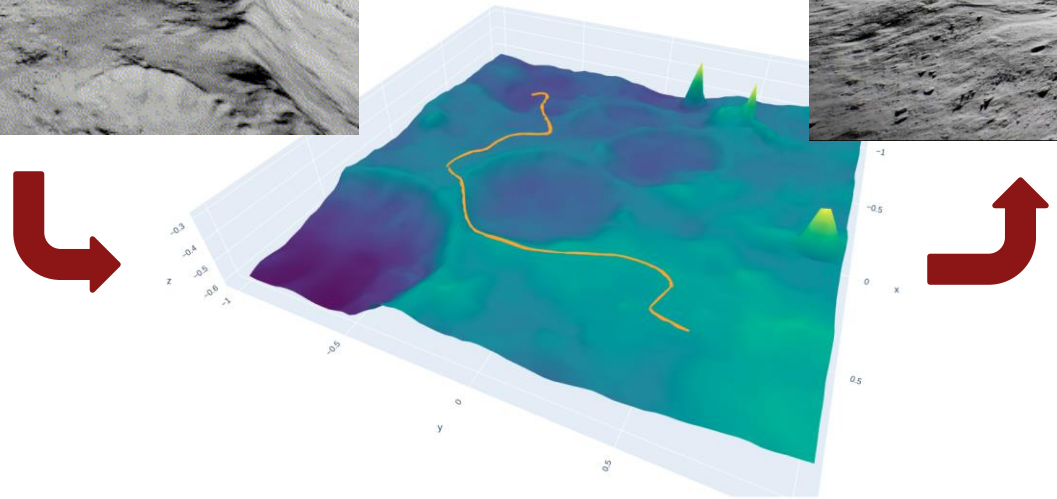


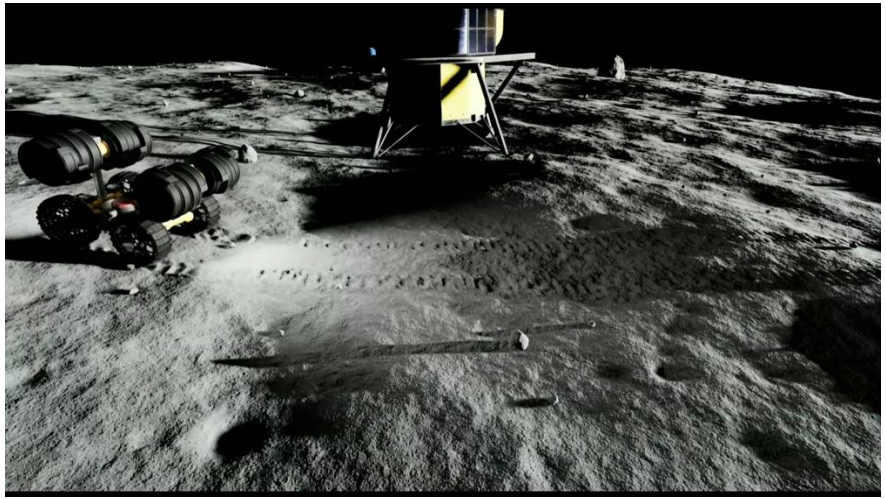
Example Moon Surface Path Planning

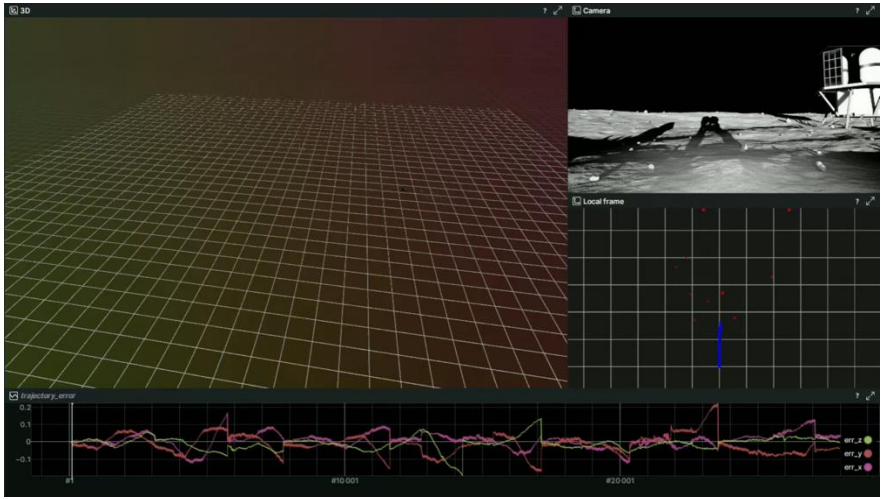




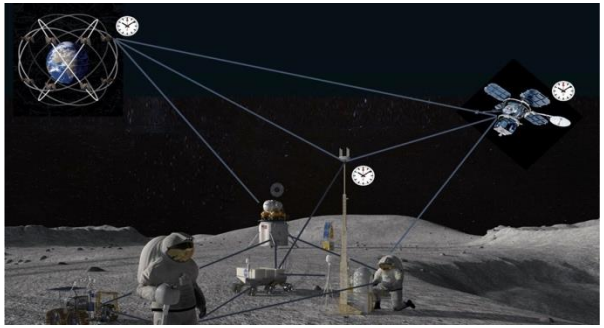
NASA Lunar Autonomy Challenge

- A six-month long competition, finished on May 15, 2025
- Using a digital twin of NASA's In-Situ Resource Utilization Pilot Excavator (IPEx)
- Our NAV Lab won 1st place





Summary of Projects in the Stanford NAV Lab



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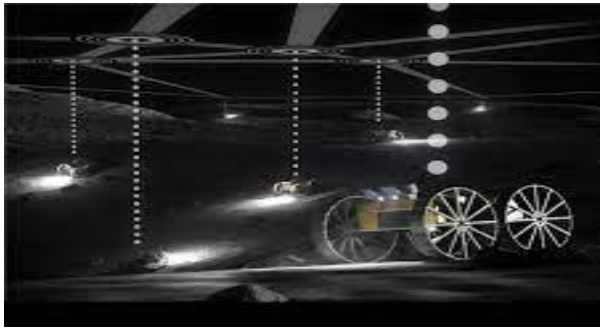

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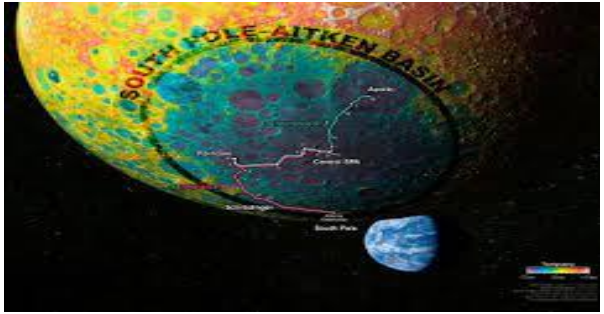

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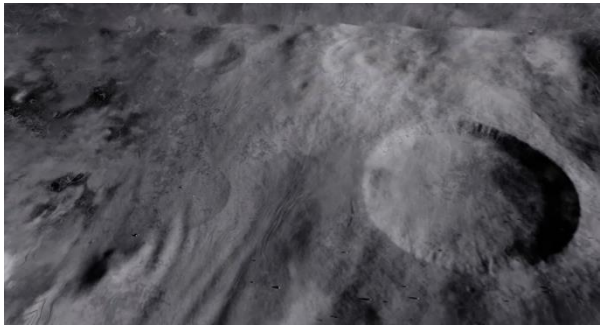

Neural Moon Surface Maps

Thank You!