STARPATH
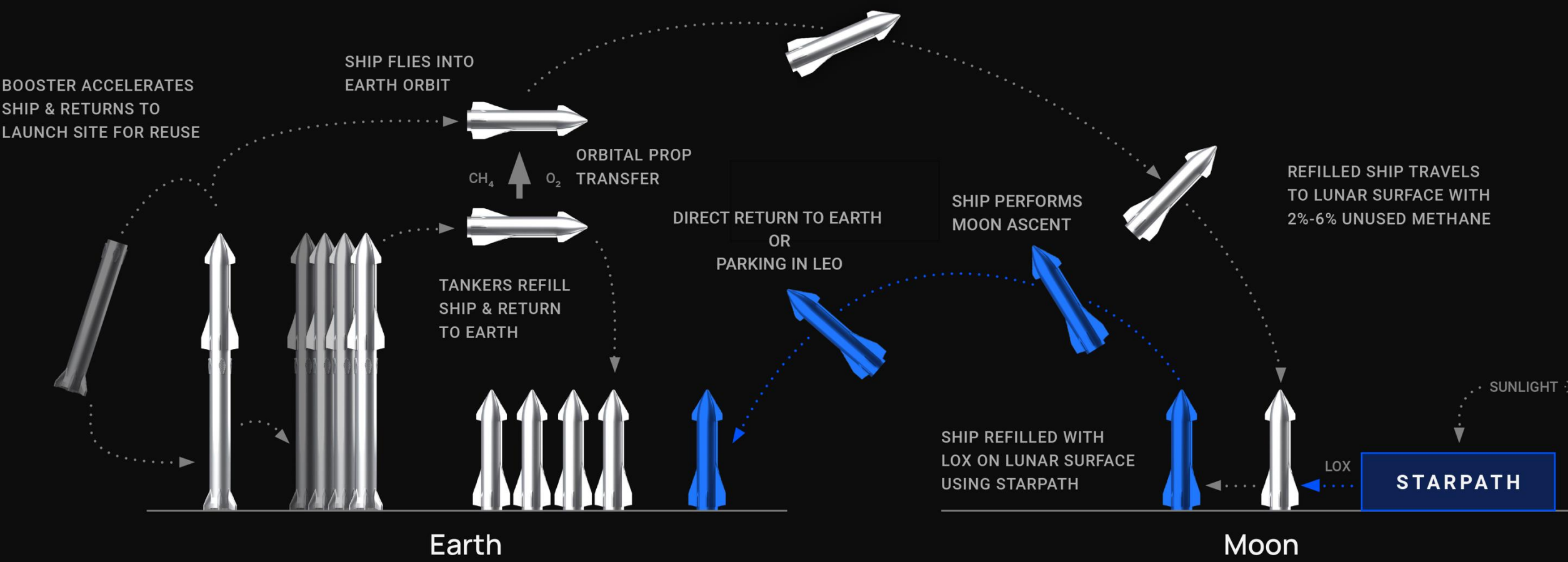
Starmine: An End-to-End Robotic System for Lunar Mining and LOX Production

Brian Yamauchi

Space Robotics Workshop 2025

Starpath Mission

BOOSTER ACCELERATES SHIP & RETURNS TO LAUNCH SITE FOR REUSE

SHIP FLIES INTO EARTH ORBIT

ORBITAL PROP TRANSFER

CH₄   O₂

TANKERS REFILL SHIP & RETURN TO EARTH

DIRECT RETURN TO EARTH OR PARKING IN LEO

SHIP PERFORMS MOON ASCENT

REFILLED SHIP TRAVELS TO LUNAR SURFACE WITH 2%-6% UNUSED METHANE

SHIP REFILLED WITH LOX ON LUNAR SURFACE USING STARPATH

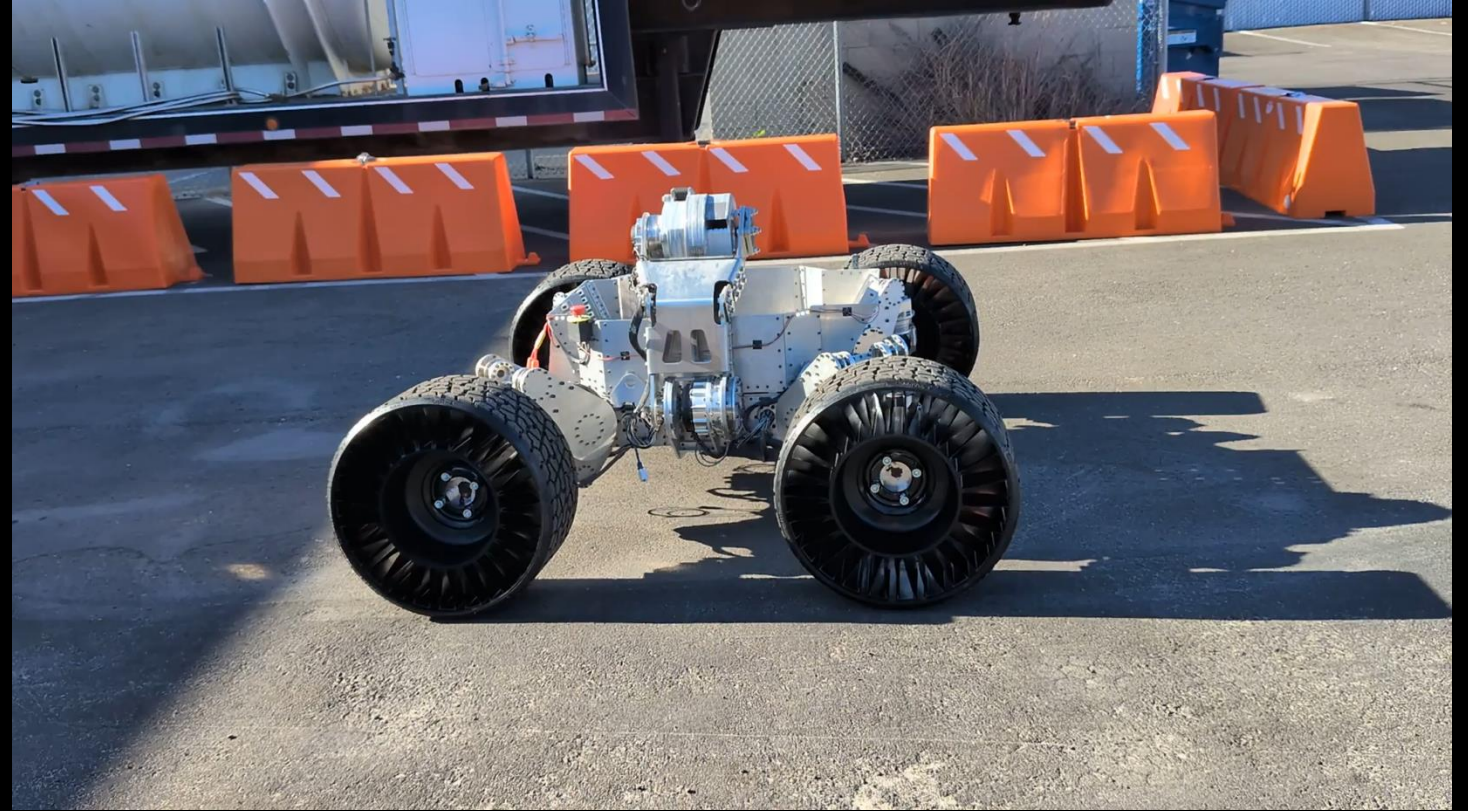SUNLIGHT

LOX

STARPATH

Earth

Moon

Starmine Concept

- Starmine components
  - Rover drives into permanently shadowed regions and mines regolith
  - Plant converts water from regolith into liquid oxygen
  - Tower provides electricity from vertical solar array
- Lunar transport
  - Launches on Starship, Falcon 9, or New Glenn
  - Delivered by Starship, Griffin, or Blue Moon to Lunar South Pole
  - Lunar Terrain Vehicle places Plant and Tower for maximum solar exposure
    - Starmine designed to be carried on Astrolab FLEX LTV

Rover

- Four independently-steerable wheels with three drive modes
    - Drive forward/backwards using Ackermann steering
    - Strafe left/right using Ackermann steering
    - Rotate in place
- Active compliant suspension
- Two arms with barrel actuators to dig and gather regolith
- Articulated dump truck for depositing regolith at Plant
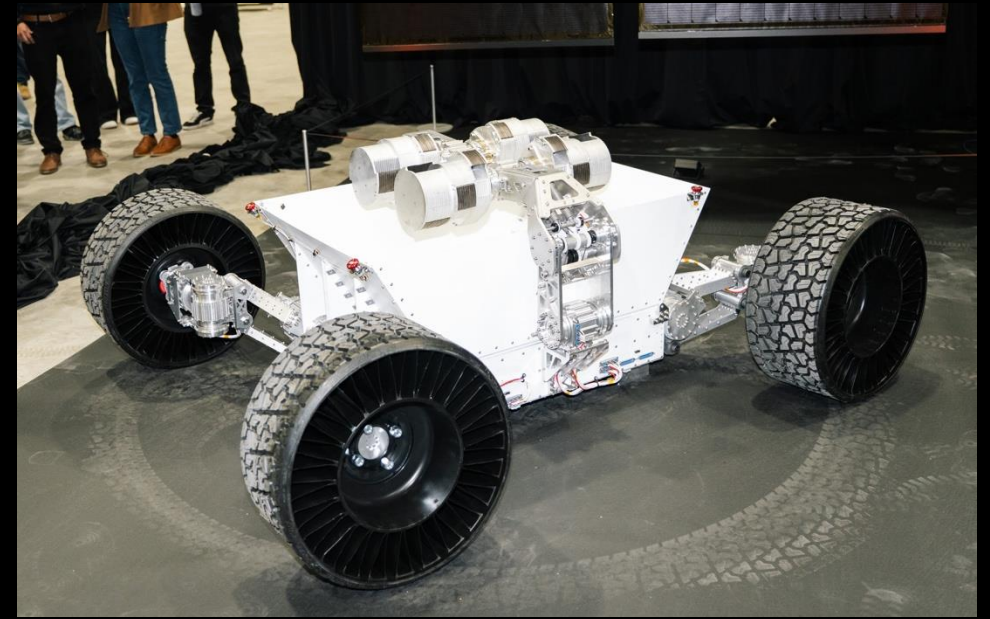
Rover Timeline

- Development started in 2022

- Rover 8
  - Won first place in 2023 NASA Break the Ice Challenge
  - Demonstrated continuous operation over 15 days

- Rover 9
  - Won second place in 2024 NASA Break the Ice Challenge
  - Demonstrated mobility over rough terrain simulating lunar surface
  - Demonstrated mining regolith simulant

- Rover 10
  - Currently in TVAC Testing at NASA Marshall Space Flight Center

Rover TVAC Testing

- Rover 10 currently being tested at NASA MSFC
- Simulated lunar conditions
  - 10^{-6} Torr vacuum
  - LN_2 cold shroud (-180° C)
    - Simulates mining in PSR for 12 hours
  - Heat lamps (1400 w/m^2)
    - Simulates traveling at lunar noon for 12 hours
  - Mining pit filled with icy regolith simulant
  - 10° traversal slope covered in regolith simulant
- Integrated testing
  - Mobility
  - Mining
  - Charging
- Hardware testing
  - Actuators
  - Sensors
  - Avionics
  - Wheels
  - Excavation barrels
  - Charger
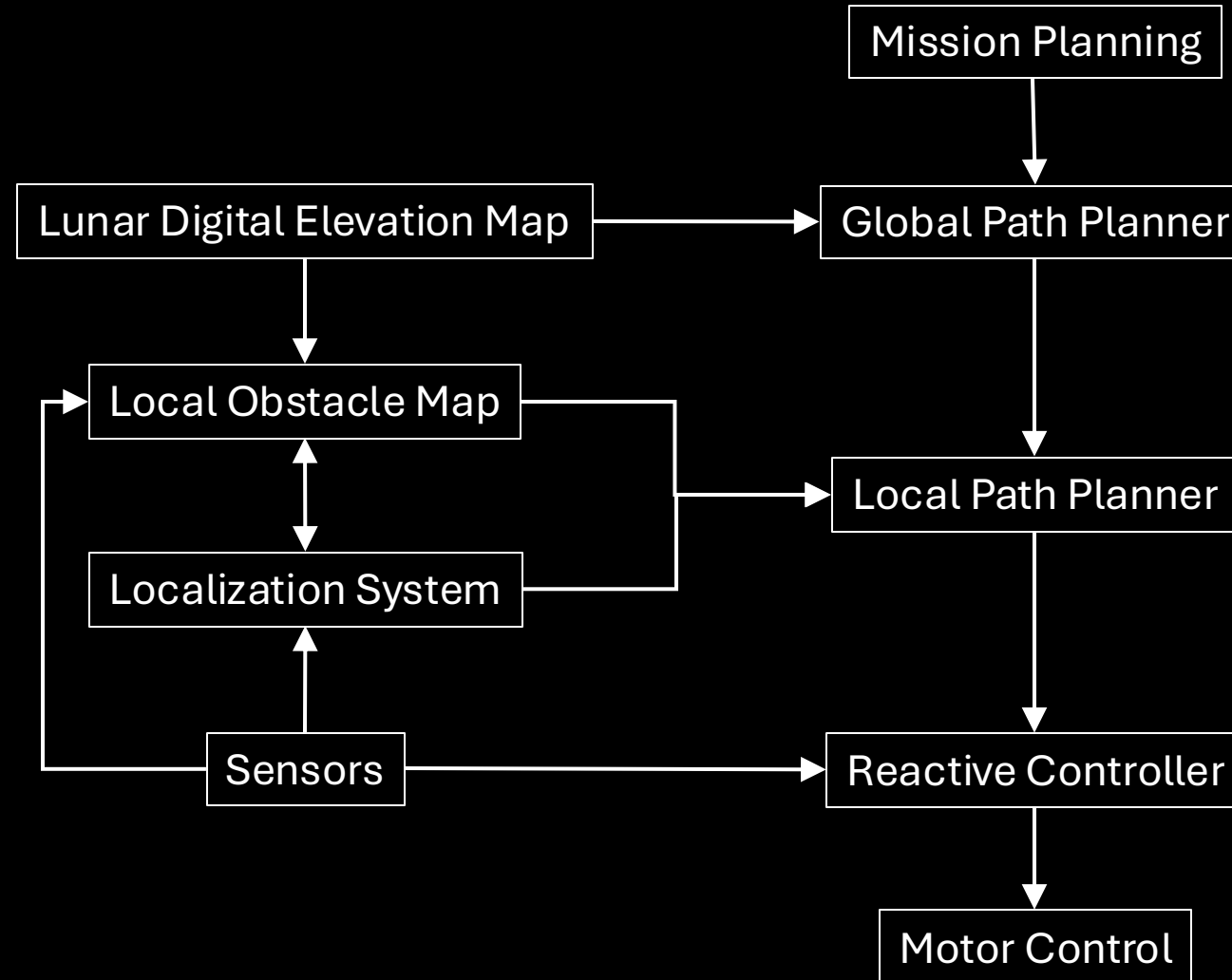- Gathering data to calibrate thermal models

Rover Sensors

- RGB camera (Lucid Triton)
  - Teleoperation and visual odometry
- Time-of-flight camera (WASP, Lucid Helios)
  - Obstacle detection, mapping, LIDAR odometry
  - Working with Nat Gill at NASA GSFC on WASP time-of-flight camera for lunar environment
- IMU (VectorNav, MicroStrain)
  - Relative orientation
- Star tracker (Rocket Lab)
  - Absolute orientation
- Wheel encoders
  - Translation distance (but expect large amounts of wheel slip)
- Radio beacon direction finder (Kraken SDR)
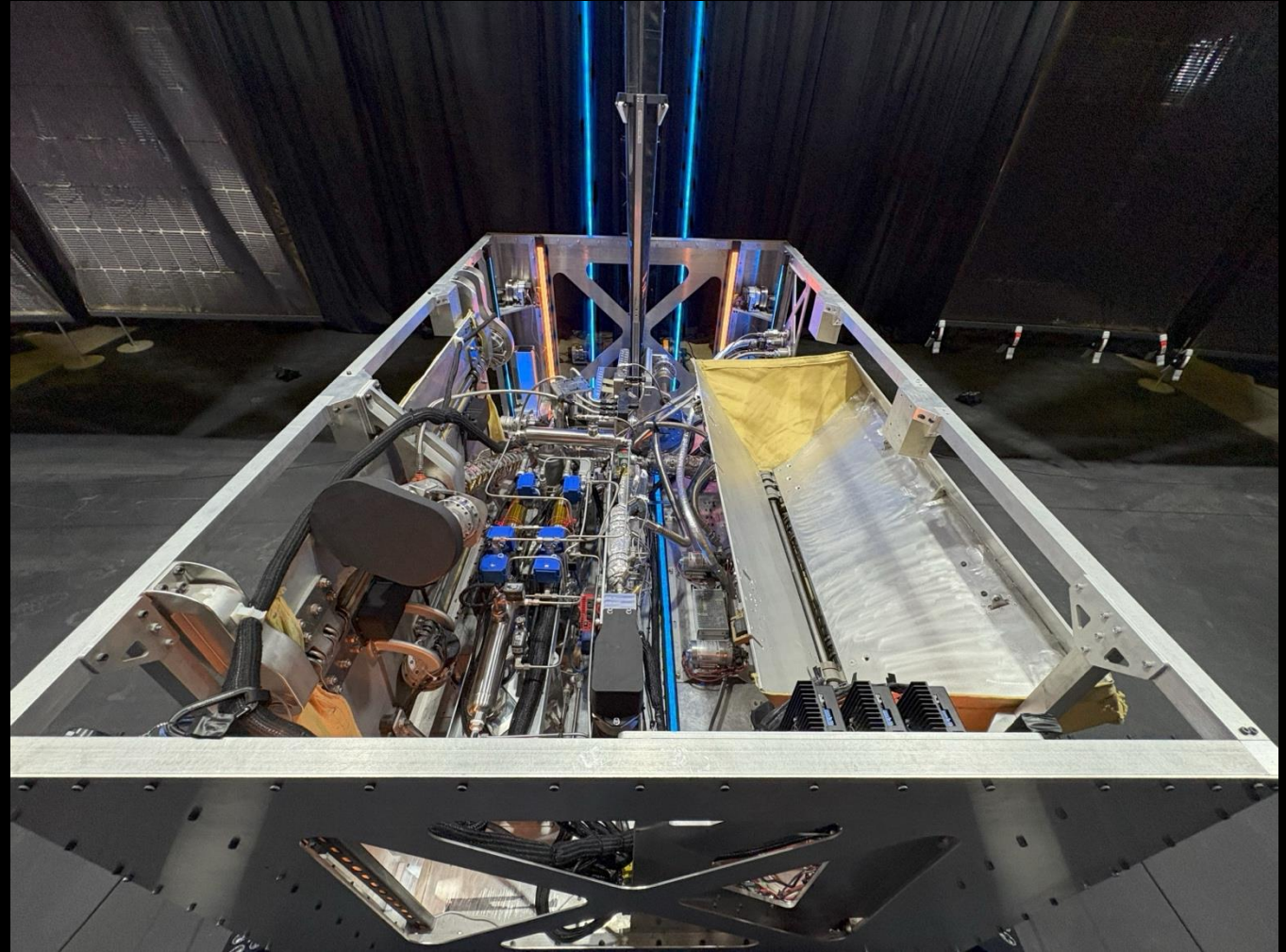 - For relative bearing to Plant/Tower
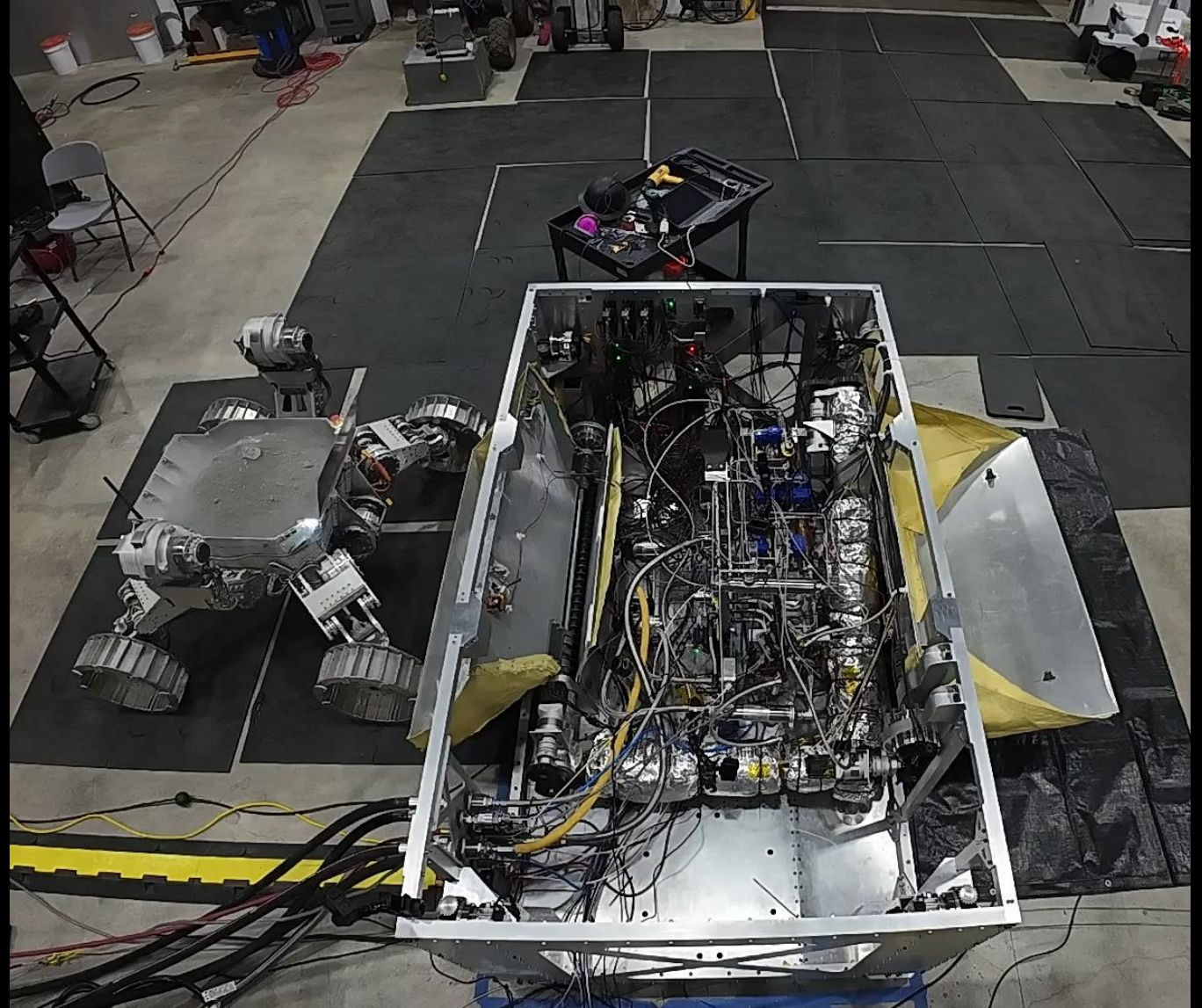
Rover Autonomy

Plant

- Converts regolith to rocket fuel
  - Auger system moves regolith through plant
  - Heats icy regolith to separate water as steam
  - Electrolyzes water into hydrogen and oxygen using proton-exchange membrane
  - Liquifies oxygen into LOX
- Production target
  - 60 metric tons of LOX per year per Plant

Integrated Test

- Rover delivered icy regolith to Plant
- Augers moved regolith through Plant processing mechanism
- Plant heated regolith and generated steam to distill water

- Icy regolith
  - Lunar highlands regolith simulant
  - Mixed with water
  - Cooled with liquid nitrogen

Regolith Desiccation and Water Distillation

Heated regolith moving through auger system

Steam refined from icy regolith

Tower

- Vertical solar array tower
  - Designed for highly illuminated regions at the Lunar South Pole

- 100 kW power generation capacity

- Yaw-axis tracking follows the Sun throughout illumination periods

- Solar banners retracted and heated to survive full-shade periods
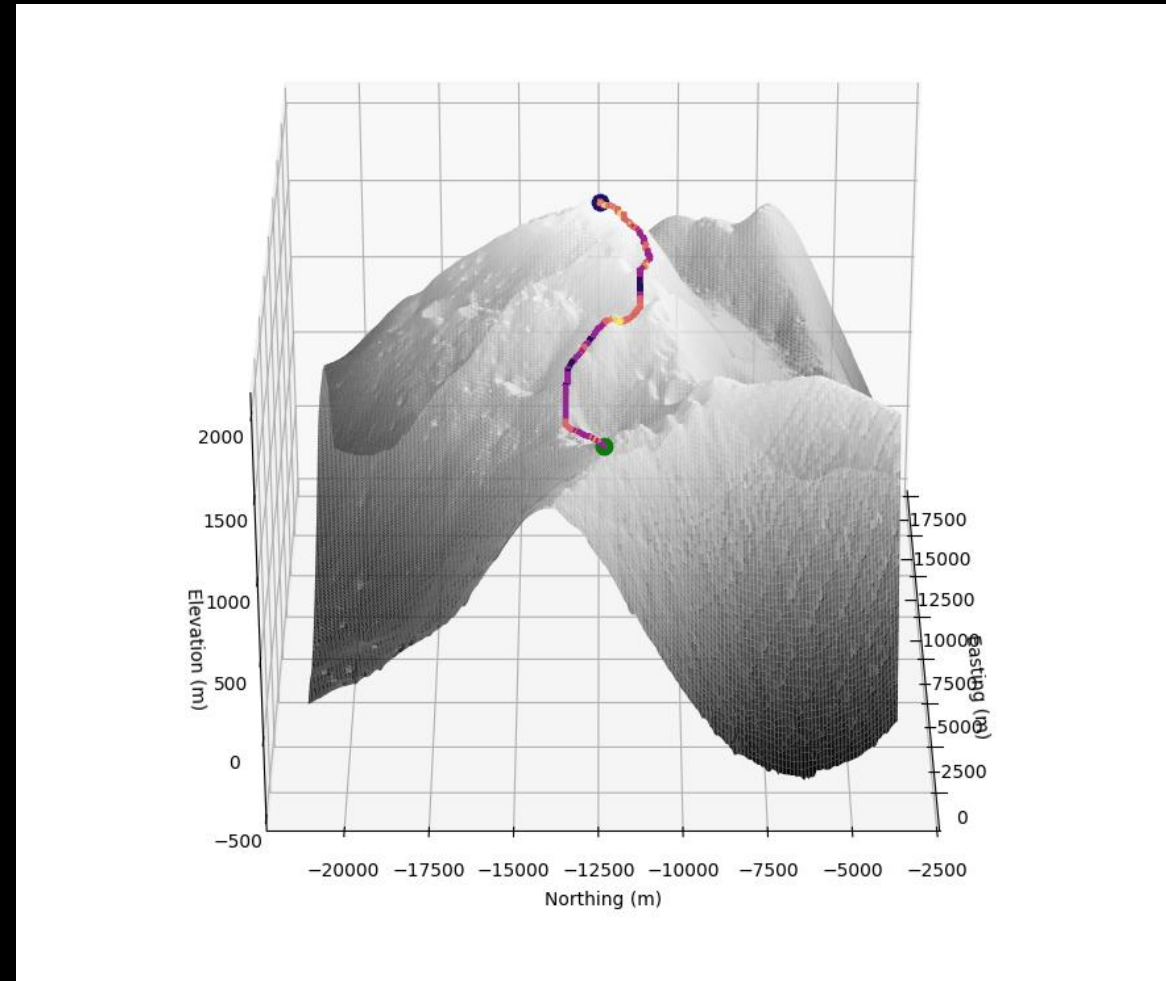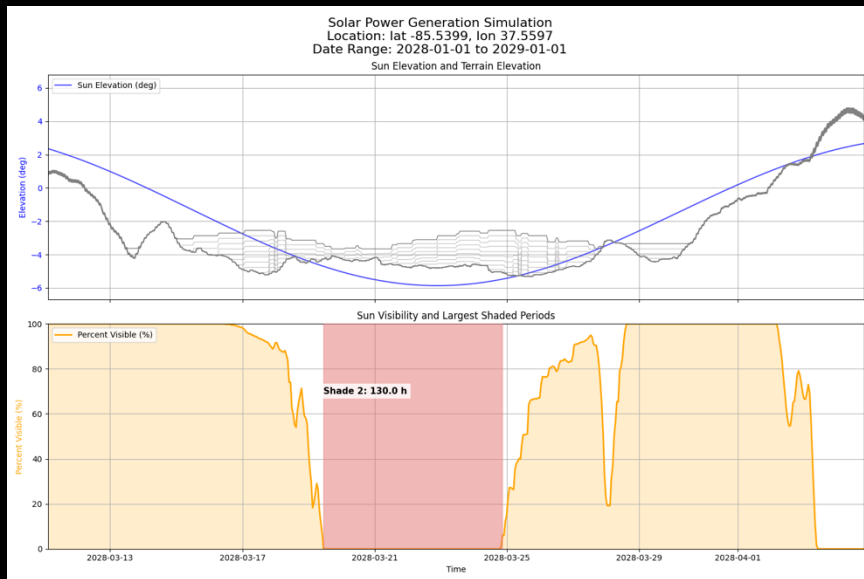

10x speed

Deployable Composite Mast

- Being developed in collaboration with Atomic-6

- 45 m tall central mast

- Launches in compact roll

- Deploys on Moon

Site Selection and Traverse Planning

- Used terrain data to find peaks near Lunar South Pole with maximum sunlight exposure
- Identified PSRs that are likely to contain water
- Plan traverse to minimize distance and slope
- Traverse based on Moon Trek data
  - Mons Mouton PSR to nearby peak
  - 8x vertical scale
  - 15 km one-way

Next Steps

- Rover 11
  - Build hardware to meet flight requirements
  - Implement autonomy system
  - Test autonomous navigation in desert

- Plant 3
  - Build, test, and integrate water extraction, processing, and electrolysis systems

- Tower 2
  - Demonstrate deployable mast integrated with solar banners

- Goal
  - Full Starmine system ready for flight by 2027