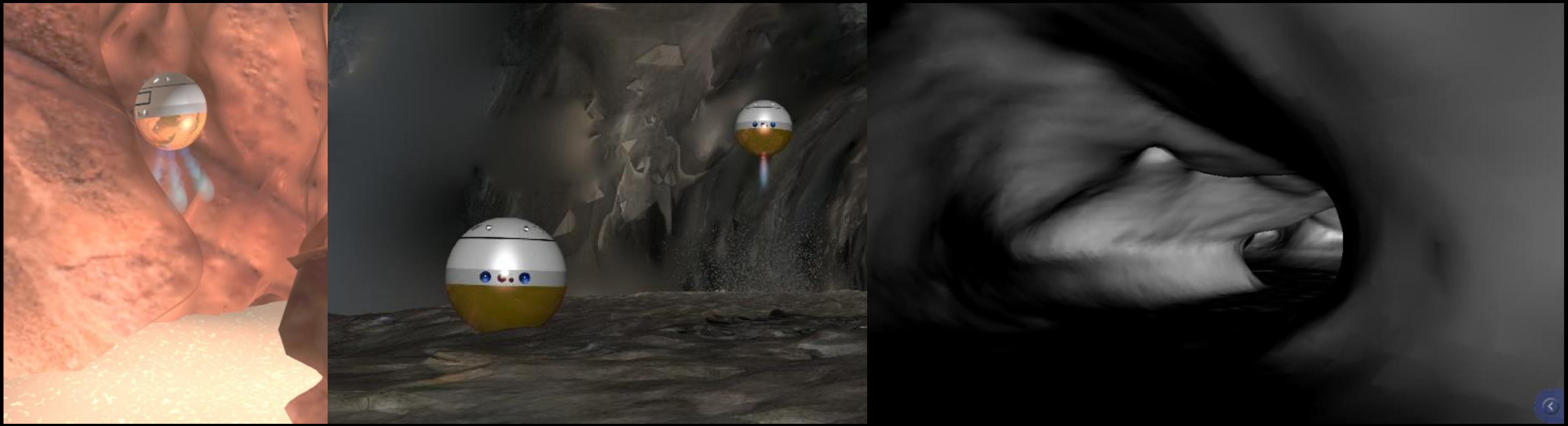


End to End Strategies for Exploring Lunar/Martian Caves

Himangshu Kalita and Jekan Thangavelautham
Space and Terrestrial Robotic Exploration (SpaceTREx) Laboratory
Aerospace and Mechanical Engineering Department
University of Arizona

Outline

- Introduction
- Motivation
- SphereX Bot
- Mapping and Navigation
- Sensor Placement Strategies
- Communication Strategies
- Power Transfer Strategies
- Conclusion

Introduction

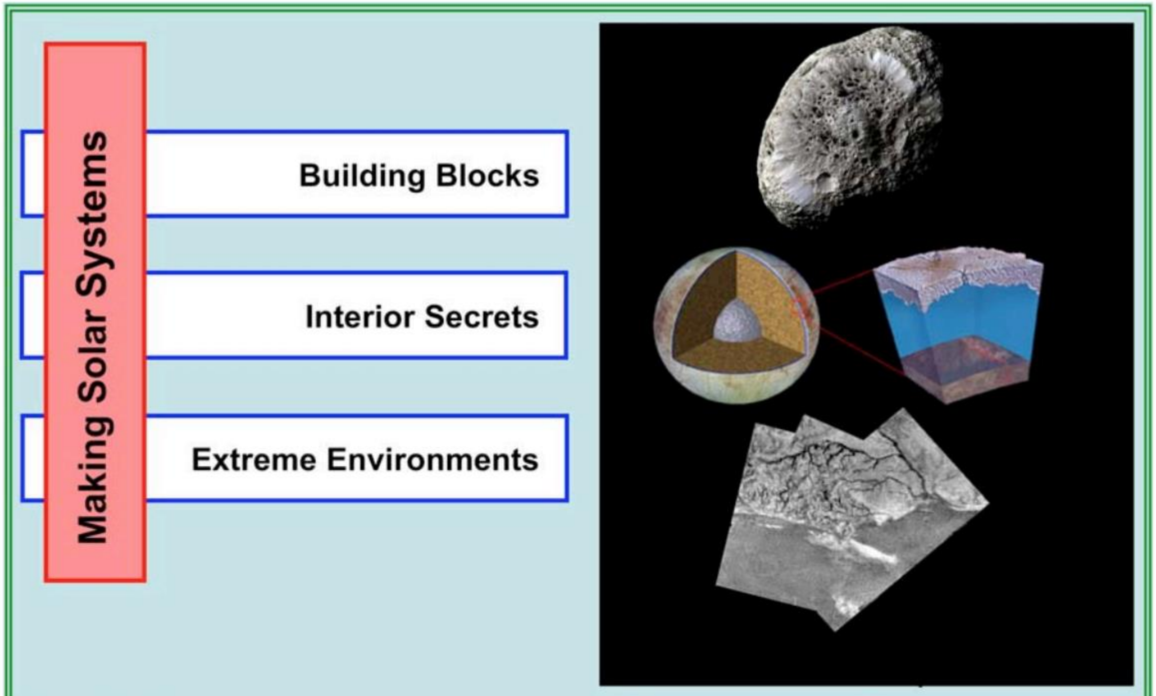


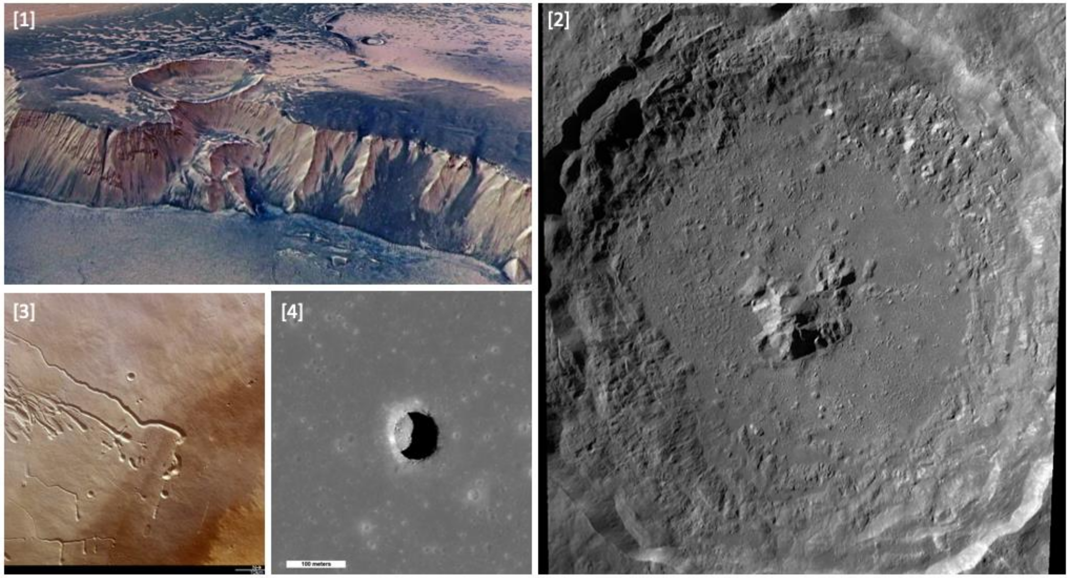
Figure 3 - Under the theme of making solar systems, OPAG's three main scientific goals are to measure the properties of the building blocks of solar systems, to probe the interiors of planetary bodies, and to explore the extreme environments in which life may have developed.

- **Science goals identified by Outer Planets Assessment Group (OPAG) with Planetary Decadal Study** [1],[2].
- **Extreme Environments:** Ascertain the range of conditions that can support life.
- **Extreme Environments:** Identify planetary processes that are responsible for generating and sustaining habitable worlds.

[1] National Academies of Sciences, Engineering and Medicine (2011)
[2] Scientific Goals and Pathways for Exploration of the Outer Solar System (2006)

Extreme Environments on the Moon and Mars

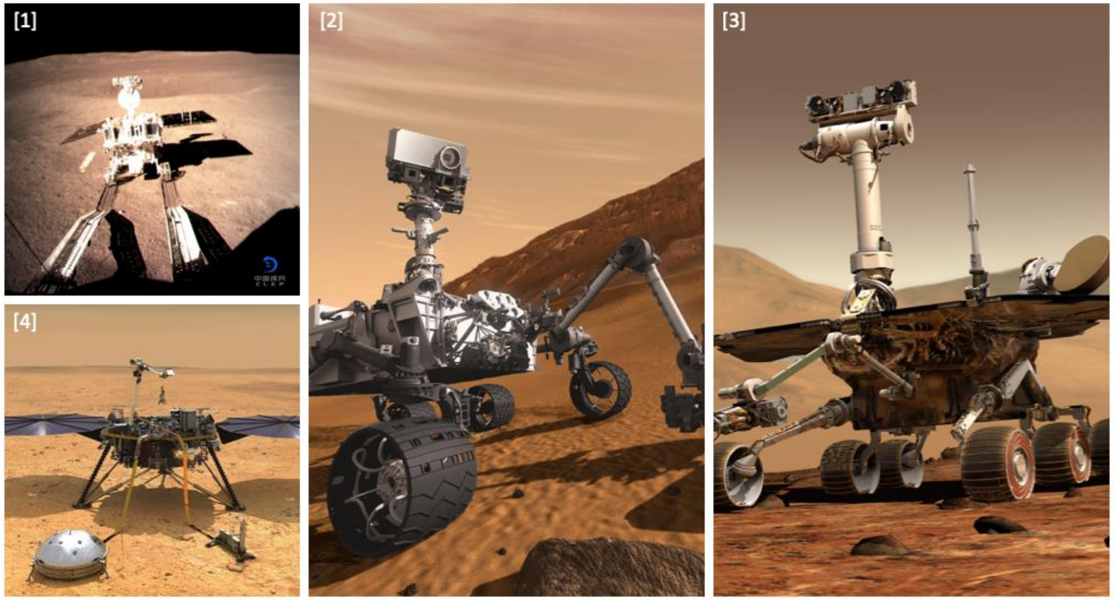
- **Extreme Environments of Moon and Mars:** Cliffs, craters, lava tubes, pits, caves.
- **These environments are rich targets of origin studies.**
- **Caves, pits and lava tubes offer natural shelter from radiation and insulated from varying high and low external temperatures.**



[1] High Cliffs Surrounding Echus Chasma on Mars (nasa.gov)
[2] Tycho Crater on Moon (NASA/Goddard/Arizona State University)
[3] Lava Tubes on Pavonis Mons on Mars (ESA)
[4] Mare Tranquilitatis pit on Moon (NASA/GSFC/Arizona State University)

Problem with exploring Extreme Environments?

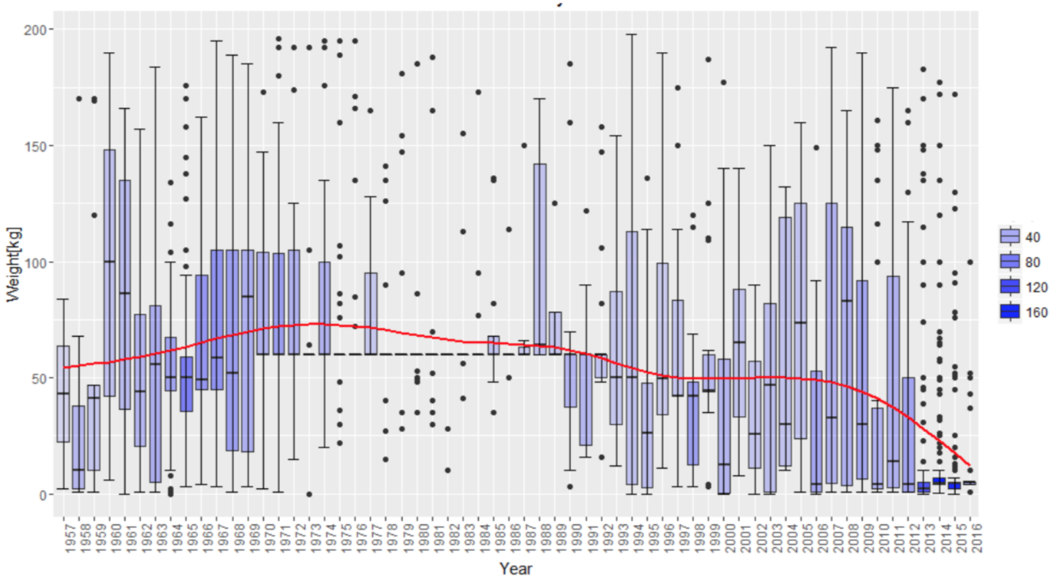
- **Current landers and rovers are unable to access these areas of high interest**
    - Limitations in precision landing
    - Inability to traverse rugged environments
    - Operations culture where risks are minimized at all costs



[1] Yutu-2 on Moon (space.com)
[2] Curiosity Rover on Mars (nasa.gov)
[3] Opportunity Rover on Mars (nasa.gov)
[4] InSight Lander on Mars (spacenews.com)

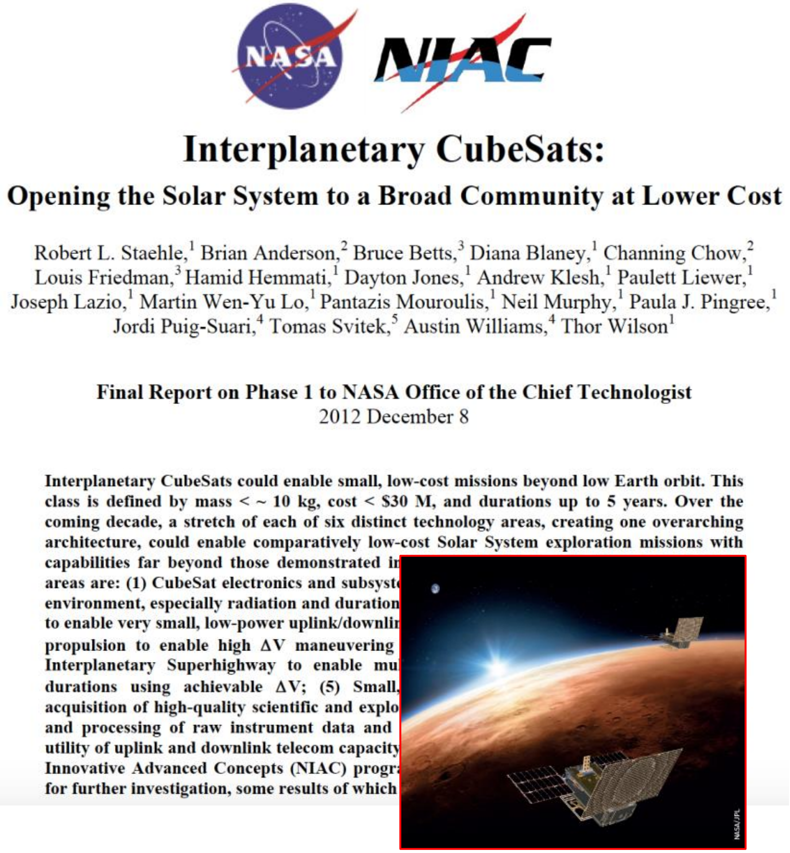
Motivation - I

- **Commercially-Off-The-Shelf (COTS) components**



Mass of all satellites under 200 kg launched from 1957 to 2016
[B. Lal et al (2017)]

Inset: Artist's rendering of NASA's twin Mars Cube One (MarCO) spacecraft flying over Mars with Earth in the distance



Interplanetary CubeSats:

Opening the Solar System to a Broad Community at Lower Cost

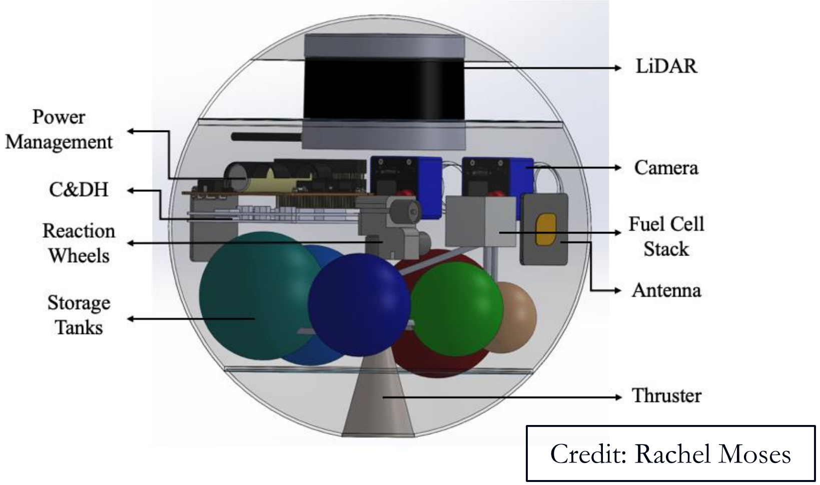
Robert L. Staehle,[1] Brian Anderson,[2] Bruce Betts,[3] Diana Blaney,[1] Channing Chow,[2] Louis Friedman,[3] Hamid Hemmati,[1] Dayton Jones,[1] Andrew Klesh,[1] Paulett Liewer,[1] Joseph Lazio,[1] Martin Wen-Yu Lo,[1] Pantazis Mouroulis,[1] Neil Murphy,[1] Paula J. Pingree,[1] Jordi Puig-Suari,[4] Tomas Svitek,[5] Austin Williams,[4] Thor Wilson[1]

Final Report on Phase 1 to NASA Office of the Chief Technologist
2012 December 8

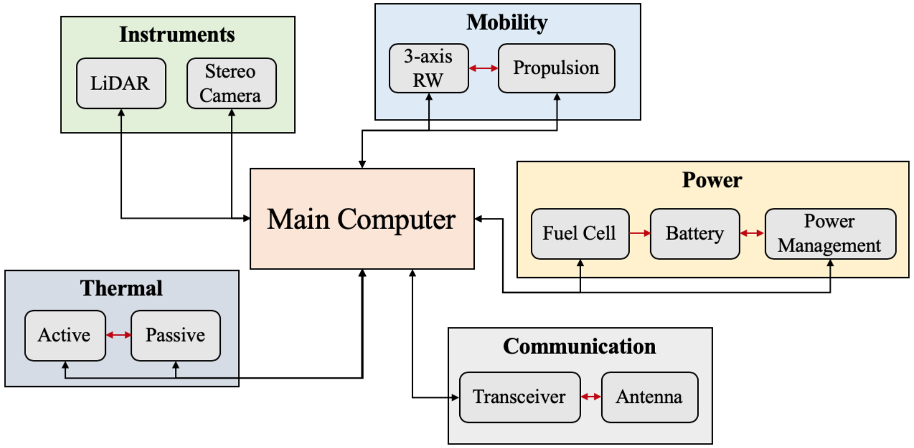
Interplanetary CubeSats could enable small, low-cost missions beyond low Earth orbit. This class is defined by mass $< \sim 10$ kg, cost $< \$30$ M, and durations up to 5 years. Over the coming decade, a stretch of each of six distinct technology areas, creating one overarching architecture, could enable comparatively low-cost Solar System exploration missions with
capabilities far beyond those demonstrated i
areas are: (1) CubeSat electronics and subsyste
environment, especially radiation and duration
to enable very small, low-power uplink/downlin
propulsion to enable high ΔV maneuvering
Interplanetary Superhighway to enable mu
durations using achievable ΔV; (5) Small,
acquisition of high-quality scientific and explo
and processing of raw instrument data and
utility of uplink and downlink telecom capacity
Innovative Advanced Concepts (NIAC) progr
for further investigation, some results of which

Proposed Solution: SphereX

- **Small low-cost, modular spherical robot (SphereX)**
  - Mobility system for exploration
  - Space-grade electronics
  - Power system for power generation
  - UHF/S-band antennas for communication
  - Thermal and Shielding system for survival
  - Outer shell for structural robustness
  - Payload capacity for science instruments



Credit: Rachel Moses



Instruments
LiDAR
Stereo Camera

Mobility
3-axis RW
Propulsion

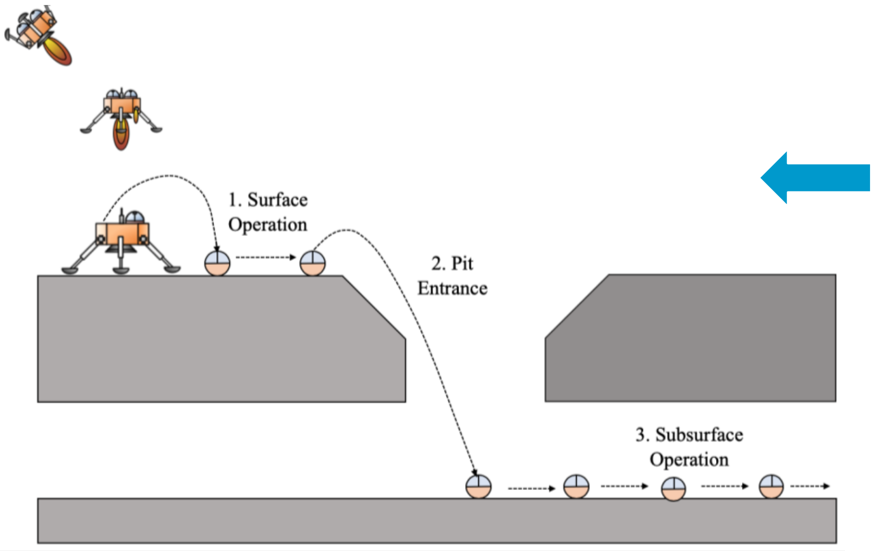
Main Computer

Power
Fuel Cell
Battery
Power Management

Thermal
Active
Passive

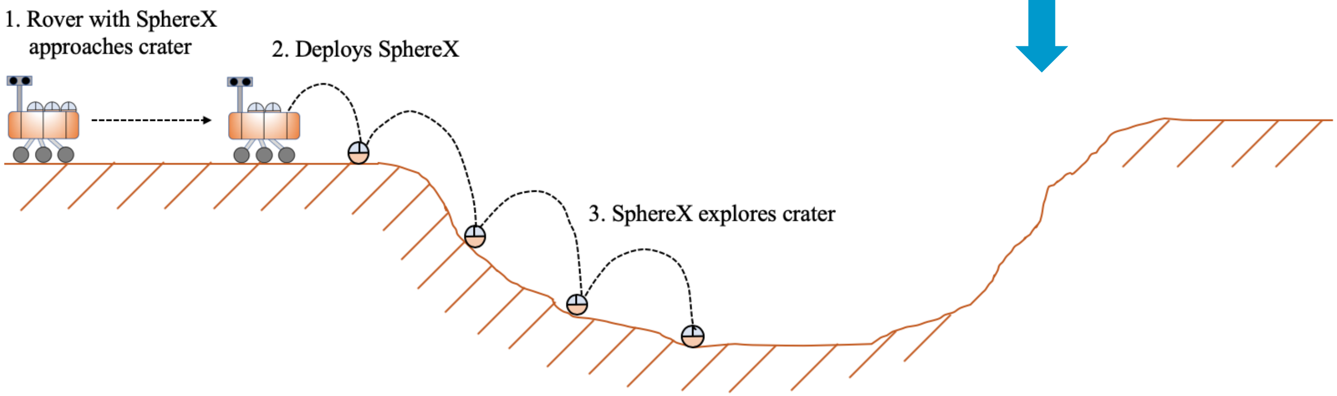
Communication
Transceiver
Antenna

Exploration of Pits, Lava Tubes and Craters



Concept of Operations for exploring planetary pits/lava tubes

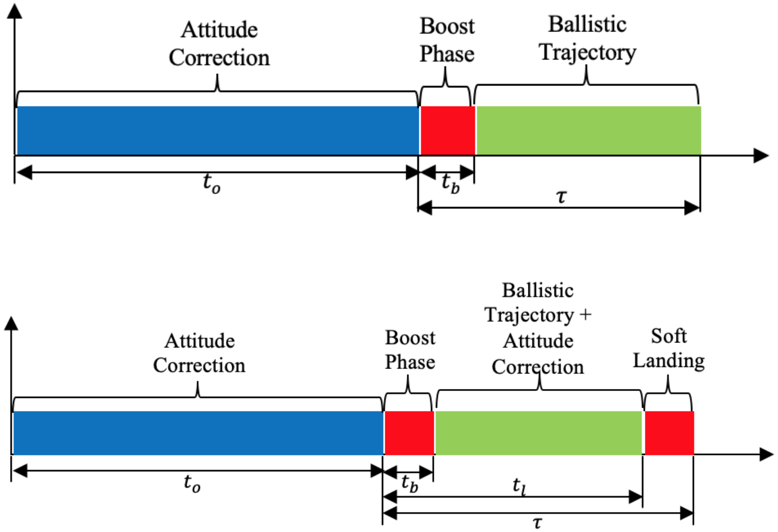
Concept of Operations for exploring planetary craters



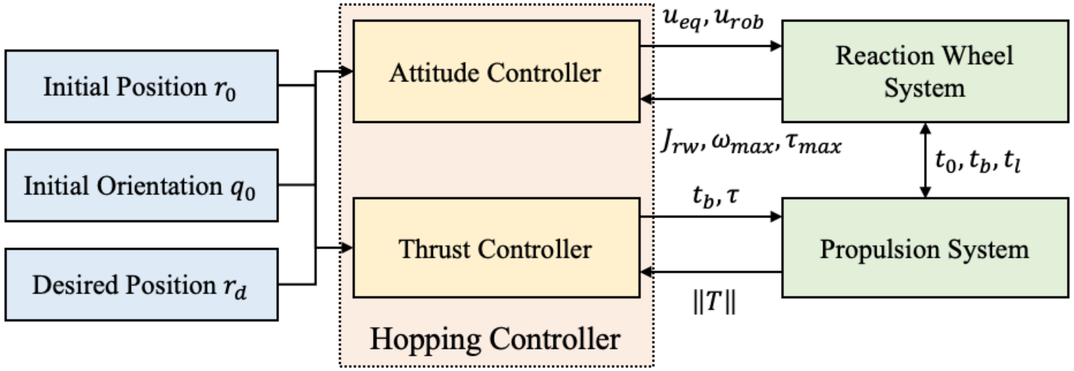
Mobility System

- **Mode of Mobility: Hopping**
- **Hopping achieved through:**
  - Miniaturized propulsion system
  - 3-axis reaction wheel system
- **2 modes of Hopping Mobility**
  - Hard-landing mode
  - Soft-landing mode

Time Diagram

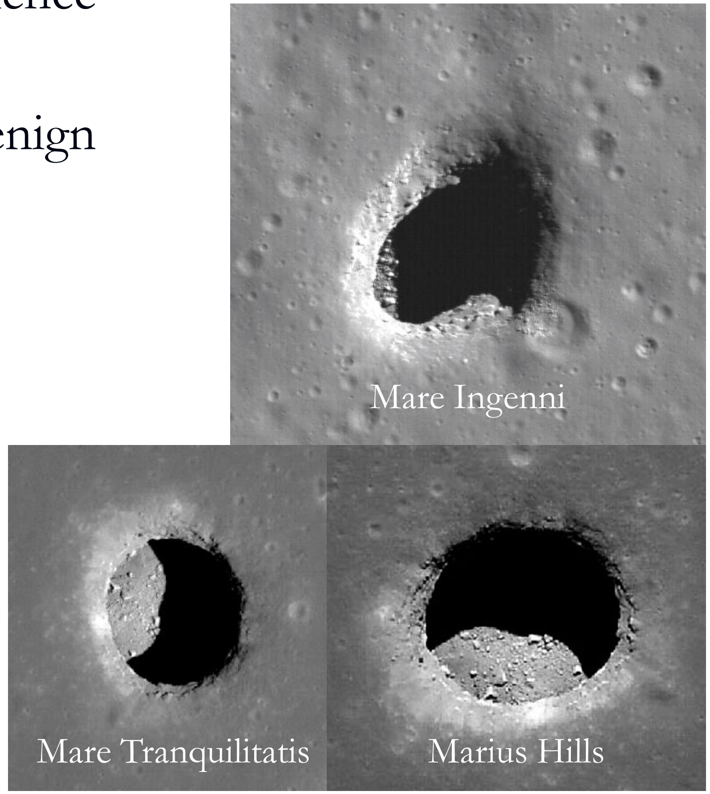


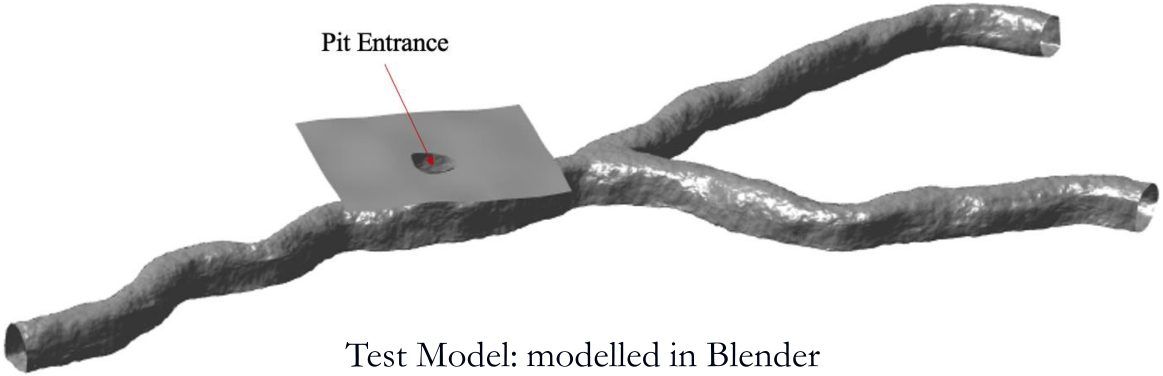
Control System Architecture



Lunar Pits

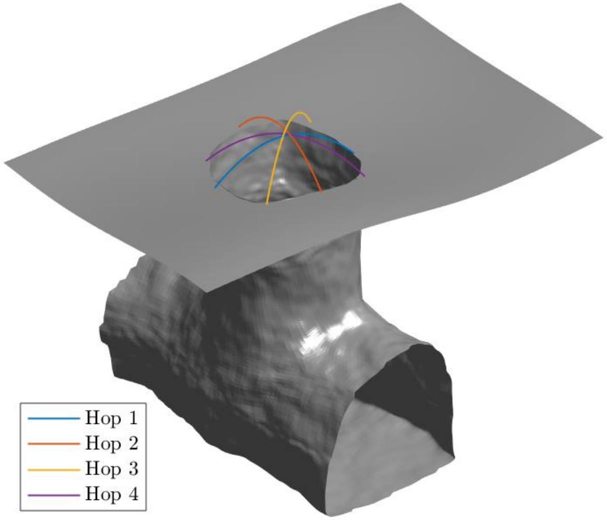
- Recently discovered lunar mare "pits" are key science and exploration targets.
- Ready made shelter for future lunar explorers, benign T (-25° C)
- Pristine preservation
    - Flow features
    - Sublimate minerals

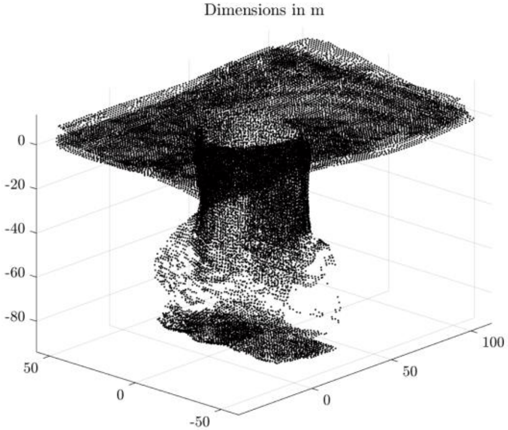




Test Model: modelled in Blender

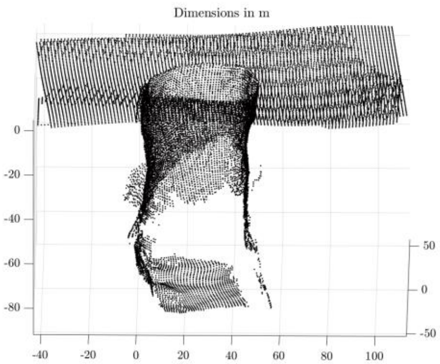
Pit Entrance Survey



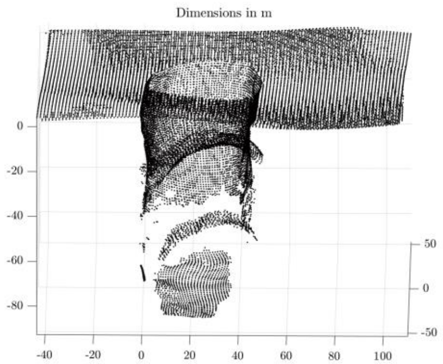


Combined Map

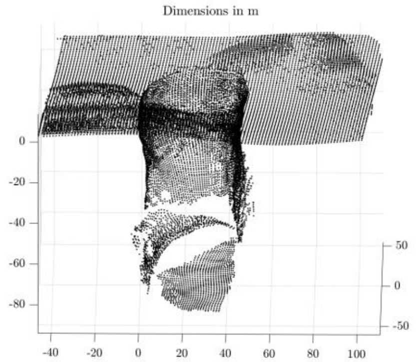
Hop 1



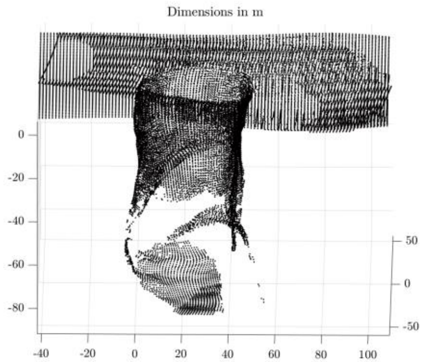
Hop 2



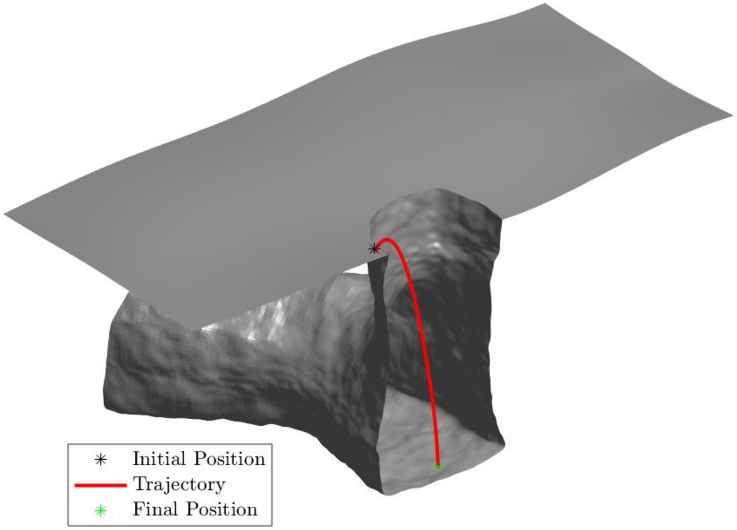
Hop 3



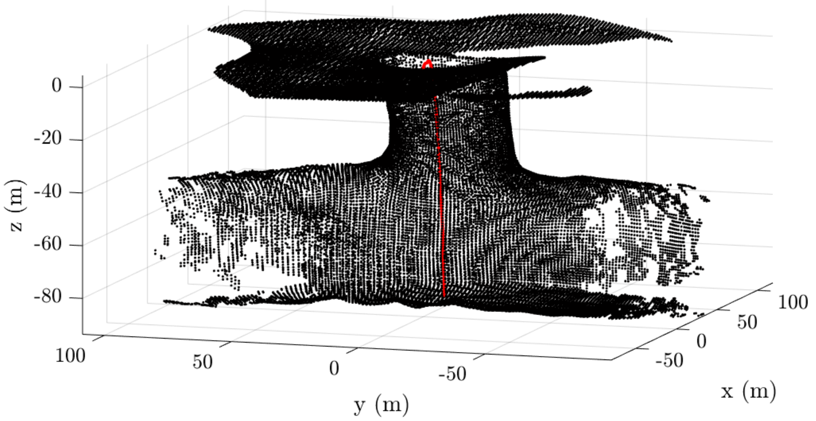
Hop 4



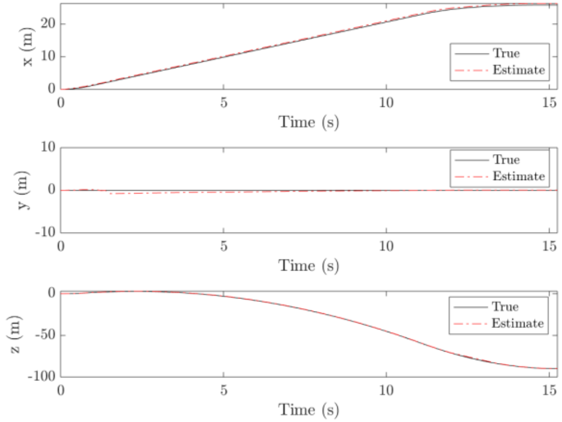
Pit Entrance



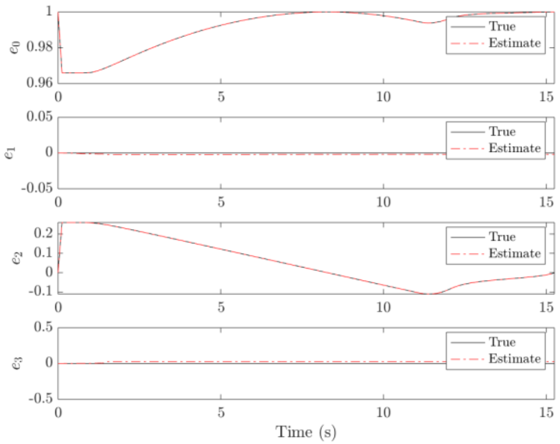
Map Generated



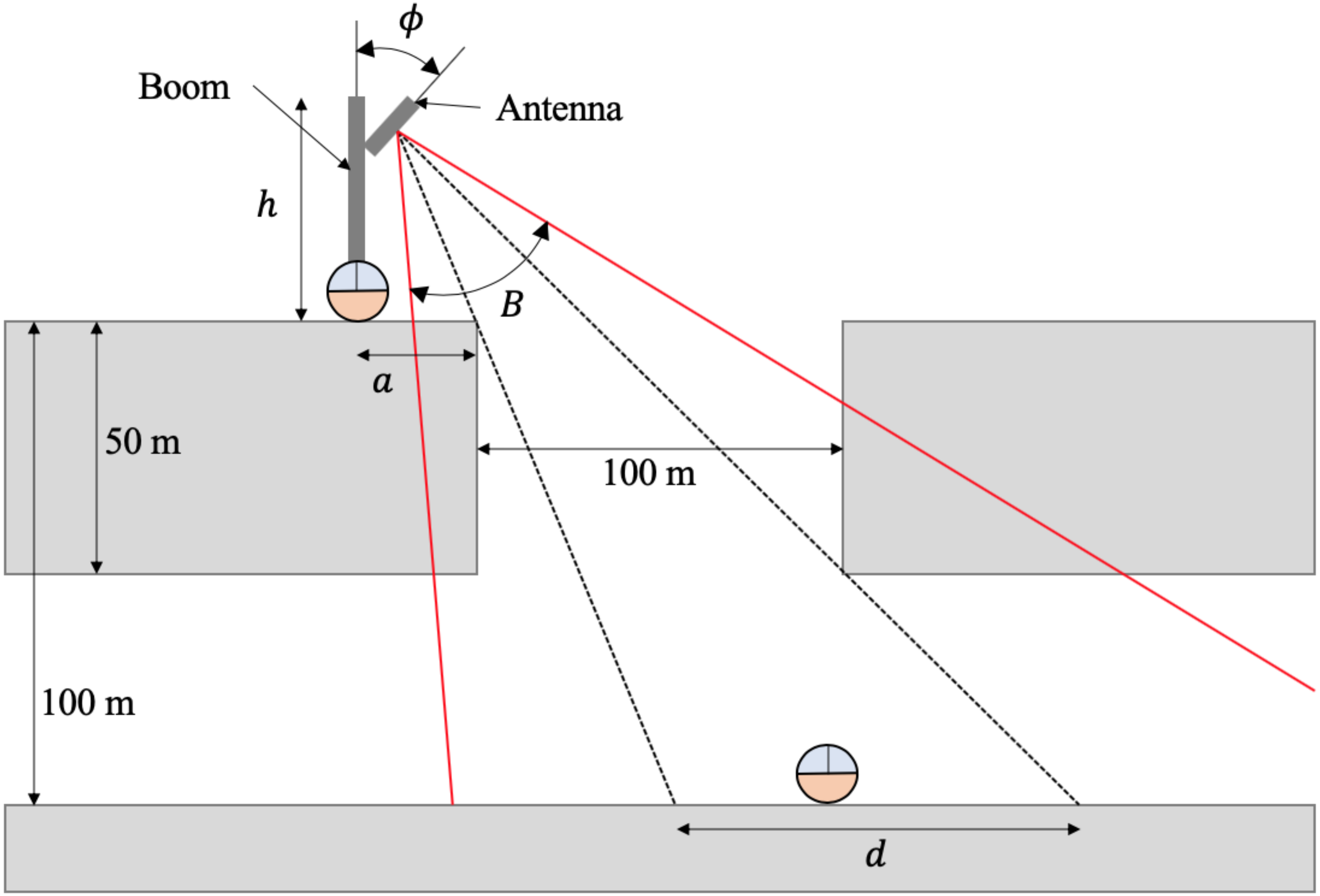
Position Estimate



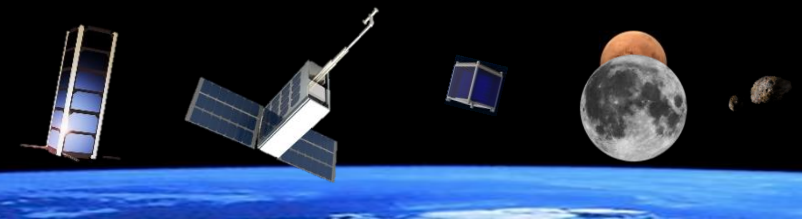
Orientation Estimate



Line-of-sight Analysis

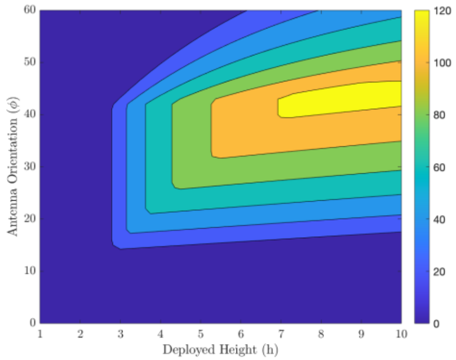


Line-of-sight from pit surface to pit floor

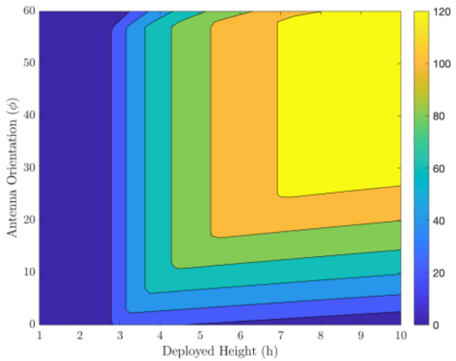


Line-of-sight Analysis

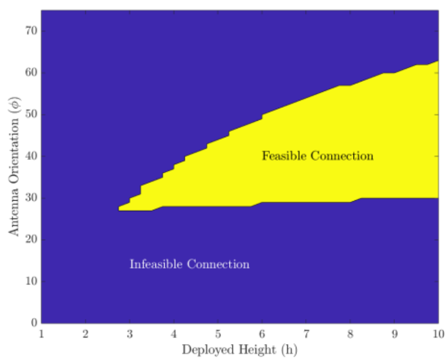
a = 5m



BW= 30°

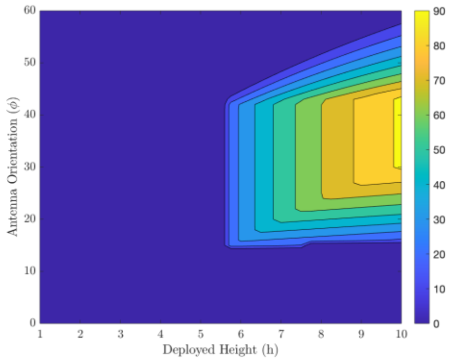


BW= 60°

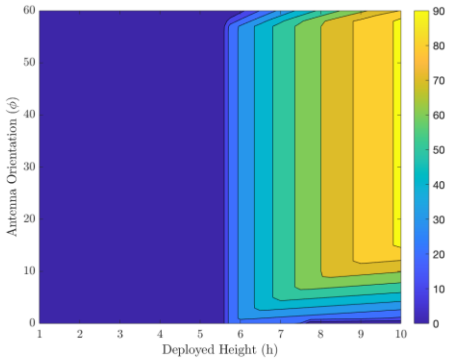


Laser

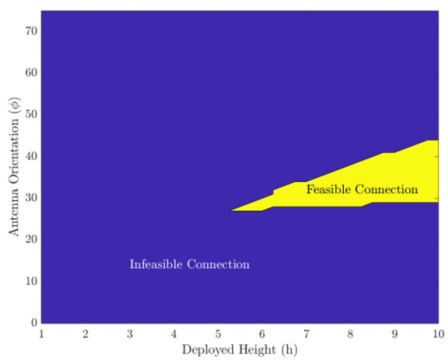
a = 10m



BW= 30°

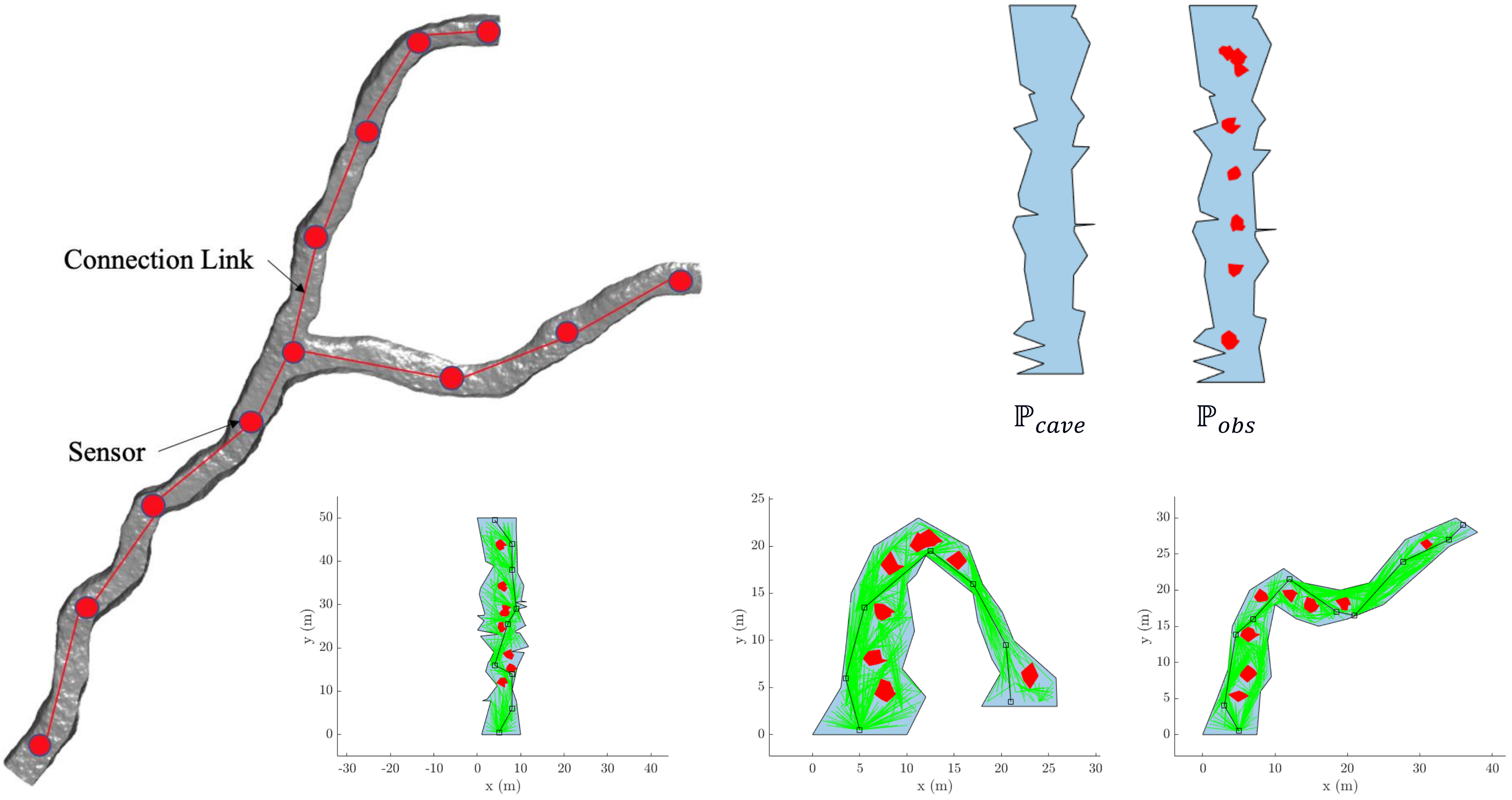


BW= 60°



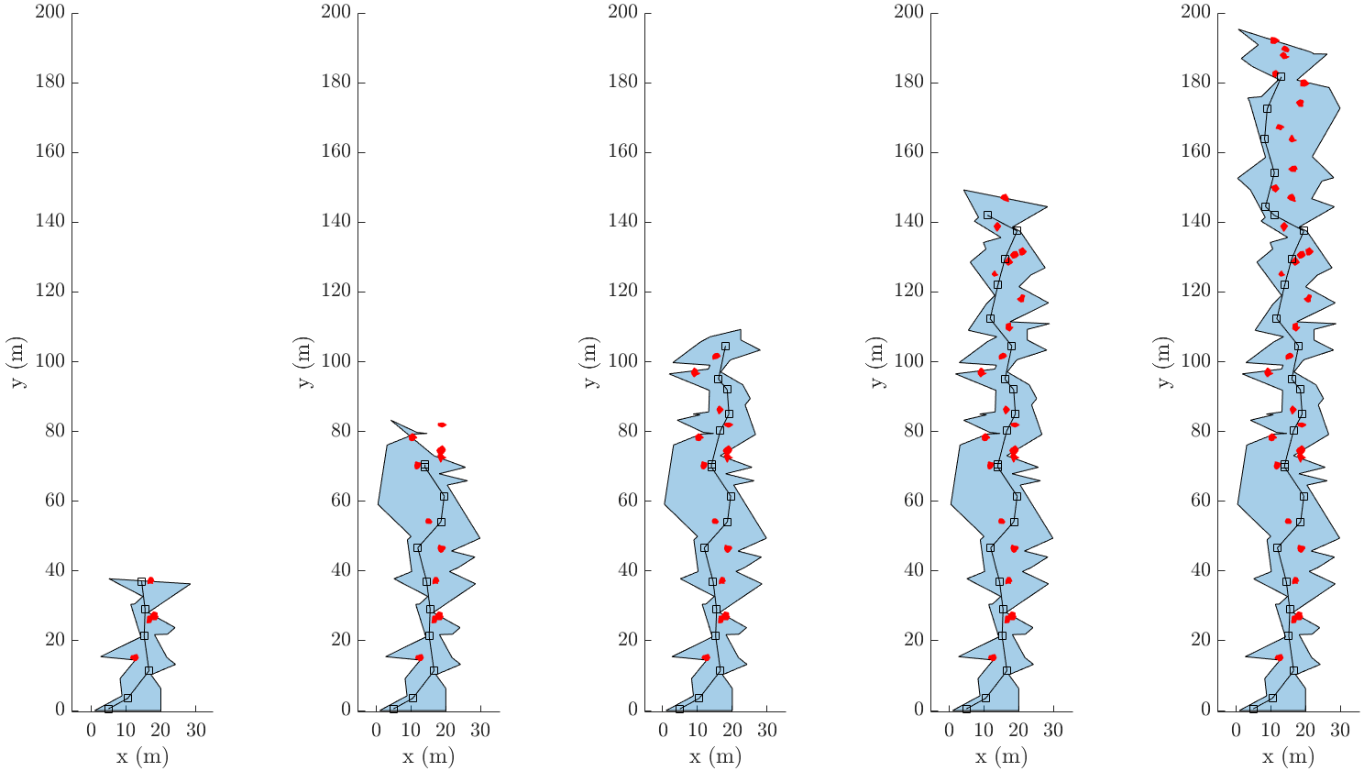
Laser

Sensor Placement



Optimal Sensor Placement using RRT*

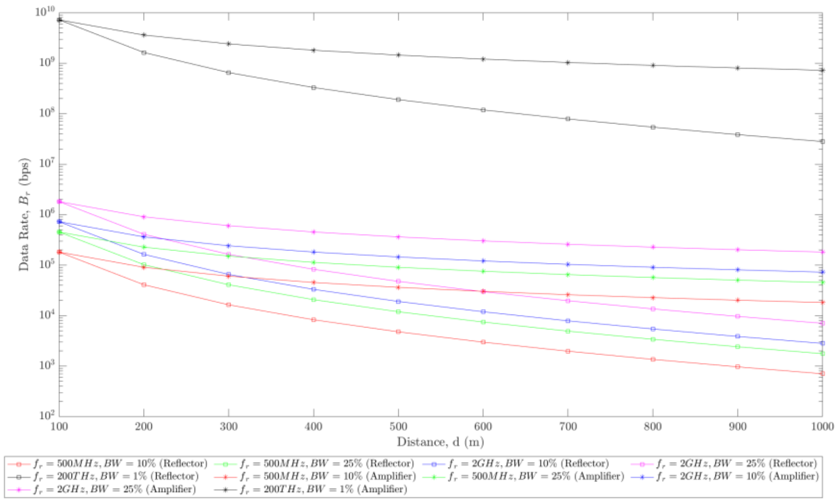
Sensor Placement



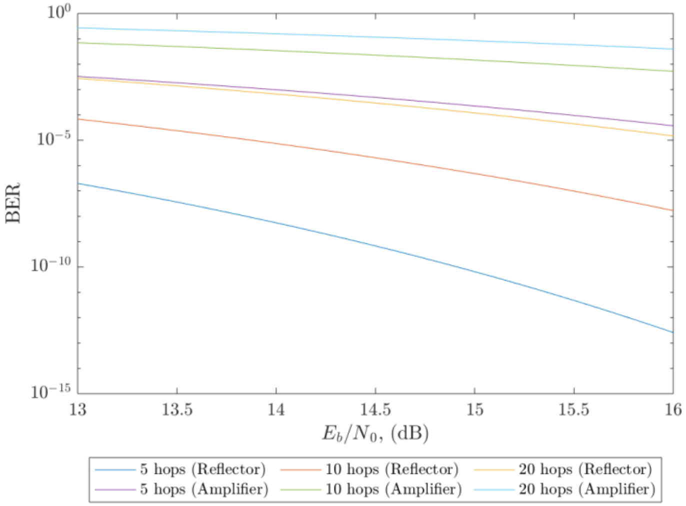
Optimal Sensor Placement using RRT* in an unknown cave through 5 successive Explore→Place sensor cycles

Communication

- Two types of sensors modeled
  - Reflectors (Inactive)
  - Amplifiers (Active)



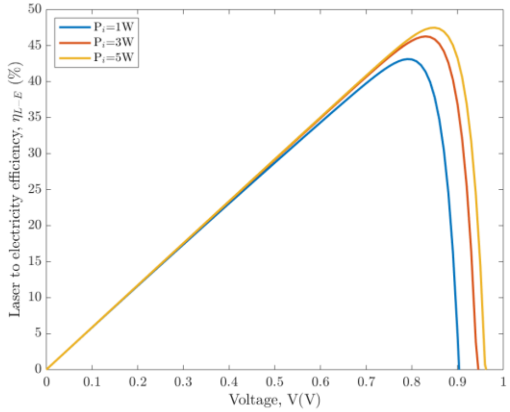
Variation of data rate B_r in bps over distance for 10 hops. The simulation is performed with RF communication (500MHz and 2GHz) with (10% and 25%) bandwidth and optical communication (200THz) with (1%) bandwidth assuming a) Reflectors, and b) Amplifiers.



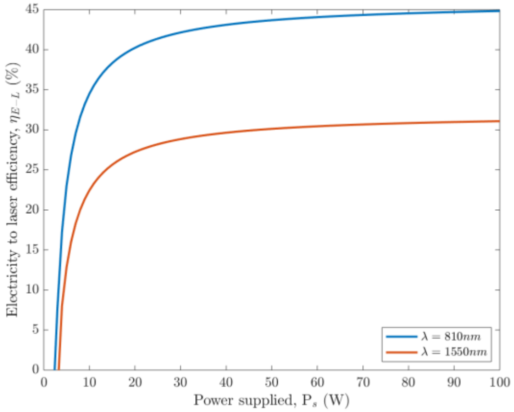
Variation of BER over E_b/N_0 for different number of hops. The simulation is performed assuming two sensor configurations a) Reflectors, and b) Amplifiers

Power Transfer

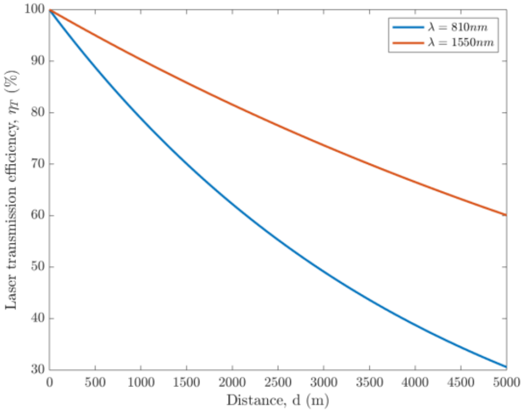
- Wireless power transfer through Lasers
    - Electricity to Laser Conversion
    - Laser Transmission
    - Laser to Electricity Conversion (P-V cells)



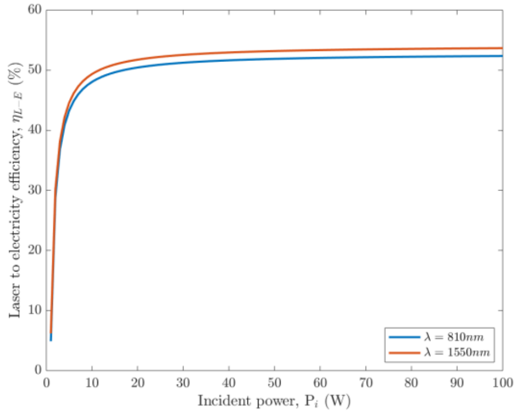
Variation of laser to electricity conversion efficiency η_{L-E} of a solar cell over voltage



Variation of electricity to laser efficiency η_{E-L} over supplied power P_s



Variation of laser transmission efficiency η_T over distance d



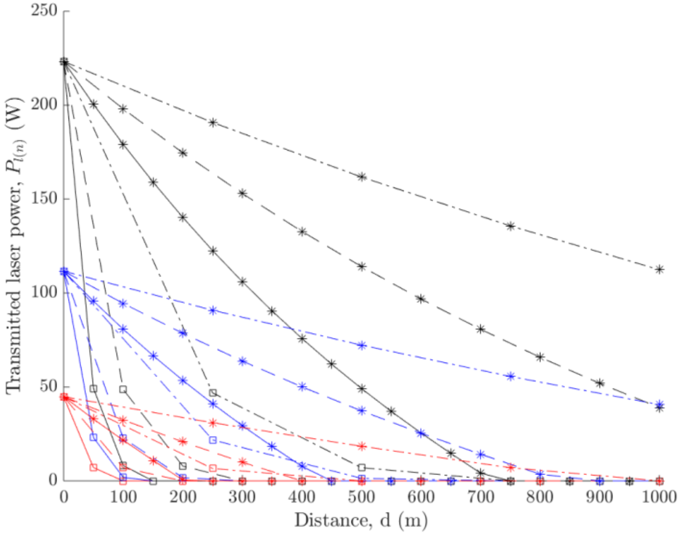
Variation of laser to electricity conversion efficiency η_{L-E} of a solar panel over incident power P_i

Power Transfer

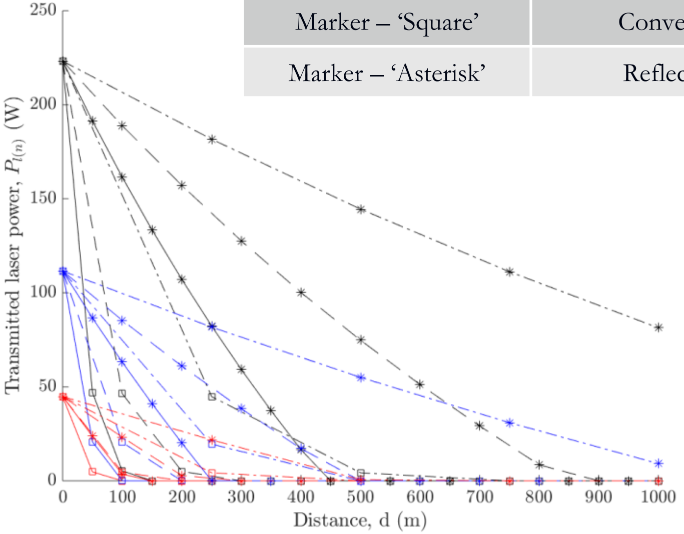
- Two types of sensors modeled
  - Reflectors
  - Converters

LineSpec	Property
Color – ‘red’	$P_s = 100$ W
Color – ‘blue’	$P_s = 250$ W
Color – ‘black’	$P_s = 500$ W
LineStyle – ‘Solid’	$d = 50$ m
LineStyle – ‘Dashed’	$d = 100$ m
LineStyle – ‘Dash-dot’	$d = 250$ m
Marker – ‘Square’	Converters
Marker – ‘Asterisk’	Reflectors

Laser wavelength $\lambda = 810$ nm



Variation of transmitted power over distance for $P_{sensor} = 5\ W$



Variation of transmitted power over distance for $P_{sensor} = 5\ W$

Power Transfer

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LineSpec	Property
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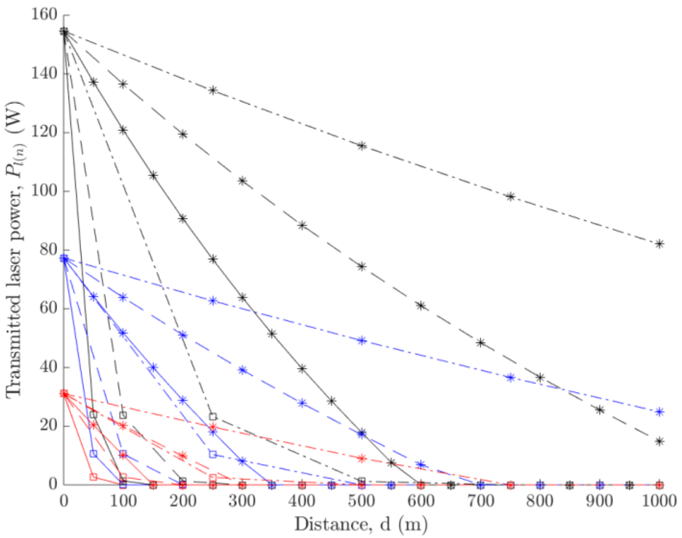
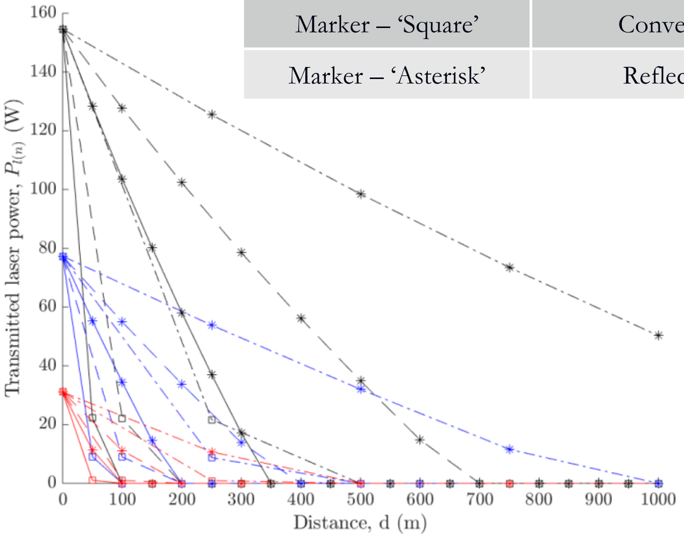
Color – ‘black’	$P_s = 500$ W
LineStyle – ‘Solid’	$d = 50$ m
LineStyle – ‘Dashed’	$d = 100$ m
LineStyle – ‘Dash-dot’	$d = 250$ m
Marker – ‘Square’	Converters
Marker – ‘Asterisk’	Reflectors

Laser wavelength $\lambda = 1550$ nm



Variation of transmitted power over distance for $P_{sensor} = 5\ W$



Variation of transmitted power over distance for $P_{sensor} = 5\ W$

Conclusion

- **Presented Strategies for exploring Lunar/Martian caves that includes**
  - Mobility
  - Mapping and Navigation
  - Communication
  - Power Transfer
- **Use of multiple sensors to maintain a direct line-of-sight connection link for both wireless communication and power transfer**
- **Use of Lasers for both communication and power transfer has an advantage**


Thank You

Questions ?