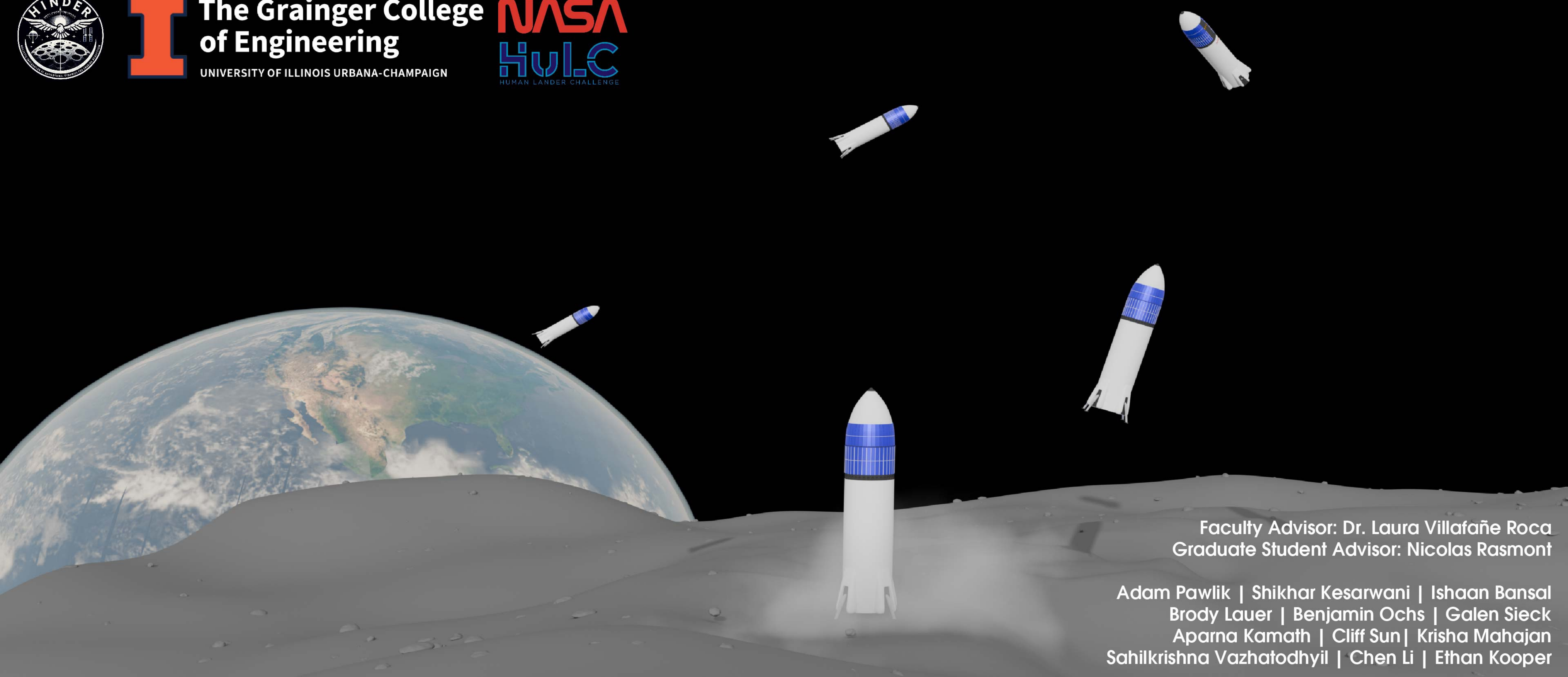
HINDER

Holistic Integration of Navigational Dynamics for Erosion Reduction

The Grainger College of Engineering
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

NASA HuLC HUMAN LANDER CHALLENGE



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Overview

- Theme requirements
- State of the art and technology gaps
- Value Proposition

Concept of Operations

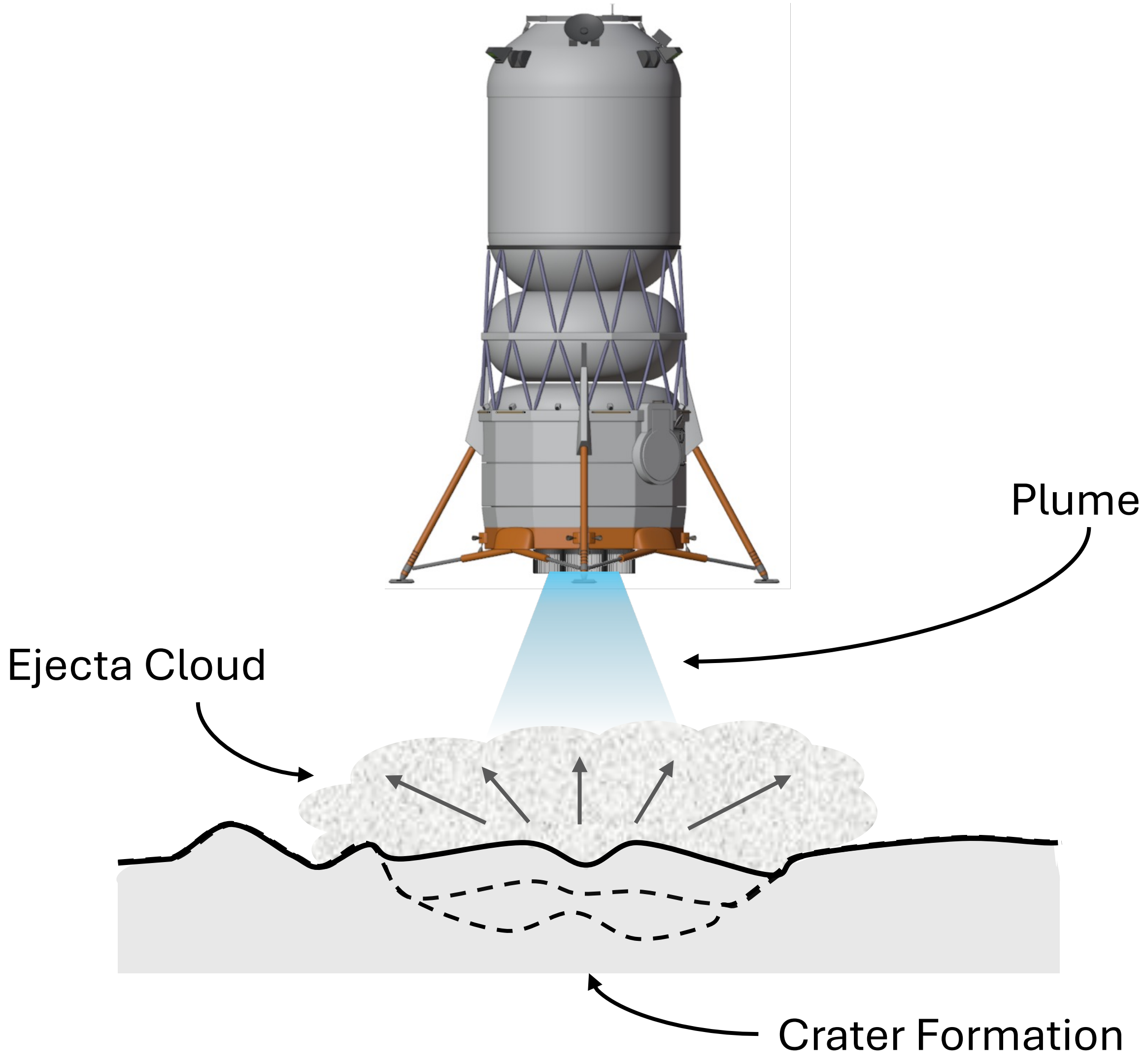
- Target site selection
- Hazard relative navigation
- Hazard detection and avoidance
- Surface measurements

Integration

- HLS Integration
- Configurations

Mission Assessment

- Architecture timeline
- Cost analysis
- Risk analysis

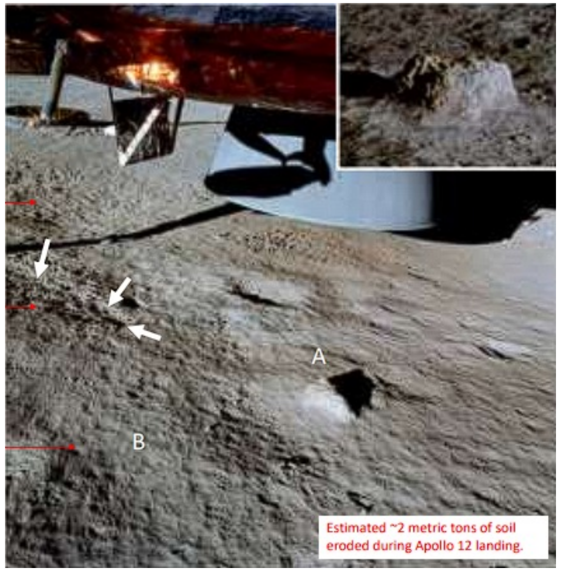


What is PSI

- Interaction between lander exhaust and planetary surfaces
- Leads to adverse effects such as visual obscuration and lander instability
- Proper management of PSI is crucial to prevent damage to mission critical equipment and enhance overall safety of lunar expeditions

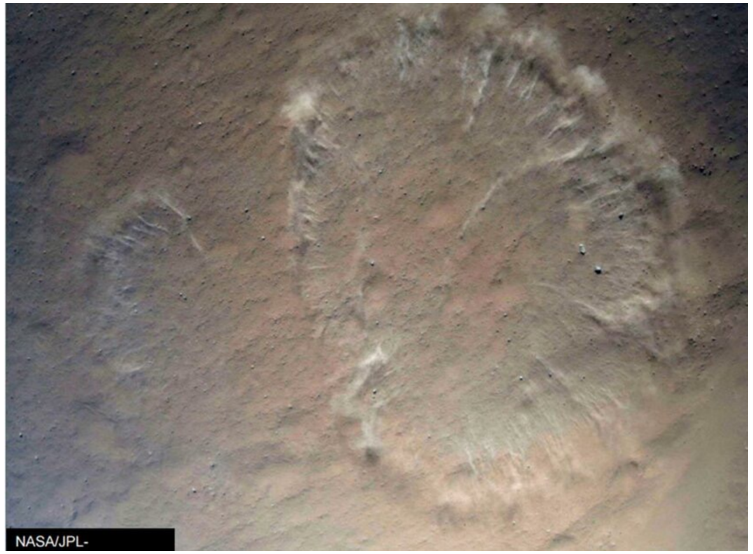
Lander Safety

- Surface visibility obscured
- Plume recirculation
- Uneven surface erosion



Architecture Sustainability

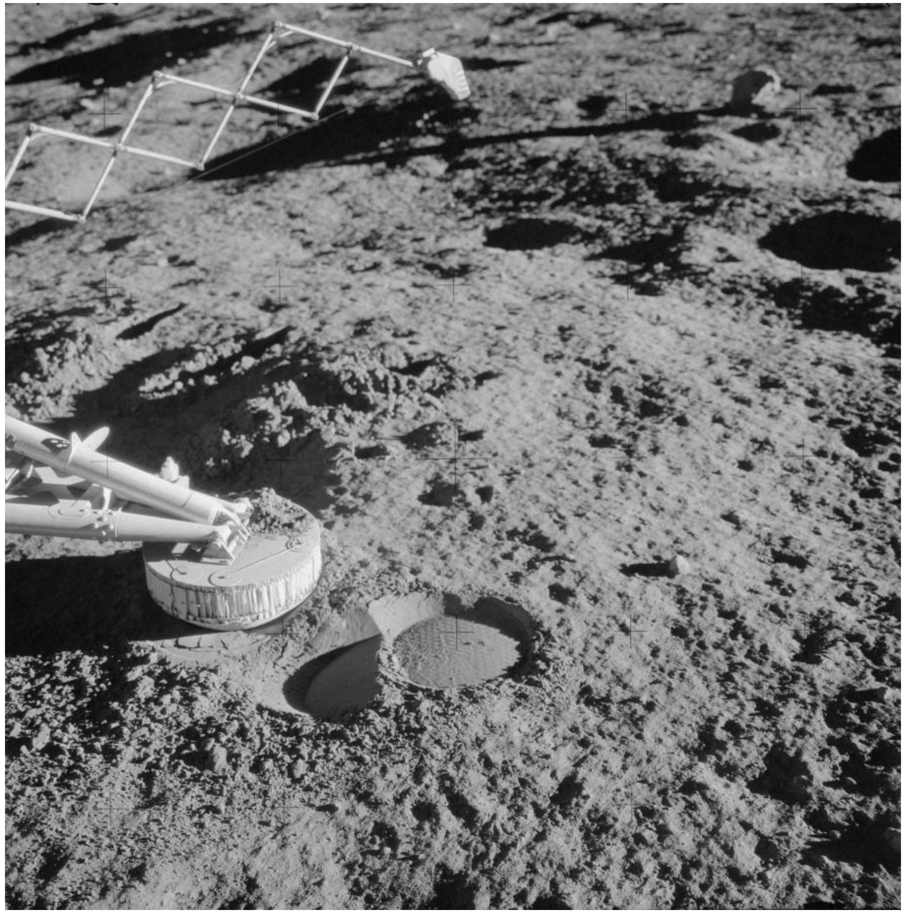
- Damage to nearby hardware
- Soil modified for next mission



Scientific Interests

- Contamination of the surface and exosphere with volatiles
- Local morphological changes

- Goal: Quantify relative PSI vulnerability
- Site selection is based on rapid modeling
  - Insufficient data for high fidelity models
  - Broad trends, not fine optimization
- Geotechnical properties
  - Particle size
  - Particle shape
  - **Bulk density**
  - Cohesion
  - Permeability



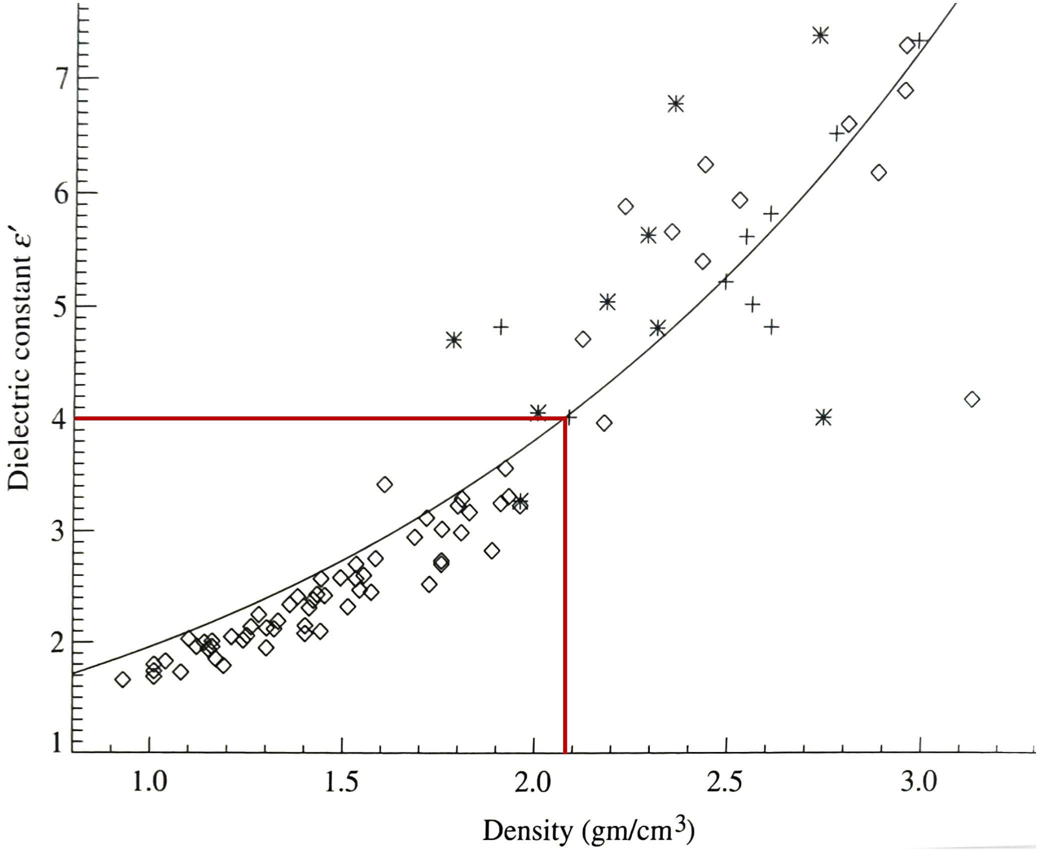
PSI surface erosion scales inversely with surface bulk density based on rapid models

*"In light of NASA's Artemis III mission [...], here we utilized radar observations from the **Miniature Radio Frequency (Mini-RF) instrument** on board LRO to characterize this South Pole - crossing ray. Radar observations can [...] **constrain bulk density** and composition (i.e., dielectric permittivity)."* -Rivera-Valentín et. al, 2024

*"Combined, these datasets can characterize the radar scattering properties of the lunar surface [...] and are uniquely valuable for **identifying landing hazards and constraining the dielectric properties** [...] of regolith within the Artemis landing zones."* -Patterson et. al, 2023

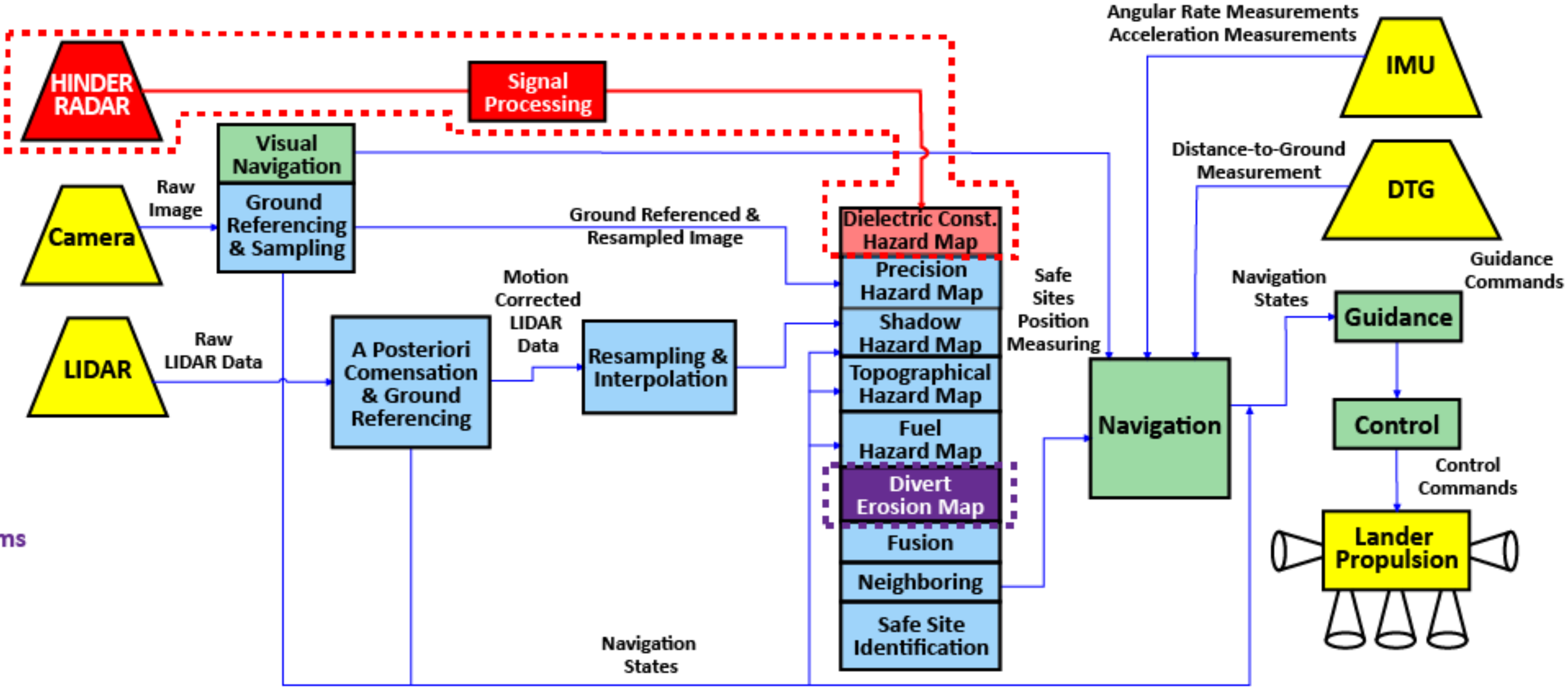
Radar Remote Sensing of Planetary Surfaces

Campbell (2002) [12]

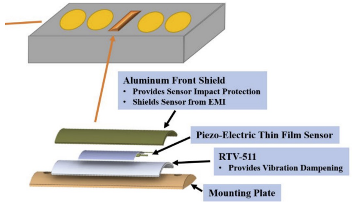


Bulk density can be estimated using dielectric constant with radar

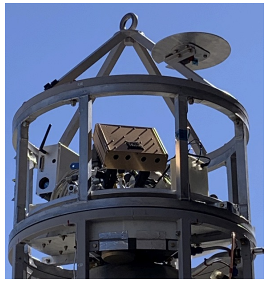
- Hazard Detection & Avoidance
- LIDAR Sensor-Level Processes
- GNC including Divert Guidance
- Sensors and Actuators
- HINDER Instrumentation System
- HINDER Divert Analysis Algorithms



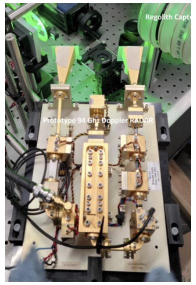
PSI Sensors



PIE
Impact Sensor

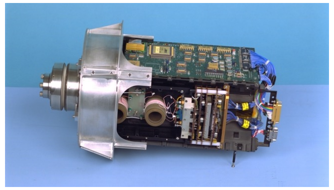


Ejecta STORM
Laser Scattering



DERT
mm Wave Doppler

SCALPSS
Stereo Camera



SEAL
Mass Spectrometer

LLBI
Aerothermal Effects

Technical Gap: Preventative action prior to the onset of PSI

Navigation and Hazard Avoidance

- Active terrain relative navigation (TRN)
  - Camera images of the surface
  - Active lidar measurements
- Landing within 100m of a target
  - Requirement set for HLS
  - Demonstrated by the JAXA SLIM lander
- Interest in diversifying Precision Landing & Hazard Avoidance (PL&HA) capability
  - Lidar & radar, multi-function sensors

Technical Gap: PSI relevant hazards and navigation

HINDER addresses gaps in PSI and PL&HA sensors

HINDER | CONCEPT OF OPERATIONS

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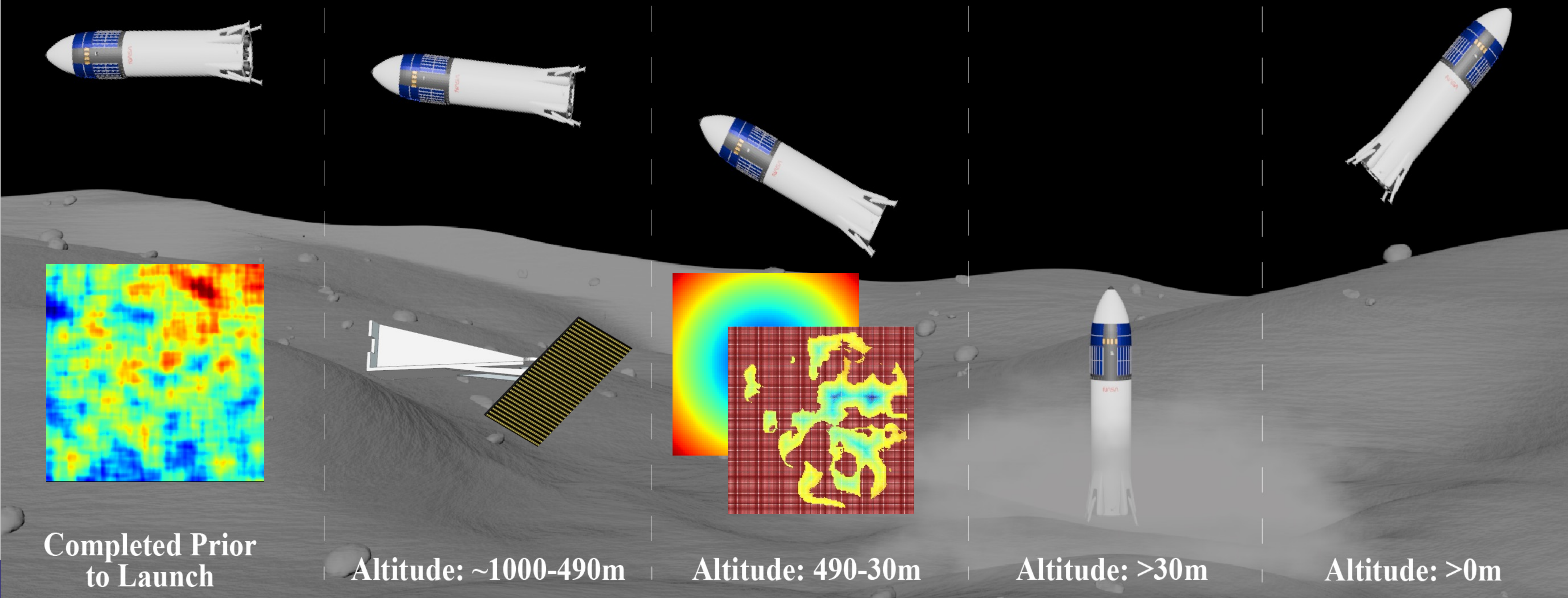
Phase 0: Target Site Selection

Phase 1: Hazard Relative Navigation

Phase 2: Hazard Detection & Avoidance

Phase 3: Surface Measurements

Phase 4: Ascent



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2024: Exploratory Phase

Concept and Technology Development

Focus in on PSI model research and radar component selection

Initial prototyping of hardware and software

TRL 1-3

2025-2027: Foundational Phase

Pathfinder Experiments and Product

Pathfinder is developed and tested on terrestrial lander testbeds. Preliminary results used for developing a precursor mission.

Precursor launch on Artemis III with the sensor in data collection mode

TRL 4-8

2028: Operational Phase

Mission Deliverable

HINDER's performance from Artemis 3 is evaluated and necessary design changed are made

The final iteration is integrated into Artemis IV with full operational capability

TRL 9

HINDER will launch a precursor mission on Artemis III, with a full-scale mission on Artemis IV

ASSUMPTIONS AND MODELLING

- Problem: Apollo experience cannot be extrapolated to HLS
- Response: Define a high-level approach which can be applied to other models
  - Demonstrate the concept using Apollo era experience and data
  - Use Roberts' Model as a preliminary rapid model of higher altitude effects
- Assumptions: Volumetric erosion rate decreases with increasing bulk soil density

Roberts' Model

$$\frac{\partial y}{\partial t} = \frac{2(\tau - \tau^*)}{a \cdot u \cdot \sigma \cdot c \cdot \cos(\beta)}$$

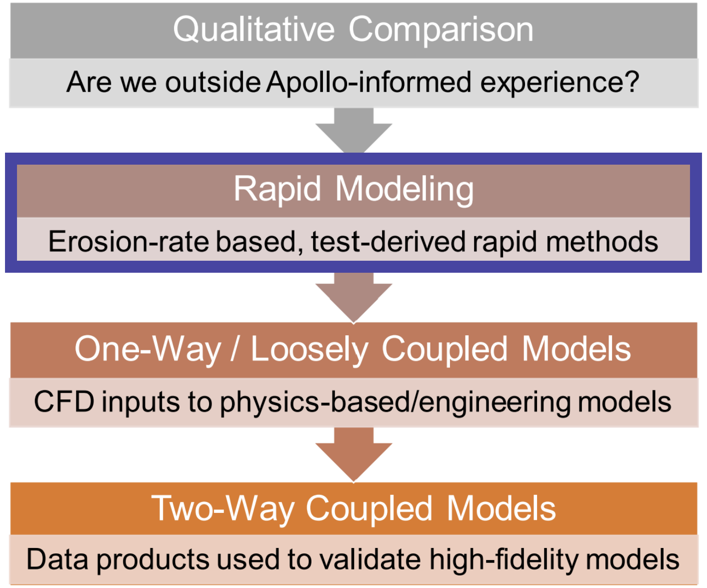
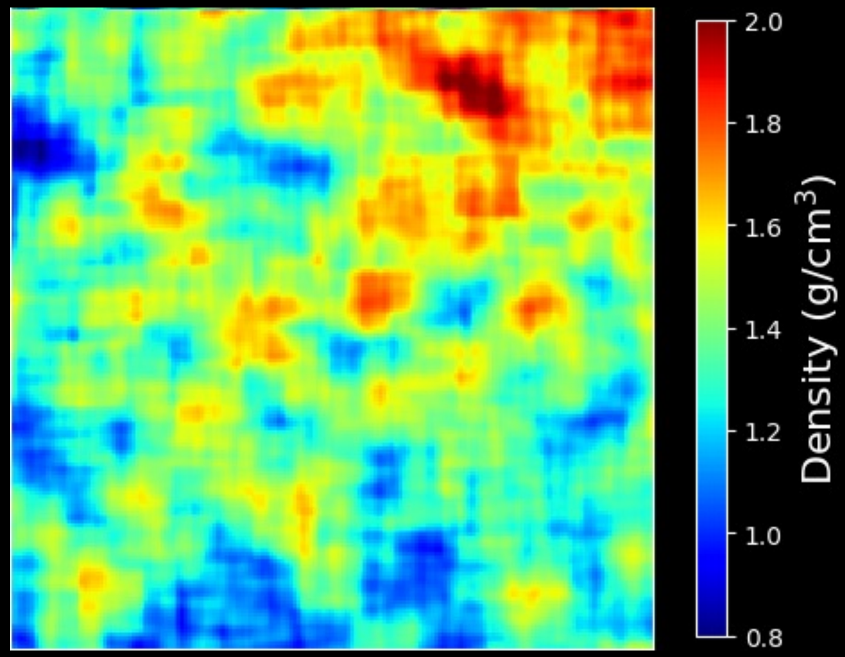


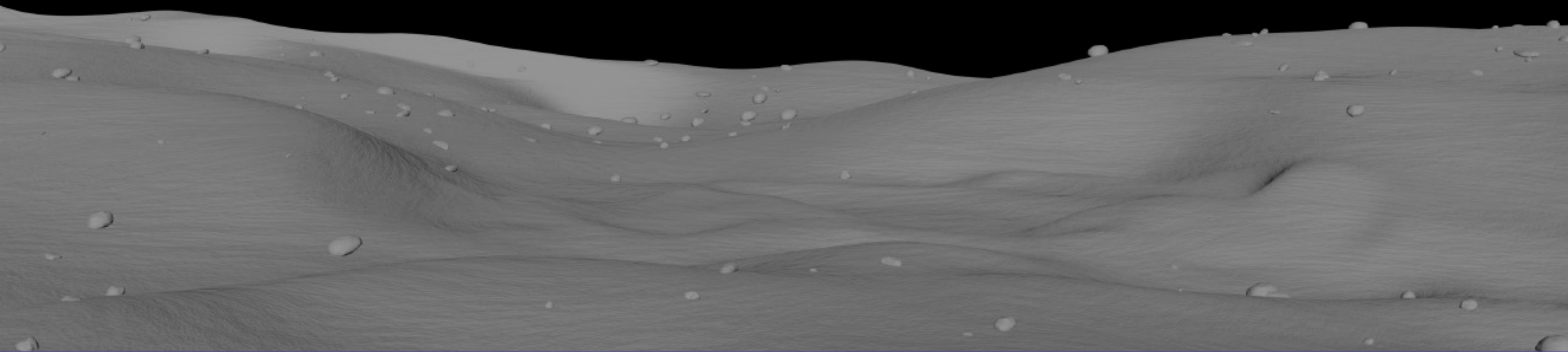
Image from [8]

Simple, rapid Apollo era models are used for concept demonstration

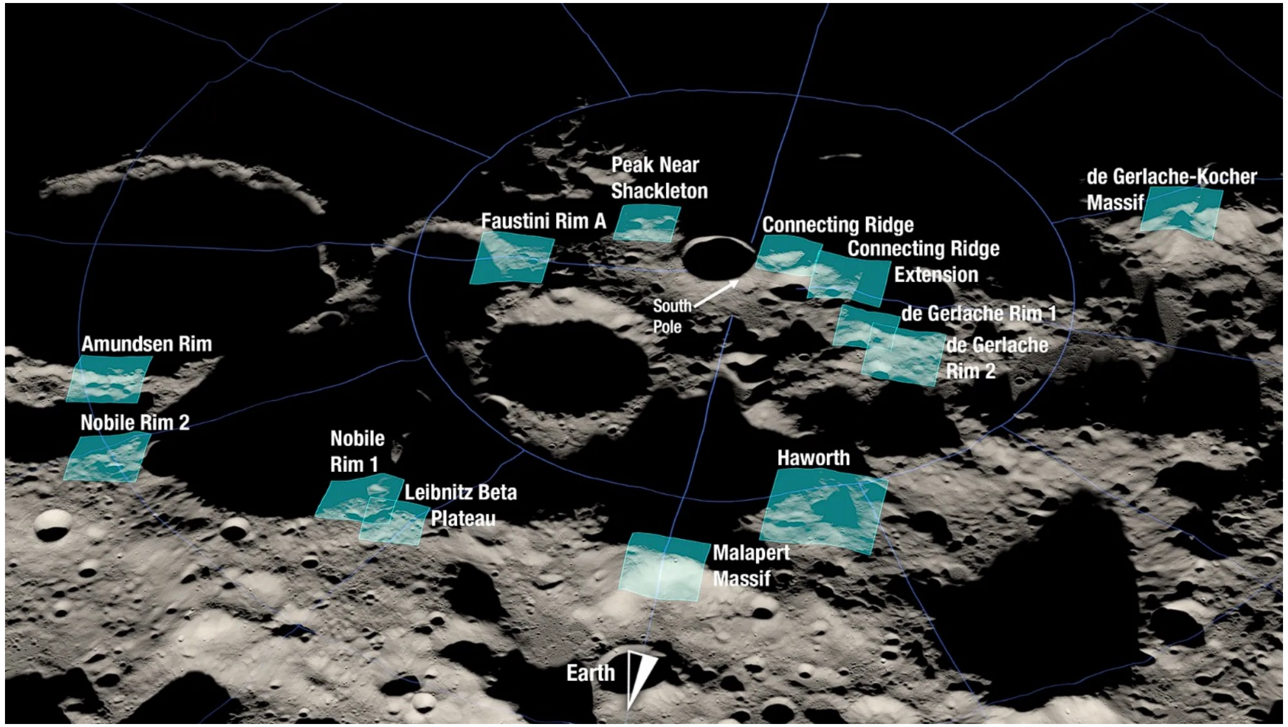
Phase 0: Preliminary Site Selection

Conducted prior to launch





- Selected from 13 candidate regions
  - Multiple sites per region
  - Unprepared sites
- Selection factors
  - Accessibility (timing dependent)
  - Terrain slope
  - Line of sight to Earth
  - Lighting conditions
  - **Gap: PSI vulnerability**



Artemis Candidate Landing Regions, Image from [34]

A target landing site can be selected to reduce PSI vulnerability

MODELS REPLICATED FOR ANALYSIS

- Top models are sufficient for hazard detection
  - High performance models have reported errors <5%
  - Dielectric constant range of >30%
  - Insufficient for fine optimization within about 5% variation
- Proof of concept
  - Two simple models selected for demonstration
  - Full implementation should use a higher accuracy model

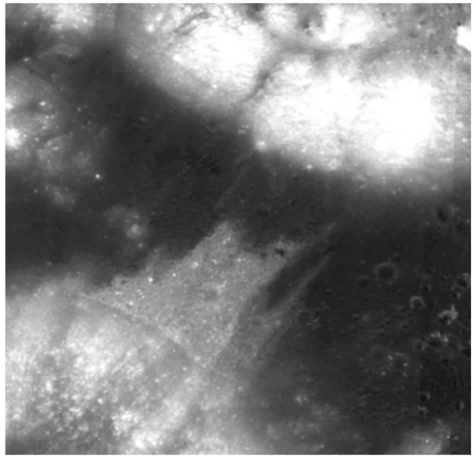
Dielectric Constant Model	Source	Reported Error
Fresnel Reflection Coefficients	Kumar et. al, 2022 [14]	< 3% (6 samples)
Modified Campbell Inversion	Calla et. al, 2013 [15]	< 20% (5 samples)
Co-Polarization Ratio	Singh et. al, 2022 [16]	N/A
Hybrid Polarimetric Scattering Similarity	Gao et. al, 2023 [17]	~10% (16 samples)
Symmetric Coherency and Anisotropy	Bhattacharya et al. (2015) [18]	N/A

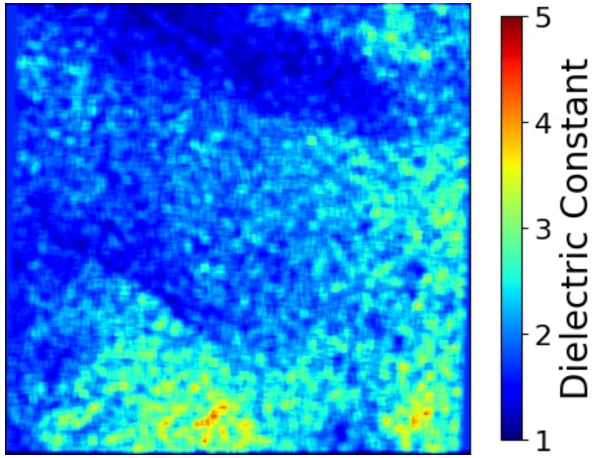
- Applied to preexisting data
  - Mini-RF: Lunar Reconnaissance Orbiter and Chandryaan-1
  - Near global coverage at 30m/pixel
- Demonstrated using data over the Apollo 17 site
  - In-situ measurements can be used to verify the accuracy of the model

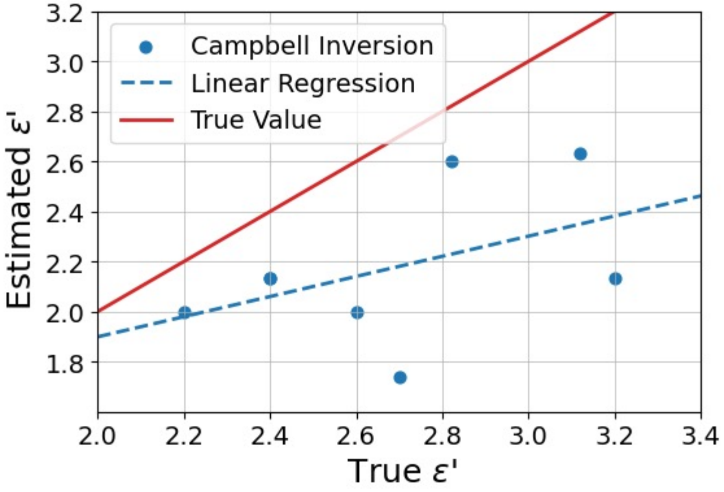
$\sigma^0{}_{LH} \approx \frac{1}{2}(S_1 + S_2)$ $\sigma^0{}_{LV} \approx \frac{1}{2}(S_1 - S_2)$ ϕ: Look angle

$$\varepsilon' = \left(\frac{\sin[\phi]}{\sin\left[\cos^{-1}\left(\frac{\sigma^0{}_{LH}}{\sigma^0{}_{LV}}\right)^{0.25} - \phi\right]} \right)^2$$

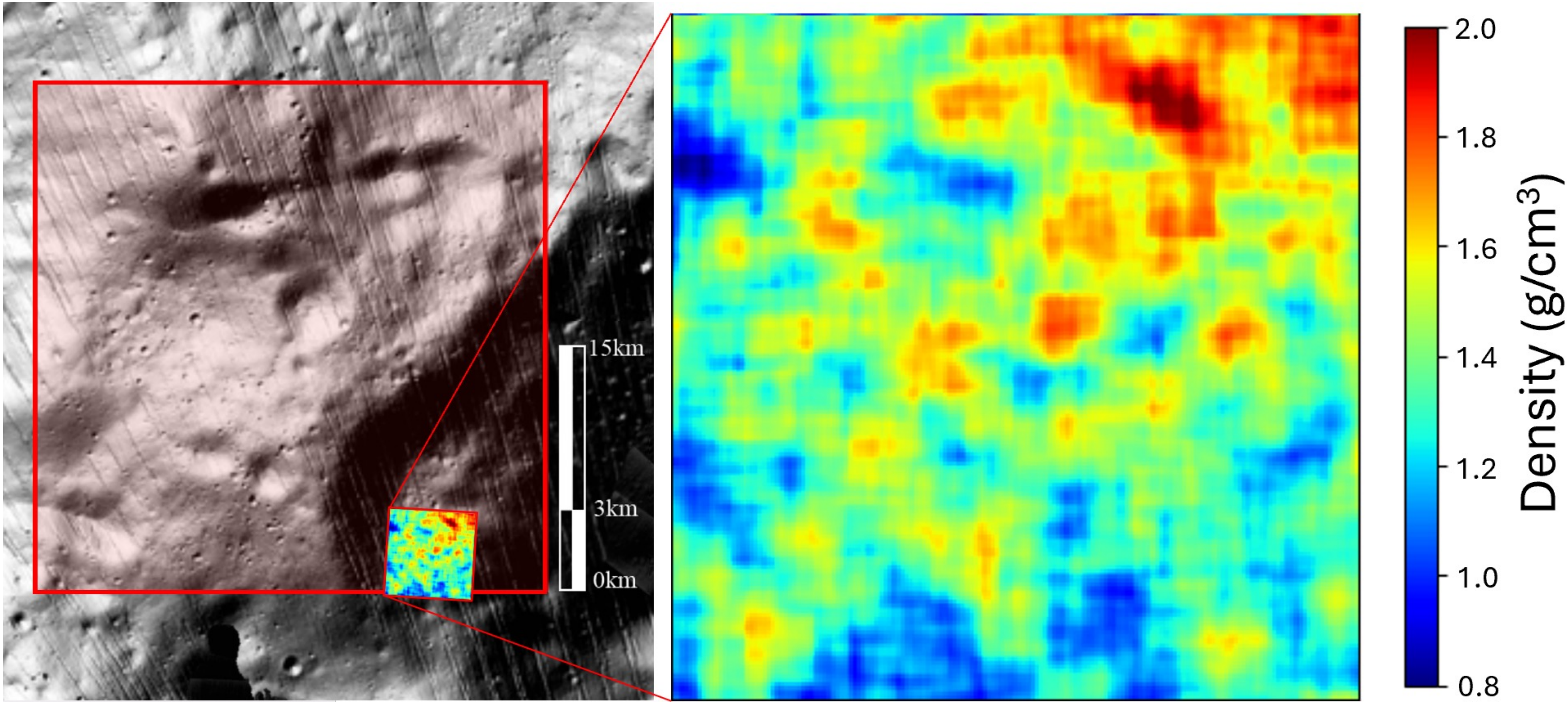
Apollo 17 Site Analysis



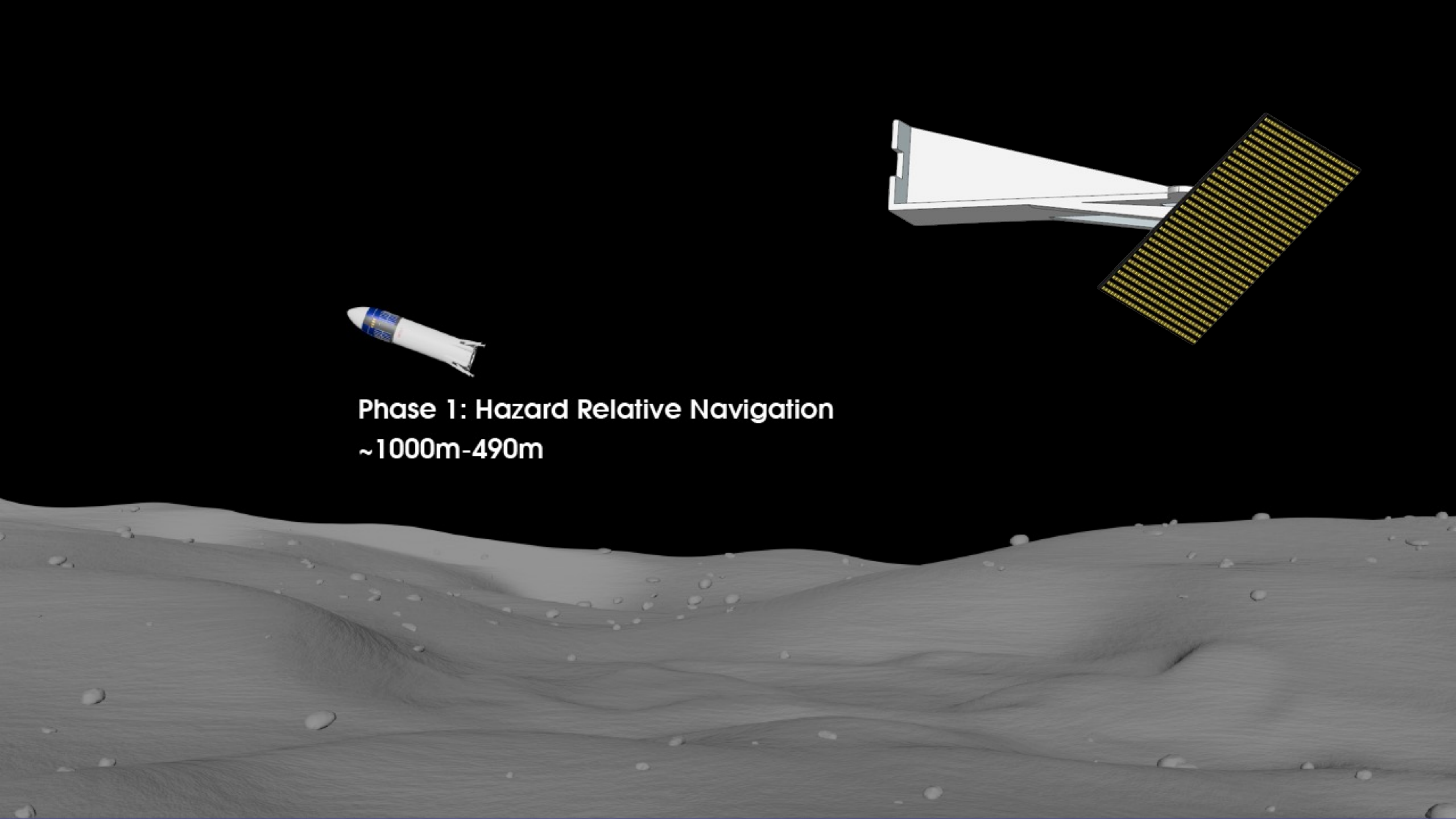




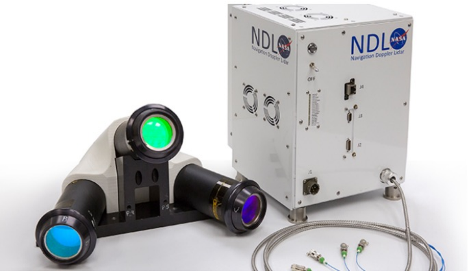
The modified Campbell model can be used as a proof of concept


15km
3km
0km
2.0
1.8
1.6
1.4
1.2
1.0
0.8
Density (g/cm^3)

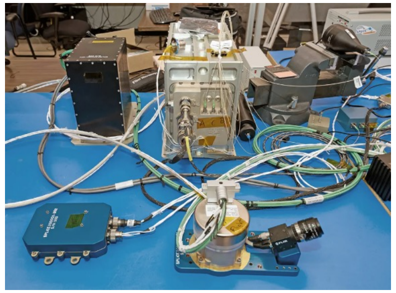
- Performed on Earth, prior to mission launch
  - Use pre-existing data from lunar orbiters
  - Suggested by members of the Mini-RF team for scientific purposes
- Use bulk density estimates to identify PSI hazards in a landing region
  - Apply more accurate dielectric constant estimation methods
  - Estimated >25% variation in bulk density within 1km diameter
- Requires minimal changes to HLS
  - Fast and at low cost


Phase 1: Hazard Relative Navigation
~1000m-490m

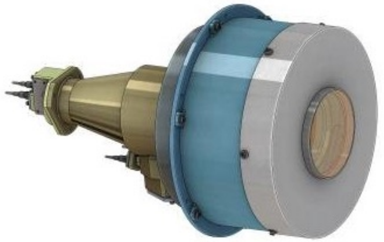
PL&HA Sensors



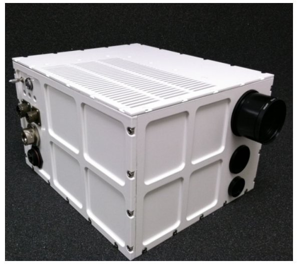
NDL
Navigational Doppler Lidar



SPLICE
Computer for PL&HA processing



HDL
Hazard Detection Lidar



ALHAT
Sensor suite for PL&HA

Technical Gap: Enabling real-time preventative action

Navigation and Hazard Avoidance Gaps

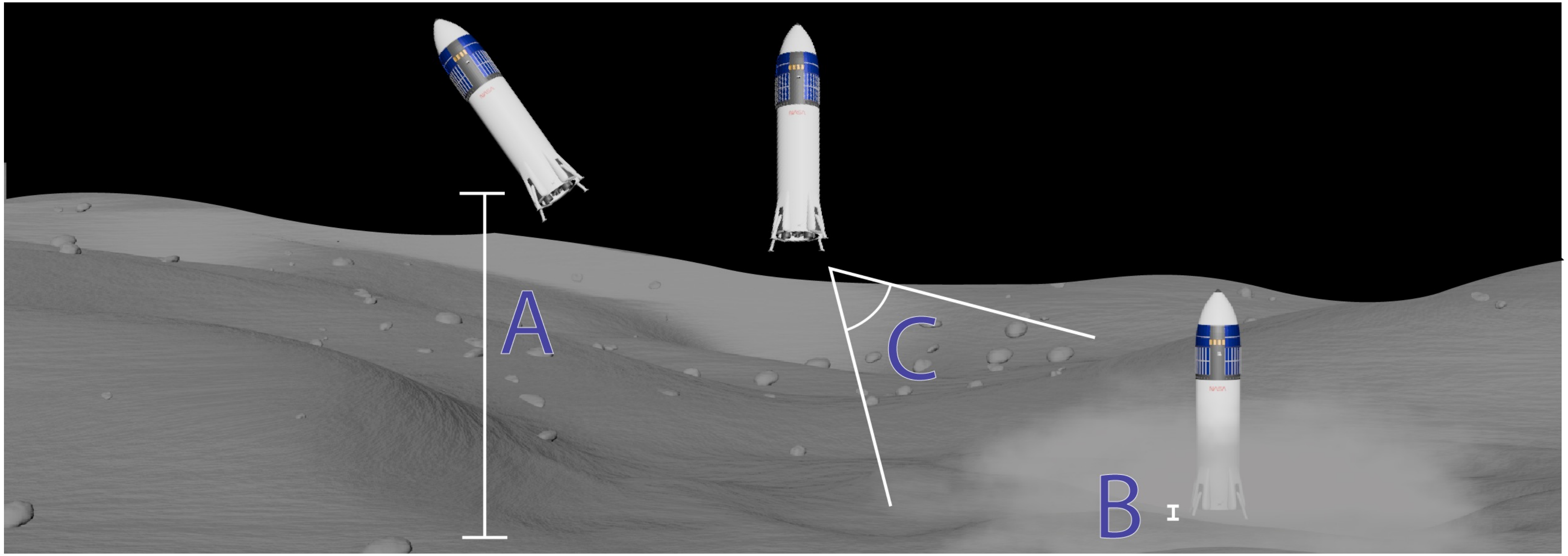
- **Terrain Relative Navigation**
  - Active terrain sensing to enable TRN and hazard detection during descent over dark, shadowed, or illuminated surfaces
- **Sensor Capabilities**
  - New technological advancements in radar & lidar, multi-function sensors, reductions in SWaP (size, weight, and power)
  - Facilitate technology transfer and invest in commercial solutions

Technological Gap: hazard detection and terrain relative navigation

HINDER addresses technological gaps existing in NASA's PL&HA and HDA sensor suite

	Radar	Lidar	Optical Cameras
Accuracy in Dielectric Constant Measurement	High	Low	Low/None
Penetration Depth	Moderate	Low	None
Resolution	Moderate-High	High	High
Weight & Power Requirements	Moderate	Low	Low
Data Processing Complexity	Moderate	Low	Low
Integration Capability with Trajectory Profile	Moderate	High	High
Operation-ability in dark/illuminated/ shadowed regions	High	High	Low/None

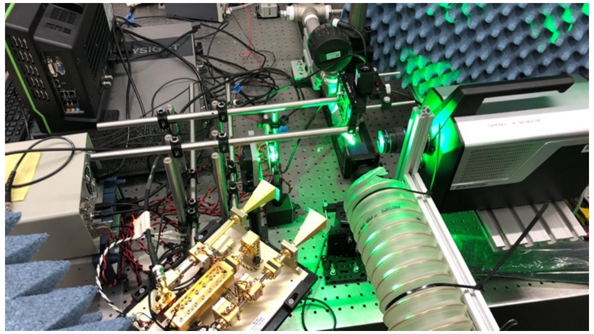
Radar is selected over other technologies due to heritage in dielectric constant measurements



Instrument Performance Requirements

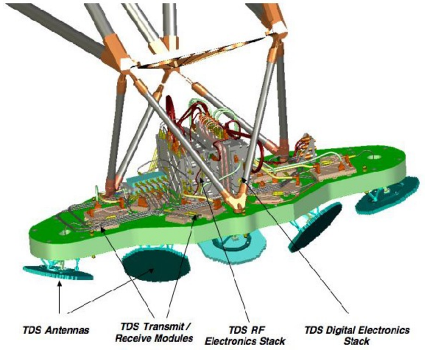
Parameter	Identifier	Value	Notes
Maximum Altitude of Operation	A	~1000+150m (15% margin)	Begins with HRN initiation
Minimum Altitude of Operation	B	0.33m	Lowest payload height
Min. Radar Spot Diameter at 50m Altitude		3.5m	Blue Ghost's Diameter; Smallest US-based lander
Minimum Field of View	C	60°	

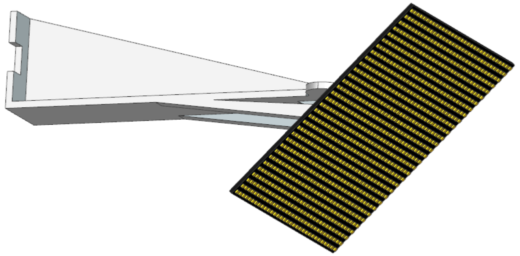
	DERT	MSL TDS	Starlink Gen. 2	HINDER Radar
Frequency	94 GHz	36 GHz	15 GHz	24 GHz
Power Usage	2.6 W	5-20 W	50-75 W	20 W
Beam Width	16 deg	3 deg	0.1-3.5 deg	3.5 deg
Transmit Power	24.5 dBm	33 dBm	35 dBm	115 dBm
Antenna Size	Ø 2 cm	Ø 20 cm	Ø 41 cm	□ 36 cm
Steering	None	None	AESA	AESA



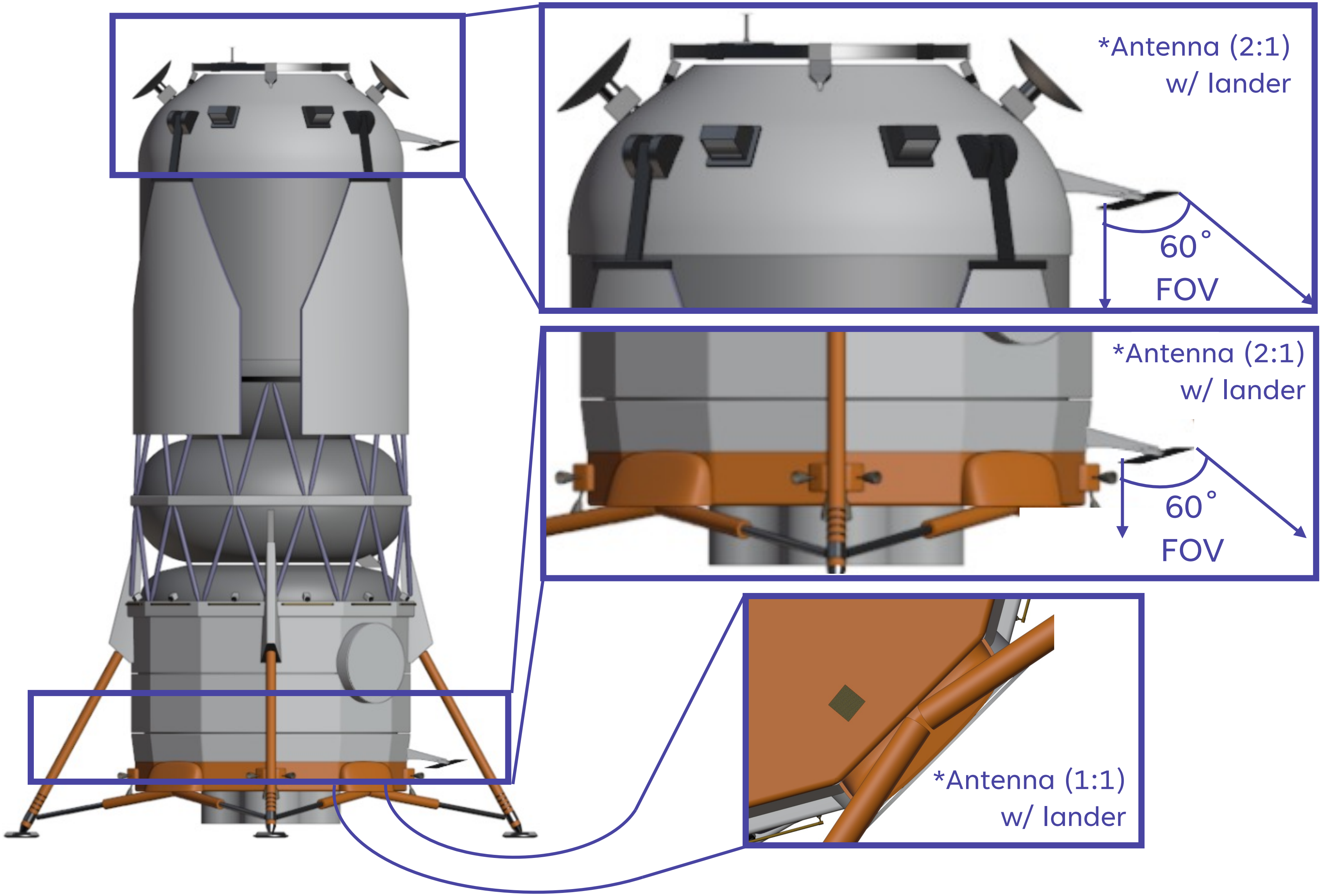
NASA LaRC Dust Ejecta Radar Technology (DERT)

NASA JPL Mars Science Laboratory Terminal Descent Sensor (MSL TDS)



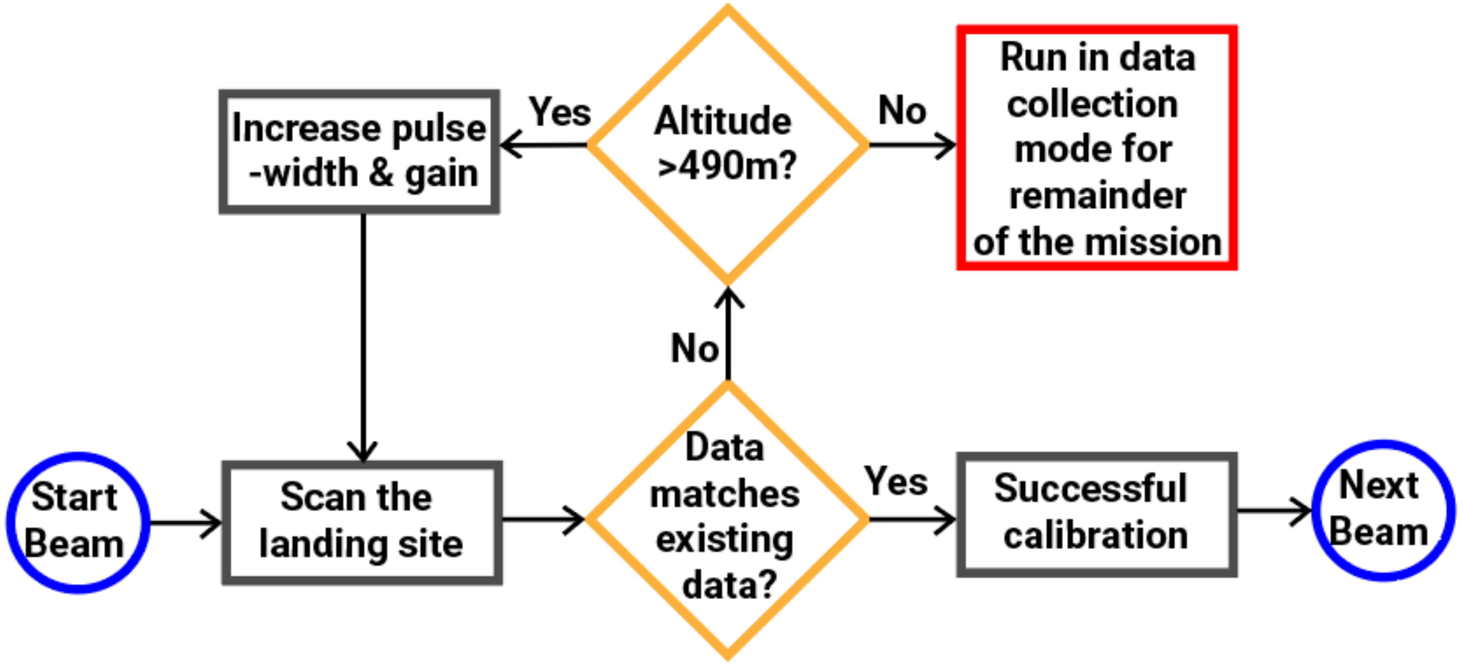


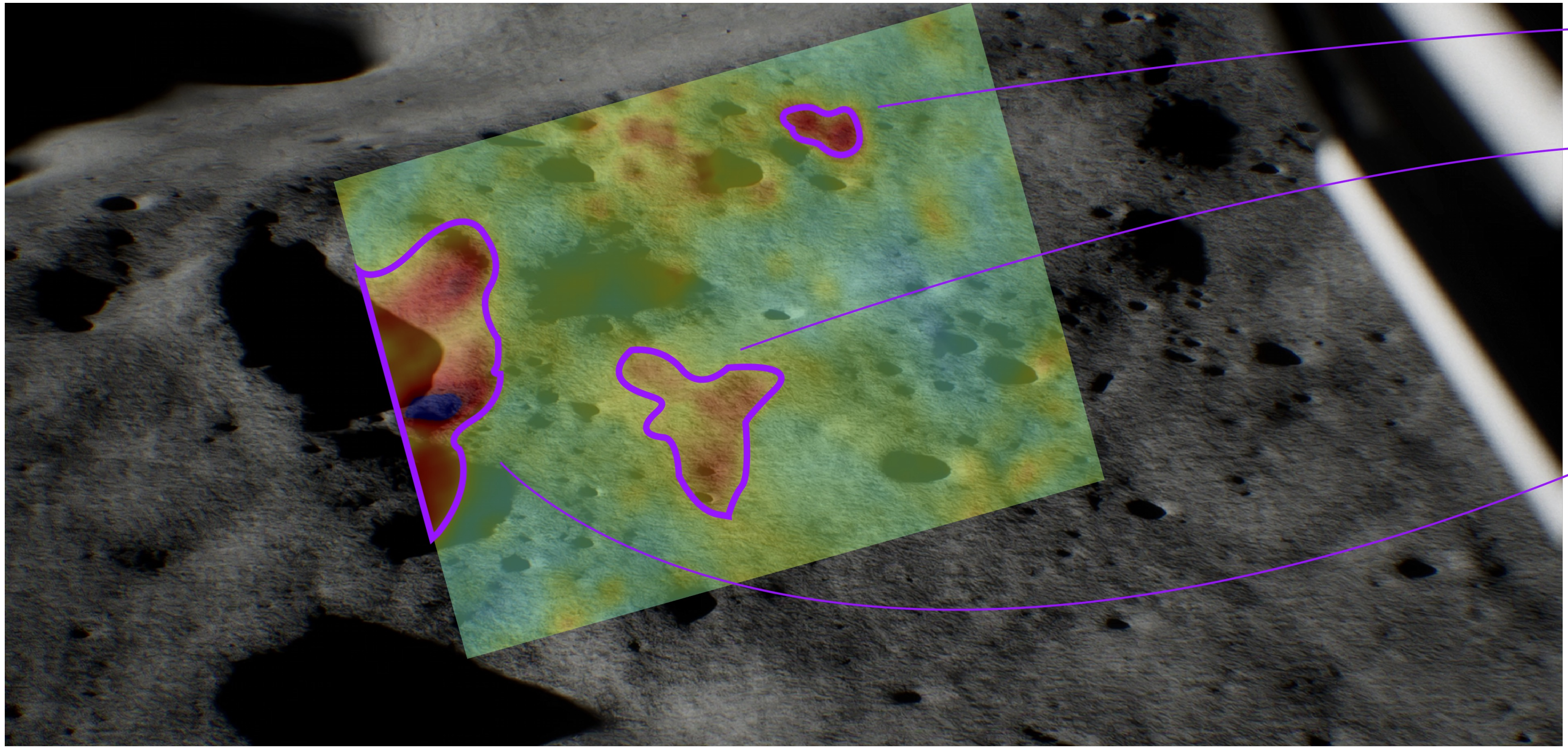
HINDER Radar Sensor



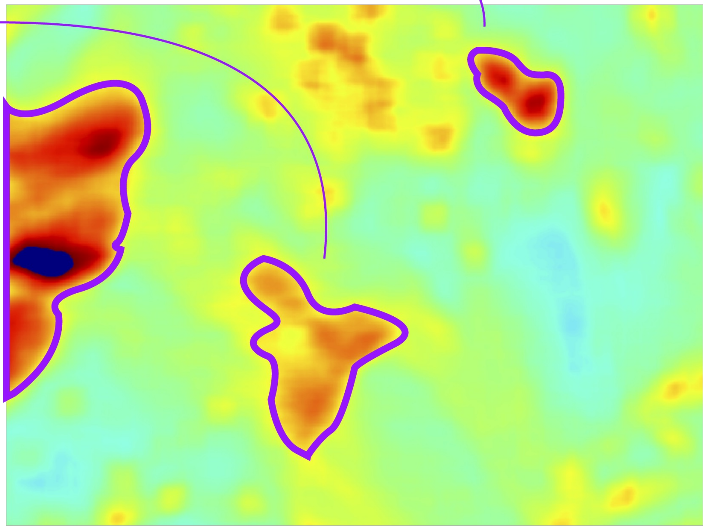
- Radar aptly designed for integration ease and flexibility
- Multiple potential integration points aboard lander for stakeholder to choose
- Bracket and integration procedures follow closely to that of SCALPSS

- Measurements begin at ~1000m altitude
  - Similar to other Hazard Detection instruments
  - Calibration from 1000m-490m altitude
- Real-time data is verified against existing data
  - Signal processing filters out abnormal data



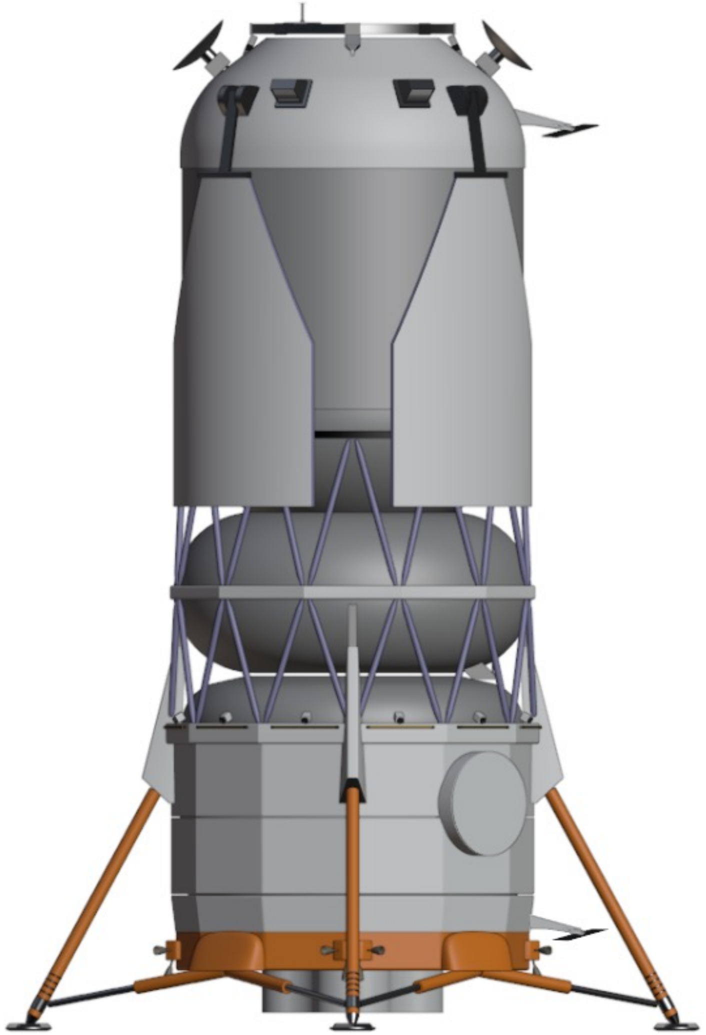


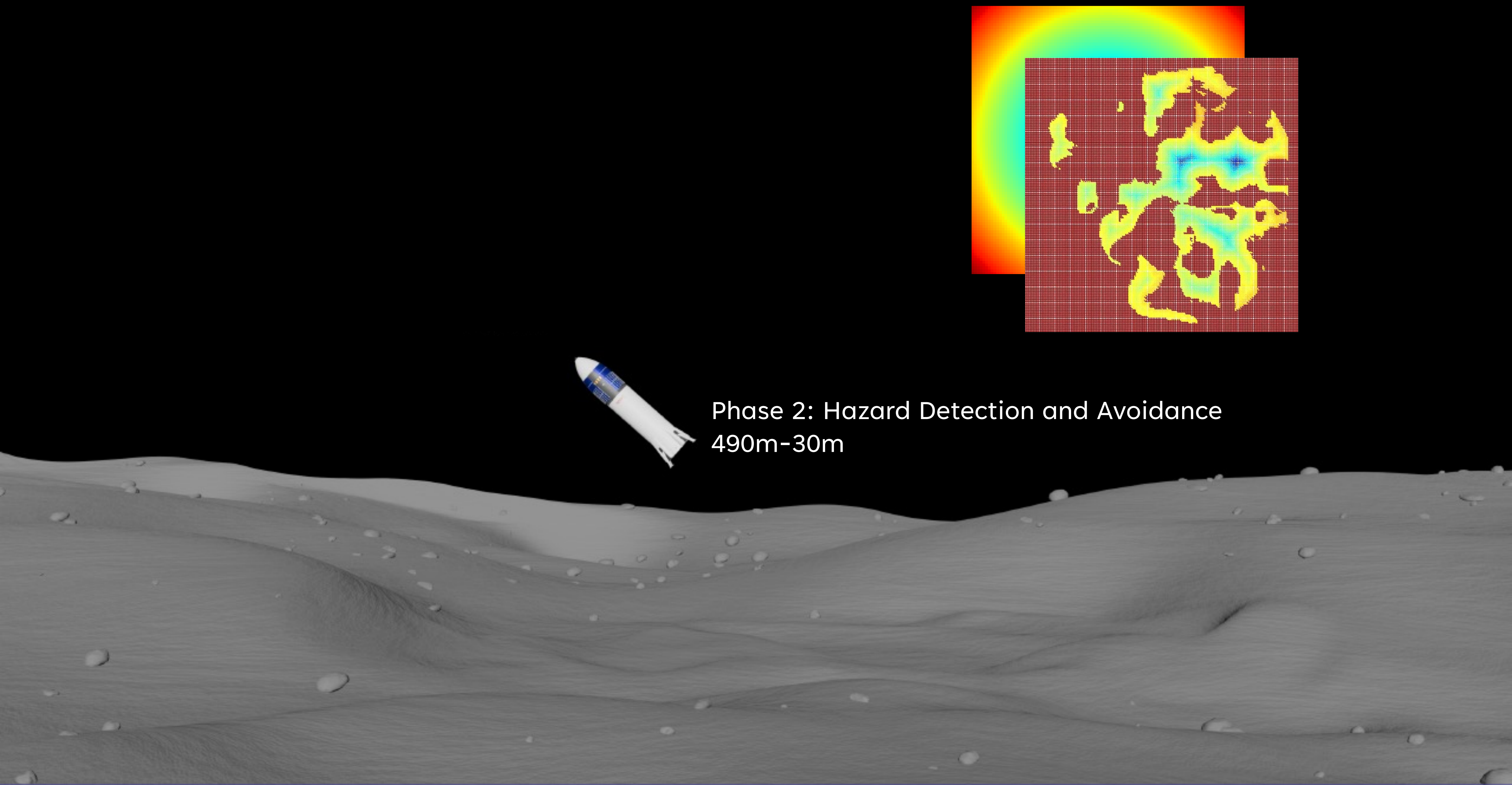
Radar POV with Overlayed Dielectric Constant Map



LRO Map from equivalent location

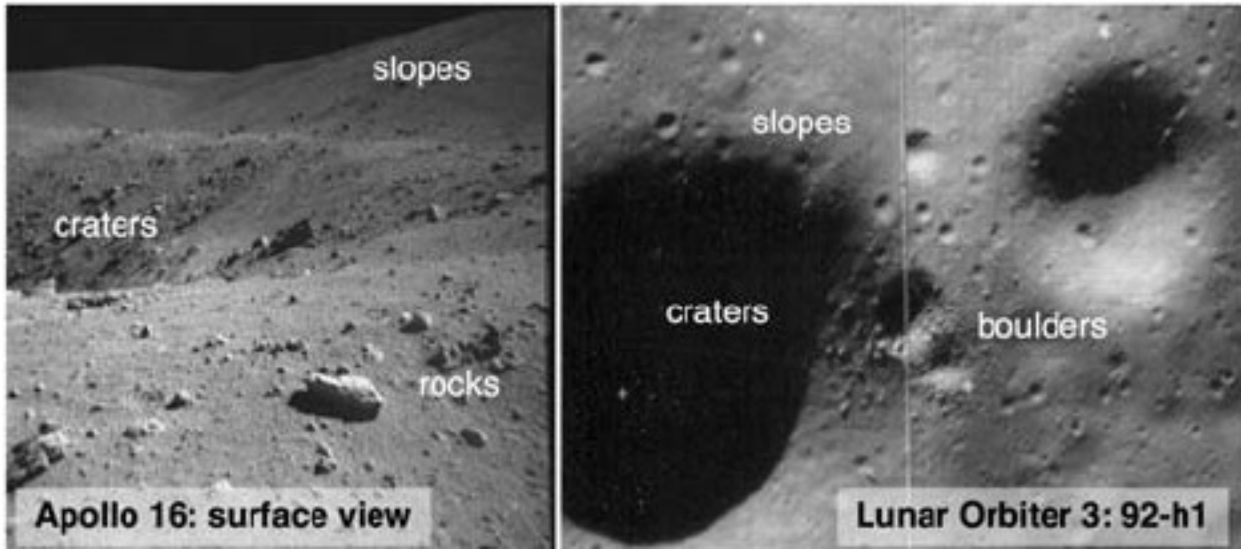
- Begins during at ~1000m altitude
  - Majority of PL&HA instruments initiate concurrently
- Use phased-array radar to match obtained data to existing LRO data
  - Done for verifying nominal radar operations
  - Used as an additional method of terrain relative navigation
- Requires integration of L-SWaP Phased-Array radar
  - Relatively moderately-sized payload for CLPS
  - Small payload for HLS




Phase 2: Hazard Detection and Avoidance
490m-30m

The **Hazard Detection & Avoidance (HDA)** sensors aboard HLS detect:

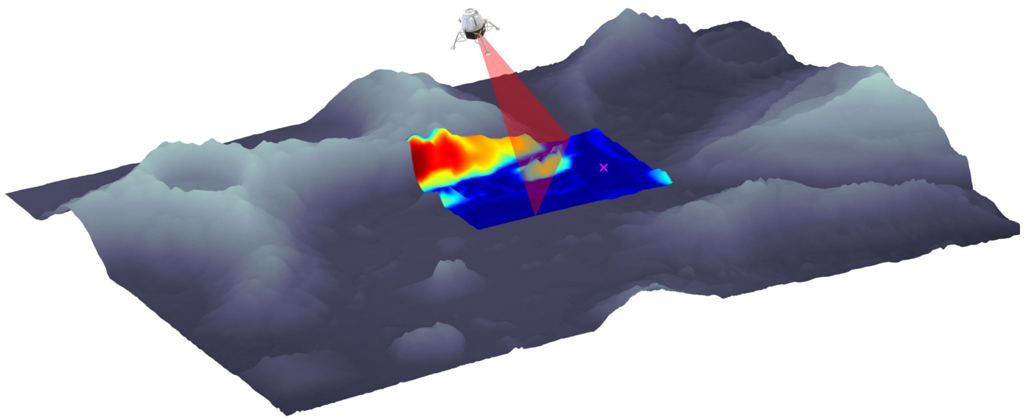
- Craters
- Steep Slopes
- Boulders
- Other physical obstacles



HDA does NOT consider geotechnical variations of potential landing sites that can affect cratering and ejecta

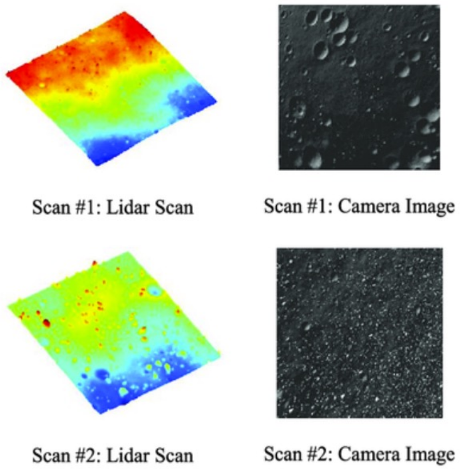
Current Technology:

- Limited resolution of data before flight
- Sensors
  - Optical Cameras
  - Lidar
  - Inertial Measurement Units (IMU)

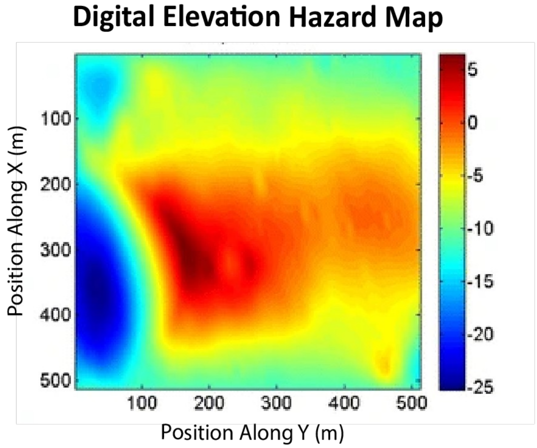


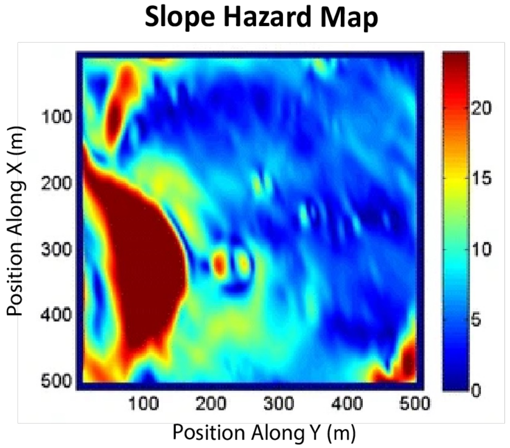
Advancements:

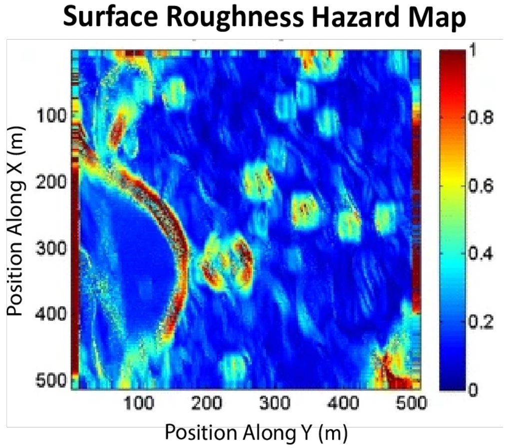
- More hazard maps needed for sensor fusion process
  - Computing methods translate sensor data into hazard maps
  - Hazard maps are cost maps intended to continuously update and choose safest landing site

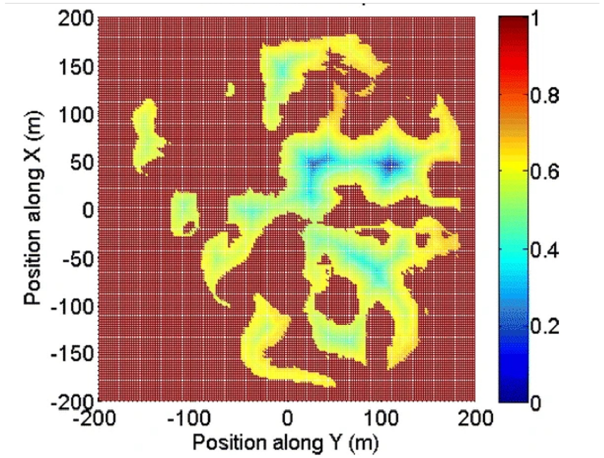


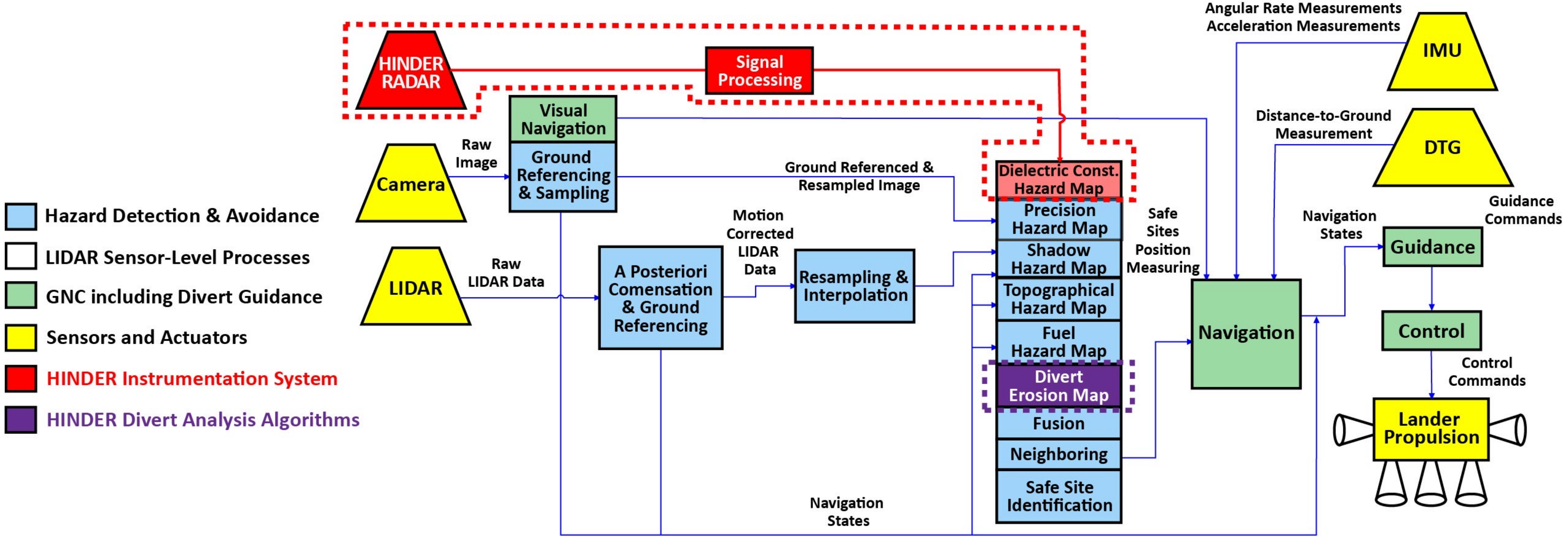
- Multitude of HDA sensors fuse data together
- Creates a more accurate model of landing terrain
- Fused map is used to select final landing site at lowest “cost”

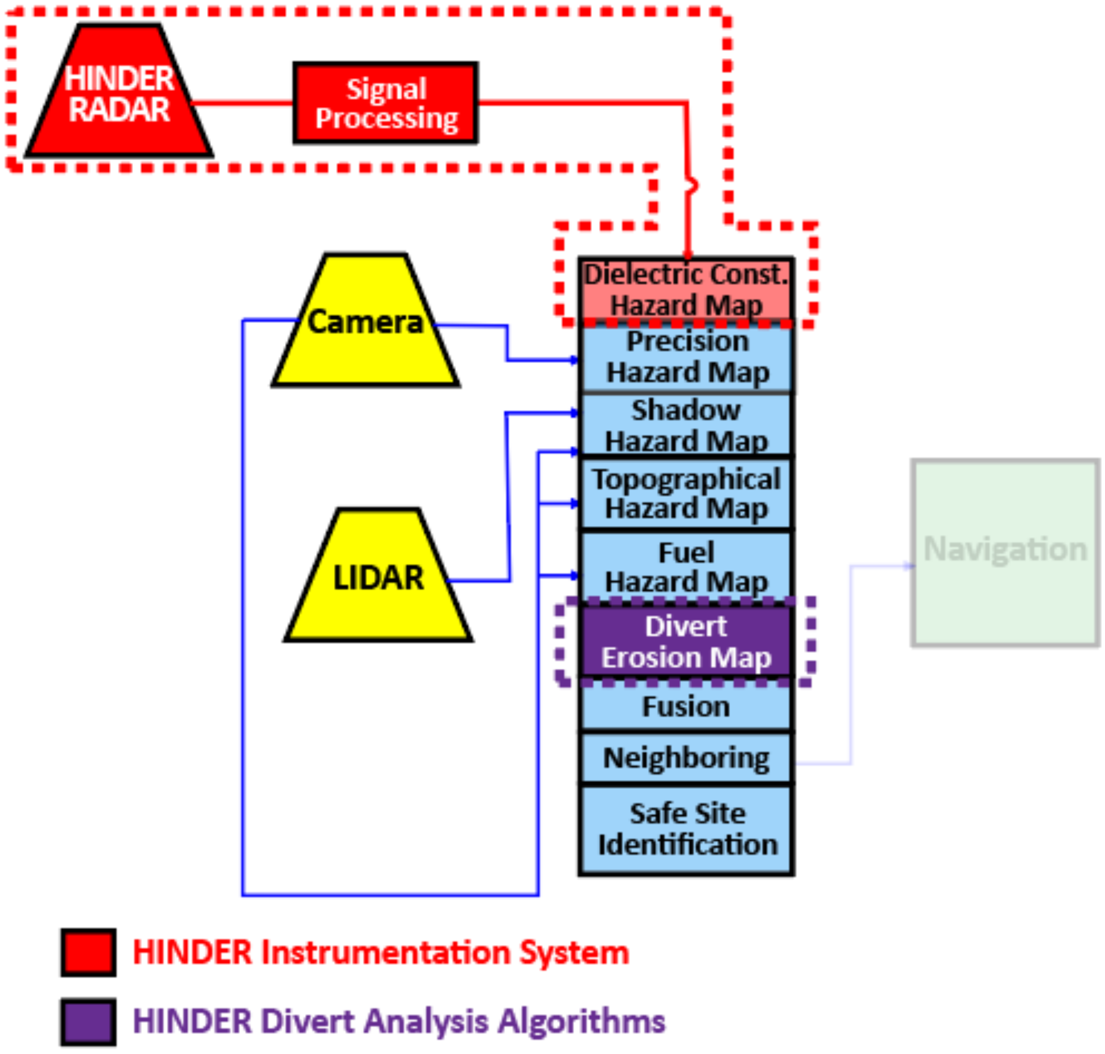


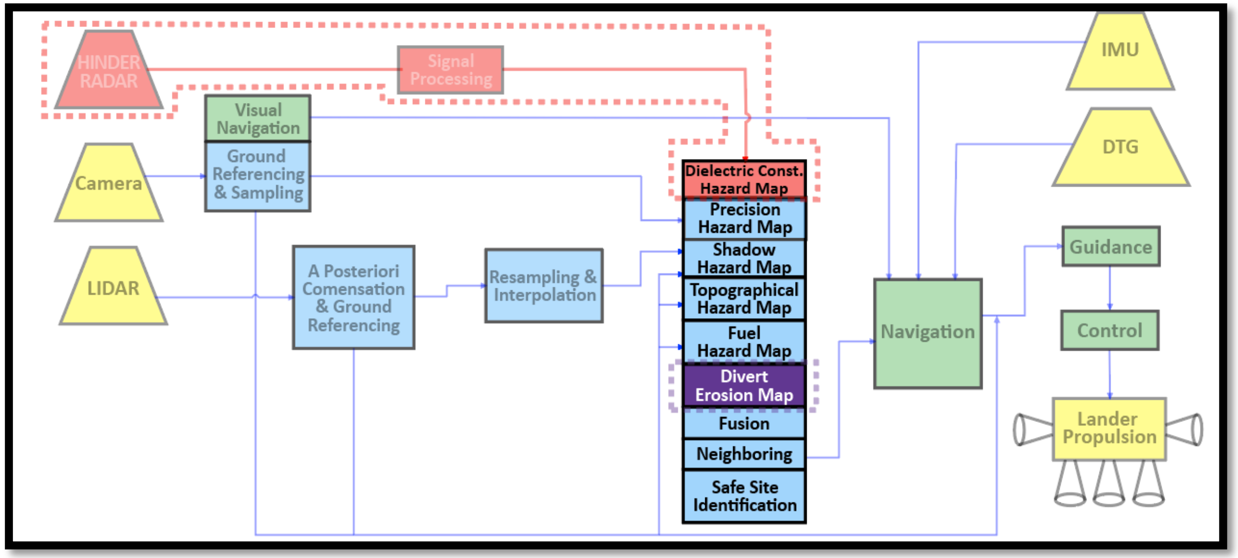






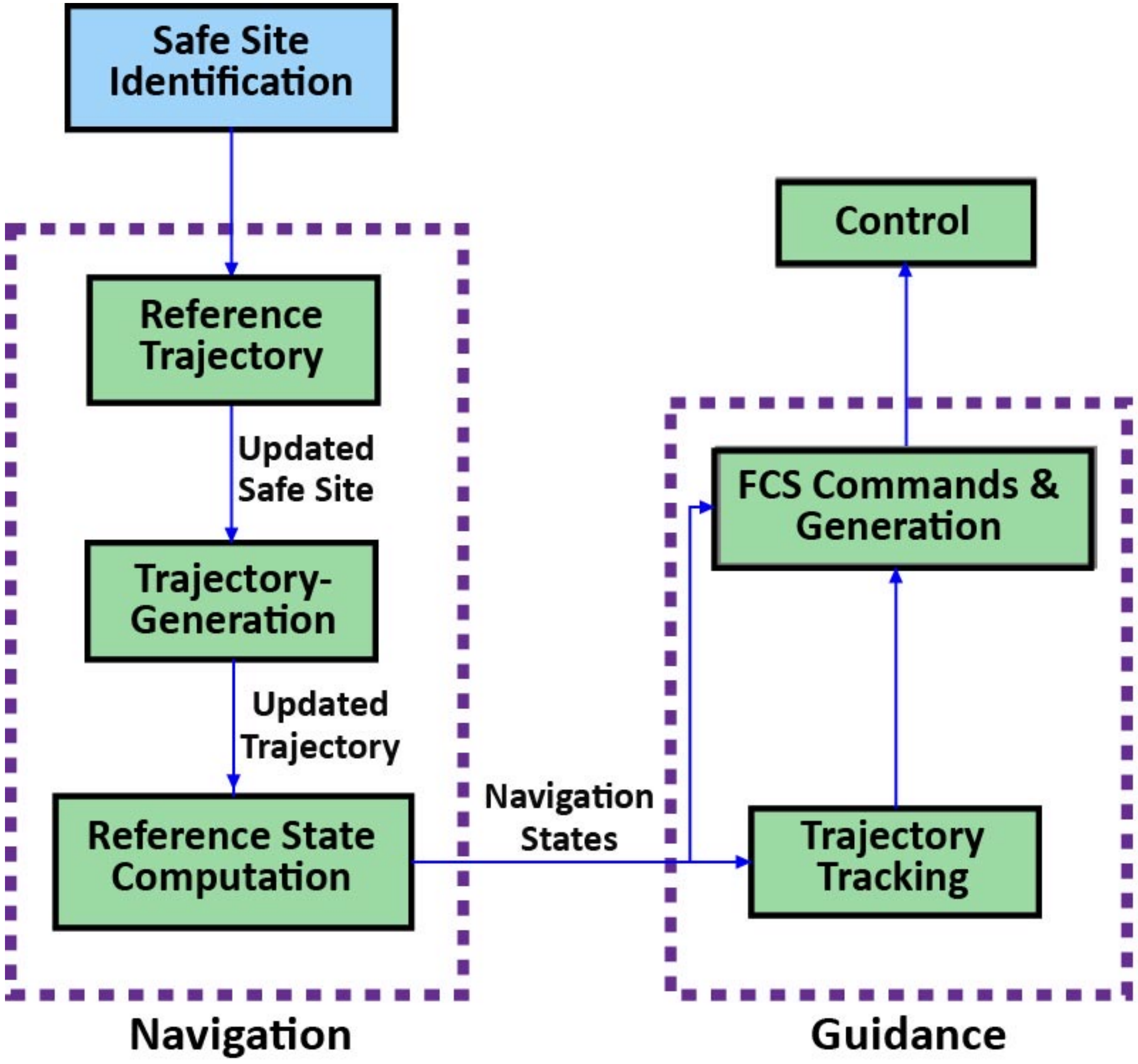

Hazard Detection & Avoidance
LIDAR Sensor-Level Processes
GNC including Divert Guidance
Sensors and Actuators
HINDER Instrumentation System
HINDER Divert Analysis Algorithms
HINDER RADAR
Signal Processing
Camera
Raw Image
Visual Navigation
Ground Referencing & Sampling
LIDAR
Raw LIDAR Data
A Posteriori Comensation & Ground Referencing
Motion Corrected LIDAR Data
Resampling & Interpolation
Ground Referenced & Resampled Image
Dielectric Const. Hazard Map
Precision Hazard Map
Shadow Hazard Map
Topographical Hazard Map
Fuel Hazard Map
Divert Erosion Map
Fusion
Neighboring
Safe Site Identification
Safe Sites Position Measuring
Navigation States
Angular Rate Measurements
Acceleration Measurements
IMU
Distance-to-Ground Measurement
DTG
Navigation
Navigation States
Guidance Commands
Guidance
Control
Control Commands
Lander Propulsion

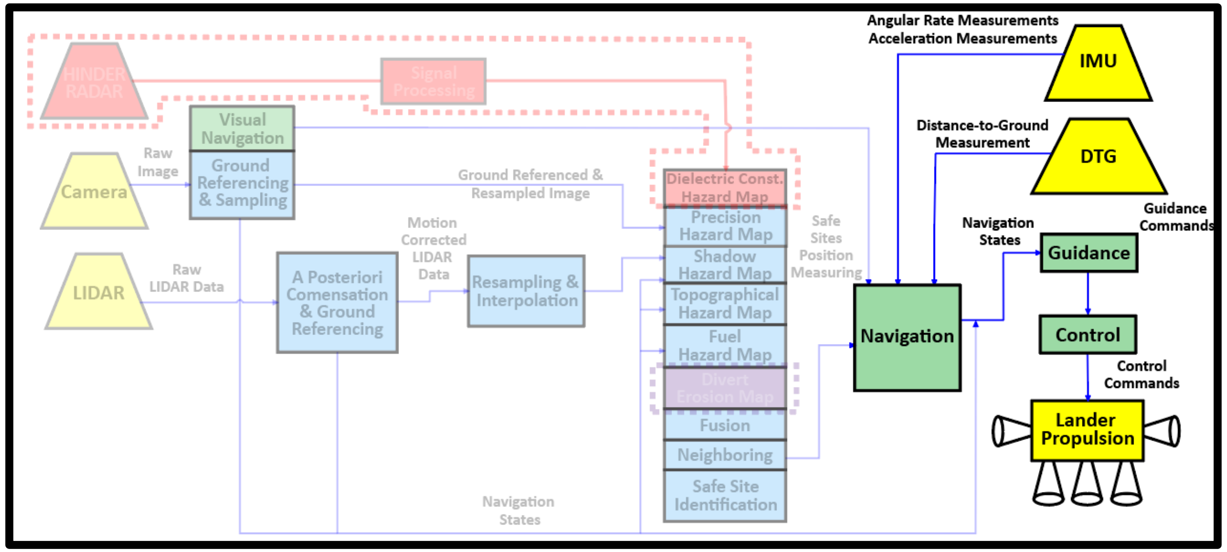




Hazard Map:

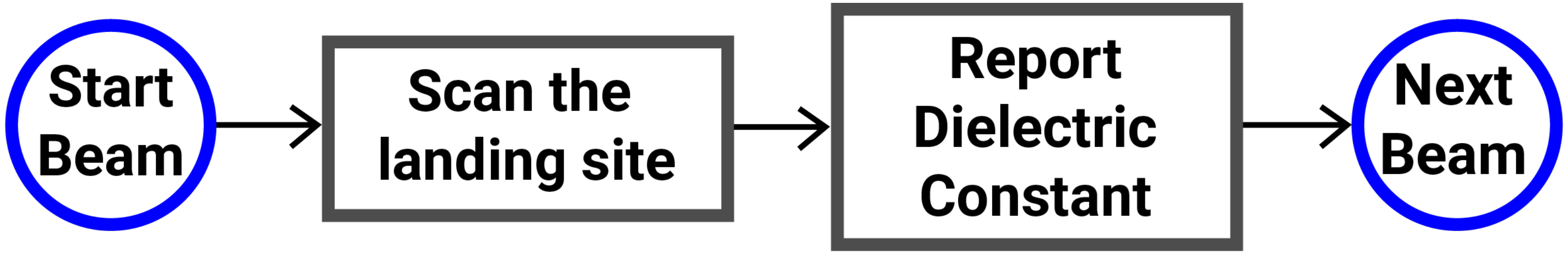
- HINDER integrates into the lander by adding dielectric constant hazard map and divert analysis map to existing hazard map suite in C&DH
- All hazard maps go through sensor fusion process to create fused hazard map





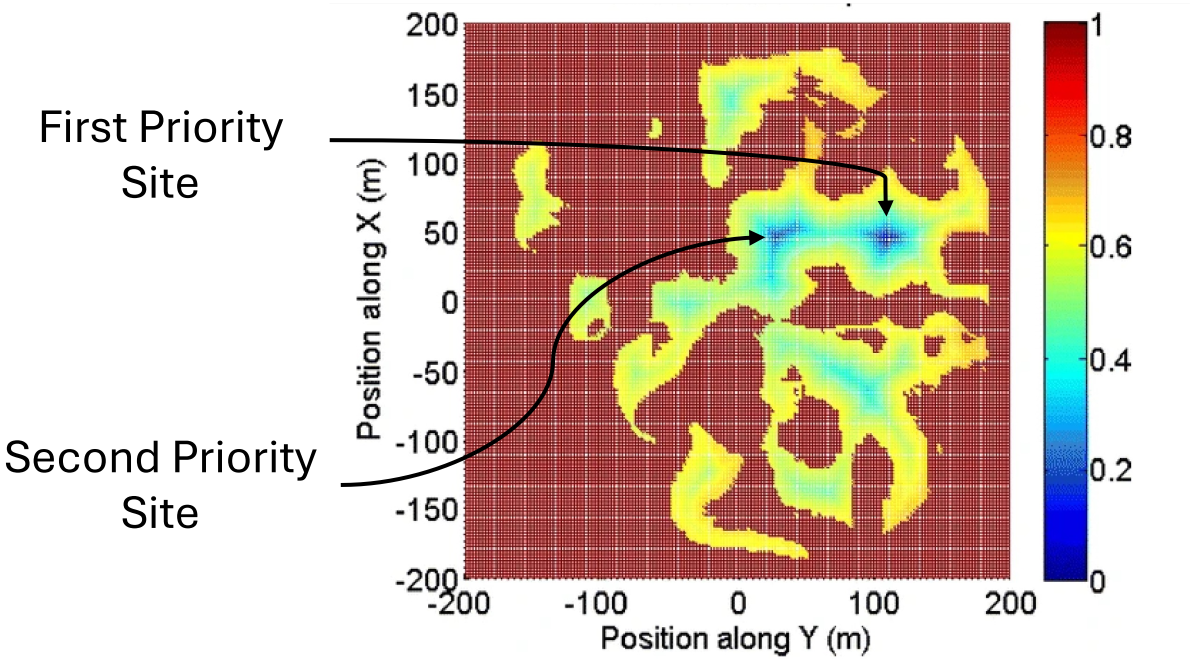
GNC SYSTEM:

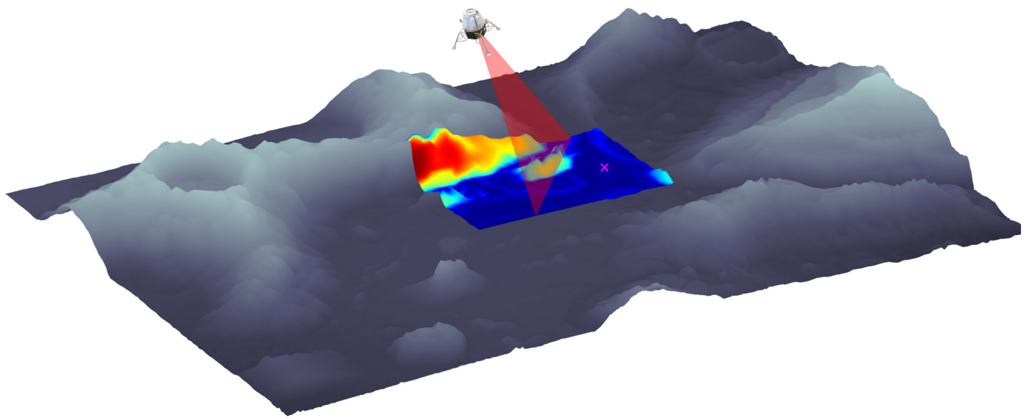
- Fused maps used for safe site identification.
- Data is used for guidance, navigation and control.
- HINDER is integrated with existing GNC system.



- HINDER's Hazard Avoidance & Detection initiates at ~490m altitude
  - Below 490m altitude, radar resolution is better than that of LRO
- Measurements taken continuously update a dielectric constant hazard map
  - Radar measurements verified accurate already

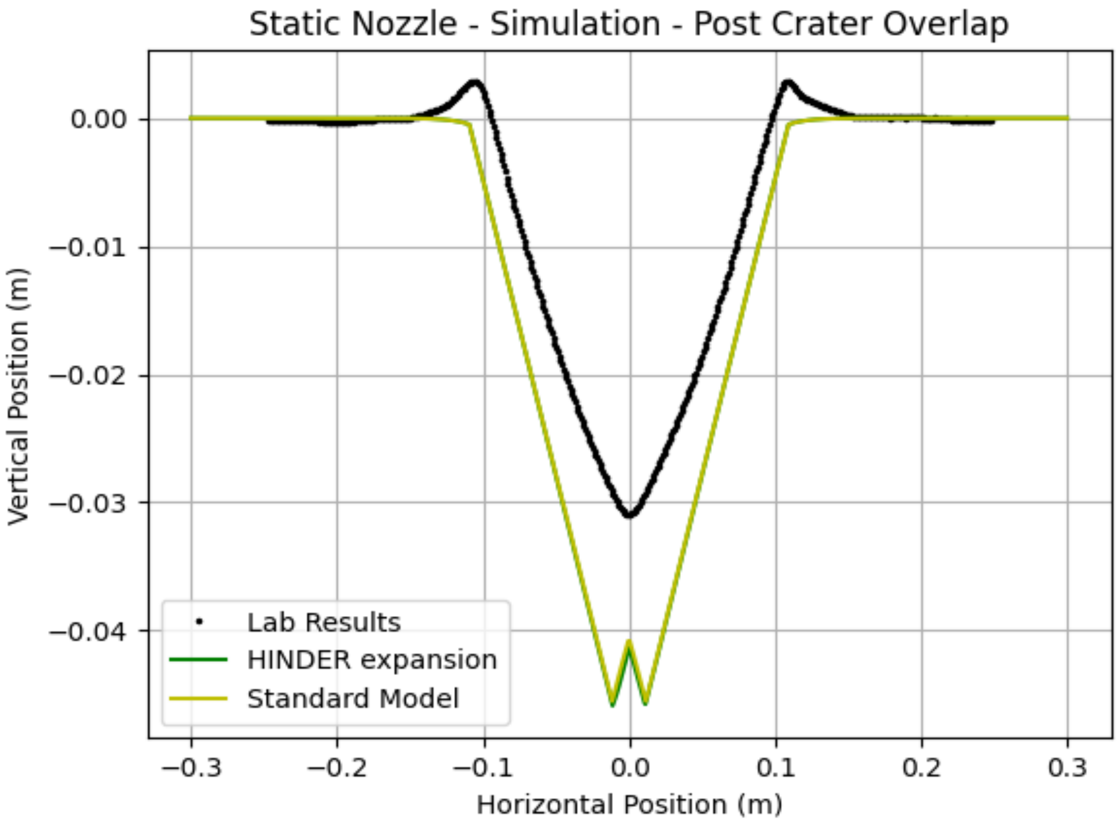
- Purpose: **Avoid hazards** and change target landing site
- Dielectric constant map inform of **site vulnerability** to PSI
- Gap: Map to inform of **path vulnerability** to PSI



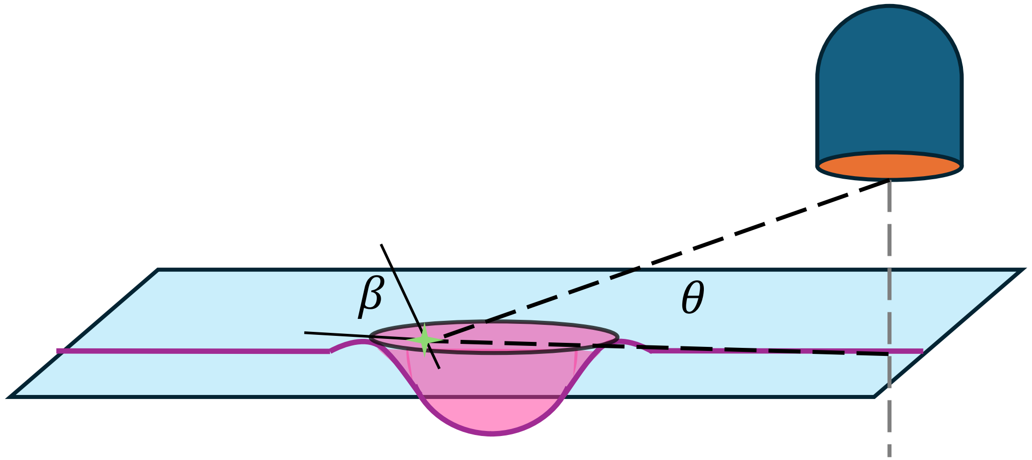


Validated Roberts' Model simulation with experimental cratering results in vacuum conducted at UIUC

a) UIUC PSI Testing Vacuum Chamber



b) Simulation vs Lab Results



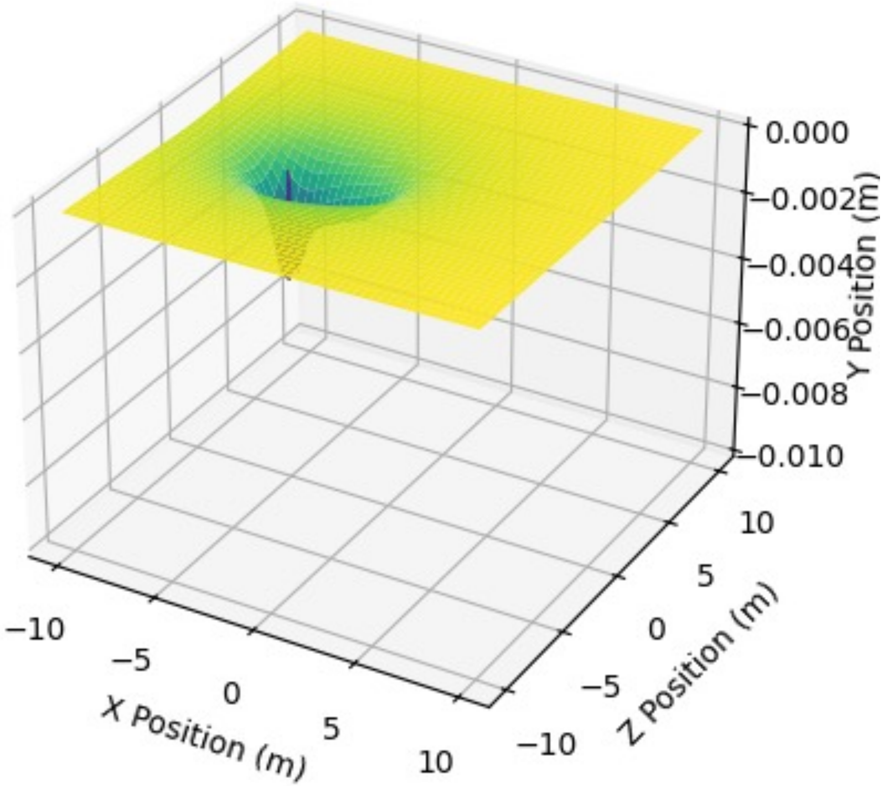
Use vector algebra to obtain values relative to nozzle for Roberts' Model. Need to find β *and* θ

Where β is the local slope in the plane intersecting the nozzle centerline and point i.e.

$$\tan\beta = \frac{dy}{dr} \approx \frac{|\overrightarrow{\Delta y}|}{|\overrightarrow{\Delta r}|}$$

And θ is the azimuth angle which changes as the nozzle moves

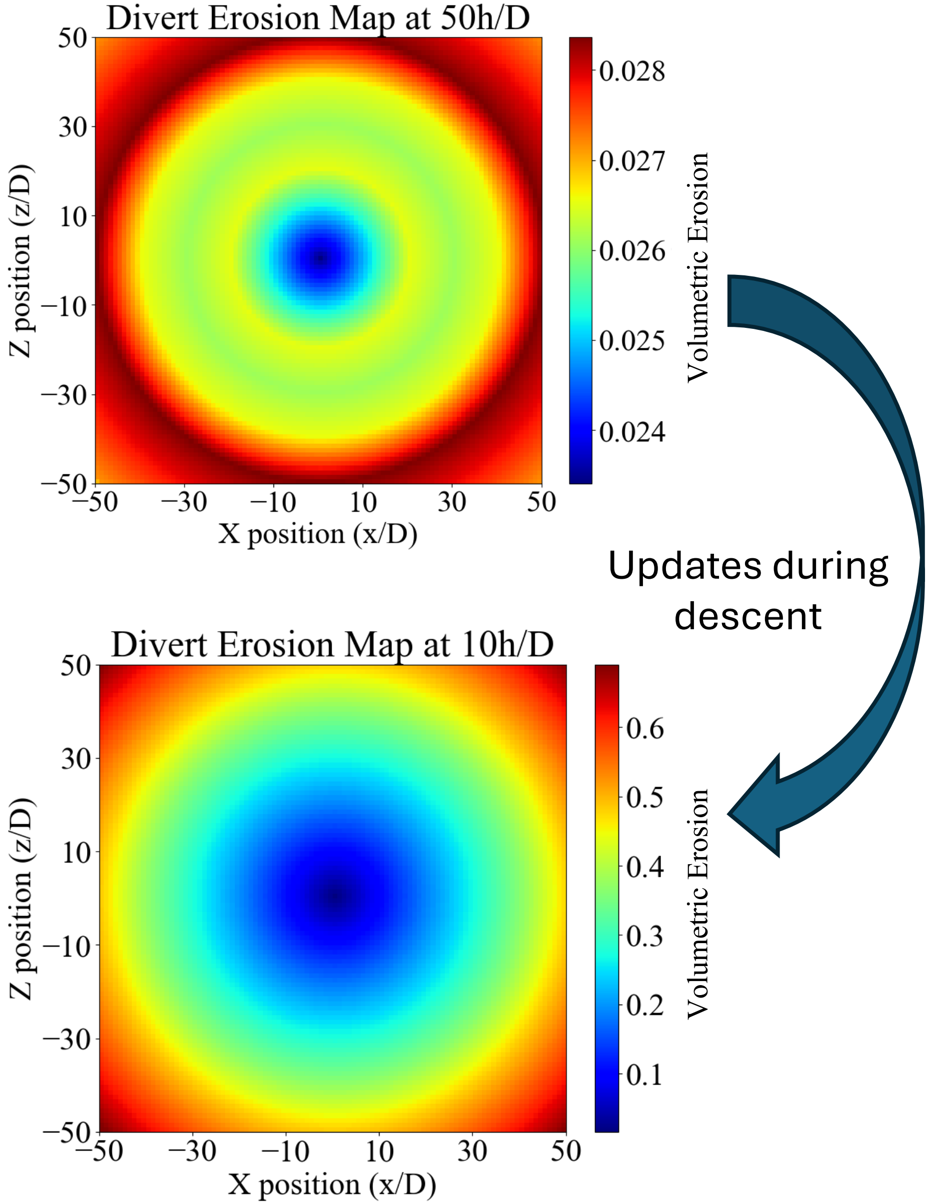
Simulation Demonstration



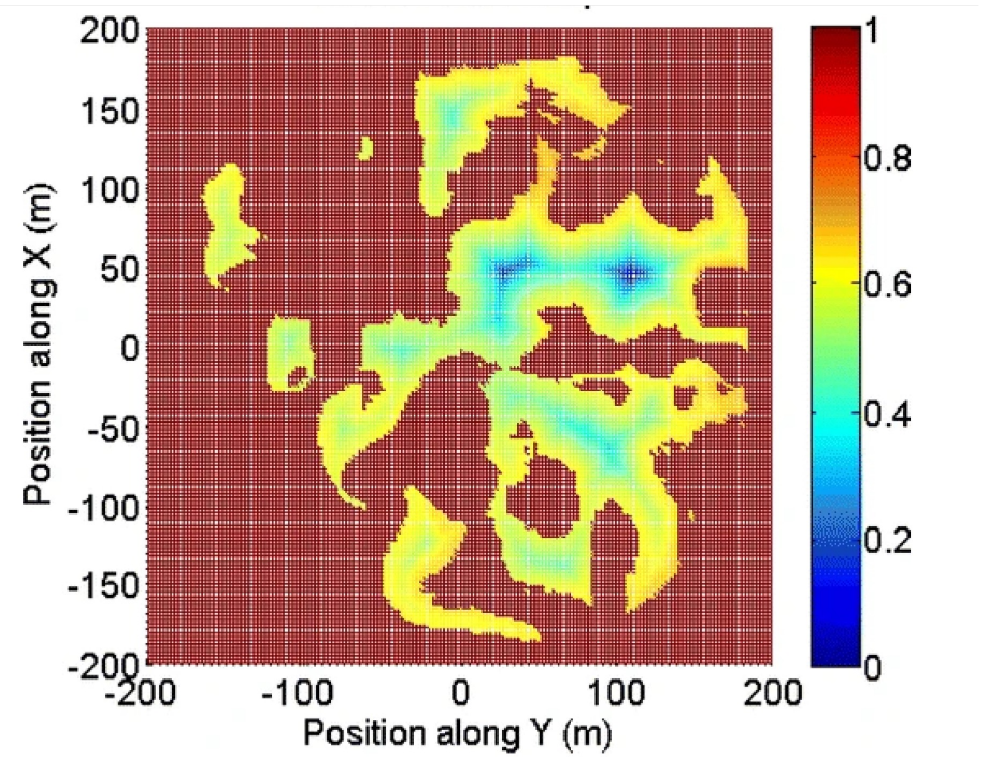
Moving nozzle for 0.5s then Static for 0.5s

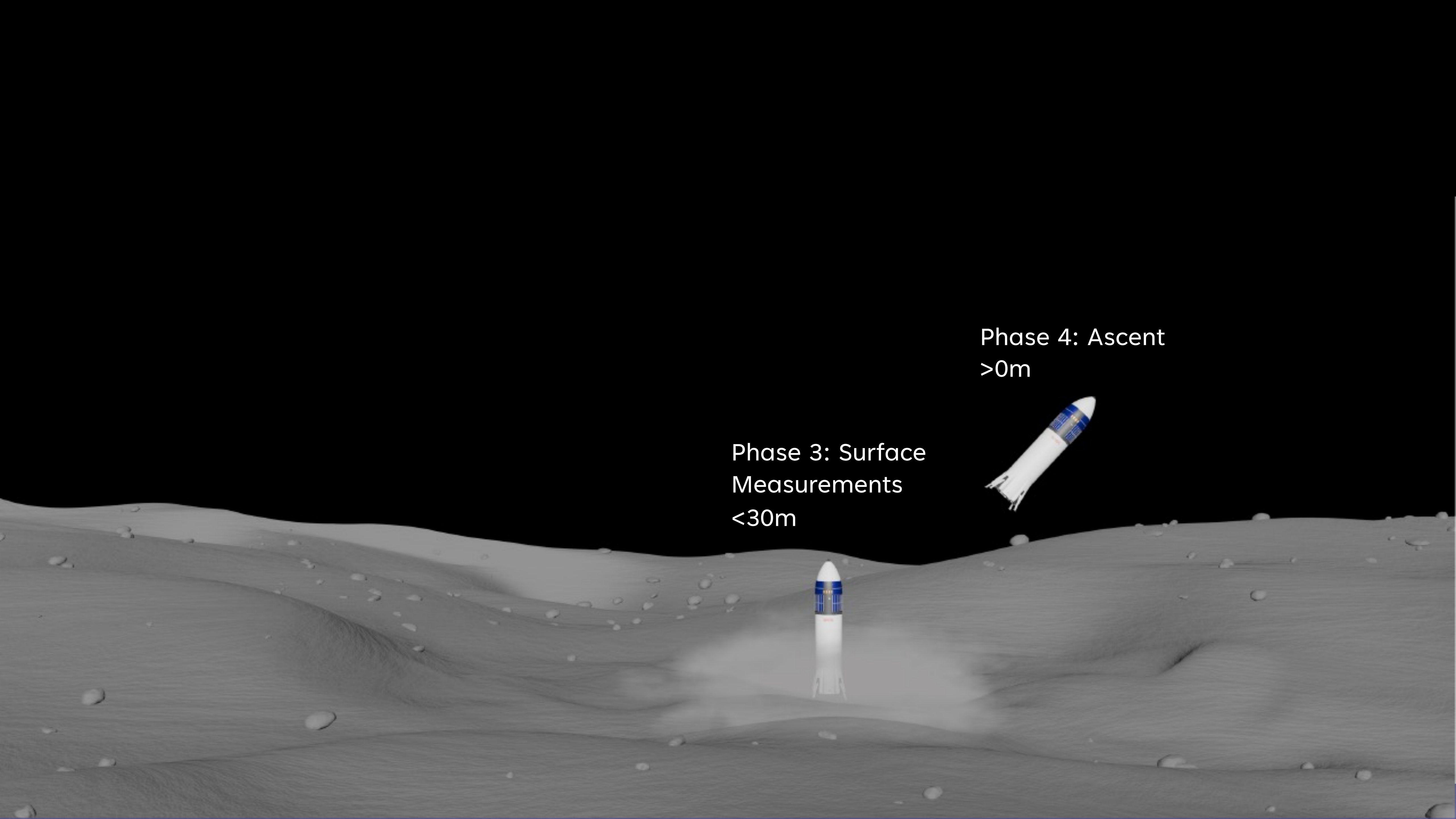
EROSION HAZARD MAP DEMO

- Developed erosion hazard map simulation tool using Roberts' Model
- Calculates and updates map of total volumetric erosion for each landing site over the course of descent
  - Magnitude and distribution of erosion depend on lander height and surface characteristics
  - Continuously informs lander of which landing sites are most optimal
- Can be expanded upon with increased accuracy using more advanced software
  - POST2
  - NASA MSFC's Loci-CHEM GGFS tool

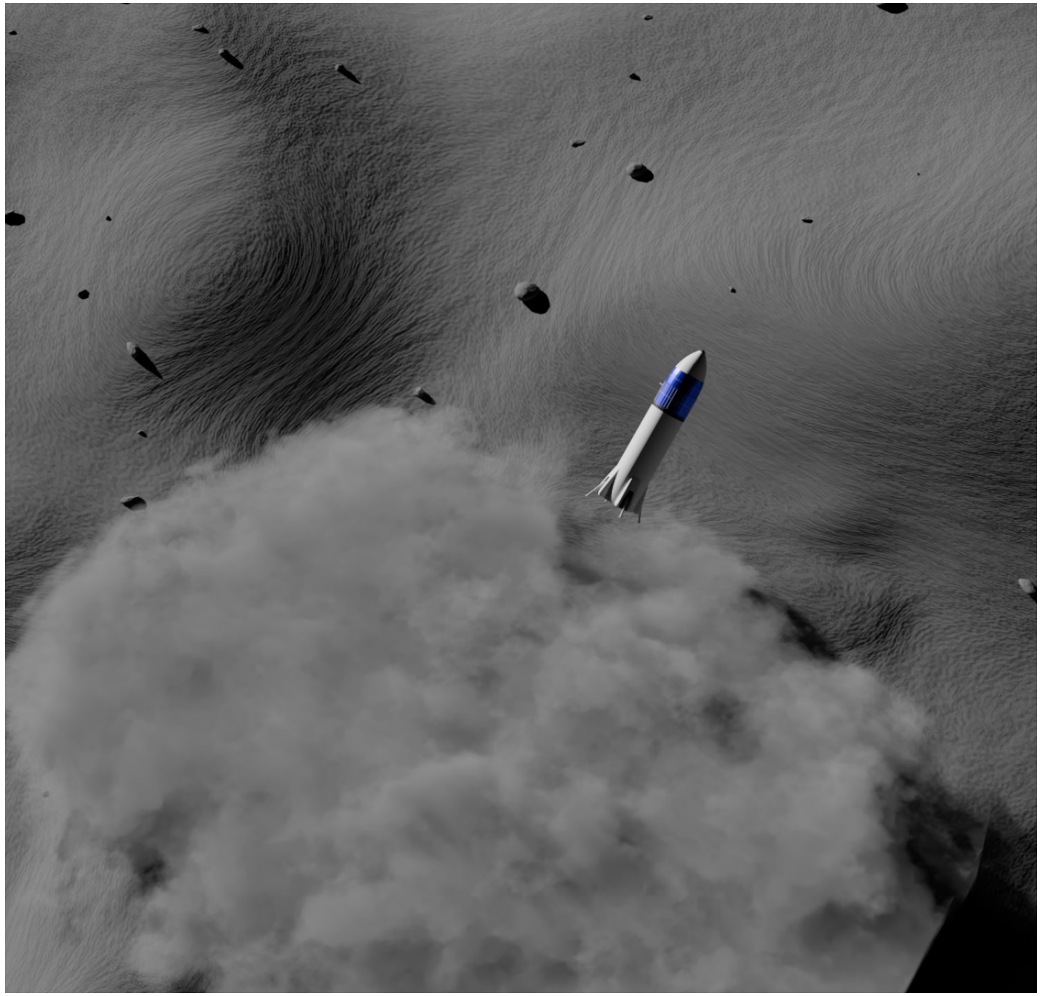


- Begins at ~490m altitude
- Bulk density and divert induced erosion map are fed into the VPU to form a single fused hazard map
  - Demonstrated divert induced hazard map as a proof of concept using rapid modelling
- The final fused map is used to select a landing site and guides the lander using existing GNC systems

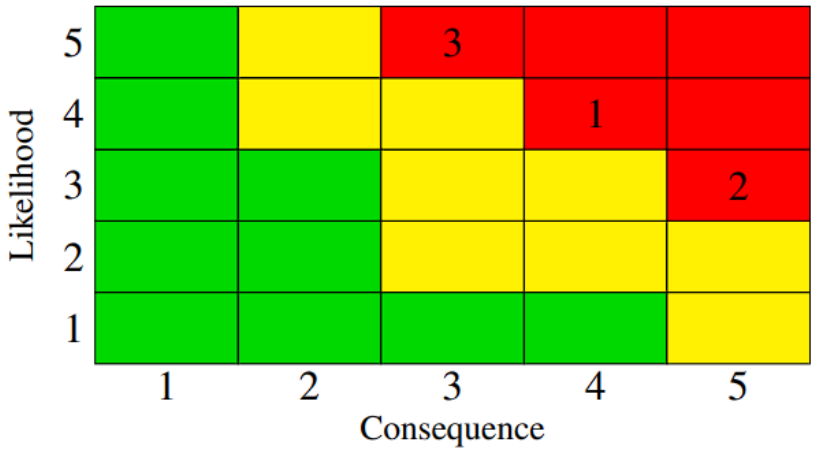


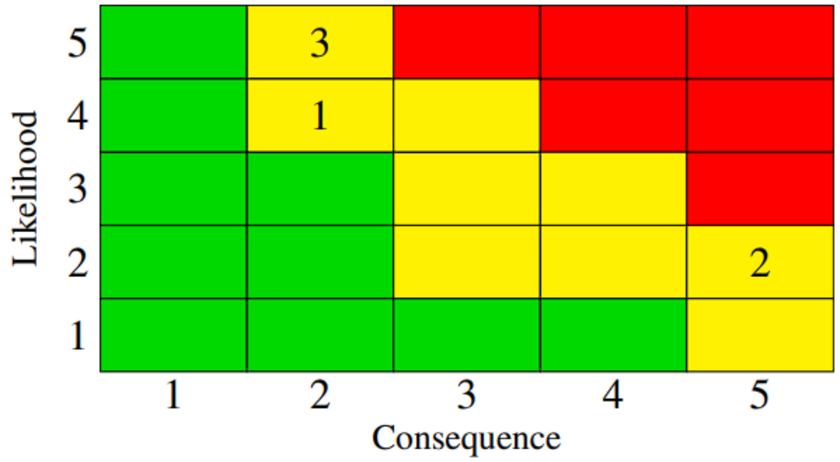

Phase 4: Ascent
>0m
Phase 3: Surface
Measurements
<30m

- Additional data collection as opportunity provides
  - Instrument may be vulnerable to damage
- Measure PSI impacts on local geology
  - Before and after comparisons post-flight
  - Compare measurements on the ground to in-situ measurements by crew
- Small area of focus
  - Area of maximum impact is known
  - Revisit potential on ascent for points measured on descent



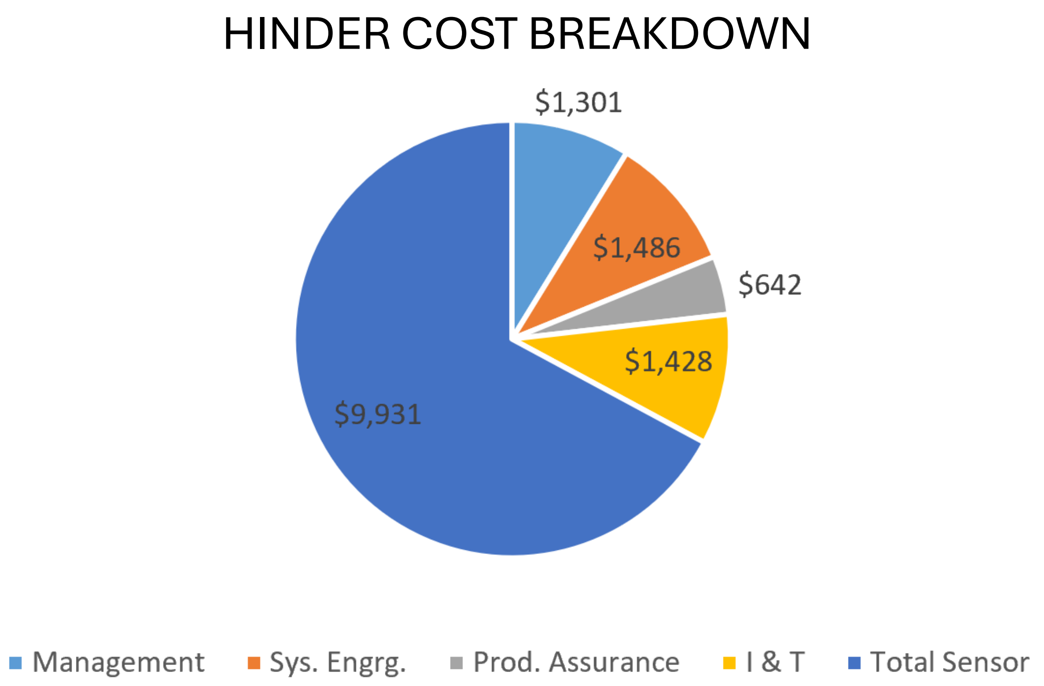
Risk Informed Decision Making

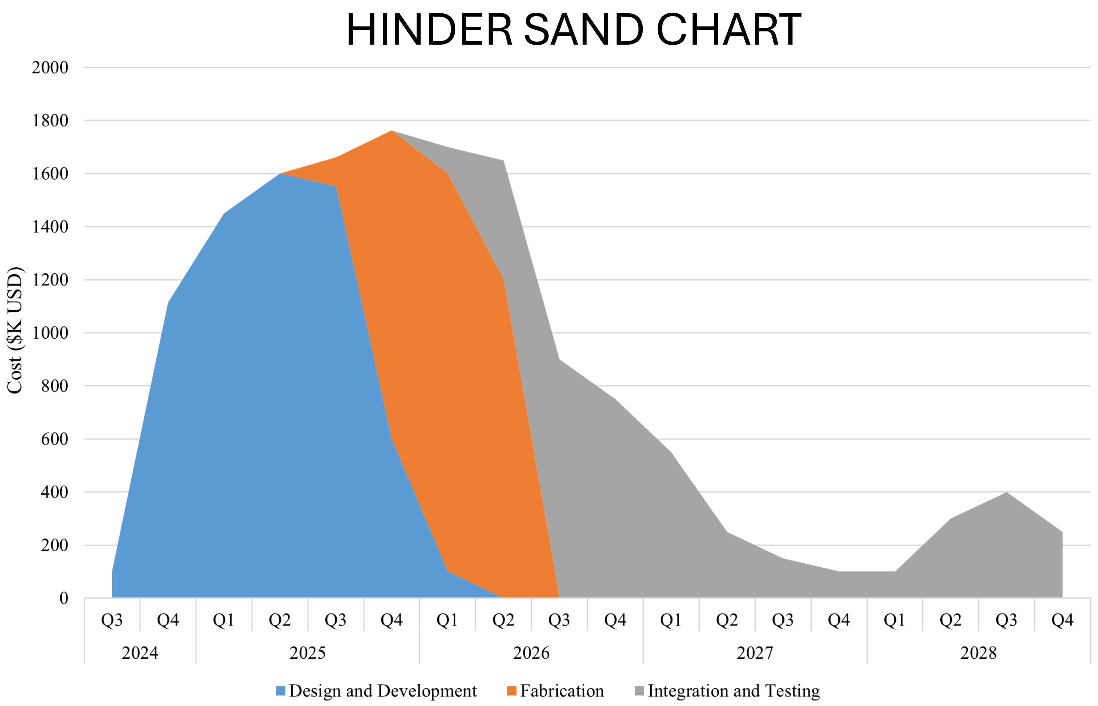


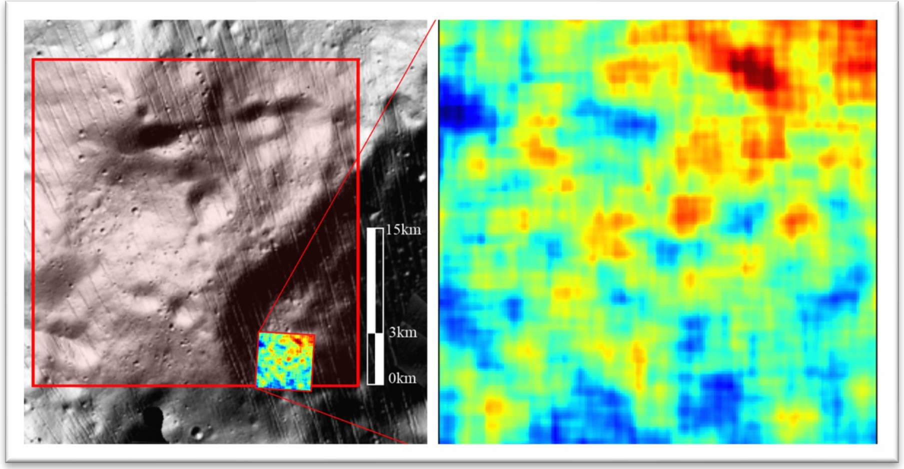


ID	Risk	Mitigation	Design Impact
1	Funding reduced	Flexible tiered development approach	Development on different phases are done in parallel and independently
2	Radio interference	Sensor uses narrow beam K-band radar	Antenna is designed based on a frequency band, subject to change with further development
3	Testing Failure	Can operate in passive data collection mode	The first implementation of the radar instrument will be fully separated from the flight controls

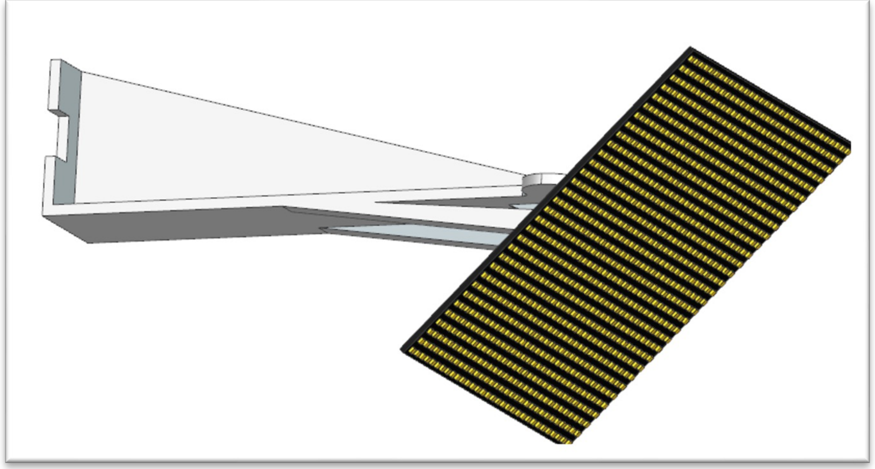
- Two estimates are created using existing Nasa tools
  - Uses mass and power-driven cost estimation relationships (CERs) based on heritage instrument development
- Lower bound: 1.36 million USD
- Upper bound: 12.78 million USD



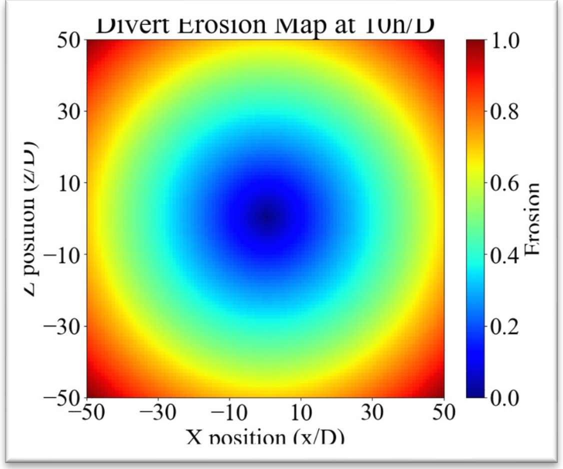




Using existing lunar data to select a target landing site based on bulk density



Using an active phased array radar that measures dielectric constant to avoid high PSI susceptible sites



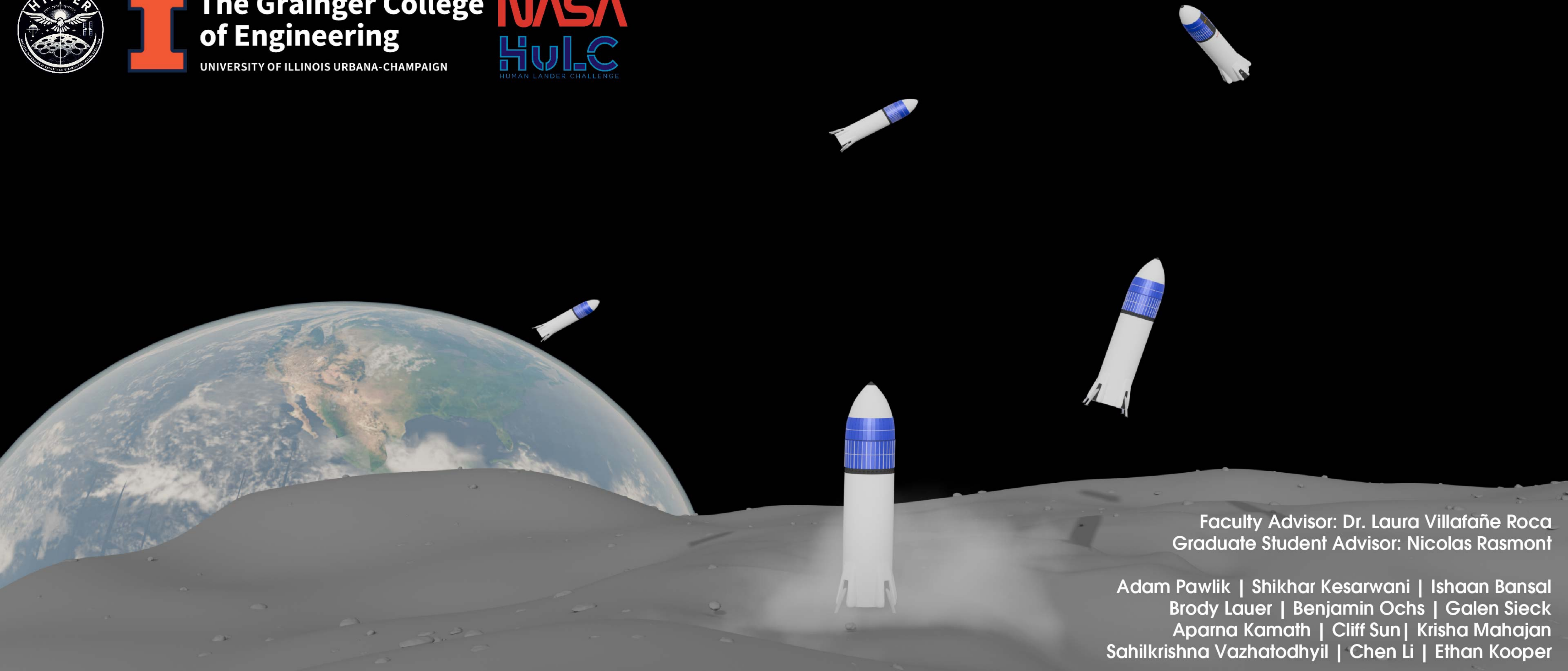
Adding fused hazard maps to conduct diverts to advantageous landing sites

HINDER

Holistic Integration of Navigational Dynamics for Erosion Reduction

The Grainger College of Engineering
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

NASA
HuLC
HUMAN LANDER CHALLENGE



Faculty Advisor: Dr. Laura Villafañe Roca
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Brody Lauer | Benjamin Ochs | Galen Sieck
Aparna Kamath | Cliff Sun| Krisha Mahajan
Sahilkrishna Vazhatodhyil | Chen Li | Ethan Kooper

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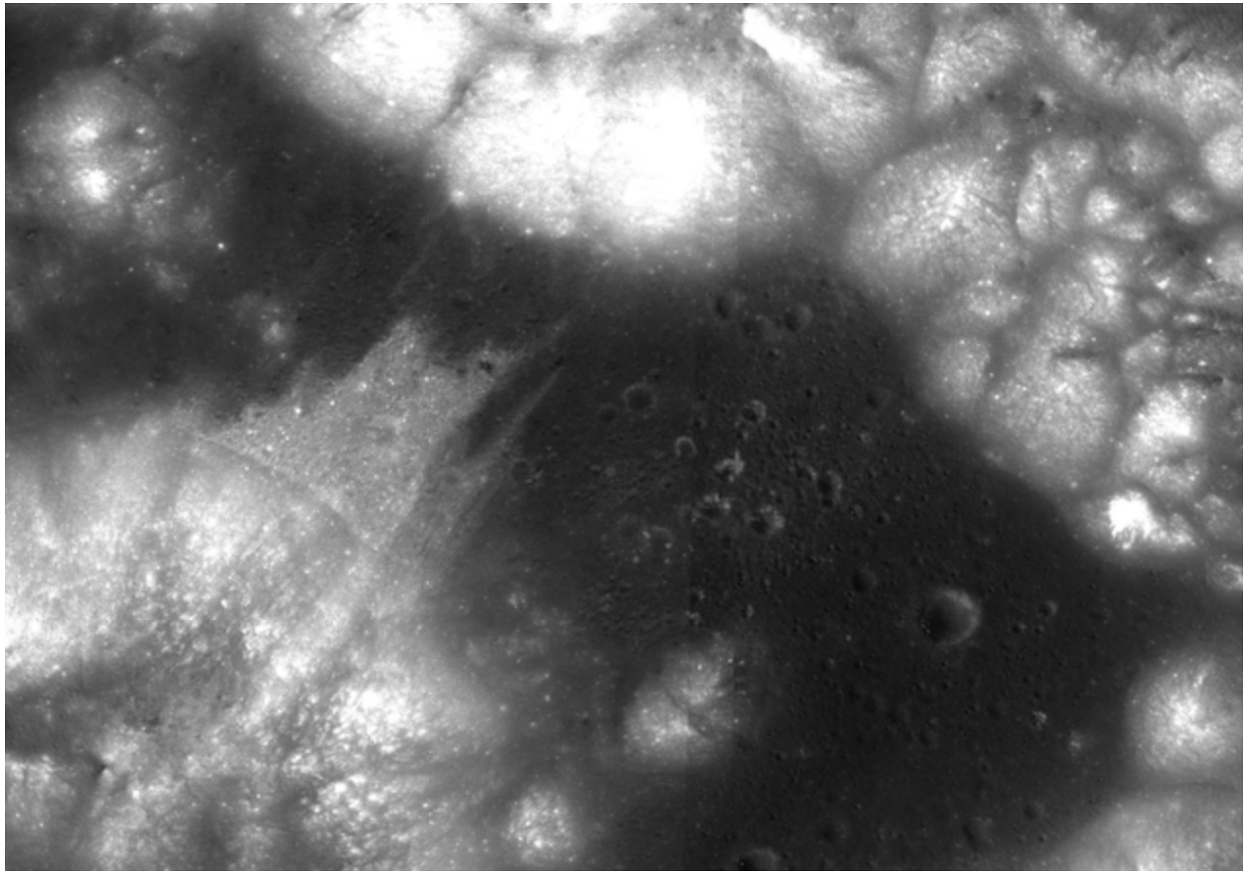
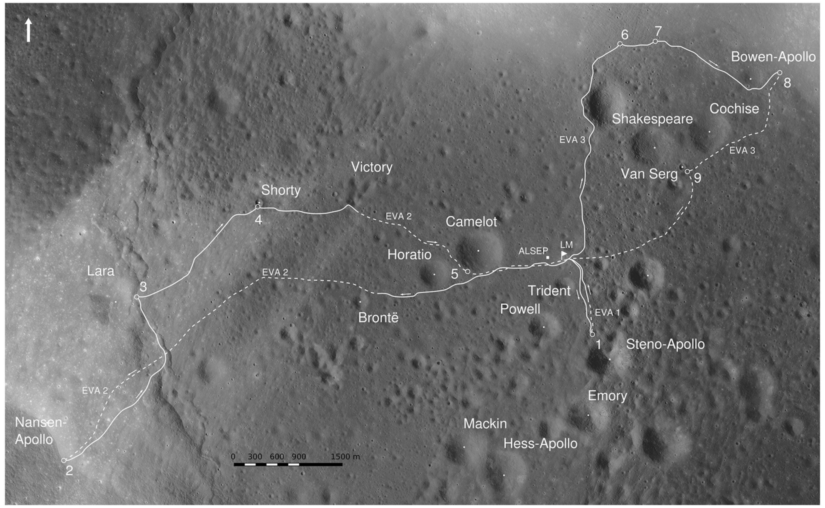
Apollo 17 Landing Site and Area of Activity



Lunar Reconnaissance Orbiter (LRO) Narrow Angle Camera (NAC) mosaic



Earth and Space Science, Volume: 6, Issue: 1, Pages: 59-95, First published: 07 December 2018, DOI: (10.1029/2018EA000408)

Apollo 17 surface measurements allow remote estimates to be evaluated

Erosion Rate Models

- Robert's and Metzger's models are equations used to estimate soil erosion rate
- Both models can be condensed to functions of soil parameters
- Erosion rate can be minimized by targeting the site with the highest soil bulk density

Roberts' Model

$$\frac{\partial y}{\partial t} = \frac{2(\tau - \tau^*)}{a \cdot u \cdot \underbrace{\boldsymbol{\sigma} \cdot \boldsymbol{c}}_{\boldsymbol{\rho_b}} \cdot \cos(\beta)}$$

$$\frac{\partial y}{\partial t} = f(D, \rho_b, A_{coh}, \tau_{coh}, \alpha)$$

D = Particle Size
ρ_b = Bulk Density
A_{coh} = Cohesion parameter
τ_{coh} = Cohesive stress
α = Internal friction angle

Metzger's Model

$$\dot{V} = \frac{\dot{M}}{\rho_b} = C \frac{\rho_e v_e^2 A_e}{\boldsymbol{\rho_b} g \beta \langle D \rangle + \alpha}$$

$$\dot{V} = f(\rho_b, D, \alpha)$$

ρ_b = Bulk Density
D = Avg. Particle Diameter
α = Cohesive Energy

- High TRL remote sensing capabilities (green)
- Low TRL remote sensing capabilities (yellow)
- No remote sensing capabilities (red)

ANISOTROPY MODEL

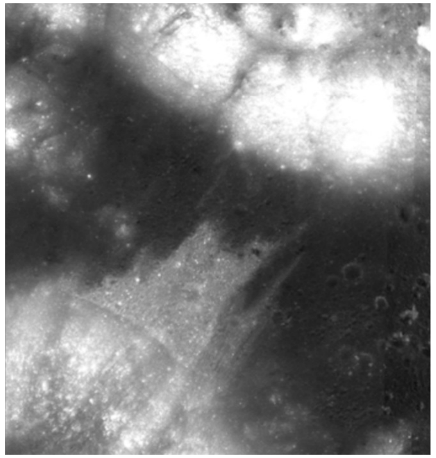
- On analysis, this model shows inverse trend of ground data
  - Demonstrates general map characteristics and verification process
  - Original model was verified on the average value, not local trends

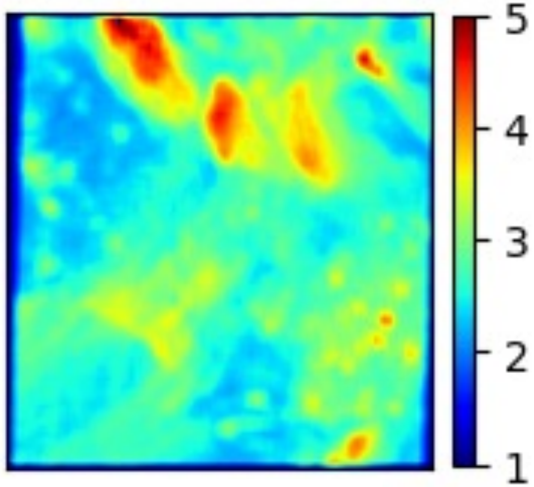
$$\sigma_0 = {S_1}^2 + {S_2}^2 - \frac{1}{2}{S_3}^2 + \frac{1}{2}{S_4}^2$$

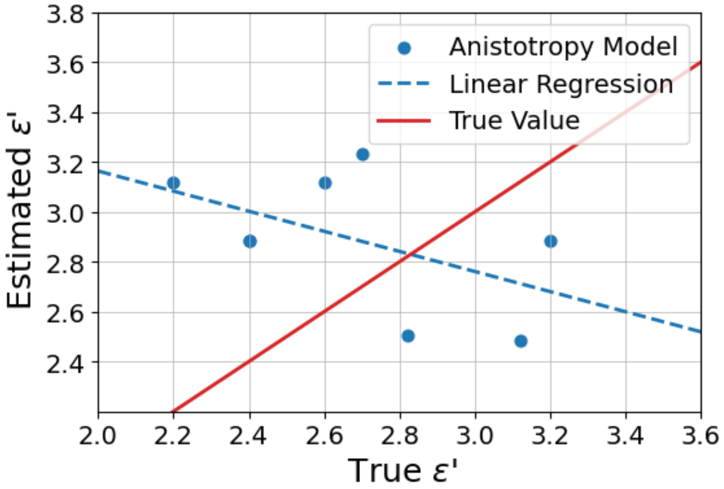
$$A = \frac{2}{2 + \sqrt{30|\sigma_0|}}$$

$$\varepsilon' = \frac{1}{A} + \frac{1}{2}\left|\frac{1}{A} - 2A + 1\right|$$

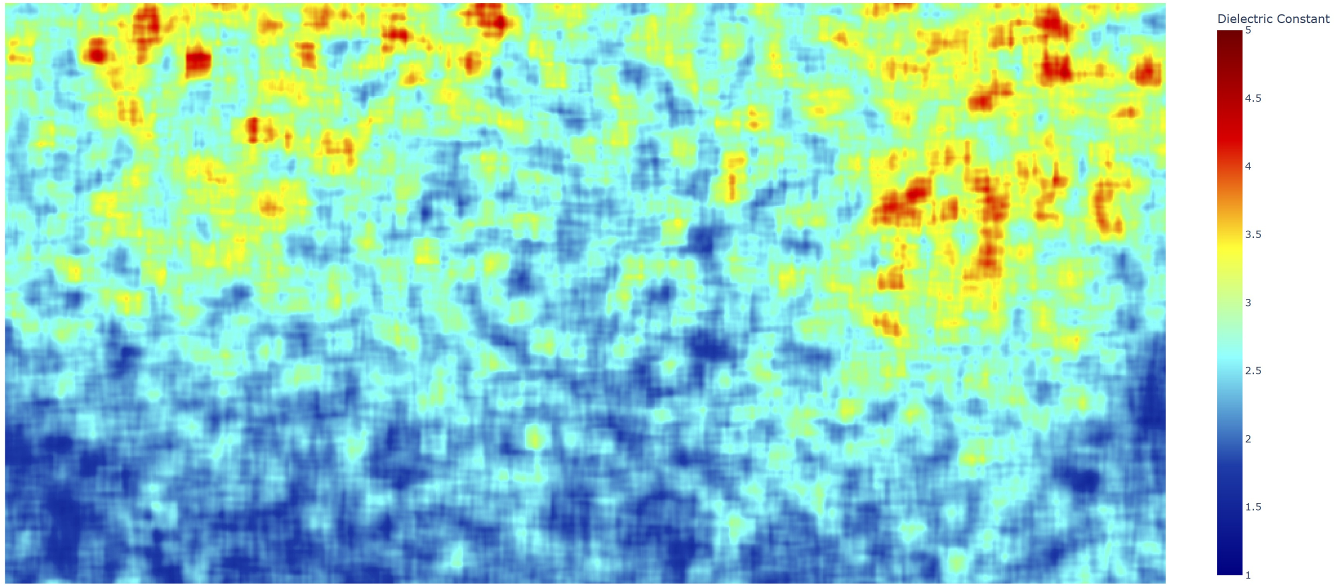
Apollo 17 Site Analysis



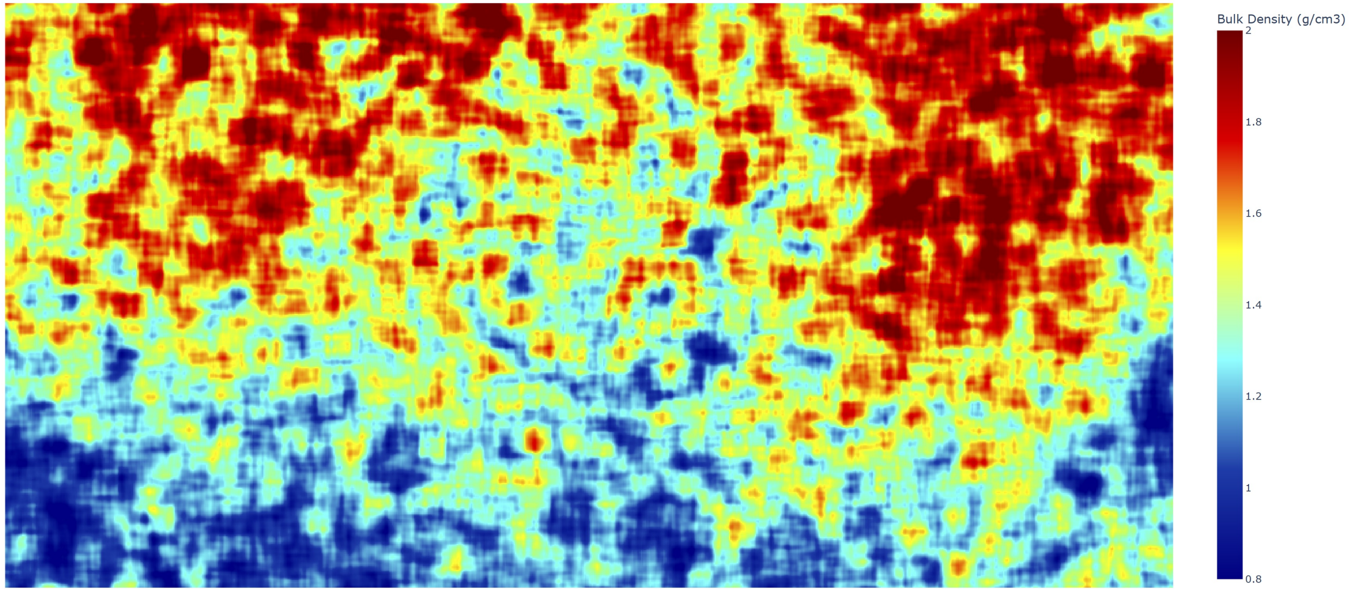




Models which do not match ground data can be avoided



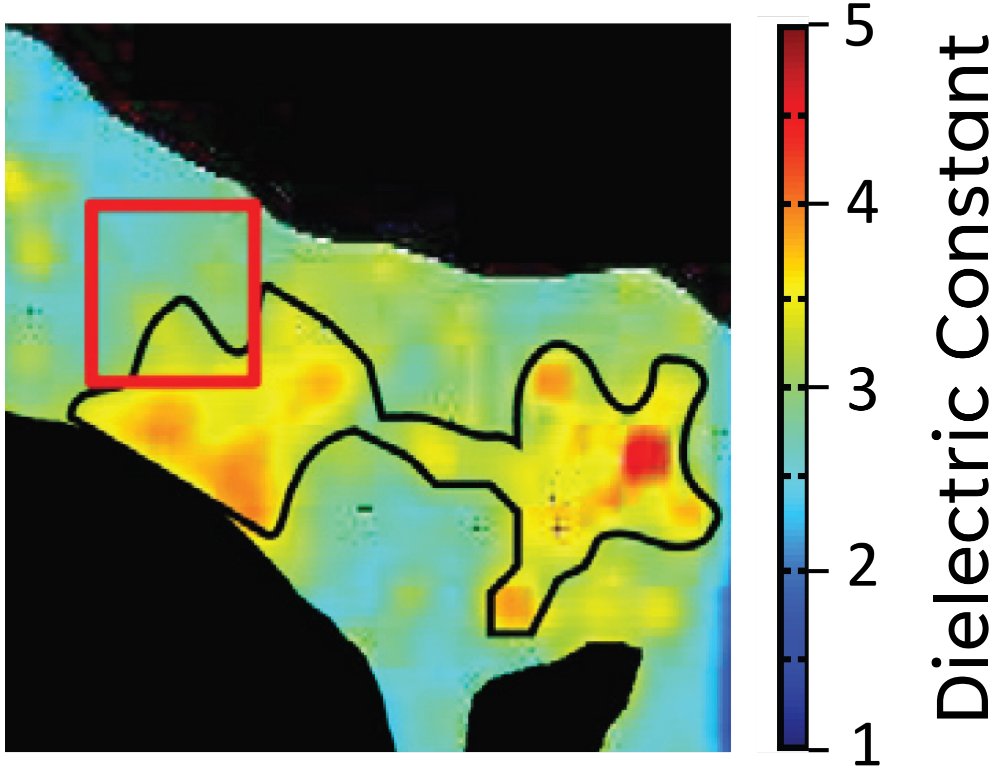
Dielectric Constant



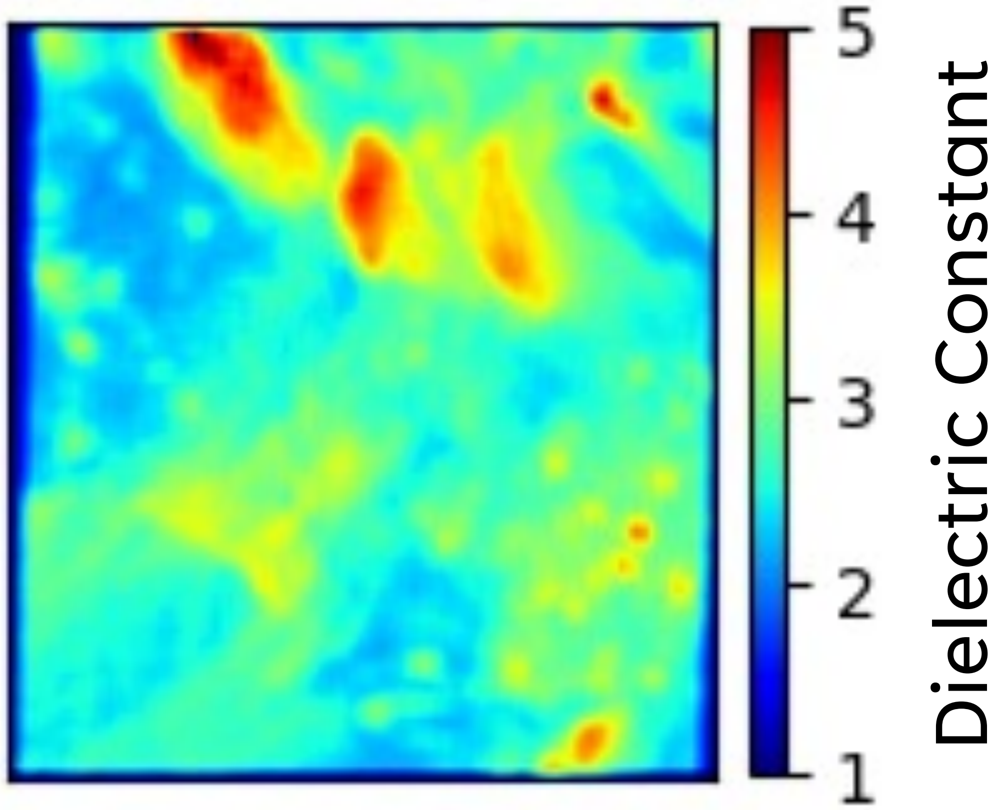
Bulk Density

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Bhattacharya et al. (2015) [18]



HINDER Anisotropy Model



	Phased Array Synthetic Aperture	Phased Array (PA) Real Aperture	Single Synthetic Aperture	Single Real Aperture
[Example]	PA-SAR	PA-Scatterometry	Ground Penetrating Radar	Scatterometry
Beam Steering	Digital	Digital	Mechanical	Mechanical
Power Consumption	High	Medium	Low	Low
TRL	8	8	6-9	7

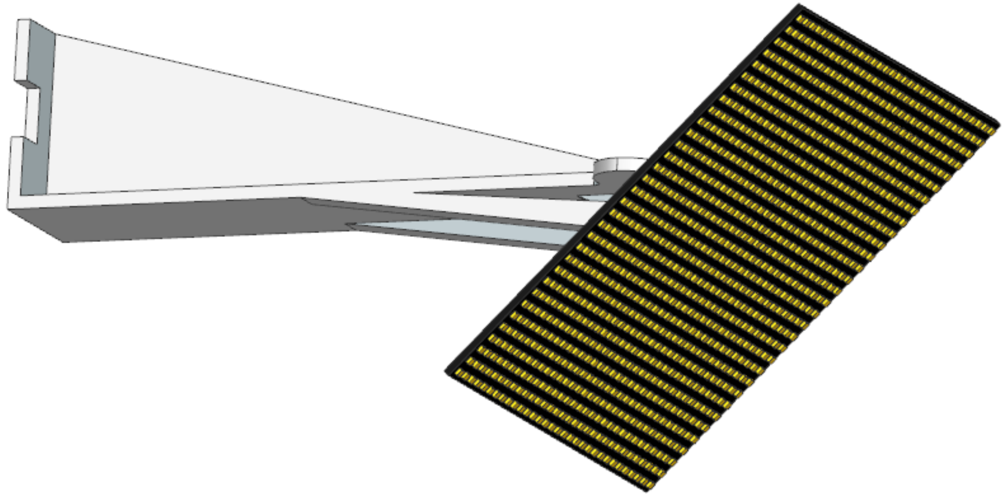
A Phased Array Scatterometry radar operating mode is selected

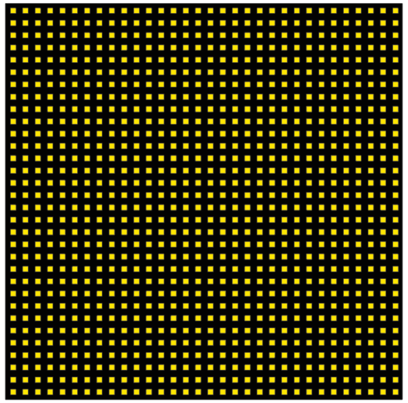
	Low Frequency Radar	High Frequency Radar	Optical/Infrared Laser
Frequency	2-30 GHz	30-300 GHz	0.4-400 THz
Wavelength Scale	cm	mm	µm
Resolution	Low	Medium	High
Ground/Dust Penetration	High	Low/None	None
Transmitter Size	High	Medium	Low

A relatively low-frequency band is selected for high ground and dust penetration

Table 2: Key Instrument Parameters

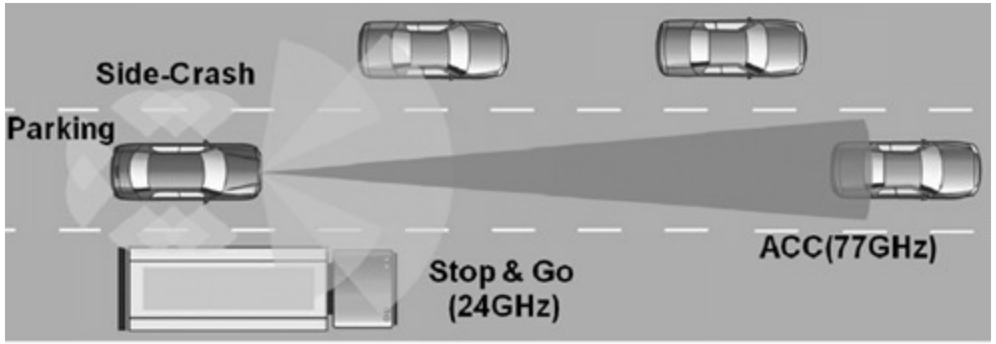
Parameter	Value
Frequency	24 GHz (K-Band)
Antenna Size	0.36 x 0.36m (14 x 14in)
Beam Steering	Active Electronically Scanning Array (AESA)
Array Beamwidth	3.1°-3.5° (0°-30° Beam Direction)
Number of TX/RX Elements	1024
Total Power Consumption (with Avionics)	20W
Pulse Width	1ns
Transmit Power	115 dBm



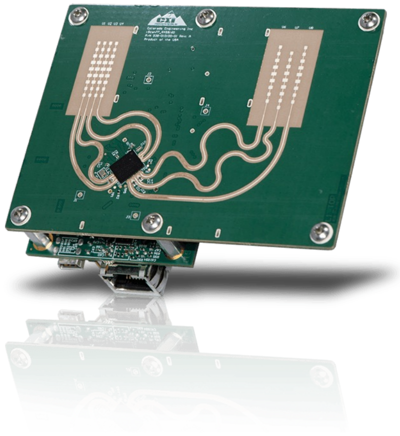


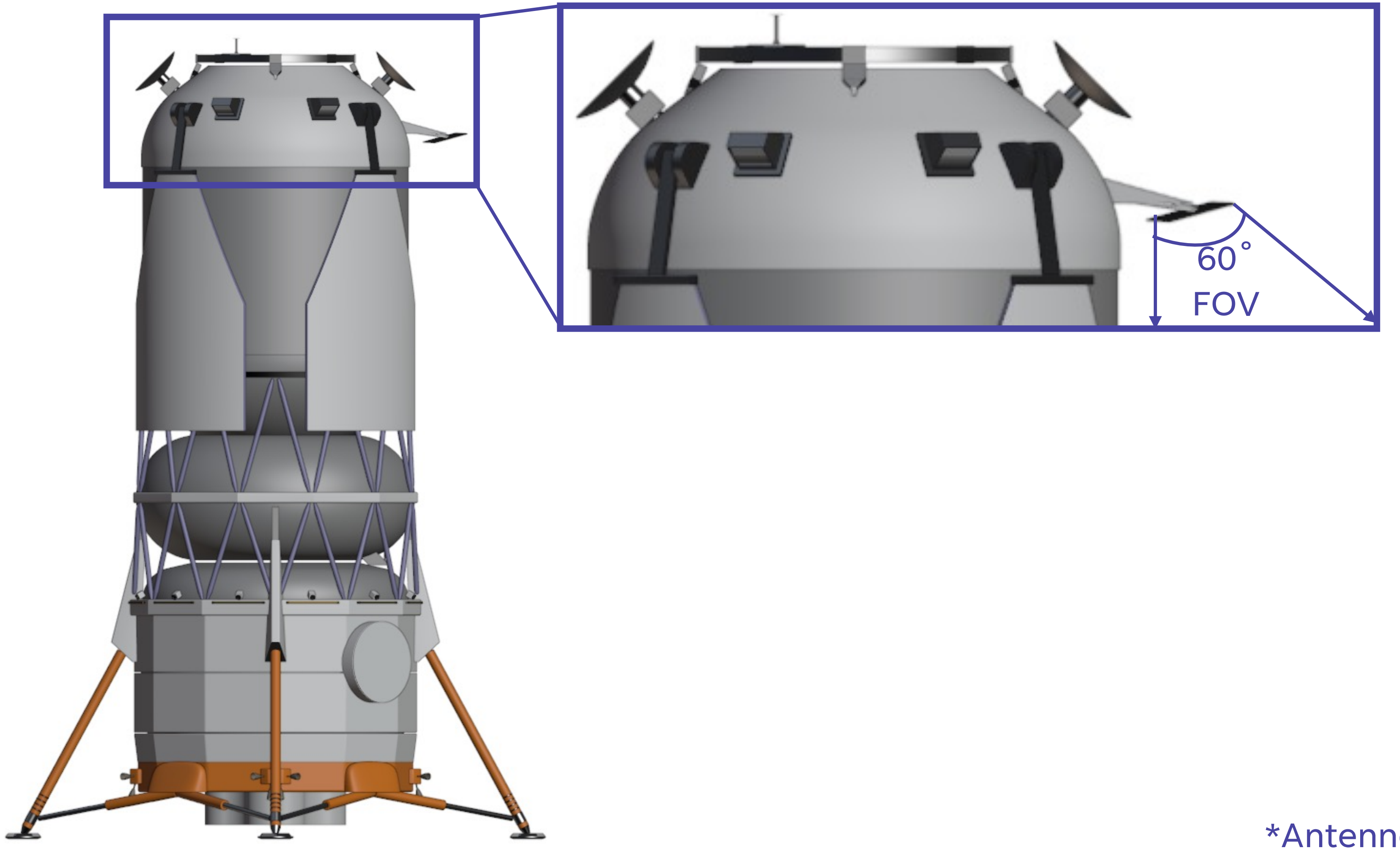
Antenna Closeup
- Element Width: 5mm
- Element Spacing: $\frac{\lambda}{2}$

- HINDER joins NASA initiatives in leveraging Commercial-off-the-Shelf (COTS) systems to find more cost-effective development paths
  - Taking advantage of the abundance in analog testing conducted in the real-world
- Automotive radars operating at 24 GHz used for hazard detection on the ground level were examined
  - Signal processing hardware and methods can be leveraged for robust hazard detection uses in space
- HINDER uses automotive COTS components and design approaches to increase performance and reliability at a lower cost



	Freq.	BW	Modulation	Angle	Range	Resolution	Application
Short Range	24GHz	7GHz	Pulsed	70°	10m	< 10cm	Side-Crash Parking
Mid Range	24GHz	250MHz	FMCW	30°~60°	40m	~ 1m	Stop & Go
Long Range	77GHz	1GHz	FMCW	16°	150m	~ 1m	ACC





Advantages:

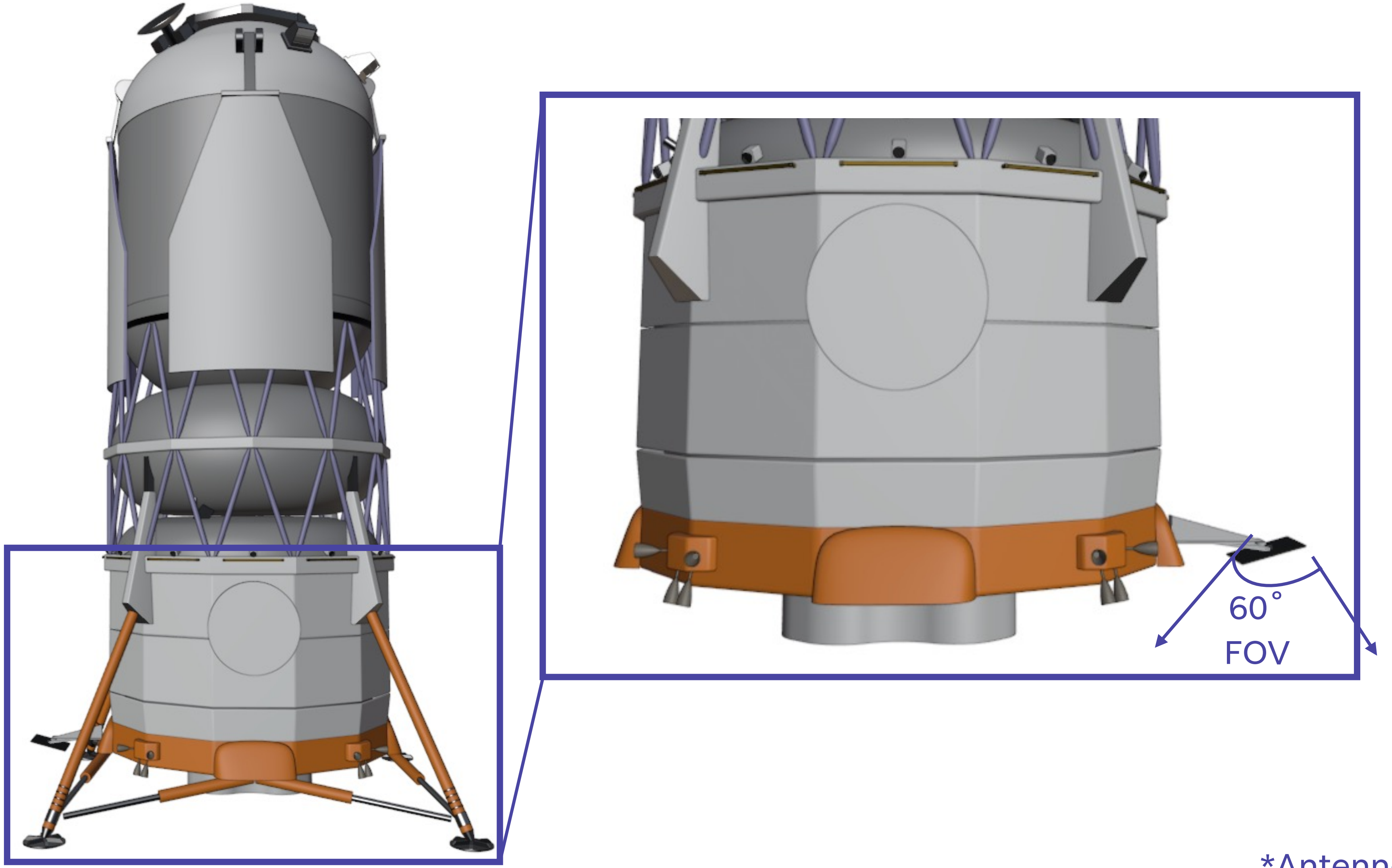
- Top is typically where majority of instrumentation is integrated
    - Simpler to harness
- Out of the way of any landing-mechanisms (leg deployments, propulsion, etc)

Disadvantages:

- Antenna must be angled further away from the lander for the structure to not interfere with the FOV
- May impact vehicle dynamics as the top is far from the CG

*Antenna made bigger (2:1 scale) everywhere on the slide for visual demonstration purposes

EXAMPLE INTEGRATION OPTION II



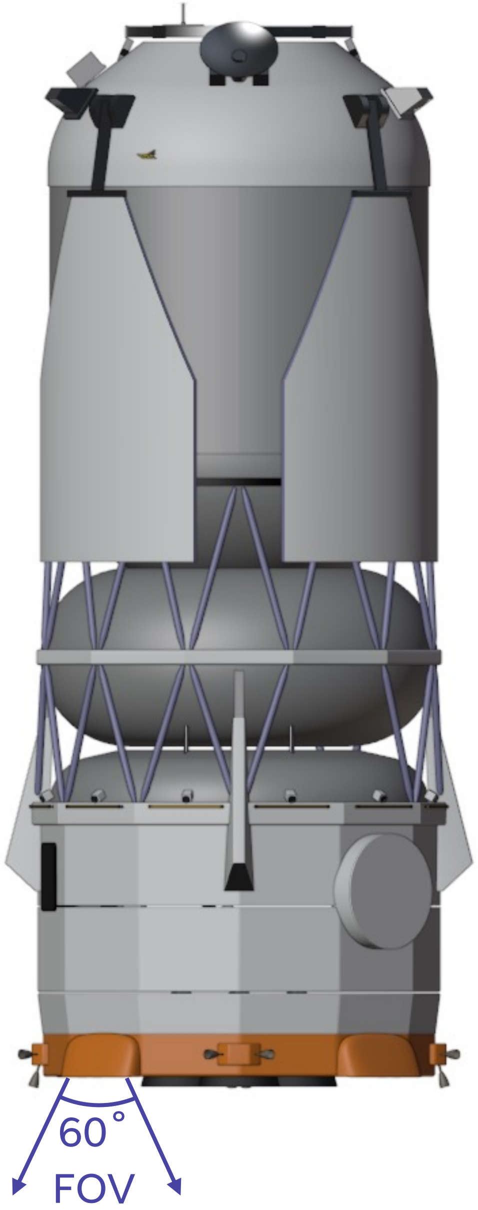
Advantages:

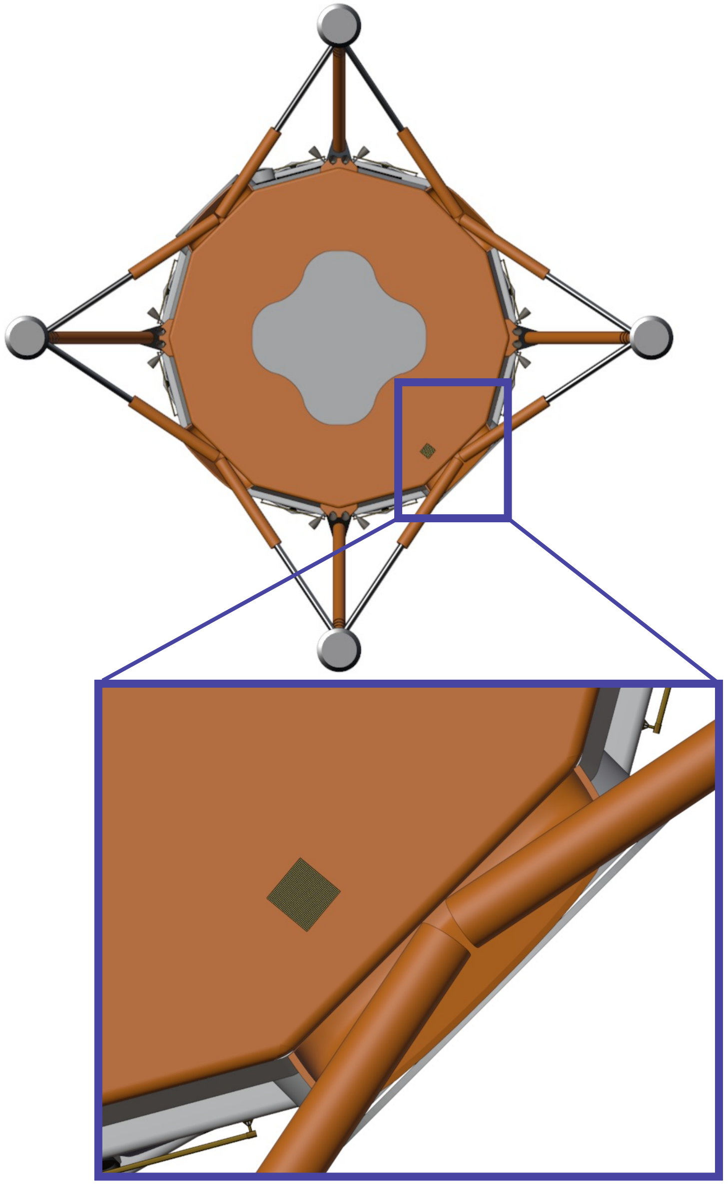
- Top is typically where majority of instrumentation is integrated
- Out of the way of any landing-mechanisms (leg deployments, propulsion, etc)

Disadvantages:

- Landers are typically sized to their launch vehicles' fairings, and an extended bracket might exceed size limits

*Antenna made bigger (2:1 scale) everywhere on the slide for visual demonstration purposes





Advantages:

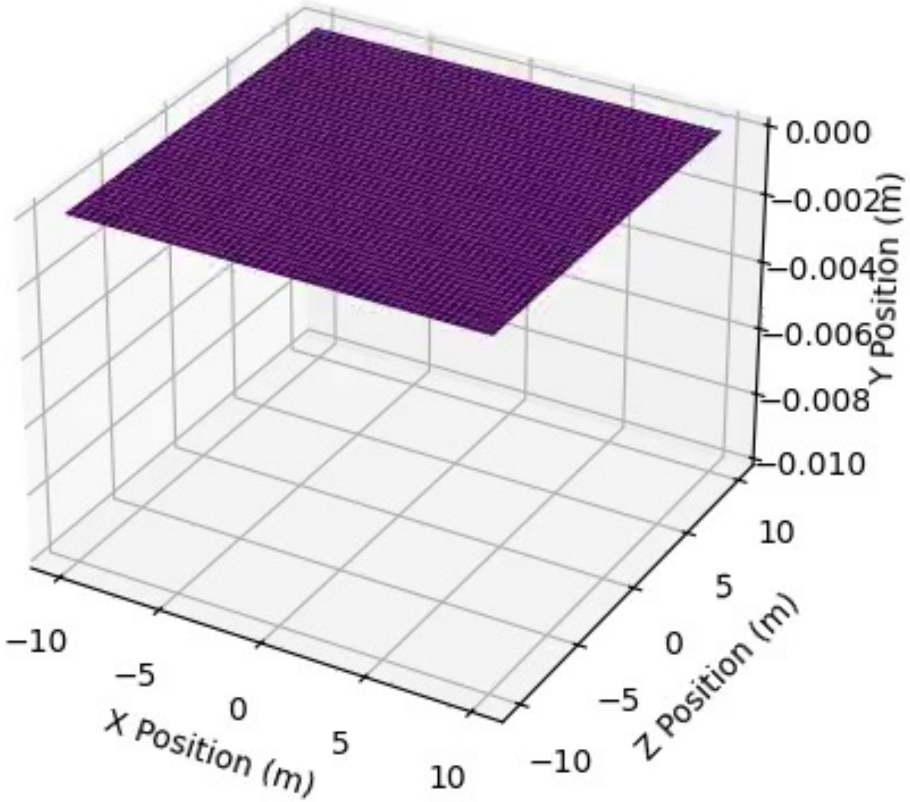
- Unobstructed FOV
- Close to CG thus minimizing changes in vehicle dynamics

Disadvantages:

- Must integrate near critical propulsion and thermal systems
    - CLPS landers, such as Firefly's Blue Ghost, might have a radiator and TPS on the bottom of the structure which cannot be obstructed.
- More difficult to harness on HLS landers

*Antenna to-scale (1:1) everywhere on this slide

Simulation Demonstration



Moving nozzle for 0.5s then Static for 0.5s

- Plotted Erosion Rate vs. Height using Robert's Model
  - Pressure chambers determined from previous lunar missions [30]
- Negligible Erosion above 100 h/d
- Conclusions supported by Marshall Space Center's work for Firefly Aerospace [7, 31]