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Precision Lunar Landing Using Lunar Satellite Navigation, Onboard LiDAR, and Ground Laser Retroreflector

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Outline

- The Lunar Exploration
- ALBS “Space-Port” Concept
- Solution Overview
- Scenarios Definition
- Simulations and Results
- Conclusion
- Future Work

The Lunar Exploration Context

- **The New Era of Exploration:** Driven by international programs like NASA's Artemis and growing commercial initiatives.
- **The Goal:** Safe, high-precision lunar landings require continuous and robust navigation capabilities across all mission phases.
- **LunaNet:** Lunar communication and navigation standards and protocol to provide interoperable, resilient, and scalable support for lunar operations.
  - **Lunar Communications Relay and Navigation Systems (LCRNS) (NASA)**
  - **Moonlight Initiative / Lunar Communication and Navigation System (LCNS) (ESA)**





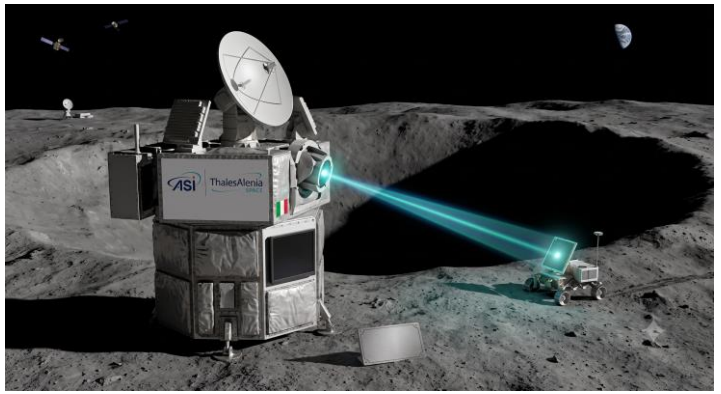




The Advanced Lunar Beacon System (ALBS)

- **ALBS:** Lunar Surface-based beacon infrastructure
  - Founded by the Italian Space Agency (ASI)
  - Provides supplementary ranging and observational measurements.
  - Enhances positioning, navigation, and timing (PNT) services.

- **Much more than just a PNT node!**
  - **Additional systems/sensors like:**
    - **Camera,**
    - **LiDAR,**
    - **3GPP**
    - **LRA,**
    - **Optical Markers**



The Advanced Lunar Beacon System (ALBS)

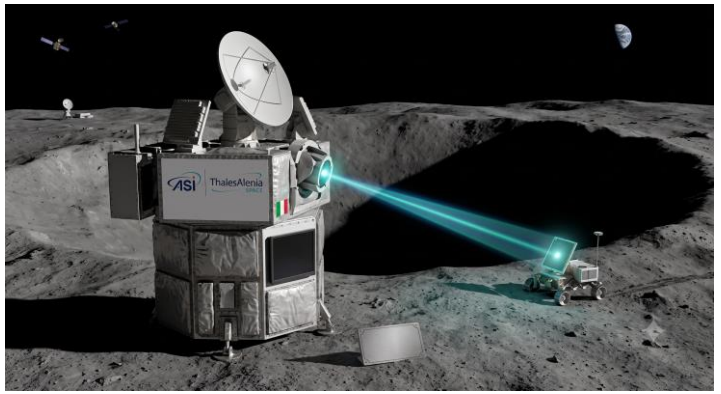
ALBS is a multifunctional lunar infrastructure providing navigation and augmentation services to support spacecraft and landers during lunar operations.

- ✓ Differential reference station
- ✓ Power distribution
- ✓ Pseudolite
- ✓ Communication and data relay

ALBS can provide additional observables for high-accuracy onboard navigation:

- ✓ **Range and Angles between the spacecraft and ALBS by the use of Laser retroreflector arrays (LRAs) installed on board ALBS**

ALBS may be a key enabler for the development of "lunar spaceports", providing the augmentation infrastructure needed to support multiple landers in safe and precise landing operations, much like modern augmentation and navigation systems support aircraft at airports on Earth.



The Proposal for Moon Space Port

- ✓ **An integrated navigation architecture for the spacecraft landing phase, for absolute spacecraft position estimation, exploiting a smooth transition between satellite, laser ranger and laser scanner instead of the use of the classical laser altimeter**

- ✓ **The Surface Asset:**
  - ✓ Only a passive Lunar Laser Retroreflector Array (LRA) deployed at a precisely surveyed location on the Moon as part of the ALBS infrastructure.

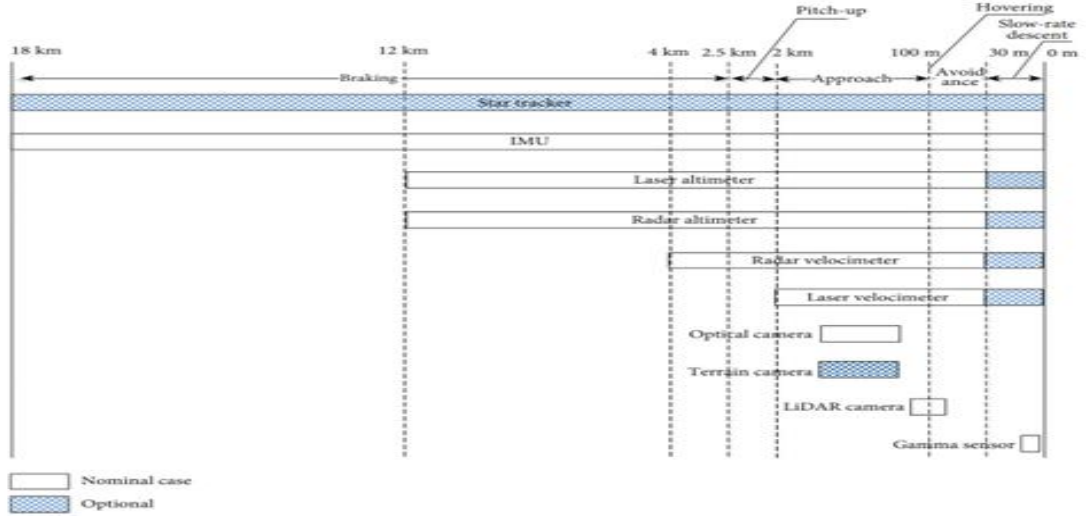
- ✓ **The Spacecraft Asset**:
  - ✓ LCNS/LCRNS Receiver
  - ✓ ATTITUDE determination
  - ✓ Lidar altimeter and laser scanner (typically borrowed from the modern laser altimeter) for range (and angle) measurements

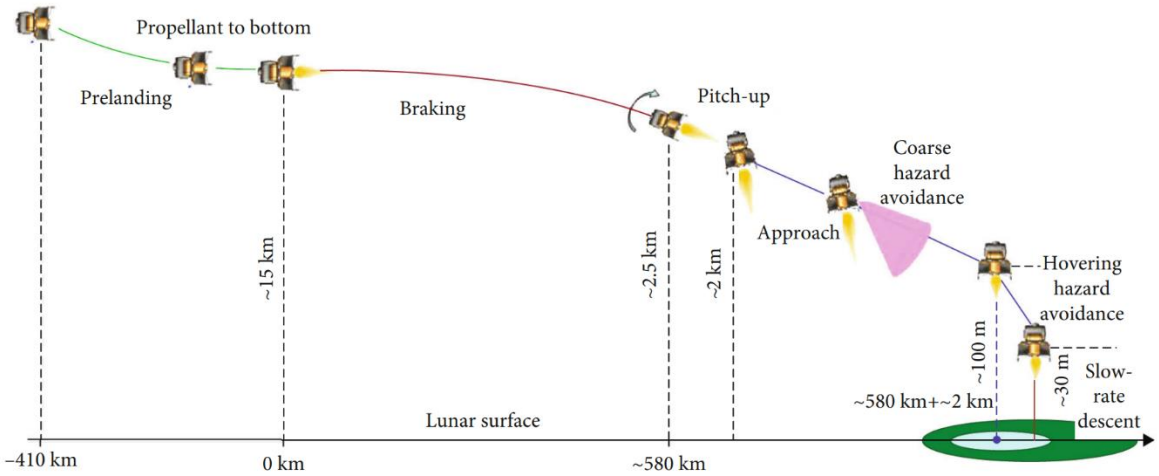


The Classical Approach (Baseline Scenario - ALT)

- ✓ Lunar Navigation Satellites + Attitude Determination + Laser Altimeter (Surface Relative Measurement).
  - ✓ Conventional laser altimetry provides only surface-relative altitude measurements.
  - ✓ Absolute position errors rely heavily on Digital Elevation Models (DEMs) and provide weak constraints on lateral positioning right when absolute localization is most critical.

- ✓ Example in recent missions:
  - ✓ **Chang'E-5:** *pitch-up maneuver and sensor usage*
  - ✓ **Sensors:** *laser altimeter, star tracker, 3D imaging sensor, and laser velocity sensor.*

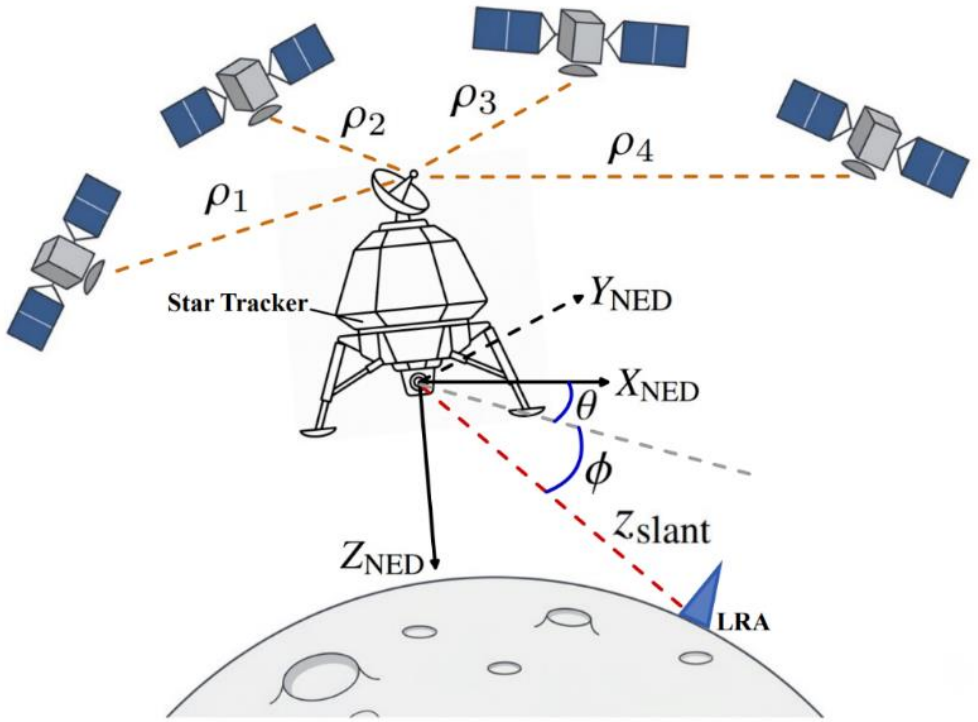




The Proposed Architectures (SR and ASR)

- ✓ **Configuration I (before pith-up):**
  - Lunar Navigation Satellites
  - Slant-Ranging (SR)
  - Attitude Determination
  - LiDAR operating as a slant-range sensor to the LRA.

- ✓ **Configuration II (after pitch-up)**:
  - Lunar Navigation Satellites
  - Angle-Aided Slant-Ranging (ASR)
    - LiDAR operating as a 3D scanner (slant-range + AoA measurements)
  - Attitude Determination



Performance Evaluation by CRLB

$$\mathbf{x} = [x, y, z, c\delta t_u]^T = [\mathbf{p}^T, b_u]^T$$ ***State to be estimated***

Satellite pseudoranges

$$\rho_i = \|\mathbf{p} - \mathbf{p}_{s,i}\| + b_u + \epsilon_{\rho,i}$$

$$\sigma_{\rho,i} = \sqrt{\sigma^2_{\text{sat-pos}} + \sigma^2_{\text{clk}} + \sigma^2_{\text{rx}} + \sigma^2_{\text{mp}}}$$

$$\mathbf{h}_{\rho,i} = \frac{\partial \rho_i}{\partial \mathbf{x}} = \left[\frac{x - x_{s,i}}{r_i}, \quad \frac{y - y_{s,i}}{r_i}, \quad \frac{z - z_{s,i}}{r_i}, \quad 1\right]$$

Altimeter

$$z_{\text{alt}} = \|\mathbf{p} - \mathbf{p}_{\text{surf}}\| + \epsilon_{\text{alt}}$$

$$\sigma_{\text{alt}} = \sqrt{\sigma^2_{\text{meas}} + \sigma^2_{\text{DEM}}} \quad \sigma_{\text{meas}} = \sqrt{\sigma^2_{\text{intrinsic}} + \sigma^2_{\text{pointing}}}$$

$$\mathbf{h}_{\text{alt}} = \left[\frac{x - x_{\text{surf}}}{r_{\text{alt}}} \quad \frac{y - y_{\text{surf}}}{r_{\text{alt}}} \quad \frac{z - z_{\text{surf}}}{r_{\text{alt}}} \quad 0\right]$$

Slant Range

$$z_{\text{slant}} = \|\mathbf{p} - \mathbf{p}_{LRA}\| + \epsilon_{\text{slant}}$$

$$\sigma_{\text{slant}} = \sqrt{\sigma^2_{\text{LiDAR,range}} + \sigma^2_{\text{anchor-pos}}}$$

$$\mathbf{h}_{\text{slant}} = \frac{\partial z_{\text{slant}}}{\partial \mathbf{x}} = \left[\frac{x - x_{LRA}}{r_{\text{slant}}}, \frac{y - y_{LRA}}{r_{\text{slant}}}, \frac{z - z_{LRA}}{r_{\text{slant}}}, 0\right]$$

AOA

$$\theta = \text{atan2}\,(\Delta y, \Delta x) + \epsilon_\theta$$

$$\phi = \arcsin\left(\frac{\Delta z}{\|\Delta \mathbf{p}^{NED}\|}\right) + \epsilon_\phi$$

$$\sigma_{\text{AoA,H}} = \sqrt{\sigma^2_{\text{LiDAR,H}} + \sigma^2_{\text{ST}}}, \quad \sigma_{\text{AoA,V}} = \sqrt{\sigma^2_{\text{LiDAR,V}} + \sigma^2_{\text{ST}}}$$

$$\mathbf{h}^{MCMF}_\theta = \left[\left(\mathbf{h}^{NED}_\theta \cdot G^{NED}_{MCMF}\right), \quad 0\right]$$

$$\mathbf{h}^{MCMF}_\phi = \left[\left(\mathbf{h}^{NED}_\phi \cdot G^{NED}_{MCMF}\right), \quad 0\right]$$

Performance Evaluation by CRLB

$$\mathbf{x} = [x, y, z, c\delta t_u]^T = \left[\mathbf{p}^T, b_u\right]^T$$ ***State to be estimated***

Reference Scenario

$$\mathbf{H}_{\text{ALT}} = \left[\mathbf{h}_{\rho,1}^T \dots \mathbf{h}_{\rho,n}^T \quad \mathbf{h}_{\text{alt}}^T\right]^T$$

$$\mathbf{R}_{\text{ALT}} = \text{diag}\left(\sigma_{\rho,1}^2, \dots, \sigma_{\rho,n}^2, \sigma_{\text{alt}}^2\right)$$

Configuration 1

$$\mathbf{H}_{\text{SR}} = \left[\mathbf{h}_{\rho,1}^T \dots \mathbf{h}_{\rho,n}^T \quad \mathbf{h}_{\text{slant}}^T\right]^T$$

$$\mathbf{R}_{\text{SR}} = \text{diag}\left(\sigma_{\rho,1}^2, \dots, \sigma_{\rho,n}^2, \sigma_{\text{slant}}^2\right)$$

Configuration 2

$$\mathbf{H}_{\text{ASR}} = \left[\mathbf{h}_{\rho,1}^T \dots \mathbf{h}_{\rho,n}^T \quad \mathbf{h}_{\text{slant}}^T \quad \mathbf{h}_{\theta}^{MCMF\,T} \quad \mathbf{h}_{\phi}^{MCMF\,T}\right]^T$$

$$\mathbf{R}_{\text{ASR}} = \text{diag}\left(\sigma_{\rho,1}^2, \dots, \sigma_{\rho,n}^2, \sigma_{\text{slant}}^2, \sigma_{\text{AoA,H}}^2, \sigma_{\text{AoA,V}}^2\right)$$

WLS problem inversion (or Kalman filtering)

CRLB formulation

CRLB formulation for a first evaluation of the performance at glance

$$\sigma_{3D} = \sqrt{C(\theta)_{11} + C(\theta)_{22} + C(\theta)_{33}}$$

$$\sigma_{Hor} = \sqrt{C(\theta)_{11} + C(\theta)_{22}}$$

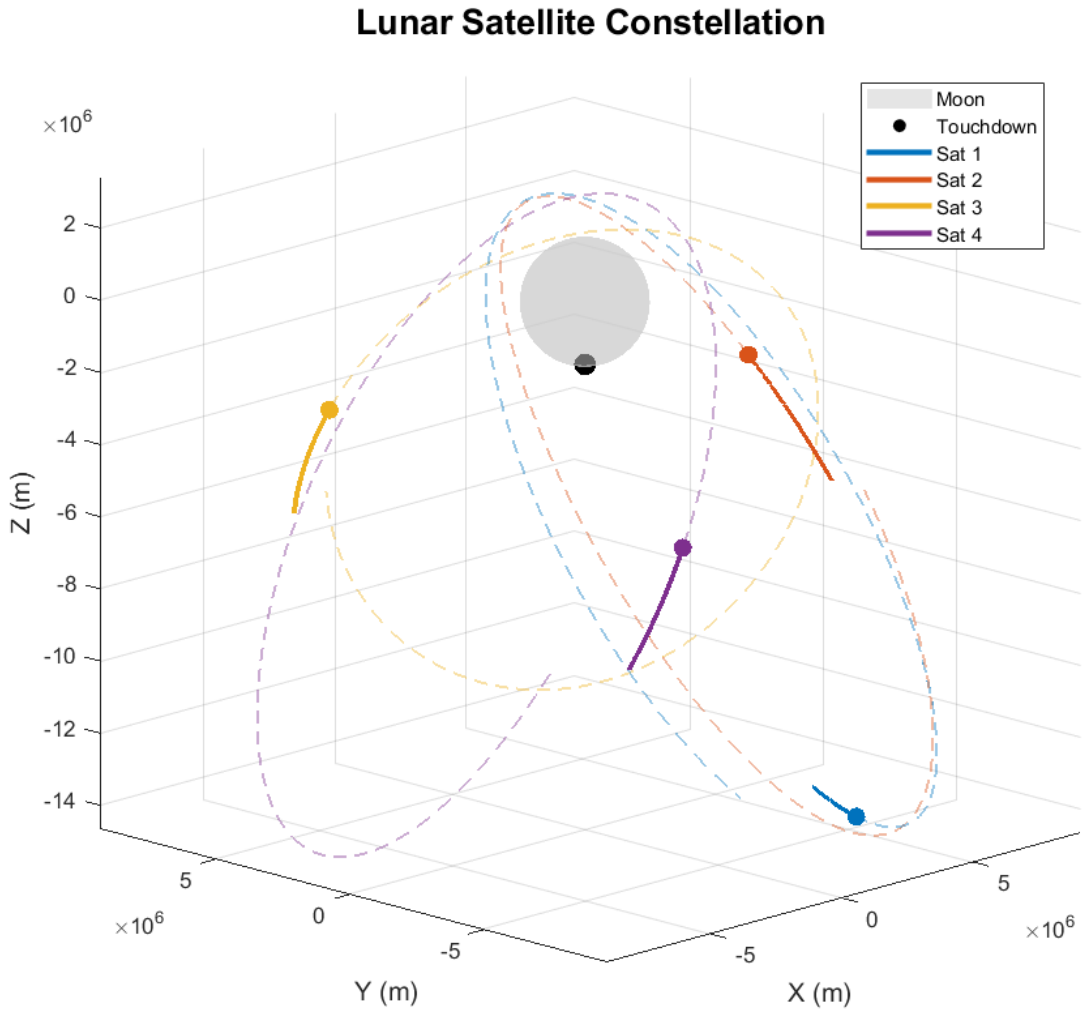
$$\sigma_{Vert} = \sqrt{C(\theta)_{33}}$$

Simulated Scenario

- ✓ The CRLBs were evaluated on a trajectory simulating a landing on the Moon:
  - ✓ with 4 LCNS satellites
  - ✓ 16 different ALBS positions,
  - ✓ 2 specific time instants:
    - ✓ PITCH-UP
    - ✓ TERMINAL TOUCHDOWN

- ✓ Constellation parameters:

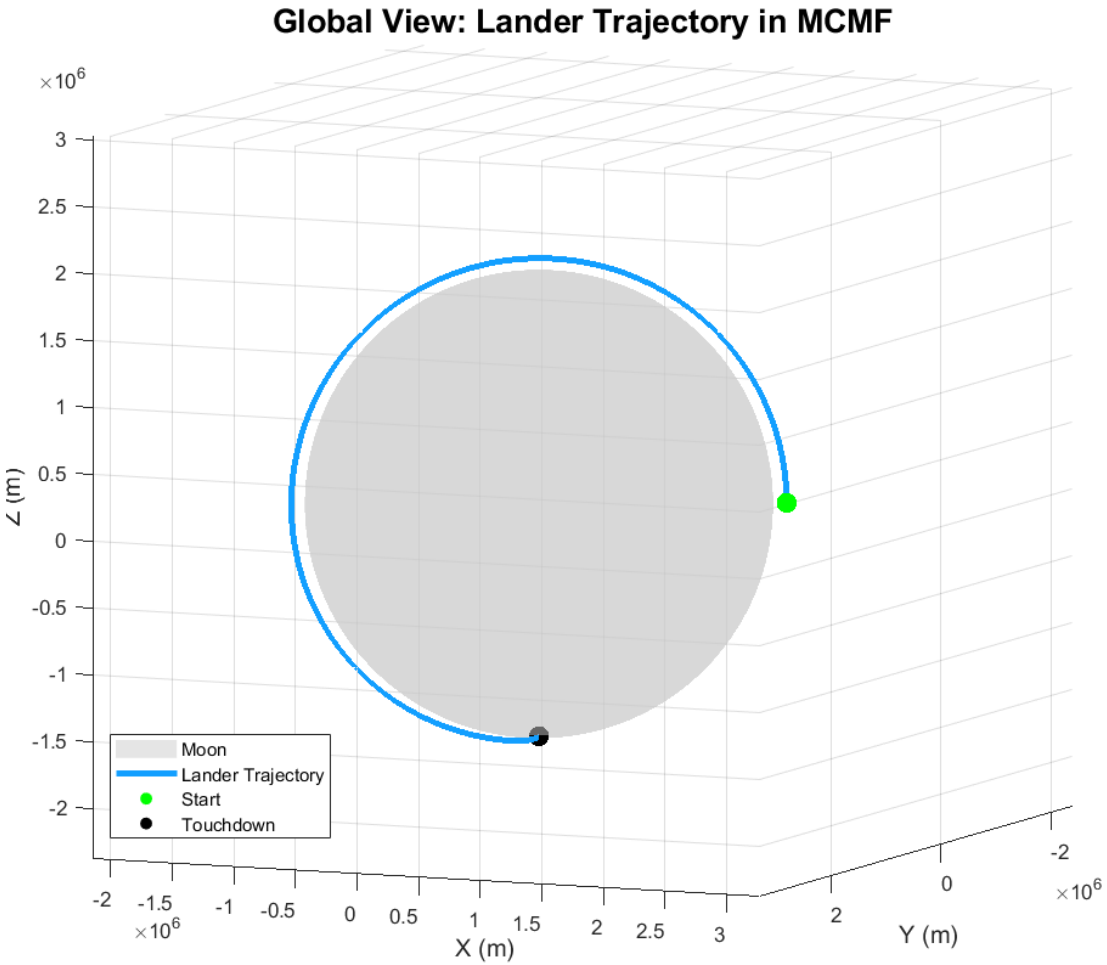
Parameter	Value
Number of Satellites	4
Number of Planes	4
Semi-major axis (a)	9,750 km
Eccentricity (e)	0.6 – 0.7
Inclination (i)	48° – 57°
Nominal Orbital Period (T)	24 h



Lander Trajectory & Measurement Error Budgets

- ✓ Descent orbit and spacecraft approach to the landing site.
- ✓ Assumption on the errors affecting the system:

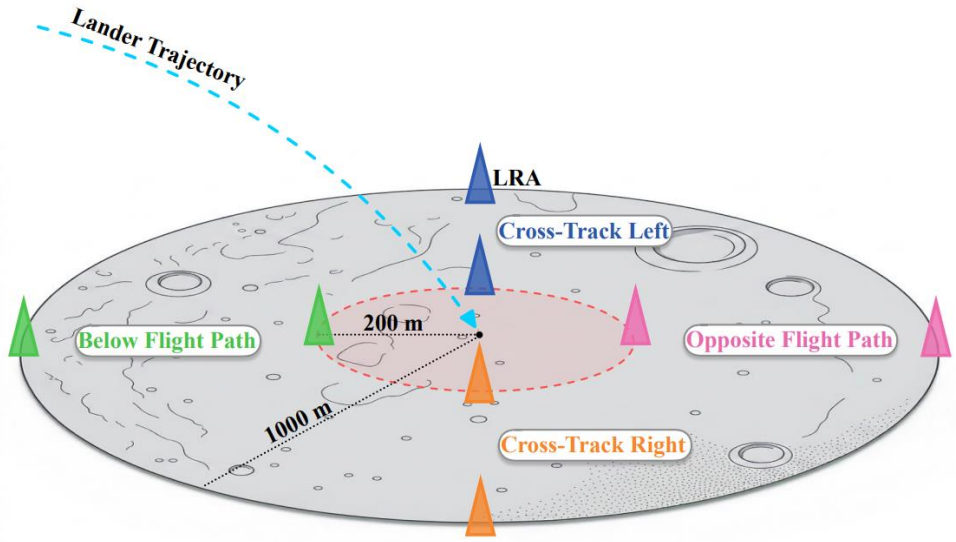
System / Category	Parameter	Value (1σ)
Navigation Satellite	Satellite Position Error ($\sigma_{\text{sat-pos}}$)	4.0 m
	Satellite Clock Error (σ_{clk})	8.5 m
	Receiver Noise (Thermal) (σ_{rx})	0.9348 m
	Multipath Error (σ_{mp})	0.3 m
Proposed (SR/ASR)	Anchor Position Uncertainty ($\sigma_{\text{anchor-pos}}$)	0.10 m
	Slant Range Error ($\sigma_{\text{LiDAR,range}}$) [6]	0.125 m
	Vertical Angle Error (AoA) ($\sigma_{\text{AoA,V}}$)[a]	0.026°
	Horizontal Angle Error (AoA) ($\sigma_{\text{AoA,H}}$)[a]	0.011°
	Pitch-up Maneuver Altitude	2,500 m
Baseline (ALT)	Altimeter Intrinsic Noise ($\sigma_{\text{intrinsic}}$) [6]	0.125 m
	Altimeter Pointing Error (σ_{pointing})[b]	1.466 m
	DEM Uncertainty (σ_{DEM})[c]	10.0 m
	Altimeter Coverage Limit (h)	12,000 m



LRA Surface Geometries

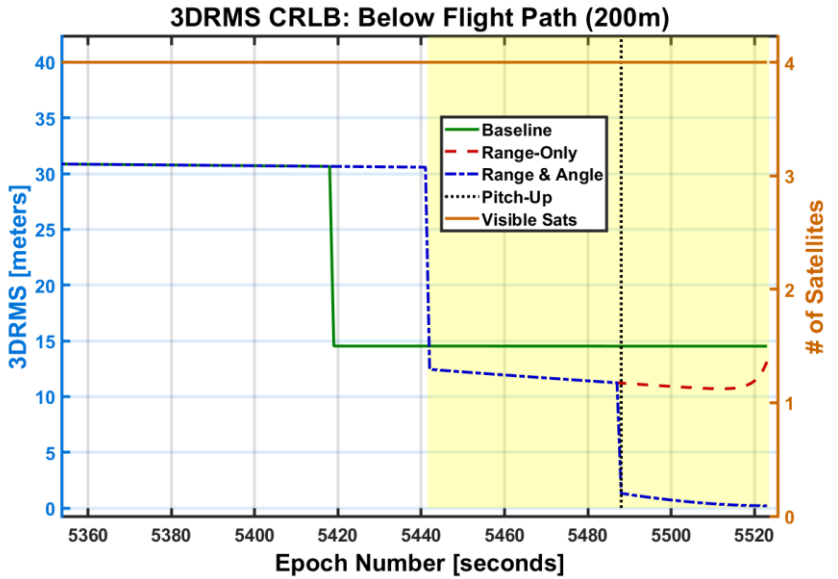
✓ ALBS (LRA) was simulated at 8 distinct positions relative to the touchdown point:

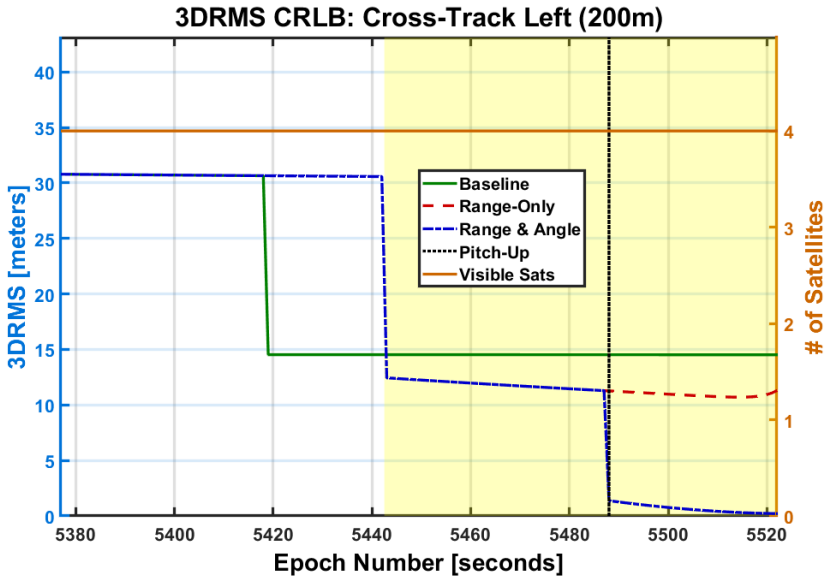
- **Radial Proximities:** Close-proximity (200 m) and Extended-range (1,000 m).
- **Flyover Geometry:** Lander directly overflies the LRA.
- **Forward-Facing Geometry:** LRA is located opposite the approach path.
- **Cross-Track Geometries:** LRA is placed orthogonally (left or right) to the flight path to constrain lateral drift.



Examples of Plots (3D)

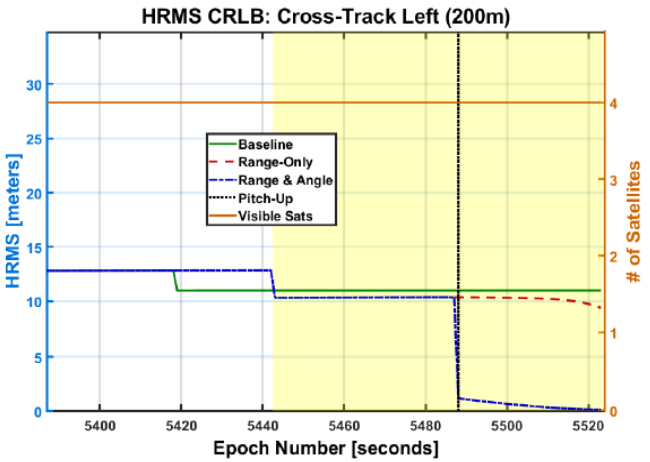
- ✓ **CRLB performance plots for 200m Flyover and 200m Cross-track left]**
  - ✓ **Yellow Shaded Region:** The operational envelope where the lander drops below the 12 km LiDAR limit and begins acquiring absolute slant-range to the LRA
  - ✓ **Solid Orange Line:** Constant visibility of the 4 lunar navigation satellites.
  - ✓ **Black Dashed Line:** The pitch-up maneuver (2.5 km)
  - ✓ **Solid Green Line**: Reference solution
  - ✓ **Dashed red line:** Configuration 1
  - ✓ **Dashed blue line:** Configuration 2



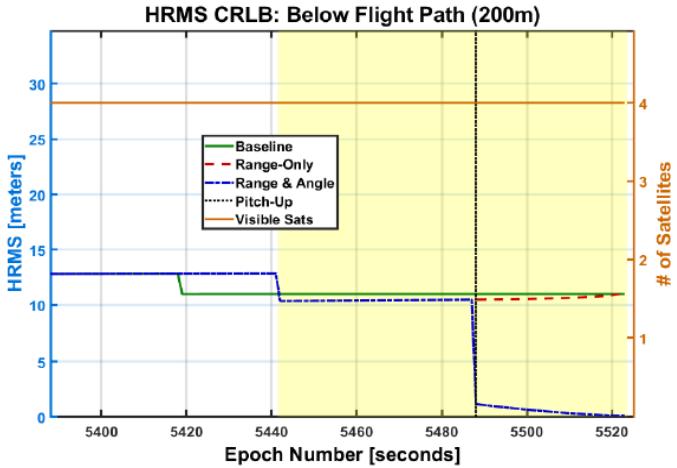


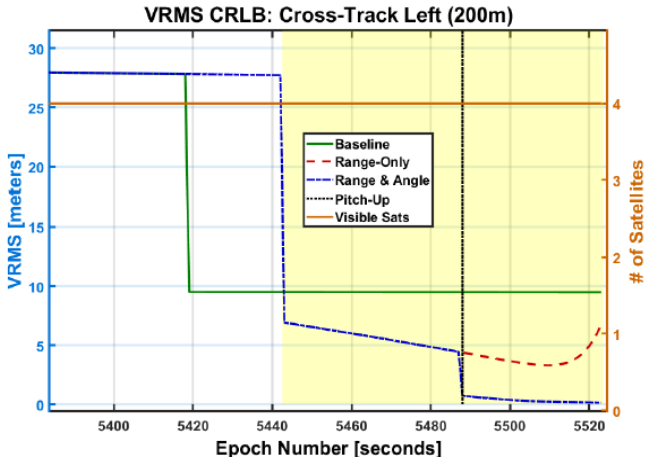
Examples of Plots (H&V)

Cross Track

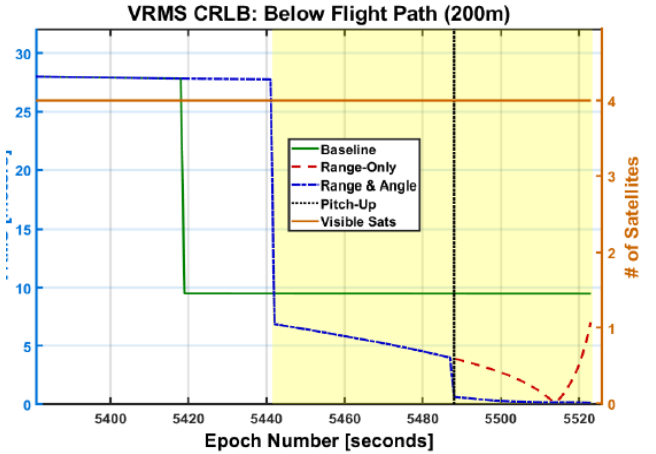


Horizontal





Vertical



Below Flight path

Performance at the Pitch-Up Epoch

- ✓ **Baseline (ALT):** Maintains a 3D CRLB error of 14.52 meters.
- ✓ **Range-Only (SR) Pre-Pitch**: Outperforms the baseline due to favorable slant geometry at 2.5 km altitude
- ✓ **Range + AoA (ASR) Post-Pitch**: 3D error drops dramatically to between 1.16m - 1.69m

Architecture	Surface Anchor Position (LRA)	Hor. CRLB (m)	Ver. CRLB (m)	3D CRLB (m)	Improvement
Baseline (ALT)	N/A	10.99	9.49	14.52	–
Range-Only (Pre-Pitch)	Below flight path (1km)	10.61	1.89	10.78	+25.8%
Range-Only (Pre-Pitch)	Cross-track left (1km)	10.03	4.80	11.12	+23.4%
Range-Only (Pre-Pitch)	Below flight path (200m)	10.50	3.99	11.23	+22.7%
Range-Only (Pre-Pitch)	Cross-track left (200m)	10.38	4.44	11.29	+22.2%
Range-Only (Pre-Pitch)	Cross-track right (200m)	10.56	4.62	11.53	+20.6%
Range-Only (Pre-Pitch)	Opposite flight path (200m)	10.44	4.99	11.57	+20.3%
Range-Only (Pre-Pitch)	Opposite flight path (1km)	10.34	6.84	12.40	+14.6%
Range-Only (Pre-Pitch)	Cross-track right (1km)	10.96	5.81	12.41	+14.5%
Range+AoA (Post-Pitch)	Below flight path (1km)	1.12	0.31	1.16	+92.0%
Range+AoA (Post-Pitch)	Below flight path (200m)	1.15	0.64	1.32	+90.9%
Range+AoA (Post-Pitch)	Cross-track left (200m)	1.16	0.73	1.37	+90.6%
Range+AoA (Post-Pitch)	Cross-track right (200m)	1.16	0.73	1.37	+90.6%
Range+AoA (Post-Pitch)	Opposite flight path (200m)	1.17	0.81	1.42	+90.2%
Range+AoA (Post-Pitch)	Cross-track left (1km)	1.18	0.85	1.45	+90.0%
Range+AoA (Post-Pitch)	Cross-track right (1km)	1.18	0.85	1.46	+89.9%
Range+AoA (Post-Pitch)	Opposite flight path (1km)	1.23	1.16	1.69	+88.4%

Performance at Terminal Touchdown

- ✓ **Range-Only (SR) Vulnerability**:
  - ✓ As the lander approaches the surface, SR suffers from Geometric Dilution of Precision (GDOP). In far-field geometries (1km offsets), 3D error spikes up to 28.14m.
- ✓ **ASR Mitigation:**
  - ✓ Fusing range and AoA completely neutralizes these geometric vulnerabilities.
- ✓ **Sub-Meter Precision:**
  - ✓ The ASR architecture drives terminal 3D error down uniformly into the sub-meter level across all eight LRA positions.

Architecture	Surface Anchor Position (LRA)	Hor. CRLB (m)	Ver. CRLB (m)	3D CRLB (m	Improvement
Baseline (ALT)	N/A	10.99	9.49	14.52	–
Range-Only (SR)	Cross-track left (200m)	9.40	6.76	11.58	+20.2%
Range-Only (SR)	Below flight path (200m)	11.07	7.03	13.11	+9.7%
Range-Only (SR)	Opposite flight path (200m)	10.21	8.88	13.53	+6.8%
Range-Only (SR)	Cross-track right (200m)	12.19	11.35	16.65	-14.7%
Range-Only (SR)	Cross-track left (1km)	7.99	15.21	17.18	-18.3%
Range-Only (SR)	Opposite flight path (1km)	9.80	20.11	22.37	-54.1%
Range-Only (SR)	Below flight path (1km)	11.00	25.86	28.11	-93.6%
Range-Only (SR)	Cross-track right (1km)	9.11	26.62	28.14	-93.8%
Range+AoA (ASR)	Below flight path (200m)	0.14	0.14	0.19	+98.7%
Range+AoA (ASR)	Cross-track right (200m)	0.15	0.14	0.20	+98.6%
Range+AoA (ASR)	Cross-track left (200m)	0.15	0.14	0.20	+98.6%
Range+AoA (ASR)	Opposite flight path (200m)	0.16	0.14	0.22	+98.5%
Range+AoA (ASR)	Below flight path (1km)	0.26	0.43	0.50	+96.5%
Range+AoA (ASR)	Cross-track right (1km)	0.26	0.46	0.53	+96.3%
Range+AoA (ASR)	Cross-track left (1km)	0.26	0.45	0.53	+96.3%
Range+AoA (ASR)	Opposite flight path (1km)	0.27	0.47	0.55	+96.2%

Optimal Configuration: *The 200m Flyover geometry achieves an astonishing 0.19m 3D precision (98.7% improvement over baseline).*

Conclusion, Future Works, Drawbacks

- **An integrated architecture fusing a sparse 4-satellite constellation with onboard LiDAR tracking a passive surface retroreflector (LRA).**
  - SR improves early descent but suffers from GDOP near the surface.
  - ASR completely mitigates GDOP by fusing slant distance with AoA measurements.
  - ASR can provide a totally independent navigation solution
  - ASR achieves sub-meter 3D accuracy at touchdown across all anchor positions.
  - *No power needed on the ground*
  - *Smooth Transition from LCNS to a local high-performance navigation system*
- **Future work:**
  - Test with Monte Carlo runs and WLS, Kalman filter to improve the models
  - Test on LuGRE and other real mission paths

- **Drawbacks to be investigated**
  - Performance in case of degraded environmental conditions (lunar dust, reduced visibility)

Thank you for your attention.



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