DRAPER'S VISION-BASED NAVIGATION ENHANCED LUNAR LANDER AND OPPORTUNITIES FOR ISRU

Space Resources Roundtable – Technical Session 6

Providing Lunar Access and Surface Infrastructure

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Who Are We?

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Recognized world leader in **GN&C**

APOLLO

safely brought NASA astronauts to the moon and back

$600M+
in U.S. government and commercial contracts annually

Key participant in
100% of NASA
human space missions
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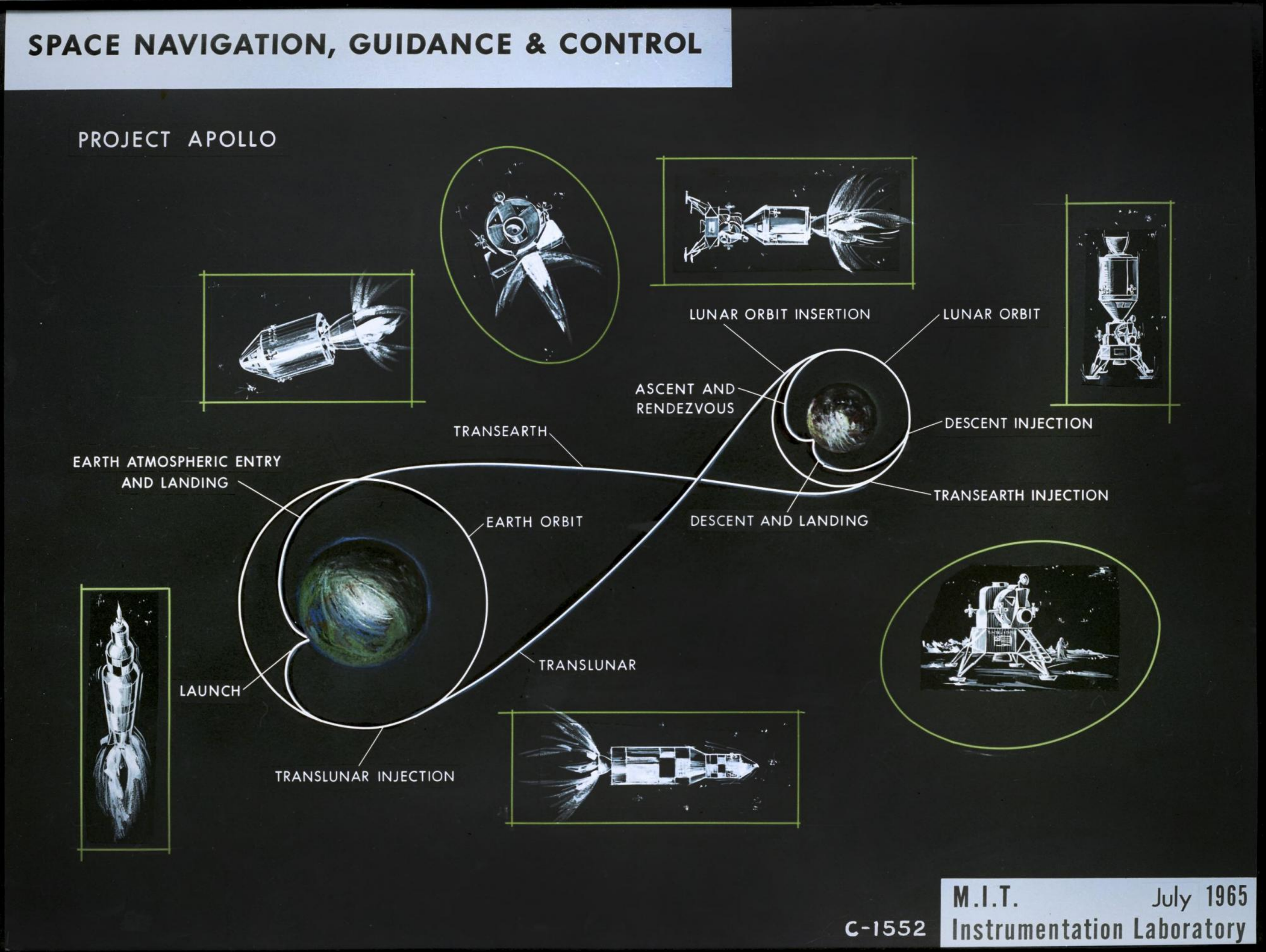

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Lander Performance and ISRU

- Strategic lander placement
  - Crater rim – light/power beaming
  - Edge of lava tube – tether anchor
  - Recharging stations for rovers
- Avoid hazards
- Reduce traverse times for rovers
- Co-location of additional infrastructure

Draper Vision-Based Navigation can make it happen!

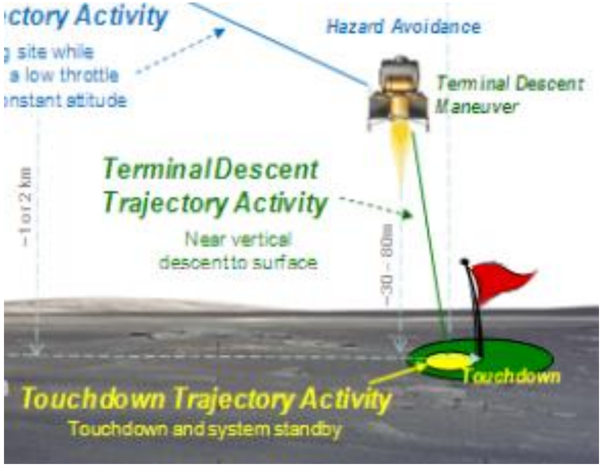
Draper CLPS Vehicle

Precision Lunar Landing: History and Objectives

Li, Shuang, Xiuqiang Jiang, and Ting Tao. "Guidance summary and assessment of the Chang'e-3 powered descent and landing." *Journal of Spacecraft and Rockets* 53.2 (2016): 258-277

Table 1 Landing error summary of all successful lunar landing missions

Missions	Manned or not	Launch date (yyyy.mm.dd)	Landing error
Apollo 11	Manned	1969.07.16	~6.6 km
Apollo 12	Manned	1969.11.14	~160 m
Apollo 14	Manned	1971.01.31	~340 m
Apollo 15	Manned	1971.07.26	~550 m
Apollo 16	Manned	1972.04.16	~280 m
Apollo 17	Manned	1972.12.07	~400 m
Surveyor 1	Unmanned	1966.05.30	~18.96 km
Surveyor 3	Unmanned	1967.04.17	~2.76 km
Surveyor 5	Unmanned	1967.09.08	A few km
Surveyor 6	Unmanned	1967.11.07	
Surveyor 7	Unmanned	1968.01.07	
Luna 9	Unmanned	1966.01.31	A few km to tens of km
Luna 13	Unmanned	1966.12.21	
Luna 16	Unmanned	1970.09.12	
Luna 17	Unmanned	1970.11.10	
Luna 20	Unmanned	1972.02.14	
Luna 21	Unmanned	1973.01.08	
Luna 24	Unmanned	1976.08.09	
Chang'e -3	Unmanned	2013.12.02	~89 m

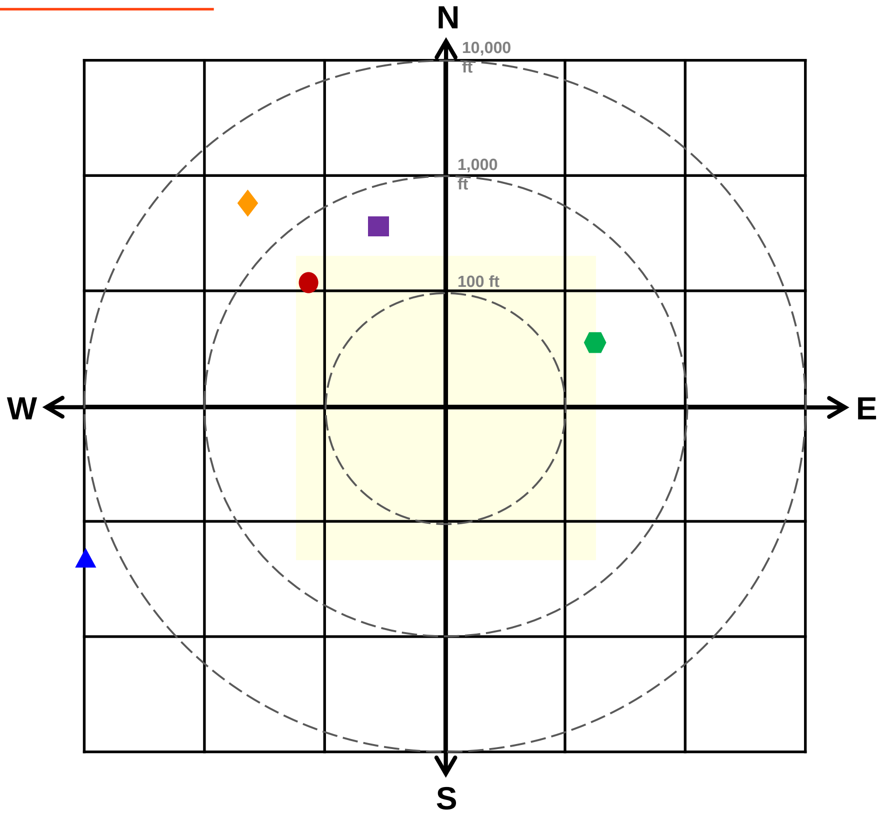


Objective:
Less than 10 m 3-sigma landing error

An order of magnitude better than prior human or robotic landings

Apollo Landing Performance

Referenced to Pre-Mission Planned Landing Point



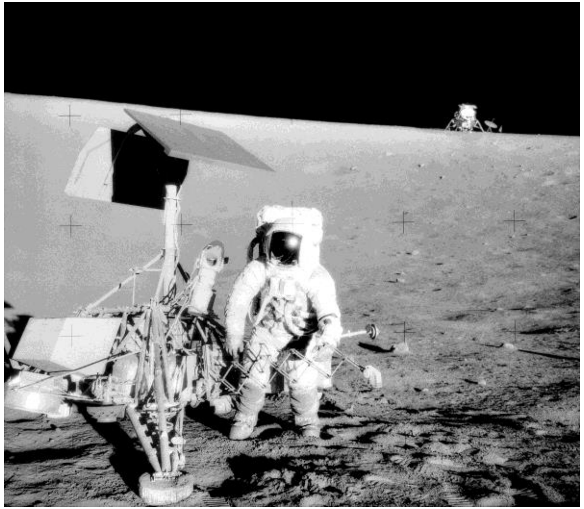
- ▲ Apollo 11 (21,309 ft W, 4366 ft S)
- ● Apollo 12 (380 ft W, 220 ft N)
- ⬢ Apollo 14 (165 ft E, 55 ft N)
- ◆ Apollo 15 (1,110 ft W, 1,341 ft N)
- ■ Apollo 16 (197 ft W, 886 ft N)
- ✚ Apollo 17 ("within 656 ft of plan") [not shown; no directionality]

Proposed ALHAT Scan Areas

- 45 m sq.
- 90 m sq. (shown)
- 180 m sq.
- 360 m sq.

Surveyor 3 Landing Accuracy

- The Surveyor I spacecraft was soft-landed on the lunar surface 18.96 km from the desired location.
- Surveyor III 2.76 km from its desired location.
- The landings were within the predicted regions of uncertainty as determined in flight,
  - Surveyor I: approximately 39 km, 3-σ
  - Surveyor III: approximately 15 km, 3-σ
  - The major sources of landing site error are the orbit determination computational accuracy and the spacecraft hardware tolerance uncertainties.
- The landing locations were determined from Lunar Orbiter and spacecraft photographs along with Earth-based radio tracking data.



Charles “Pete” Conrad Jr., Apollo 12 Commander, stands next to Surveyor 3. In the background is the Apollo 12 Lunar Module, Intrepid.

RIBARICH, J. (1968). Surveyor spacecraft landing accuracy. Journal of Spacecraft and Rockets. 5. 10.2514/3.29355.

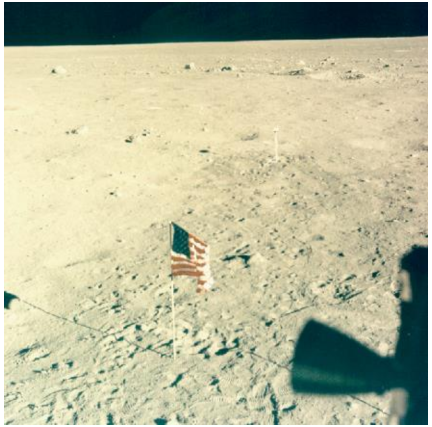
For next generation robotic lunar landers, we are designing a navigation system to increase our accuracy by several orders of magnitude

From Apollo 11 to the Future of Safe and Precise Lunar Landing

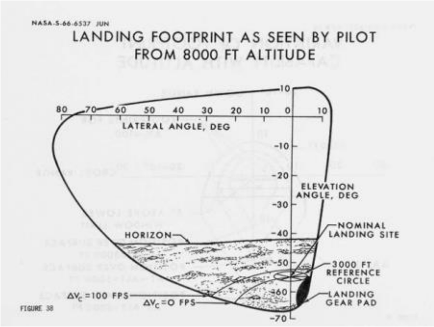
Key enablers for autonomous precision lunar landing:

1. Vision-Based Navigation – including terrain relative navigation (template and crater matching) and visual odometry (optic flow)
2. Hazard Detection (crater, boulder, slope)
3. Safe Site Selection and Hazard Avoidance (divert capability)

- We have done precision landing with hazard avoidance and safe site selection on the moon before, but using human/astronaut eyes for:
  - Navigating and identifying the landing region
  - Identifying hazards, or hazardous areas
  - Selecting a safe site to land and diverting there

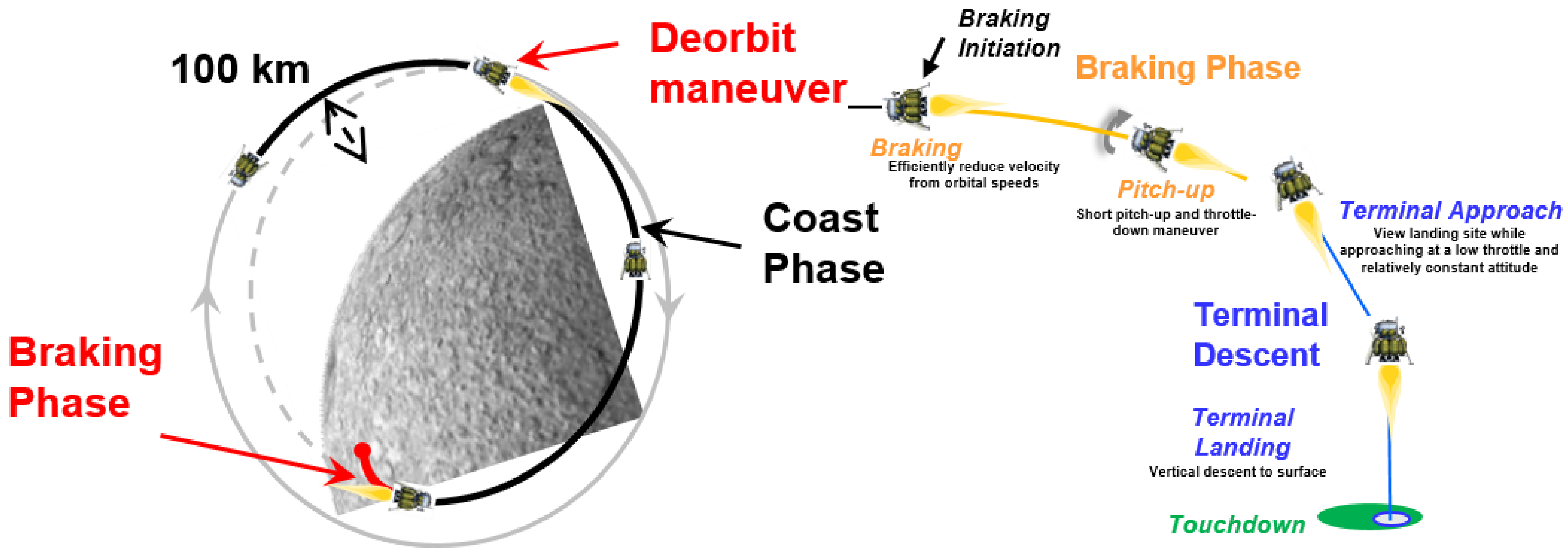


https://www.lpi.usra.edu/lunar/missions/apollo/apollo_11/images/n_boulders_lg.gif

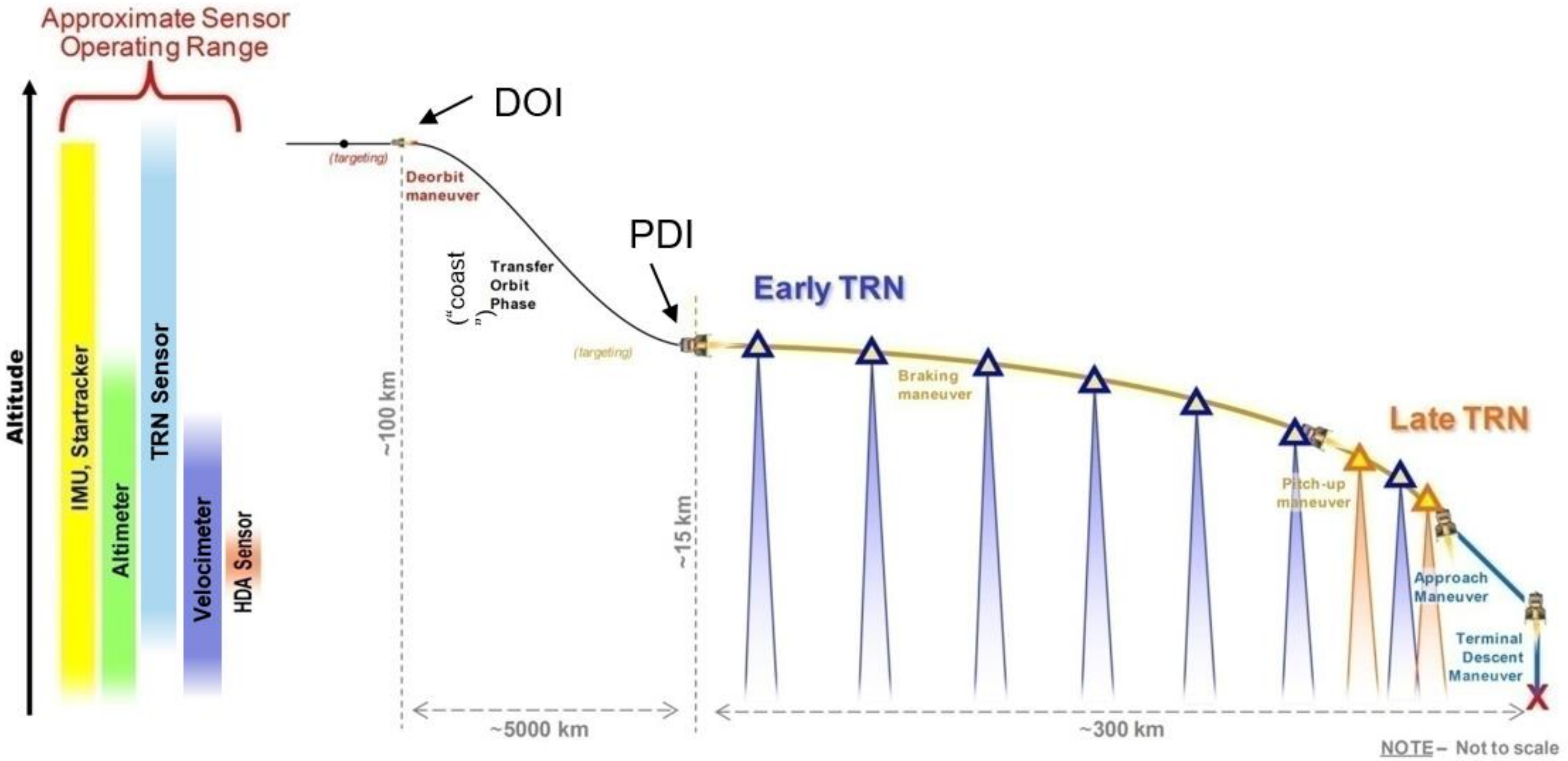


Reference Mission

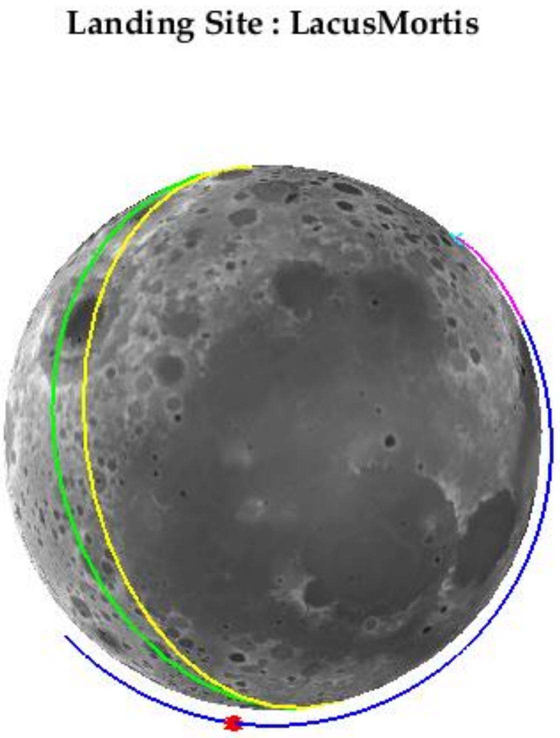
Mission Overview and Terminology



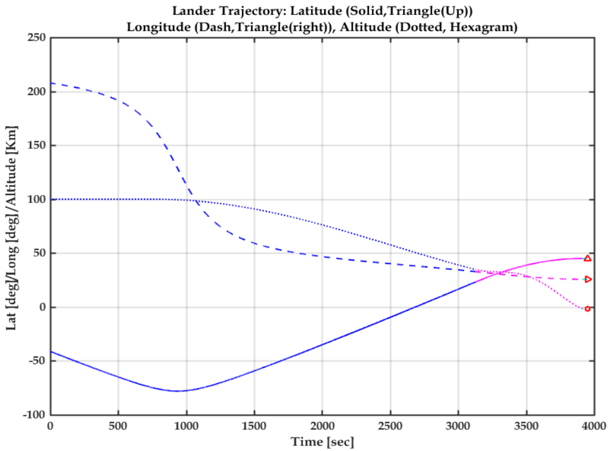
Draper Descent GN&C Maneuvers and Sensors

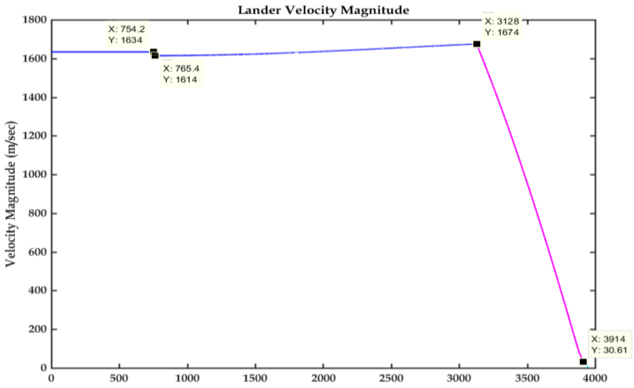


Lacus Mortis: Descent Trajectory and Velocity



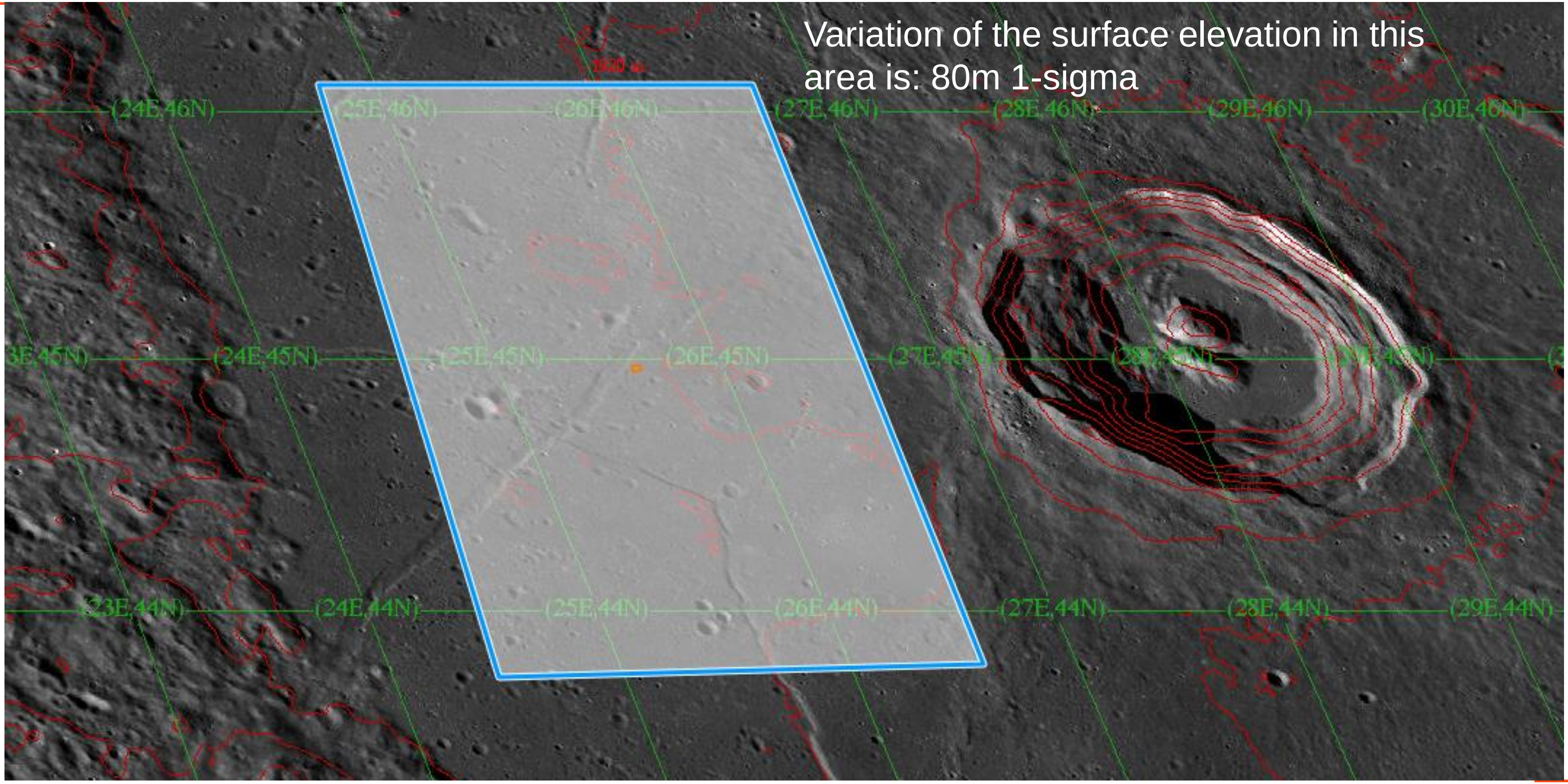
Courtesy: https://astropedia.astrogeology.usgs.gov/download/Moon/LRO/LOLA/thumbs/Moon_LRO_LOLA_global_LDEM_1024.jpg





Region Around Lacus Mortis

4 km x 10 km landing target for “blind” landing



Vision-Based Navigation

What is Vision-aided Navigation?

- Vision-aided Navigation Definition
  - **Vision**: Extracts information from images – use a camera as a sensor
  - **Aided**: Vision measurements are added to a filter that fuses information from multiple sensors, typically including at least an IMU
  - **Navigation**: Estimation of system position, velocity, and attitude

- Unknown Feature Tracking (“Relative” Navigation)
  - Detect and track features that were not known *a priori* through a series of images
  - Informs relative motion of the system (i.e., drifts slowly over time)
- Terrain Relative Navigation (TRN) (“Absolute” Navigation)
  - Match features in an image to a database of landmarks with known location and appearance
  - Informs absolute position of the system relative to some coordinate frame (drift-free)
  - Approach 1: Detect features in the environment and then match them to known landmarks
  - Approach 2: Search for specific landmarks predicted to appear in the camera field of view

Tracker: Unknown Feature Tracking

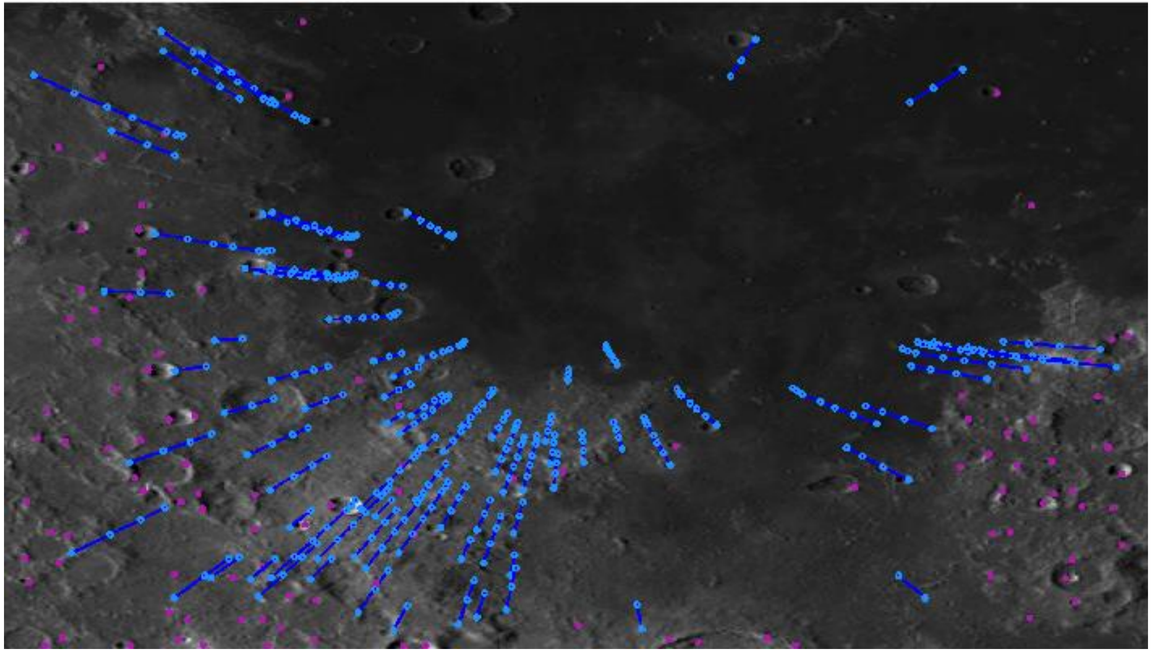
Detects and tracks *opportunistic* landmarks in consecutive images

<u>Algorithm Description</u>:

Features (points of high contrast) are detected in an image and then tracked (re-detected) in subsequent images, forming a list of 2D measurements in time.

New features are detected to replace tracks that end. Information content is proportional to track length, so the goal is to track long-lived features.

Outliers are detected and removed geometrically using multi-modal 2-frame RANSAC.



Catena: Crater-based Terrain Relative Nav

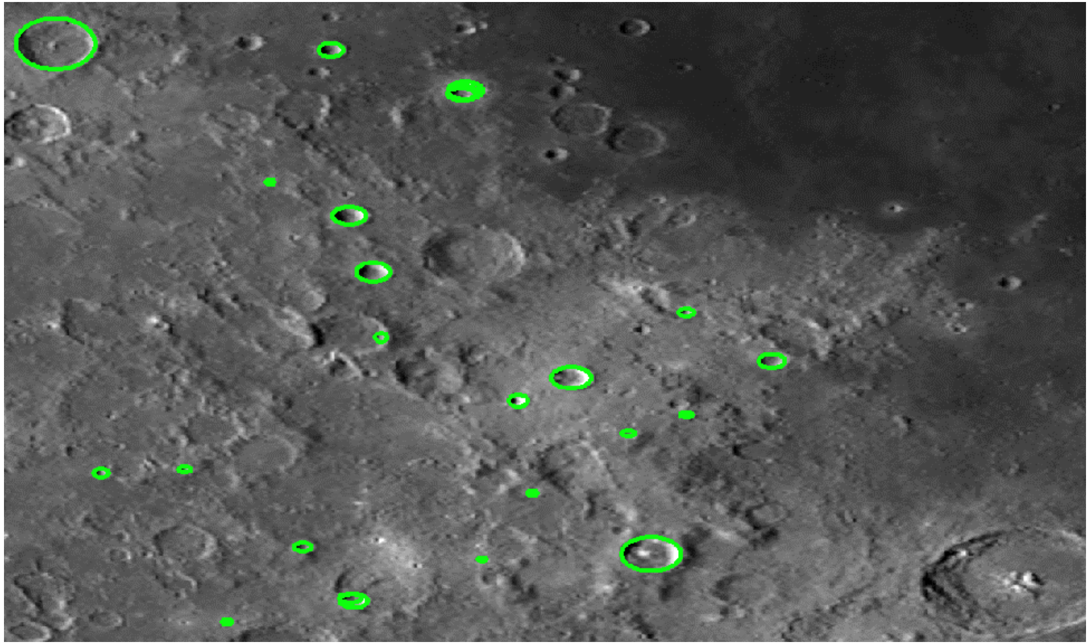
Detects craters in the camera image and matches them to a database

<u>Algorithm Description</u>:

When the sun is sufficiently low (e.g., Lunar dawn), one side of a crater is in a very dark shadow and the opposite side appears very bright in the image.

Using knowledge of the sun direction, we pair dark and bright regions of the image, extract their edges corresponding to a possible crater rim, and then fit an ellipse to these edges.

Detected craters are matched to the database using a nearest-neighbor constellation match.



IBAL: Image-based Absolute Localization (TRN)

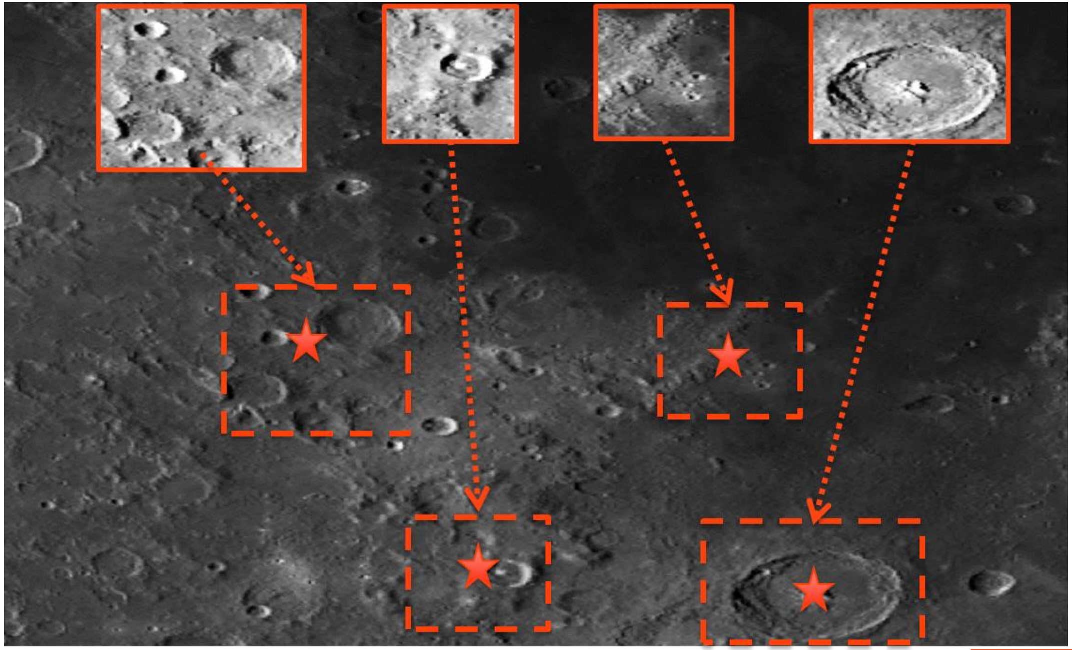
Algorithm Description:

Based on the predicted camera pose, we find the set of landmarks expected to appear in the field of view and warp them to the camera projection.

Each landmark is compared pixel-wise against the camera image using normalized cross-correlation. The landmark is located at the peak of the correlation surface.

Outliers are detected and removed geometrically using the PnP RANSAC algorithm.

Correlate terrain image patches against the camera image



Navigation Performance Analysis

Navigation System Sensitivity Analysis

- A navigation analysis was conducted using Draper's linear covariance (LinCov) tool to determine the landing error due to uncertainties or errors in the navigation system
- The vehicle's capability depends on its navigation uncertainty and guidance/control capability.
  - Preliminary <u>navigation error</u> analysis is presented
  - Guidance and control capability are assumed to be ideal for this analysis
  - No <u>dispersion</u> analysis done yet (i.e., trajectory disturbances due to guidance and control errors, unmodeled accelerations, etc.)
- This first order analysis gives a rough idea of the overall system capability including sensitivities for **position** and **velocity** navigation errors based on sensitivity to:
  - initial navigation errors
  - process noise
  - each sensor, treated as a whole

Baseline Sensors

IMU	*LN200C*
Star Tracker	*MAI-SS*
Rangefinder	*Navigation Doppler Lidar*
Velocimeter	*Navigation Doppler Lidar*
Camera	*512 x 512 pixels; 43.3 deg full FOV*

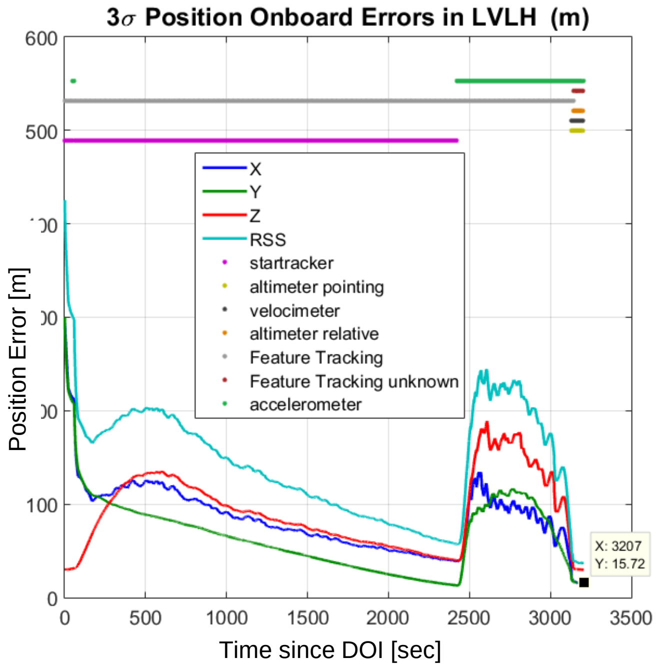
Known Feature Tracking (crater or template matching)

Up to 3 features tracked in 0.5 Hz images

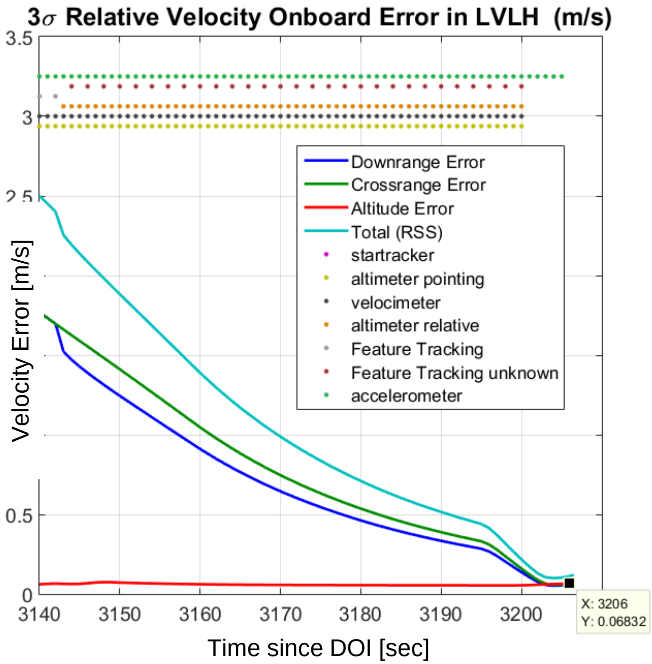
Unknown Feature Tracking

Up to 3 features tracked in 0.5 Hz images

Touchdown Absolute Position and Relative Velocity Performance



Final 3σ absolute horizontal position error = ||[15.02 15. 72]|| = 21.7 m



Final 3σ relative horizontal velocity error = ||[0.061 0.068]|| = 0.09 m/s

DOI = De-orbit insertion (start of descent from 100 km circular orbit to the lunar surface)

Vision-Nav Sensitivity Analysis

Precision Landing Relative to a Lunar Target

Component	3σ Terminal Errors		
	Absolute (Inertial) Horizontal Position [m]	Target-Relative Horizontal Position [m]	Target-Relative Horizontal Velocity [m/s]
Others (no errors active here)	0.0	0.0	0.00
Zero (no errors active)	0.0	0.0	0.00
Initial Conditions	0.7	0.0	0.00
Process Noise (SRP, attitude control)	0.0	0.0	0.00
Gyro	2.7	0.2	0.03
Accelerometer	4.4	0.4	0.05
Startracker	0.7	0.0	0.00
Altimeter Pointing	1.8	0.0	0.00
Altimeter Relative	0.5	0.1	0.00
Range Sensor (rangefinder measurement for HD)	0.1	0.0	0.00
Optical Features (camera measurement for HD)	0.0	0.1	0.00
Known Feature Tracking	20.3	0.1	0.01
Unknown Feature Tracking	5.7	1.3	0.08
Velocimeter	2.5	1.0	0.07
RSS (Total)	**22.0**	**1.7**	**0.12**
Requirement		**10.0**	**0.30**

Draper and The New Moon Race

Draper is part of five teams selected by NASA recently to conduct studies and produce prototypes of human landers for the agency’s Artemis lunar exploration program. The NASA contracts, which carry a potential value of up to $45.5M, further the agency’s goal to put American women and men on the Moon by 2024 as a step toward establishing sustainable missions by 2028.

Image Credit NASA


Discussion
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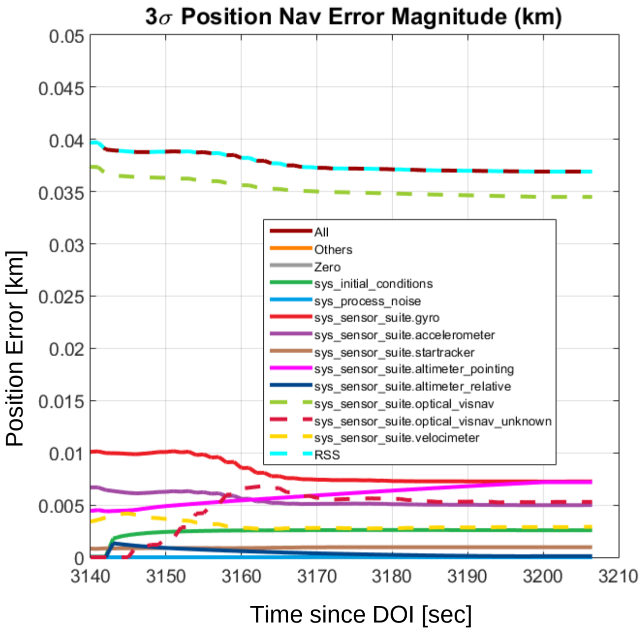
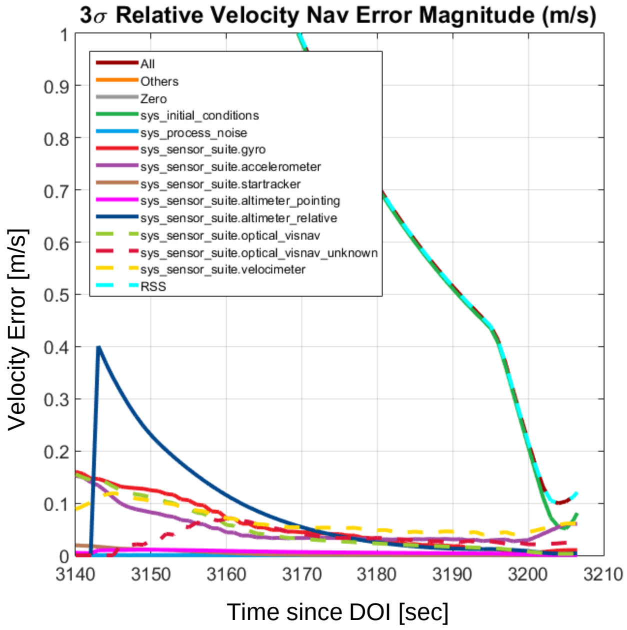
Final Position and Velocity Nav Error Sensitivity





DOI = De-orbit insertion (start of descent from 100 km circular orbit to the lunar surface)

Final position error sensitivity dominated by known feature tracking, followed by unknown feature tracking and rangefinder

Final velocity error sensitive to velocimeter, IMU, unknown feature tracking

Complementary and Future Work

- Camera trade studies and radiometry modeling
- Space-qualified processor evaluation for image processing and navigation measurement generation
- Computational benchmarking of VBN algorithms
- Closed-loop GN&C and VBN using hardware and software in-the-loop
- SPLICE Flight Test of VBN algorithms in terrestrial environment
- Draper selected as a NASA CLPS prime contractor
- Draper is a subcontractor to ispace for blind and precision lunar landings