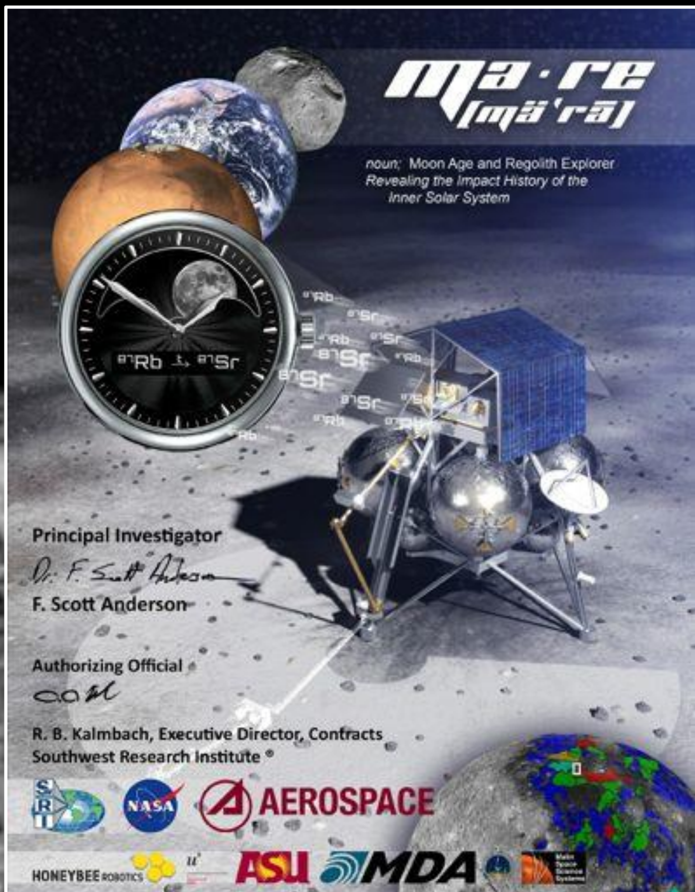
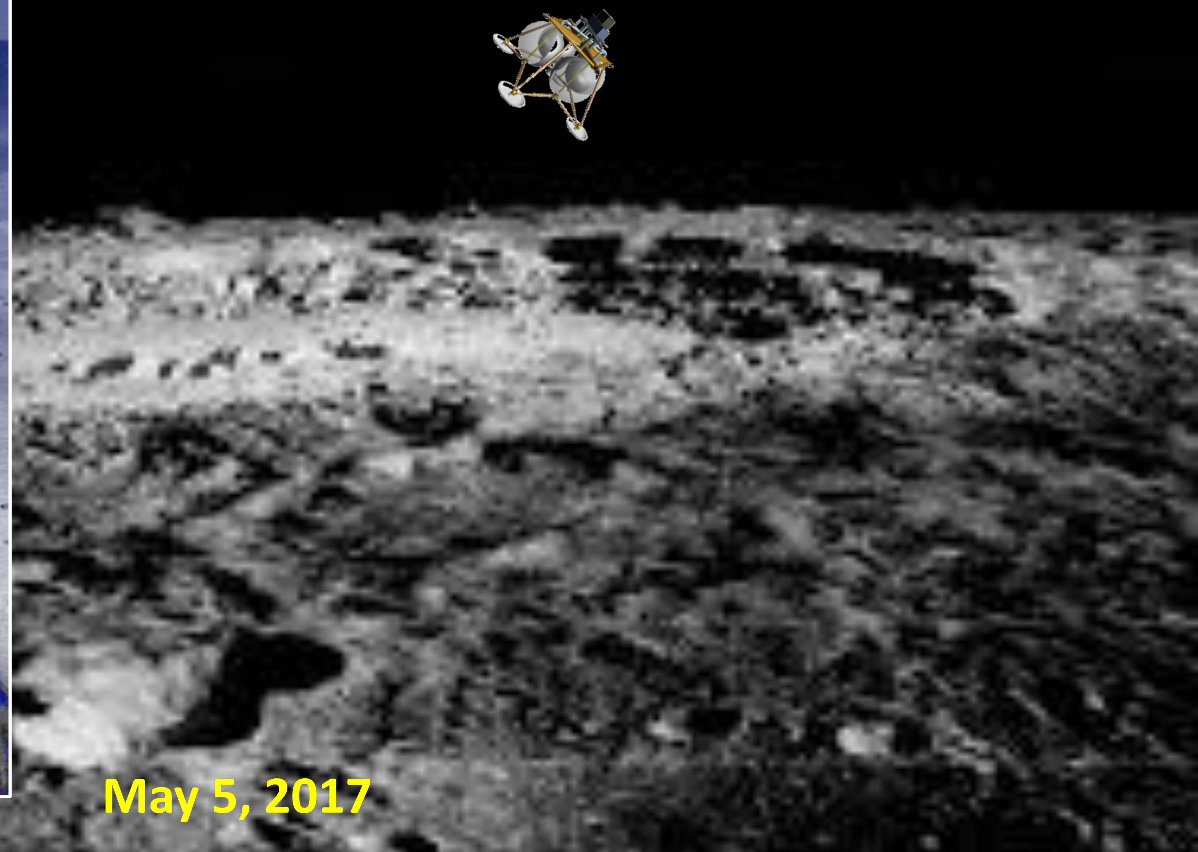
MOON AGE AND REGOLITH EXPLORER MISSION DESIGN AND PERFORMANCE

2017 Annual Technical Symposium





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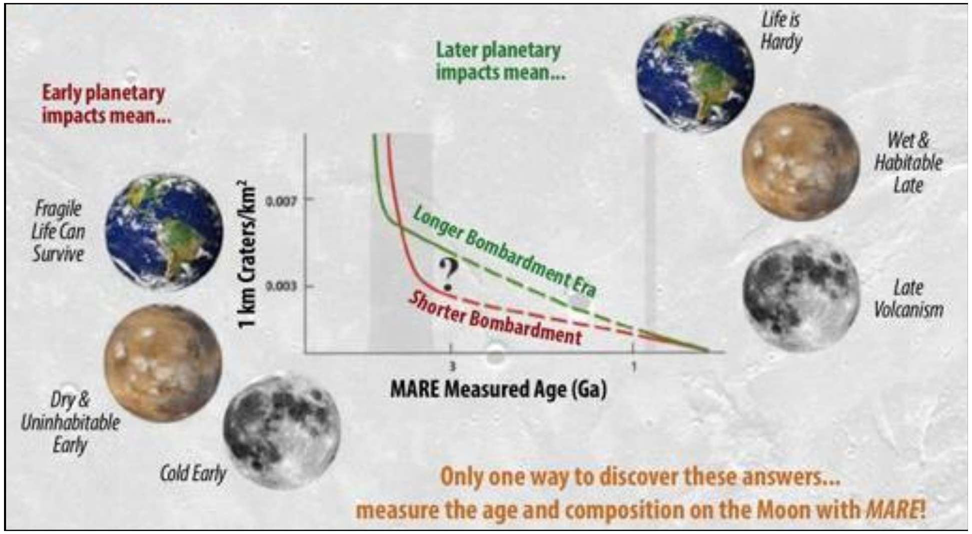
Science Rationale

- Current inner-solar-system chronology models have billion-year uncertainties in period of 1-3 billion years ago
- Understanding the timing of geological events is keystone to understanding chronology
- Lunar crater counting and sample dating provide chronology basis
  - Used to extrapolate events on Mars, Mercury, Venus, Vesta, and others
  - Used in the dynamics modeling of the early solar system



- Problem: crater counted terrains may not have been source of dated samples, and Lunar Reconnaissance Orbiter (LRO) Camera images are revealing higher crater counts than previously observed.
- Solution: date samples with well understood origins from terrain with well understood crater counts.

Science/Mission Objectives

Science Objectives

- Collection and dating of 2-3 cm rocks in a smooth, basaltic maria terrain region southwest of Aristarchus crater
- Thermophysical and mineralogical data from samples can be directly correlated with LRO data to revise lunar chronology
- Hundreds of candidate landing sites in the overall region

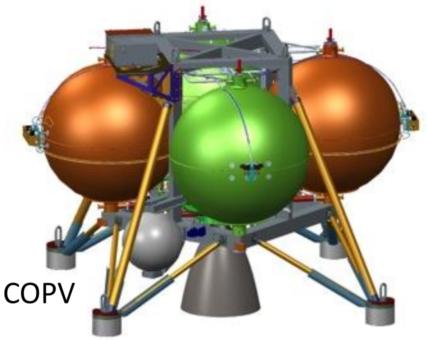
NASA Autonomous Vehicle for In-situ Science

Technical Objectives (GN&C-centric)

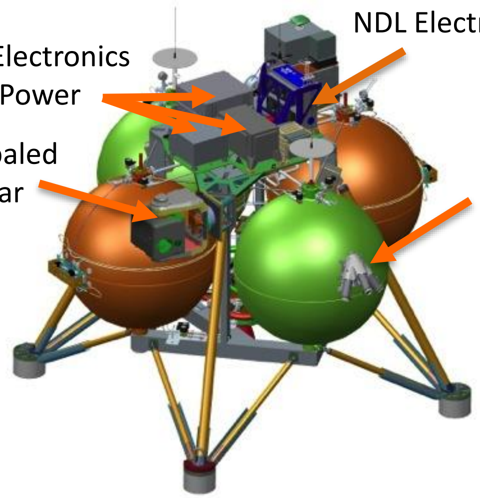
- Science requirement: land within 100m of site. Science goal: land within 20m
- Land near lunar dawn (10° Sun elevation)
- Ensure safe landing: terrain consists of surface features (e.g., small sharp craters and rocks/boulders) that pose quantifiable landing risk to the NAVIS spacecraft

Morpheus Vehicle Provided an Early Prototype for MARE NAVIS and for Testing GN&C and Propulsion

Integrated LOx/LCH_4 Propulsion System
- Throttleable Main Engine
- Integrated Cryogenic RCS
- Helium Pressurization System
- Cryogenic Feedsystem
- Aluminum Propellant Tanks



Precision landing GN&C System
- Software/Algorithms/Hardware for autonomous precision landing
- Hazard Detection (HD) for safe site identification (prototype designed for human-lander, not NAVIS, requirements)
- Navigation Doppler LiDAR (NDL) for velocimetry (NAVIS will also use for range)
- No Terrain Relative Navigation (TRN)



Integrated GN&C and Propulsion System Demonstrated in Multiple Morpheus Flight Tests

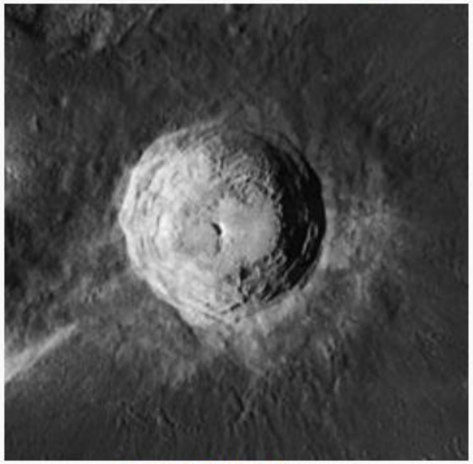
Mission Design Assumptions

- Lunar Landing Site, Lighting, and Epoch
  - Landing coordinates:
    - latitude= 23.7°, longitude= -47.4°, altitude= 0 m
    - Lunar mare terrain near Aristarchus crater
  - Landing opportunities in 2021
  - Landing epoch selected when sun elevation is 10° at landing site, at lunar dawn
    - Apollo landings required sun elevation angles between 7° and 20°*. To maximize sun-lit time in the first lunar day, suggest selecting the lowest possible sun elevation that is still supportable with landing navigation (nav).

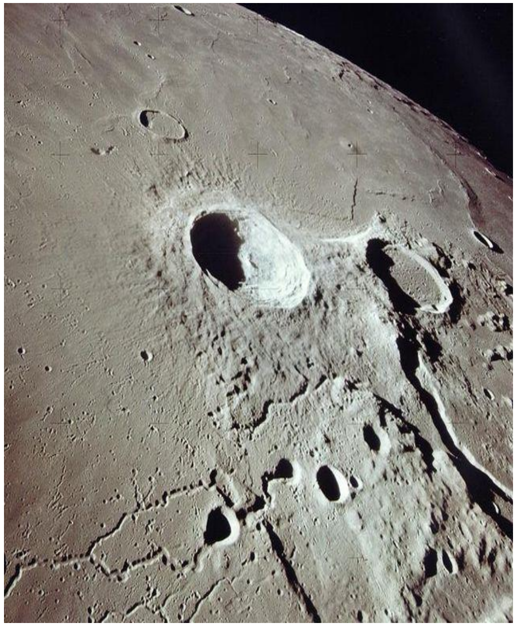
- Retrograde inclination arrival
  - LOI, DOI maneuvers conducted on lunar far side out of Earth view
  - Approach over lit surface with Sun behind spacecraft – good for visual nav

* For purposes of providing crew with good surface feature discernment and sun behind spacecraft during descent (to avoid sun glare at approach).

Aristarchus (crater)

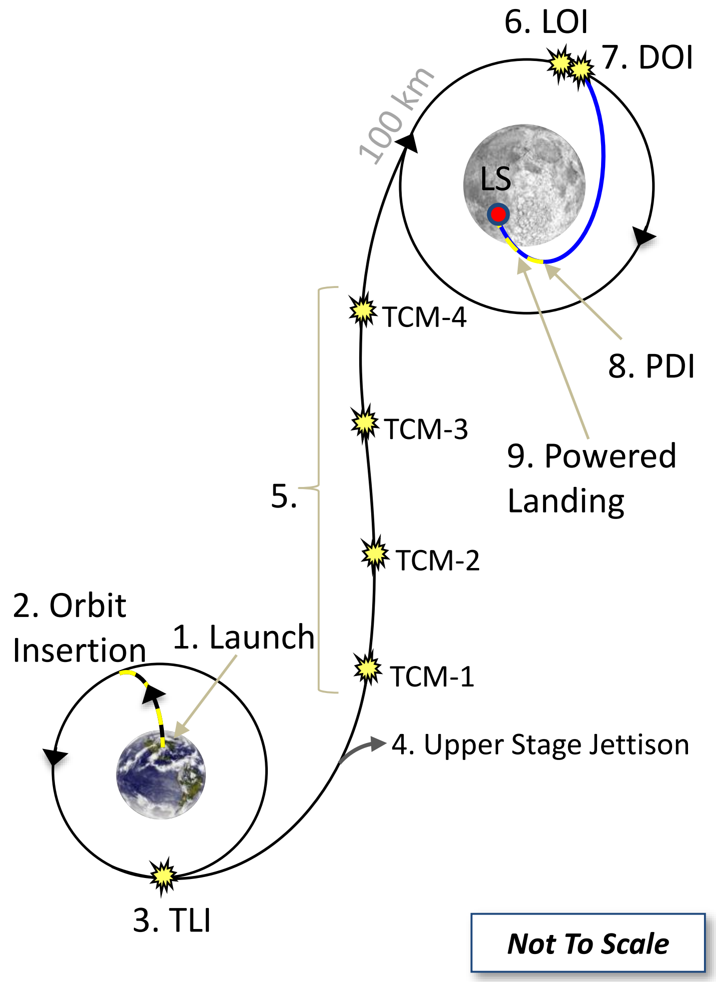


Lunar Orbiter 4 image

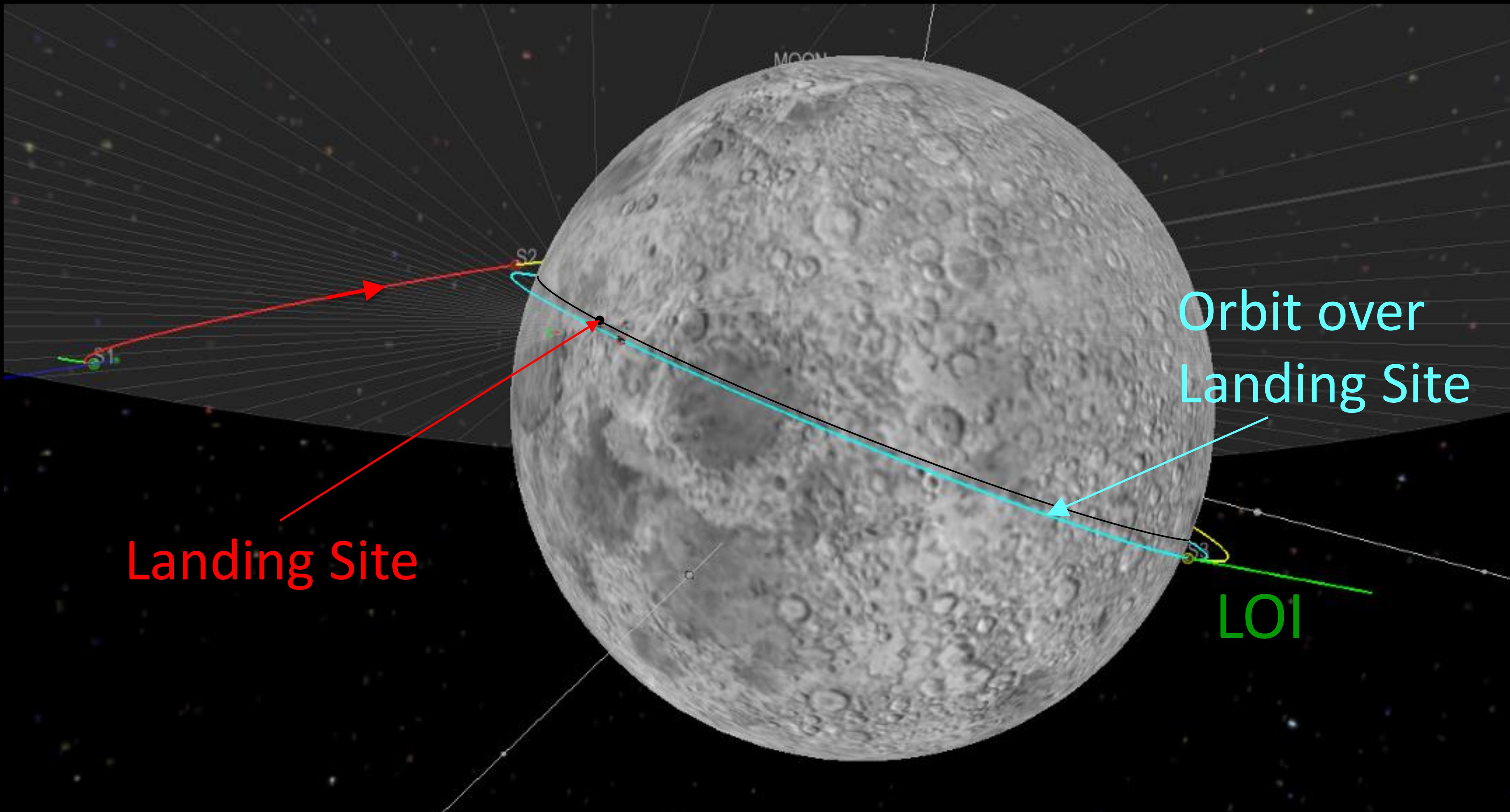


Mission Design Overview

1. Launch due East on an Atlas V 411 Launch Vehicle (LV)
2. LV inserts NAVIS into a temporary, circular Low Earth Orbit (LEO) for TLI phasing – nearly co-planar with transfer orbit
3. LV upper stage (Centaur) performs Trans-Lunar Injection (TLI) burn to achieve lunar intercept in 3-8 days (depending on launch date)
4. Upper stage jettison (all remaining maneuvers use NAVIS onboard propulsion)
5. Design for 3 Trajectory Correction Maneuver (TCM) burns – margin for optional 4th TCM
6. Lunar Orbit Insertion (LOI) burn into 100-km retrograde Low Lunar Orbit (LLO) with landing near lunar dawn and favorable approach lighting geometry for optical nav
7. Descent Orbit Initiation (DOI) burn to setup PDI
8. Powered Descent Initiation (PDI) at ~15 km altitude
9. Continuous main engine burn during Powered Descent to Landing at the science site near Aristarchus Crater



Lunar Orbit Insertion (LOI)



Lunar transfer (red, later switching to yellow) to LOI maneuver into LLO sets up spacecraft for coplanar landing.

Lunar Landing – Sun Elevation, Azimuth, Mask Angle, Sunlit and Dark Durations vs Lunar Landing Epoch

Cycle	Landing epoch	Sun Azimuth	Loss of Power/Sundown Epoch	Sunlit/Dark Duration	
	Sun Elevation Angle (deg)		Mask Angle (Deg)	Mask Angle (Deg)	
	10		5	5	
	(deg) … and rising	(deg)	(deg) … and dropping	(Days - Sunlit)	(Days - Dark)
1	January 26, 2021 20:18:44	95.67	February 09, 2021 05:18:41	13.37	15.78
2	February 25, 2021 10:52:29	96.07	March 10, 2021 19:07:16	13.34	15.76
3	March 27, 2021 00:16:07	95.97	April 09, 2021 08:24:54	13.34	15.72
4	April 25, 2021 12:21:14	95.42	May 08, 2021 21:02:43	13.36	15.65
5	May 24, 2021 23:21:04	94.60	June 07, 2021 09:02:46	13.40	15.58
6	June 23, 2021 09:44:22	93.72	July 06, 2021 20:36:36	13.45	15.53
7	July 22, 2021 20:06:47	93.02	August 05, 2021 08:01:12	13.50	15.51
8	August 21, 2021 07:02:38	92.67	September 03, 2021 19:34:43	13.52	15.53
9	September 19, 2021 18:58:10	92.78	October 03, 2021 07:33:15	13.52	15.57
10	October 19, 2021 08:06:18	93.34	November 01, 2021 20:08:16	13.50	15.64
11	November 17, 2021 22:22:45	94.20	December 01, 2021 09:24:15	13.46	15.72
12	December 17, 2021 13:25:03	95.13	December 30, 2021 23:16:17	13.41	

Performance Trades

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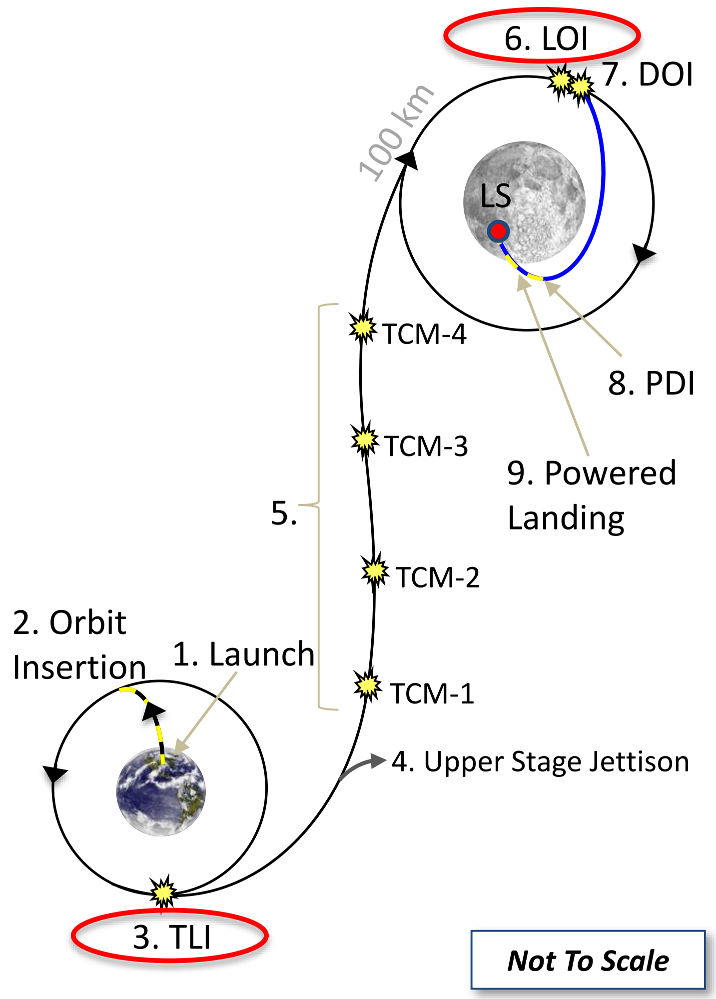
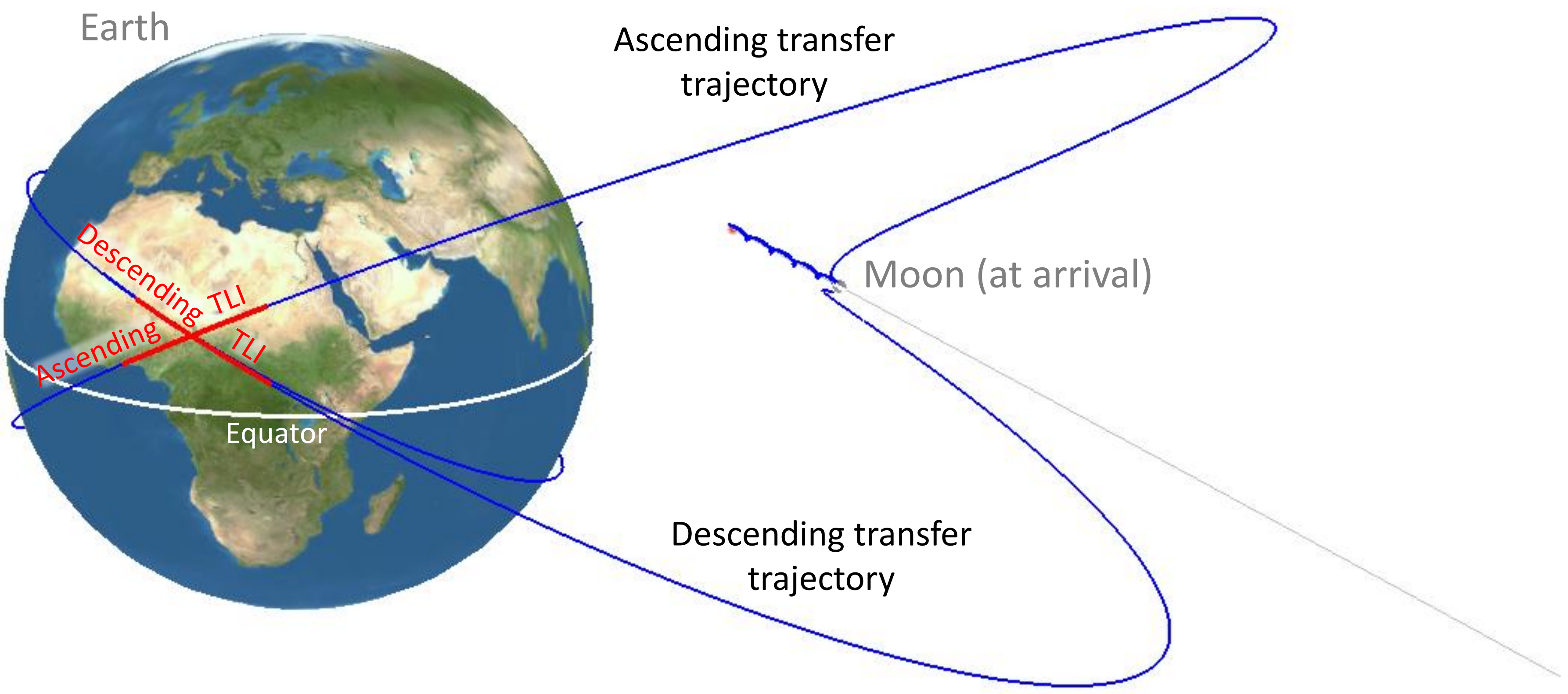
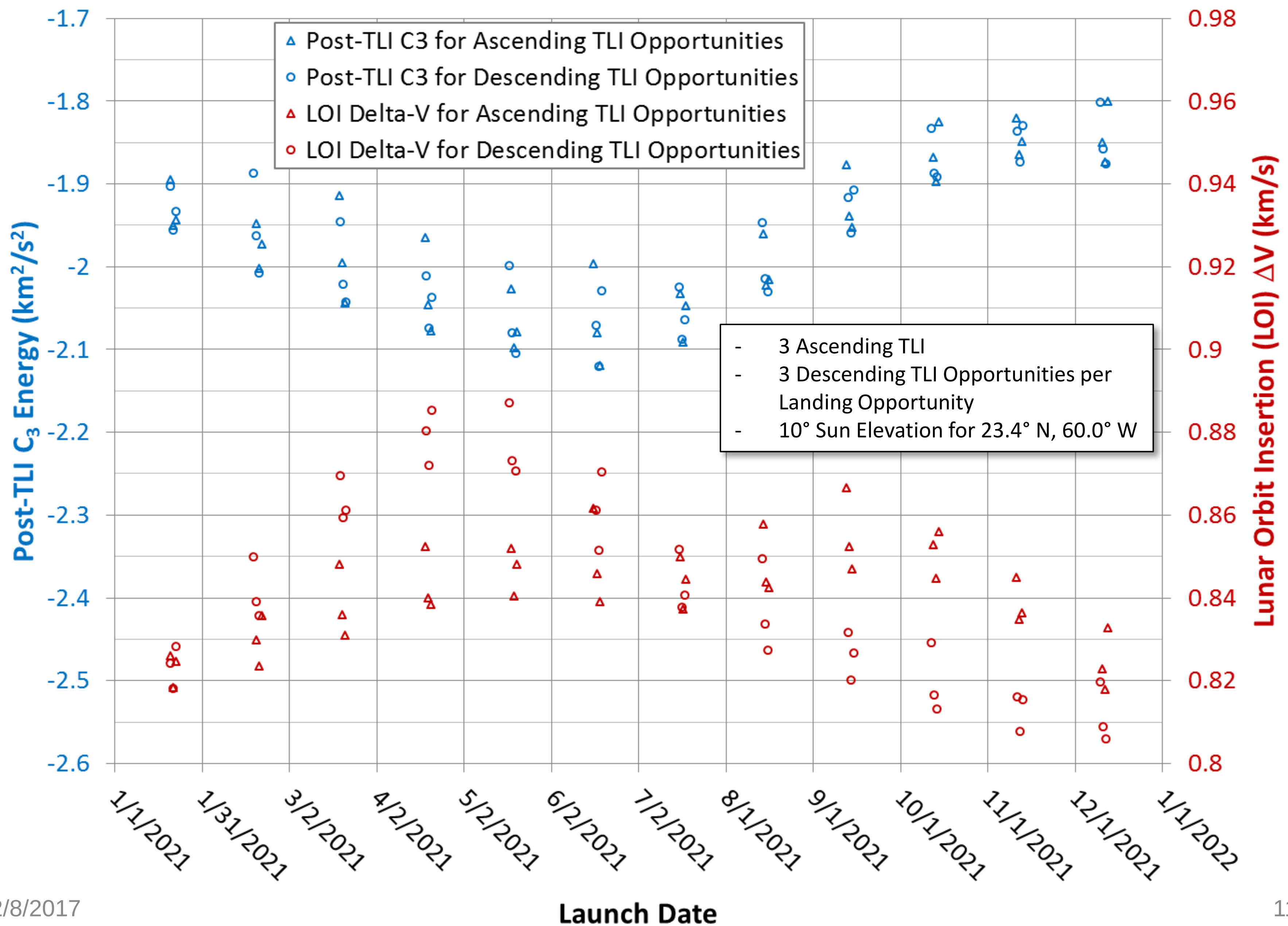
8. Powered Descent Initiation (PDI) at 15 km altitude
9. Continuous main engine burn during Powered Descent to Landing at the science site near Aristarchus Crater



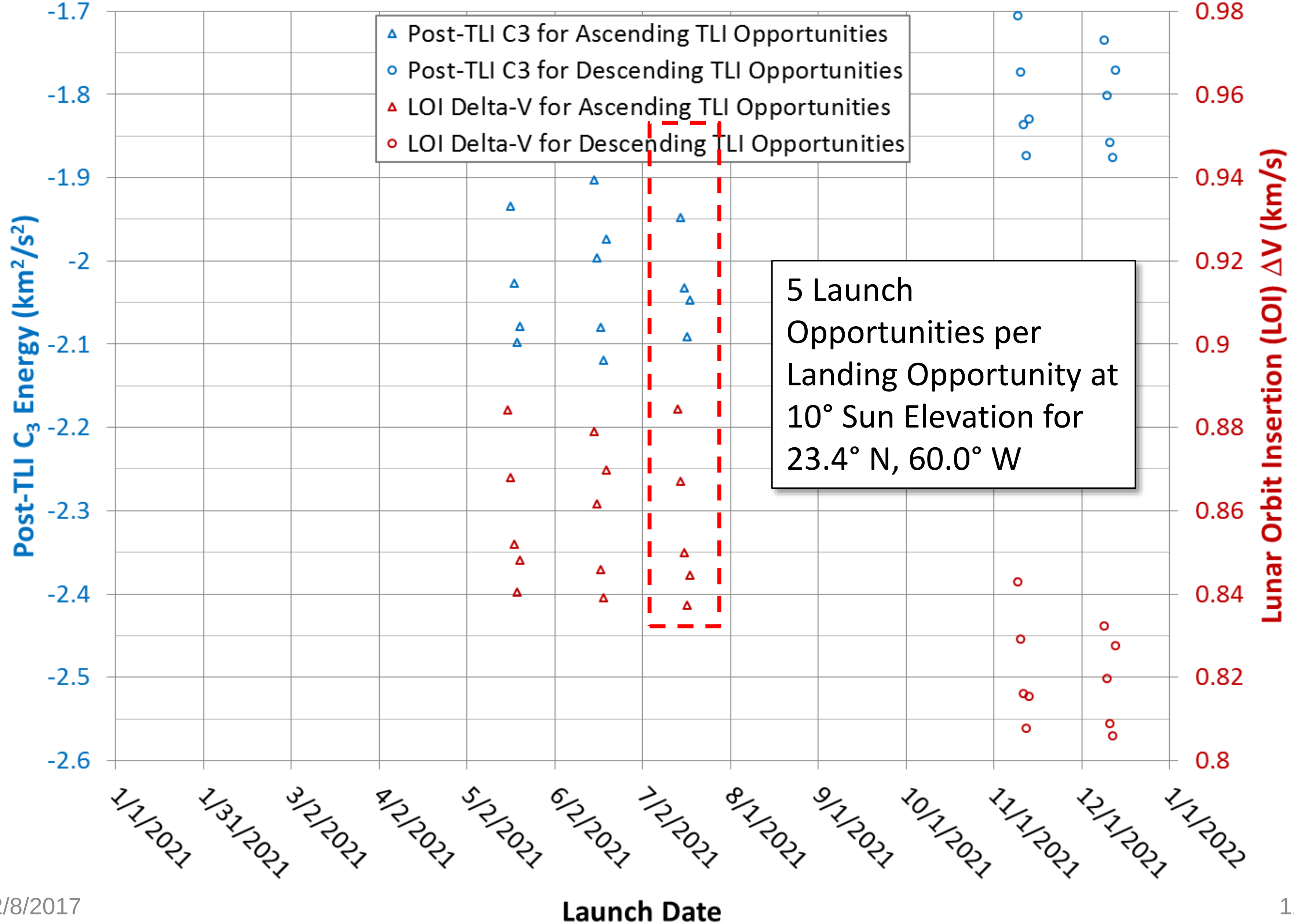
TLI: Ascending vs Descending Node Departure



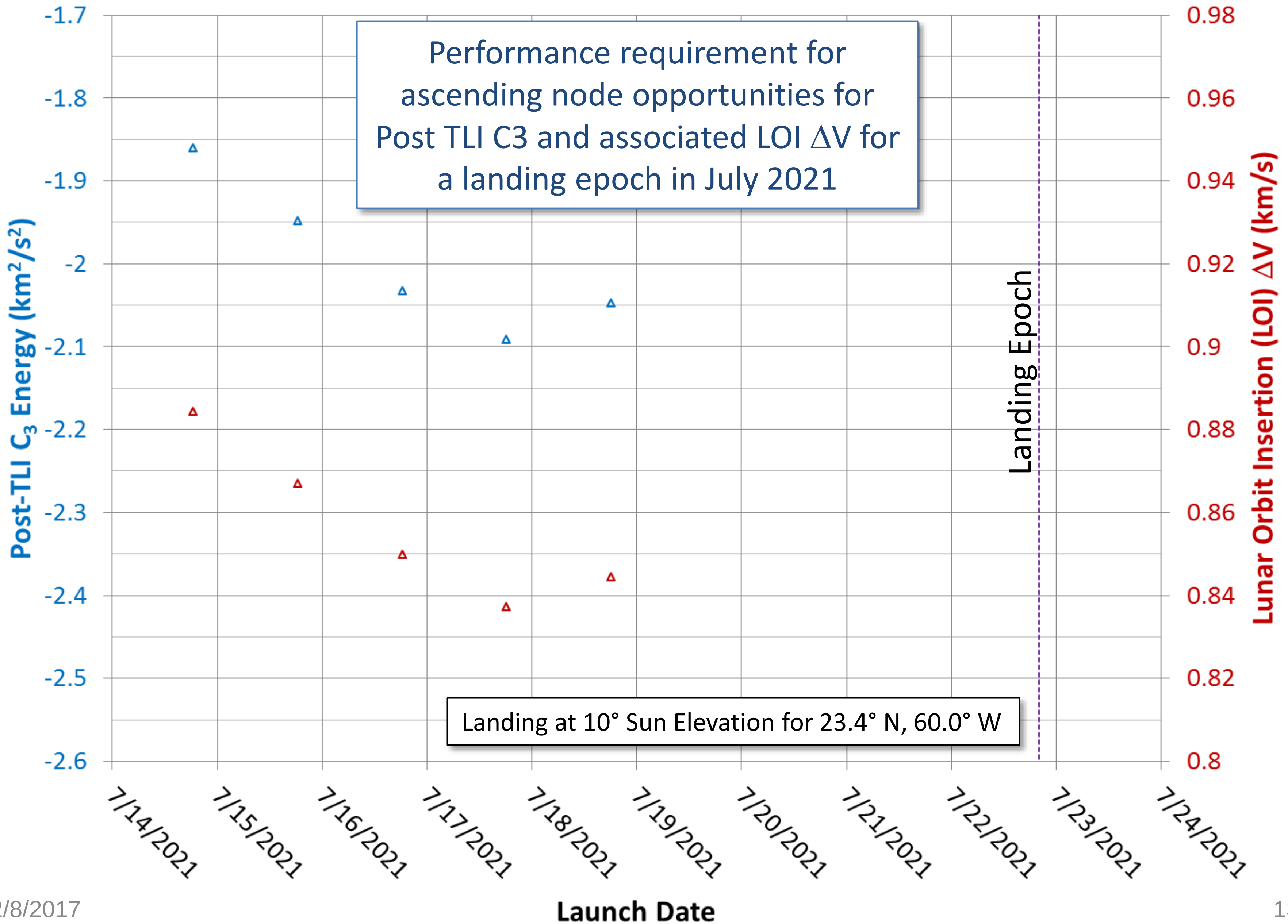
TLI and LOI Performance Scan for 2021



Worst TLI and LOI Performance Cases for 2021

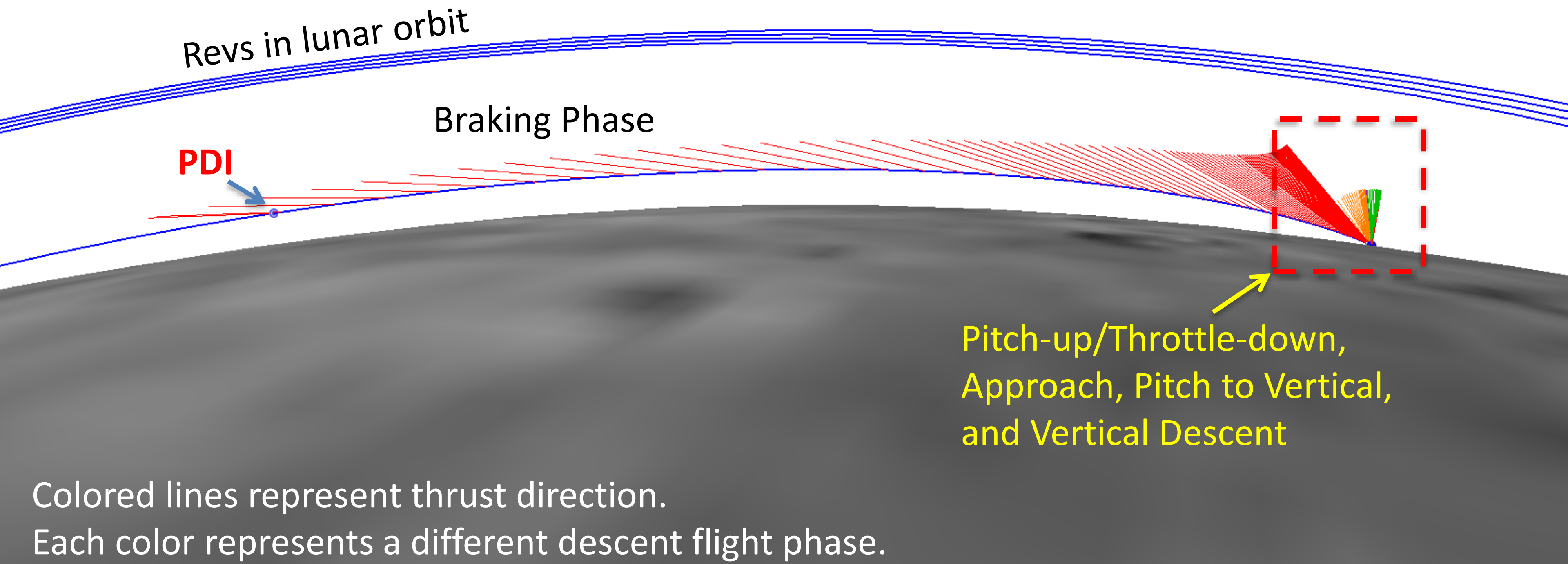


TLI and LOI Performance for Launch Opportunities in July 2021



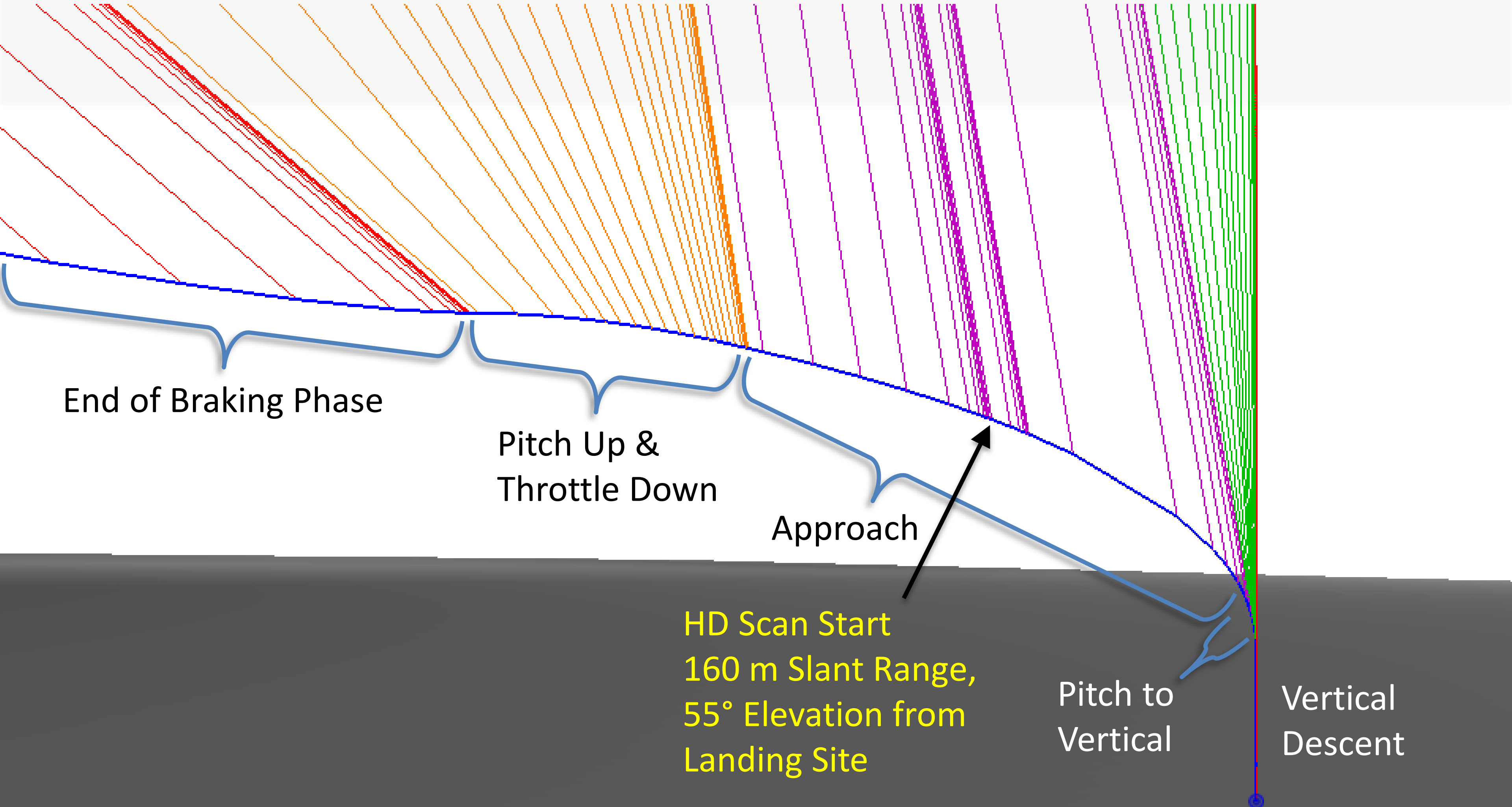
Powered Descent/Landing Sequence

- DOI to PDI coast time - 1hr
- PDI to touchdown: 11 min, 522 km surf dist, 17.2° arc
- Nominal braking phase throttle set to 80% for control authority



Powered Descent Landing Phases

Pitch-up/Throttle-down, Approach, Pitch to Vertical, and Vertical Descent

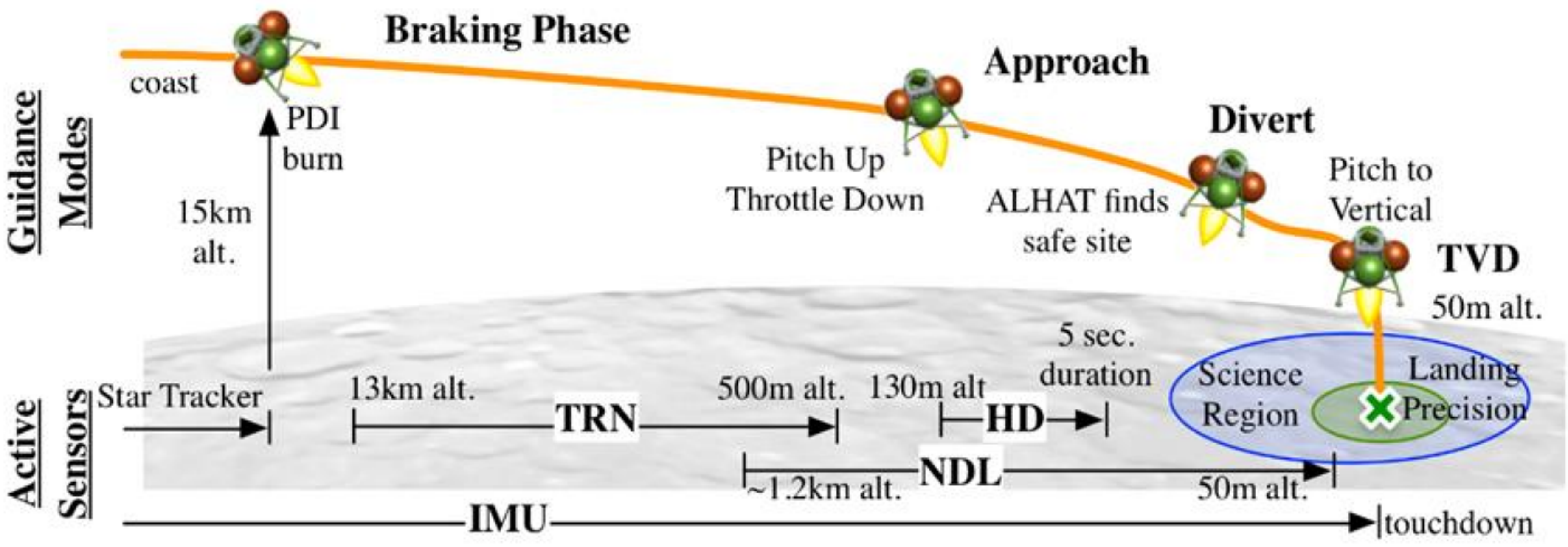


Colored lines represent thrust direction.
Each color represents a different flight phase.

Powered Descent
Including Active Sensors

PDI	Powered Descent Initiation
TRN	Terrain Relative Navigation
HD	Hazard Detection
NDL	Navigation Doppler Lidar
IMU	Inertial Measurement Unit
TVD	Terminal Vertical Descent

Notional



Example Nominal Mission Timeline

Mission Event	Epoch (UTC)	MET	Event Duration	Nominal ΔV	Active Vehicle	Comments
	(m/d/yyyy hh:mm:ss)	(h:mm:ss)	(h:mm:ss.s)	(m/s)		
Launch	7/16/2021 18:15:07	0:00:00	0:09:00.0	TBD: Provided by Atlas V & Centaur	Atlas V	Due East launch.
Orbit Insertion / Stage 2 MECO	7/16/2021 18:24:07	0:09:00			Centaur Upperstage	Insertion into 200 km circular LEO at 28.5 deg inclination.
LEO Coast			1:17:54.6		Centaur Upperstage	LEO Duration between 10-120 min.
TLI (Impulsive)	7/16/2021 19:42:02	1:26:55	TBD	TBD: Centaur	Centaur Upperstage	
Begin Trans-Lunar Coast			135:36:03.9		Centaur Upperstage	Transfer times from 3 to 8 days.
Jettison TLI Stage	TBD	TBD		TBD	Centaur & MARE Lander	Target Centaur US to impact moon.
TCM 1	TBD	TBD		TBD	MARE Lander	
TCM 2	TBD	TBD		TBD	MARE Lander	
TCM 3	TBD	TBD		TBD	MARE Lander	
LOI Start	7/22/2021 11:18:05	137:02:58	0:05:28.2	849.9	MARE Lander	Insertion into 100 km circ retrograde LLO.
LOI End	7/22/2021 11:23:34	137:08:27			MARE Lander	
LLO Coast			7:30:44.6		MARE Lander	3-4 revs in LLO for Nav.
DOI Start	7/22/2021 18:54:18	144:39:11	0:00:05.4	16.0	MARE Lander	DOI reduces periapse to 15 km.
DOI End	7/22/2021 18:54:24	144:39:17			MARE Lander	Assumes MARE main engine.
Descent Orbit			1:01:20.0		MARE Lander	About half a rev.
PDI / Braking Start	7/22/2021 19:55:44	145:40:37	0:09:47.4	1811.9	MARE Lander	80% throttle setting.
Pitch Up and Throttle Down	7/22/2021 20:05:31	145:50:24	0:00:44.6	72.0	MARE Lander	Reduced throttle.
Approach Start	7/22/2021 20:05:39	145:50:32			MARE Lander	Approach pitch 80°. HD Lidar scan.
Pitch to Vertical	7/22/2021 20:06:14	145:51:07			MARE Lander	
Vertical Descent	7/22/2021 20:06:16	145:51:09			MARE Lander	Vertical descent from 50 m alt.
10 m Altitude	7/22/2021 20:06:34	145:51:27	0:00:18.2	31.9	MARE Lander	Brake to 1 m/s at 10 m altitude.
Touchdown	7/22/2021 20:06:47	145:51:40	0:00:13.1	21.8	MARE Lander	Touchdown at 1 m/s

Summary

- There exist feasible mission opportunities given the assumed launch vehicle capabilities and lander assumptions for the MARE mission
- There are multiple launch opportunities corresponding to each monthly landing opportunity
- The trajectory design supports navigation sensor suite pointing requirements within available propellant (ΔV) limits

Epilogue

- MARE was not selected as a 2015 NASA Discovery Mission
- The MARE studies developed analysis tools, design concepts, and capabilities that can be leveraged for future proposals or projects
- The flow down of MARE mission requirements into NAVIS GN&C is driving follow-on ALHAT project efforts
  - 3rd-generation NDL prototype to achieve performance needed for both NAVIS and other Mars-landers. Will be flight tested in 2016 through ALHAT COBALT project.
  - The HD design concept for NAVIS is being further developed through other ALHAT development efforts within the NASA/AES CATALYST program

References

- F.V. Bennett, "Apollo Experience Report – Mission Planning For Lunar Module Descent And Ascent.", *NASA Technical Note, NASA TN D-6846,* June 1972, pp. 21-25
- J.Y. Giorgini, "JPL's On-Line Solar System Data Service." *Bulletin of the American Astronomical Society*, Vol. 28, No. 3, 1996, p. 1158.
- C.A. Ocampo and J.S. Senent, "The Design and Development of Copernicus: A Comprehensive Trajectory Design and Optimization System." *Proceedings of the International Astronautical Congress*, 2006
- J. Williams, J.S. Senent, D.E. Lee, "Recent Improvements to the Copernicus Trajectory Design and Optimization System." *Advances in the Astronautical Sciences*, 2012.
- J. Williams, J.S. Senent, C.A. Ocampo, R. Mathur, "Overview and Software Architecture of the Copernicus Trajectory Design and Optimization System." *4th International Conference on Astrodynamics Tools and Techniques*, 2010.
- W.M. Folkner, J.G. Williams, D.H. Boggs, "The Planetary and Lunar Ephemeris DE 421." *Interplanetary Network Progress Report*, August 15, 2009, pp. 42-178.
- B.A. Archinal, A'Hearn, M. F., Bowell, E., Conrad, A., Consolmagno, G. J., Courtin, R., . . . Williams, I. P. (2011, February). Report of the IAU Working Group on Cartographic Coordinates and Rotational Elements: 2009. *Celest Mech Dyn Astr*, 109(2), pp. 101-135. doi:10.1007/s10569-010-9320-4
- C.D. Epp, E.A. Robertson, J.M Carson III, "Developing Autonomous Precision Landing and Hazard Avoidance Technology from Concept through Flight-Tested Prototypes," Proc. AIAA GN&C Conference, AIAA 2015-0324, Kissimmee, FL, Jan. 5–8 2015
- J.M. Carson, A.E. Johnson, G.D. Hines, W. Johnson, F.S. Anderson, S. Lawrence, D.E. Lee, A. Huertas, F. Amzajerdian, J.B. Olansen, J. Devolites, W.J. Harris, N. Trawny, G.L. Condon, L. Nguyen, "GN&C Subsystem Concept for Safe Precision Landing of the Proposed Lunar MARE Robotic Science Mission", 2016 AIAA SciTech/GN&C Conference, AIAA 2016-0100, doi: 10.2514/6.2016-0100.
- G. L. Condon, D. E. Lee, J. M. Carson, "Moon Age and Regolith Explorer (MARE) Mission Design and Performance" , 2017 Space Flight Mechanics Meeting, San Antonio, Texas, AAS 17-259.

Proposed Delta-V Sizing Budget*

Maneuver	Vehicle ΔV
TCM1	5 m/s
TCM2	1 m/s
TCM3	1 m/s
LOI	1000 m/s
DOI	20 m/s
PDI to Pitchover/Throttle-Down	700 m/s
Pitchover/Throttle-Down	700 m/s
Vertical Landing	600 m/s
LOI Dispersion	20 m/s
Landing Dispersion	20 m/s
RCS Control	10 m/s

* Pre-analysis

Total ΔV = 2,977 m/s

Lander Mission

- Two weeks of science during lunar daylight
- Robotic arm on lander acquires samples for science instruments
- Surface power: fixed solar arrays and rechargeable batteries
- Landing oriented for power generation and thermal dissipation