Apollo Mission Techniques
Lunar Orbit Activities - Part 1a

Objectives

- Identify and describe the following aspects of the Apollo lunar orbit activities from a trajectory perspective:
  - Planned sequence of events/rationale for all missions
  - Flight experiences and lessons learned

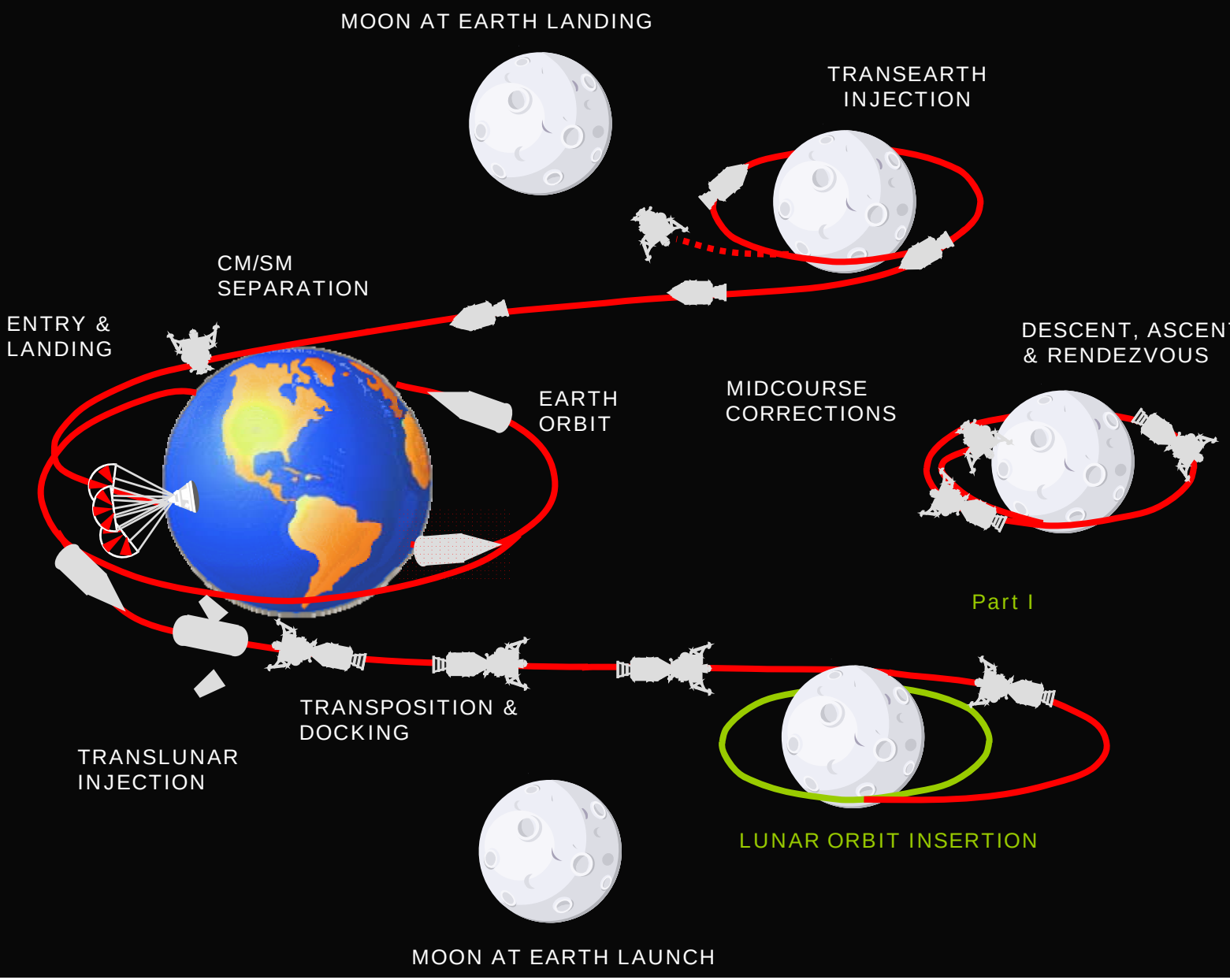
Part 1b of this lesson will cover:

- Detailed mission techniques and decision points for the Apollo J-series (15-17) missions

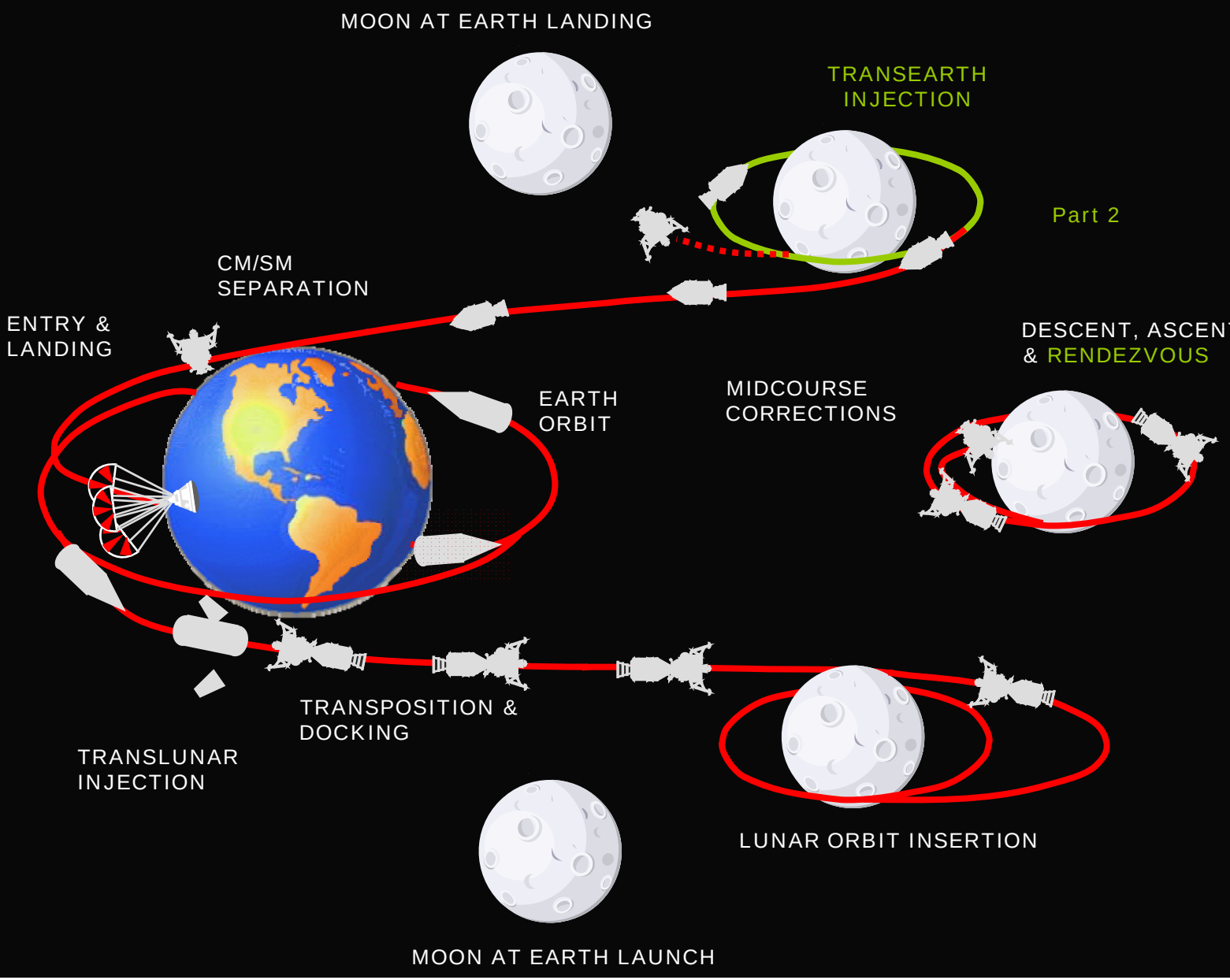
Scope

- Apollo Mission Techniques lesson sequence:
  - Launch and Launch Phase Aborts
  - Earth Parking Orbit and Translunar Injection
  - Translunar Midcourse Corrections and Lunar Orbit Insertion (LOI)
  - Lunar Orbit Activities, Part 1a and 1b
    - LOI to Powered Descent Initiation (PDI)
  - Lunar Descent
  - Lunar Surface Phase
  - Lunar Powered Ascent
  - Lunar Orbit Activities, Part 2a and 2b
    - Post-insertion to Transearth Injection (TEI)
  - TEI, Midcourse Corrections, and Entry

Scope


MOON AT EARTH LANDING
TRANSEARTH INJECTION
CM/SM SEPARATION
ENTRY & LANDING
EARTH ORBIT
MIDCOURSE CORRECTIONS
DESCENT, ASCENT & RENDEZVOUS
Part I
TRANSPOSITION & DOCKING
TRANSLUNAR INJECTION
LUNAR ORBIT INSERTION
MOON AT EARTH LAUNCH

Scope


MOON AT EARTH LANDING
TRANSEARTH INJECTION
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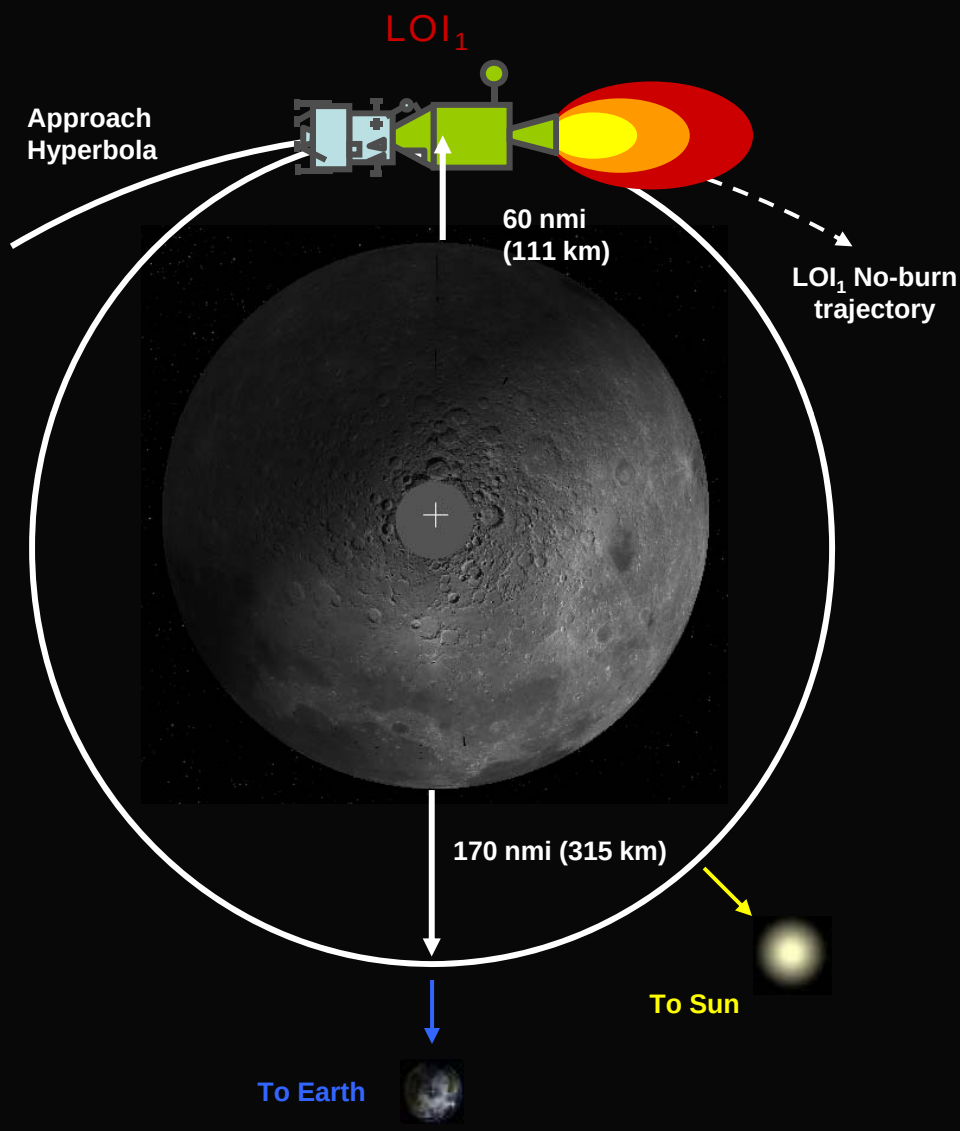
Initial Conditions: Lunar Orbit Insertion

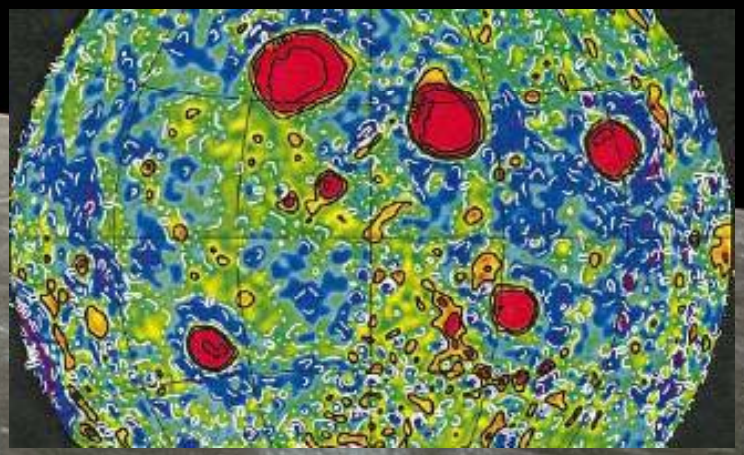
- Targeted by Mission Control Center (MCC) to place the Command and Service Module (CSM)/Lunar Module (LM) stack in a 170x60 n.mi. (315x111 km) lunar orbit
- Performed using the Service Propulsion System (SPS)
- Magnitude ranged from 2800 to 3000 fps (850-915 m/s)



Lighting shown representative of Fra Mauro landing (Apollo 13-14)

Apollo 8 Objectives

- Primary Mission Objective
  - Test CSM in lunar orbit
- Lunar Orbit Objectives
  - Perform landmark tracking and photography of prospective Apollo landing sites
  - Measure the effects of irregularities in lunar gravity (mascons) on an orbiting spacecraft
    - First observed during Lunar Orbiter program



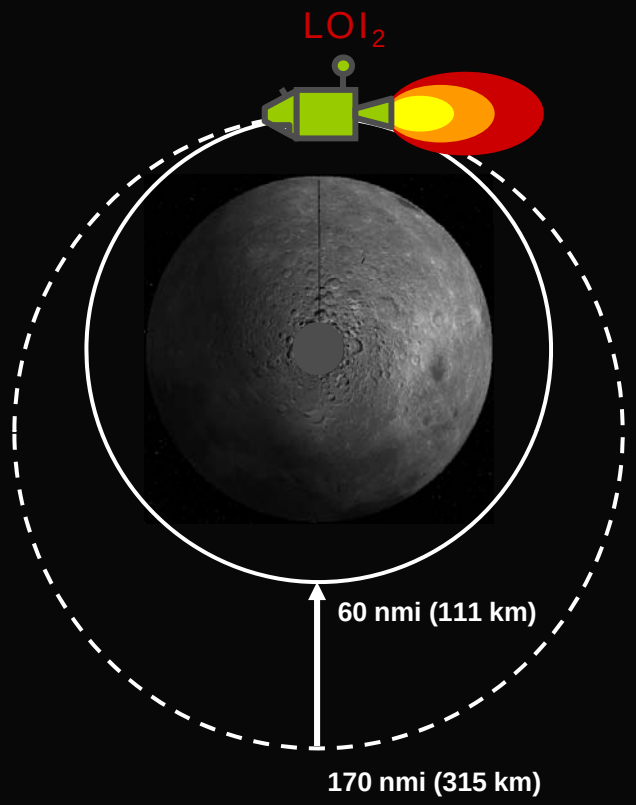
Gravitational map of lunar near side (Konopliv *et al*)

Apollo 8 Sequence of Events

Event	GET (h:m:s)*	PROP	ΔV_{TOT}, fps(m/s)*	HAxHP, nmi(km)*
LOI_1	69:07:29	SPS	2991 (912)	170x60 (315x111)
LOI_2	**73:30:53**	**SPS**	**138 (42)**	**60x60 (111x111)**

***Planned values for Ground Elapsed Time (GET), total delta-V (ΔV_{TOT}), height of apocynthion (HA), and height of pericynthion (HP)**

- LOI_2 targeted by MCC to circularize CSM in a 60 n.mi. (111 km) lunar orbit
- Performed using the SPS two orbits after LOI_1
- TEI performed ten orbits after LOI_1



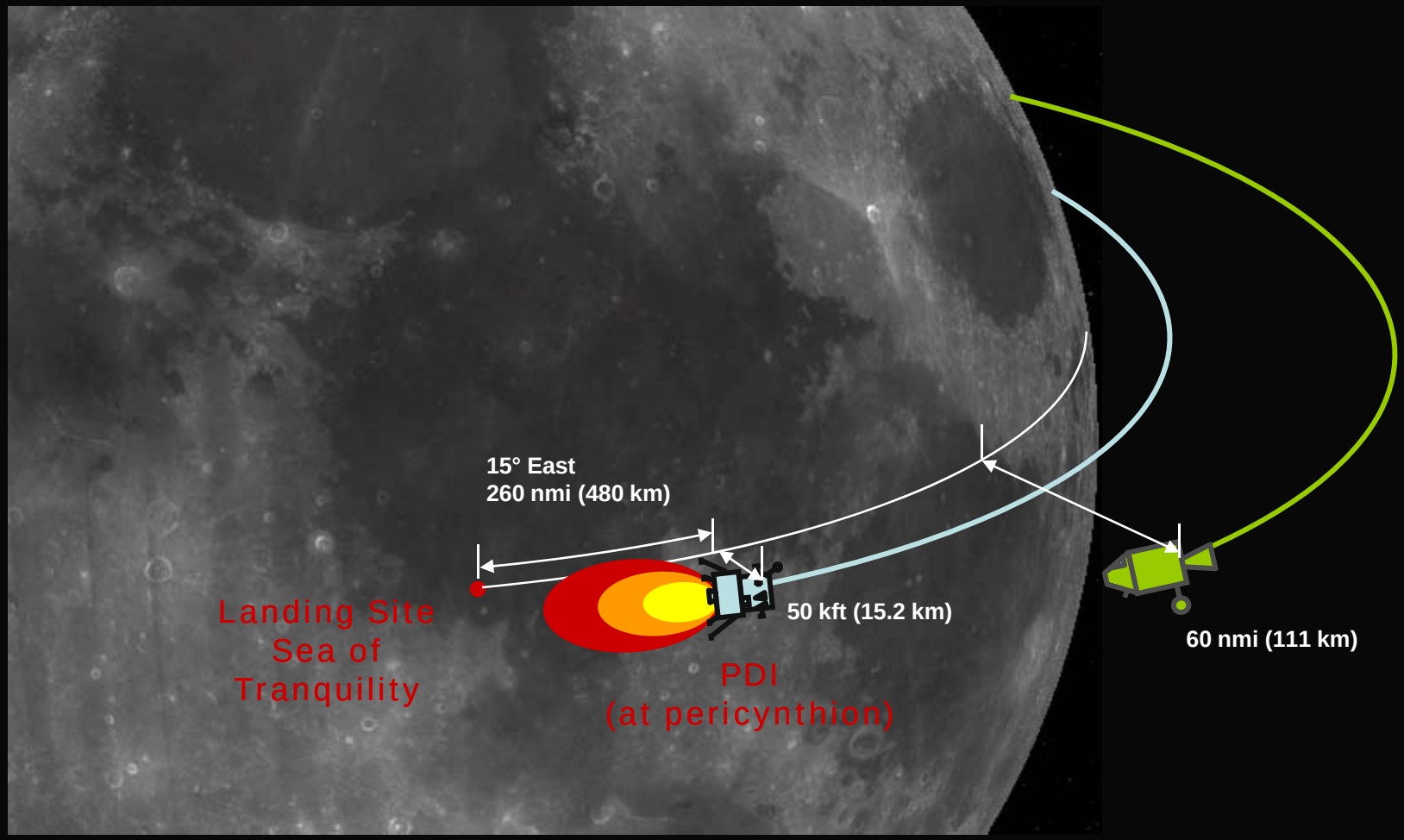
Apollo 8 Flight Experience

- Effects of mascons on Apollo 8 trajectory were approximately twice that expected from Lunar Orbiter results
  - Height of pericynthion decreased, and apocynthion increased, approximately 0.3 nmi (0.56 km) per rev
  - Final orbit 63.6 x 58.6 nmi (118 x 109 km)
  - Did not affect Apollo 8 targeting but could have had significant effects on a lunar landing
  - Resulted in intensive effort to refine lunar gravity models for future missions

Apollo 10 Objectives

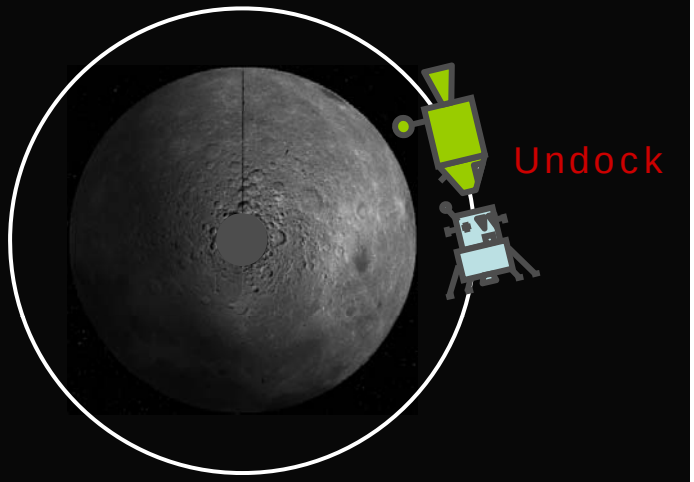
- Primary Mission Objective
  - Test LM in lunar orbit
- Lunar Orbit Objectives
  - Perform “dress rehearsal” for Apollo 11 landing
  - Same lunar orbit, same targeted landing site
  - Further refine lunar gravity models

End Conditions: Powered Descent Initiation

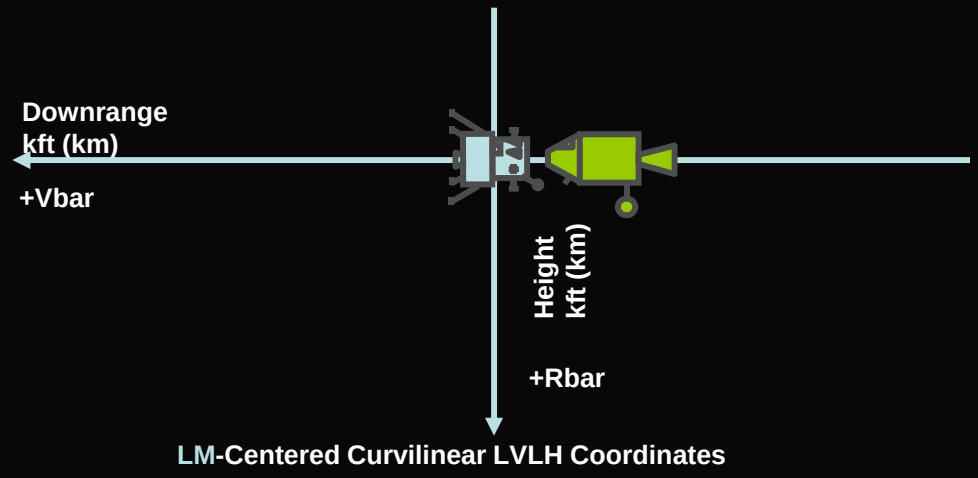


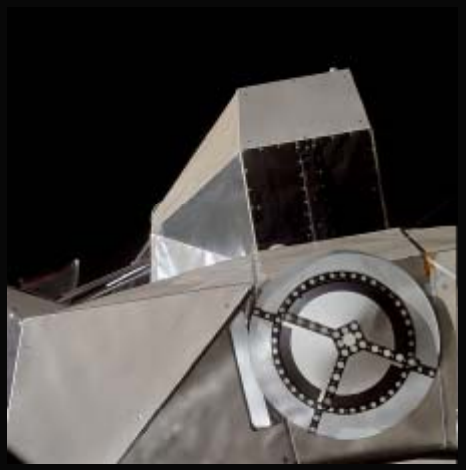
Apollo 10 Sequence of Events

Event	GET (h:m:s)	PROP	ΔV_{TOT}, fps(m/s)	HAxHP, nmi(km)
LOI_1	75:45:43	SPS	2974 (907)	170x60 (315x111)
LOI_2	80:10:45	SPS	138 (42)	60x60 (111x111)
Undock	**98:10:00**			
SEP	98:35:16	SM RCS	2.5 (0.76)	
DOI	99:33:59	DPS	71 (22)	60x8 (111x15)
POI	100:46:21	DPS	195 (59)	194x8 (359x15)
Staging	102:33:34			
AOI	102:43:18	APS	207 (63)	45x8 (83x15)



- LOI_1, LOI_2 same as Apollo 8
- Undocking one rev earlier post-LOI_1 relative to Apollo 11 to reduce length of crew day
- Undocking ~1¼ orbits prior to planned PDI





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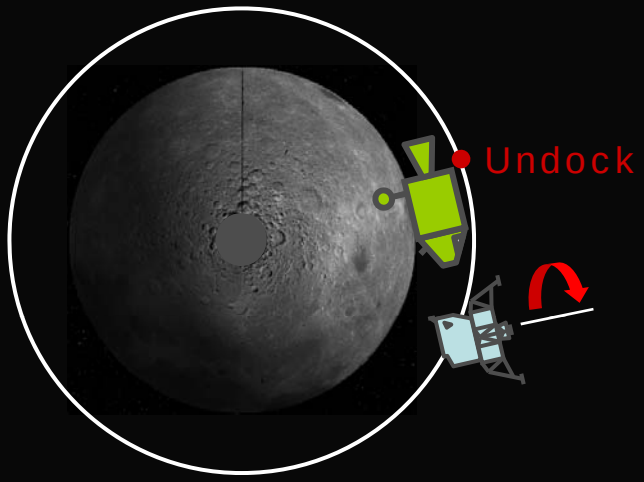
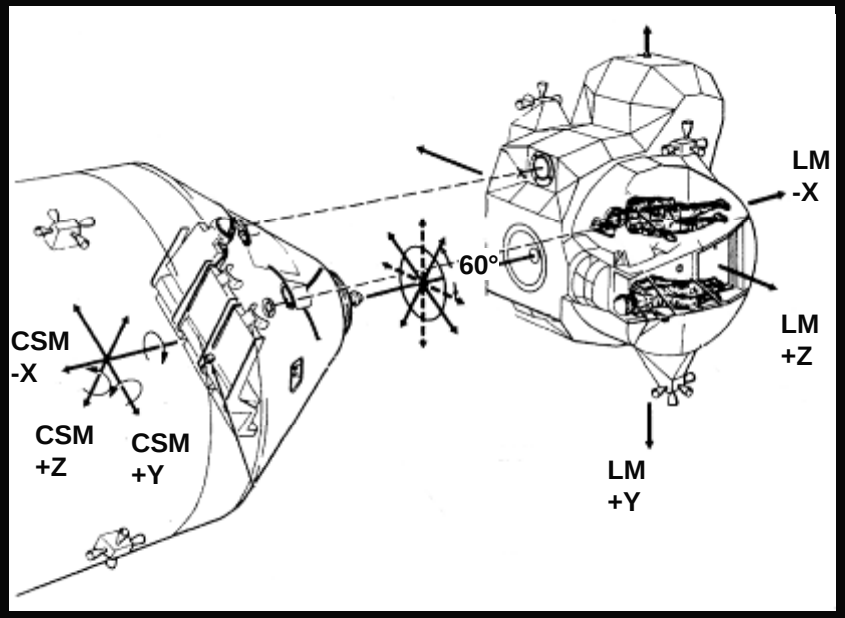
- LM yawed left 60°, pitched up 90° to point forward windows at CSM, then yawed 360° for landing gear inspection





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POI	100:46:21	DPS	195 (59)	194x8 (359x15)
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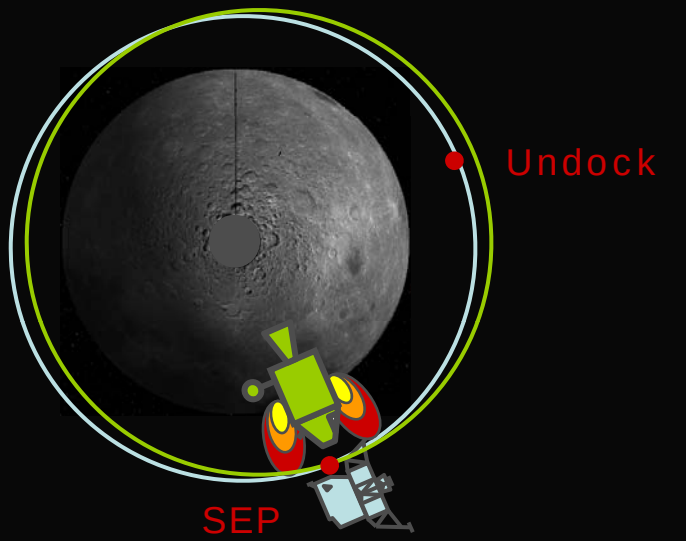
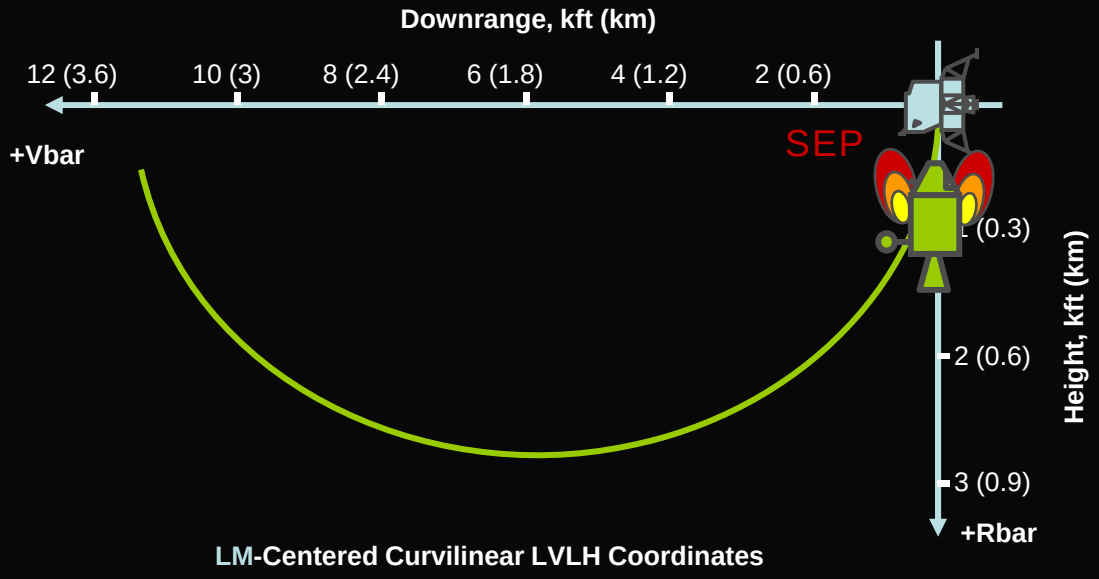
- CSM performed radial-in RCS SEP burn one orbit before planned PDI time





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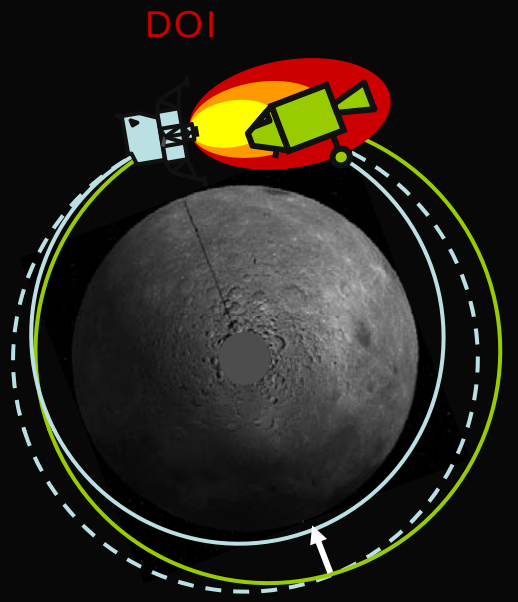
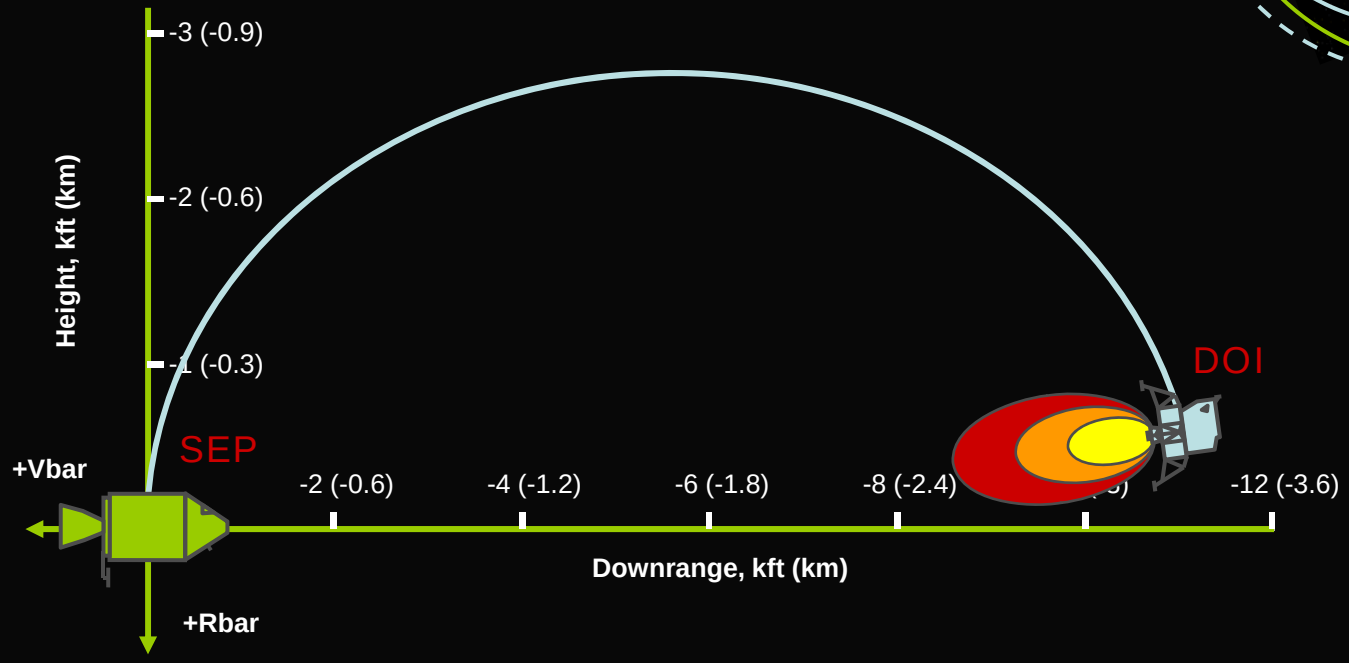
POI	100:46:21	DPS	195 (59)	194x8 (359x15)
Staging	102:33:34			
AOI	102:43:18	APS	207 (63)	45x8 (83x15)

- LM performed Descent Orbit Initiation (DOI) ½ orbit prior to planned PDI time





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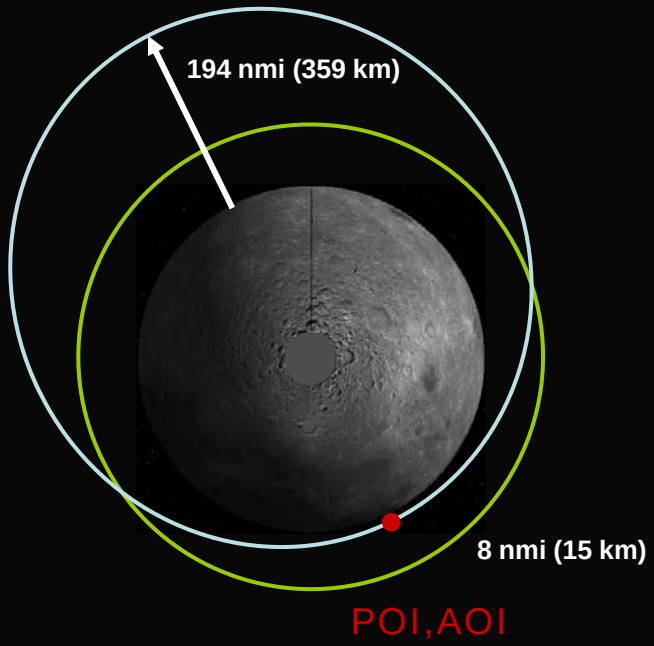
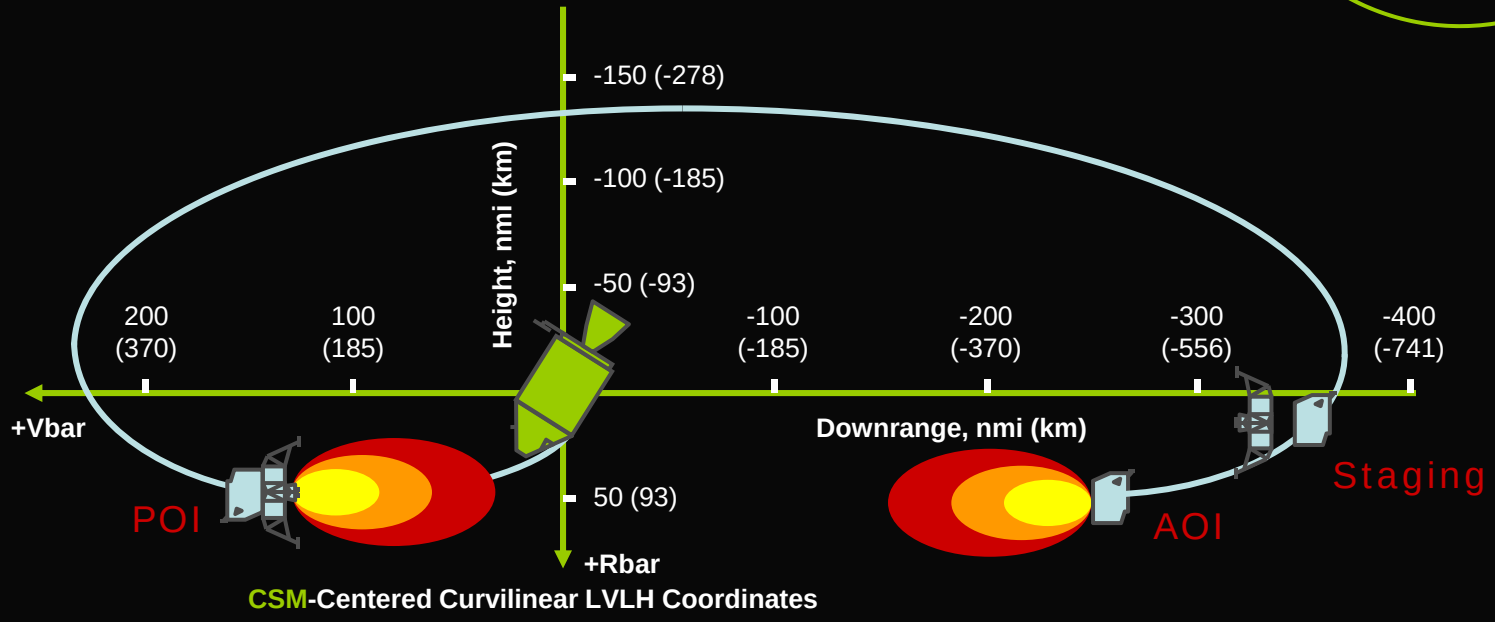
DOI	99:33:59	DPS	71 (22)	60x8 (111x15)
POI	**100:46:21**	**DPS**	**195 (59)**	**194x8 (359x15)**
Staging	**102:33:34**			
AOI	**102:43:18**	**APS**	**207 (63)**	**45x8 (83x15)**

- Phasing Orbit Insertion burn 16 minutes after planned PDI
- Ascent Orbit Insertion burn set up initial conditions for rendezvous



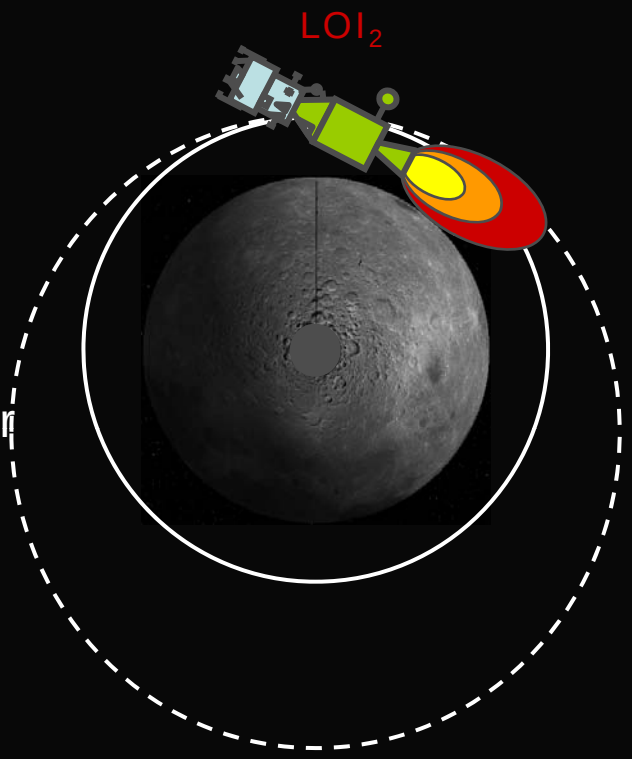


Apollo 11 Objectives

- Primary Mission Objective
  - Perform a piloted lunar landing and return

Apollo 11 Sequence of Events

Event	GET (h:m:s)	PROP	ΔV_{TOT}, fps(m/s)	HAxHP, nmi(km)
LOI_1	75:54:28	SPS	2924 (891)	170x60 (315x111)
LOI_2	**80:09:30**	**SPS**	**158 (48)**	**66x54 (122x100)**
Undock	100:09:50			
SEP	100:39:50	SM RCS	2.5 (0.76)	
DOI	101:38:48	DPS	74 (23)	60x8 (111x15)
PDI	**102:35:13**	**DPS**	**6761 (2061)**	



- LOI_2 targeted 66x54 nmi lunar orbit that, under the influence of mascons, would become 60 nmi circular by the time of rendezvous
- PDI ½ orbit after DOI

Apollo 11 Flight Experience

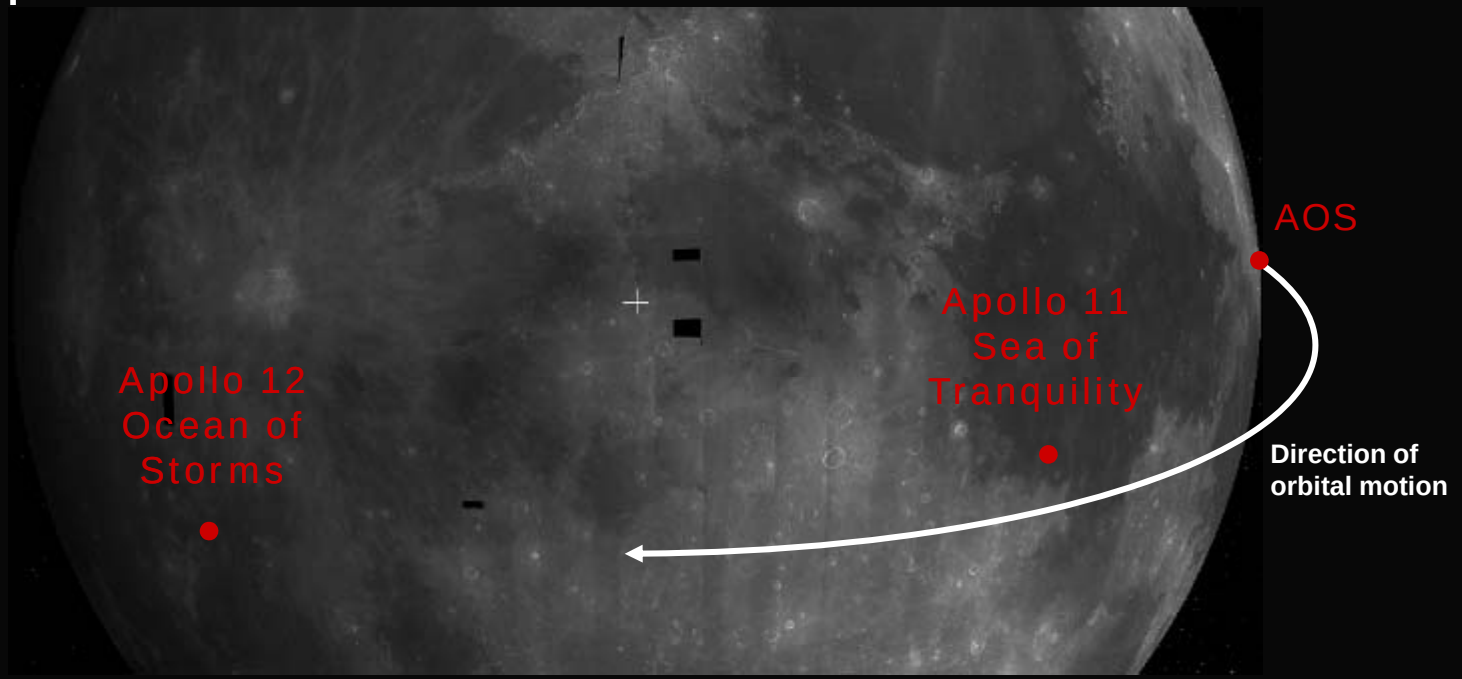
- Downrange dispersion during powered descent
  - LM landed almost four miles long
  - CDR took manual control early to avoid boulders in targeted landing area
  - Caused by combination of:
    - Uncoupled thruster firings during the docked landmark tracking exercise
    - Unaccounted-for velocity accrued during undocking and subsequent inspection and station-keeping activity
    - DOI burn residual
    - Propagated errors in the lunar gravity model
    - Lunar module venting
- CSM orbit not quite circular by time of rendezvous
  - Lunar gravity models still needed improvement

Apollo 12 Objectives

- Primary Mission Objective
  - Perform a precision lunar landing in the Ocean of Storms near the Surveyor 3 landing site
  - Surrounding area flat – safe landing still possible even if precision landing could not be achieved

Apollo 12 Ground Tracking

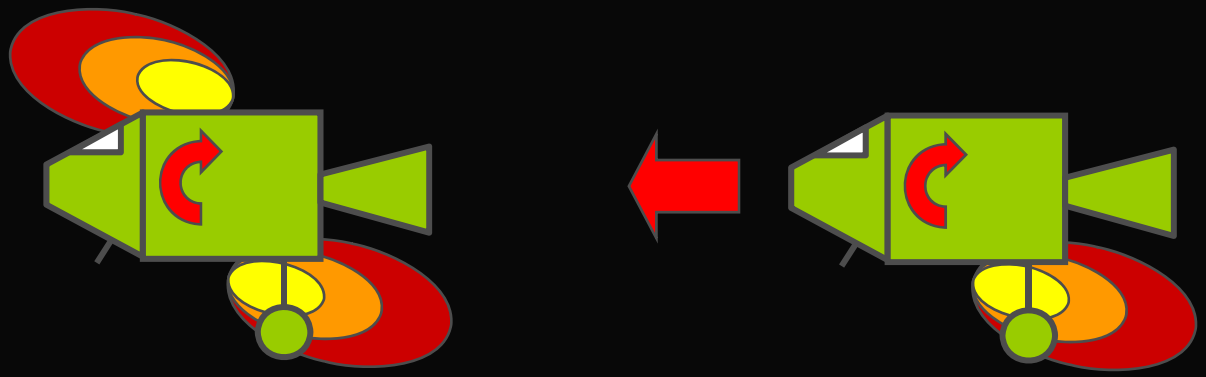
- Westerly landing site allowed more tracking after acquisition of signal (AOS)
- Allows last state vector uplink to occur after DOI
  - On Apollo 11, this was before DOI, allowed dispersions to build



(separation between sites exaggerated by perspective view)

Apollo 12 Procedure Changes

- Use of balanced RCS couples for attitude control
- Dumps and vents rescheduled
- LM RCS “hot-fire” test reduced and modified
  - No translational hot firings
  - Rotational hot firings use balanced couples and minimum pulse duration

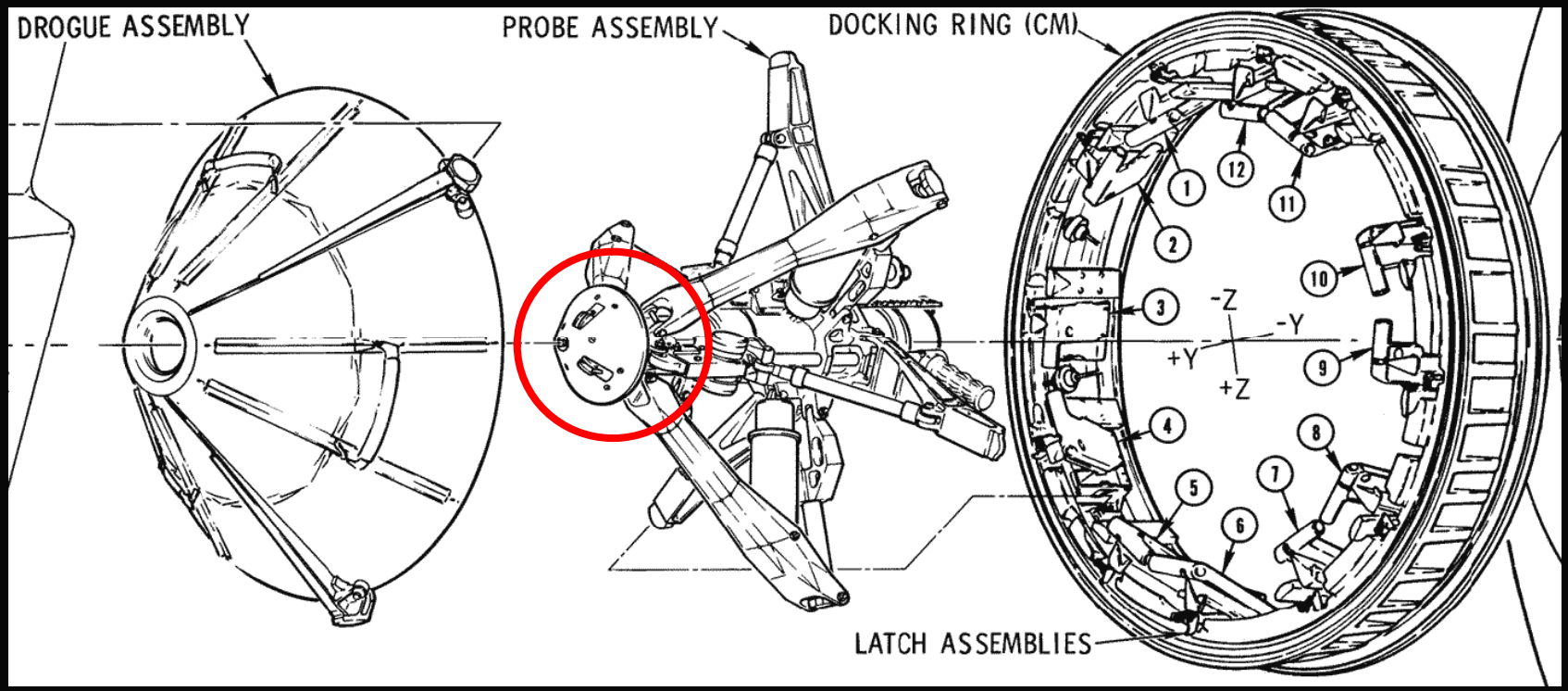


Balanced (+pitch) RCS couple

Unbalanced (“cross-coupled”) +pitch

Apollo 12 Procedure Changes

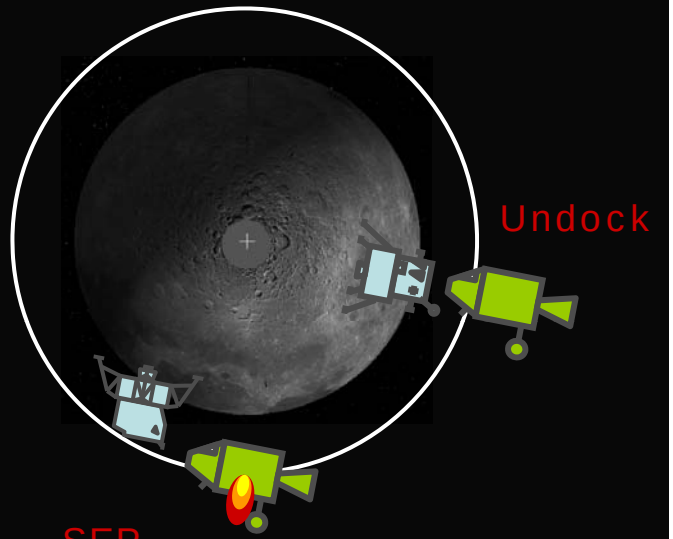
- "Soft undocking" procedure to minimize perturbing effects on LM
  - CM docking probe extended prior to opening hooks
  - CSM performed small RCS firing to pull the probe loose
- Post-undocking LM yaw maneuver only performed if required
  - Onboard indication (visual, barberpole talkback) that landing gear had not deployed properly
- All stationkeeping performed by CSM

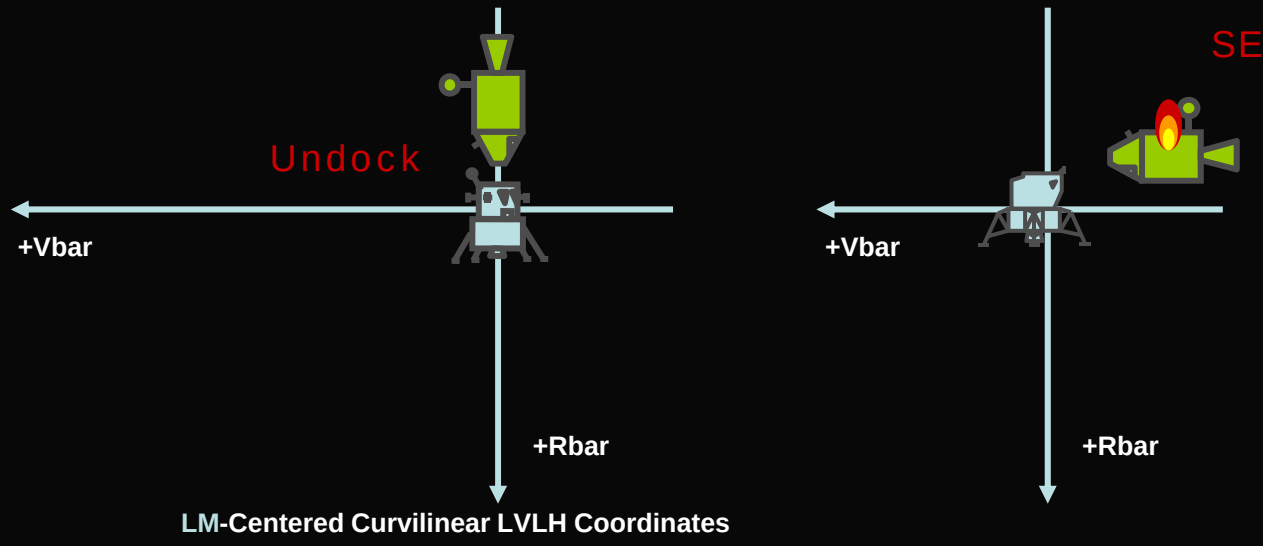


Apollo 12 Sequence of Events

Event	GET (h:m:s)	PROP	ΔV_{TOT}, fps(m/s)	HAxHP, nmi(km)
LOI_1	83:25:00	SPS	2890 (881)	170x60 (315x111)
LOI_2	87:44:00	SPS	169 (52)	66x54 (122x100)
Undock	**107:58:00**			
SEP	**108:28:00**	**SM RCS**	**2.5 (0.76)**	
DOI	109:23:00	DPS	72 (22)	60x8 (111x15)
PDI	110:20:00	DPS	6779 (2066)	

- Undocking attitude changed to CSM above
- SEP burn performed with -Z-axis RCS
- Postburn relative motion practically unchanged





Apollo 13 Objectives

- Perform a precision lunar landing in the Fra Mauro highlands

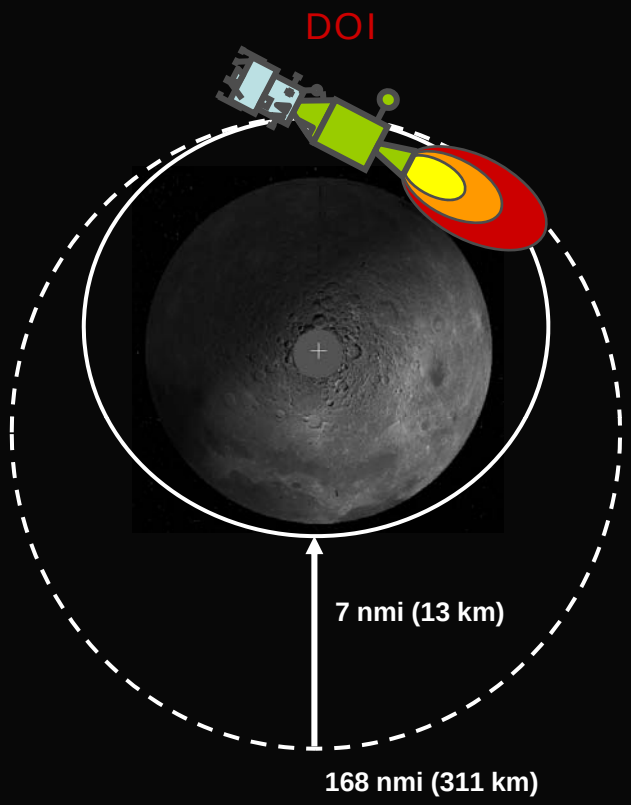
Objective of Apollo 13 Changes

- Surrounding area rugged - precision landing now a crew safety requirement
- Maximize amount of ground tracking while in descent orbit
- Maximize LM hover time by increasing propellant reserves (minimize LM maneuvers prior to PDI)

Apollo 13 Sequence of Events

Event	GET (h:m:s)	PROP	ΔV_{TOT}, fps(m/s)	HAxHP, nmi(km)
LOI	77:25:00	SPS	2815 (858)	168x57 (311x106)
DOI	**81:45:00**	**SPS**	**213 (65)**	**57x7 (106x13)**
Undock/SEP	99:16:00	SM RCS	1.0 (0.3)	
CIRC	100:35:00	SPS	70 (21)	62x52 (115x96)
PDI	103:31:00	DPS	6635 (2022)	

- LOI_2 and DOI combined into a single CSM burn
- Designed to converge, under lunar gravitational influence, to proper conditions at PDI (58.9x8.3 nmi, PDI at pericynthion)
- Allowed 11 revs of tracking in the descent orbit prior to PDI
- Conserved LM prop for additional hover time during landing
- Burn monitoring critical – one-second overburn would result in negative pericynthion (lunar impact within ½ rev)
- MCC would call for DOI bailout burn after AOS if required
- Downside – CSM landmark tracking near pericynthion degraded due to fast movement of landscape
- If post-burn pericynthion drifted out of limits, DOI Trim burn may be inserted
  - Could possibly require waking the crew from sleep



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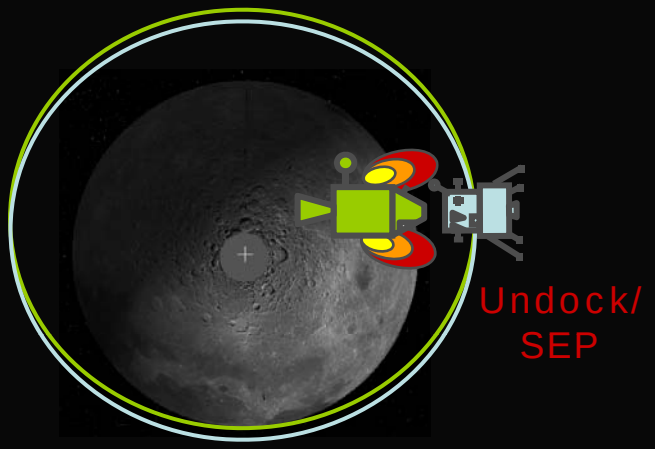
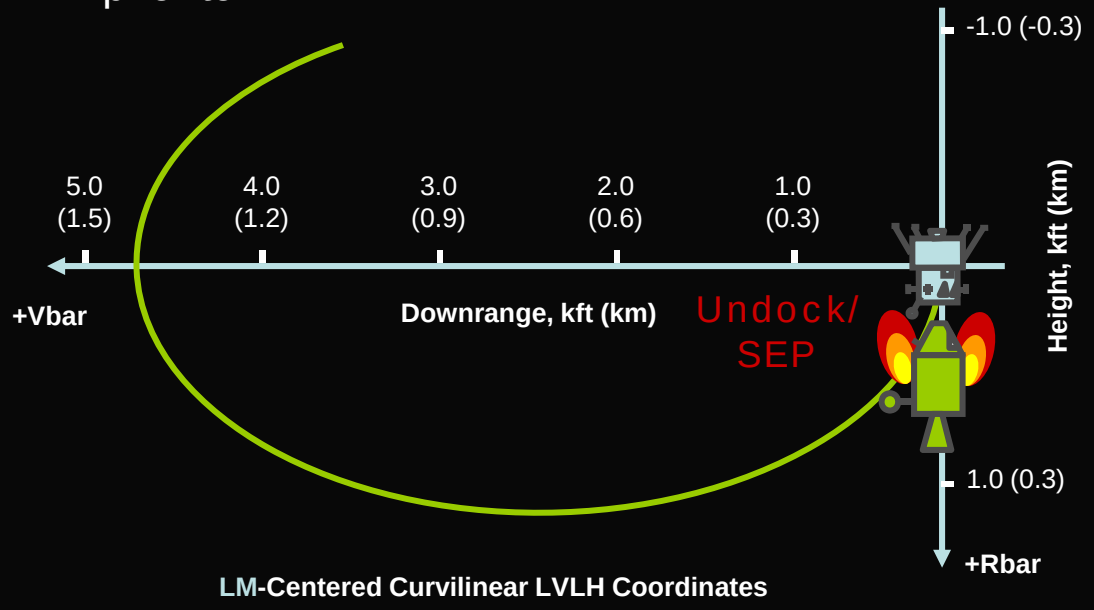
PDI	103:31:00	DPS	6635 (2022)	

- SEP burn performed simultaneously with soft undocking, magnitude reduced to 1 fps
- Moved 1 rev earlier (2¼ rev before PDI) to allow CSM to recircularize and perform landmark tracking prior to PDI





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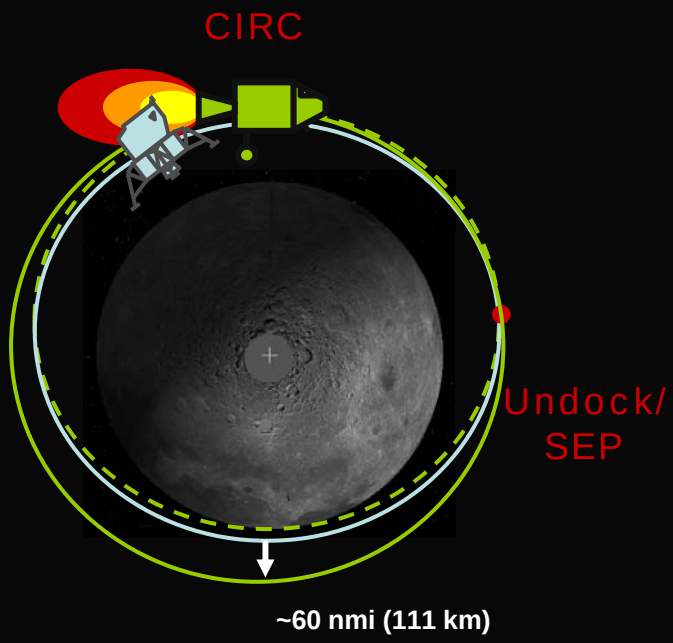
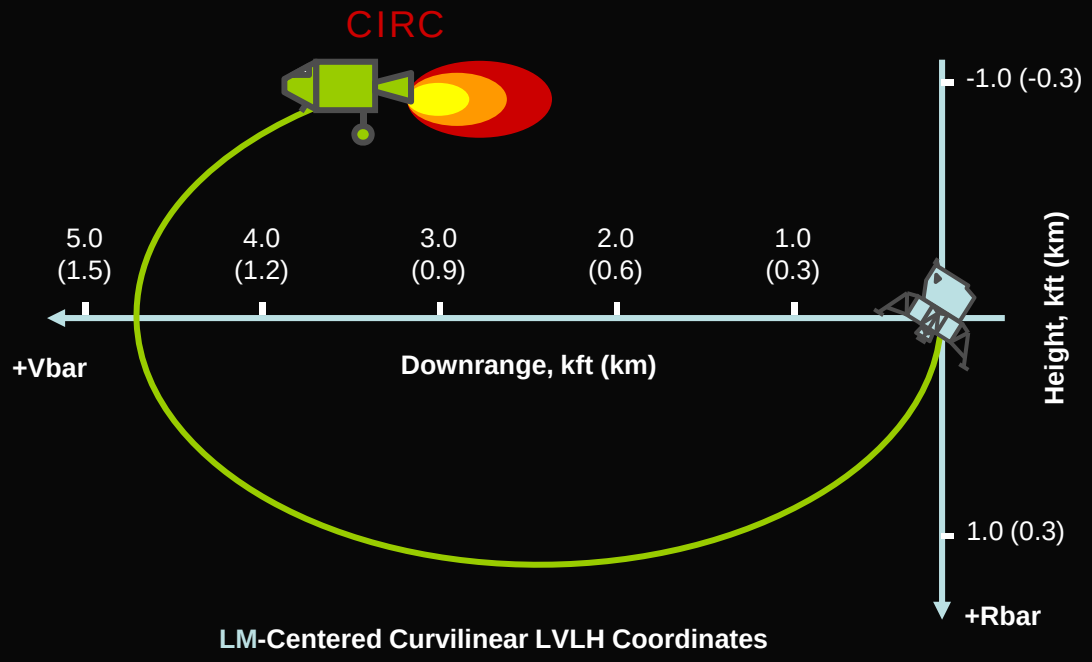
CIRC	**100:35:00**	**SPS**	**70 (21)**	**62x52 (115x96)**
PDI	103:31:00	DPS	6635 (2022)	

- CIRC burn targeted for orbit that would become 60 nmi circular by the time of planned rendezvous





LM-Centered Curvilinear LVLH Coordinates

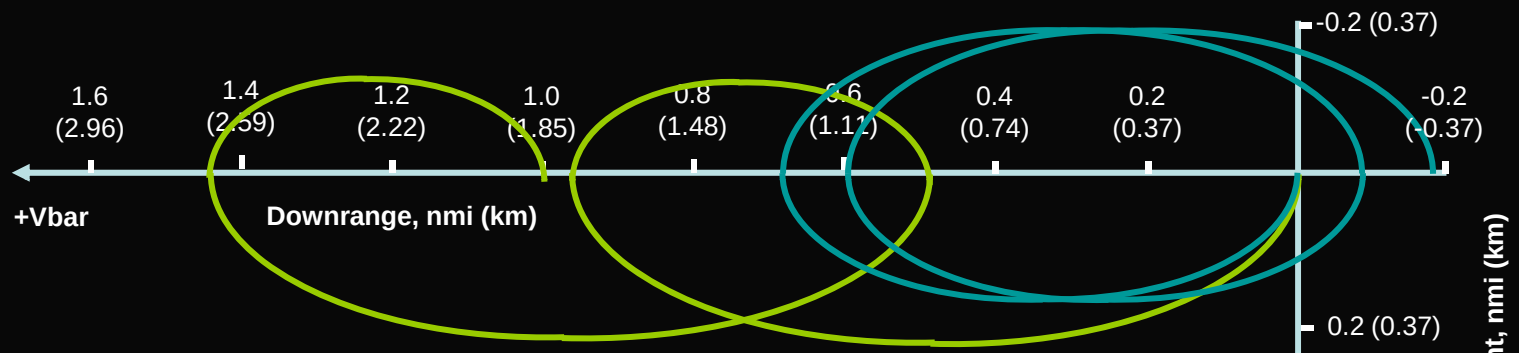
Apollo 13-16 Flight Experience

- Apollo 13 mission aborted after CSM oxygen tank failure
- Sequence of events remained relatively stable for Apollo 14-16
  - Apollo 15 required DOI Trim burn
    - Fortunately did not require early crew wakeup
  - Apollo 16 undocking-PDI timeline moved one rev earlier to allow EVA-1 to be performed on landing day

Apollo 16 Flight Experience

- SPS Sec Yaw Gimbal Anomaly post-undocking
  - Resulted in NO-GO for CIRC
  - CSM performed “brute-force” rendezvous with LM on second orbit after undocking
    - Crew had low confidence in MCC estimates of relative motion
    - LM crew verbally relayed RR data to CMP to assist
  - Test and analysis showed gimbal usable and safe
  - Mission continued nominally after a three-orbit delay
  - Postflight analysis indicated that a slight retrograde dispersion at SEP (~0.17 fps) caused the CSM to be 6000 ft in front of the LM at initiation of re-rendezvous instead of 1000 ft behind, as indicated by MCC states

Apollo 16 Post-Undocking Relative Motion



LM-Centered Curvilinear LVLH Coordinates

CSM relative motion from MCC state vectors

CSM relative motion reconstructed post-flight with 0.17 fps retrograde dispersion

Plot from time of undocking to initiation of brute-force rendezvous

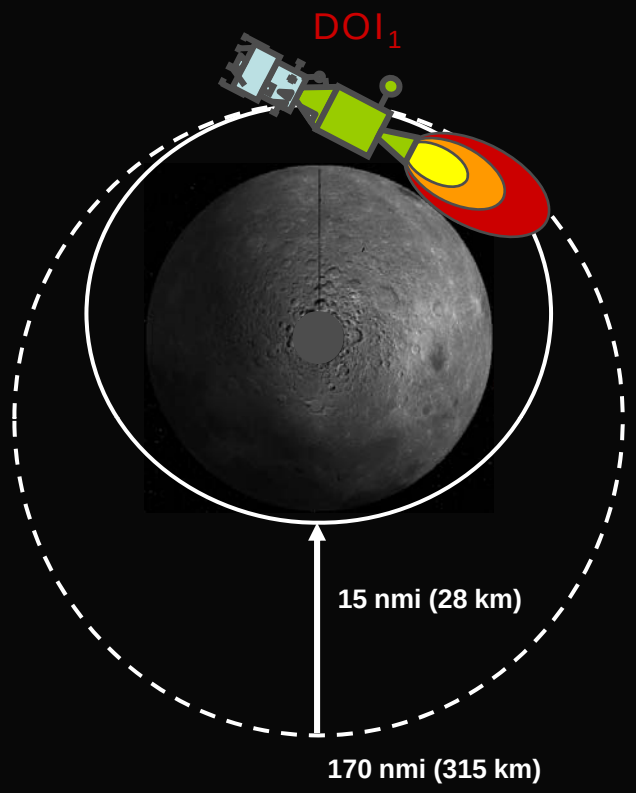
Apollo 17 Objectives

- Perform a precision lunar landing in the Taurus-Littrow valley

Apollo 17 Sequence of Events

Event	GET (h:m:s)	PROP	ΔV_{TOT}, fps(m/s)	HAxHP, nmi(km)
LOI	88:55:00	SPS	2980 (908)	**170x51 (315x95)**
DOI_1	**93:13:00**	**SPS**	**199 (61)**	**59x15 (109x28)**
Undock/SEP	110:28:00	SM RCS	1.0 (0.3)	
CIRC	111:55:00	SPS	70 (21)	70x54 (130x100)
DOI_2	**112:00:00**	**LM RCS**	**9.4 (2.9)**	70x7 (130x13)
PDI	**112:49:00**	**DPS**	**6701 (2043)**	

- LOI pericynthion reduced to 51 nmi (increased performance)
- Far easterly landing site would have placed post-DOI pericynthion very soon after AOS
- DOI split into two burns, DOI_1 and DOI_2
- Pericynthion location shifted west of landing site
  - Provide sufficient time for MCC to evaluation post-DOI_1 orbit
  - Reduce probability of needing DOI_1 bailout burn
  - CSM landmark tracking enhanced by higher altitude
  - Preclude early crew wakeup for a DOI trim maneuver
- DOI_2 lowers pericynthion from 80,000 to 43,000 ft
  - Performed with LM RCS to preserve descent propellant
- Net gain LM hover time ~3 sec, SPS reserves ~25 fps



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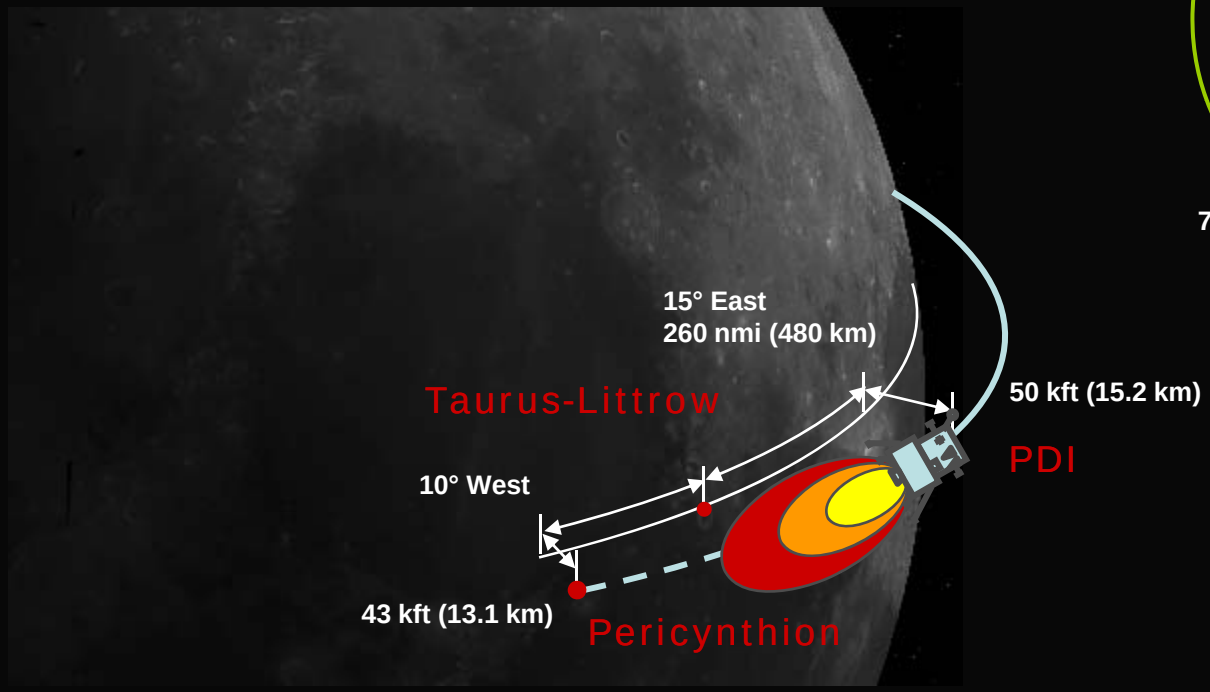

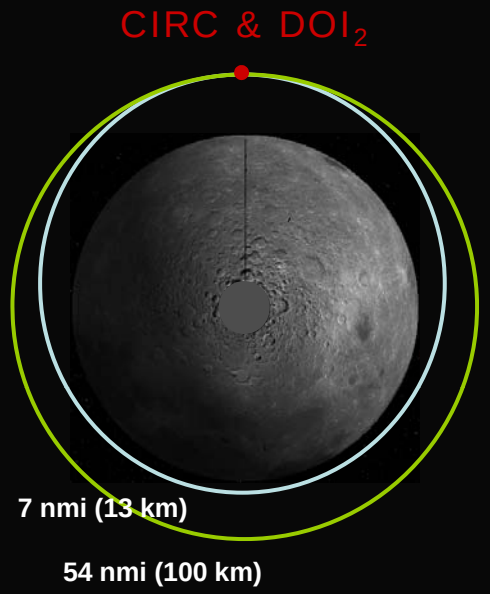

Summary

- Consistently performing precision landings required that Apollo lunar orbit activities devote considerable attention to:
  - Improving fidelity of lunar gravity models
  - Maximizing availability of ground tracking
  - Minimizing perturbations on the trajectory
  - Maximizing LM propellant reserves for hover time
- Use of radial separation maneuvers
  - Allows passive re-rendezvous after each rev, but…
  - Sensitive to small dispersions in initial sep direction

Credits

- Lunar 3D renderings generated by NASA World Wind 1.4
  - http://worldwind.arc.nasa.gov/
- Apollo 16 postflight report provided by Ryan Jackson from the collection of Apollo RETRO Jim I'Anson

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