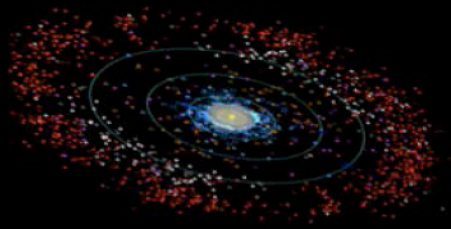
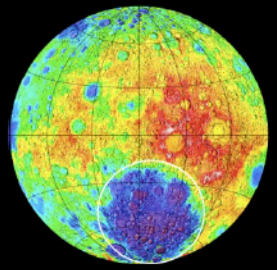
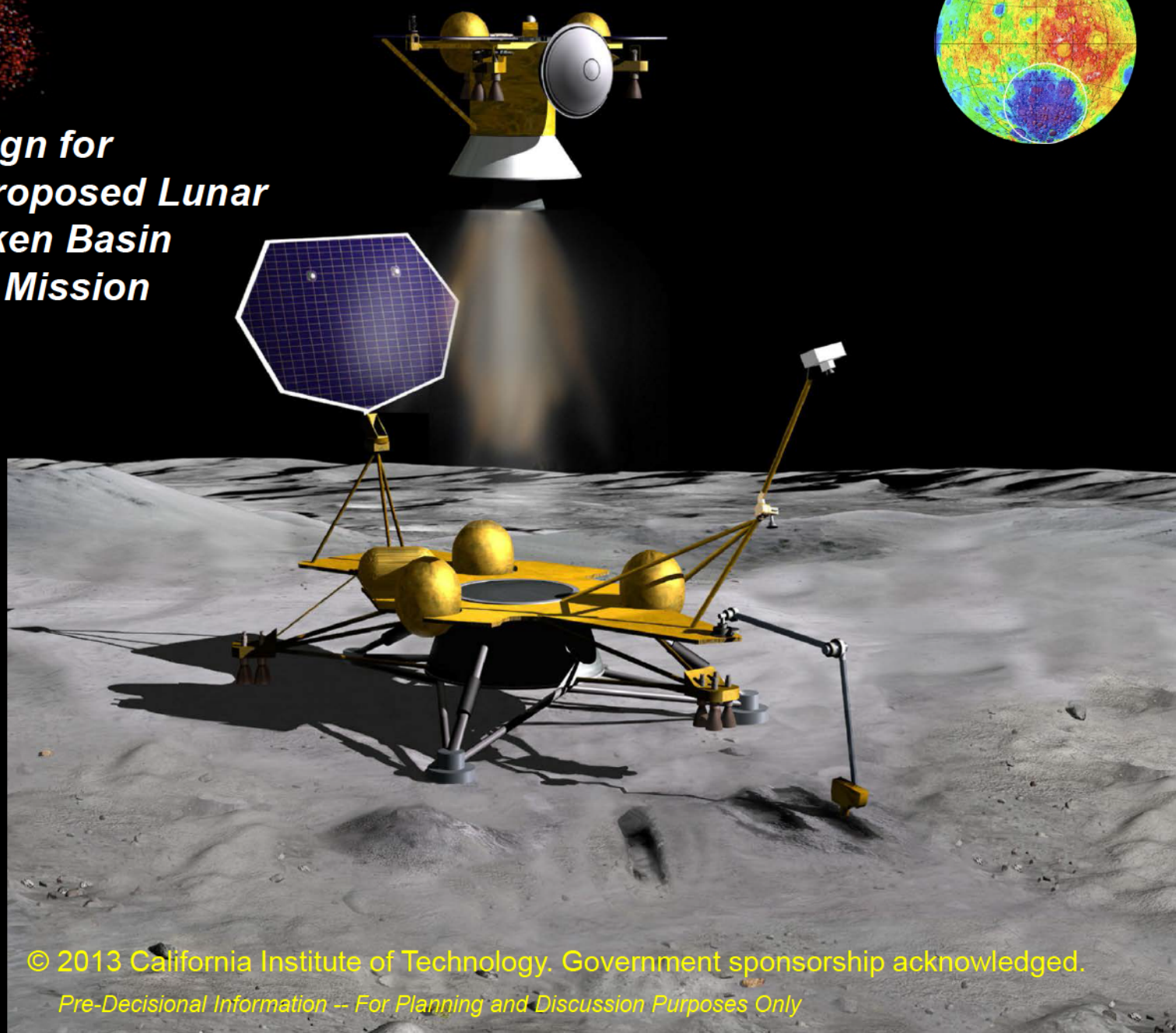


Trajectory Design for MoonRise: A Proposed Lunar South Pole-Aitken Basin Sample Return Mission





MoonRise
A NASA New Frontiers Mission Proposal

AAS 13-882

Jeffrey S. Parker
Timothy P. McElrath
Rodney L. Anderson
Theodore H. Sweetser

Jet Propulsion Laboratory, California Institute of Technology

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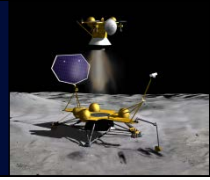
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Introduction



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  - New Frontiers 2009 Step 2 / Phase A study

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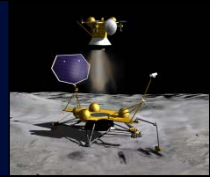

- ***MoonRise* is a proposed South Pole – Aitken Basin (SPAB) sample return mission**
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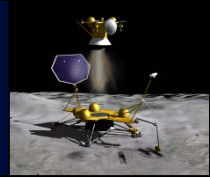
- **The science community is very interested in retrieving samples from the SPAB**
  - Samples from SPAB would determine the age of key events in the history of the Solar System
  - Test the Cataclysm hypothesis and the early bombardment period of the Earth-Moon system.
  - Sample deeper into the crust and even mantle of the Moon

Introduction



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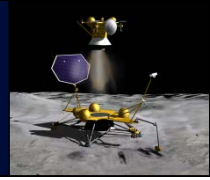
  - Test the Cataclysm hypothesis and the early bombardment period of the Earth-Moon system.
  - Sample deeper into the crust and even mantle of the Moon

- **Other similar proposed mission concepts:**
  - Moonrise: a Phase A study led by Prof. Mike Duke in response to the 2004 New Frontiers AO.
  - Orion/MoonRise: a modification of the 2009 MoonRise concept, replacing the ComSat and SRC with a crewed Orion vehicle.

MoonRise's Mission Objectives

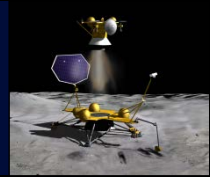


- **Major Mission Design Objectives and Constraints:**
  1. Launch from Cape Canaveral, Florida
  2. Land safely in the SPAB with a communication relay satellite in view
  3. Remain on the surface long enough to ensure successful sample acquisition
  4. Return samples to Earth, preferably landing in the Utah Test and Training Range (UTTR)

- **Mission Design Drivers**
  1. Minimize the cost of the mission
  2. Minimize the risk and perceived risk of the mission
  3. Maximize the science return from the mission

- **Purpose of Paper**
  - To present the high level design trades and the mission design solution for this proposed MoonRise mission.

Early Design Decisions



Early architecture trades settled on the following:

1. **A single vehicle would land on the surface.**
   - A single lander would return sufficient samples to satisfy all mission goals.
   - A single lander fits within the New Frontiers cost cap.

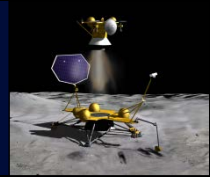
1. **A low-cost communication relay satellite would support the surface mission.**

1. **The lander would include a scoop and no mobility.**
   - Hence, the ascent would take place at the same location as the landing.

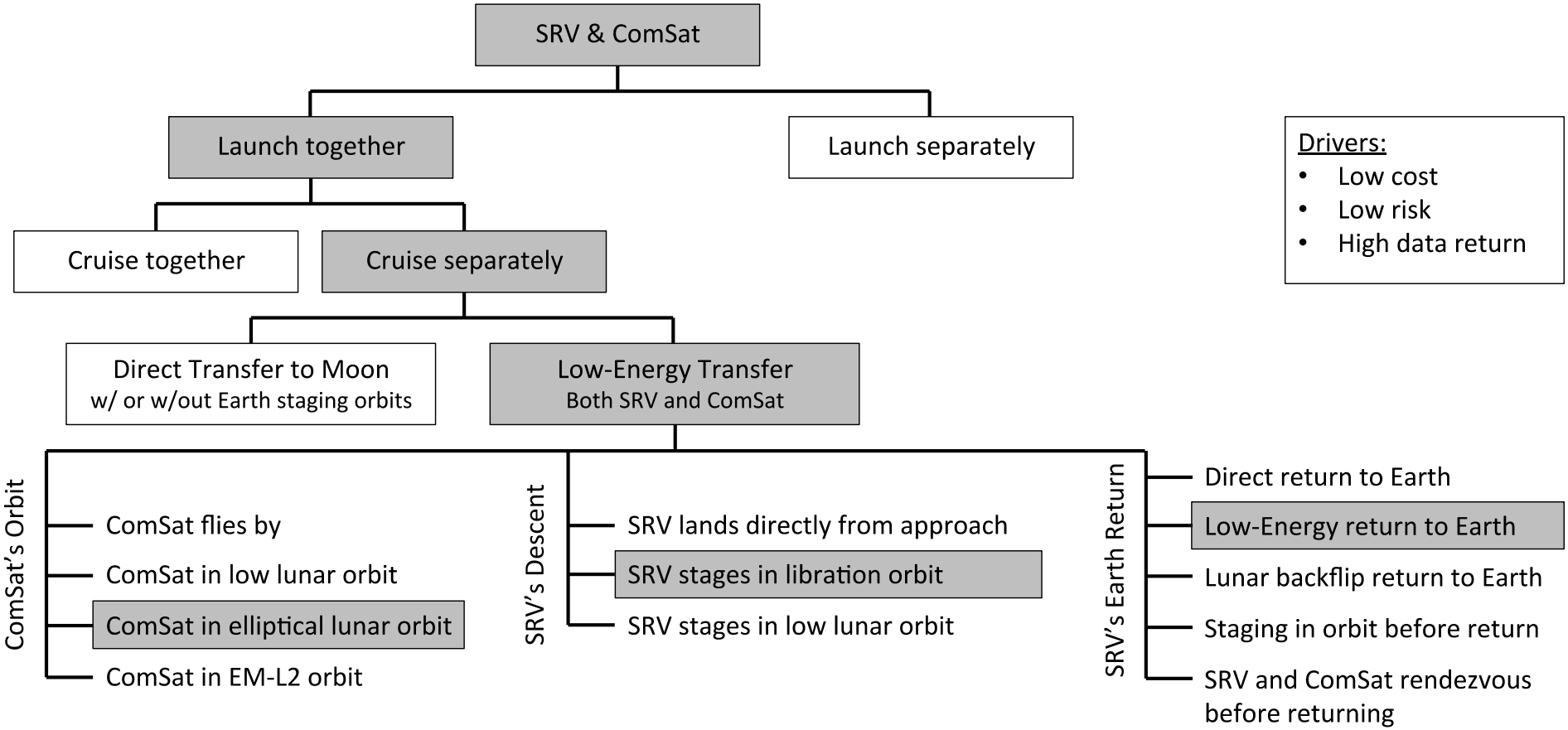
1. **The design would highly favor the use of solid rocket motors (SRMs) for large burns, such as landing and ascent.**
   - Reduces cost compared to bipropellant systems.
   - Demands that the mission include only small maneuvers except for landing and ascent.

1. **The lander would not be designed to survive a lunar night.**

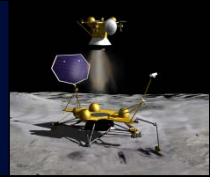
Trajectory Options



- **A tree of choices for the Sample Return Vehicle (SRV) and the Communication Relay (ComSat)**

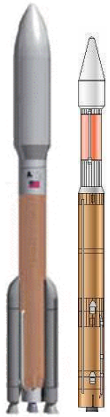


Trajectory Options



SRV & ComSat

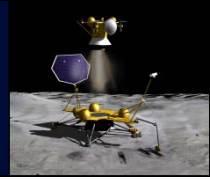
- Launch together
- Launch separately



Drivers:
- Low cost
- Low risk
- High data return

- **Launch Options**
  1. Launch together (Low cost, but less flexible)
  2. Launch separately (High cost, but very flexible)

Trajectory Options



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Drivers:
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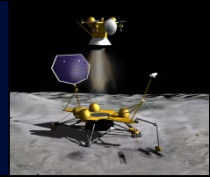
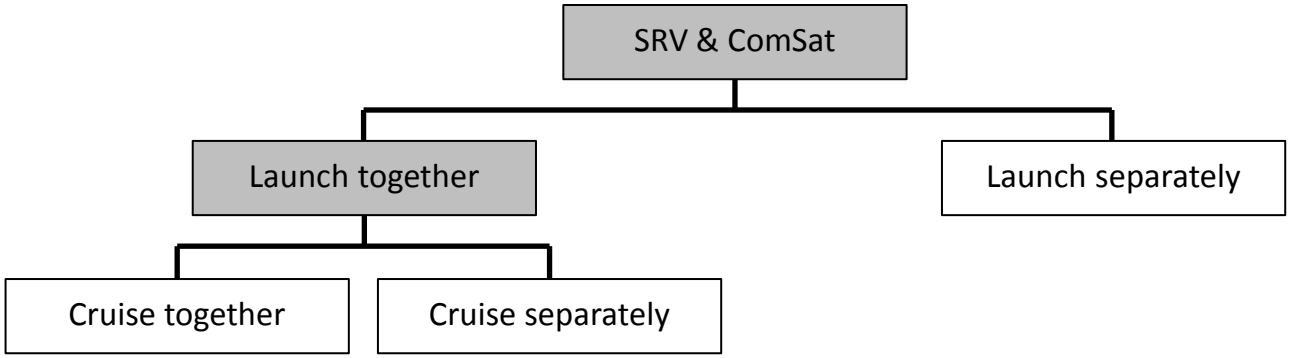
- **Launch Options**
  1. **Launch together** **(Low cost, but less flexible)**
  2. Launch separately (High cost, but very flexible)

Designer Notes:
- Make sure no vehicles collide
- Optimize trajectories to keep all vehicles within their ΔV limits

Trajectory Options





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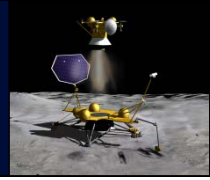
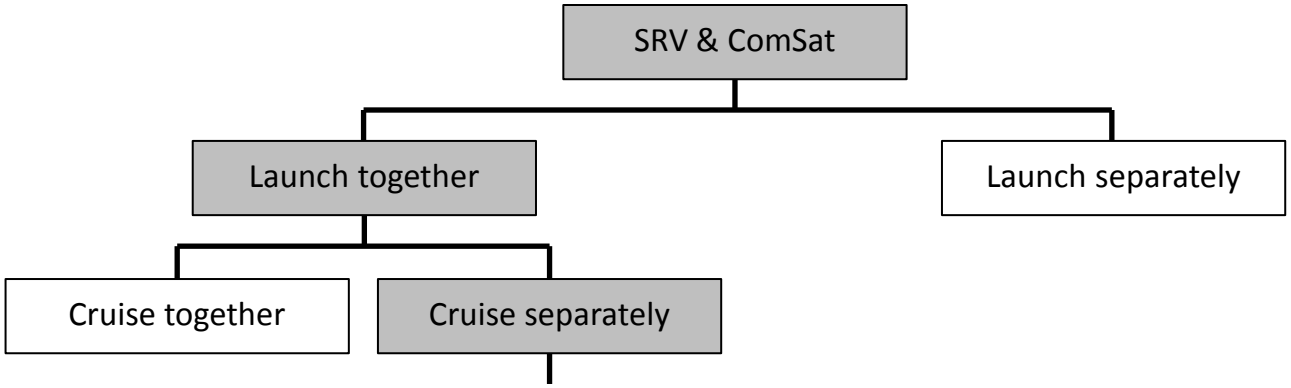
- **Cruise Options**
  1. Cruise together to Moon (One vehicle to support, but more configurations; fewer options upon arriving at Moon)
  2. Cruise separately to Moon (Most flexibility, but two vehicles to operate simultaneously)

Trajectory Options





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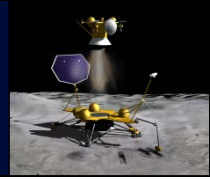
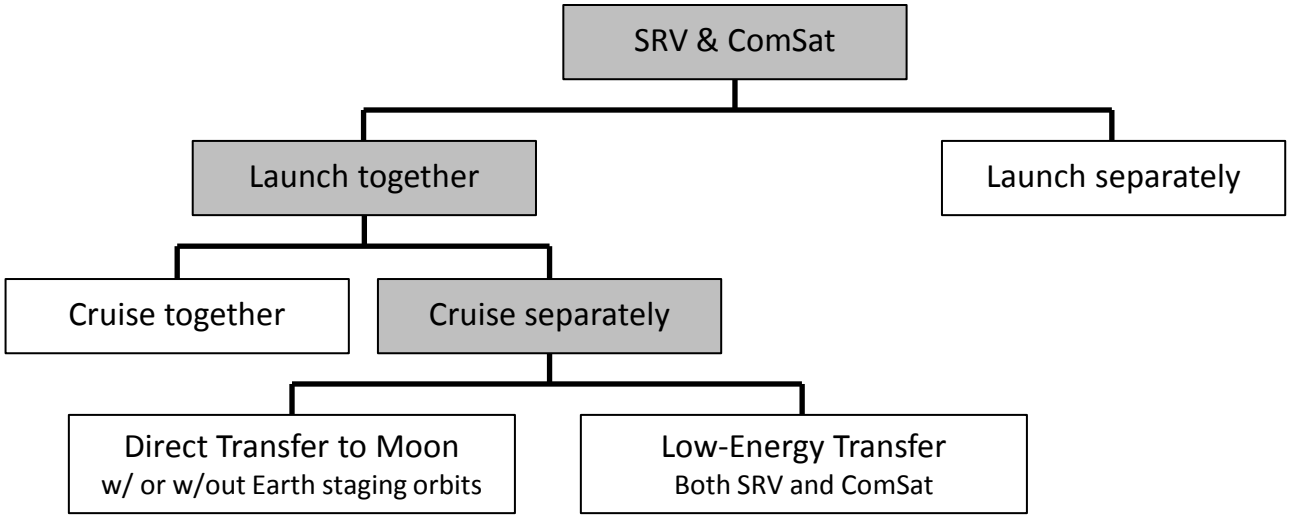
  1. Cruise together to Moon (One vehicle to support, but more configurations; fewer options upon arriving at Moon)
  2. **Cruise separately to Moon** **(Most flexibility, but two vehicles to operate simultaneously)**

Designer Notes:
- Separate all maneuvers in time to reduce operations challenges

Trajectory Options





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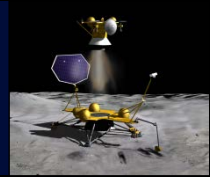
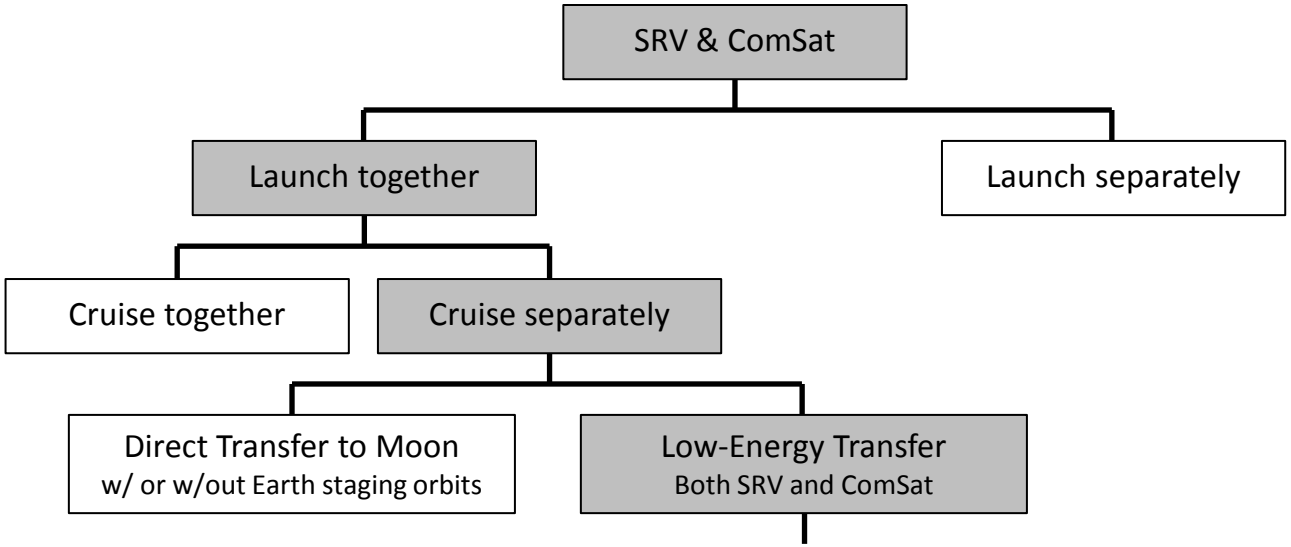
- **Cruise Options**
  1. Direct Transfer to the Moon (Low launch costs, short transfer, high spacecraft fuel reqts)
     - A. w/ Earth staging orbits: (Permits launch period)
     - B. w/out Earth staging orbits: (Shortest transfer, but not flexible)
  2. Low-energy Transfer
     - A. One vehicle, but not the other: (Higher fuel costs)
     - B. Both vehicles (Lowest fuel costs, contingency options, flexibility, longer transfer)

Trajectory Options





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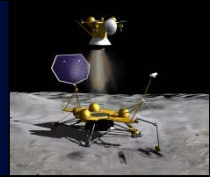

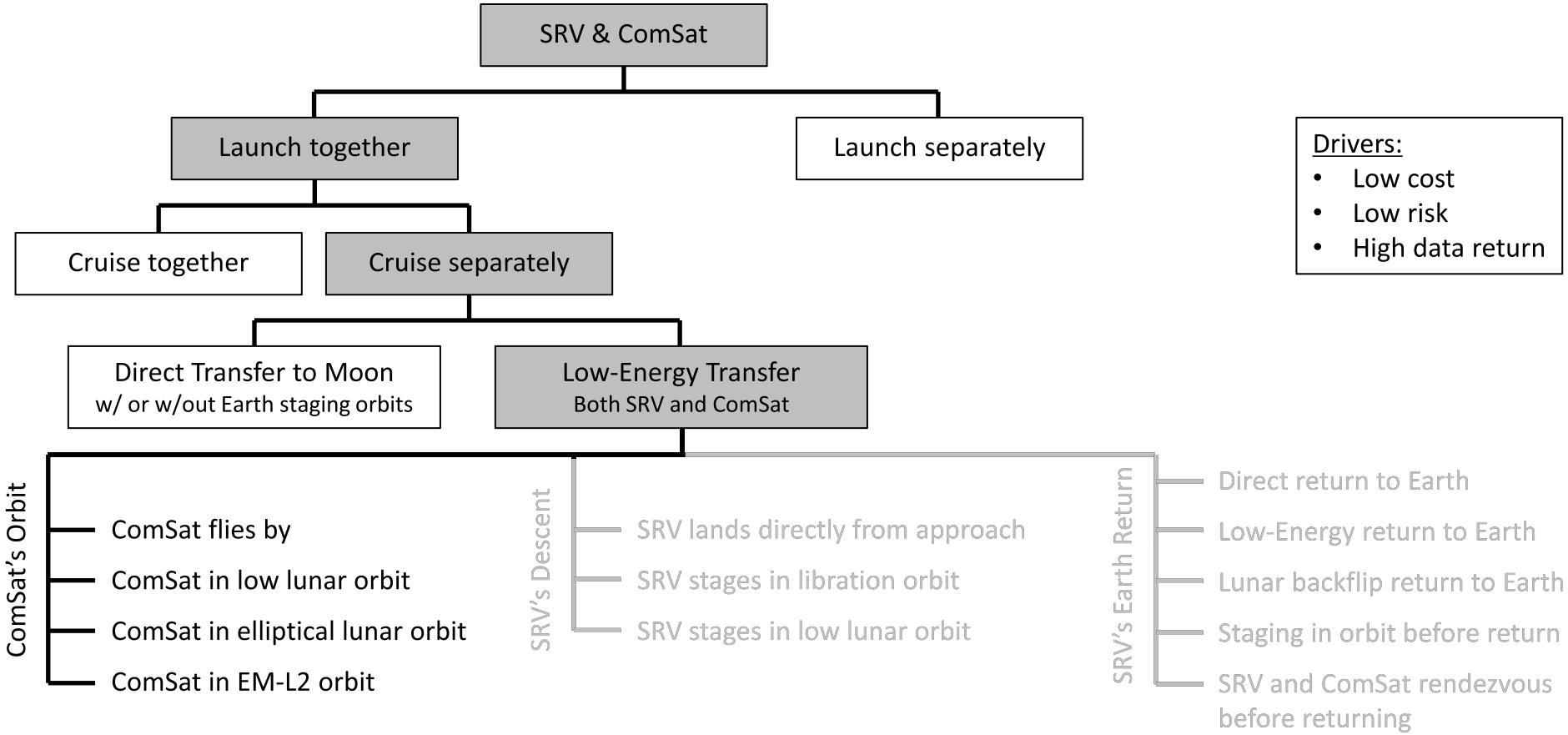

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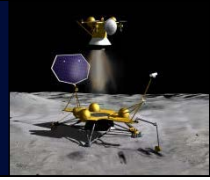
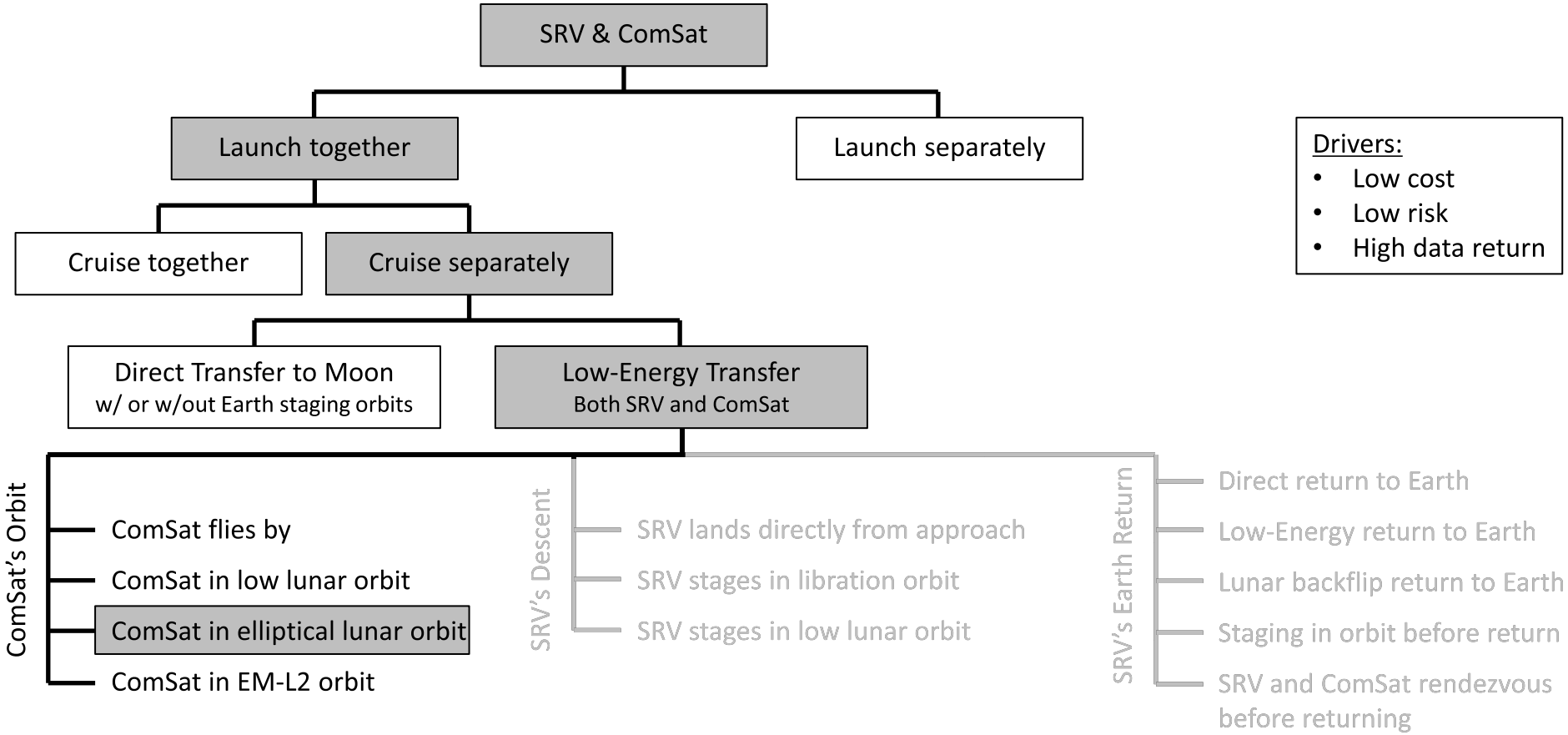
- **ComSat's Orbit:**
  1. Fly-by (large link distances, no contingency options)
  2. Low lunar orbit (very short link distances, short pass durations, large fuel requirements)
  3. Elliptical orbit (short link distances, non-continuous coverage, large fuel reqts)
  4. L2 orbit (large link distances, continuous coverage, little fuel requirements)

Trajectory Options





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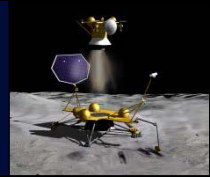

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          - SRV stages in libration orbit
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        - SRV's Earth Return
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          - Low-Energy return to Earth
          - Lunar backflip return to Earth
          - Staging in orbit before return
          - SRV and ComSat rendezvous before returning
  - Launch separately

Drivers:
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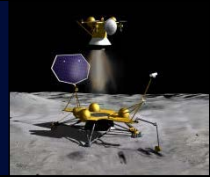
- **SRV's Descent Options:**
  1. Direct landing from approach (no time for ComSat to prepare for landing)
  2. Staging in libration orbit (no big burns, contingency opportunities)
  3. Staging in low lunar orbit(several big burns)

Trajectory Options



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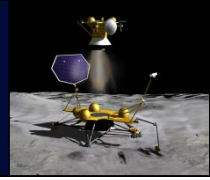

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  1. Direct return to Earth (does not permit landings in UTTR)
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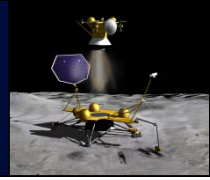
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Trajectory Options



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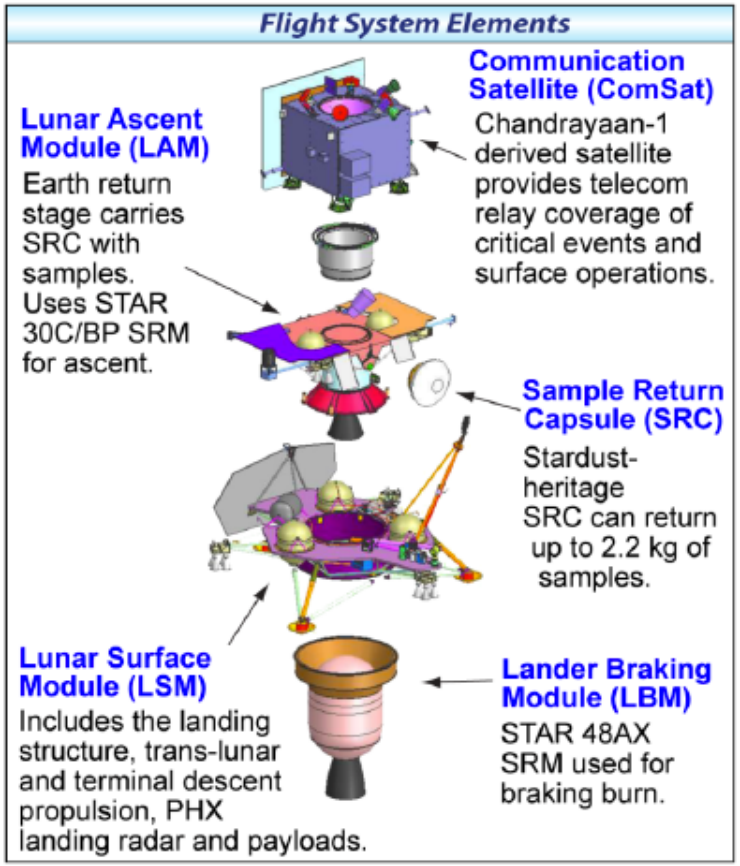
Proposed System

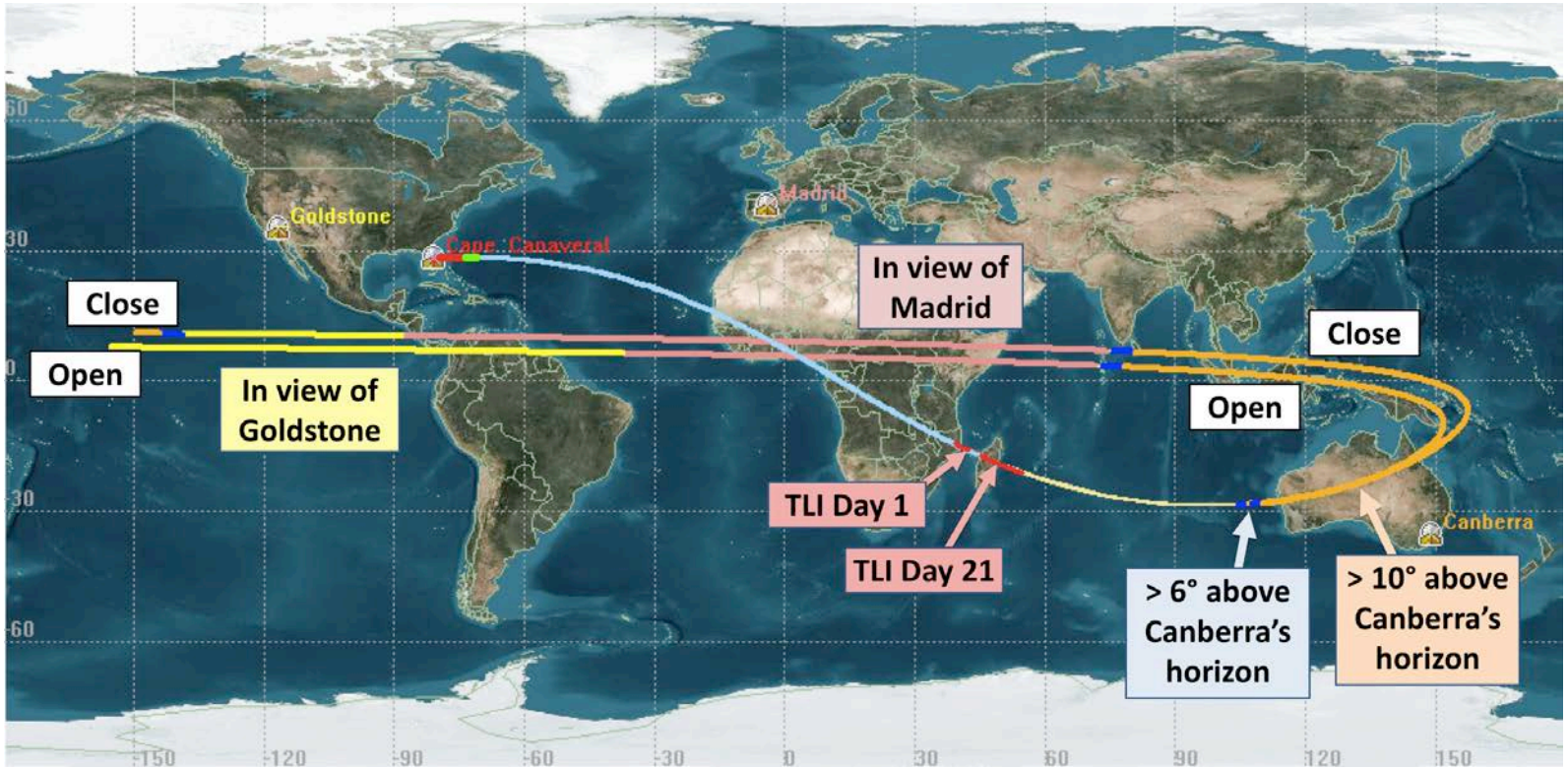
- **Two vehicles**
  - SRV and ComSat
- **SRV is composed of several *modules:***
  - LBM: Lander Braking Module
  - LSM: Lander Surface Module
  - LAM: Lunar Ascent Module
  - SRC: Sample Return Capsule
- **Propulsion**
  - Solid rocket motors for landing and ascent
  - Hydrazine systems on LSM and LAM



Launch

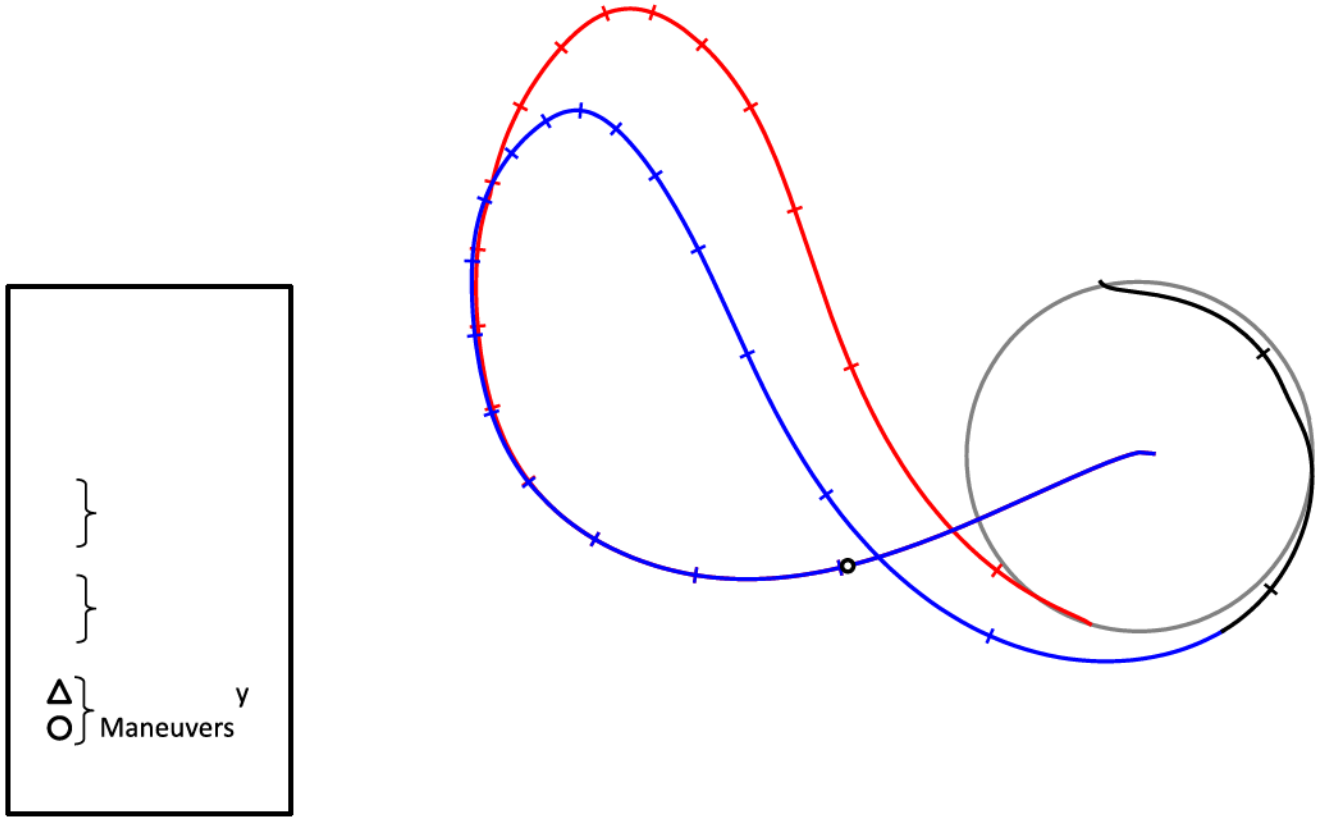
- **21-day launch period: July 7 – 27, 2016**

- **The SRV and ComSat launch together. After injection, the launch vehicle's upper stage deploys each separately.**



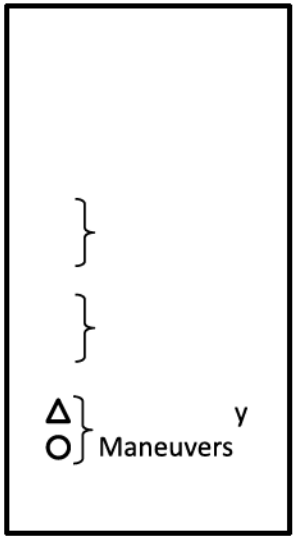
Trans-Lunar Cruise

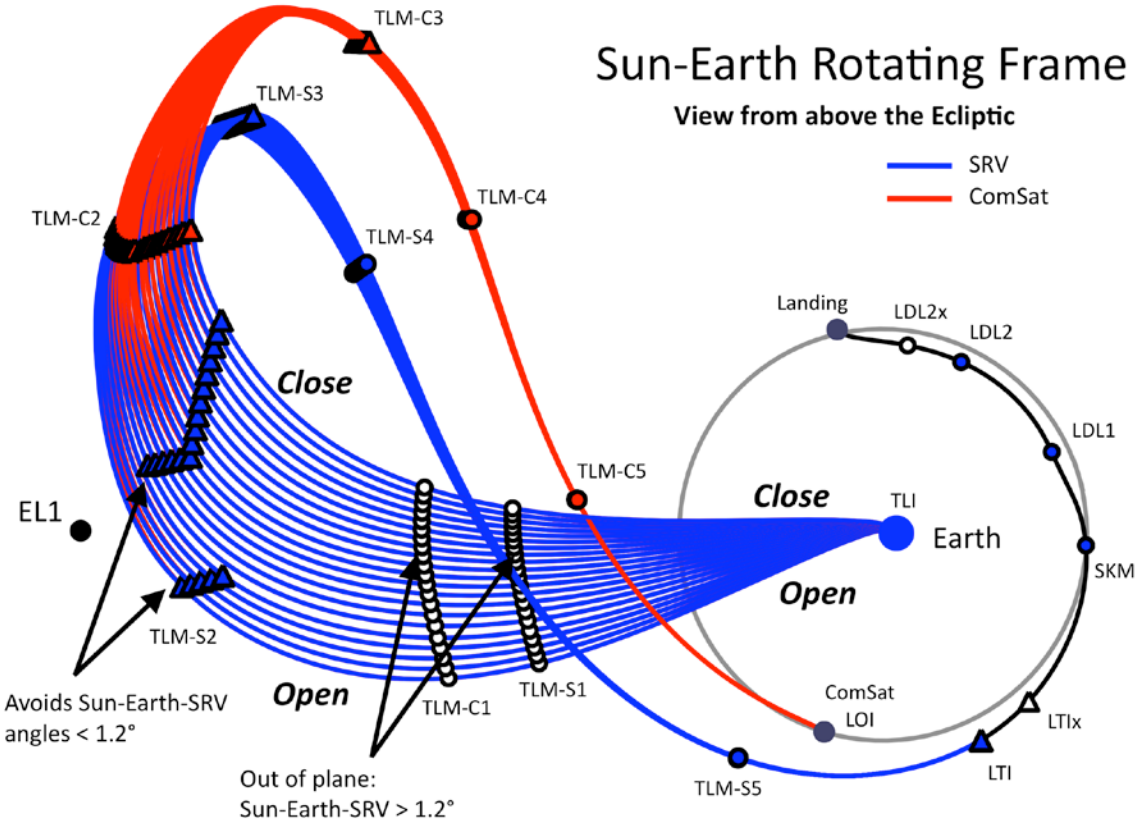
- **Trajectories for 1st day in launch period**



Trans-Lunar Cruise

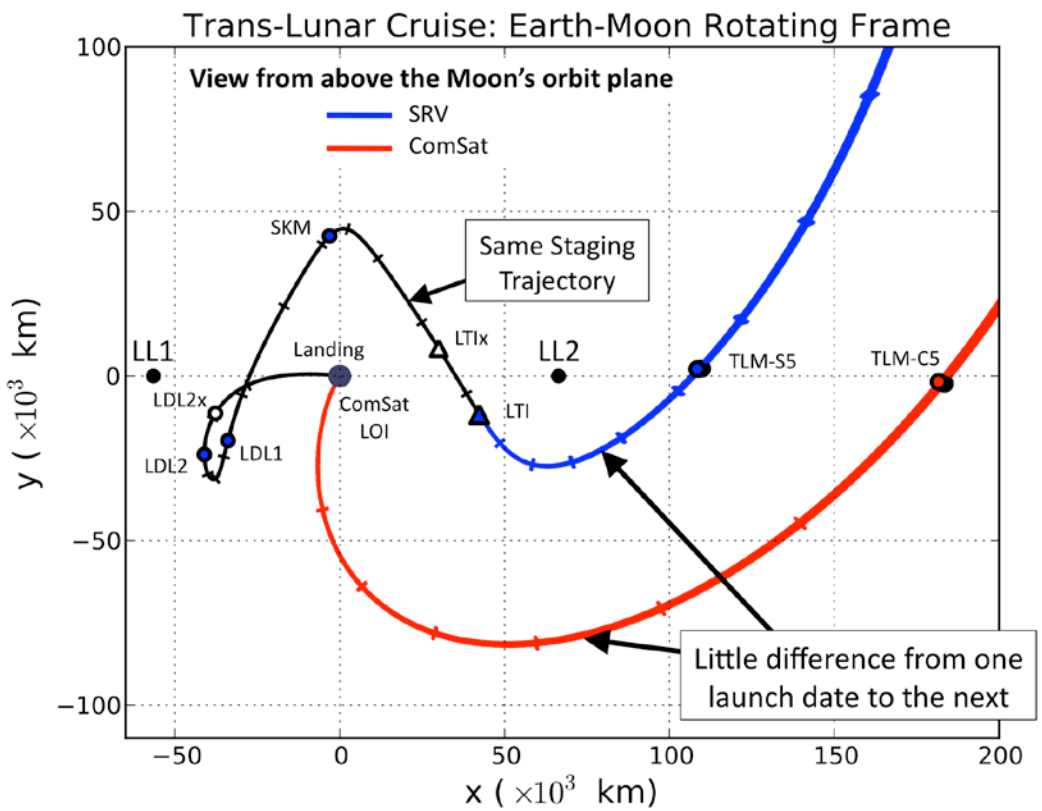
- **All 21 trajectories in launch period, assuming one launch per day (likely to be more)**



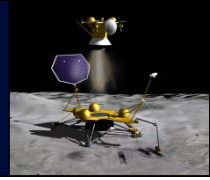


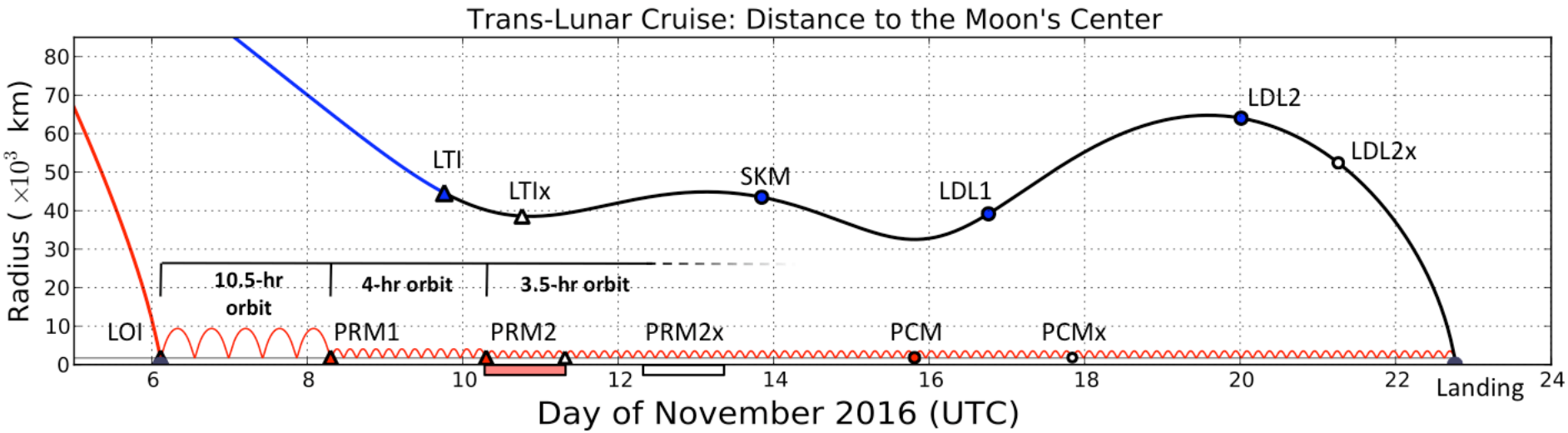
Trans-Lunar Cruise

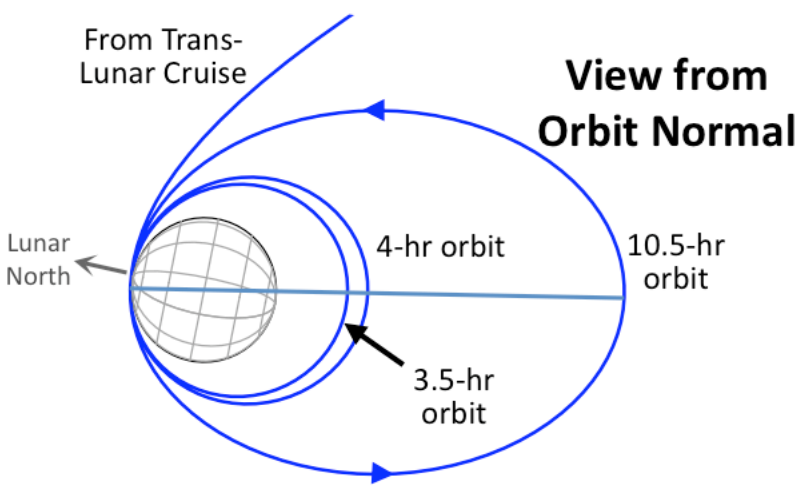
- **Launch: 7/7 – 7/27/2016 UTC**
- **ComSat LOI: 11/6/2016 UTC**
- **SRV LTI: 11/9/2016 UTC**
- **SRV BB: 11/22/2016 UTC**
- **SRV Ascent: 11/22 – 12/2**
- **SRV EDL: 4/17/2017 UTC**

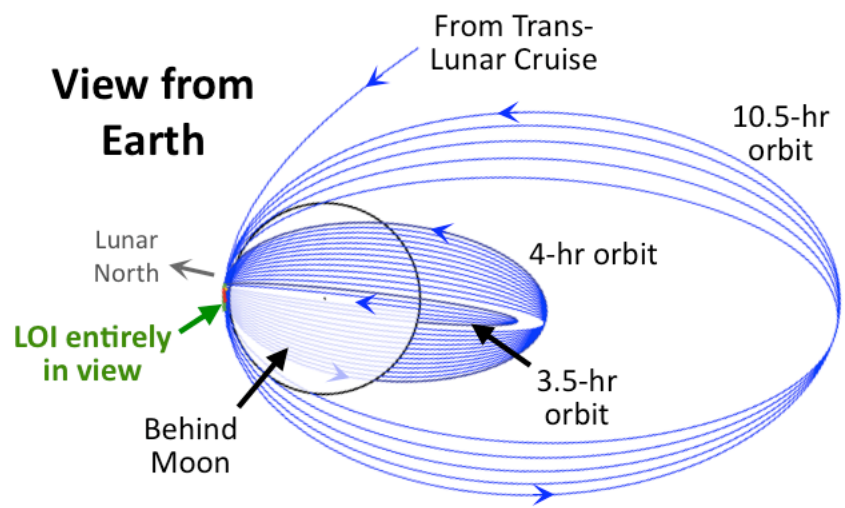


ComSat LOI and Commissioning

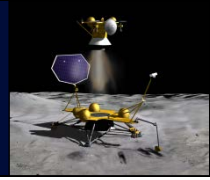








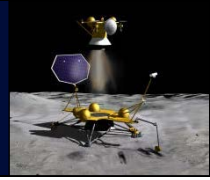
Braking Burn Interface



- **Nominal Landing Site: 200° E, 60° S, -5.575 km alt**
- **The SRV targets the following BB Interface for each and every launch in the period.**

Parameter	Value	Notes
BB Epoch	22 Nov 2016 18:17:10.74 ET	In the middle of a DSN overlap period.
Time since TLI	137.78 days	Duration of time since the SRV's TLI.
Time since CLOI	16.65 days	Duration of time since the ComSat's LOI.
Local Solar Time	7.93969 hours = 7:56:23 am	The time of the lunar day at the landing site.
Latitude	63.746507°S	Spherical, Moon-fixed coordinates
Longitude	203.21025°E	Spherical, Moon-fixed coordinates
Altitude	8.425 km	Assuming a spherical Moon with radius 1737.4 km
Radius	1745.825 km	
Height above Landing Site	14.000 km	The difference in radii between the landing site and the BB interface.
Uprange distance	122.025 km	The arc distance to the landing site.
Flight Path Angle	-6.957218°	Inertial coordinate frame, relative to a spherical surface.
Flight Path Azimuth	-23.279047°	0° = N, 90° = E, etc; inertial coordinates.
Velocity	2335.195 m/s	Inertial velocity relative to the Moon.

Braking Burn Interface



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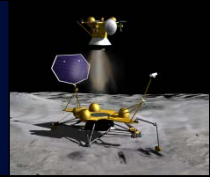
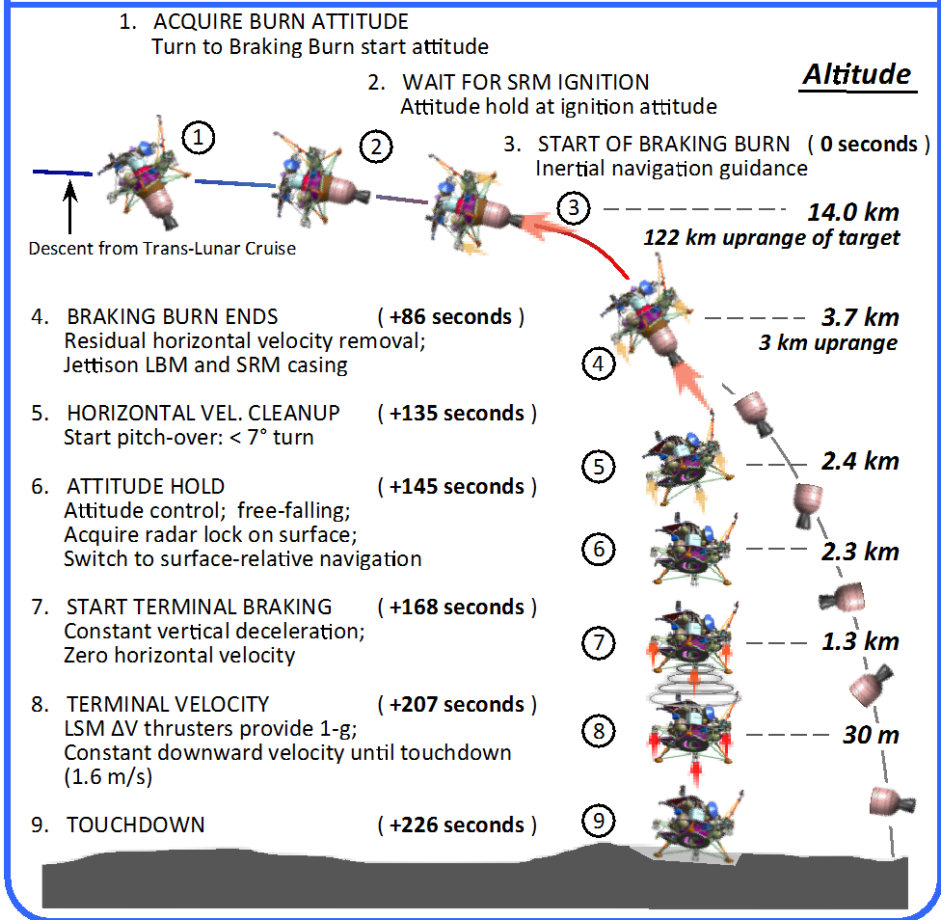
Lunar Descent and Landing



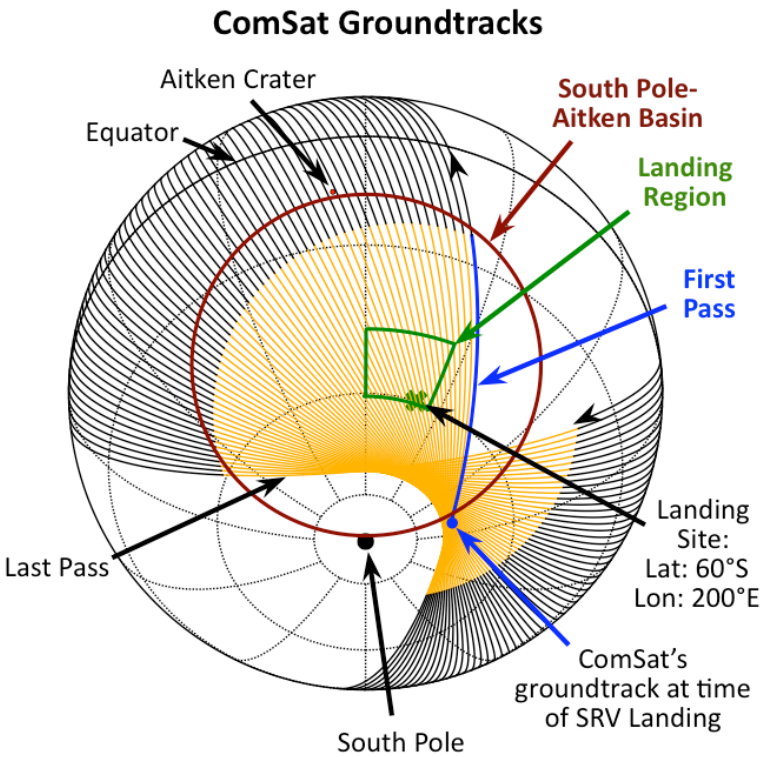
Lunar Descent and Landing

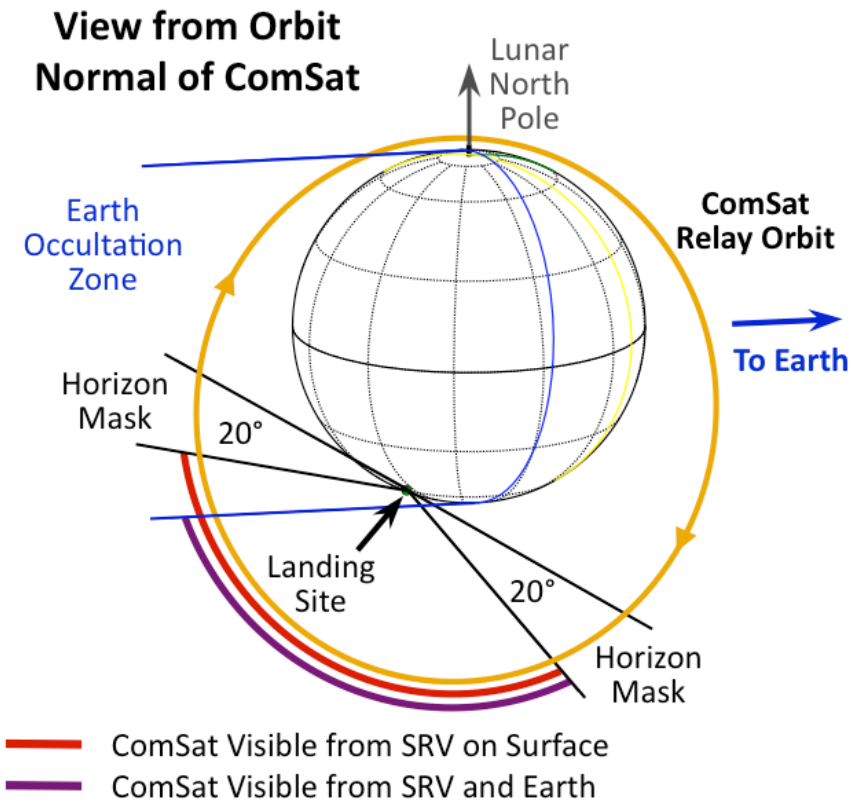
- Exact same approach for all launch days
- Robust design capable of absorbing flight and navigation errors
- Nominal touchdown time: 22 Nov 2016 18:19:51 UTC



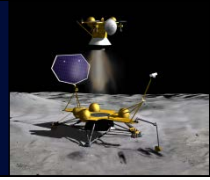
- **Resulting landing dispersion: 12 km x 1 km "landing strip"**

Surface Operations





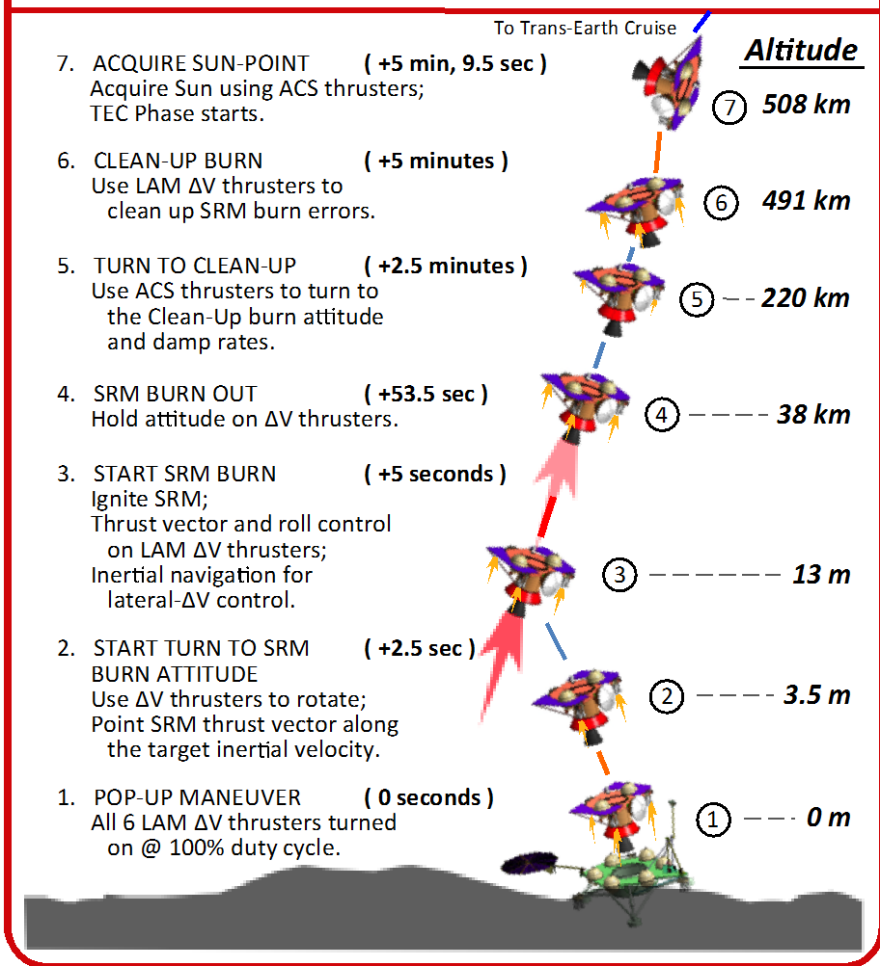
Lunar Ascent



- **Nominal lift-off time: 3:02 pm local solar time.**
- **The SRV can lift off immediately after landing.**
- **The SRV can lift off anytime during the lunar day; several opportunities would be prepped.**

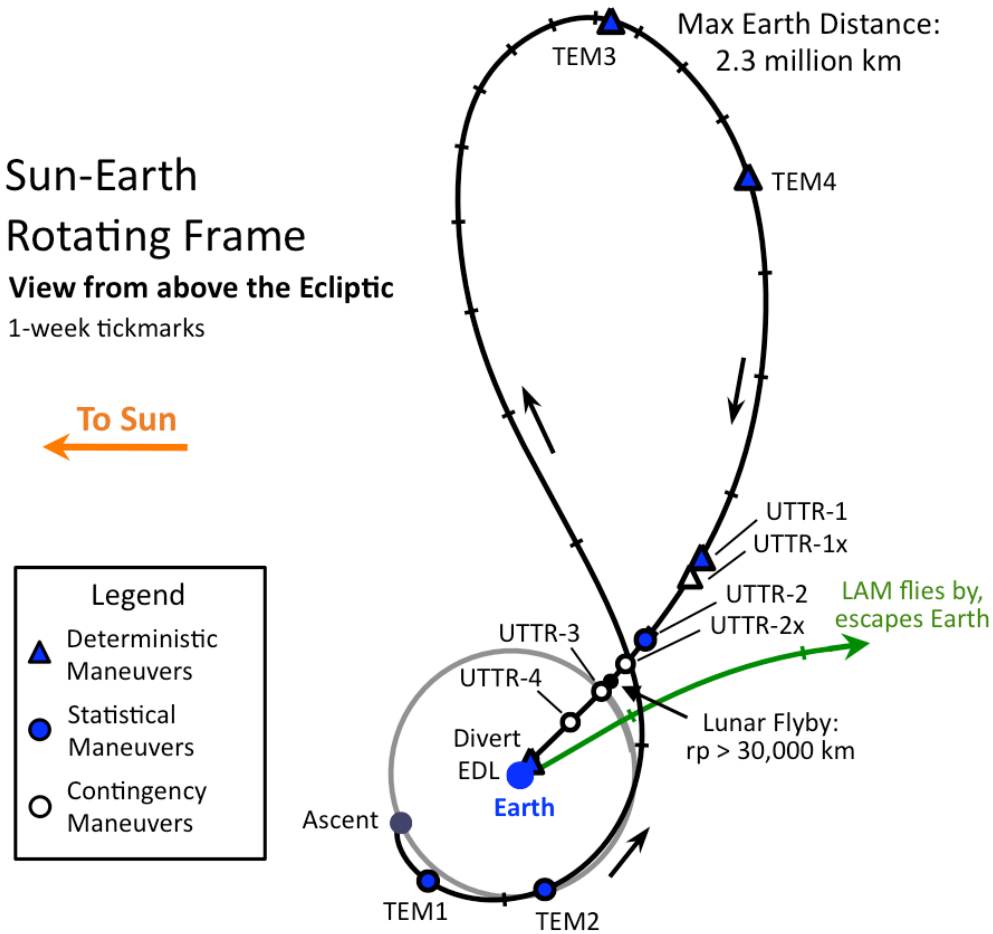
Lunar Ascent

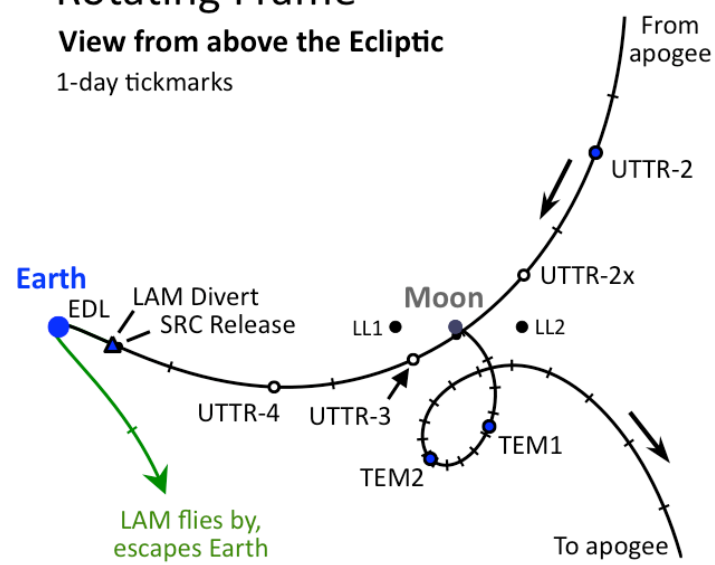
- The SRV may ascend any time during the surface mission
- The SRV will see Earth 2 minutes after pop-up
- Nominal ascent time: 1 Dec 2016 11:51:30 UTC



Trans-Earth Cruise

- **All ascent trajectories wind their way to UTTR-1**

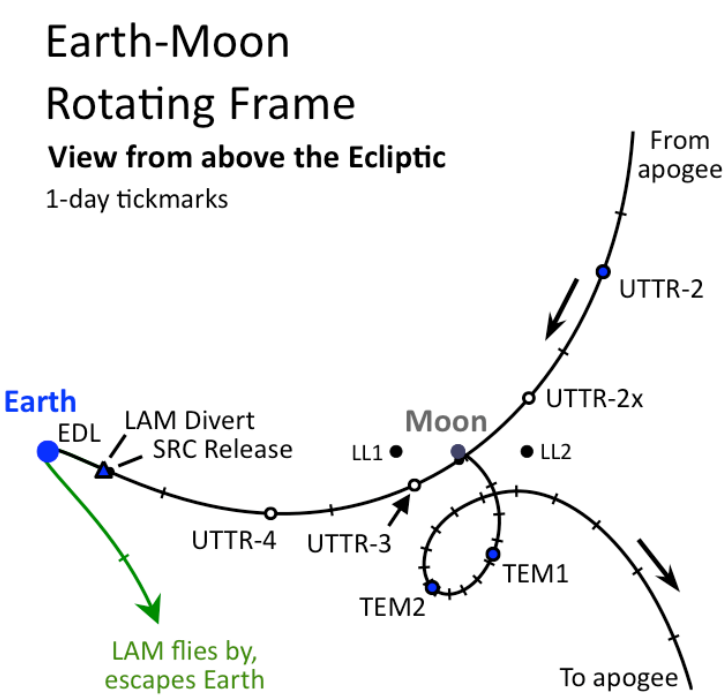




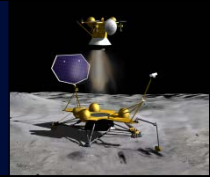
Earth Entry

- **All ascent and trans-Earth cruise trajectories arrive at the Earth at the same state.**

- TEC: Nominally misses Earth by > 200 km
- UTTR-1: E-8 days; Shifts target point onto UTTR
- UTTR-1x: E-7 days; Backup
- UTTR-2: E-4 days; Clean-up
- UTTR-2x: E-3 days; Clean-up opportunity
- Close approach to Moon
- UTTR-3: E-2 days; Clean-up opportunity
- UTTR-4: E-1 days; Clean-up opportunity
- Deploy SRC 4 hours prior to entry
- Divert LAM 3.5 hours prior to SRC's entry (19 m/s, targeting a miss-distance of 200 km)

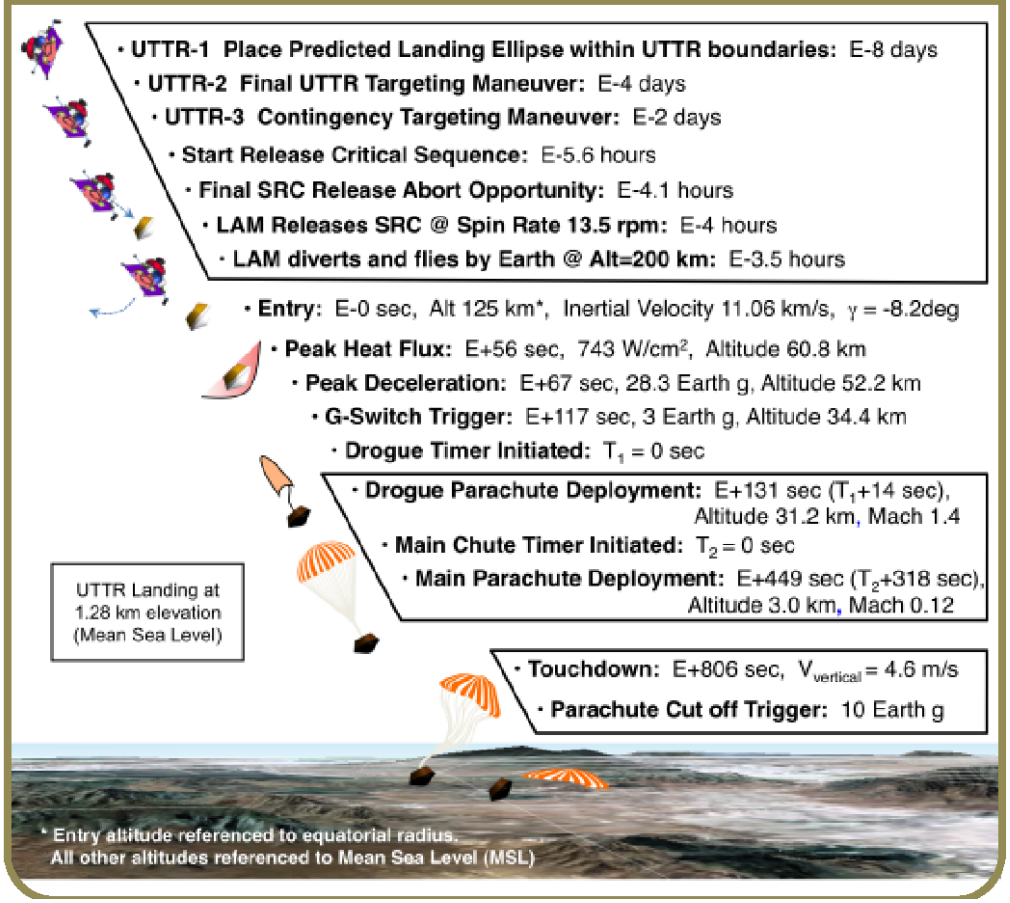


Entry, Descent, and Landing



Approach, Entry, Descent, and Landing

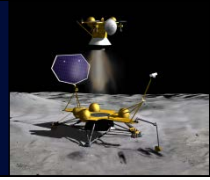
- Spin Rate: 13.5 rpm
- SRC Max Entry Mass: 53.4 kg
- Total Integrated Heat Load: 23.05 kJ/cm^2



Entry Interface:

Alt:	125 km
Inertial Velocity:	11.06 km/s
FPA:	-8.2 deg

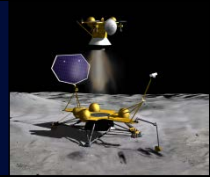
Summary



- **The proposed MoonRise mission design is an innovative solution to a very complex problem.**
  - Includes numerous features that add robustness and reduce risk.
  - Minimizes cost
  - Minimizes risk and perceived risk
  - Maximizes science return

- **Example features that appear in this proposed solution:**
  - Extended launch period
  - Reasonable operations plans: maneuvers spread out among vehicles with lots of time and opportunity for contingencies
    - Back-up landing dates; back-up ascent times
  - Constant dates and geometry for LOI, landing, and EDL
  - Optimized ComSat orbit for maximum science return
  - Options to ascend from the lunar surface any time
  - Only 1 large TLC burn (BB) and 1 large TEC burn (Ascent)
    - Permitting solid rocket motors, with robust designs
  - Safe approach to Earth and EDL
  - Redundant tracking stations for critical events
  - Opportunity to have ComSat contributed by ISRO

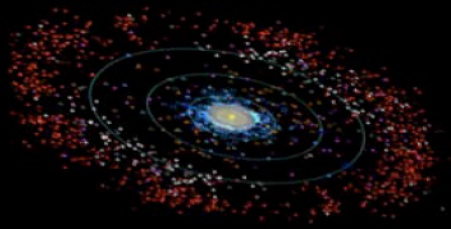
Acknowledgements



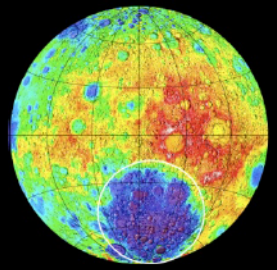
- This work would not have been possible without many people who contributed to the proposed 2009 New Frontiers MoonRise concept design, including the PI Dr. Bradley Jolliff, the capture lead Leon Alkalai, and the team members within the Jet Propulsion Laboratory, Lockheed Martin, ISRO, CSA, DLR, and elsewhere.

- Many people contributed to various elements of the proposed trajectory design, including Gene Bonfiglio, Min-Kun Chung, Sara Hatch, Dan Johnston, Stuart Kerridge, Ralph Roncoli, Guru Singh, Evgeniy Sklyanskiy, and Roby Wilson.

- The research presented in this paper has been partially carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Government sponsorship acknowledged.



Trajectory Design for MoonRise: A Proposed Lunar South Pole-Aitken Basin Sample Return Mission



MoonRise
A NASA New Frontiers Mission Proposal

AAS 13-882

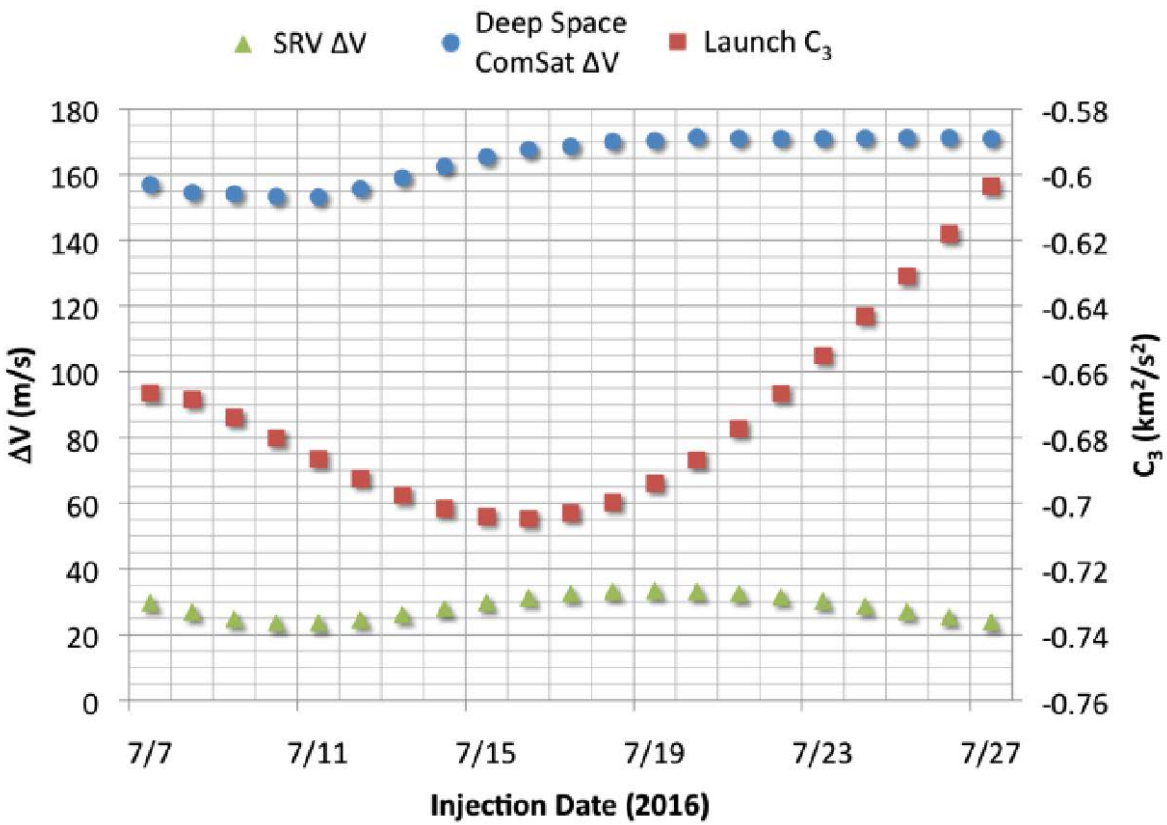
Jeffrey S. Parker
Timothy P. McElrath
Rodney L. Anderson
Theodore H. Sweetser

Jet Propulsion Laboratory, California Institute of Technology

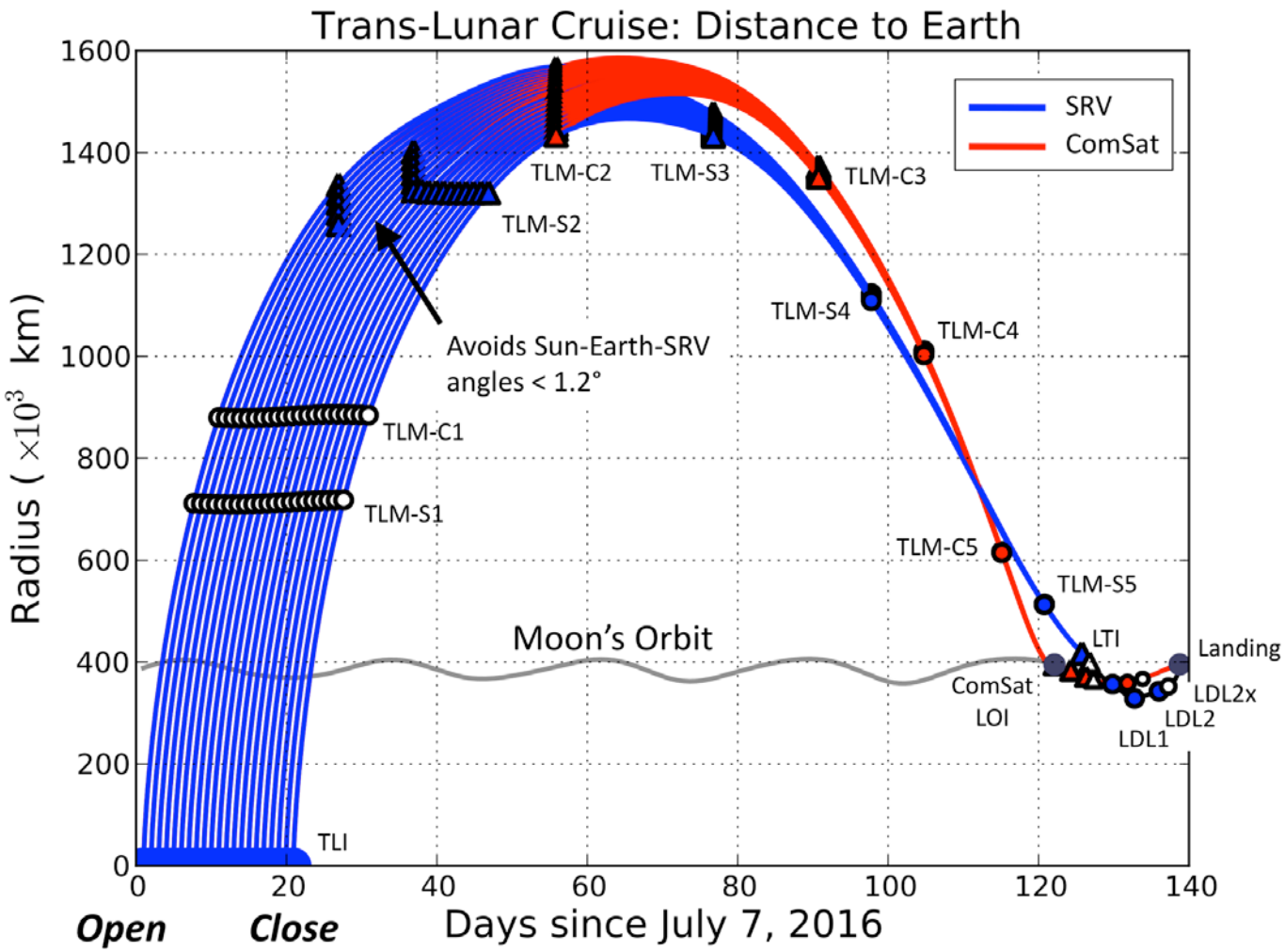
Pre-Decisional Information -- For Planning and Discussion Purposes Only

Launch Period

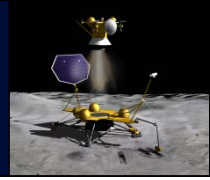
- **The 21-day launch period may be extended as needed, including launching a month or more later.**



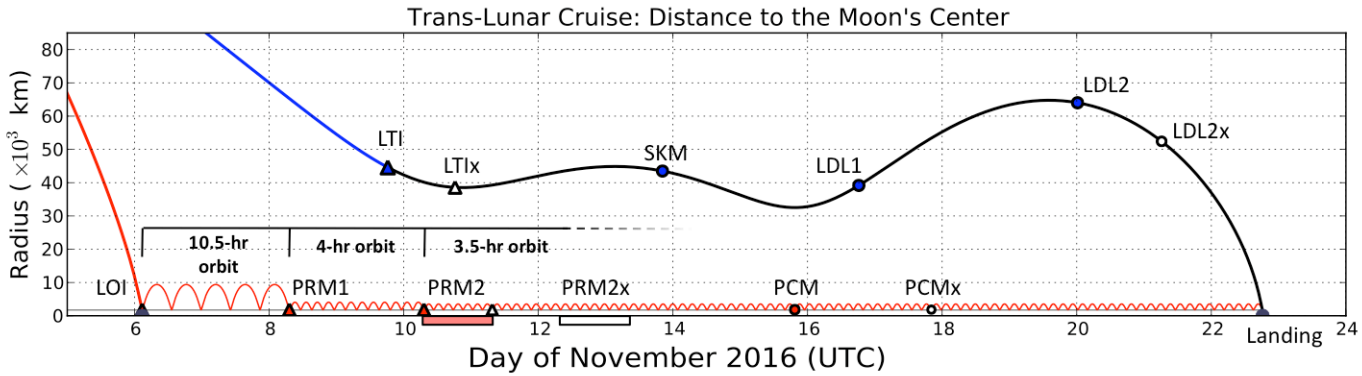
Trans-Lunar Cruise

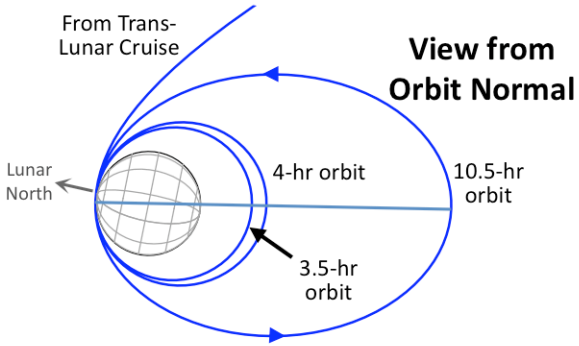


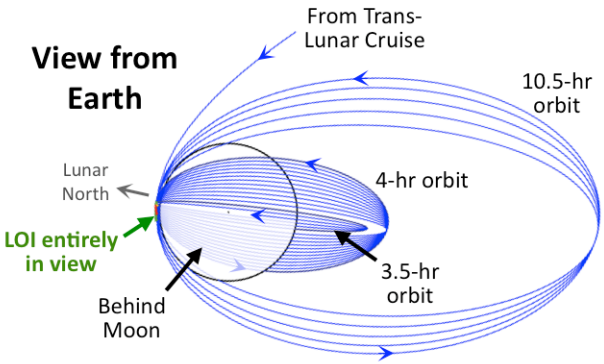
ComSat LOI and Commissioning



- Fixed LOI date: 6 Nov 2016 2:41:11 UTC
- ComSat has over 16 days to prepare before the SRV's landing.
- ComSat's LOI is entirely visible from Earth.
- LOI, PRM1, and PRM2 are pre-designed maneuvers, only needing a time update.
- PRM2's location is selected to properly phase the ComSat for landing.
- PCM corrects phasing

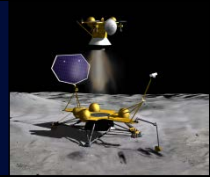


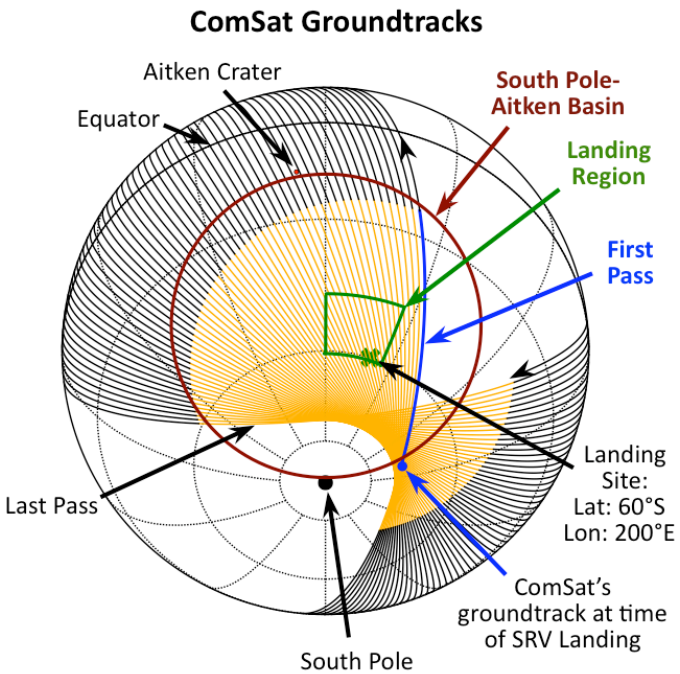


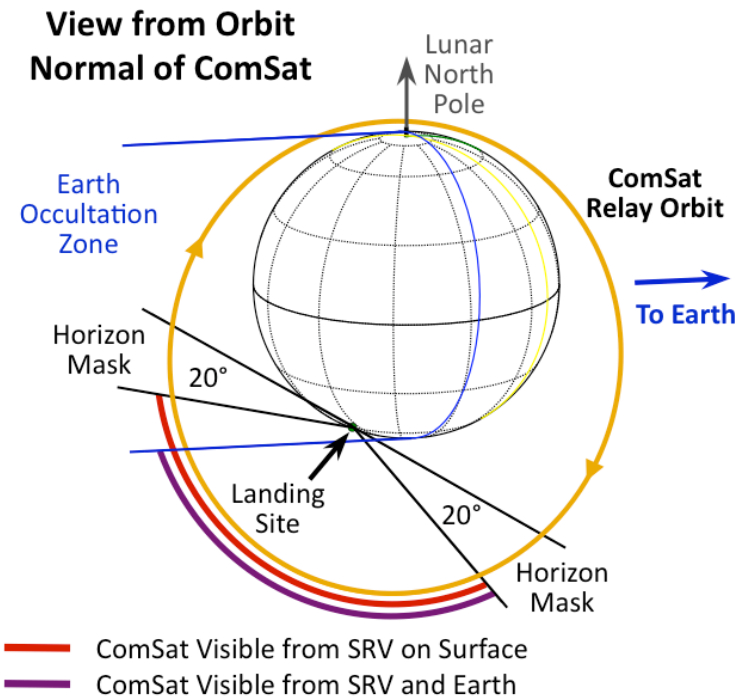


Maneuver	Duration	Resulting Orbit	
LOI	4.6344 min	10.50 hours	97.7 km × 7660.8 km
PRM1	3.6472 min	4.00 hours	104.4 km × 2326.9 km
PRM2	0.7318 min	3.50 hours	106.9 km × 1821.3 km

Surface Operations







Communication Passes:

- Durations: 68 – 77 minutes

Occultations:

- Worst: 11/23: 48.8 min.
- End: 11/27

ComSat Orbital Elements at Landing in Moon Principal Axis Frame

Period:	3.509 hr
Periapse Altitude:	129.4 km
Inclination:	105.3°
Argument of Periapsis:	99.1°
Longitude of Node:	196.5°
True Anomaly:	-178.5°
Elevation w.r.t. the SRV:	47.9°

ComSat Eclipses

Worst eclipse before landing:

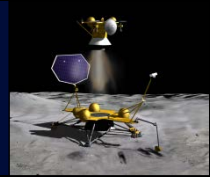
Nov 10: 23.6 min (23.0 min Umbra)

Worst eclipse after landing:

Nov 22: 8.9 min (7.1 min Umbra)

No eclipses past Nov 25

ΔV Budgets



- **SRV**

SRV Mission Phase / ΔV & Propellant Cost Component	Initial mass (kg)	ΔV (m/s)	Isp(s)	Propellant cost (kg)			Notes
				SRM (incl. expelled inert)	Hydrazine		
					LSM	LAM	
LV injection mass	5654.53						
Trans-Lunar Cruise	−672.75						ComSat + CS & LV adaptors are 672.75 kg
Deterministic ΔV	4981.78	33.60	226.00		74.94		Worst-case combination of deterministic and statistical
Statistical	4906.82	7.70	226.00		17.02		
ACS	4889.81					3.25	Worst-case
Landing							Δ-Vs are from one Monte Carlo case
BB SRM + attitude control	4886.56	2232.34	288.05	2653.83	15.60		Isp is weighted average of 288.41s for STAR 48AX and 226s for MR-104s
Velocity cleanup	1946.56	167.64	226		141.81		Jettison 270.57 kg LBM stage, incl 1kg resid prop
Terminal descent & landing	1804.75	172.48	226		135.13		Worst-case
Landed mass	1669.63						Includes 8.33 kg usable LSM prop
Ascent	−654.03						Jettison 656.23 kg LSM, add 2.2kg sample
Pop-up	1015.60	12.45	225.66			5.70	
AB SRM + attitude control	1009.90	2351.28	291.13	561.00		5.69	Isp is weighted average of 291.8 s for STAR 30C/BP and 225.14s for MR-104s
Clean-up	443.21	63.49	224.47			12.60	
Statistical	430.61	25.75	223.91			5.02	Prop mass to bounding ascent case
TEC							
Deterministic Δv	425.59	41.56	223.58			7.99	Worst case for any ascent LST
Statistical	417.60	37.50	223.23			7.09	Mostly corrects ascent SRM errors
Margin	410.51	4.25	223.07			0.80	
ACS						2.08	
Divert	354.23	19.23	222.92			3.10	After separating 53.4 kg SRC
Totals	351.04			3214.83	384.51	53.32	LSM usable 392.8 kg, LAM usable 53.4 kg

ΔV Budgets

- **ComSat**

ComSat Mission Phase / ΔV & Propellant Cost Component	Initial mass (kg)	ΔV (m/s)	Effective Isp (s)	Propellant cost (kg)
Post-SRV and adaptor separation	578.20			
Trans-Lunar Cruise				
Deterministic ΔV	578.20	173.58	313.1	31.78
Statistical	546.42	10.80	313.1	1.92
LOI & Commissioning				
LOI	544.50	231.85	313.1	40.26
PRM1	504.24	195.74	313.1	31.14
PRM2	473.10	40.83	313.1	6.25
PCM	466.85	0.73	313.1	0.11
ΔV Margin	466.74	24.7	313.1	3.74
ACS	463.00			1.20
Totals	461.80	682.23		116.4