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LunarCube Transfer Trajectory Options

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Introduction

- **Numerous Earth-Moon (EM) trajectory and lunar orbit options are available for LunarCube missions**
- **Our investigation of potential trajectories highlights several transfer and lunar capture scenarios**
    - Low Earth orbit (LEO); Geostationary transfer orbits (GTO); Higher energy direct lunar transfer orbits (EM-1)
    - Lunar elliptical and circular orbits with minimal capture requirements
    - Yield a wide range of transfer durations, fuel requirements, and final destinations including Sun-Earth and Earth-Moon libration orbits, and heliocentric designs
- **Given the limited injection infrastructure, many designs are contingent upon the modification of an initial condition of the injected or deployed orbit**
- **Restricted by subsystems selection such as propulsion or communication**
- **Application Earth-Moon dynamical system design approach**
    - Apply natural trajectory flow and take advantage of system perturbations
    - For missions with an intended lunar orbit, much of the design process is spent optimizing a ballistic capture

Introduction

- Trajectory - Propulsion trades drive many mission design options
  - Both low and high-thrust transfers are feasible assuming sufficient power or fuel mass
- For the EM-1 injected initial design, modify the lunar flyby distance to alter the system energy, matching that of a typical Sun-Earth system heteroclinic manifold
  - Option uses dynamics similar to the ARTEMIS mission design
  - Manifold and maneuvers raise perigee to that of a lunar orbit, adjust the timing wrt the Moon, rotate the line of apsides, and target a ballistic lunar encounter.
  - Orbital energy (C3) with respect to the Moon is targeted to $< -0.1\ km^2/s^2$
- LEO or GTO design options use impulsive maneuvers to phase onto a local Earth-Moon manifold, which then transfers LunarCube to a lunar encounter
- Investigation concludes with several design options which provide estimated ΔV requirements, achieved lunar orbit parameters, and associated transfer trajectory information
- The use of Goddard's dynamical systems mission design tool, Adaptive Trajectory Design (ATD), and operational software (GMAT, Astrogator) are utilized to generated results

Constraints

Low thrust and impulsive maneuvers concepts

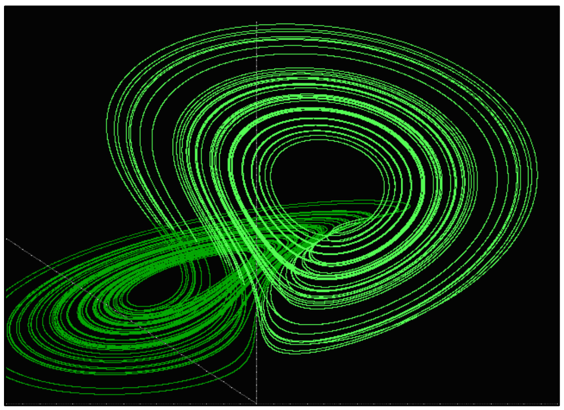
- Low thrust level investigated vary from μN to mN,
  - Limits the control authority and trajectory modifications
  - Power limited, with power < 100W(?)
- Attitude control and pointing constraints may impede use or drive designs
- Impulsive designs drive fuel mass, deterministic ΔVs, or timing

Launch vehicle and related primary trajectories

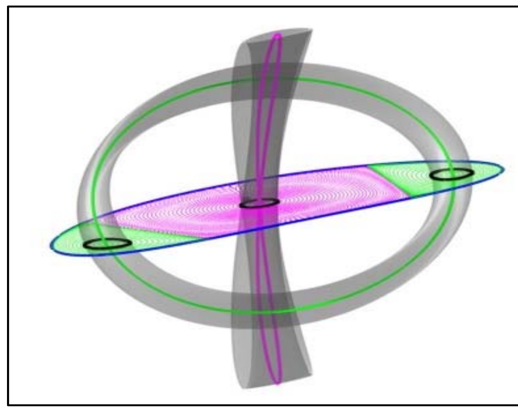
- Secondary payloads cannot drive primary mission goals but can provide a minimal cost approach
- Constrain the mission design wrt launch/ injection parameters
  - Injection energy can vary over launch period or window
  - Number of launch opportunities can be limited
- Three injection options limitations
  - LEO – launch dates, inclination and accelerations (Nodal precession and atmospheric drag)
  - GTO – launch dates and line of apsides alignment
  - EM-1 – launch dates, varying injection energy over window, unknown trajectory (apoapsis) direction

Dynamical Systems Theory

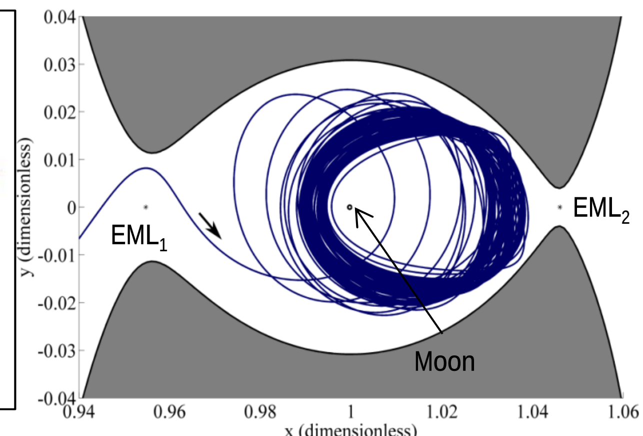
- Describes long-term qualitative behavior of complex dynamical systems
- Employs differential equations (continuous) / difference equations (discrete) to model system behavior
- Nonlinearity lead to complexity but not necessarily a loss of predictability.
- Focus not on precise solutions, but on general exploration of space (periodic orbits, quasi-periodic motion, chaos, …)



Lorentz Attractor – a non linear system sensitivity



Earth-Moon Poincare map of manifolds to hyperplane

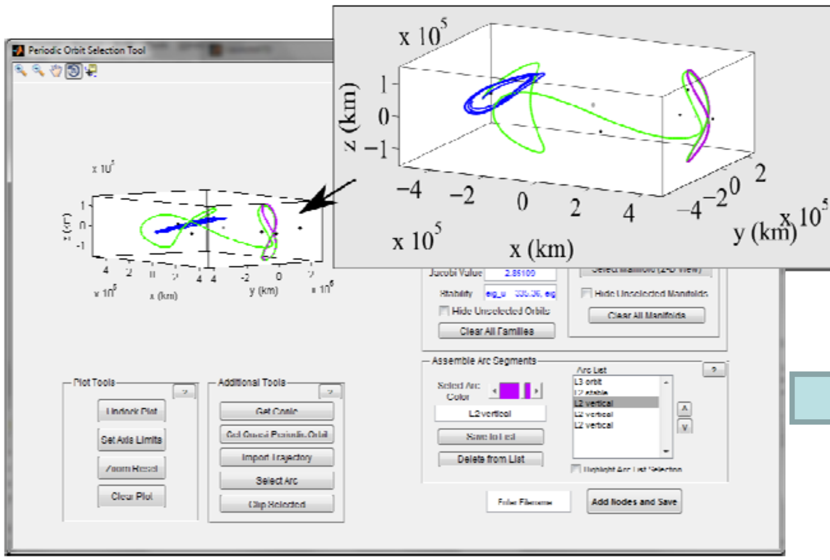


Periapsis Poincare map

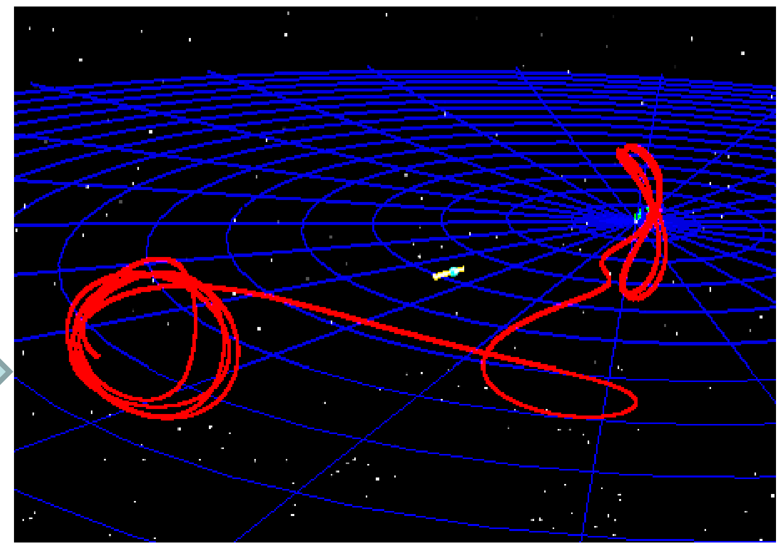
- Poincaré maps and invariant manifolds useful to locate long-term capture trajectories about the smaller primary in CR3BP
- Images from Howell, Craig Davis, and Haapala, *Journal of Mathematical Problems in Engineering*, Special Issue: Mathematical Methods Applied to the Celestial Mechanics of Artificial Satellites, 2012.

Circular Restricted Three-Body Problem

- Simplified model, autonomous system
- Provides useful information about fundamental solutions (libration point orbits, stable/unstable invariant manifolds, retrograde orbits, …)
- Solutions from CR3BP transitioned to ephemeris model, generally, maintain orbit characteristics



Earth-Moon CR3BP (ATD©)



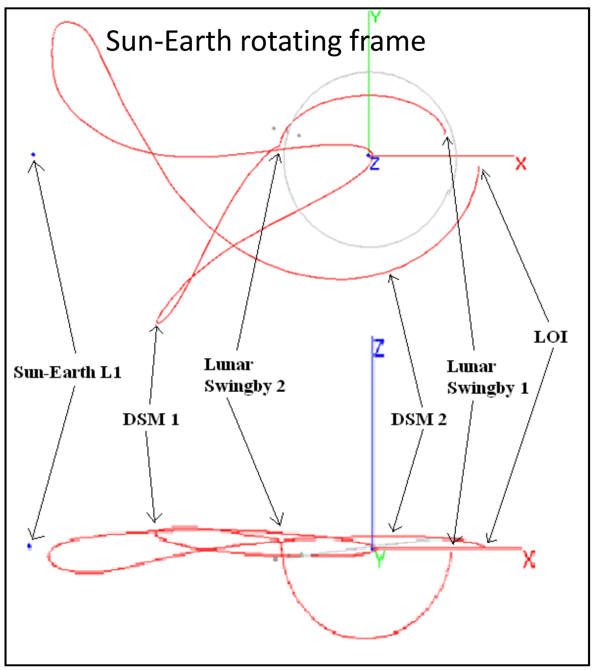
Sun-Earth-Moon (GMAT)

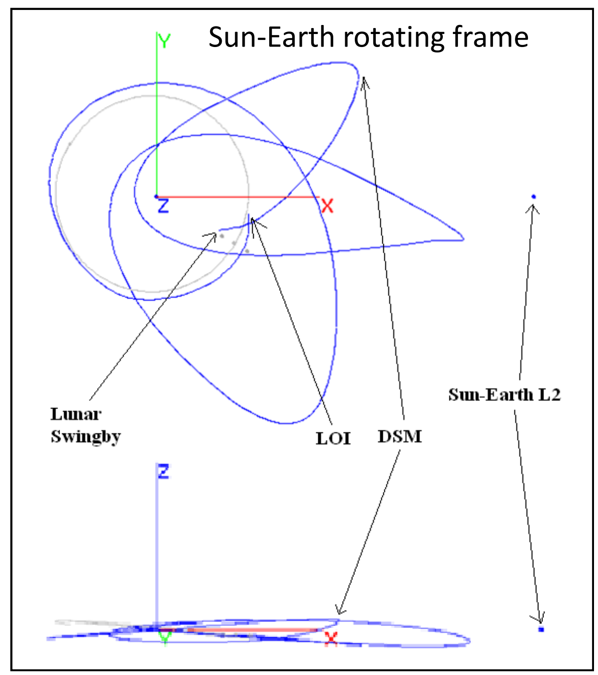
** *Images from Haapala, Vaquero, Pavlak, Howell, and Folta, AAS/AIAA Astrodynamics Specialist Conference, 2013.*

The ARTEMIS Connection

- In 2009, two small spacecraft where transferred from low elliptical Earth orbits to lunar elliptical orbits
  - Use of a dynamical system (manifold) approach with numerical targeting
  - Lower thrust propulsion system (4N) with constrained thrust direction on a spinning spacecraft
  - Orbit-Raising maneuvers performed near periapsis to raise apoapsis to lunar distance
  - Lunar Gravity Assists (LGAs) to align trajectory for Earth-moon libration insertion and to raise periapsis

P1 Design

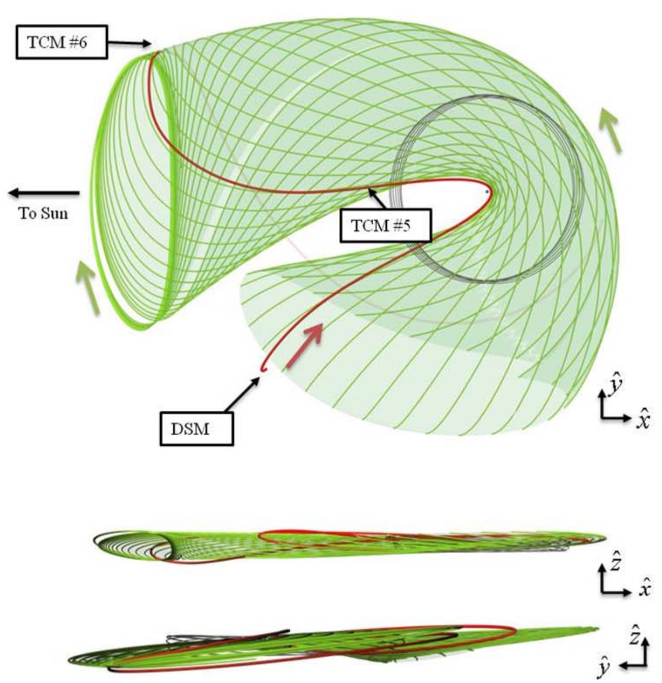




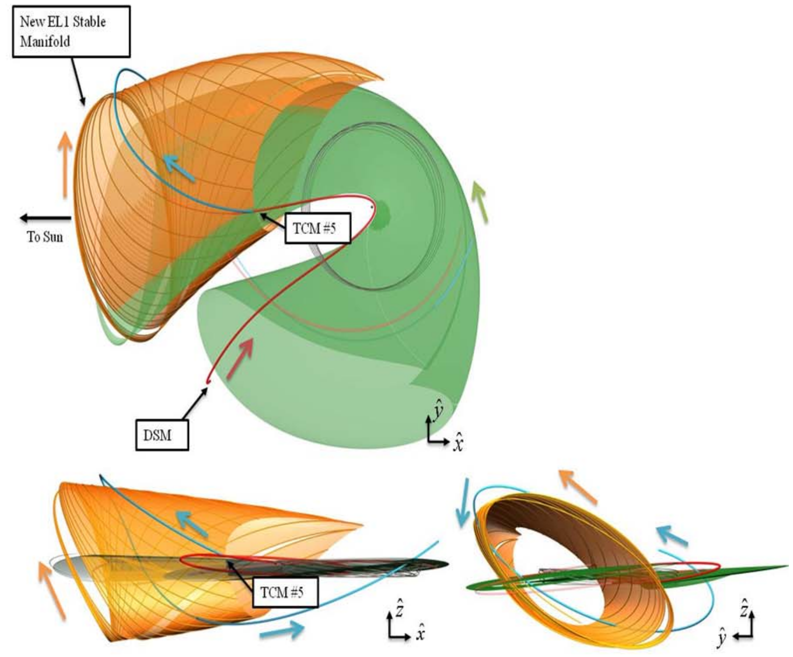
P2 Design

The ARTEMIS Connection - Manifolds

- In an ARTEMIS example, consider only the outbound arc of P1
- Follow the original outbound path to the location of a correction maneuver which shifted the spacecraft onto a different path, (orange) manifold
- Subsequent to and along the outbound trajectory two outbound manifold arcs emerge
- Represent potential outcomes from flow along the optimal path and the alternative that incorporates a possible correction maneuver



P1 Planned Stable Sun-Earth



P1 Pre and Post TCM5 Stable Sun-Earth Manifold

Deployment options

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- The local Earth-Moon manifold has a particular geometry and design that is based on the Earth and moon dynamics (CRTB)
- This manifold as illustrated provides a background on the types of trajectories desired for a natural flow towards either the moon or the Earth-Moon libration point orbits, EML_1 or EML_2.
- The premise is that a spacecraft is inserted onto an intermediate orbit which asymptotically converges onto the manifold or intersects with the manifold
- A manifold matching DV places the spacecraft onto one of the manifold trajectories which then flows to the region of lunar interest.

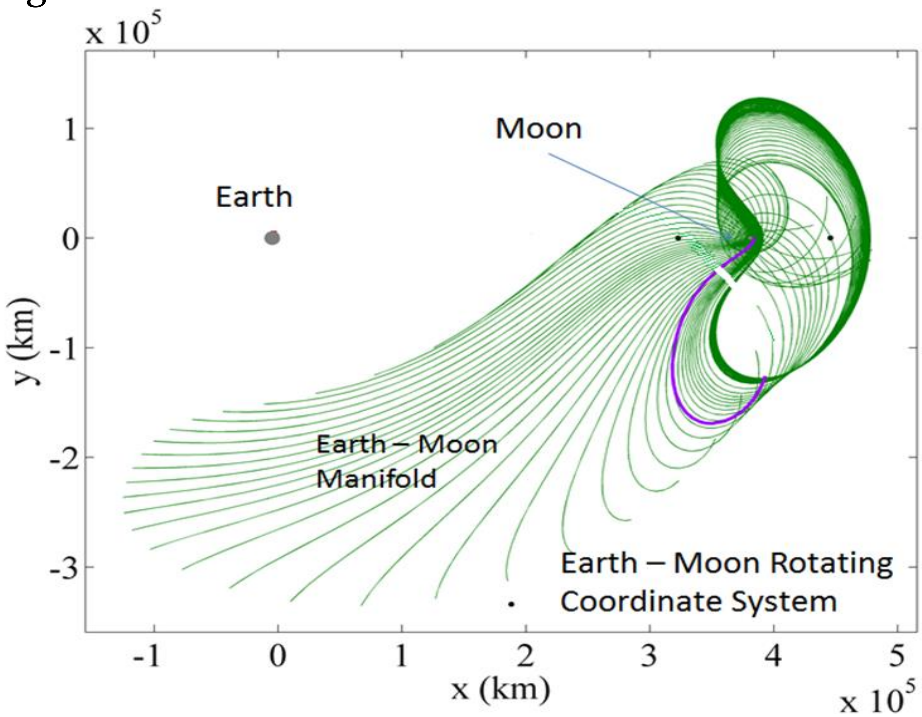
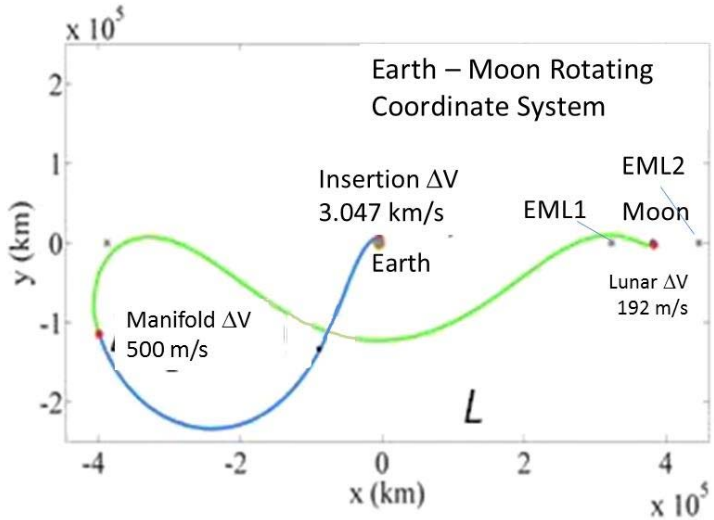
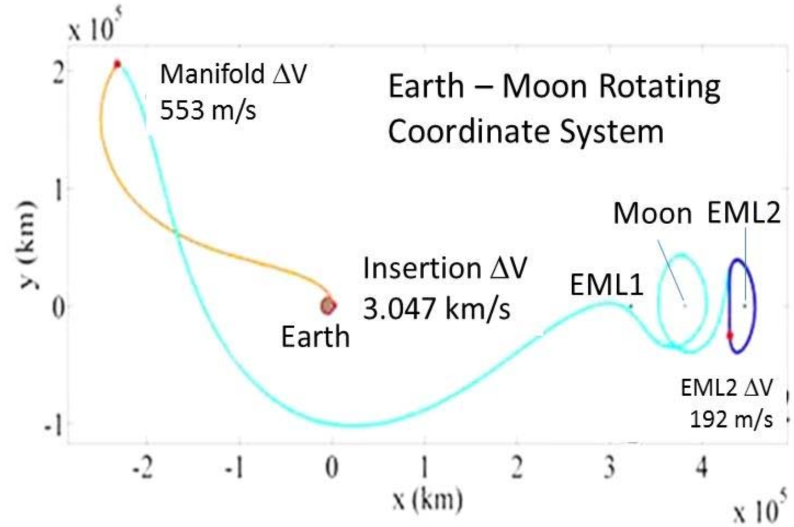


Figure 8. Example of Earth-Moon Local Manifold

LEO to the Moon





	Design-1 (figure 9)	Design-2 (figure 10)	Design-3 (figure 11)	Design-4 (figure 12)
Insertion DV (m/s)	3137	3047	3046	3099
DV 1 (m/s)	500	553	1183	899
DV 2 (m/s)	192	192	507	524
S/C DV total (m/s)	692	745	1690	1423
Manifold duration (days)	10	27	25	32
Transfer Duration (days)	13	30	27	36

- Initial orbit assumed 200 km LEO Final lunar orbit 1000 km,
- Trajectories designed using ATD©

GTO to the Moon

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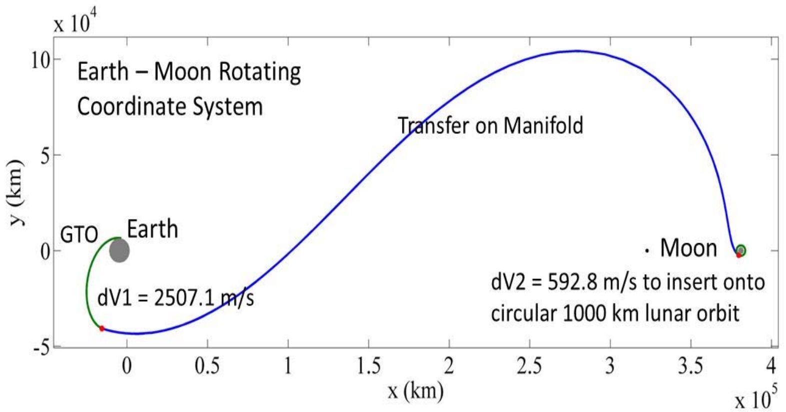
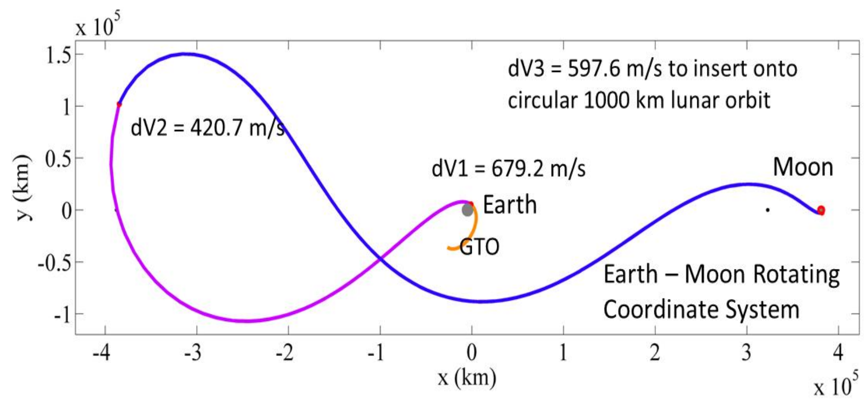
- Initial orbit assumed 200 km, 24 deg inclination, LEO Final lunar orbit 1000 km,
- Trajectories designed using ATD©
- Insertion from GTO Peripais and intermediate transfer reduces manifold matching DV cost





	Design-1 (figure 15)	Design-2 (figure 16)	Design-3 (figure 17)	Design-4 (figure 18)
DV 1 (m/s)	2507	676	719	679
DV 2 (m/s)	0	0	824	421
DV (m/s) (Lunar)	593	731	517	598
S/C DV total (m/s)	3100	1407	2060	1698
Transfer Duration (days)	5.4	4.7	20.3	16.2

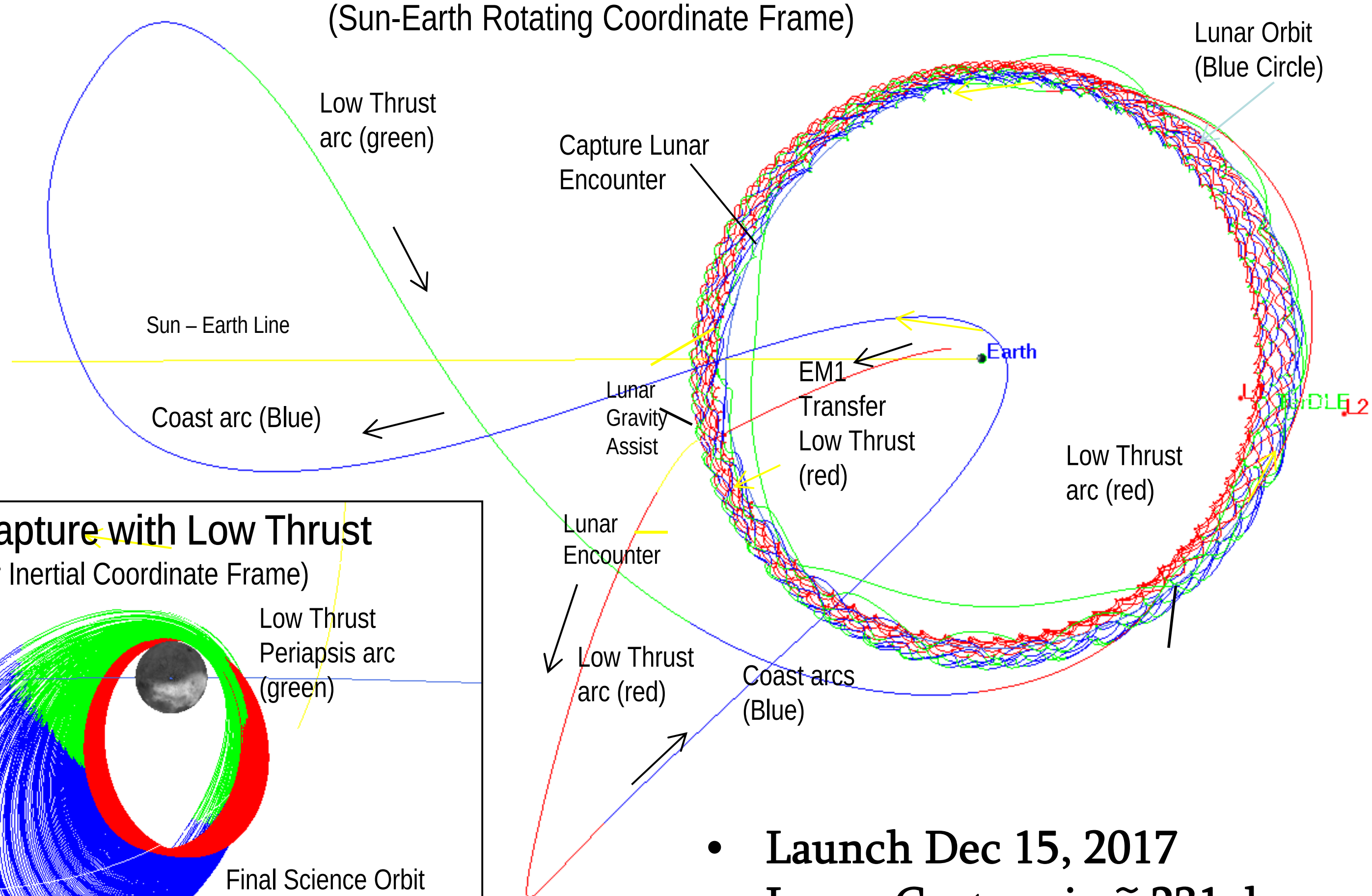
EM-1 to the Moon

- Without altering the EM-1 injection energy, a LunarCube would perform a close lunar flyby and depart into heliocentric space
- Options to alter LGA energy include changing the flyby distance and orientation, permit trajectories to Sun-Earth L_1/L_2, Earth-moon L_1/L_2 , and lunar orbits
- Slow down from EM-1 injection approaching lunar flyby
  - Immediately after injection from EM1, thrust against velocity vector (relative to Earth) for several days
  - Option-1: Enter highly eccentric orbit around Earth and gradually raise perigee and lower apogee to approach Moon, in both orbit and phase
  - Option-2: Achieve LGA to enter onto Manifold to raise perigee and approach moon
  - Thrust against velocity vector (relative to Moon) to capture / spiral into a distant lunar orbit
  - or change elliptical eccentricity
- Speed Up from EM-1 injection approaching lunar flyby
  - Immediately after injection from EM1, thrust along velocity vector (relative to Earth)
  - Achieve LGA to insert into a highly eccentric Earth orbit, with inclination close to
  - Moon orbit.
  - Raise perigee and lower apogee to approach Moon, in both orbit and phase
  - Thrust against velocity vector (relative to Moon) to capture / spiral into a distant lunar orbit
  - or change elliptical eccentricity

EM-1 to the Moon, A low Thrust Option

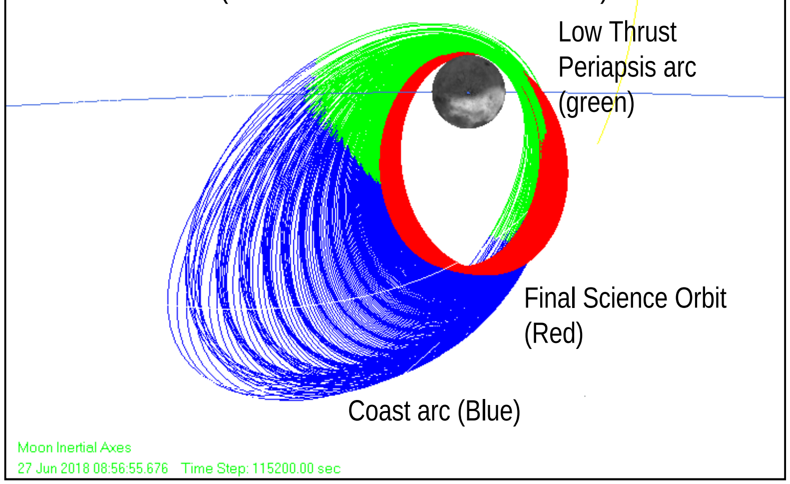
Transfer Trajectory with Low Thrust

(Sun-Earth Rotating Coordinate Frame)



Lunar Capture with Low Thrust

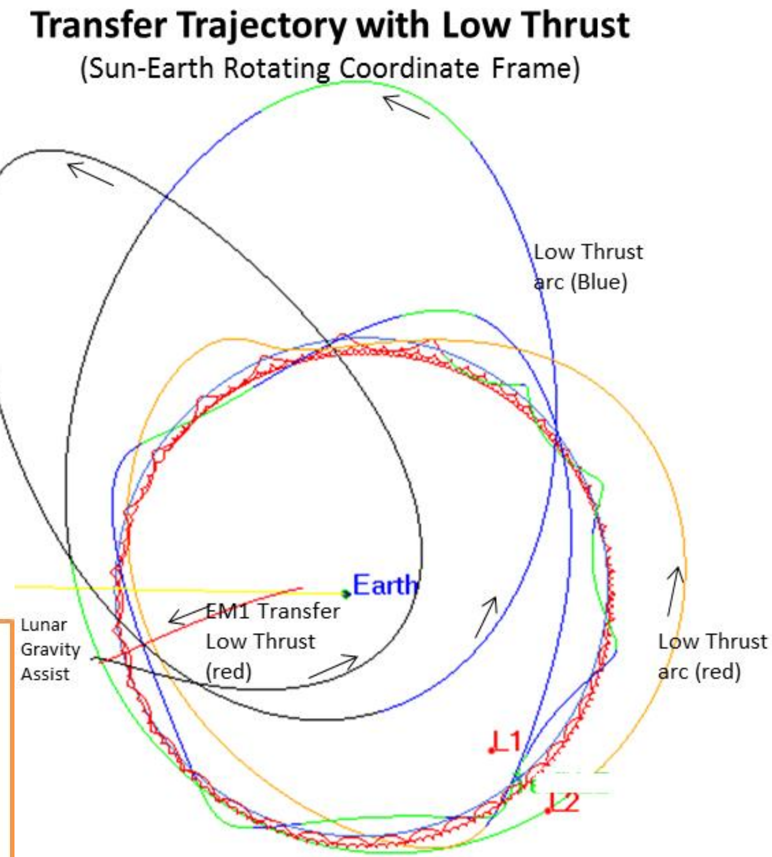
(Lunar Inertial Coordinate Frame)

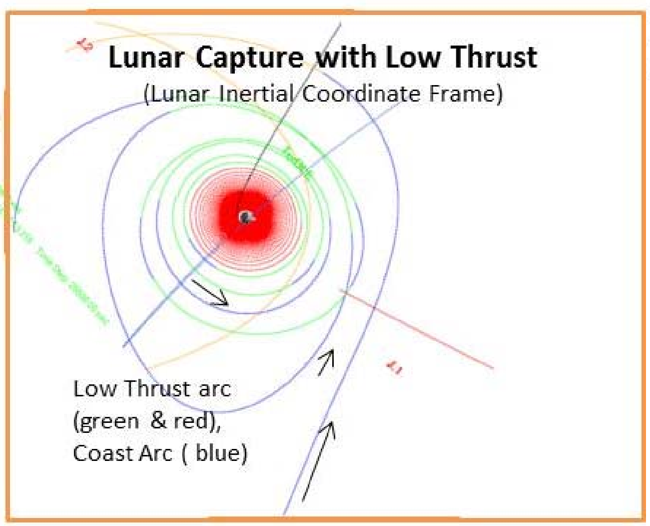


- Launch Dec 15, 2017
- Lunar Capture in ~ 231 days
- Total DV of ~ 869 m/s

EM-1 to the Moon, A low Thrust Option

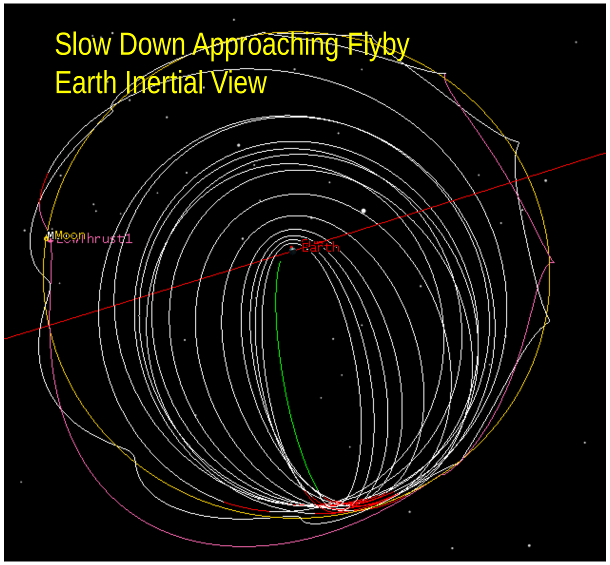
- Launch Dec 15, 2017
- Lunar Capture in ~ 171 days
- Total DV of ~ 1554 m/s

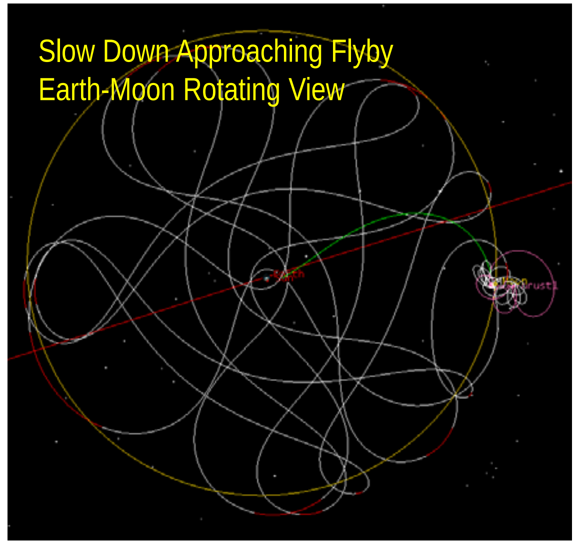




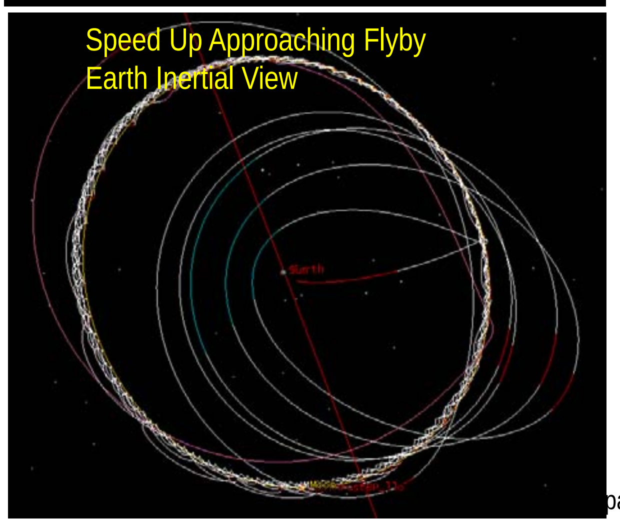
EM-1 to the Moon

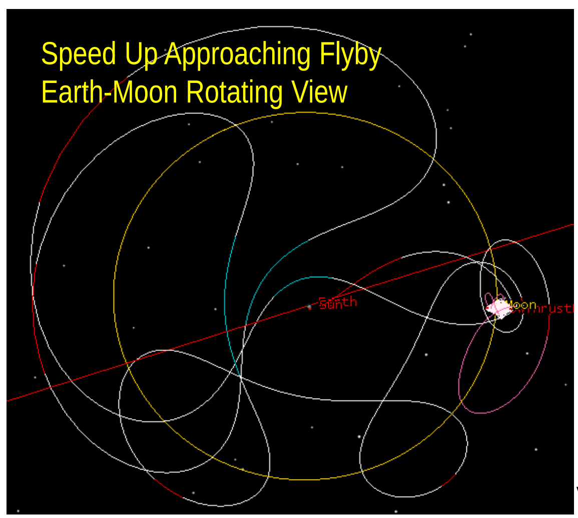
Other options to maintain apoapsis near lunar orbit distance and then raise periapsis for a minimal lunar orbit capture





	Slow down	Speed up
Injection date	15-Dec-2017	15-Dec-2017
Science orbit insertion	6-Aug-2018	31-Jul-2018
Transfer time (days)	234	228
Delta-V (m/sec)	1142	1315





Lunar Cube Transfer Trajectory Options

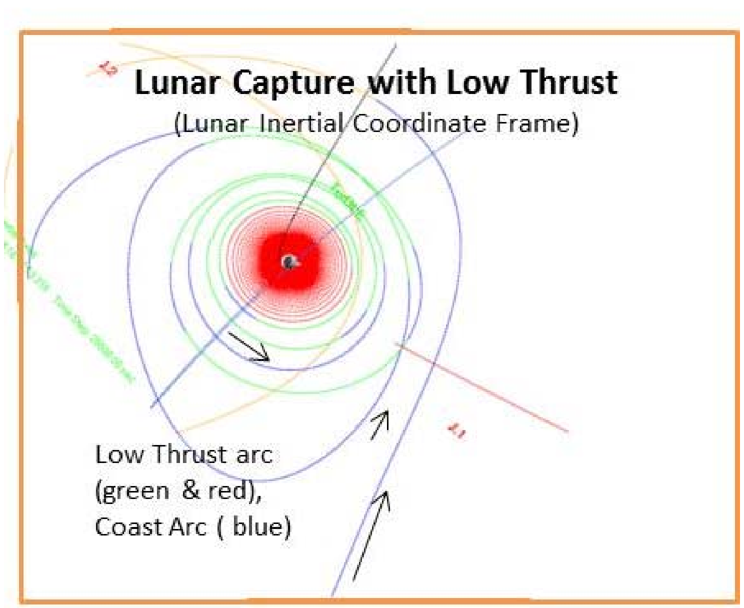
Sample EM-1 Transfer Comparisons

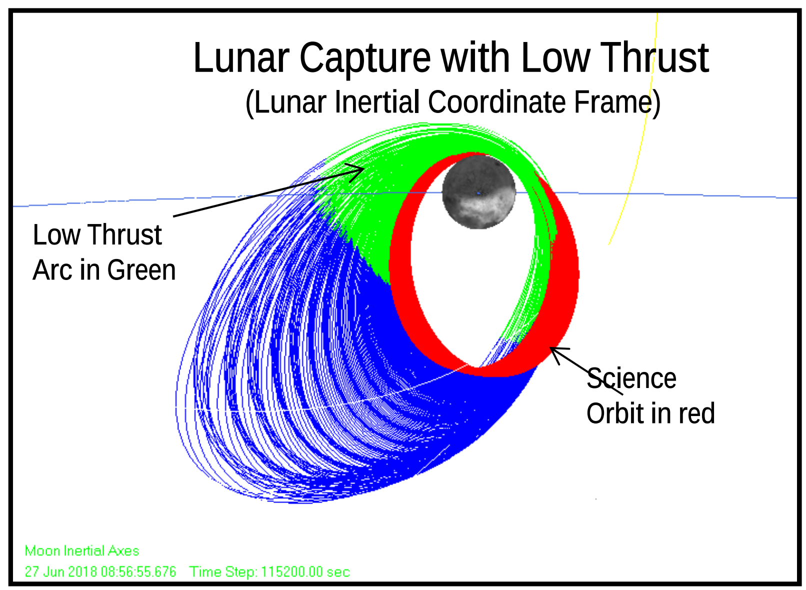
	Decreased Velocity	Decreased Velocity	Decreased Velocity	Increased Velocity	Increased Velocity
Related Fig	16	17	18	19	20
Initial Mass (kg)	9	12	Need	12	Need
Thrust Level (mN)	0.5	2	3	2	3
Total DV (m/s)	869	629	1314	1595	1141
Transfer DV (m/s)	673	190	1082	557	860
Lunar Capture DV (m/s)	196	439	41	1038	25
Lunar Flyby Radius (km)	6763	5025	4696	2510	6318
Max Transfer Range (Km)	1,524,000	1,719,925	447,959	1,154,950	467,698
Total Transfer Duration to Capture (days)	231	250	41	171	214
Lunar Capture Duration (days)	60	27	11	65	15
Maximum Lunar Eclipse Duration (hrs)	1.0	4.6	0.9	4.0	3.3
Lunar Orbit apoapsis x periapsis (km)	6800 x 100	9993 x 1545	tbd	350 x 50	tbd
Lunar Orbit Inclination (deg)	20	144	32	165	139

Lunar Missions

A variety of lunar science orbits can be achieved from any of these analyzed transfers

- Low thrust capture and insertion using a ballistically captured lunar orbit
- Perform an alignment of periapsis (apsides) with science goals
- Target a given periapsis altitude or periapsis decay over time
- Target various eccentricity, semi-major axis, inclinations
- Achieve various science parameters, e.g. Solar angles





Conclusions

- There are numerous Lunar Cube Transfer Trajectory Options available
- The deployment strategy, as a secondary payload, drives the available designs options
- Both low thrust and high performance propulsion systems can be used
  - High thrust can result in mass / volume considerations
  - Low thrust ranging from μ-N to m-N can augment the trajectory given the proper initial conditions
  - Power level will drive low thrust capabilities and the ensuing trajectory design
- Transfer and lunar capture into science orbit durations can be time-consuming
- Use of dynamical systems, aka manifolds, can aid in the design and provide an intuitive approach in addition to optimization
- Combining dynamical systems techniques with high or low thrust propulsion systems provides versatile, efficient techniques for transfers to the Moon, especially for low-thrust options on high energy deployment trajectories.
- With a lower cost and many secondary payload opportunities, Lunar Cubes can be the next step for flexible trajectory designs, to the Moon and beyond