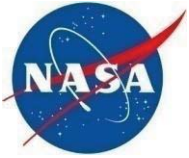# Ways to the Moon: Trajectory Options From Earth GEO Transfer Orbit to the Moon

Donald Dichmann, David Folta, Frank Vaughn, Joel Parker
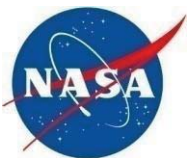
NASA Goddard Space Flight Center

11 Apr 2013

Overview

- Flight Dynamics Mechanisms –Ballistic and Powered Flight
- Ballistic Flight with Nonlinear Dynamics ("Chaos")
  - 2-Body, 3-Body, 4-Body
- Powered Flight
  - High Thrust (Apollo) vs. Low Thrust (SMART-1)
- Creative Combinations
- Trajectory simulations
  - Low thrust trajectory from GTO to Moon
  - Gravity Assist
  - Weak Stability Boundary
- Mission Trade-offs
- Conclusion and Future Work

Ballistic 2- and 3-Body Motion

- 2-Body (Keplerian) motion:
  - Classical ellipses
  - Ellipse evolves if central body is non-spherical like Earth or lumpy like the Moon
- 3-Body Motion: Earth-Moon-S/C
  - Gravity assist
    - Switch from Earth-S/C to Moon-S/C and back to change orbit energy and angular momentum (esp. inclination)
    - Double Lunar Swingby acrobatics allows us to explore translunar space, and rotate orbit axis to track Sun (far left image)
  - Unstable Motion around Collinear Libration Points L1 and L2
    - Unstable dynamics allows small change to have large long-term effects
    - Low energy transfers from Earth to Moon via EM L1 "corridor" (Conley, 1968, center image)
    - First LPO mission ISEE-3 (1978) designed by Farquhar et al. at NASA GSFC
    - Stable and unstable manifolds can be used for low-energy transfer, e.g. by ARTEMIS mission (right image)

Perigee 2.0 R_E
Apogee-1 61.0 R_E
Apogee-2 256.0 R_E

Trajectory shown with respect to fixed Sun-Earth line

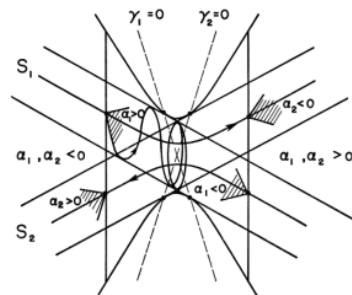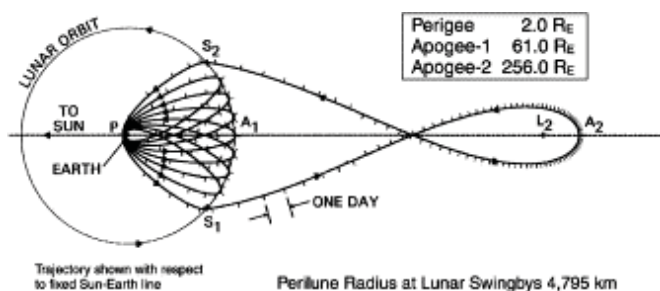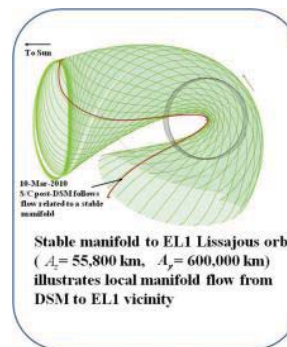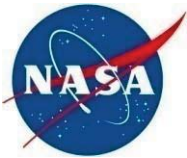Perilune Radius at Lunar Swingbys 4,795 km

FIG. 1. The flow in the equilibrium region. Shown are the periodic orbit, a typical asymptotic orbit (coming from the boundary of a wedge) and the two optimal crossing orbits.


Stable manifold to EL1 Lissajous orbit (A_z = 55,800 km, A_y = 600,000 km) illustrates local manifold flow from DSM to EL1 vicinity

Ballistic 2- and 3-Body Motion (cont'd)

- Earth-Moon Resonance
  - Highly Elliptical Earth orbit resonant with Moon to get regular small changes from Moon
    - Stable: Keep apogee far from Moon to gain long-term stability and eliminate maintenance maneuvers (IBEX, Left image)
    - Unstable: put apogee near Moon and let Moon raise apogee (e.g. SMART-1 and trajectory concept in Right Image)
      - This type of asymptotic trajectory was described by Deprit & Henrard (1965)
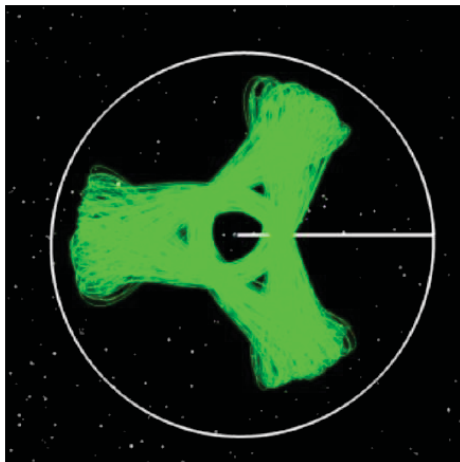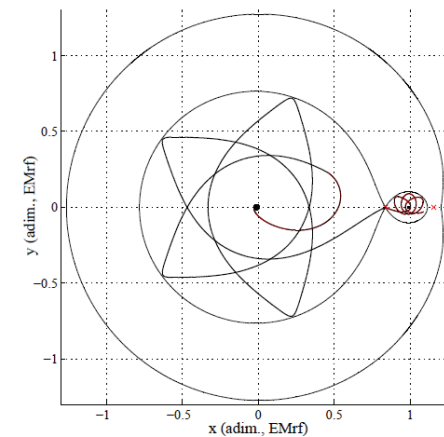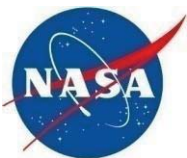

IBEX, launched from a Pegasus

Figure 6.12: An Earth-to-Moon transfer departing from a LEO. This solution requires a cost equal to $\Delta v = 3244 \; m/s$ and a time of transfer $\Delta t = 65.1 \; days$.

Ballistic 4-Body Motion

- 4-Body Motion: Sun-Earth-Moon-S/C
  - Weak Stability Boundary (WSB) transfers
    - Switch from Earth-Moon-S/C to Sun-Earth-S/C and back to change orbit angular momentum (orbit shape and inclination)
    - S/C is sent to vicinity of Sun-Earth L1 or L2, roughly 1.5 million km from Earth
    - Developed by Belbruno and Miller at JPL
    - First demonstrated with Japanese Hiten mission (1990)
      - Primary mission in Highly Eccentric Orbit with apogee 476,000 km to swing past Moon.
      - Belbruno proposed lunar swingby to send S/C near Sun-Earth L1, then return to Moon with no delta-V required for lunar capture. (Left image)
    - In 2011, WSB was used to transfer GRAIL S/C to lunar orbit (Right image)
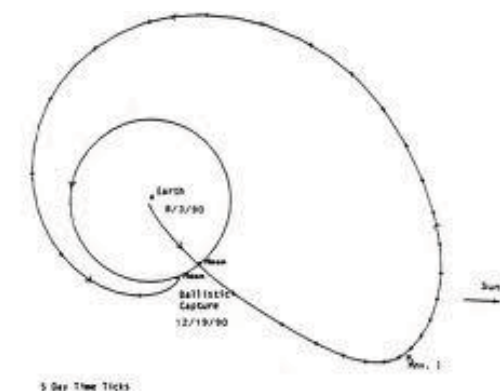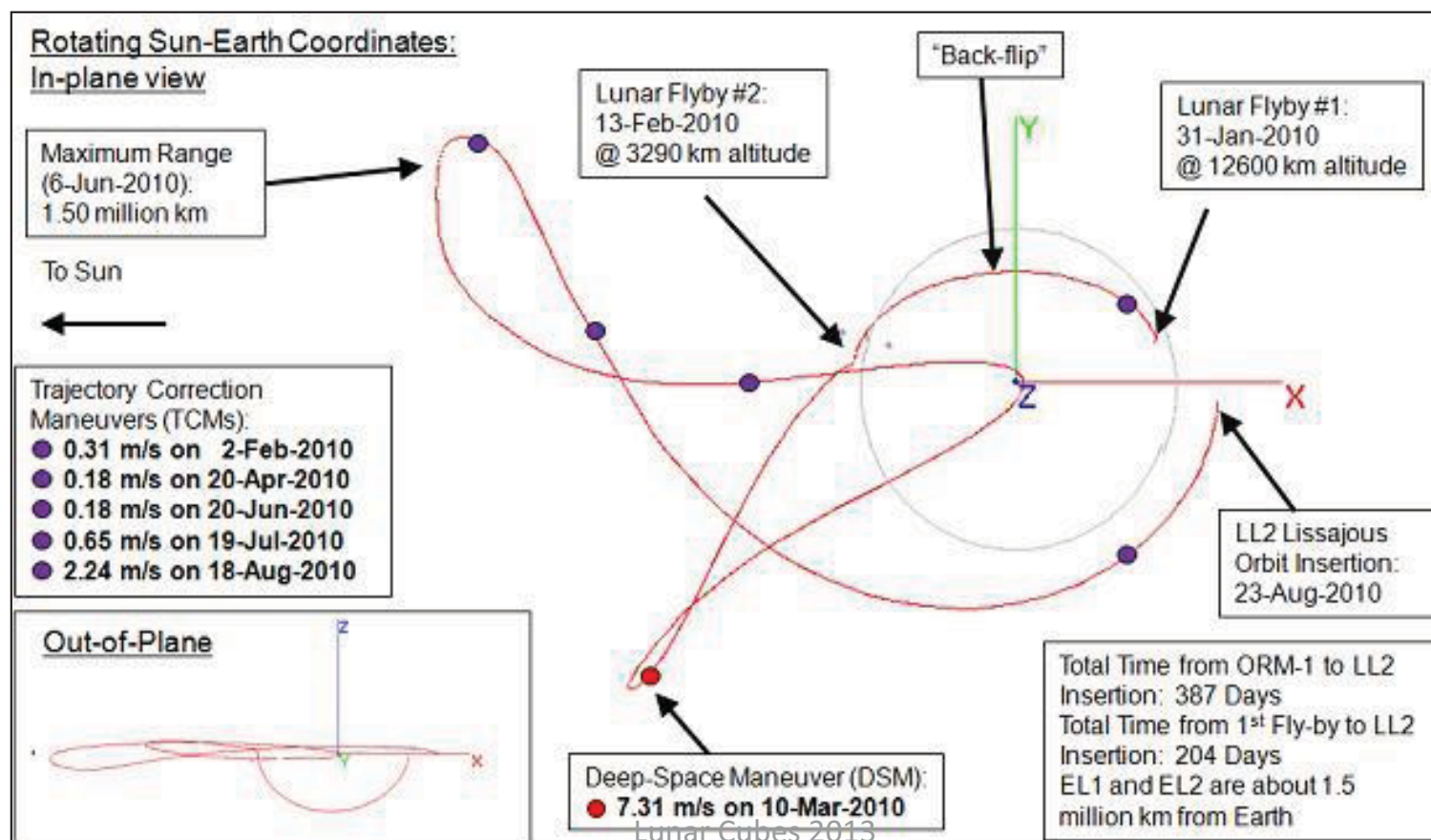

Numerical simulation of a ballistic capture transfer trajectory for the Japanese spacecraft Hiten: ecliptic plane projection, sun's direction indicated at Earth injection. (from Belbruno and Miller [1993])
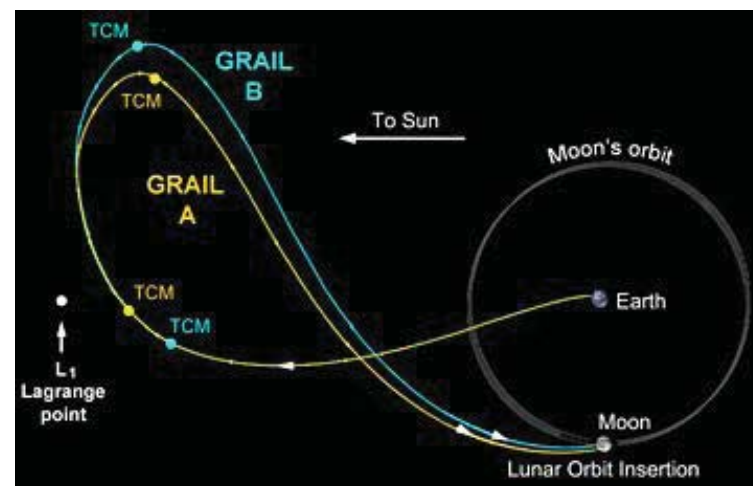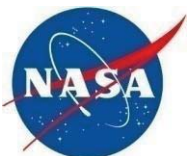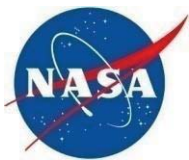
ARTEMIS Transfer Trajectory – P1

- Use of Multi-body Environment to raise periapsis to lunar orbit
- Two lunar gravity assist separated by 13 days for flip of apoapsis direction
- Deterministic Deep Space Maneuver (DSM1) was performed 33 days later
- All maneuvers target the Earth-Moon libration insertion state
- Unstable Lissajous manifold towards the Earth-Moon system
- An L_2 Lissajous insertion orbit maneuver of 2.56 m/s

Rotating Sun-Earth Coordinates: In-plane view

Maximum Range (6-Jun-2010): 1.50 million km

To Sun

Lunar Flyby #2: 13-Feb-2010 @ 3290 km altitude

"Back-flip"

Lunar Flyby #1: 31-Jan-2010 @ 12600 km altitude

Trajectory Correction Maneuvers (TCMs):
- 0.31 m/s on 2-Feb-2010
- 0.18 m/s on 20-Apr-2010
- 0.18 m/s on 20-Jun-2010
- 0.65 m/s on 19-Jul-2010
- 2.24 m/s on 18-Aug-2010

LL2 Lissajous Orbit Insertion: 23-Aug-2010

Out-of-Plane

Deep-Space Maneuver (DSM):
- 7.31 m/s on 10-Mar-2010

Total Time from ORM-1 to LL2 Insertion: 387 Days
Total Time from 1st Fly-by to LL2 Insertion: 204 Days
EL1 and EL2 are about 1.5 million km from Earth
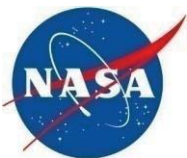
Lunar Cubes 2013

6

ARTEMIS P1 TCM Unstable Manifolds

- Unstable manifold and the effect of TCM5 on the return orbit
- Original planned and the corrected post TCM5 trajectory shown
- For the actual maneuver, the difference is slight in terms overall design but the shift in the general direction of the flow is consistent with a new manifold
- The post TCM5 path with a small shift in direction guaranteed that P1 would reach its Cartesian goal at the proper epoch

AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 31-August 4, 2011
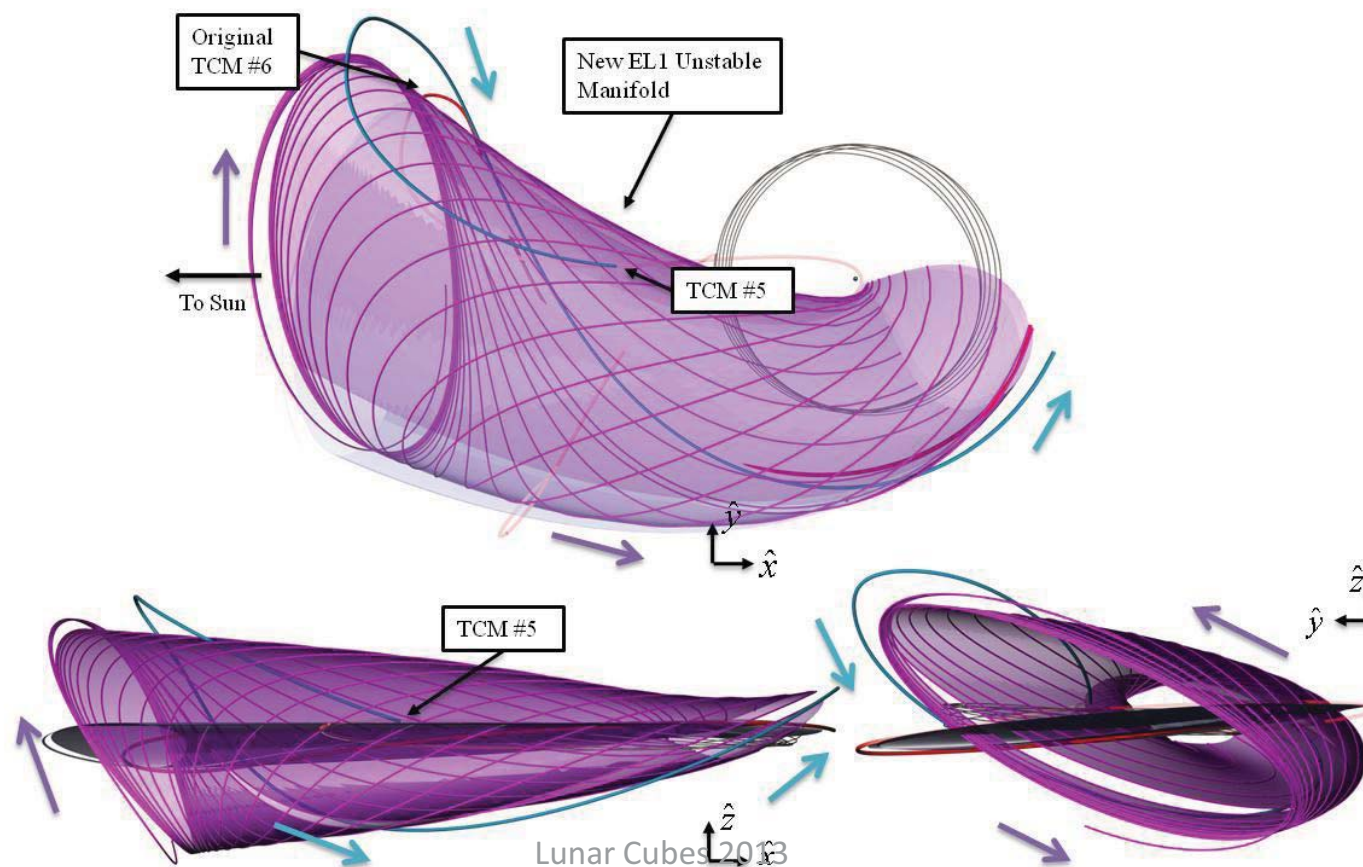
Targeting Chaos using Resonance

- Bollt & Meiss (1995) proposed a low-energy transfer to the Moon using chaotic behavior near Earth-Moon L1 point.
  - Transfer would take two years.
- Schroer & Ott (1997) proposed low-energy trajectories exploiting resonances that reduced the transfer time to 377 days and 293 days.
  - Center image shows Highly Eccentric Orbit near 5:3 then 3:2 resonance with Moon
- Bernelli-Zazzera et al. (2003) found a simpler trajectory that used resonance to reach the Moon in 61 days (Bottom image).
- NOTE: These trajectories are in the Planar Circular Restricted 3-Body Problem. Three-dimensional motion and the Moon's orbit eccentricity present additional challenges
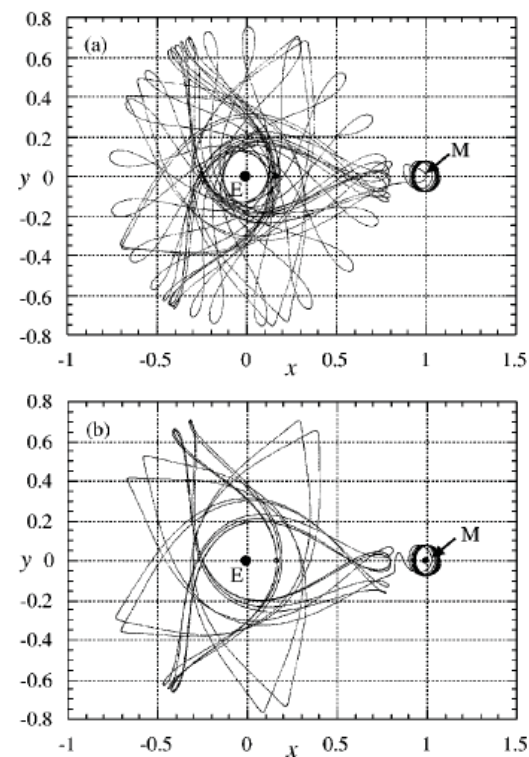

FIG. 6. Controlled chaotic trajectories to a stable lunar orbit. (a) Starting from a circular orbit 59 669 km above the earth's center (time required for transfer: 377.5 days). (b) Starting from the period three orbit denoted by open circles in Figure 5 (time required for transfer: 293 days).
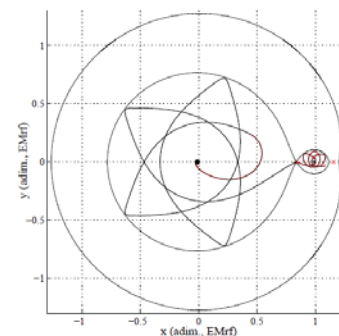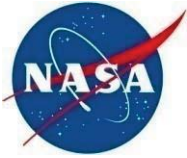

Figure 6.12: An Earth-to-Moon transfer departing from a LEO. This solution requires a cost equal to $\Delta v = 3244\ m/s$ and a time of transfer $\Delta t = 65.1\ days$.

Powered Flight

APOLLO 11 FLIGHT PROFILE

- High Thrust Rockets and Engines, Apollo style
  - Uses Hohmann Transfer to minimize impulsive velocity change (delta-V)
  - Requires delta-V to escape Earth orbit, and to enter Moon orbit
  - Allows fast transfer to the Moon, within 3 to 4 days
- Low Thrust Engines, SMART-1 style
  - Continuous thrusting for long intervals, spiraling out from Earth/in toward Moon
  - Typically takes months
  - Does not require carrying large propellant mass, so can deliver more mass to final destination

- **For best results, we combine ballistic flight with powered flight options**
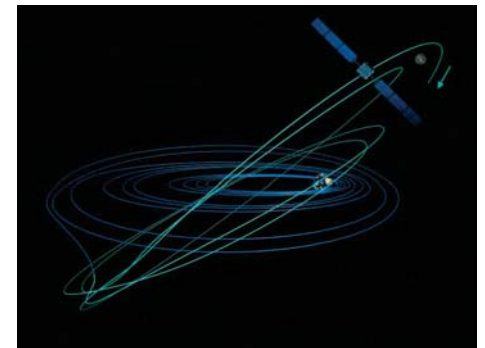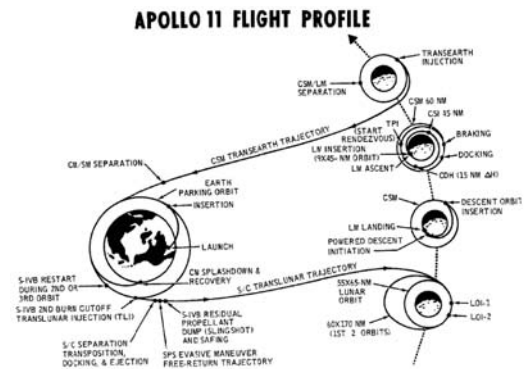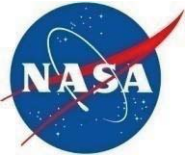
Combining Low Thrust, Resonance and Stable Manifolds

- Belbruno's 1987 paper on Lunar Capture Orbits combined low thrust with use of L1 corridor. (Top image)

- Mingotti, Toputto, Bernelli-Zazzera (2006) found a trajectory that starts with low thrust from GTO, reaches a resonance orbit, then rides the corridor around Earth-Moon L1 to an L2 orbit (Bottom image)

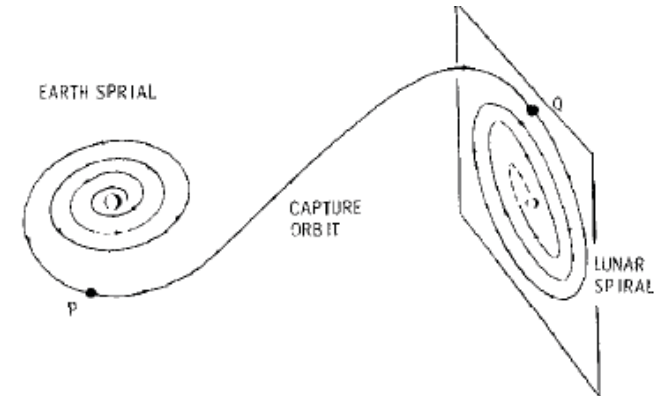- Martin and Conway (2010) employed a similar approach to reach lunar orbit
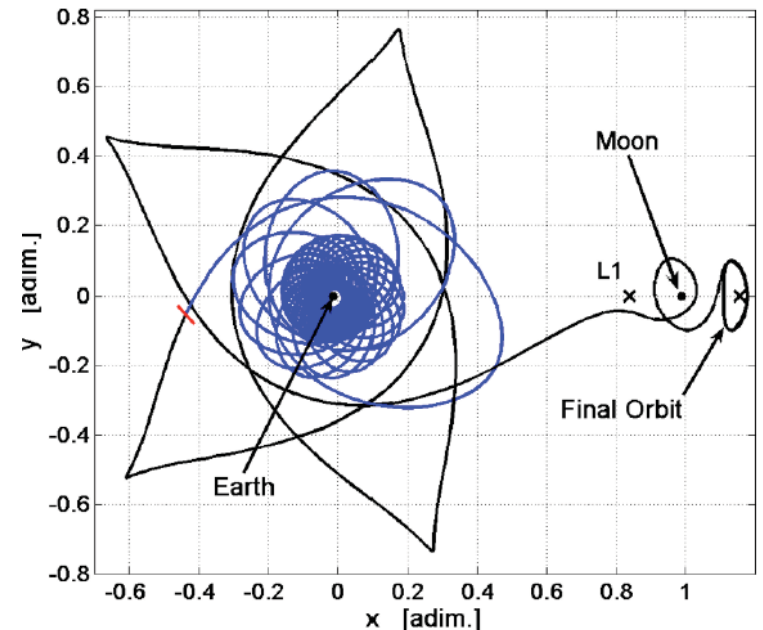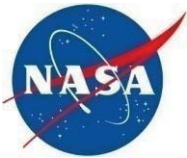

Figure 1. Earth Moon Trajectory

SMART-1

- Trajectory design "based originally on interior transfer" described in Belbruno's 1987 Lunar Capture Orbits paper
- Launched 27 Sept 2003 into GTO from French Guiana (low inclination)
- Continuous thrust to raise perigee out of radiation belts, using SEP
- Thrust around perigee to raise apogee
- Use Moon resonances to achieve lunar capture (5:1, 4:1, 3:1, 2:1)
- Spiral into moon orbit
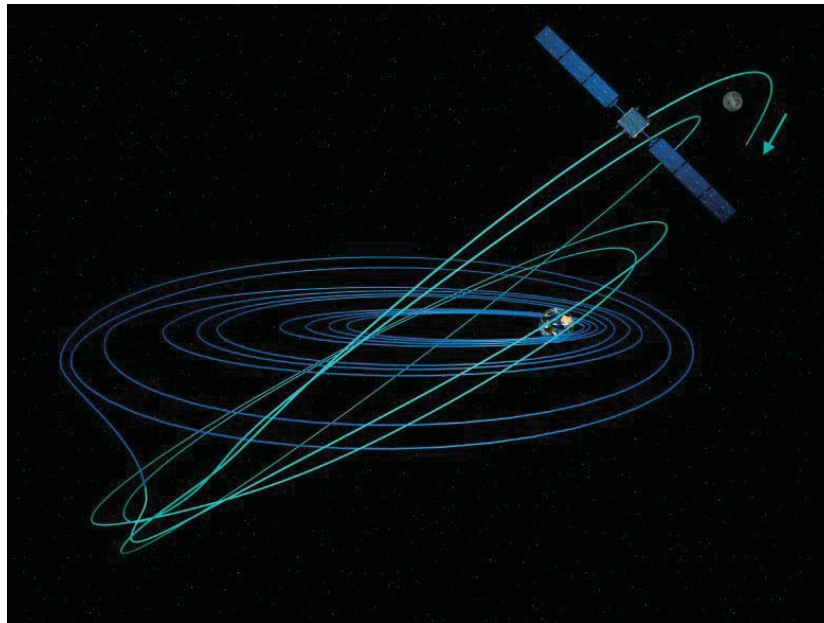- Arrived in lunar orbit Feb 2005 (13 month transfer)

Fig. 3. From long eclipse to moon capture (Thrust: dotted line; Diamond: resonance; Apogee: plus sign).
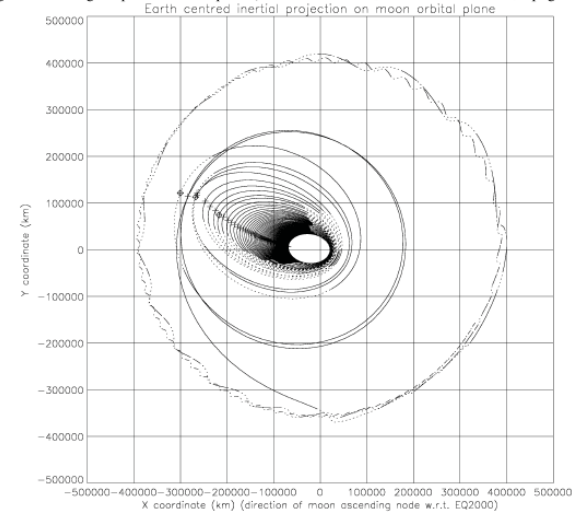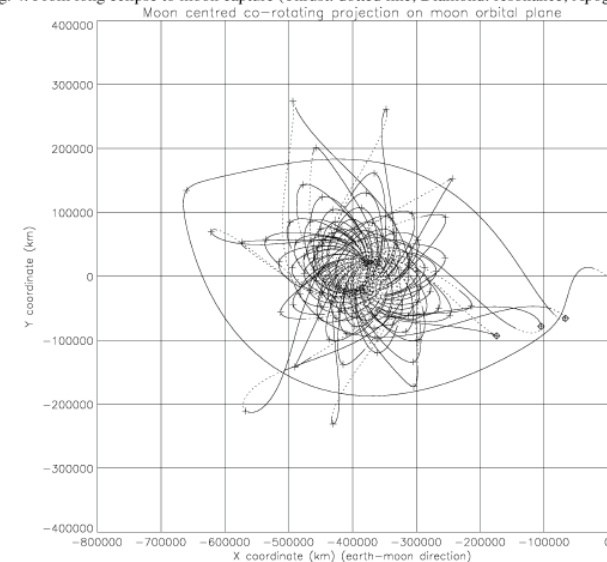
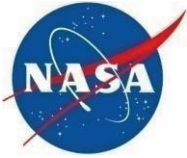

Fig. 4. From long eclipse to moon capture (Thrust: dotted line; Diamond: resonance; Apogee: plus sign).

SMART-1-like Approach

- After examining the various options, we decided to focus on a trajectory similar to SMART-1
- We have a software tool "LTOC" developed by JAQAR Engineering, that specifically models low-thrust transfer from GTO to lunar orbit
- The LTOC solution has the following segment:
  - Raise apogee using low-thrust arcs near perigee
  - Spiral out from Earth using continuous low-thrust along velocity vector
  - Coast to time encounter with Moon
  - Lunar capture
  - Spiral in toward Moon using continuous low-thrust along anti-velocity vector
- In the following charts we present some results from that LTOC solution
- We also used the LTOC solution as a starting point to create a trajectory in STK/Astrogator, which uses an gravity assist to achieve plane change for lunar encounter
- NOTE: These are trajectory concepts, not yet fully developed trajectory design. Propulsion system design and constraint analysis (e.g. power, communications) remain to be done.
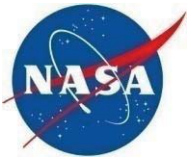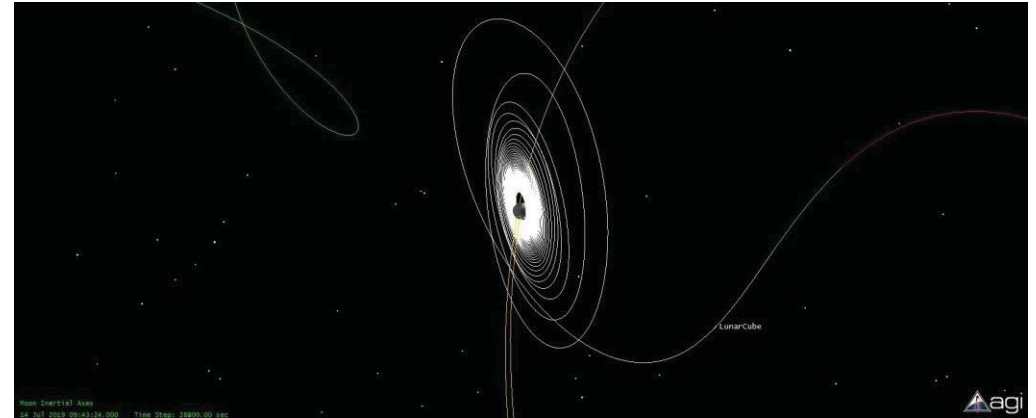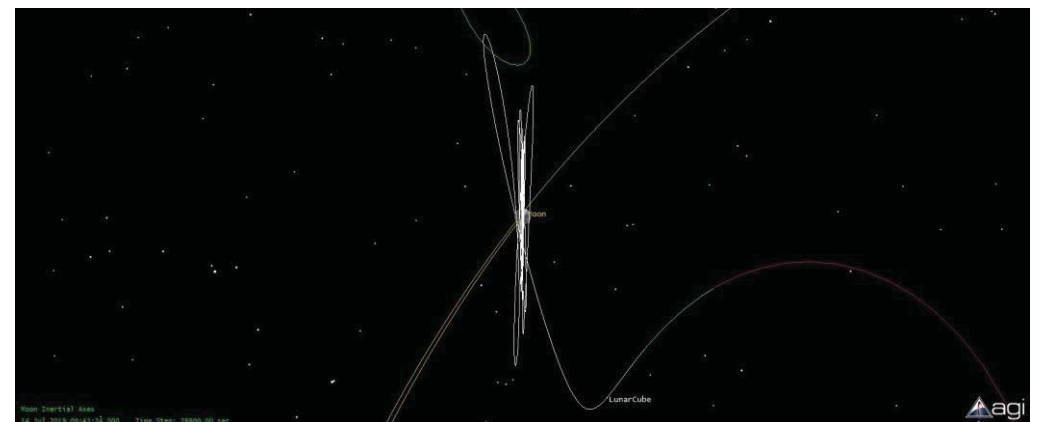
LTOC Trajectory
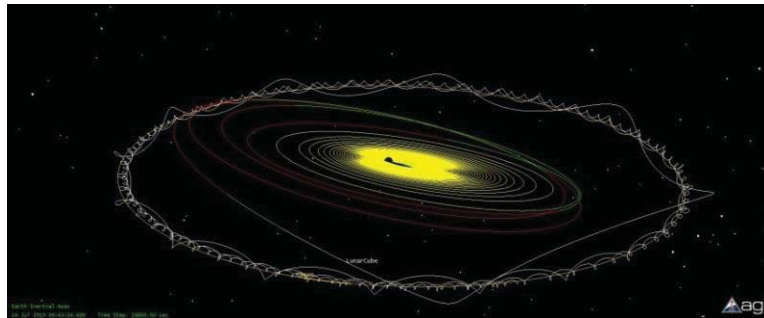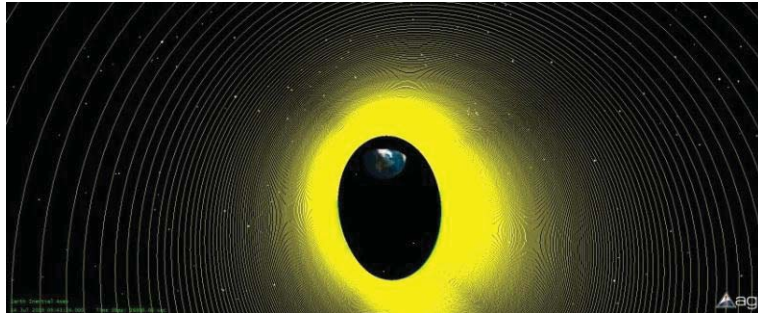
Earth centered top views
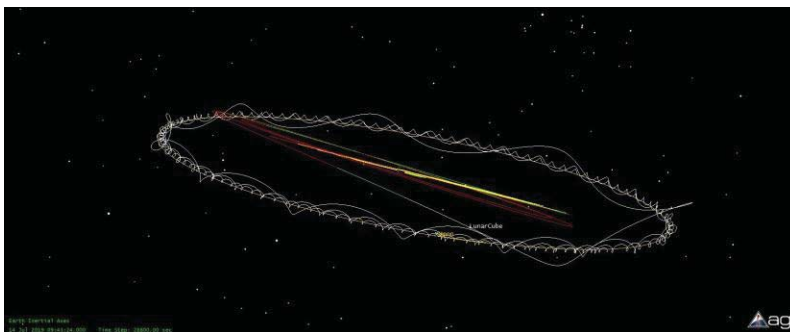
Earth centered edge view

Moon centered view

Moon centered edge view (polar orbit)

Sunlight Conditions
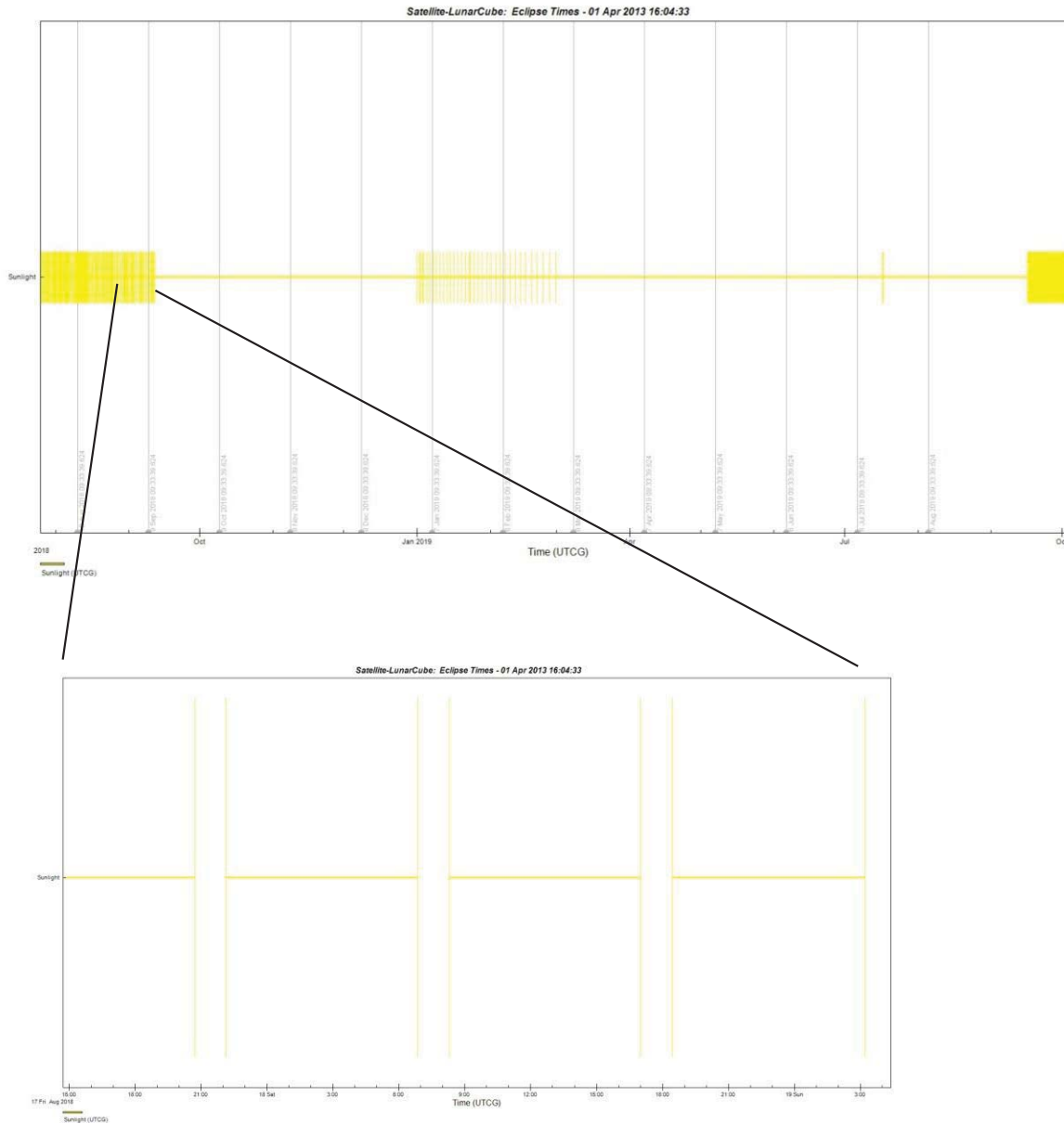
LTOC design does not consider Sun lighting constraints, but it is an important consideration for Solar Electric Propulsion

Earth Inertial Axes
17 Aug 2019 02:12:29.450   Time Step: 14400.00 sec

STK Scenario: WSB Edge View

Earth Inertial Axes
17 Aug 2019 02:12:29.450   Time Step: 14400.00 sec

Earth Inertial Axes
17 Aug 2019 02:12:29.450   Time Step: 14400.00 sec
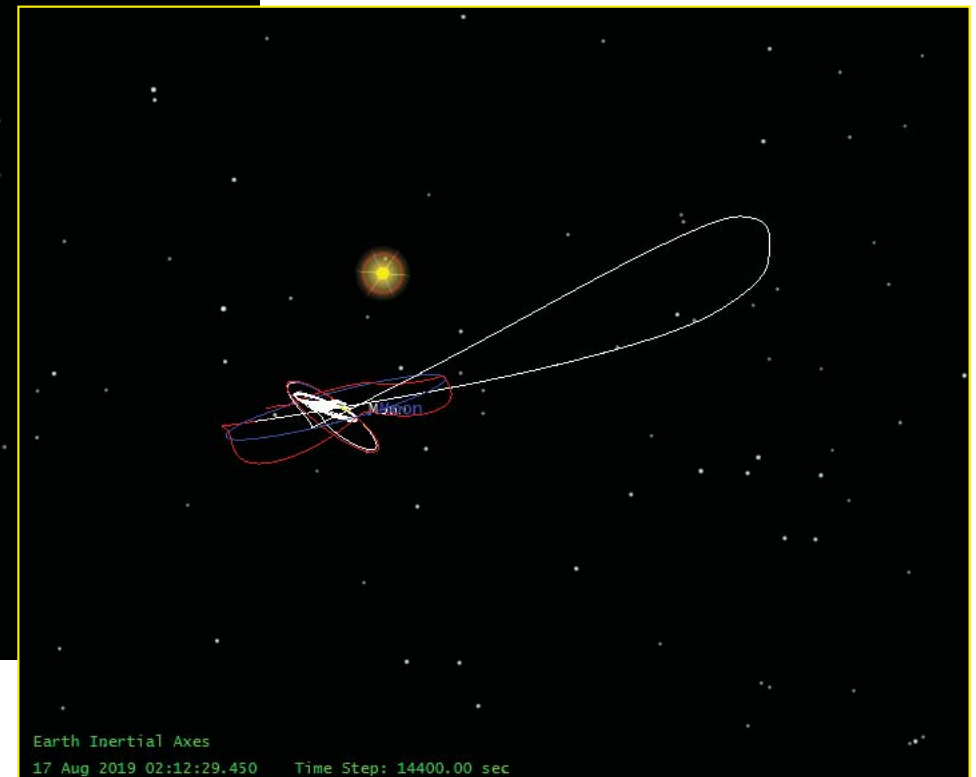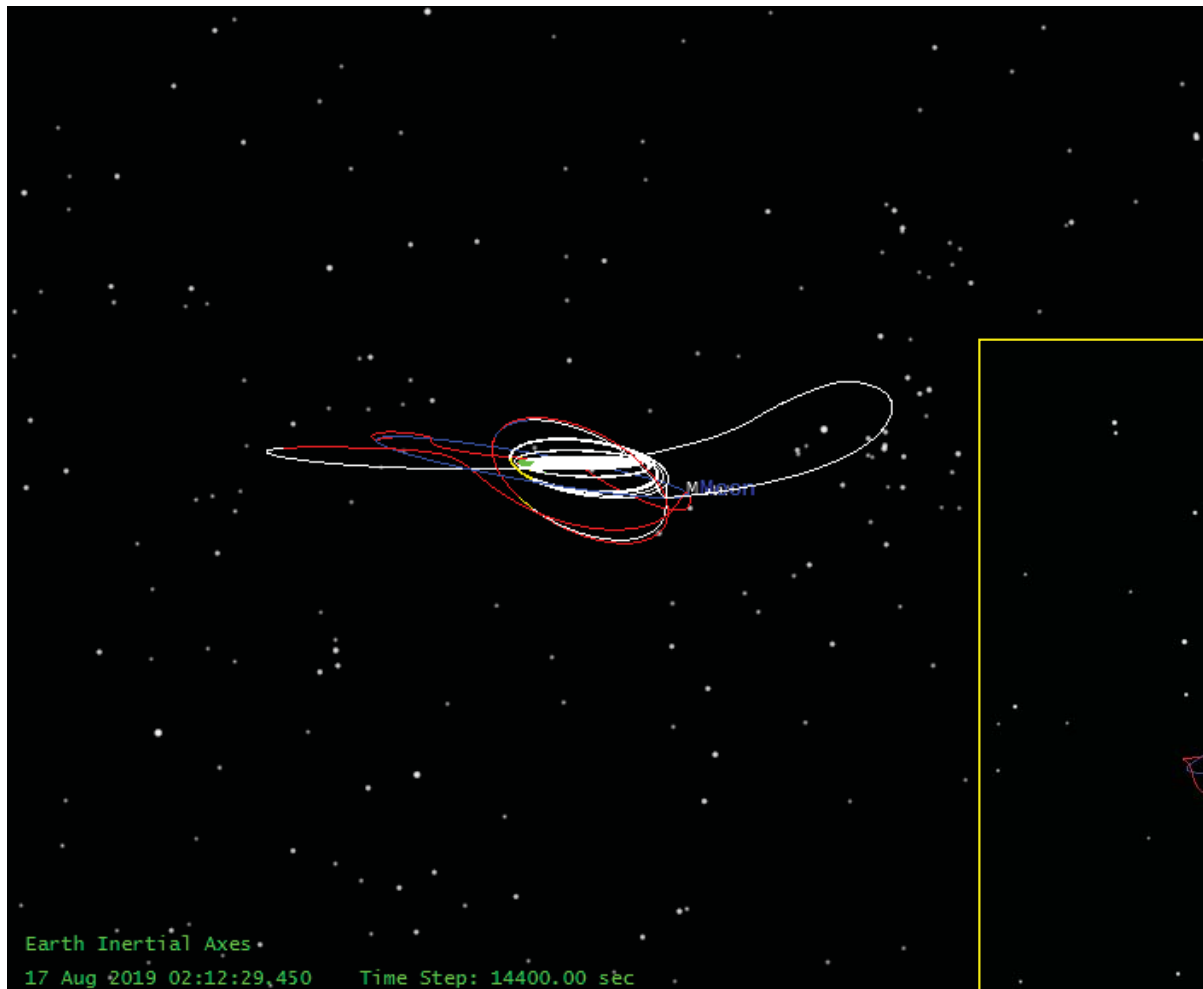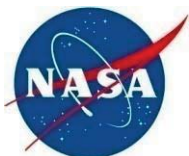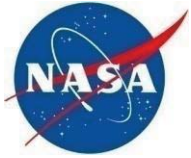
Trade-off Table

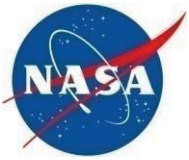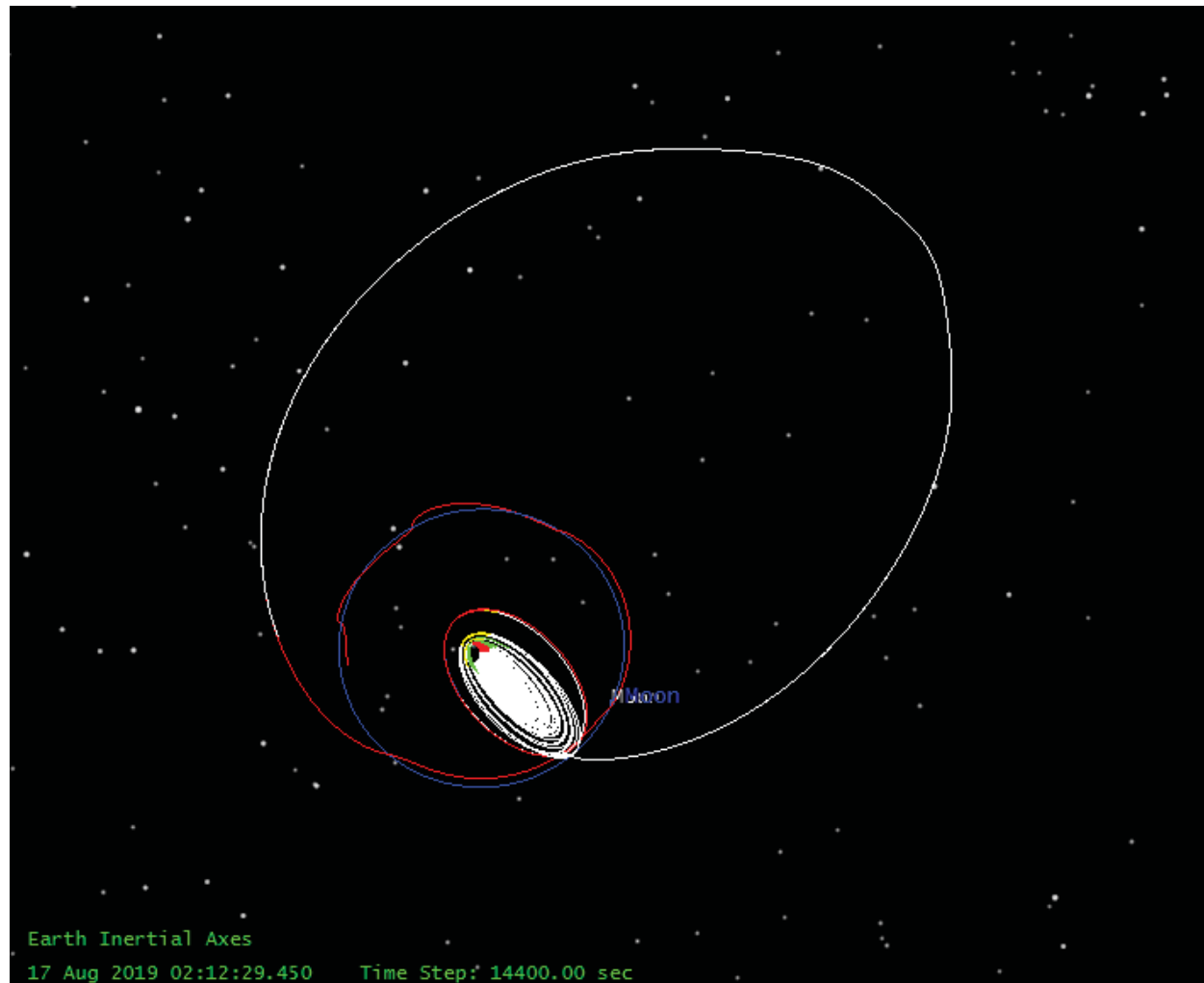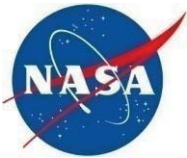| Type	Duration (days)	Isp (sec) Dv (m/s)	Fuel mass (kg)	% Fuel	Comments
Impulsive (mono-prop)	76	220 / 750	2.9	30%	• Single impulsive to achieve a Weak Stability Boundary transfer
Low Thrust Continuous – GTO	314	2500 / 3500	1.5	15%	• Uses Lunar assist for orbit plane change
Low Thrust - GTO / JAQAR Tool	428	2500 / 3880	2	20%	
Low Thrust periapsis maneuvers - GTO	1048	2500 / 1500	0.6	6%	• Minimal shadows • Uses Lunar assist for orbit plane change
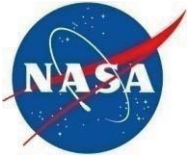
Conclusions and Future Work

- We have examined the diverse mechanisms of ballistic and powered flight to send a spacecraft from GTO to lunar orbit

- We chose to focus on a SMART-1 like trajectory, but that does not exclude the possibility of using a different approach.

- The LTOC tool by JAQAR Engineering allowed us to develop an initial trajectory from GTO to polar lunar orbit. However LTOC is limited in its design capability

- We then developed a similar scenario in STK, using a lunar gravity assist to achieve plane change (like Hiten). Thus far we have trajectory concepts but not a trajectory solution

- We have begun a study to examine trade-offs in transfer duration, mass to mission orbit, range from Earth, radiation exposure

- For further trajectory design we need to define the propulsion system

- We need to develop our software tools to accurately model the many spirals around Earth during low thrust orbit raising

- We would also like to add dynamical systems analysis to the trajectory design, to identify useful manifolds

Backup Charts
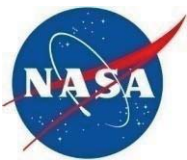
Transfer Trajectory – P1

- Use of Multi-body Environment to raise periapsis to lunar orbit
- Two lunar gravity assist separated by 13 days for flip of apoapsis direction
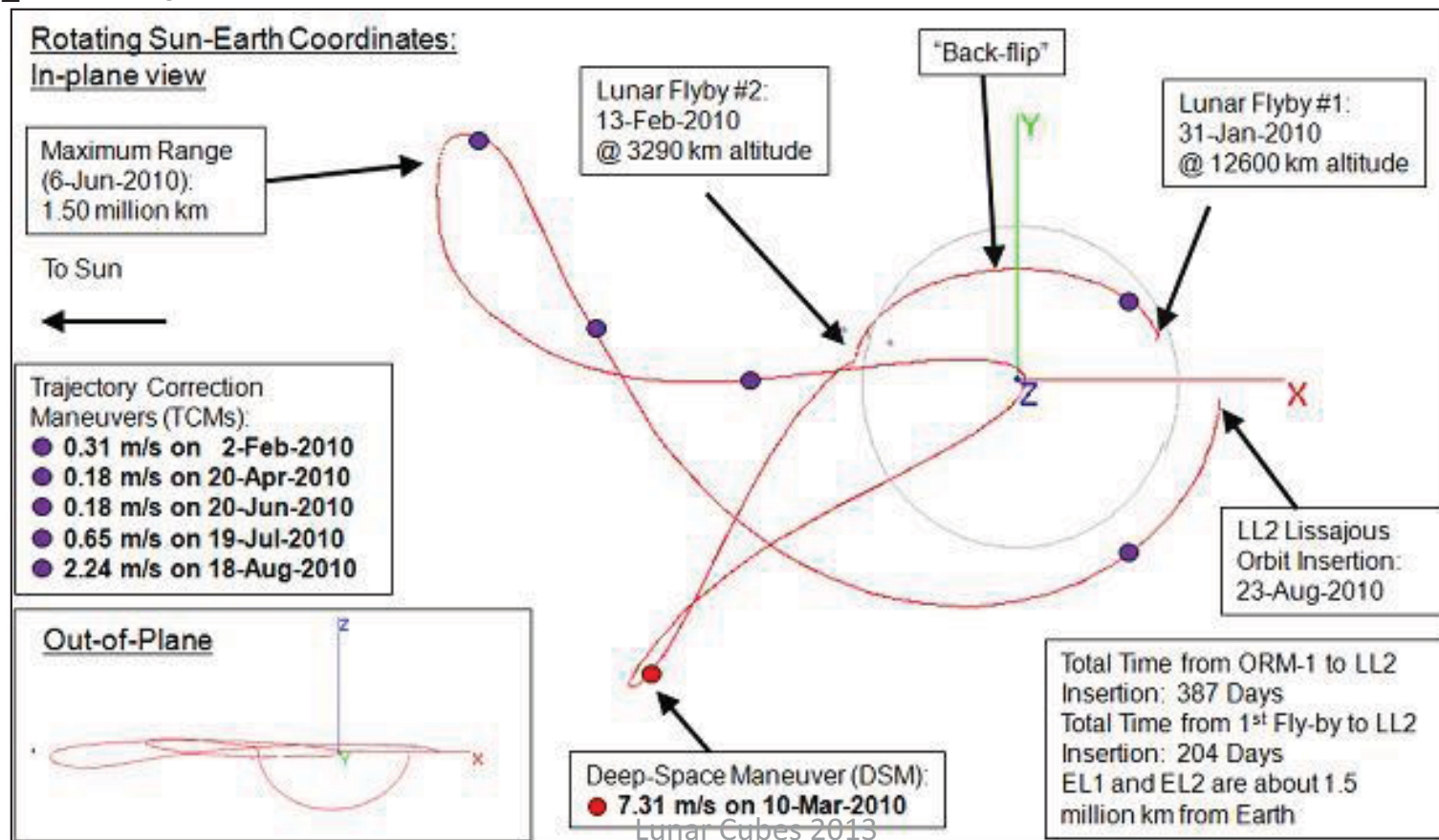- Deterministic Deep Space Maneuver (DSM1) was performed 33 days later
- All maneuvers target the Earth-Moon libration insertion state
- Unstable Lissajous manifold towards the Earth-Moon system
- An L_2 Lissajous insertion orbit maneuver of 2.56 m/s

Rotating Sun-Earth Coordinates:
In-plane view

"Back-flip"

Lunar Flyby #2:
13-Feb-2010
@ 3290 km altitude

Lunar Flyby #1:
31-Jan-2010
@ 12600 km altitude

Maximum Range
(6-Jun-2010):
1.50 million km

To Sun

Trajectory Correction
Maneuvers (TCMs):
- 0.31 m/s on 2-Feb-2010
- 0.18 m/s on 20-Apr-2010
- 0.18 m/s on 20-Jun-2010
- 0.65 m/s on 19-Jul-2010
- 2.24 m/s on 18-Aug-2010

LL2 Lissajous
Orbit Insertion:
23-Aug-2010

Out-of-Plane

Deep-Space Maneuver (DSM):
- 7.31 m/s on 10-Mar-2010

Total Time from ORM-1 to LL2
Insertion: 387 Days
Total Time from 1st Fly-by to LL2
Insertion: 204 Days
EL1 and EL2 are about 1.5
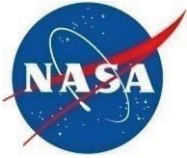million km from Earth

Lunar Cubes 2013

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Transfer Trajectory – P2

- Use of Multi-body Environment to raise periapsis to lunar orbit
- Single lunar gravity assist
- Three Deterministic Deep Space Maneuvers were performed
- All maneuvers target the Earth-Moon libration insertion state
- Unstable Lissajous manifold towards the Earth-Moon system
- An L_1 Lissajous "insertion" orbit maneuver of 0.25 m/s

Rotating Sun-Earth Coordinates: In-plane view

To Sun

Deep-Space Maneuvers (DSMs):
- 3.68 m/s on 13-May-2010
- 23.3 m/s on 1-Jun-2010
- 3.28 m/s on 9-Sep-2010

Maximum Range (18-Jun-2010): 1.2 million km

Trajectory Correction Maneuvers (TCMs):
- 2.15 m/s on 20-Jul-2010
- 0.72 m/s on 2-Aug-2010
- 0.31 m/s on 1-Oct-2010
- 0.25 m/s on 12-Oct-2010

Lunar Fly-by: 28-Mar-2010 @ 8070 km altitude

LL1 Lissajous Orbit Insertion: 22-Oct-2010

Out-of-Plane

Total Time from ORM-1 to LL1 Insertion: 458 Days
Total Time from Fly-by to LL1 Insertion: 208 Days
EL1 and EL2 are about 1.5 million km from Earth

AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 31-August 4, 2011
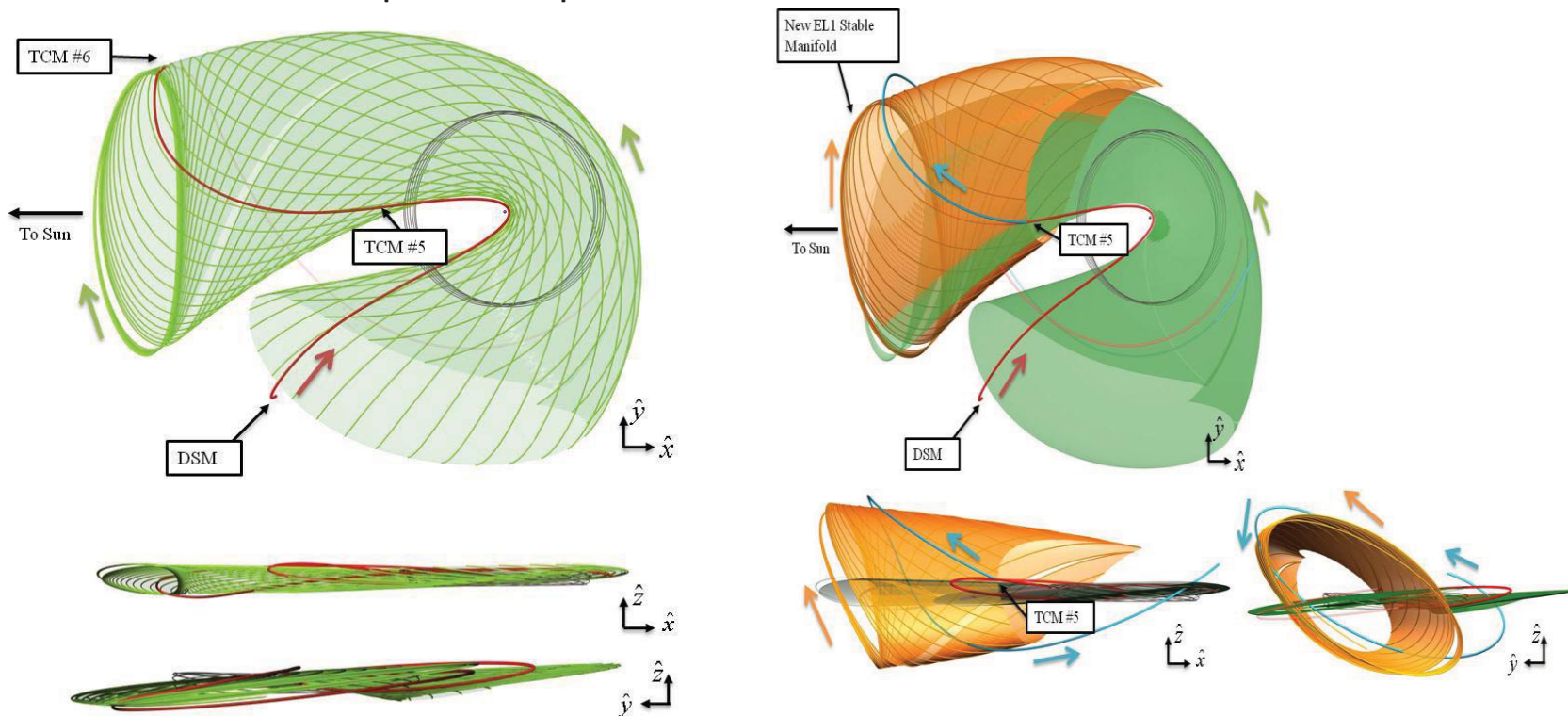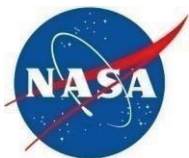
P1 Trajectory Correction Maneuvers

• As the transfer trajectory was flown, Trajectory Correction Maneuvers (TCM) were required to adjust for previous maneuver performance
  ✓ Function of temperatures and general propulsion system performance
  ✓ Spacecraft attitude errors and spin pulsing directions (pulse width)
  ✓ Navigation errors

• To find a maneuver location, a DC and an optimization was run to determine the optimal maneuver location

  ✓ Determine an a priori maneuver location
  ✓ Achieve an intuitive feel for maneuver results
  ✓ Meet DSN coverage
  ✓ Minimize DV
  ✓ Optimization includes S/C maneuver direction constraints
  ✓ Analysis reflects manifold behavior (up DV on one side can be down DV on the other)

• *Final planning was a combination of Optimization, Manifold Information, and experience in order to meet spacecraft constraints and insertion target goals*
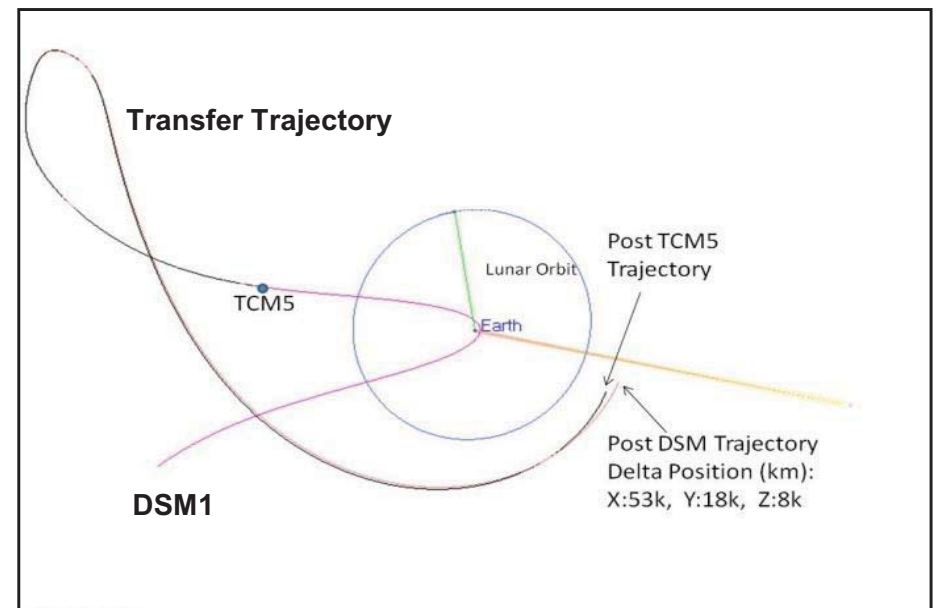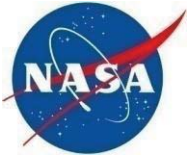
P1 TCM Stable Manifolds

- Consider only the outbound arc and TCM5 maneuver.
- From the DSM, P1 follows the original outbound path to the location of TCM5
- TCM5 will shift the spacecraft to a different path, one that can be envisioned in terms of a different (orange) manifold
- Subsequent to the DSM, and along the outbound trajectory two outbound manifold arcs emerge from the TCM5 location
- These two manifolds represent the potential outcomes from (1) flow along the optimal path and (2) the alternative that incorporates a possible TCM5 maneuver

P1 Planned Stable Sun-Earth

P1 Pre and Post TCM5 Stable Sun-Earth Manifold

23

AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 31-August 4, 2011

P1 TCM Unstable Manifolds

- Unstable manifold and the effect of TCM5 on the return orbit
- Original planned and the corrected post TCM5 trajectory shown
- For the actual maneuver, the difference is slight in terms overall design but the shift in the general direction of the flow is consistent with a new manifold
- The post TCM5 path with a small shift in direction guaranteed that P1 would reach its Cartesian goal at the proper epoch
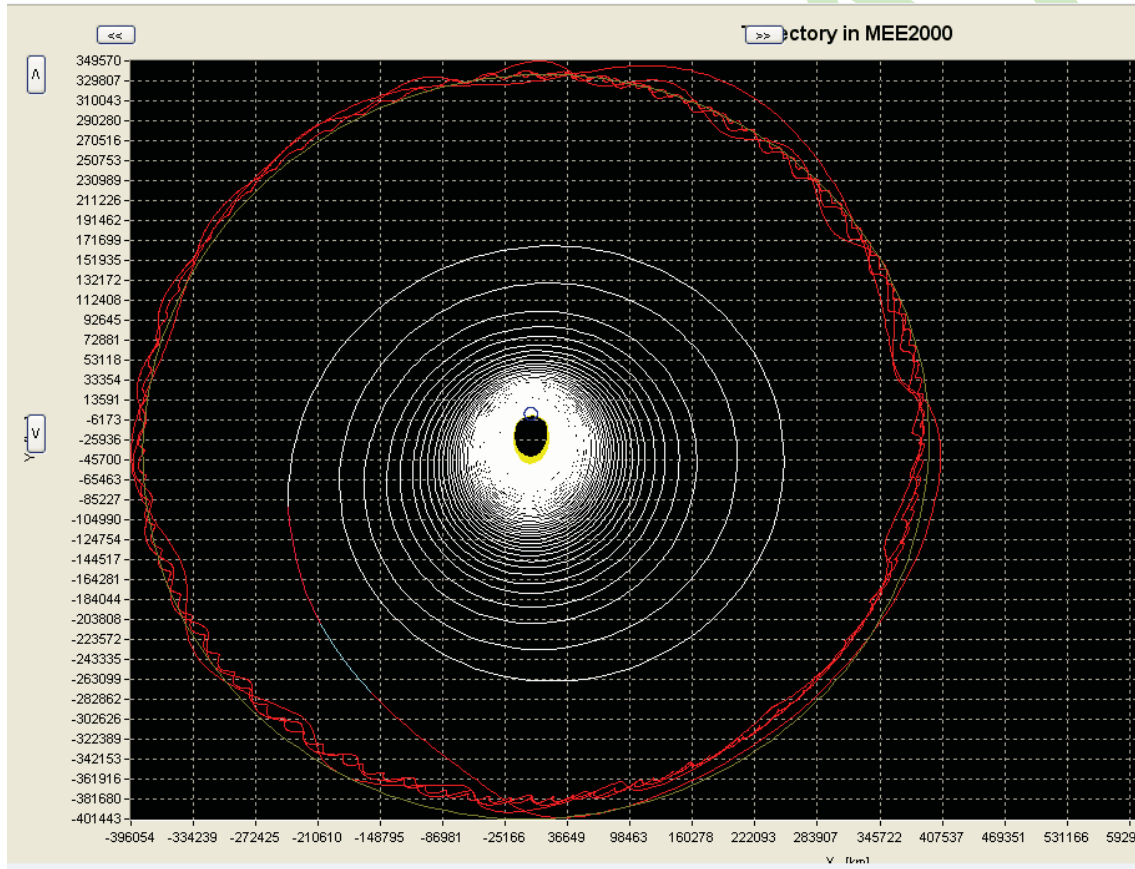
AAS/AIAA Astrodynamics Specialist Conference, Girdwood, Alaska, July 31-August 4, 2011
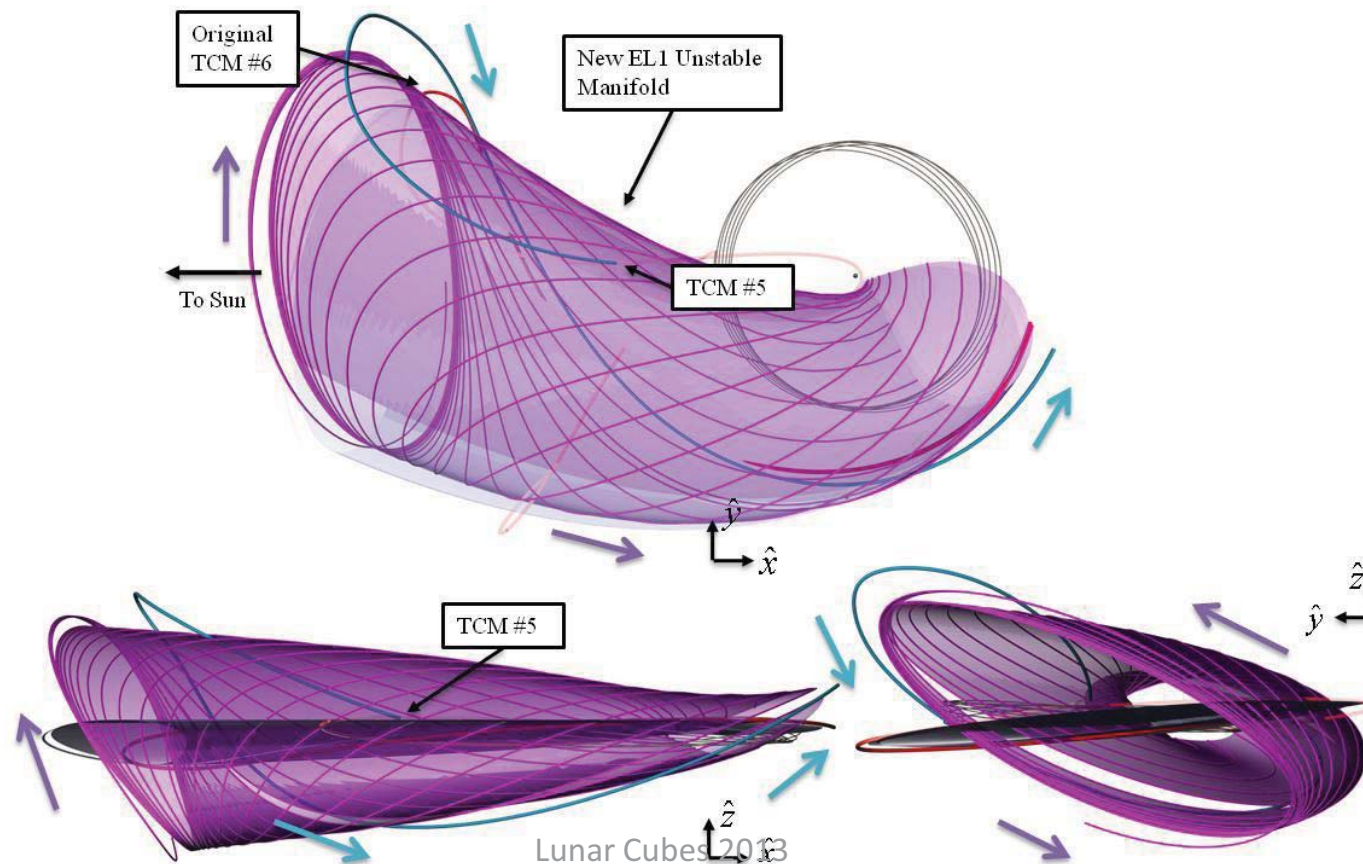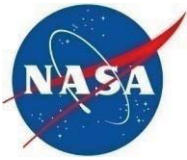
A First Cut

- Using an optimization low thrust simulation tool
- Identified a sample design

TO Calculator Optimisation Output
****

Earth-Moon Low-thrust Optimisation
Solution does not comply or only partially complies with user inputs
****

Launch from Earth Orbit - free orbit and free epoch
Launch Mass: **12 kg**
****

Earth orbit at TLI:
TLI time: 19 Sep 2016 13:19:58
TLI delta-V: 2.72393 km/s
semi-maj. axis: 27477.976 km
Eccentricity: 0.76061
Pericenter: 199.707 km
Apocenter: 41999.972 km
Inclination: 27.199 deg
RAAN: 19.572 deg
Arg. of peri: 72.909 deg
True anomaly: -92.192 deg
****

Transfer orbit:
TLI time: 19 Sep 2016 13:19:58
Phase 1: Apo raising (thrusting between TA -101.38 and +101.38 deg)
Phase ends: 27 Jan 2017 2:21: 8
Phase 2: s.m.a. raising (continuous tangential thrusting)
Phase ends: 22 Sep 2017 23: 7:16
Phase 3: Targeting to Moon (thrusting between TA -101.38 and +101.38 deg)
Phase ends: 24 Sep 2017 6:26:49
Phase 4: Coast phase (no thrusting)
Phase ends: 25 Sep 2017 6:26:49 (entry Moon SOI)
Phase 5: LOI (tangential thrusting within Moon frame)
Transfer time: 468.96047 days
LOI time: 1 Jan 2018 12:23: 2
LOI delta-V: 1.16050 km/s
****

Moon orbit parameters:
semi-major axis: 2953.200 km
Eccentricity: 0.37756
Perilune: 100.000 km
Apolune: 2330.000 km
Inclination: 90.000 deg
RAAN: 224.467 deg
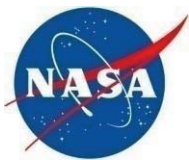Arg. of peri: 270.000 deg
Lat. of peri: -90.000 deg
B-plane B*R: 56344.359 km
B-plane B*T: 53016.530 km
****

Total delta-V: 3.88443 km/s
Final Mass: 10.000 kg
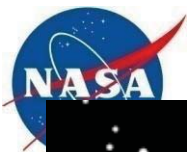
LunarCube Low-Thrust Trajectory Design

- Simulation uses a 10 kg mass and a 1.4 mN thruster with an Isp of 2500 sec
- Thrusting is continuous along the velocity vector until it achieves a fairly circular orbit just below the lunar orbit
- The optimizer permits the s/c to enter into the a multi-body dynamical region to use the lunar gravity to 'rendezvous' with the moon at one of the relative node crossings
- Optimal approach LT maneuver back propagates to an optimal lunar distance to begin the low thrust lunar targeting sequence to capture into an elliptical orbit that is further decreased in semi-major axis by continuous thrusting after lunar capture
- The final orbit achieved is

Keplerian   - Moon Fixed

sma:	9705.0226067659096000 km		RAAN:	104.5707969374672 deg
ecc:	0.8076956451338013		w:	5.582162902317398 deg
inc:	109.2596992424557 deg		TA:	359.9999999991558 deg
C3:	-0.5051818295180461 km^2/sec^2		Energy:	-0.2525909147590231 km^2/sec^2
Rad. Peri:	1866.3181113559920000 km		Vel. Peri:	2.1791742423983500 km/sec
Rad. Apo:	17543.7271021758280000 km		Vel. Apo:	0.231822595774652 km/sec

- Periapsis is ~ **128 km**. The period is **1-day**
- The total transfer time of **314 days,** from Sept 19, 2016 to July 30, 2017
- Total DV required is 3.458 km/s and the fuel mass required is 1.316 kg (13% of initial wet mass)
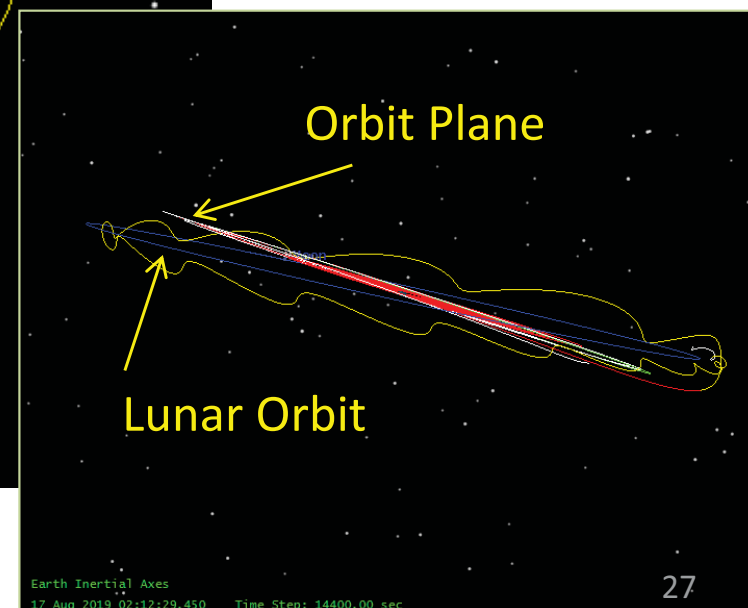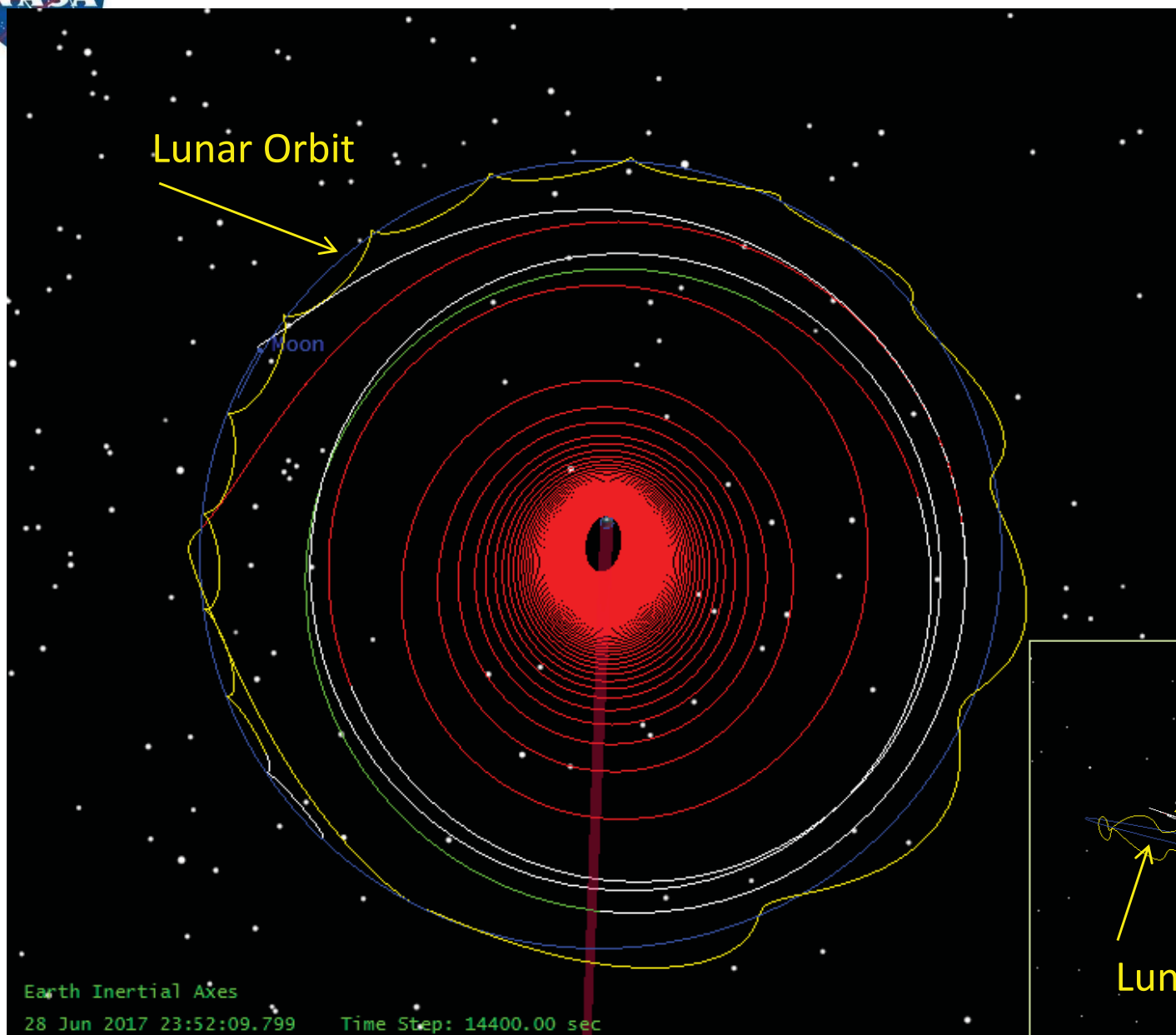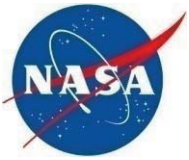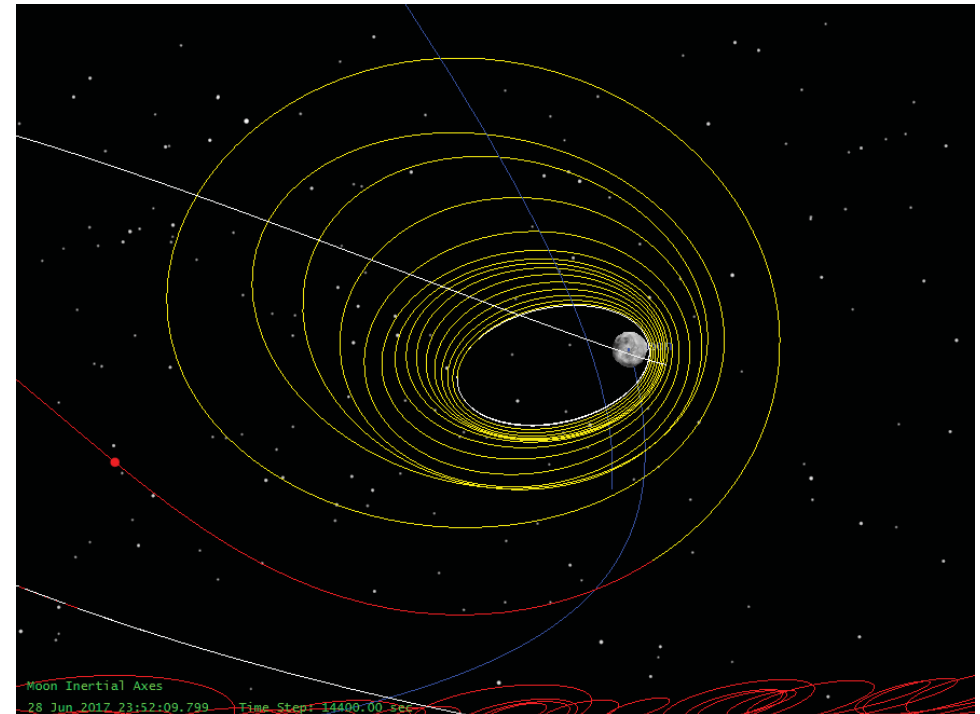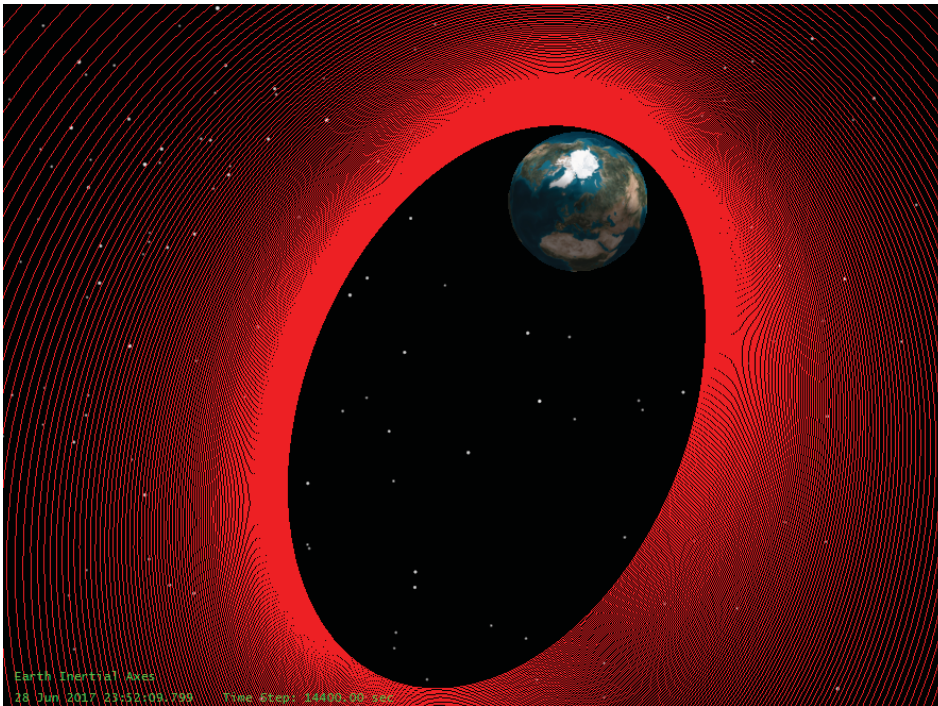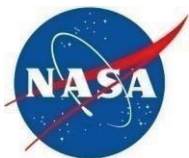
LunarCube Low-Thrust Trajectory Design

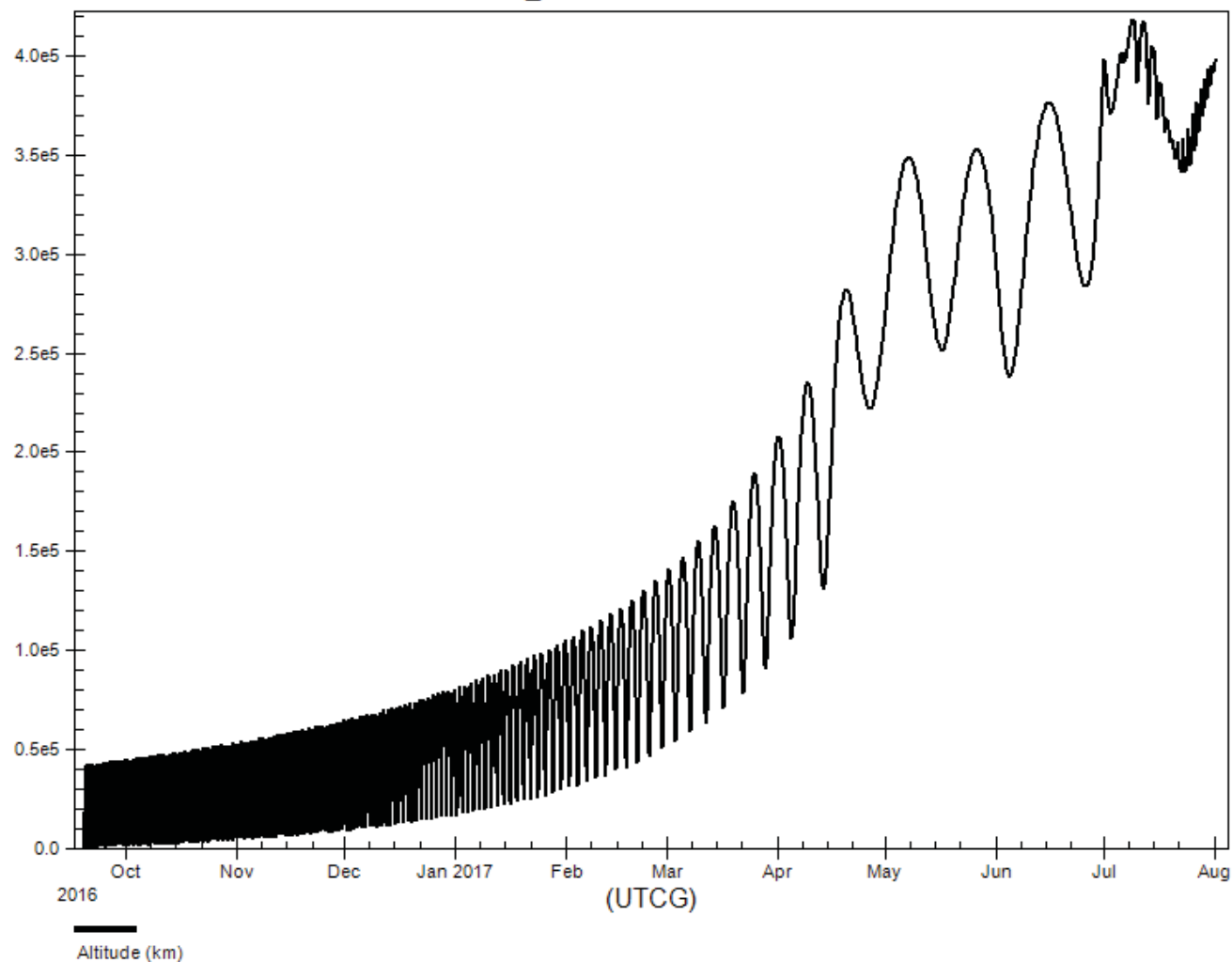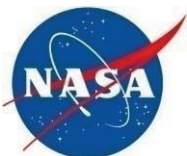# • Earth Departure and Lunar Capture

LunarCube Low-Thrust Trajectory Design

Altitude

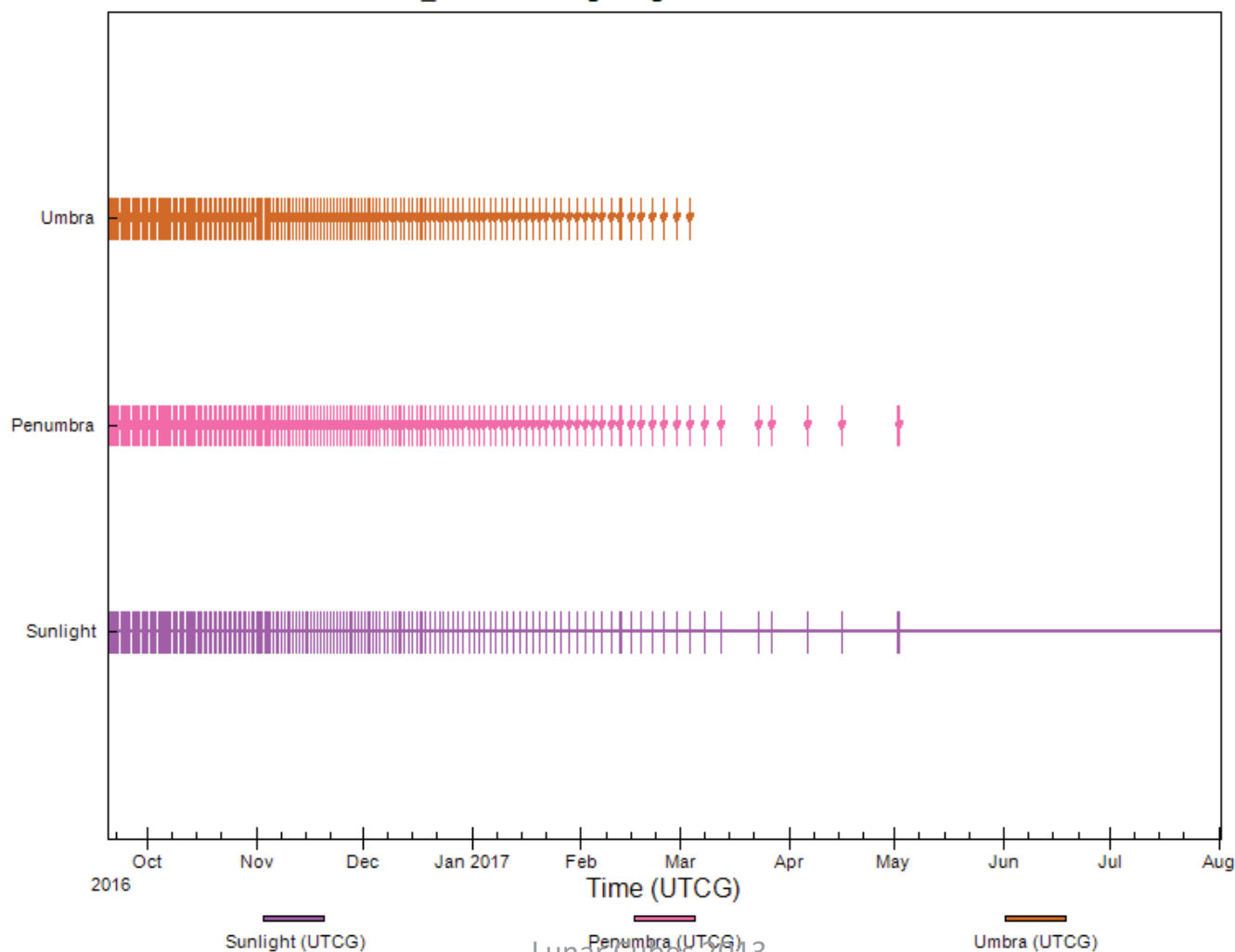Satellite-Lunar_Cubesat - 20 Mar 2013 09:24:45

LunarCube Low-Thrust Trajectory Design

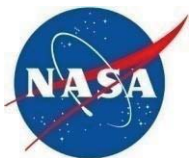## Shadows

Umbra Eclipse Duration statistics

|			
Min Duration	3 Mar 2017 21:16:35.078	3 Mar 2017 21:34:11.342	17.604 minutes
Max Duration	4 Feb 2017 08:38:19.742	4 Feb 2017 09:22:47.661	44.465 minutes
Mean Duration			36.215 minutes

Satellite-Lunar_Cubesat: Lighting Times - 20 Mar 2013 09:27:55

LunarCube Low-Thrust Trajectory Design

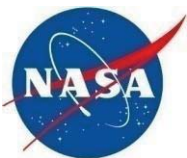- Simulation uses a 10 kg mass and a 1.4 mN thruster with an Isp of 2500 sec
- Thrusting is performed only near periapsis along the velocity vector until it achieves a lunar encounter at apoapsis
- The optimizer permits the s/c to enter into the a multi-body dynamical region to use the lunar gravity to 'rendezvous' with the moon at one of the relative node crossings
- Optimal approach LT maneuver back propagates to an optimal lunar distance to begin the low thrust lunar targeting sequence to capture into an elliptical orbit.
- Periapsis is ~ **3200 km**. The period is **4-day. Orbit is weakly captured and will impact after several days.**
- The total transfer time of **1048 days,** from Sept 19, 2016 to Aug 3, 2019
- Total DV required is ~1.5 km/s and the fuel mass required is ~0.6 kg (6% of initial wet mass)
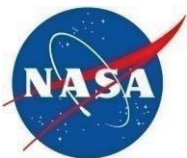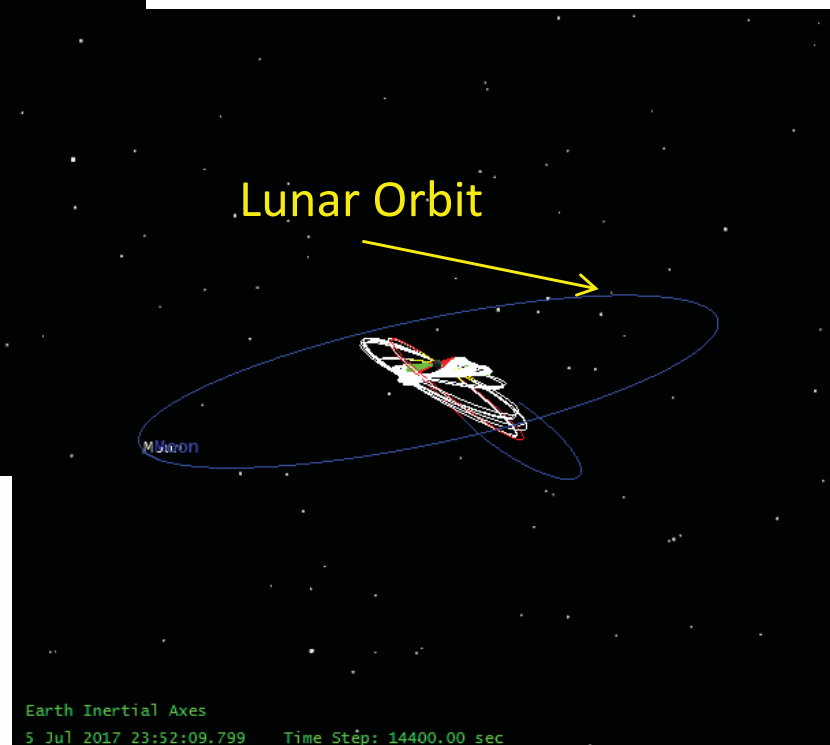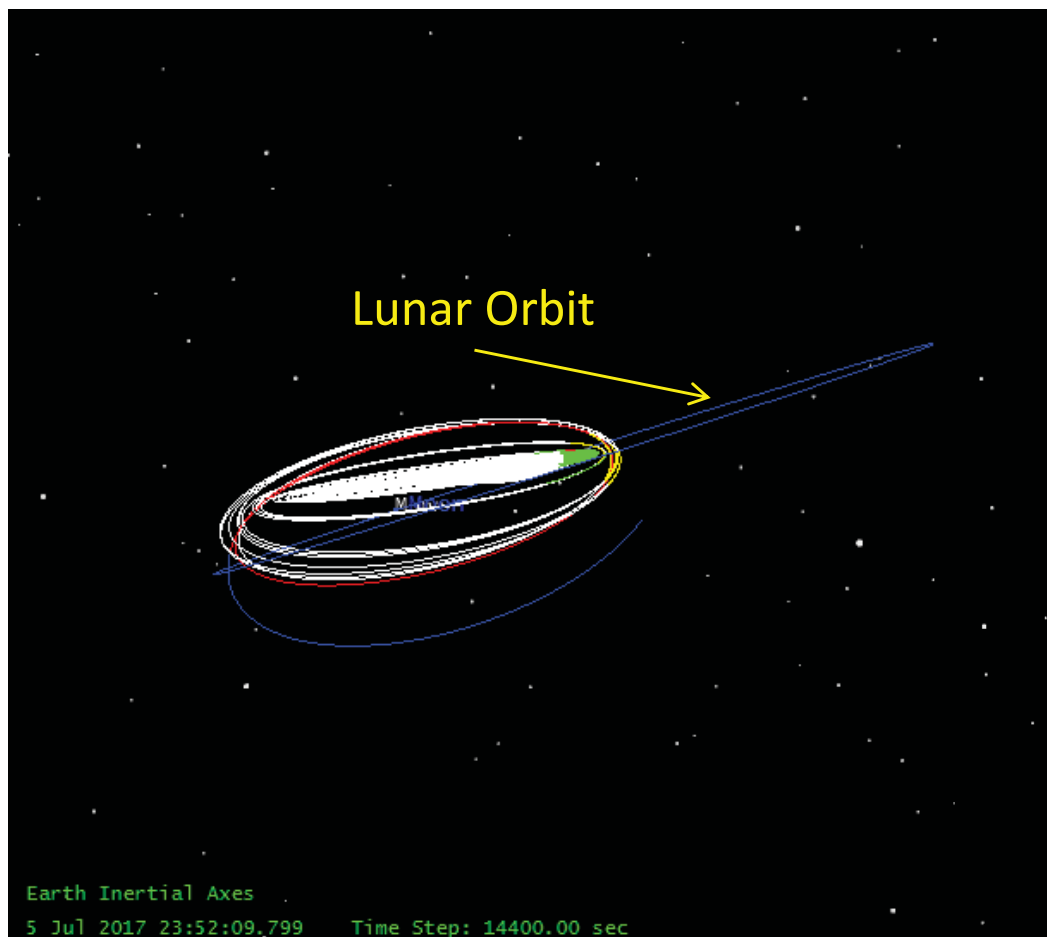
LunarCube Low-Thrust Trajectory Design

- Sept 2016 to Jan 2019
- Thrust only at periapsis – from ta ~ 225 to 130 deg
- Three distinct periapsis maneuver scenarios
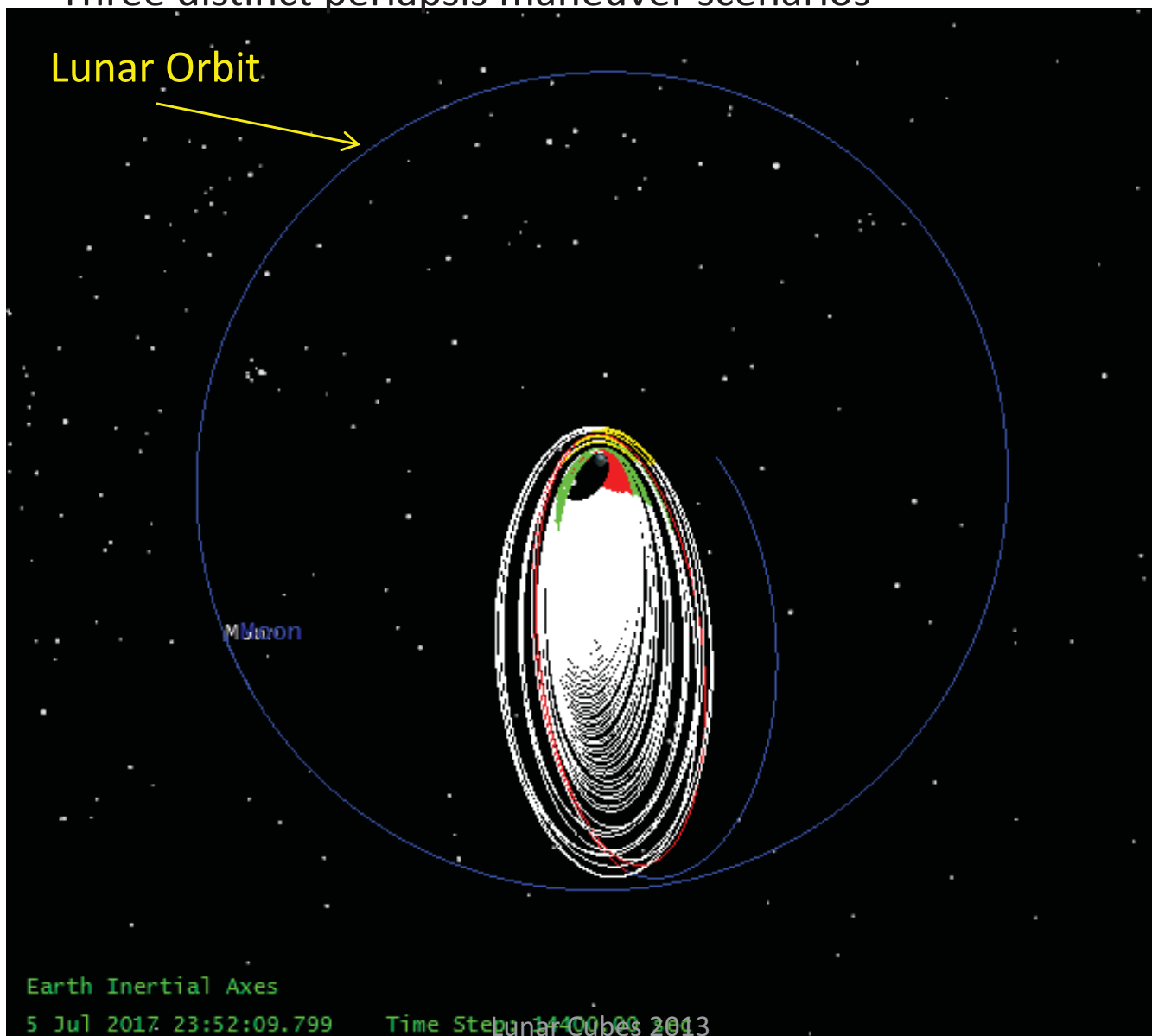
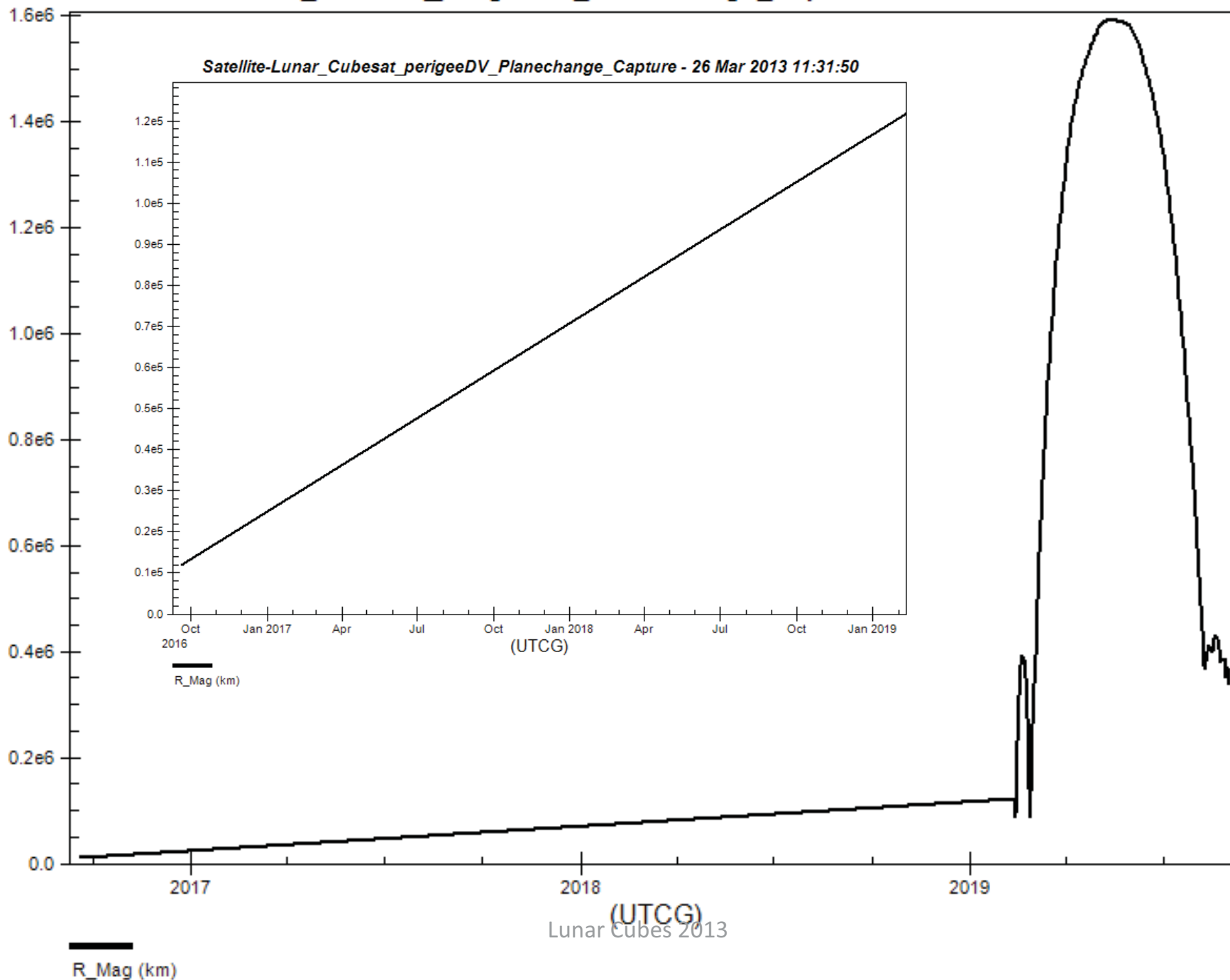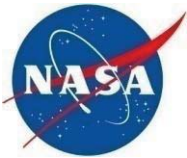# LunarCube Low-Thrust Trajectory Design

Satellite-Lunar_Cubesat_perigeeDV_Planechange_Capture - 26 Mar 2013 11:31:50
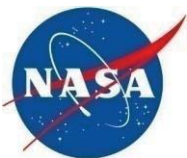
LunarCube Low-Thrust Trajectory Design

Shadows

Umbra Times

Start Time (UTCG)	Stop Time (UTCG)	Duration (hr)
19 Sep 2016 13:19:58.000	19 Sep 2016 13:19:58.000	0.000
23 Aug 2019 10:22:13.855	23 Aug 2019 10:50:47.199	0.476
28 Aug 2019 00:11:30.889	28 Aug 2019 00:35:30.555	0.400
31 Aug 2019 12:07:23.194	31 Aug 2019 12:21:19.196	0.232

Global Statistics

Min Duration	19 Sep 2016 13:19:58.000	19 Sep 2016 13:19:58.000	0.000
Max Duration	23 Aug 2019 10:22:13.855	23 Aug 2019 10:50:47.199	0.476
Mean Duration			0.277
Total Duration			1.108

LunarCube Low-Thrust Trajectory Design

- Earth Departure Dv at Periapsis ~ 720 m/s