End to End System Budget and Performance for Moon Communication and Navigation Missions

PhD Programme: Innovative Technologies for Space Missions and Radiation Detection

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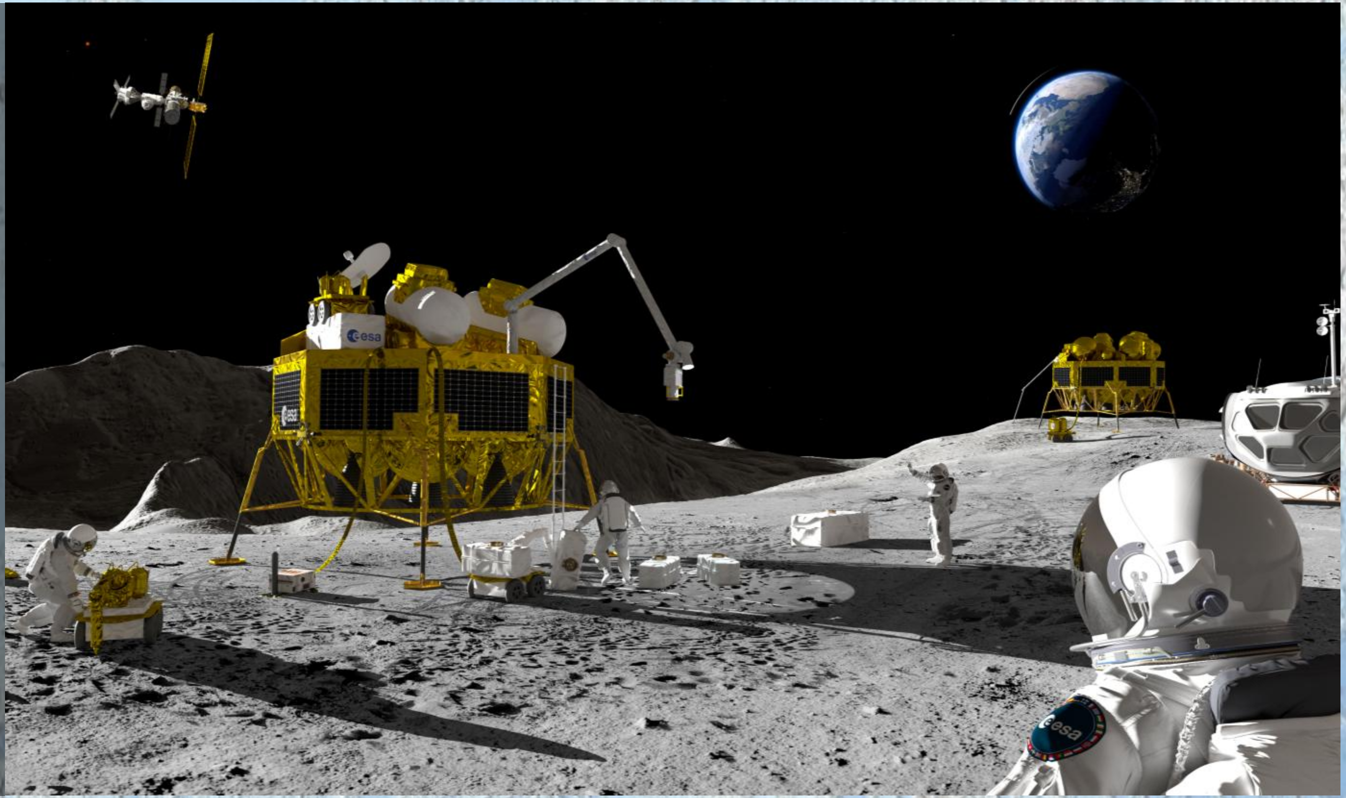
2025-2026 Academic Year Passage Meeting

Outlines

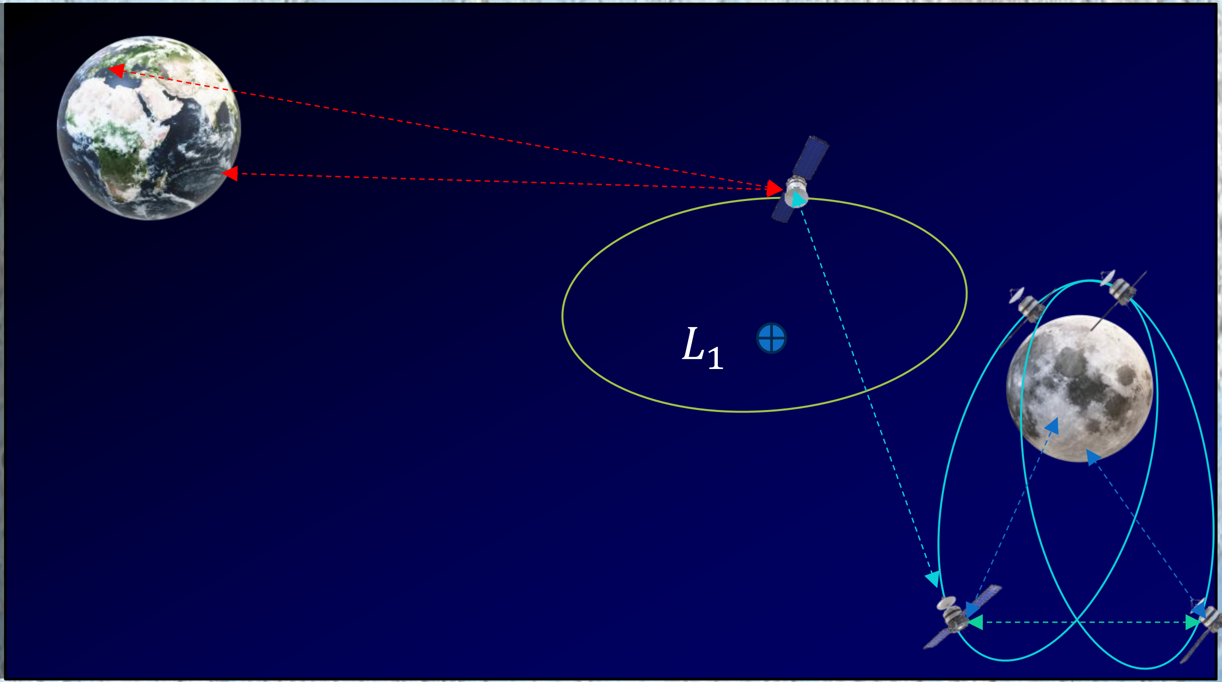
- Internship Research Period in SIA.
  - Moon Communication and Navigation: Mission objectives.
  - Orbit selection around the Moon: Elliptic Lunar Frozen Orbits (ELFO).
  - Halo Orbits around L_1 Lagrangian point as gateway for Lunar constellation deployment and Earth-Moon Communication link.
  - Preliminary Mission design (CR3BP).
  - Mission Analysis within the "Real World" environment (GMAT).
- Internship period at Telespazio (6 Months): HydRON Project.
- IAC2025 Participation/ IAF Paper publication.



Internship Research Period in SIA (10 Months)

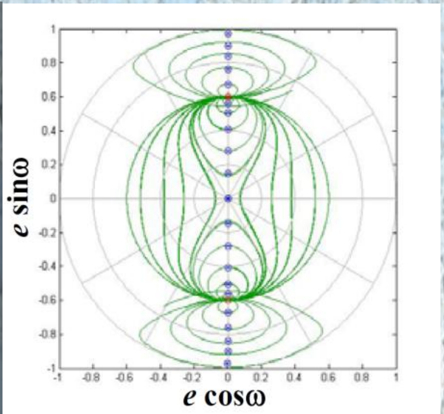
Moon Communication and Navigation: Mission Objectives

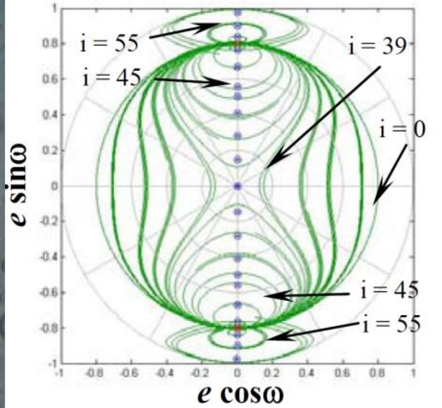
- **400** missions are scheduled to launch for the Moon in the next decade (According to ESA).
- To Design and optimise an E2E Lunar mission for deploying a Hybrid Satellite Constellation (**HSC**) that provides Lunar Positioning and Communication Services (**LPCS**).
- **HSC** consists of 5-7 satellite in total distributed in two sub-constellations:
  - 1-2 RF/ Laser Quantum Communication/ Referencing Relay satellite in a Halo Orbit around L_1 point.
  - A constellation of 4 Com/Nav satellites distributed in 2 optimised orbits to provide continuous coverage for Lunar southern hemisphere.
- A single launch is proposed (within the capabilities of many CLV).

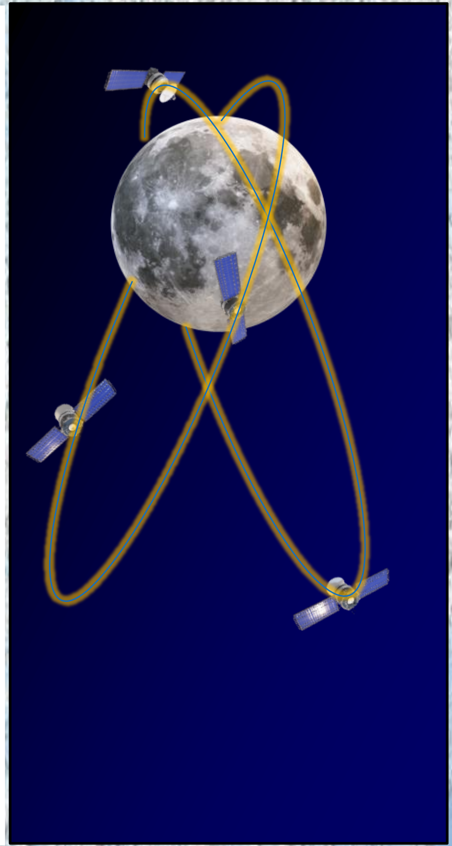


Orbit selection around the Moon: Elliptic Lunar Frozen Orbits (ELFO).

- ELFO is a highly stable, long-lasting elliptical orbit around the Moon that preserves almost constant orbital parameters with minimal station-keeping ΔV cost. (Average disturbing forces like Earth and Sun gravity, Moon gravitational harmonics, and solar radiation pressure are balanced).
- Used as constellation: Best for providing continuous coverage (Com/Nav services) for Lunar landing missions and bases in the targeted regions.
- For polar orbits: orbit plane is inertial fixed:
  - Lunar Gravity (potential) is major perturbation below 500 km altitude.
  - Earth and Sun gravity and solar radiation pressure are major perturbations above 500 km altitude.
  - The time rate of $a, i, e, \Omega, and\ \omega$ are analytically considered to be $= 0$.
  - Analytically, No ELFO can be achieved for inclinations i below $39°$

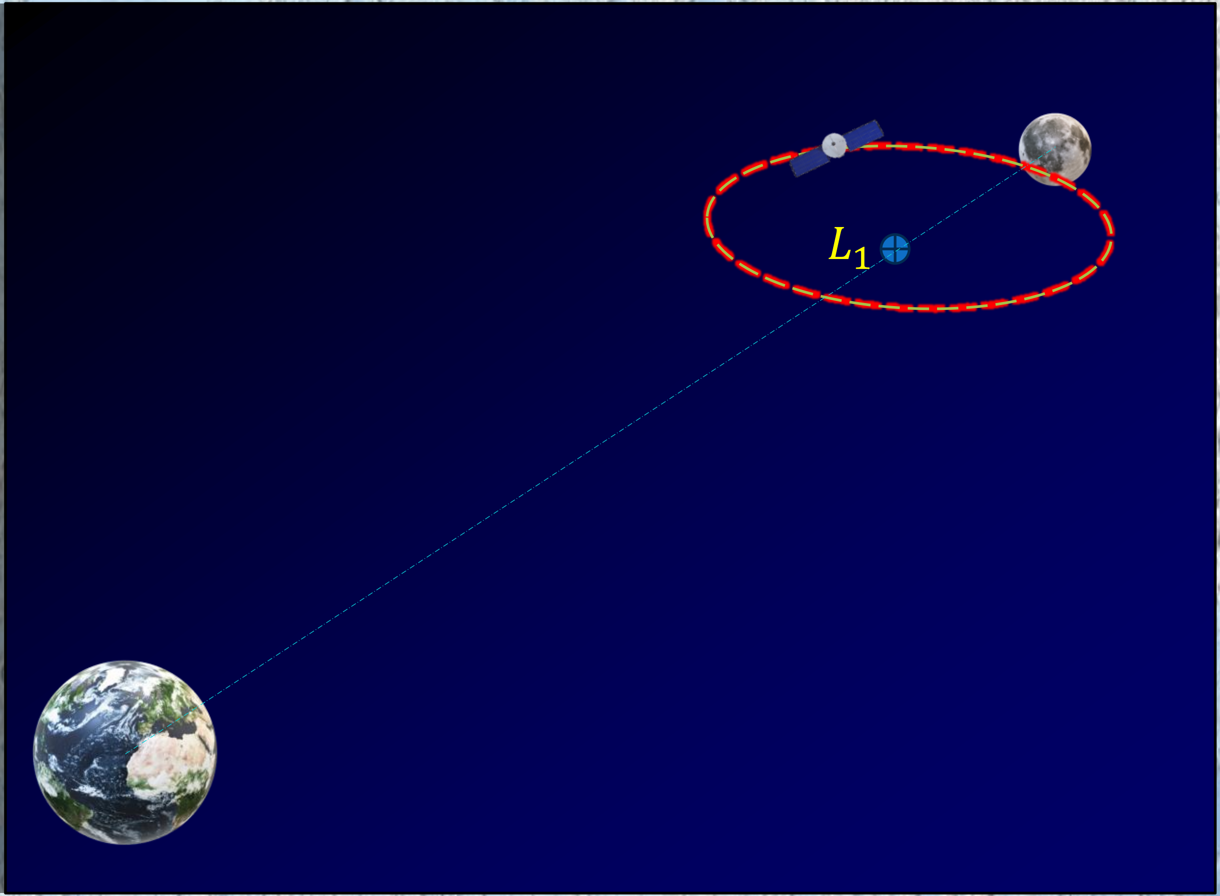






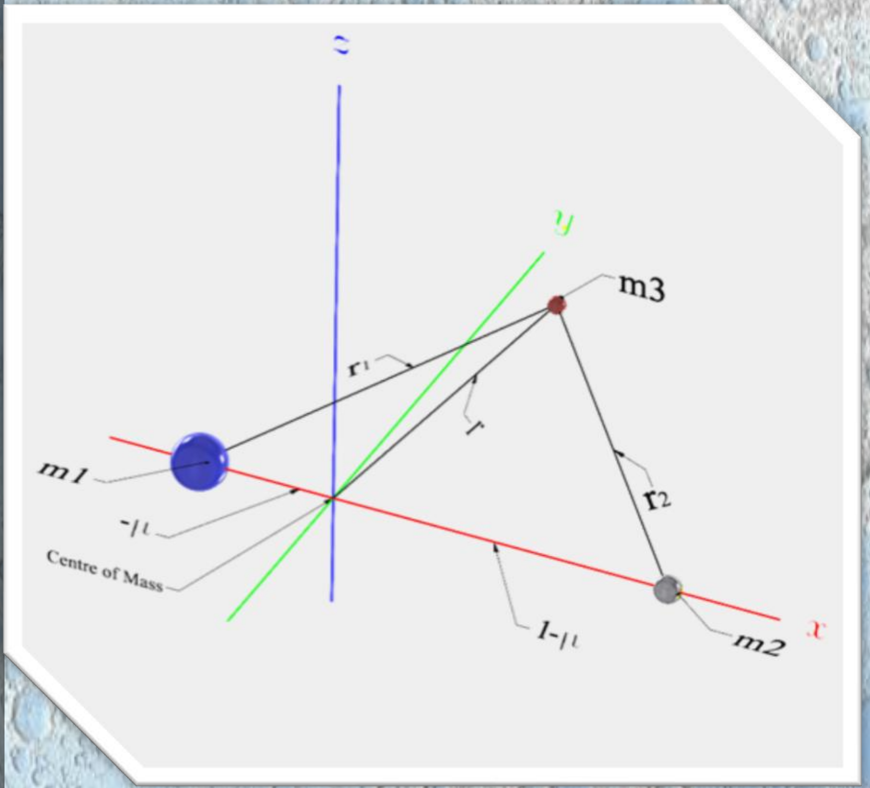
Halo Orbits around L_1 Lagrangian Point

- A Halo Orbit (HO) is a periodic, three-dimensional orbit around one of the three colinear Lagrange points, where a spacecraft seems to form a halo around the Moon as seen from Earth.
- HO is one solution (of many) to the 3-Body problem, results from the combined gravitational pull of two large celestial bodies (Earth and Moon) and the centripetal force on the spacecraft.
- HOs are naturally unstable, periodic adjustments for station-keeping are required.
- HO are suitable for missions that require a prior point for continuous observation or communication, such as space telescopes, communication relay, Space Command and Control Centre (SCCC), Cloud Data Centre, and an inhabited/ logistic Gateway station.



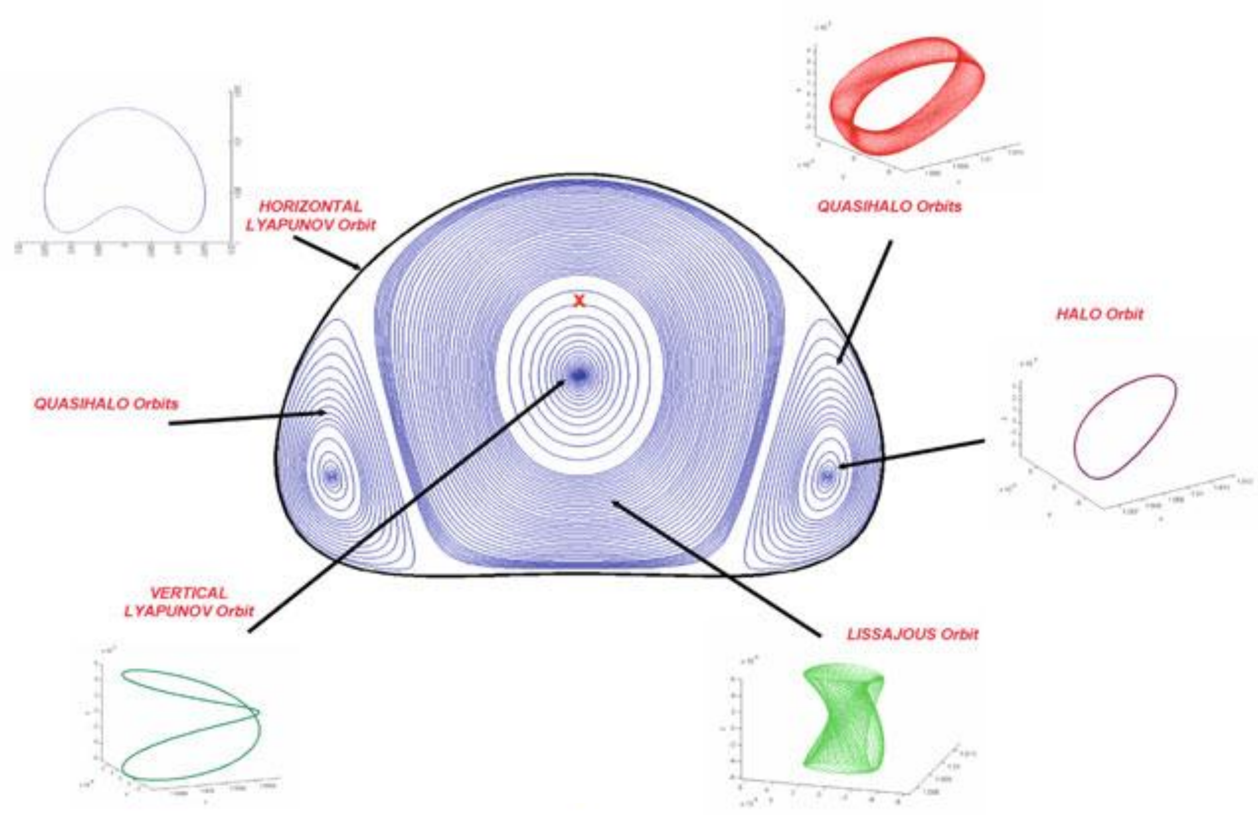
Preliminary Mission design (CRTBP)

- Circular Restricted 3-Body Problem assumes a perfect steady circular motion of the secondary massive body (m_2) and the primary massive body (m_1) about their mutual centre of mass (barycentre). (m_3) is the 3rd body mass (s/c) as $(m_3 \ll m_2 < (m_1)$.
- In a reference frame rotating with Earth-Moon, the CR3BP becomes an autonomous dynamical system. It admits one constant integral of motion, named the Jacobi constant C, that is proportional to opposite of the energy $(C = -2H)$ of the system.
- A total of 5 equilibrium points $\boldsymbol{L}_i$ with $i = 1, 2, \ldots, 5$.
- Jacobi constants computed at $\boldsymbol{L}_i$, can be proved to be $C_1 > C_2 > C_3 > C_4 = C_5$.
- The transfer trajectories between the two primaries (e.g. Earth and Moon), only exist if $C < C_1$. It follows that low-energy transfers can be studied for energy values slightly higher than $H(\boldsymbol{L}_1)$.



Preliminary Mission design (CR3BP)

- Periodic Orbits:
  - For Jacobi constant values near that of L_1, where it is sufficient to consider the linear approximation terms of the EoM, there exist two main groups of periodic orbits; the horizontal Lyapunov orbits, which are in the synodic plane, and the horizontally symmetric eight-shaped vertical Lyapunov orbits.
  - When energy is increased, nonlinear terms become important, and linear phase space is no longer sufficient a new periodic family, “Halo Orbits”, bifurcate from the horizontal Lyapunov orbit family. These orbits are three-dimensional and asymmetric about the synodic plane
- Quasiperiodic Orbits:
  - Lissajous family around the vertical Lyapunov orbits.
  - Quasi-Halos around the halo orbits. These quasiperiodic orbits are located on invariant tori about the corresponding periodic orbit.



Formal Solutions of the CR3BP inside a Ball Centred in the L_1 Libration Point

- We expanded the Hamilton function H of the CRTBP dynamics in Taylor form around L_1 up to order N=12
- We used a pair of real variables z_1, w_1 and two pairs of complex variables $z_2, w_2 = -i conj(z_2)$, and $z_3, w_3 = -i conj(z_3)$

so that , after 11 Canonical transformations, the Hamilton function of the system (up to order 12) becomes in the new variables

$$(z, w) = \mathcal{T}(x, y, z, \dot{x}, \dot{y}, \dot{z})$$

- $H_{N=12} = \rho\, \pi_1 + i\, \lambda_2 \pi_2 + i\, \lambda_3 \pi_3 + \left[h_{200}\pi_1^2 + h_{110}\pi_1\pi_2 + h_{101}\pi_1\pi_3 + h_{020}\pi_2^2 + h_{011}\pi_2\pi_3 + h_{002}\pi_3^2\right] + \cdots + h_{600}\pi_1^6 + ..$

$\pi_1 = z_1 w_1, \pi_2 = z_2 w_2, \pi_3 = z_3 w_3$ and the equations of motion are:

$$\dot{z}_i = \frac{\partial H_N}{\partial w_i} = \frac{\partial H_N}{\partial \pi_i} z_i \;,\; \dot{w}_i = -\frac{\partial H_N}{\partial z_i} = -\frac{\partial H_N}{\partial \pi_i} w_i$$

- The $\pi_i's$ **are constant** of motion, then they depend only on the initial conditions, and the equations of motion are Linear.
- Then all the complexity of the dynamics is solved by the (canonical) coordinate transformations, and the solution are as much simple as possible.

Hamiltonian Full Normalization up to order 12: The Formal Solution

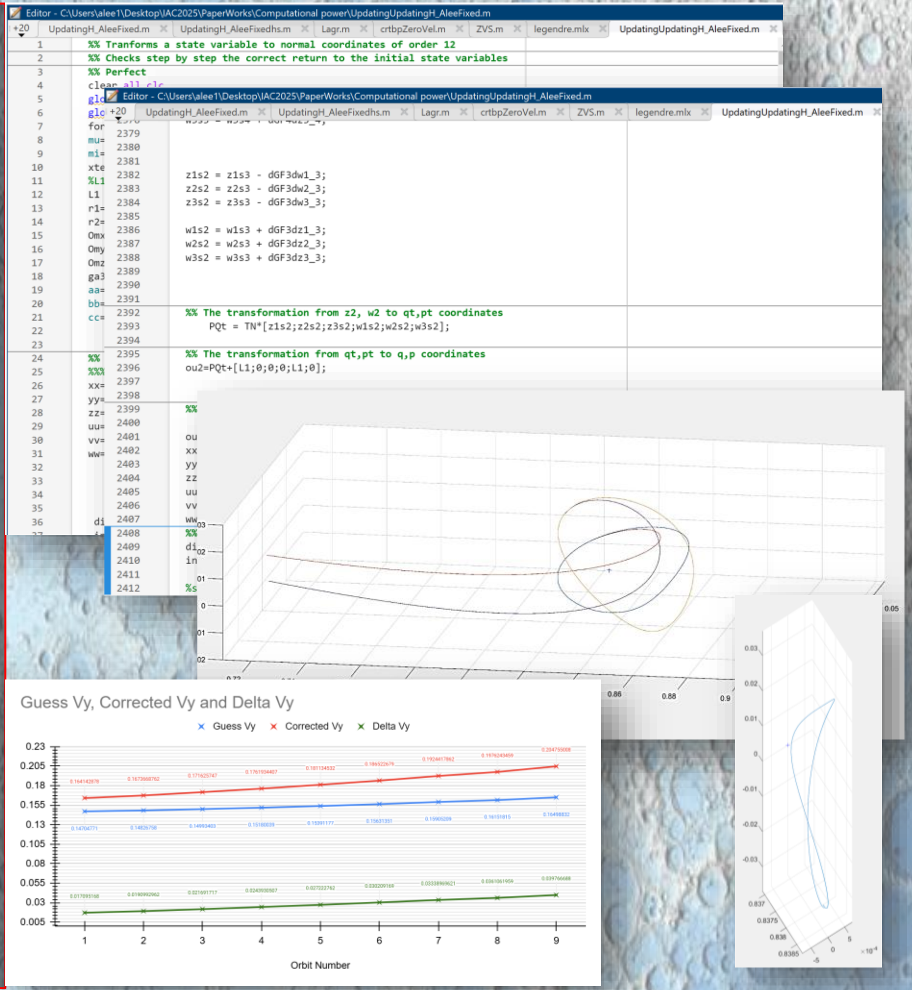
- **THE FORMAL SOLUTION:** We developed a (2400+) lines MATLAB® code with other extra calculation complementary code (5 codes) to develop and realise the following FORMAL SOLUTION:

$$z_1 = z_{1o}\, e^{Pt}$$
$$w_1 = w_{1o}\, e^{-Pt}$$
$$z_2 = z_{2o}\, e^{\Psi_2 t}$$
$$w_2 = w_{2o}\, e^{-\Psi_2 t}$$
$$z_3 = z_{3o}\, e^{\Psi_3 t}$$
$$w_3 = w_{3o}\, e^{-\Psi_3 t}$$

Where,

$z_{1o}, w_{1o}, z_{2o} = x_{2o} + iy_{2o}, , z_{3o} = x_{3o} + iy_{3o}, w_{2o} = -i\,\overline{z_{2o}}$ & $w_{3o} = -i\,\overline{z_{3o}}$ are the initial conditions,

and the frequencies $\begin{cases} P \\ \Psi_2 \\ \Psi_3 \end{cases}$ are constant and depending only on the initial conditions $\pi_{1o}, \pi_{2o}, \pi_{3o}$.



Locus of Periodic Solutions

A) 3D Periodic orbits are characterized by:

a) Null drift term $z_{1o} = w_{1o} = 0$, therefore $\pi_{1o} = 0$,

b) Equal frequencies $\Psi_2 = \Psi_3$.

The locus of periodic solutions is defined by the solutions π_{2o}, π_{3o} :

$$\Psi_2 = \frac{\partial H_N}{\partial \pi_2}(0, \pi_{2o}, \pi_{3o}) \equiv \Psi_3 = \frac{\partial H_N}{\partial \pi_3}(0, \pi_{2o}, \pi_{3o})$$

Since $\pi_2 = -\mathrm{i}\,|z_{2o}|^2$, $\pi_3 = -\mathrm{i}\,|z_{3o}|^2$, the above equation can be divided by $-\mathrm{i}$, to define a real algebraic curve of order $\frac{N}{2} - 1$ in the variables

$$\xi = |z_{2o}|^2 \qquad \eta = |z_{3o}|^2$$

$N = 2.$ gives

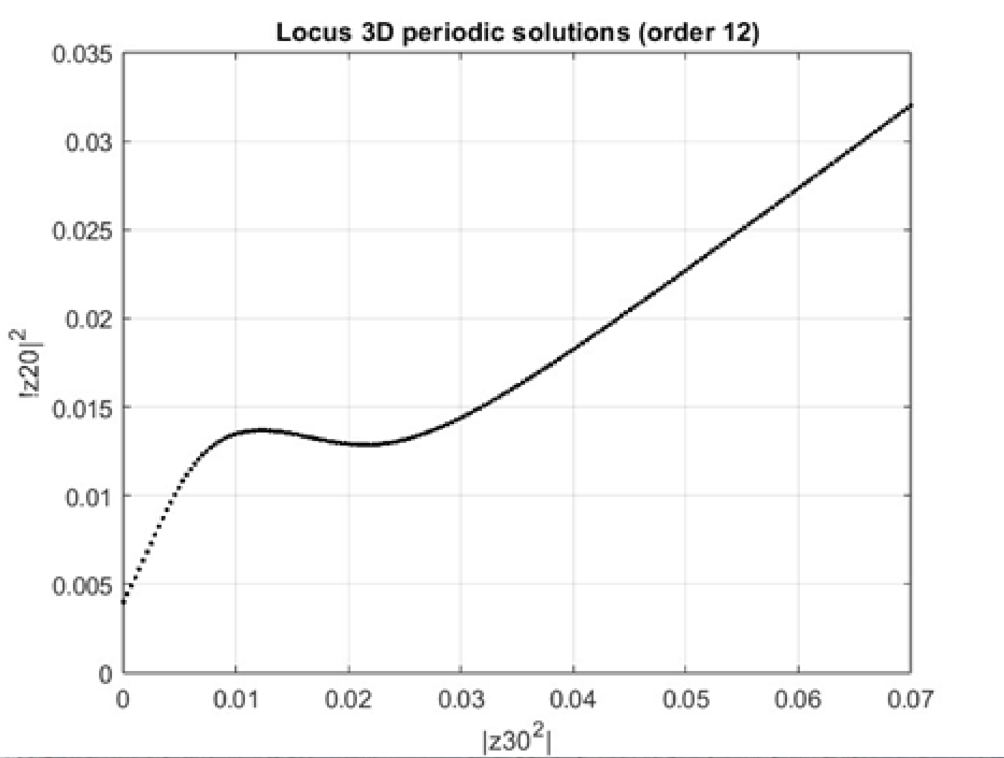
$\psi_2 - \psi_3 = 0$ → no solution

$N = 4$ gives

$\psi_2 - \psi_3 + (2h_{02020} - h_{011011})\,\xi + (h_{011011} - 2h_{002002})\,\eta = 0$

so, the locus is a straight line.

$N = 12$ gives the algebraic curve of order 5 in the Figure to the right.



Locus of Periodic Solutions

Any point on the locus determines specific pairs $(\xi = |z_{2o}|^2, \eta = |z_{3o}|^2)$.

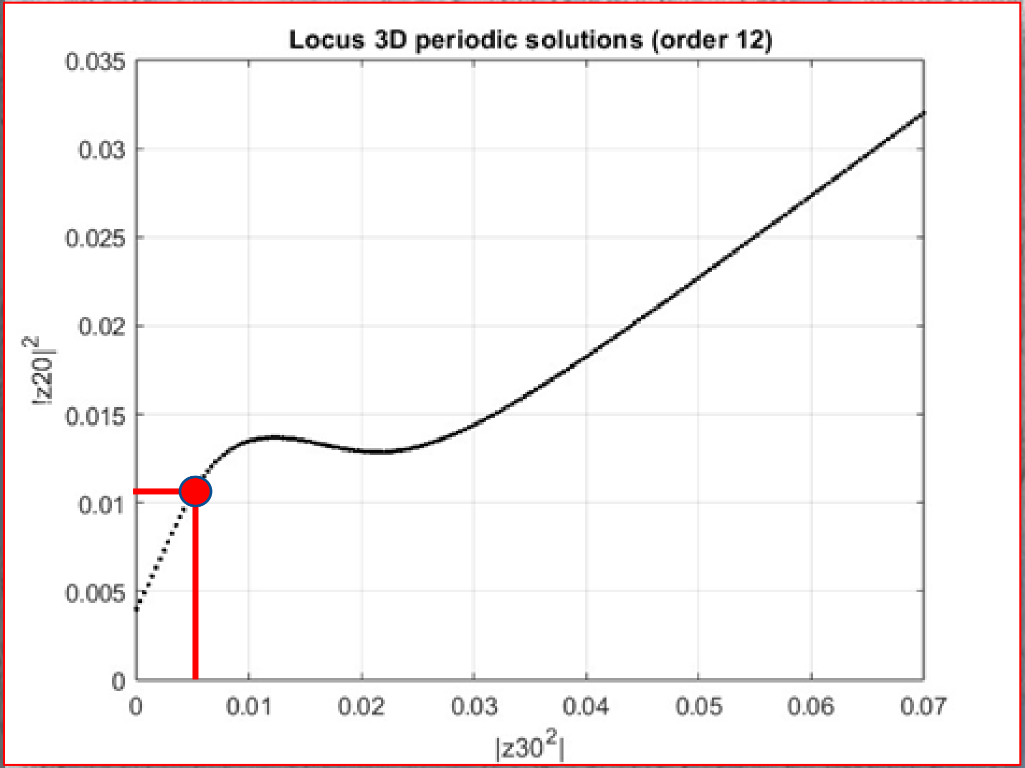
$$\begin{cases} x_{2o} = \sqrt{\xi}\cos\phi_2 \\ y_{2o} = \sqrt{\xi}\sin\phi_2 \end{cases} \rightarrow z_{2o} = x_{2o} + \mathrm{i}y_{2o}$$

$$\begin{cases} x_{3o} = \sqrt{\eta}\cos\phi_3 \\ y_{3o} = \sqrt{\eta}\sin\phi_3 \end{cases} \rightarrow z_{3o} = x_{3o} + \mathrm{i}y_{3o}$$

Then the selected point in the locus and the selected phase generate a physical state

$$(0.\,0.\,z_{20}, -i\,conj(z_{20}), z_{30}, -i\,conj(z_{30})) \xrightarrow{\mathcal{T}^{-1}} (x_0, y_0, z_0, \dot{x}_0, \dot{y}_0, \dot{z}_0)$$

Corresponding to a 3D periodic solution of the CRTBP



Locus of Periodic Solutions

B) Periodic Orbits in the (X-Y) plane are characterized by:

a) Null drift term $z_{1o} = w_{1o} = 0$, therefore $\pi_{1o} = 0$,

b) Null z_{3o} term, therefore $\pi_{3o} = 0$.

The locus of periodic solutions is defined by the initial condition π_{2o} and have frequency depending on it

$$\Psi_2 = \frac{\partial H_N}{\partial \pi_2}(0, \pi_{2o}, 0)$$

C) Vertical Periodic Orbit solutions are characterized by:

a) Null drift term $z_{10} = w_{10} = 0$, therefore $\pi_{1o} = 0$,

b) Null z_{2o} term, therefore $\pi_{2o} = 0$.

- Any point on the locus determines specific pairs $\left(\xi = |z_{2o}|^2, \eta = |z_{3o}|^2\right)$. By introducing the two phases ϕ_2 and ϕ_3 we get the variables:
- $\begin{cases} x_{2o} = \sqrt{\xi}\cos\phi_2 \\ y_{2o} = \sqrt{\xi}\sin\phi_2 \end{cases} \rightarrow z_{2o} = x_{2o} + iy_{2o}$
- $\begin{cases} x_{3o} = \sqrt{\eta}\cos\phi_3 \\ y_{3o} = \sqrt{\eta}\sin\phi_3 \end{cases} \rightarrow z_{3o} = x_{3o} + iy_{3o}$

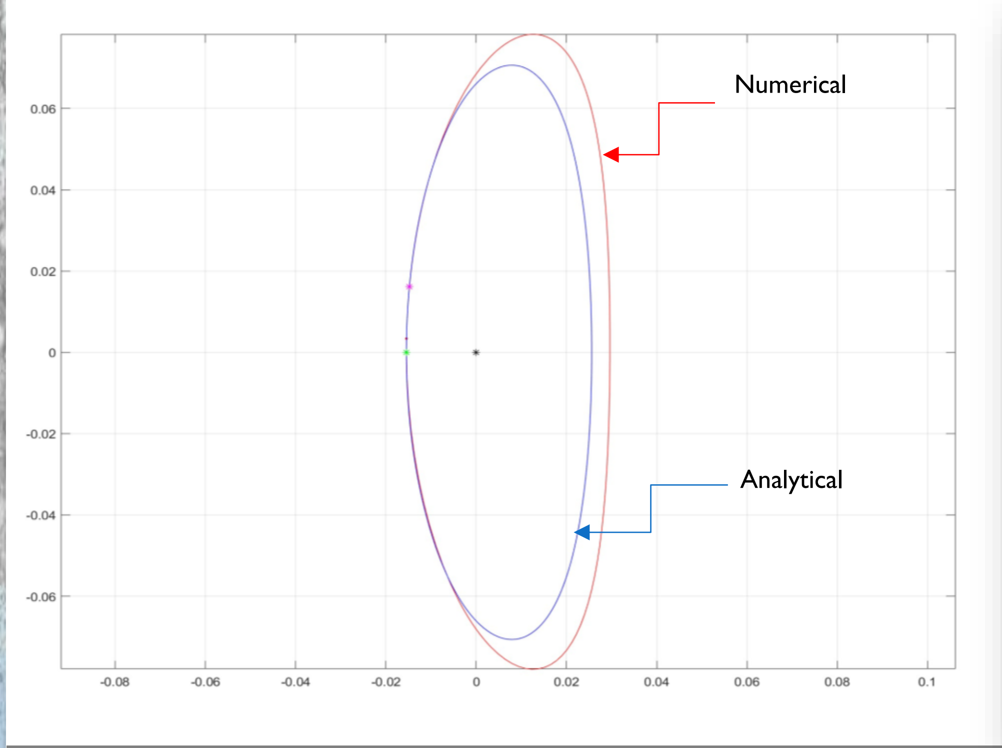
Examples of 3D Periodic Solutions

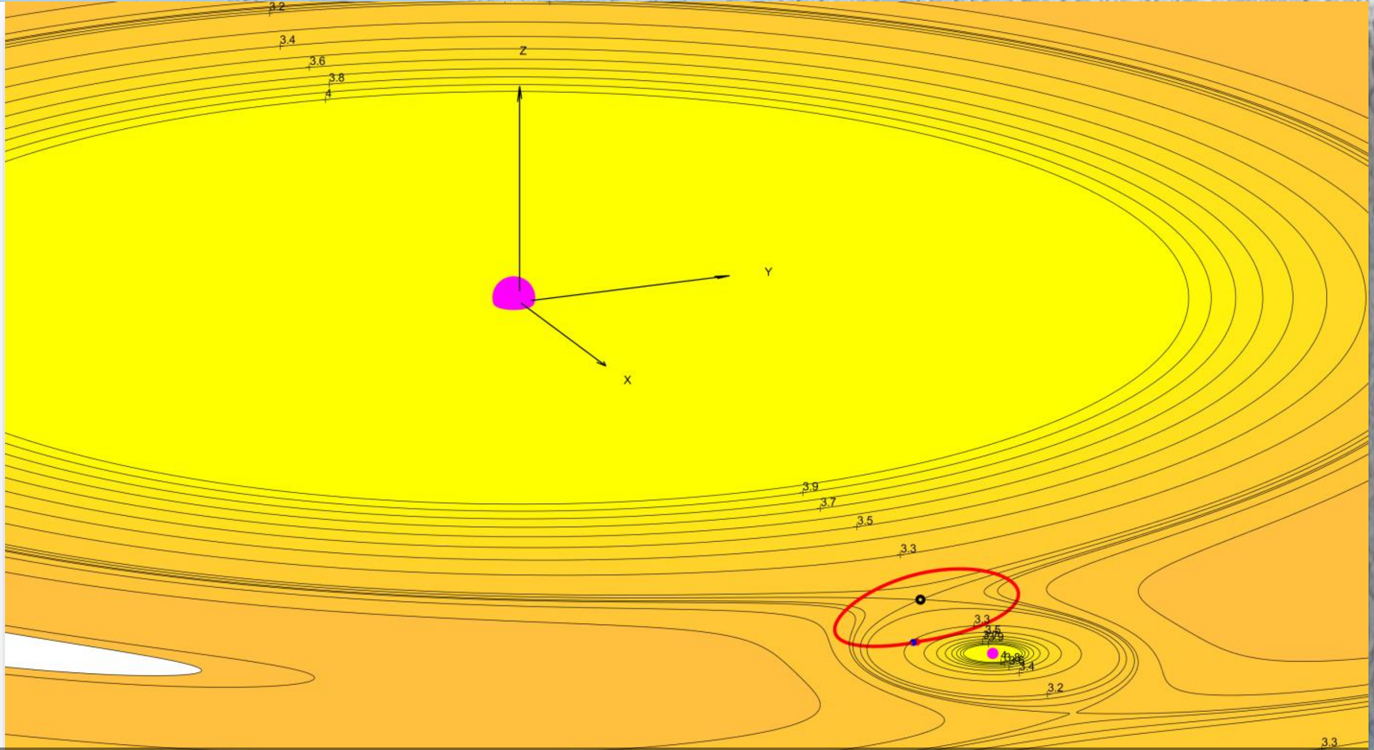
- Initial modal coordinates corresponding to periodic solutions in the range $|z_{2o}|^2 \in [4:6] \cdot 10^{-3}$ are reported, together with the (equal) frequencies and value of H_N for $n = 12$.
- It is worth noting that, the values in the upper Table, the phases φ_2 and φ_3 are both equal to $\frac{\pi}{4}$.
- *The corresponding physical state variables obtained by the Inverse of the Canonical Transformations have initial coordinates in the form $(x_o, 0, z_o, 0, v_o, 0)$, the forthcoming numerical refinement will be on one parameter only (v_o).*

$\|z_{20}\|^2$	$\|z_{30}\|^2$	x_{20}	y_{20}	x_{30}	y_{30}	Ψ_2	Ψ_3	H_{12}
4.0040040e-03	4.7183704e-06	4.4743737e-02	-4.4743737e-02	1.5359639e-03	1.5359639e-03	2.2066693e+00	2.2066693e+00	9.0884327e-03
4.2542543e-03	1.9825057e-04	4.6120788e-02	-4.6120788e-02	9.9561681e-03	9.9561681e-03	2.1974337e+00	2.1974337e+00	1.0065656e-02
4.5045045e-03	3.9020049e-04	4.7457900e-02	-4.7457900e-02	1.3967829e-02	1.3967829e-02	2.1884488e+00	2.1884488e+00	1.1035367e-02
4.7047047e-03	5.4267382e-04	4.8501055e-02	-4.8501055e-02	1.6472307e-02	1.6472307e-02	2.1814322e+00	2.1814322e+00	1.1805934e-02
4.9549550e-03	**7.3197882e-04**	**4.9774265e-02**	**-4.9774265e-02**	**1.9130850e-02**	**1.9130850e-02**	**2.1728648e+00**	**2.1728648e+00**	**1.2762904e-02**
5.2052052e-03	9.1994143e-04	5.1015709e-02	-5.1015709e-02	2.1446928e-02	2.1446928e-02	2.1645110e+00	2.1645110e+00	1.3713245e-02
5.4554555e-03	1.1066648e-03	5.2227653e-02	-5.2227653e-02	2.3523018e-02	2.3523018e-02	2.1563576e+00	2.1563576e+00	1.4657291e-02
5.7057057e-03	1.2922637e-03	5.3412104e-02	-5.3412104e-02	2.5419124e-02	2.5419124e-02	2.1483916e+00	2.1483916e+00	1.5595396e-02
5.9559560e-03	1.4768666e-03	5.4570853e-02	-5.4570853e-02	2.7174129e-02	2.7174129e-02	2.1405996e+00	2.1405996e+00	1.6527931e-02
6.1561562e-03	1.6239277e-03	5.5480430e-02	-5.5480430e-02	2.8494980e-02	2.8494980e-02	2.1344820e+00	2.1344820e+00	1.7270214e-02

	$x_0\ [DU]$	$y_0 [DU]$	$z_0 [DU]$	$u_0 \left[\frac{DU}{TU}\right]$	$v_0 \left[\frac{DU}{TU}\right]$	$w_0 \left[\frac{DU}{TU}\right]$
1	8.2052817e-01	-6.6723407e-18	3.1062119e-03	-2.6682638e-18	1.4427049e-01	-4.6307885e-19
2	8.2077505e-01	-6.2569667e-18	2.0343291e-02	-1.8409555e-18	1.4562509e-01	-3.1912478e-18
3	8.2101758e-01	-5.7968342e-18	2.8812413e-02	-9.6793268e-19	1.4704771e-01	-4.7622038e-18
4	8.2120346e-01	-5.3929661e-18	3.4218723e-02	-2.3145057e-19	1.4826758e-01	-5.9078537e-18
5	**8.2141922e-01**	**-4.8365446e-18**	**4.0067246e-02**	**7.4499196e-19**	**1.4993403e-01**	**-7.3289906e-18**
6	8.2160904e-01	-4.2119839e-18	4.5256357e-02	1.7949582e-18	1.5180039e-01	-8.8111705e-18
7	8.2176441e-01	-3.5036581e-18	4.9980710e-02	2.9336717e-18	1.5391177e-01	-1.0415363e-17
8	8.2187606e-01	-2.6908052e-18	5.4352809e-02	4.1801321e-18	1.5631351e-01	-1.2200185e-17
9	8.2193380e-01	-1.7462810e-18	5.8445029e-02	5.5581450e-18	1.5905209e-01	-1.4229114e-17
10	8.2193349e-01	-8.7251643e-19	6.1551632e-02	6.7752163e-18	1.6151815e-01	-1.6076647e-17

Numerical Refinement within the CRTBP
Numerical Model

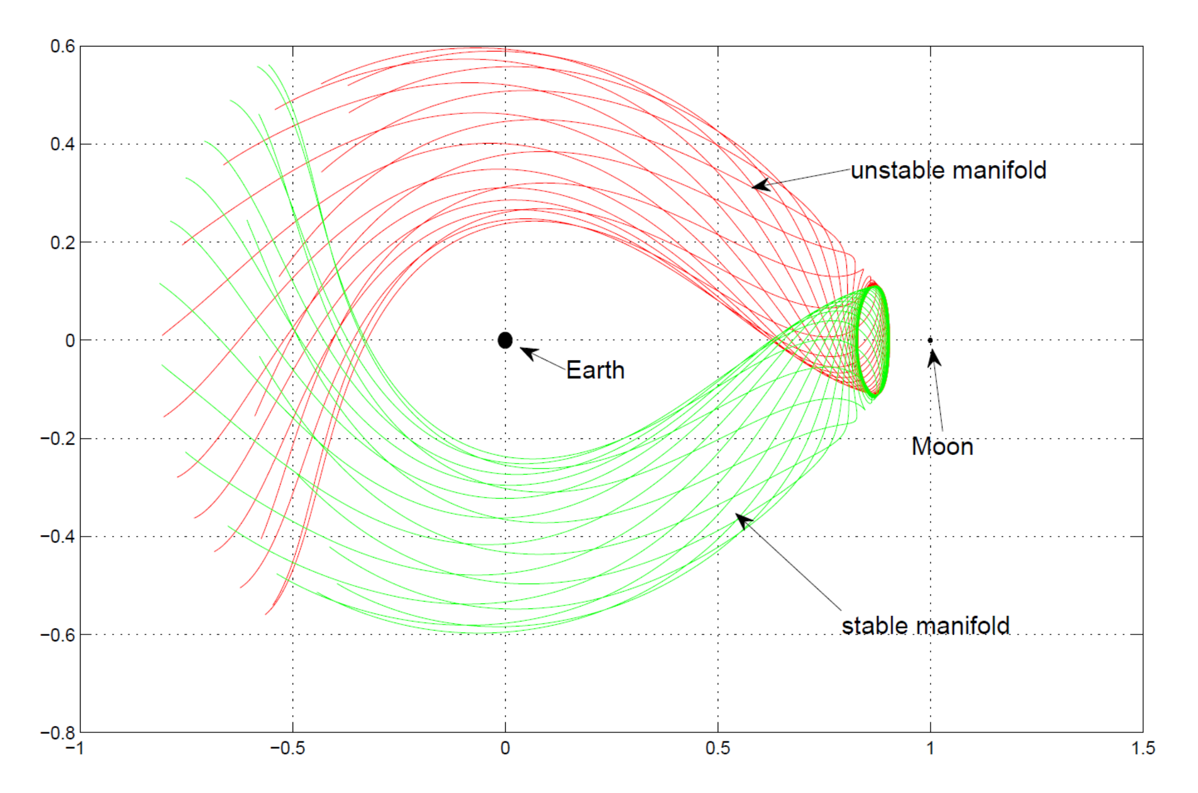




- The analytic solutions (of order 12) approximate the numerical solution. In fact, the initial condition v_0 in the previous table must be corrected to get a numerical periodic solution. The correction is higher with higher energy.
- The initial state No.5 is considered, having initial position (0.812141922, 0.00, 0.0400672) with respect to Barycentre.
- The velocity components of the analytic solution is (0.00, 0.14993403, 0.00) the numerical refinement gives: (0.00, 0.171625747, 0.00), with a percentage difference of 14.5% higher. Analytical (Blue) and Numerical (Red) are shown together here:

Stable and Unstable Manifolds of Periodic Orbits

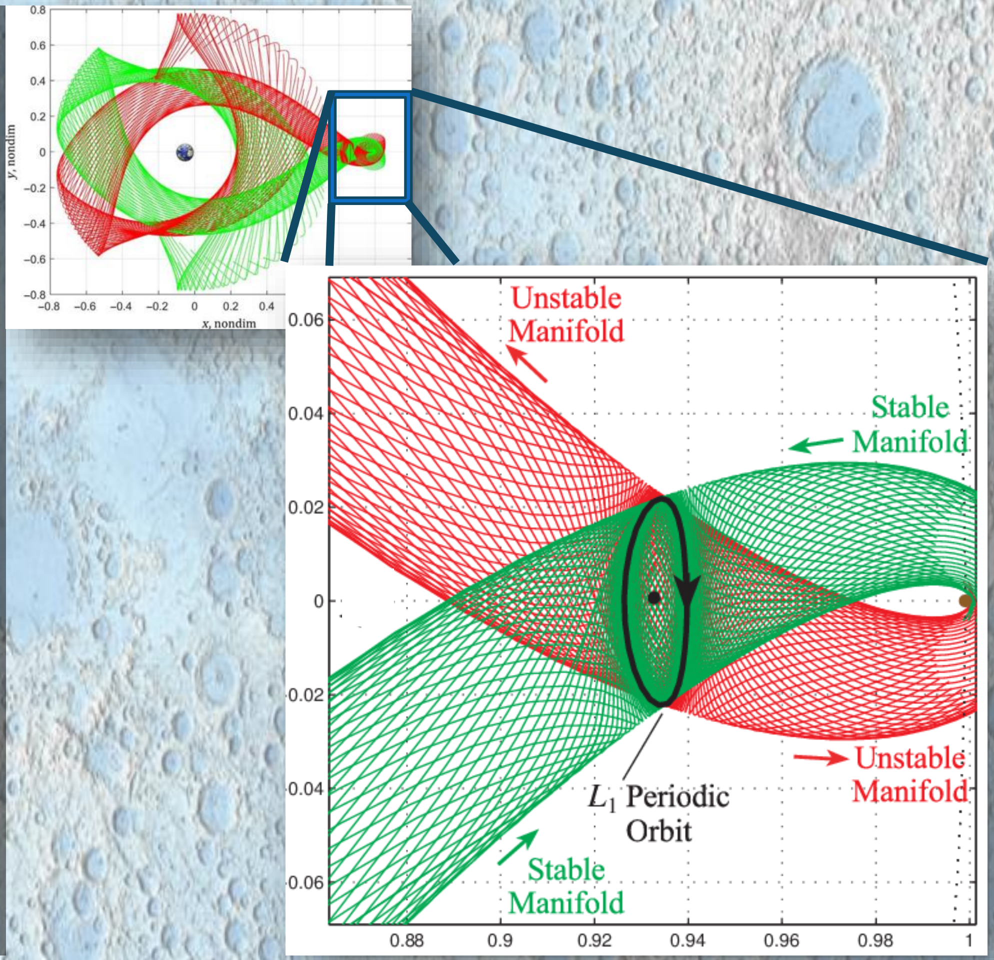
- Stable (green) and Unstable (red) invariant manifolds of the Earth-Moon system, for instance, are fabrics of gravitational trajectories through which the spacecraft is moving between orbits with minimal fuel, based on the dynamics near Lagrange points.
- The Unstable manifold shows how a spacecraft would naturally drift **away** from an orbit, while The Stable manifold represents the path a spacecraft can follow to asymptotically approach an orbit without fuel.
- Invariant Manifolds are essential for Lunar and interplanetary missions planning
- They are Unique for each periodic/quasiperiodic orbit.
- Once a periodic solution is found, then its corresponding invariant manifold can be determined by numerically integrating trajectories backward in time from a specific unstable periodic orbit (like a halo orbit) to find the stable manifold, and forward in time for the unstable manifold.



[Butcher, and Parker, 2014]

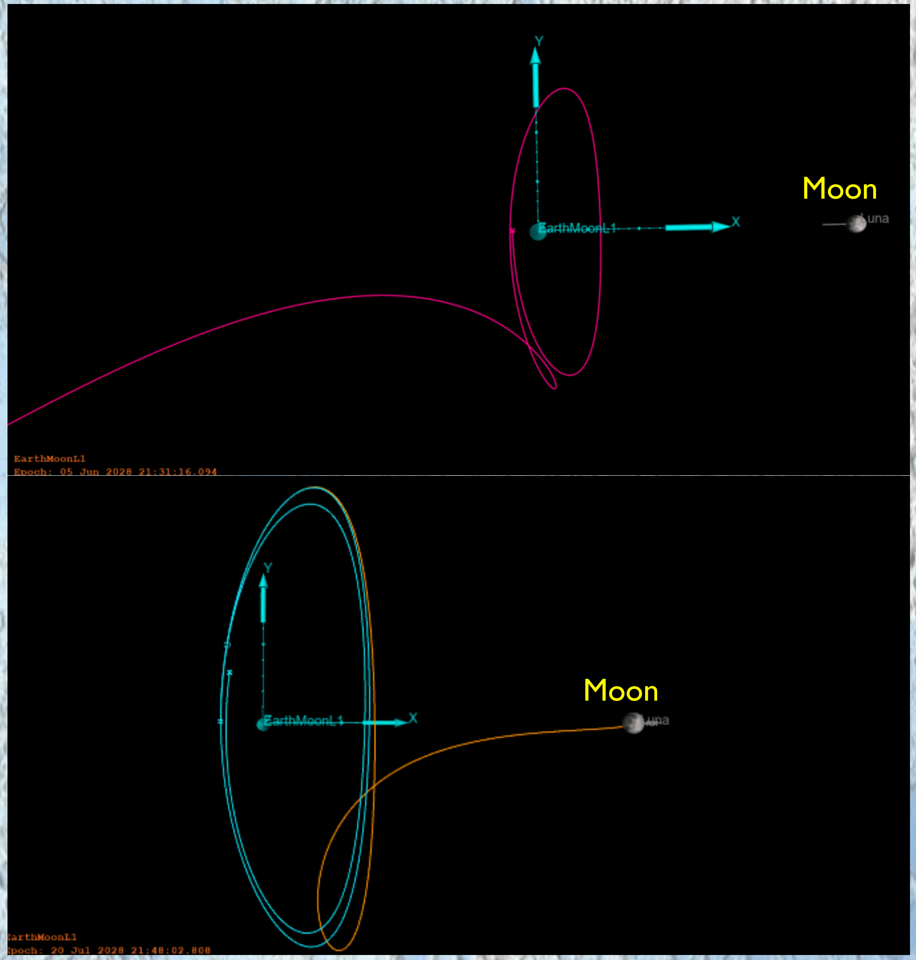
Stable and Unstable Manifolds of Periodic Orbits

- Stable and Unstable invariant manifolds also applies, for any unique periodic orbit solution.
- If we add an infinitesimal amount of energy (or positively perturbing the position state of the orbit at any point in a certain direction), then the spacecraft shall naturally depart the periodic orbit to an unstable Moon capture trajectory.
- The other way around, is the same as Earth stable manifold (the green on the left side of the HO).
- Its usefulness depends on final Lunar mission objectives, otherwise it should be adjusted.
- In both cases, Earth-Halo-Moon, Moon-Halo-Earth, a spacecraft should be guided to initially intercept one of the Stable/Unstable manifolds trajectories to be ballistically captured into a periodic orbit, or Earth/Moon orbits.



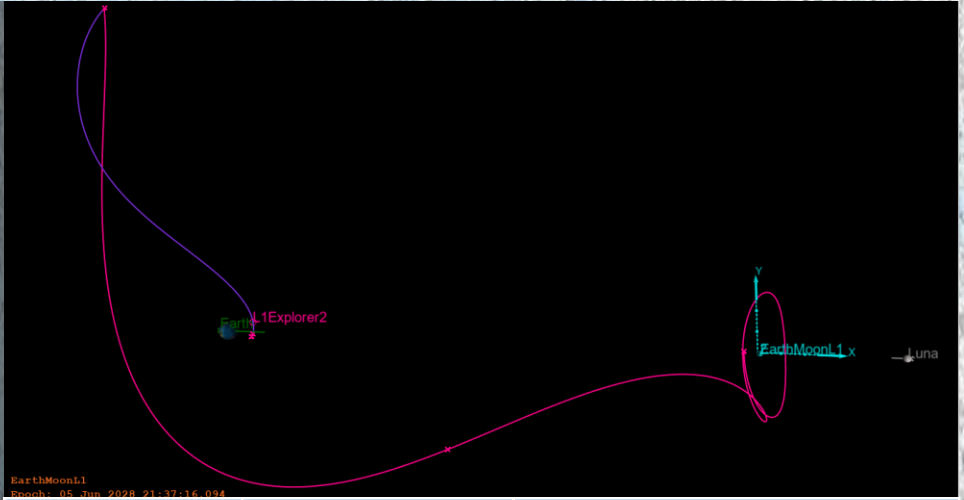
Mission Design in the "Real World" Environment

- A high-fidelity propagator, General Mission Analysis Tool (GMAT), is utilised. The previous Initial State (IS), No.5 is considered.
- The model in GMAT considers the eccentricity of the Moon orbit around the Earth, the Sun, and Jupiter gravitational effects and their consequences on the dynamics.
- A customized reference frame, introduced in GMAT, is considered inertial with respect to a pulsating Earth – Moon distance.
- With this position the numerical refinement of the initial velocity v_0 in the "Real World" environment (GMAT) is performed.
- L1Explorer1, and L1Explorer2 are defined in GMAT.
- Impulsive Burns are considered.
- IS Backward Propagation for L1Explorer2 asymptotically departing back to Earth realm within a stable manifold, until the first Apogee. "Open-Point" concept is applied to target a HEO.
- Forward Propagation for L1Explorer1 to achieve LPHO (multiple periods) and then departs toward Moon realm within a capture trajectory manifold.
- Analytical v_0 is corrected, in both Back/Forward propagations, utilising GMAT differential corrector as a BVP solver.



From Earth to Halo: Backward Propagations

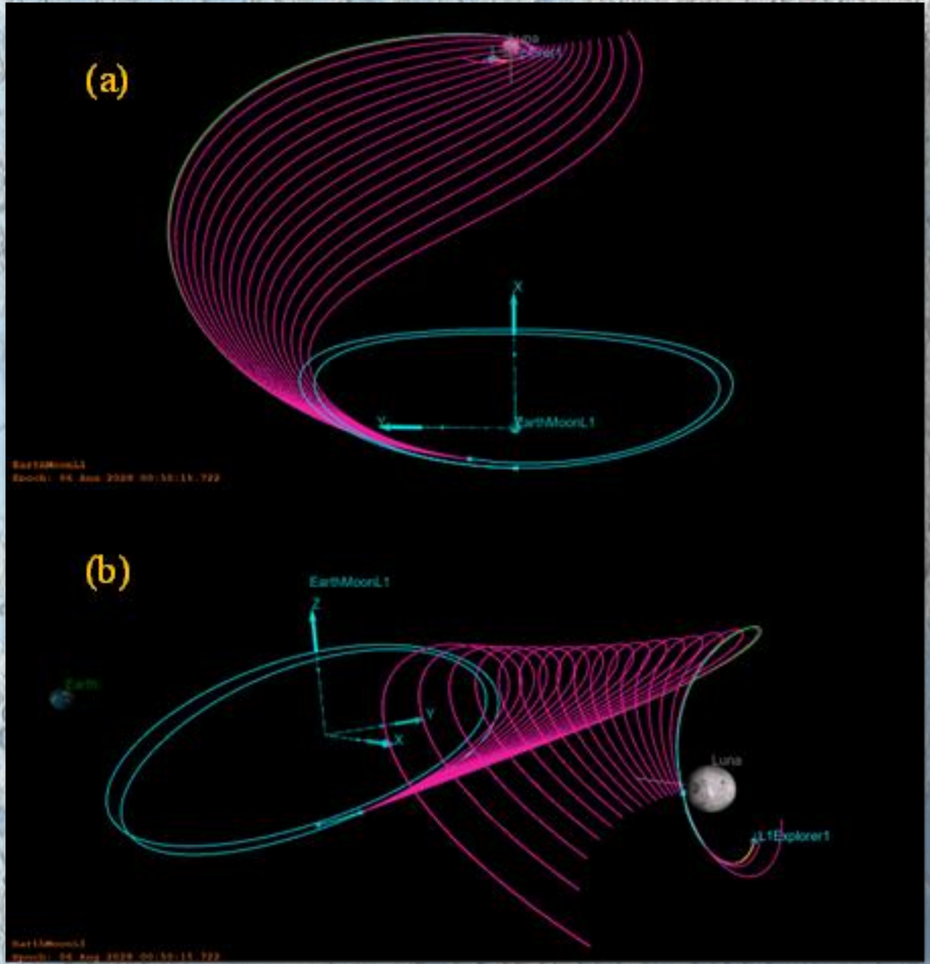
- Starting from LPHO IS assigned before, the resulted $\mathbf{v_{oCorr}}$ is 0.171 $\left[\frac{\mathbf{DU}}{\mathbf{TU}}\right]$ with an increase of 13.9% from IS $\boldsymbol{v_o}$.
- Going (backward) from ballistic capture in LPHO (Crimson Segment, $\boldsymbol{L_1}$Stable Manifold) to HEO (Violet Segment) with $\Delta\vec{\boldsymbol{V}}$ of 0.52 km/s in the Direction of $\vec{\boldsymbol{V}}$.
- Desired inclination is naturally achieved, with HEO perigee of 6690 km. (no orbit plane correction is needed)
- Finding: The more asymptotic LPHO capture trajectory achieved, the less required $\Delta\vec{\boldsymbol{V}}$(Minimal Energy transfer).



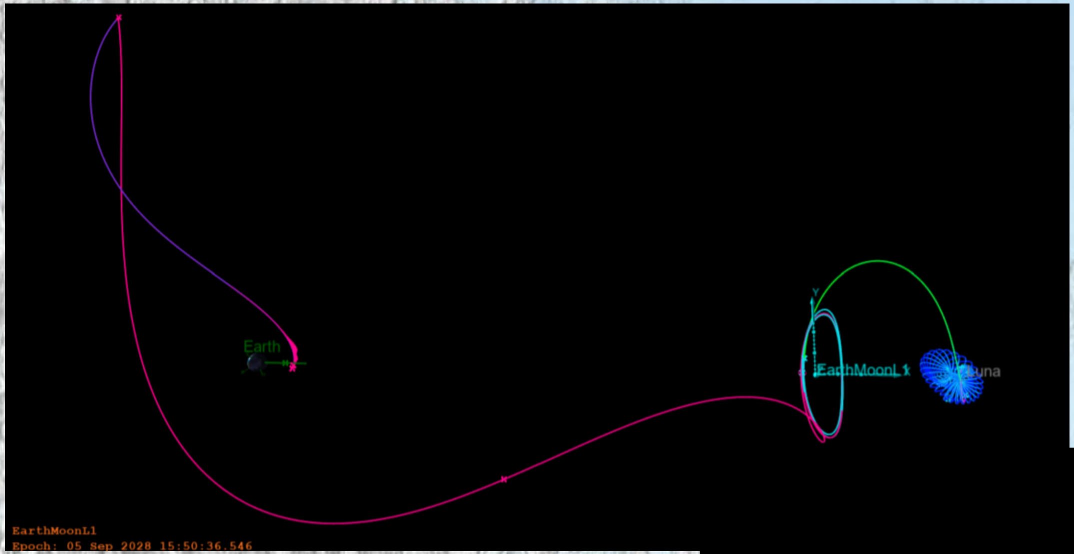
Parameter	Unit	Value
SMA	km	155793
ECC	-	0.9
INC	°	28
RAAN	°	346
AOP	°	237
TA	°	0
MA	°	0
EA	°	0

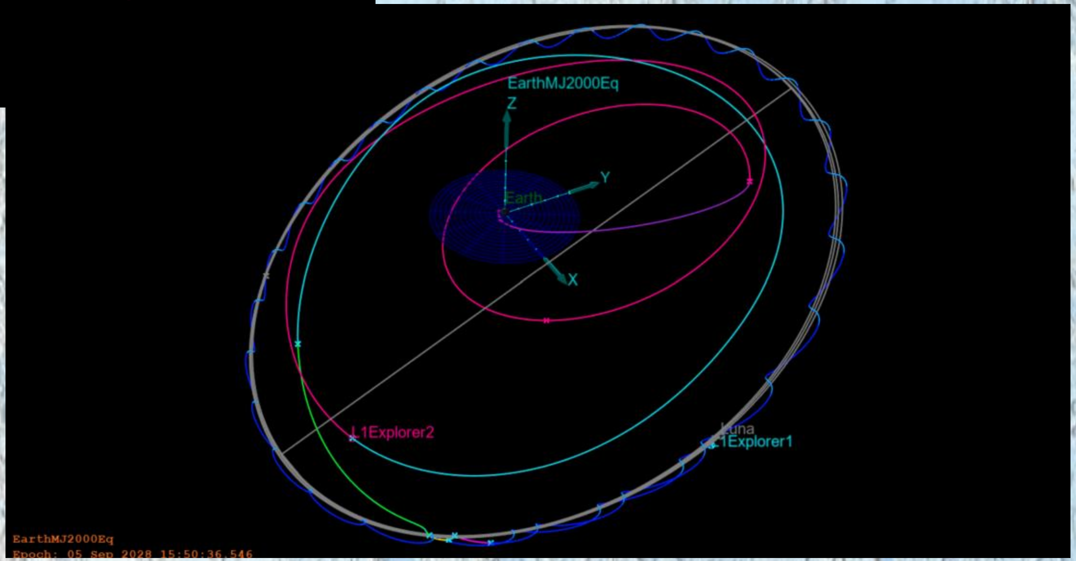
From Halo to Moon: Forward Propagations

- Again, Starting from LPHO IS.
- LPHO station-keeping requires a correction of ΔV in the order of 0.72 m/s at each period (about 12 days). By these corrections L1Explorer2 will stay on the Halo orbit.
- L1Explorer1 is Targeting required Moon capture trajectory (through a capture manifold). The resulting $\Delta\vec{V}$ from this targeting process is 0.168 km/s, $i \approx 85°$.
- A sequence of manoeuvres is then executed to adjust for the final mission orbit.
- Finding: Different inclinations can be achieved from the same starting point on the LPHO with different $\Delta\vec{V}$ only in $\vec{V}$ direction, at the expense of higher periselenium radius.



Final Mission Orbit Insertion and Adjustment

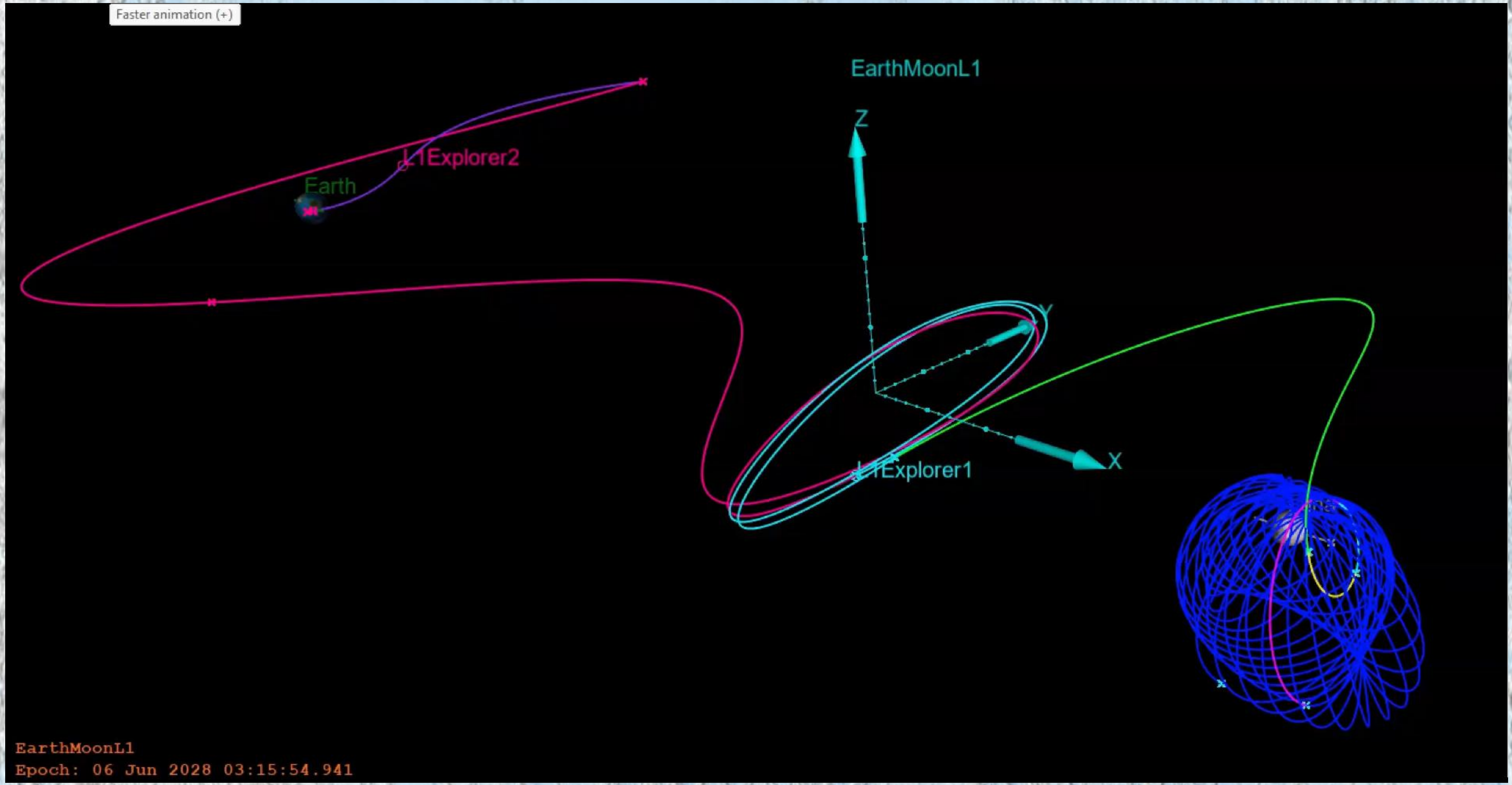




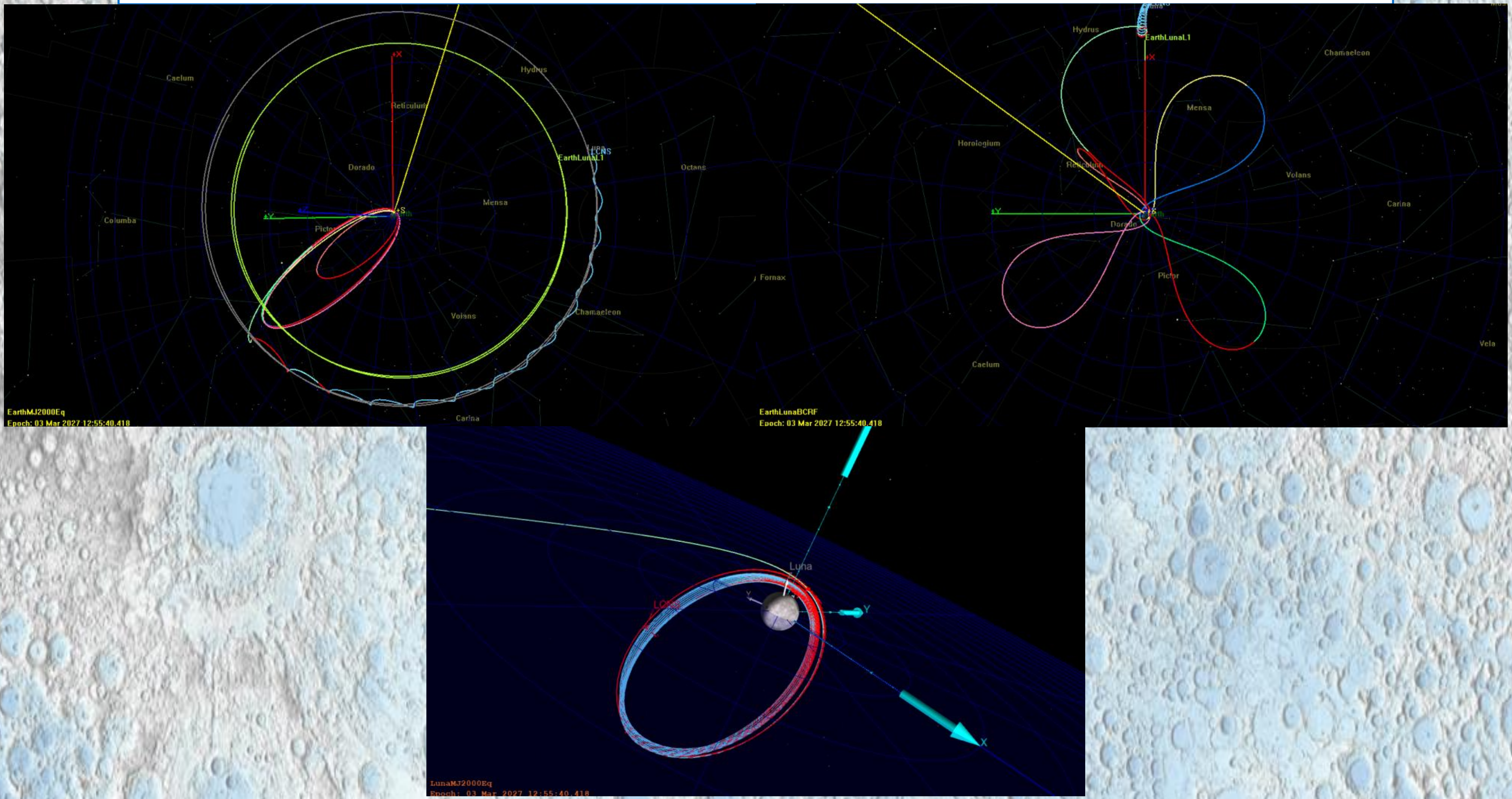
Parameter	Unit	Value
SMA	Km	9748
ECC	-	0.57
INC	°	85
RAAN	°	45
AOP	°	80
TA	°	180
MA	°	180
EA	°	180

Phase	$\Delta V\ \left[\frac{m}{s}\right]$
LPHO Ballistic Capture	258.6
LPHO Orbit Maintenance	0.7242
LPHO to Moon Capture	168.2
Adjusting Eccentricity	401.4
Adjusting SMA	264.1
Maintaining inclination	92.4
TOTAL	**1185.4**

Final Mission Orbit Insertion and Adjustment



Moon Direct Transfer (Previous Study)

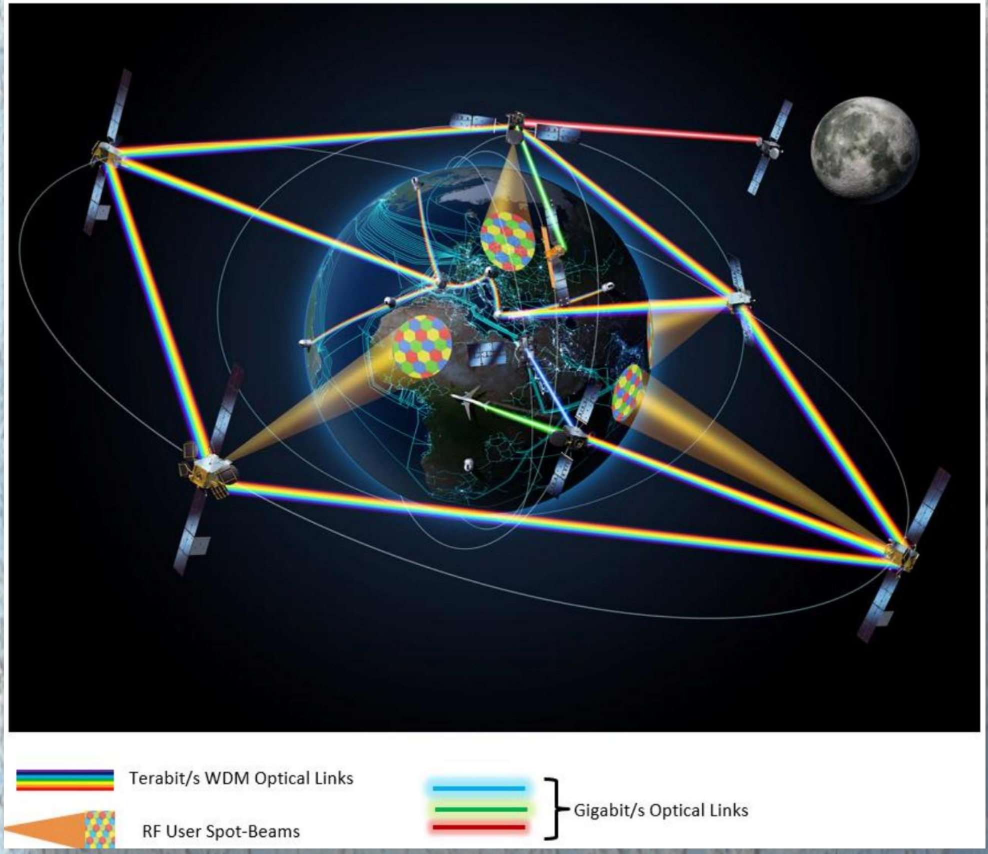


Internship Research Period in Telespazio (6 Months)

HydRON Project

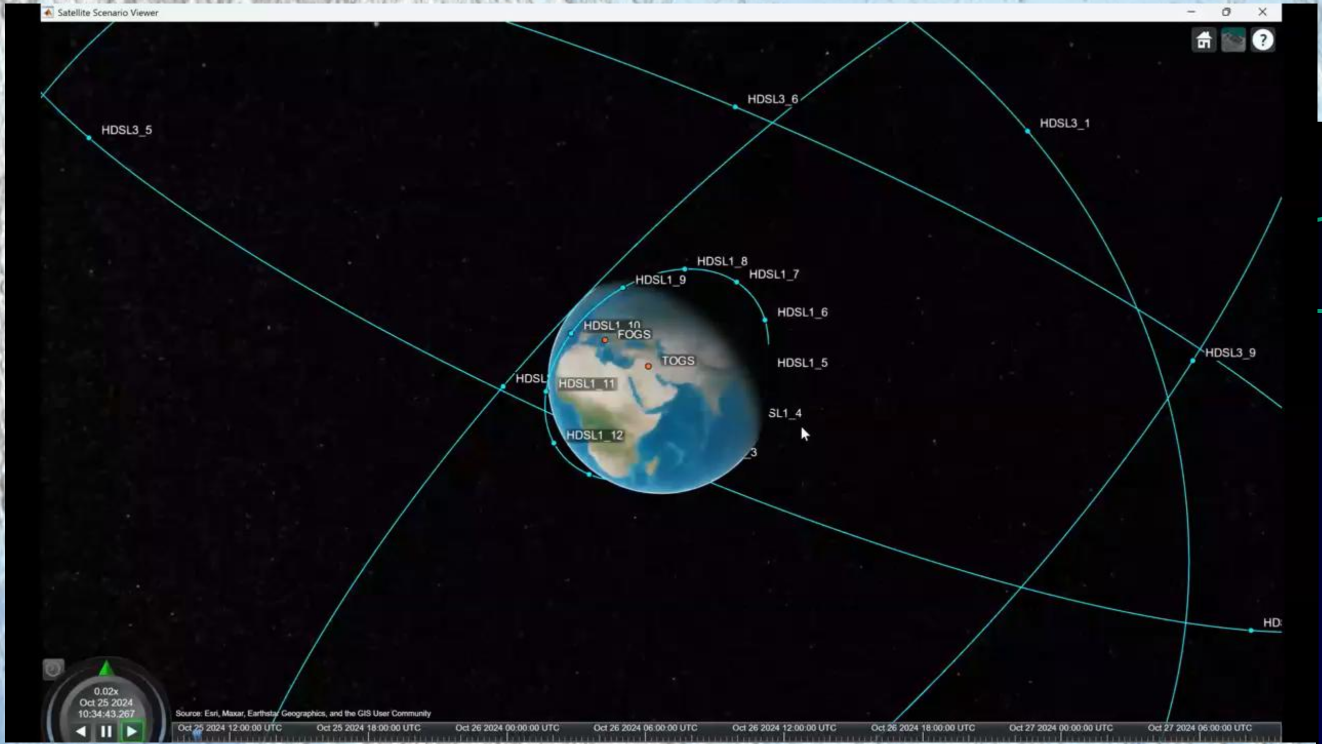
hydron TELESPAZIO a LEONARDO and THALES company

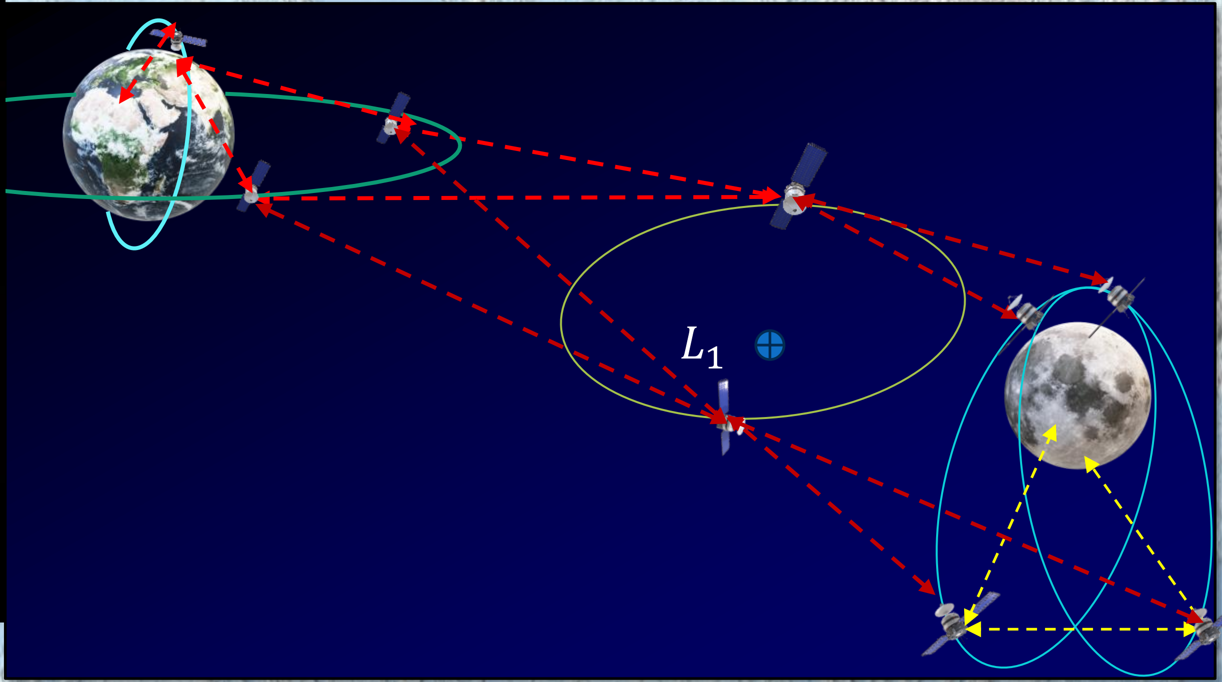
- Stands for "High ThRoughput Optical Network".
- Aims to achieve a "Fiber in the Sky" network via a Tera bit per second (Tbps) all-optical transport Earth Orbit Satellite Networks (EOSN) in space and its integration into the terrestrial high capacity fiberbased network infrastructure.
- It is an Innovative Technology Demonstrator Project aims to master All-Optical Satellite Communication.
- All-Optical Satellite Nodes (GEO/NON-GEO) can produce extremely high data throughput.
- Space Laser Networks, featuring Terabit (>>100 Gbit/s) link capabilities and enabling optical rerouting/switching of data streams can perform likewise standard fibre concepts commonly applied in terrestrial systems.
- The impact of atmospheric conditions can be reduced by making use of the HydRON network capabilities to re-distribute data in-orbit.
- A new Network Concepts with a dedicated focus on the space segment and its specific operational constraints.



Internship Research Period in Telespazio (6 Months)

HydRON Concept and Moon HSC





Internship Research Period in Telespazio (6 Months)

HydRON Orbit Determination Case Study

hydron TELESPAZIO
a LEONARDO and THALES company

hydron

E2E Precise Orbit Determination (POD) Case Study for HydRON Demonstrator Element #2

for ESA ScyLight Project

Alee K. Obeid
PH.D. CANDIDATE | GRAN SASSO SCIENCE INSTITUTE

ACADEMIC SUPERVISORS
PROF. PAOLO TEOFILATTO PROF. ROBERTO ALOISIO

TECHNICAL ADVISORS AND TUTORS FROM TELESPAZIO
DR. PAOLILLO FABRIZIO ALESSANDRO BREDA MAZZEO STEFANIA

and DSS 54 [Ref.]. The orbital configuration of HydRON demonstrator is shown in Figure (9.1).[5]

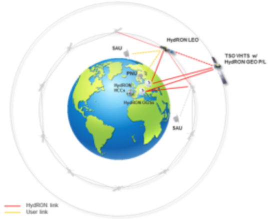


Figure 9.1 HydRON Demostrator orbital configuration. [5]

9.1 HDSE2 Simulated Orbit and Corresponding Ephemeris

HDSE2 orbit is simulated using STK 2-Body model to provide ephemeris data structured with time. The orbit is propagated for 10 days starting from 10th of March 2025. This data is used as an input to ODTK Simulator tool to be processed and prepared to act as real measurements after applying a variety of errors, biases, noises and uncertainties to look like real measurements which are already available in ODTK. Figure (9.2) shows the

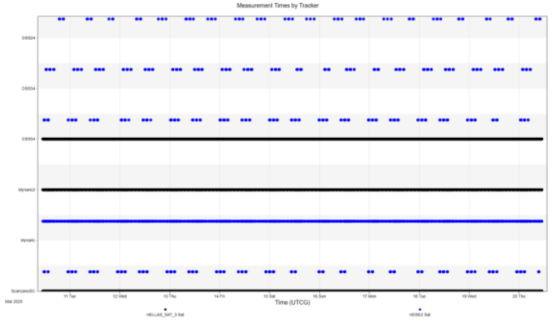


Figure 9.2 Access between the observing GS's and the 2 satellites (HDSE2, and HELLAS Sat).

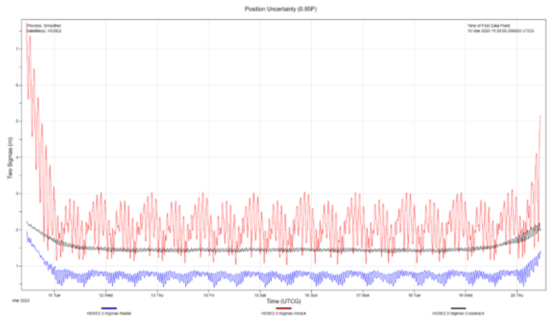


Figure 9.5 HDSE2 Position Uncertainty after applying ODTK Smoother.

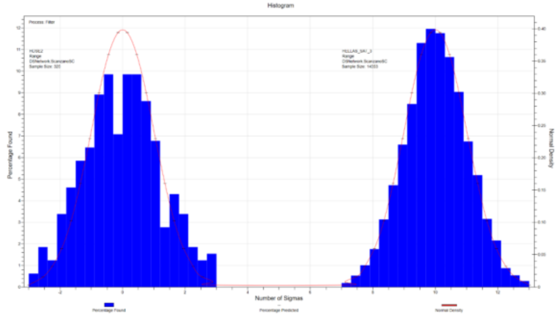


Figure 9.6 Histogram plot for smoothing Range residuals for HDSE2 and HELLASSAT3 taken in Scanzano GS.

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76th International Astronautical Congress (IAC), Sydney, Australia, 29 September - 3 October 2025.

Participation/ Paper Publication

IAC-25-C1.9.7.x102325

Optimal Analytical Solution for the Single-Launch Deployment of Lunar Constellations Based on the CR3BP

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Abstract

In recent years there has been an increasing number of missions involving the transfer and deployment of spacecraft into lunar orbit and on the lunar surface. Many of these missions rely on the use of autonomous probes, landers and rovers and are developed by national entities. In parallel, programs developed by national agencies, including NASA's Artemis, are preparing for the return of human lunar exploration missions. Both autonomous and human missions have highlighted the need for lunar navigation and telecommunications systems, whose development cannot ignore an efficient mechanism for deploying the satellites into different lunar orbits. This research proposes a method to deploy, from a single launch opportunity, multiple satellites on two different types of orbits useful for lunar navigation and telecommunications systems: (i) libration point orbits in the surrounding of the intermediate Lagrange point L1, in which satellites act as relay for Earth-Moon communications, and (ii) lunar capture orbits, whose orbital elements can be selected to meet the performance requirements of the specific lunar constellation. The method at hand is based on analytic solutions of the circular restricted 3-body problem, applicable to different regions of the phase space. In particular, the analytic solutions corresponding to higher order expansion of the Hamiltonian function are used as a tool to design Earth-Moon trajectories going through a periodic unstable orbit. The method, based on analytical results, is verified using the high-fidelity propagator of the General Mission Analysis Tool by NASA, proving the effectiveness of the solution proposed.

CEAS/AIDAA 2025 Conference
1-4th of December 2025, Turin, Italy.
Participation/ Paper Publication

Another paper was accepted in the incoming CEAS/AIDAA 2025 Conference under the tilte:

"Low energy Lunar Missions based on the Locus of Lyapunov Orbits"

The following submission has been created.

Track Name: Mission Design and Space Systems

Paper ID: 120

Paper Title: Low energy lunar missions based on the Locus of Lyapunov orbits

Abstract:
Periodic orbits at collinear equilibrium points in the restricted three-body problem are of interest for practical applications, particularly three-dimensional periodic orbits. The first mission to fly around the Sun-Earth intermediate equilibrium point was the ISEE-3 mission. Years later, the SOHO mission was centred on the same point.
These periodic solutions are unstable and the invariant manifolds of states approaching or departing from the periodic orbit are useful in mission design.
For example, the Genesis mission's transfer to the L1 halo orbit was designed using invariant manifold theory, and the SMART mission used the lunar L1 point to transition into a capture orbit around the Moon.
Similar techniques have been used to design connections between trajectories emanating from unstable periodic orbits around the L1 and L2 Earth-Moon Lagrange points.
Ideally, these connections would be travelled at zero propellant cost, which implies the possibility of performing a variety of complex Earth-Moon missions by combining different types of trajectory arc belonging to the manifolds, at the cost of modest overall propellant consumption.
The dynamics of manifold around periodic unstable orbits can also be used to define a suitable end-of-life strategy for lunar
trajectory that never approaches Earth or the Moon can be achieved by reaching the instable manifold that emanates from the pe
The forthcoming Moonlight mission will use the manifolds around periodic orbits at L1 to deploy a constellation of satellites
Deploying a lunar constellation seems to offer definite advantages in reducing the number of dedicated launches by making use
solutions around L1.
Many studies have been conducted on the existence and numerical determination of three-dimensional periodic orbits around unst
Some approaches are entirely numerical and provide a description and computation of the orbits around the neighbourhood of the
planar and vertical families of Lyapunov periodic orbits, three-dimensional quasi-periodic orbits, and halo and quasi-halo orb
numerical refinements of the initial estimates provided by analytical methods such as the Lindstedt-Poincaré expansion, averag
analytical methods rely on higher-order solutions since the linearised theory around the Lagrangian points has solutions with
of-plane motion.

Conclusions

- Low energy lunar transfer is chased passing through the unstable L1 region.
- An LPHO is considered here as a station orbit for a mission of multiple satellites to the cislunar space.
- An analytic method is used to generate periodic three-dimensional, planar and vertical Lyapunov, orbits.
- These analytic solutions provide good guesses for a high-fidelity propagator (GMAT).

YOUR ATTENTION WAS APPRECIATED..