Evolution Of Astrodynamics For Multibody Environments, Numerical Precision And Dynamical Understanding

AAS/AIAA Astrodynamics Specialist Conference, Big Sky, Montana, August 13-17, 2023

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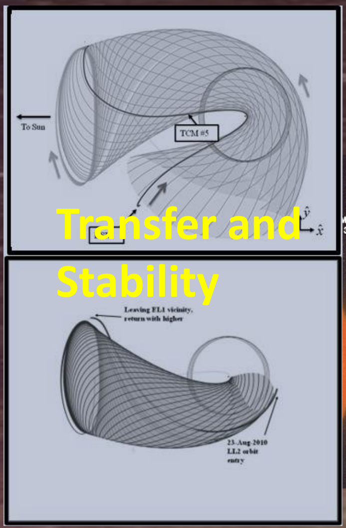
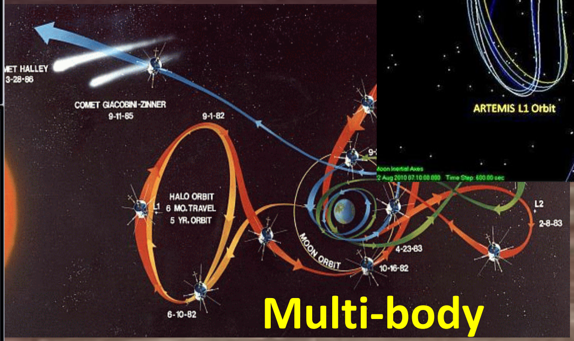
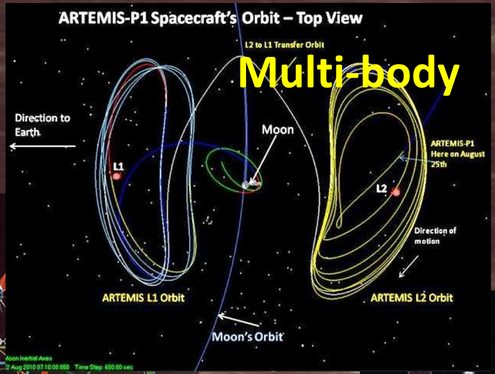
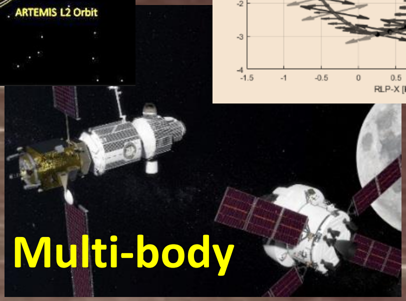
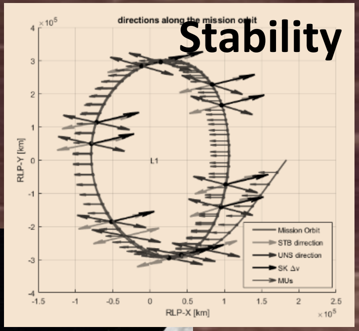










Presentation Synopsis

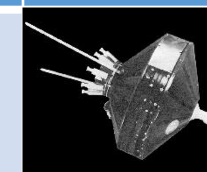
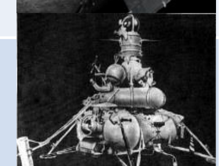
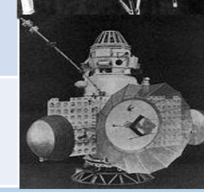
- Overview of 50 years of astrodynamics evolution applied to lunar, cislunar, and libration orbit missions
- Evaluate background of the trajectory formulation of early missions and the ensuing astrodynamics expansion which followed
- Discuss improvements
  - From a reliance on basic numerical and analytical modeling and targeting techniques to applications of dynamical systems and optimal formulations
  - Thoughts on recent designs of future missions hoping it will spark invention, regardless of how fanciful
- Thank the many astrodynamicsts at NASA, universities, commercial partners, and international collaborators who strived to discover innovative methods to not only achieve lunar missions, but to provide access to distinctive orbits about the moon and in its neighboring environment

Pre-Apollo Missions

- Let's start with the early lunar mission of the 1950-60s
- Out of the first 27 lunar missions, only three where successful!
- What was the level of fidelity of the simulations and the environmental models for trajectory design and operations?
- Design example: The Ranger-7 mission had very precise targets and objectives
  - Encountered the lunar surface in direct motion along a hyperbolic trajectory, with an incoming asymptotic direction at an angle of -5.57 degrees from the lunar equator.
  - The orbit plane was inclined 26.84 degrees to the lunar equator. After 68.6 hours of flight, Impacted in an area between Mare Nubium and Oceanus Procellarum at 10.6 S latitude, 339.3 E longitude.
  - Impact occurred at 13:25:48.82 UT at a velocity of 2.62 km/s.
  - Total research, development, launch, and support costs for the Ranger series of spacecraft (Rangers 1 through 9) was approximately $170 million.

Ref: Goddard, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1964-041A

Pre-Apollo Missions

Dates	Mission	Details	Photos
1958-1959	Pioneer, Luna NASA, SPP	After seven failures, Pioneer and Luna missions provided photographs the Moon during flyby. Luna-3 developed film and transmitted the images of lunar far side back to Earth	
1965-1969	Ranger, NASA	Six s/c series of spacecraft launched in the 1960s to explore the Moon. Designed to take images as it descended to the lunar surface for impact	
1965-1969	Surveyor NASA	Five successful Surveyors returned >87,000 photos of the lunar surface and operated for about 17 months total on the lunar surface, demonstrated the feasibility of soft-landing a spacecraft on the lunar surface.	
1960-1969	Lunar Orbiter, NASA	Designed primarily to photograph smooth areas of the lunar surface for selection of safe landing sites for the Apollo missions. LO-1 was the first U.S. spacecraft to orbit the Moon, 186 km x 1866 km	
1960-1974	Luna, SPP	Designed to take the first photographs of the surface of the Moon from lunar orbit and to obtain data on gravitational anomalies on the Moon. Fifteen successful, each designed as either an orbiter or lander. Studied Moon's composition, gravity, temperature, and radiation	
1960s	ZOND, SPP	Series of circumlunar spacecraft designed to rehearse a piloted circumlunar flight. initiated in 1965	

Ref: https://moon.nasa.gov/exploration/moon-missions/

* SPP: Soviet Space Program, Prior to Roscosmos

Sample Lunar Trajectory

- Surveyor III launched on April 17, 1967 at Cape Kennedy with the Atlas/Centaur AC-12 vehicle
- Centaur first burn injected the spacecraft into a temporary parking orbit with an altitude close to the nominal 167 km. After a 22-min coast period, the Centaur was reignited and injected the spacecraft into a very accurate lunar transfer trajectory
- The uncorrected lunar impact point was approximately 466 km from the prelaunch target point

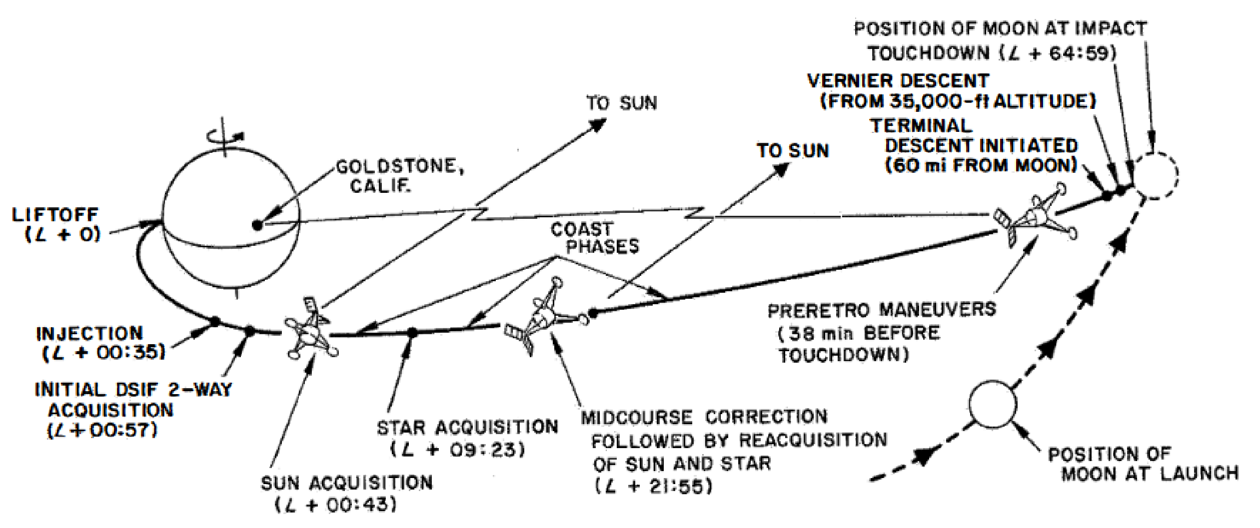


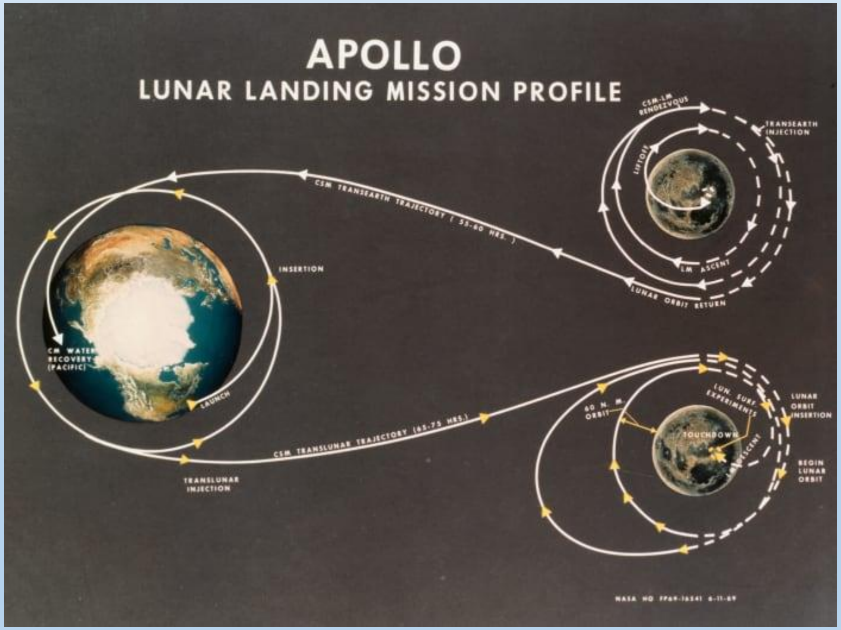
Fig. I-1. Earth-moon trajectory and major events

4 JPL TECHNICAL REPORT 32-1177

Ref: NASA Technical Report 32-1177 Surveyor III Mission Report Part I. Mission Description and Performance

Apollo Mission Transfer Trajectory

- Design based on “Hohmann-like” transfer method
- One revolution in Parking orbit before Translunar Injection
- Injection on a direct transfer to encounter lunar gravity well
- Included an Earth orbit midcourse transfer maneuver
- Capture into an elliptical orbit of ~111km x ~314 km
- A 100 km circular orbit (inclination ~ 32.5deg) with lower periapsis of ~ 18 km for the descent profile
- Descent to Landing
- Ascent profile to command module ~ 100 km orbit
- Departure to Earth
- Direct entry into atmosphere



Ref: Navigation Technical History with Lessons Learned, Mission Operations Directorate, Flight Design and Dynamics Division, Basic, April 2007, NASA, JSC

Examples of Simulation and Modeling Progress

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- Trajectory design and maneuver model resolution increased, and computer power improved, but most modeling and integration types are very similar
- Based on Apollo and NASA Libration, cislunar, and lunar missions

	Apollo Era *	1980-90 Operations (GSFC Ref for Libration and flybys)	Current Operations (GSFC ref Lib, cislunar, flybys, lunar orbiters)
Coordinate frame	Mean Celestial Eq and Vernal Equinox, IMU, LVLH,	Inertial, Rotating, Fixed, IMU, LVLH, VBN,	Inertial, Rotating, Fixed, IMU, LVLH, VBN, Body, numerous, others
Perturbations	Simplified Earth model, third body (Sun, Moon, Earth),	Earth, Moon, Point mass third body (all planets and sun), Solar radiation pressure	Earth, Moon, Point mass third body, Solar radiation Pressure flat plate and coefficients, tides
Integration	Encke and Cowell (need more here)	Cowell 12th Adams Bashforth Predictor Corrector, fixed step and Time regularized	Many RKN, RKV, Cowell, ref to GMAT and commercial s/w for examples
Atmospheric	Drag models	Drag models based on Harris Priester	Drag Models, HP, J70, MSIS, etc.

IMU = Inertial Measurement Unit, LVLH = Local Vertical Local Horizontal, VBN = Velocity Bi-normal Normal, HP = Harris Priester, J70 = Jacchia-70, MSIS = Mass Spectrometer - Incoherent Scatter

* Ref: Navigation Technical History with Lessons Learned, Mission Operations Directorate, Flight Design and Dynamics Division, Basic, April 2007, NASA, JSC

Examples of Simulation and Modeling Progress

- Trajectory design and maneuver model resolution increased and computer power improved, but most modeling and integration types are very similar still today
- Based on Apollo and NASA Libration, cislunar, and lunar missions

	Apollo Era *	1980-90 Operations (GSFC Ref for Libration and flybys)	Current Operations (GSFC ref Lib, cislunar, flybys, lunar orbiters)
Lunar Gravity Models	4x2 (based on early missions)	20x20 (Bills and Ferrari)	>150x150 based on LP, LRO, Grail
Maneuvers	Impulsive and Finite, some attitude profiles	Attitude dependent frames for Impulsive and Finite	Attitude dependent frames for Impulsive and Finite
Computer Systems	Mainframes and simplified calculators	Mainframe IBM 360-90 and 360-75, Phase over to PC in early 90's. Start of visualization	Laptops, Servers, Unix, PC, Multi-core systems, High end 3-D Visualization
Analytical	Needed for speed, lambert targeting	Speed not required for mission types, Differential Correctors and Optimization (e.g. Steepest descent)	Increase CPU capabilities, e.g. GPU, Differential Correctors, Collocation, Optimization (multiple methods, e.g. SNOPT)

* Ref: Navigation Technical History with Lessons Learned, Mission Operations Directorate, Flight Design and Dynamics Division, Basic, April 2007, NASA, JSC

Influence Of Multi-Body Dynamics

- No lunar missions were launched in the 1980s
- Lunar Exploration ended with the last of the Apollo and Luna missions, the next program was the Space Shuttle / Hubble and planetary missions
  - The last lunar missions being Apollo 17 (‘74), Luna 21 (Lunokhod 2 (rover)), 22-24 (‘76) and Luna 24 delivering a sample to Earth on August 23, 1976
- Improvements in cislunar designs and astrodynamics advancement
  - The ISEE-3 / ICE (Farquhar) mission began the improvement with first Sun-Earth libration orbiter that demonstrated multi-body dynamics and realism of circular restricted three body approach
  - Multiple lunar flybys and cislunar design
  - Comet intercept of Giacobini-Zinner in 1985
  - ISEE-3 / ICE returned to Earth in 2014, with a flyby after a completed heliocentric transfer

Influence Of Multi-Body Dynamics

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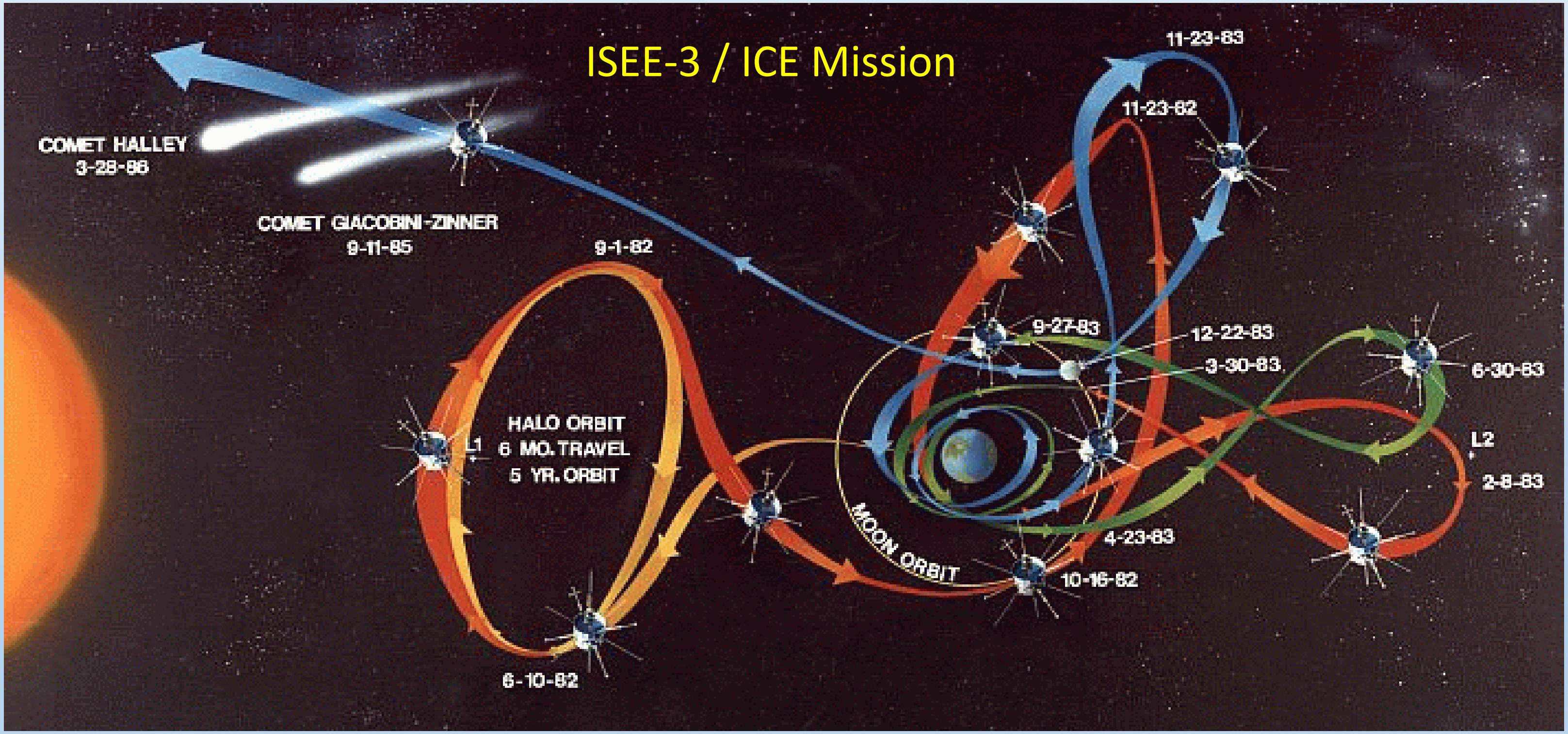
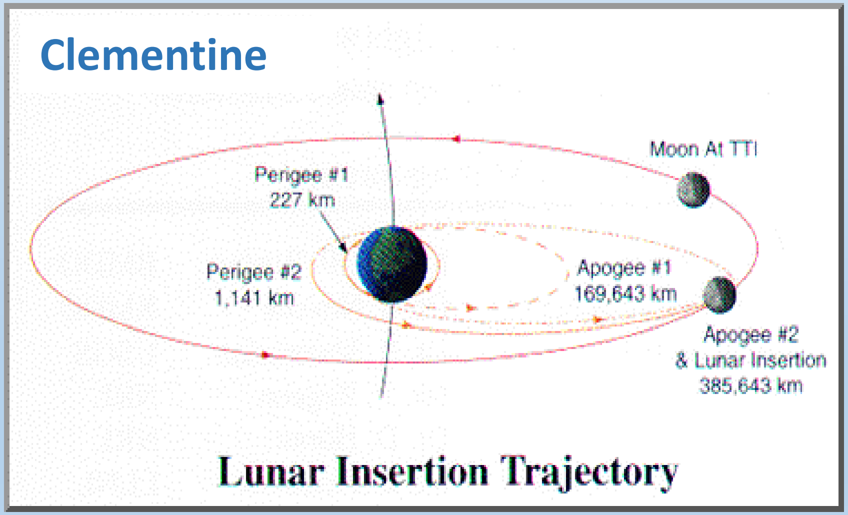
- Mathematical approaches and applications of CRTB and its expansions
- Research from Archie Roy, Victor Szebehely, Roger Broucke, David Dunham, and Bob Farquhar, Carlos Simo, Josep Masdemont, Gerard Gomez, Angel Jorba, Jerry Marsden, John Blackwell, Kathleen Howell, Martin Lo, Jim Miller, Edward Belbruno, Dan Scheeres, and many others that continued dynamical systems research



Credit: NASA /GSFC 1985 publications, also http://heasarc.gsfc.nasa.gov/Images/misc_missions/isee3_traj.gif

Restart of Lunar Exploration

- During the timeframe from Apollo to today, a principal transfer uses direct or increasing apoapsis orbits which permit a direct lunar insertion or flyby
  - The advantage of this Hohmann-like design permit rapid transfer and longer launch opportunities
- Increasing concentric elliptical orbits were used by several missions after launch, use of the Oberth effect permits increased efficiency and allows the benefits of lunar encounter timing and perturbations



Credit: NASA /GSFC, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1994-004A

Restart of Lunar Exploration

- Lunar missions in the 1990s lead to the discovery of water presence
  - **Clementine Mission (1994),** Joint mission with Ballistic Missile Defense Organization (BMDO) and NASA
    - Lunar orbit of 430 km x 2950 km in 1994, Transferred to trajectory for asteroid encounter Geographos
    - Obtaining multi-spectral imaging of the entire lunar surface, assessing the surface mineralogy of the Moon, obtaining altimetry from +/- 60 deg latitude and obtaining gravity data for the near side
  - **Lunar Prospector mission (1997**), NASA's first long duration low circular polar orbit of 100 km, Achieve orbit of ~15 km x ~40 km, and discovered frozen lunar orbit conditions Controlled impact at end of mission
    - Increased gravity model degree and order, LP inserted into orbit with a 20 x 20 deg and order Bills and Ferrari (*A Harmonic Analysis of Lunar Gravity, 1980*)
    - Six months later a 100 deg and order gravity model based on Doppler measurements (ref: Alex Konopliv / JPL and Frank Lemoine / GSFC)
    - Previous (1963) Research on the Interaction of Perturbations the permit lunar frozen orbits. Lidov, M.L., (1963), Ely and Lieb (2005), Ramanan and V. Adimurthy (2005), Park S.Y. and Junkins (1995), Elipe and Lara, (2003), Folta and Quinn (1998, 1999 (post LP mission results))

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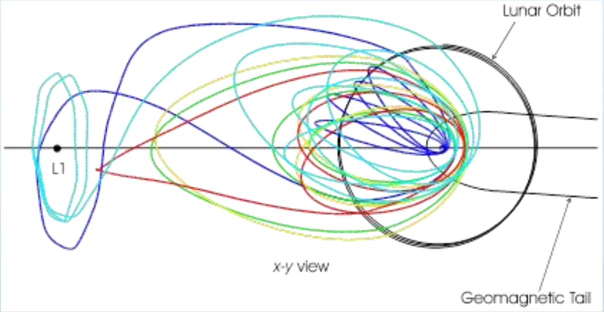
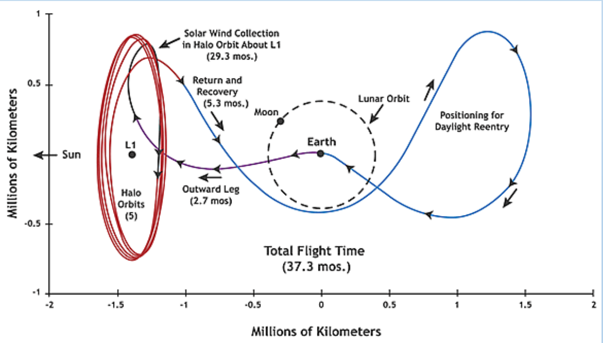
Restart of Lunar Exploration

- The 1990's provided continued improvements and mission applications for multibody dynamics and a return to the moon
- Demonstrated new methods to reach the moon and to design cislunar missions, Improve the operational accuracies and navigation requirements
- **Hiten** (1990) first use of a ballistic transfer with s/c in elliptical Earth orbit and flybys. Placed into lunar orbit
- **WIND** (1994) and **Geotail** missions did not enter lunar orbit but used lunar gravitational assist to attain their respective cislunar and Sun-Earth libration mission orbits.
- **Genesis** (2001) demonstrated the interactions of the dynamical regions for transfer to Earth entry

WIND



GENESIS



Ref: NASA/GSFC, Folta

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Two Decades of Lunar Exploration

Mission	Year	Agency	Comment
SMART-1	2003	ESA	Low thrust spiral to moon, multi body effects
SELENE	2007	JAXA	Low lunar circular orbit of 100 km
Chang'e 1	2007	CNSA	Low Lunar circular orbit of 200 km
Chandrayann	2008	ISRO	Low Lunar polar circular orbit of 200 km
LRO (LCROSS)	2009	NASA	Lunar Mapping mission, now in Frozen polar orbit, LCROSS Impactor
Chang'e 2	2010	CNSA	Low Lunar Orbit, Transfer to Sun-Earth L2 orbit, and then to Asteroid
ARTEMIS / Themis (2 s/c)	2010	NASA	First Low energy transfer to Earth-Moon L1 & L2 Orbits, heteroclinc transfer from EML2 to EML1, transfer into elliptical lunar orbits (Still active)
GRAIL (2 s/c)	2011	NASA	Low energy transfer, Measured high-quality gravitational field mapping to determine its internal structure, 25 km x 86 km orbit
LADEE	2013	NASA	Lunar laser communications demo experiment (LLCD), ~25 x ~60 km orbit
Chang'e 3 (Yutu)	2013	CNSA	Low Lunar Orbit, Lander and rover, first since Luna in 1976
Chang'e 4 (Yutu)	2018	CNSA	Lander and EM L2 Relay with back side of moon lander and rover, Yutu
Beresheet	2019	Israel	Lunar Landing attempt
Chandrayann -2	2019	ISRO	Low Lunar Orbiter, Lander, Rover
Artemis	2022	NASA	Orion S/C, lunar flyby, DRO, Earth Return
Capstone	2022	NASA	NRHO with ballistic Transfer
Chandrayann -3	2023	ISRO	Low Lunar Orbiter, South Pole Lander, Rover

Ref: https://moon.nasa.gov/exploration/moon-missions/

Multi-body Transport Network Building Blocks

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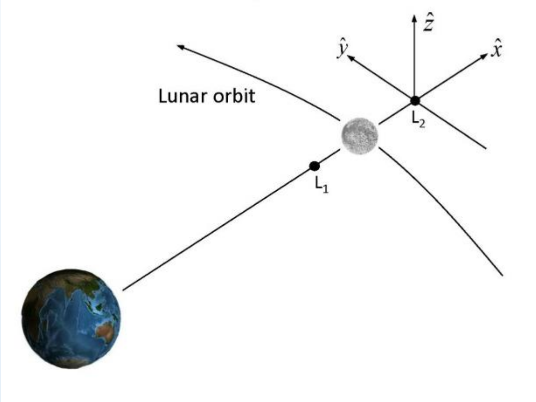
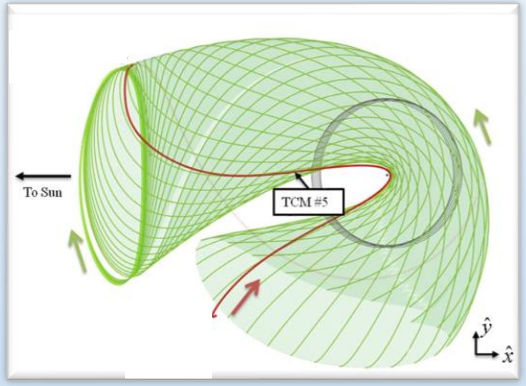
With respect to dynamical systems, in the beginning of this “application period”, we used raw data computation of state transition matrices and their monodromy matrices to determine simple intuitive concepts, e.g., visualizing and defining the stability for such libration point orbits such that the numerical targeting strategy was fully understood from a dynamical perspective.

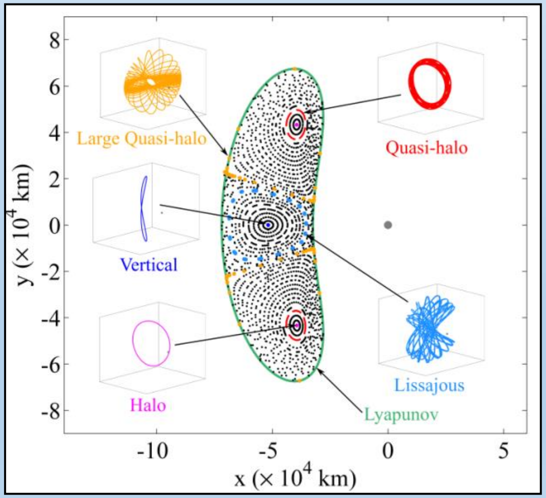
Multi-body Motion



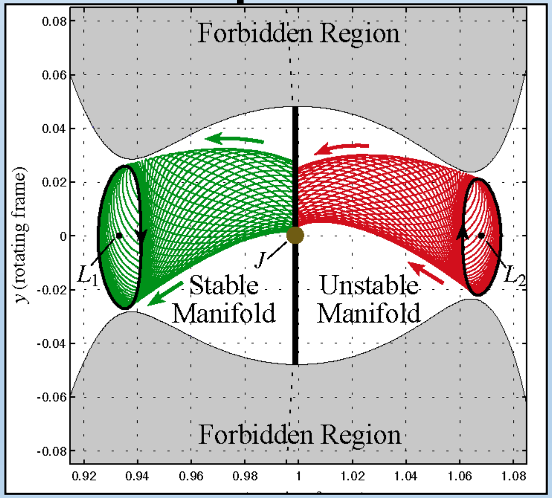
Manifolds



Poincaré Maps



Escape Flow



Credit: Martin Lo (JPL), Kathleen Howell (Purdue)

Circular Restricted Three Body Problem

- Three-body problem: an analytical solution does not exist.
- A ‘rule’ for the evolution in terms of a set of nonlinear differential equations.
  - Deterministic for one particular initial state only one set of future states evolves
- Know particular equilibrium solutions (L_1 and L_2 are equilibrium points, with two centre components,) and we have successfully determined – and learned to compute -- some periodic solutions of which there is an infinite number.
- Hamiltonian structure of the system gives rise to the different families of periodic orbits, yields a monodromy matrix with eigenvalues in reciprocal pairs.
- Approximate solution numerically, linearize to understand the motion around the libration point, yield information on the stable and unstable directions which give rise to the stable and unstable manifolds.

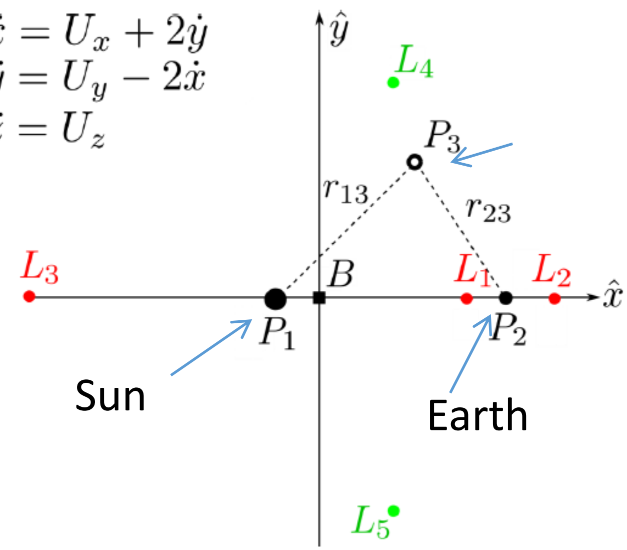
$$\vec{F}_i = -\sum_{j\neq i} G \frac{m_i m_j(\vec{r}_i - \vec{r}_j)}{|\vec{r}_i - \vec{r}_j|^3} - \vec{\nabla}\cdot\phi_{ext}(\vec{r}_i)$$

Equations of Motion and Libration Points

$$U = \frac{1}{2}(x^2+y^2) + \frac{1-\mu}{r_{23}} + \frac{\mu}{r_{13}}$$

$$\mu = \frac{m_2}{m_1+m_2}$$

$$\ddot{x} = U_x + 2\dot{y}$$
$$\ddot{y} = U_y - 2\dot{x}$$
$$\ddot{z} = U_z$$



Planar Circular Restricted Three Body Problem

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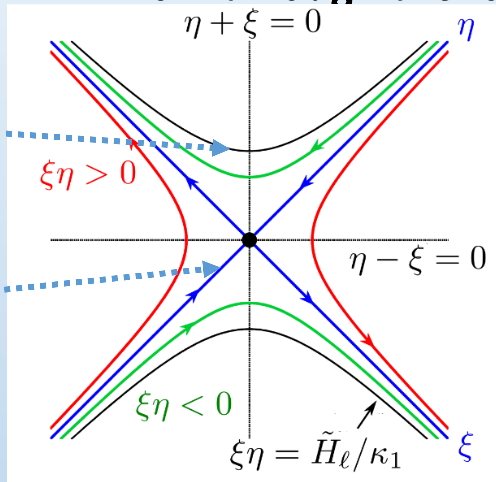
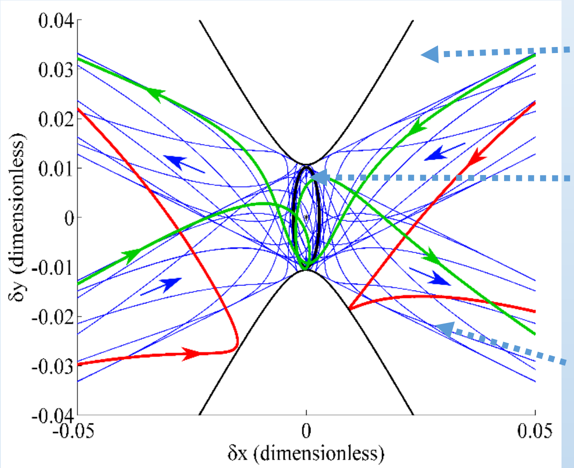
The development of design techniques originated from basic concepts in the vicinity of the equilibrium points in the CR3BP

Flow through the local region near a libration point

bounding zero-velocity curves

stable/unstable manifolds



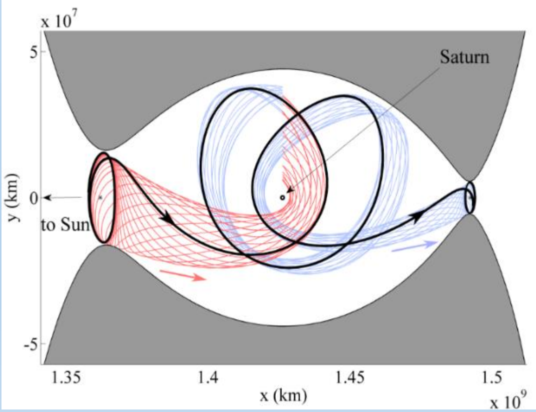


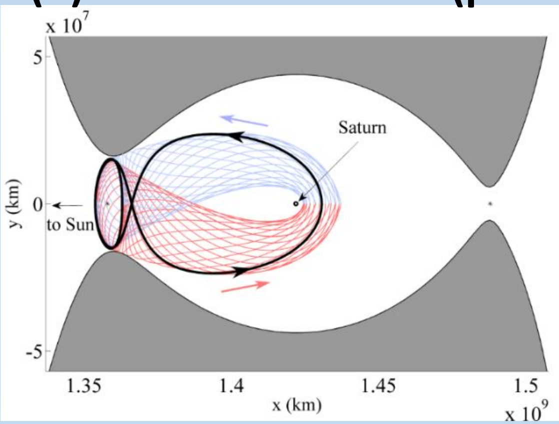
bounding zero-velocity curves

planar periodic orbit

associated stable and unstable manifold trajectories appear in blue

In the CR3BP, sample planar (a) heteroclinic and (b) homoclinic orbits (plotted in black)

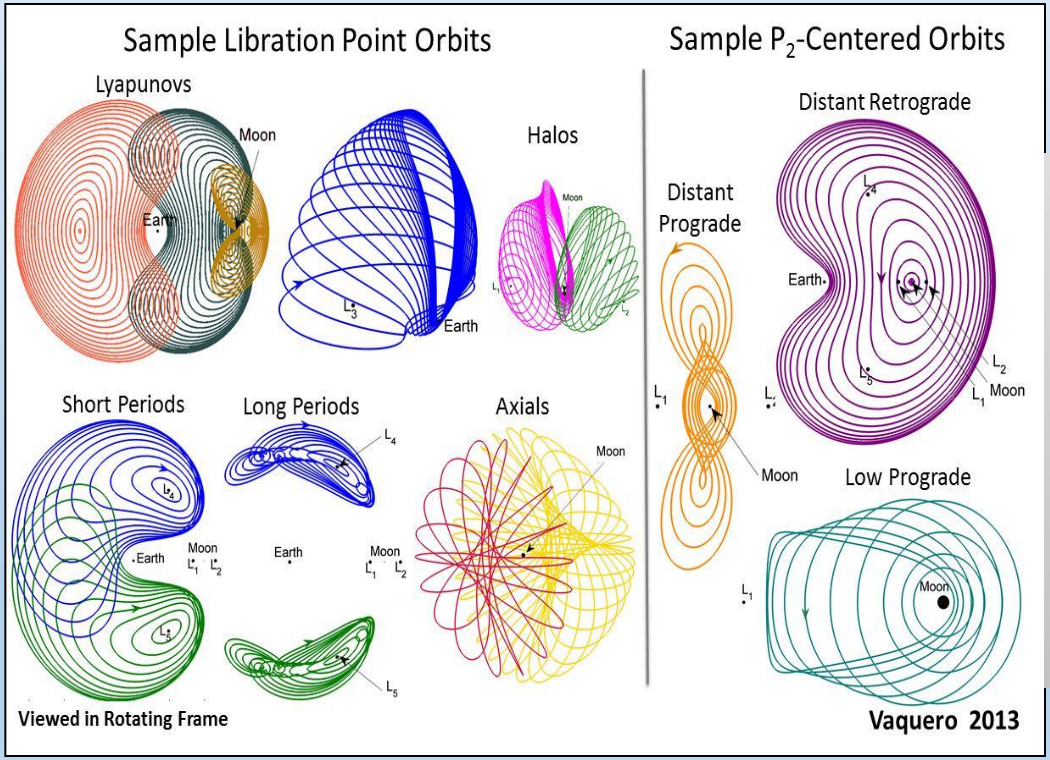




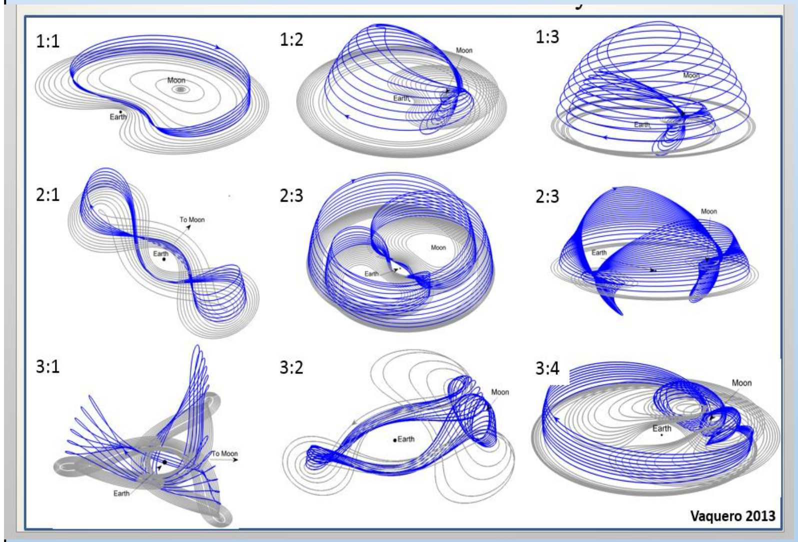
Credit: Kathleen Howell (Purdue)

CRTB and Lunar Orbit Constructs

- What did this dynamical system approach provide in cislunar orbit design?
- CRTB system can be used to define types of orbits available for cislunar mission and to define initial conditions for lunar transfers
- Planar as well as spatial resonant orbits in the CR3BP also appeared during these background development times that continue to deliver viable and beneficial characteristics for mission applications



Earth-moon orbits using dynamical system

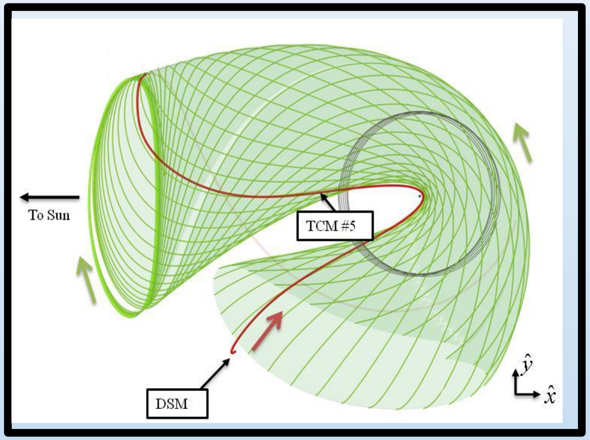


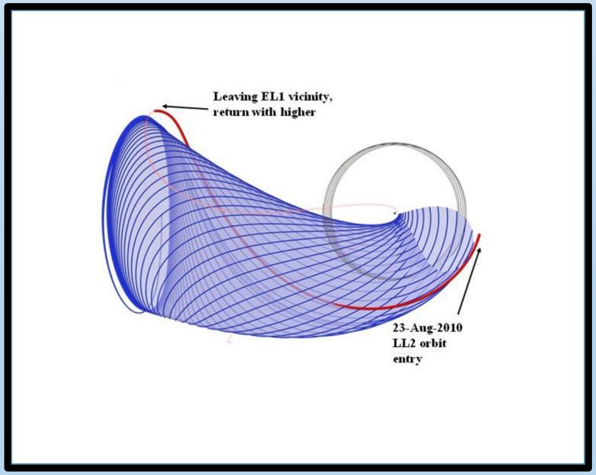
Credit: Mar Vaquero, Kathleen Howell (Purdue)

Multi-body Dynamics Applications

- The next logical step is to determine if the natural flow in the system has some structure
- If the system does not originate (initial conditions) on one of the known particular solutions, is the evolution at all predictable?
- Does the evolution of the states follow some pattern?
- Since the orbits are unstable, there is flow toward and away from these structures (manifolds) and it is the natural place to start to seek understanding of the natural flow of the system
- Natural flows evolve and we continue to learn how they are connected / linked and how they can be exploited for cislunar and lunar missions

Sample Flow towards Libration Orbit





Credit: Howell (Purdue), Folta (GSFC)

Multi-body Dynamics Applications

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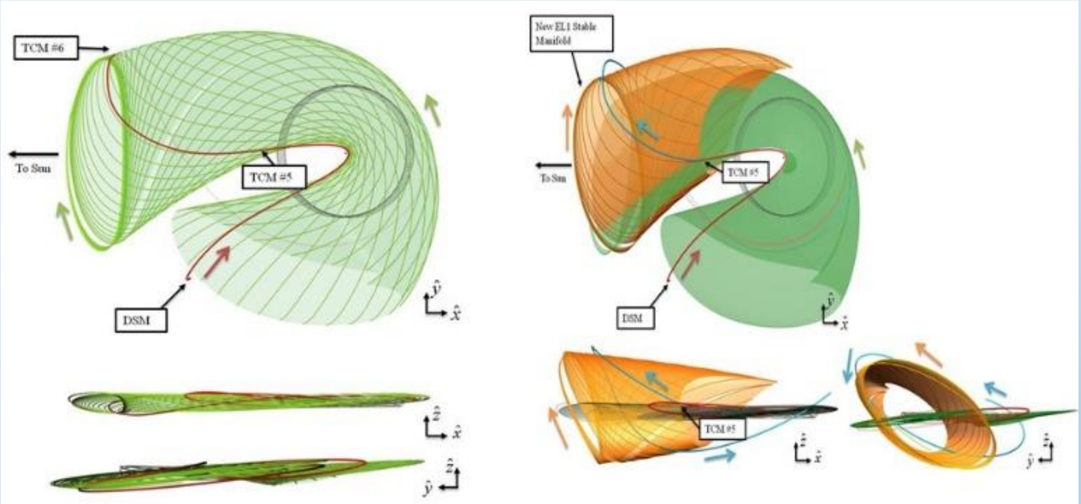
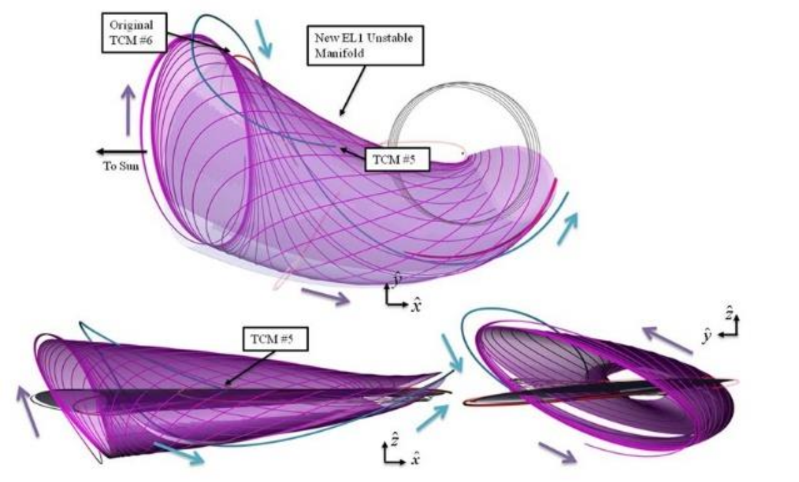
- ARTEMIS-P1 Stable (left) and Unstable (right) Manifolds used to design the Artemis/Themis Transfers
- Based on initial conditions of the post lunar flyby states and general SEL1 manifolds
- Provided guidance and locations for maneuver to 'jump' onto the correct manifold as uncertainties and Earth-moon libration targets were updated



Outbound Segment, post lunar flyby

Inbound Segment, E-M Arrival



Credit: Howell (Purdue), Folta (GSFC)

Applying Multi-body Dynamics

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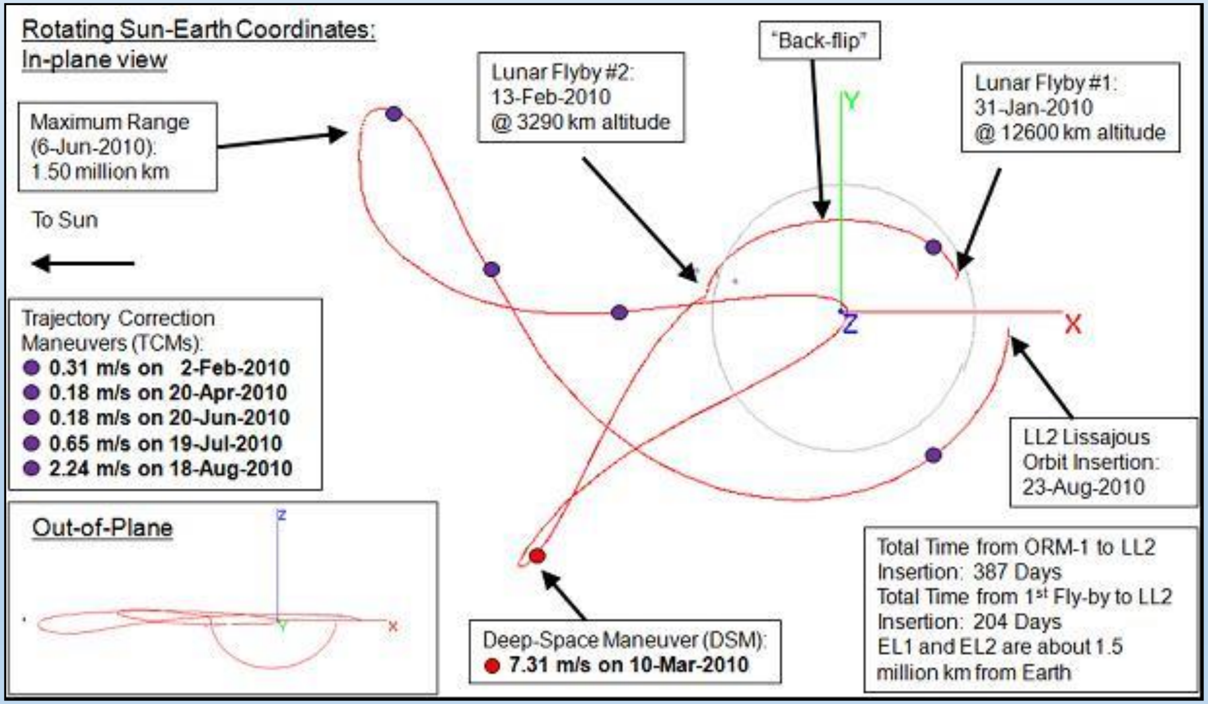
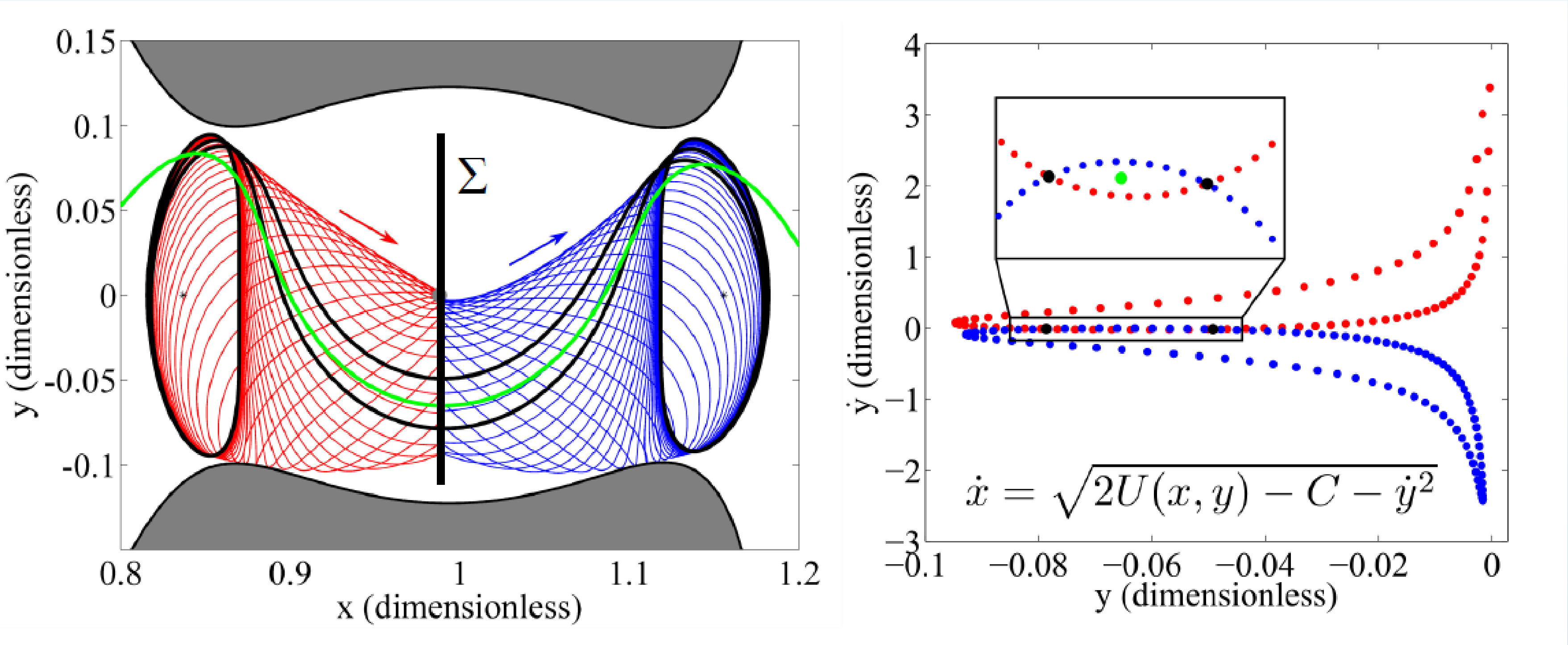
- Applied to the Themis/ Artemis P1 Mission trajectory design to achieve lunar orbit from an Earth elliptical orbit, and to raise periapsis to lunar orbit
- Two lunar gravity assist separated by 13 days for flip of apoapsis direction
- Deterministic Deep Space Maneuver (DSM1) was performed 33 days later
- 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



Credit: Folta, Woodward (GSFC), Sweetser, Broschart, (JPL)

Applying Multi-body Dynamics

Combining Manifolds for Transfer between and within Libration Point Orbits



Technique from W.S. Koon, M. Lo, J.E. Marsden, and S. D Ross, "Heteroclinic Connections Between Periodic Orbits and Resonance Transitions in Celestial Mechanics", Chaos, Vol 10, 2000, pp. 427-469

Applying Multi-body Dynamics

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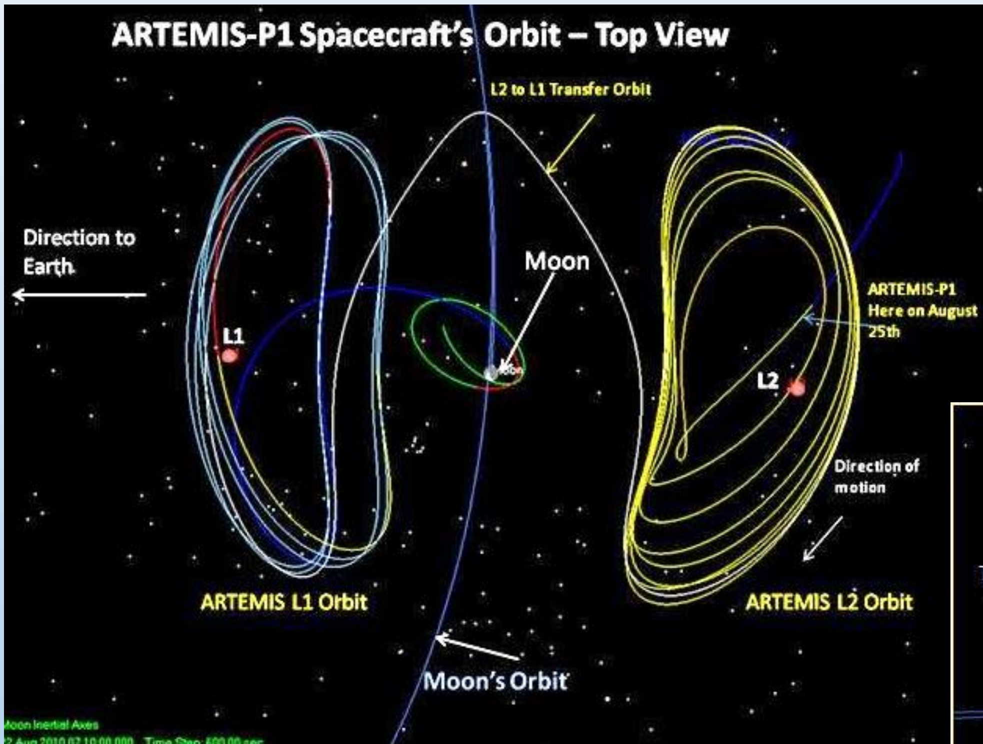
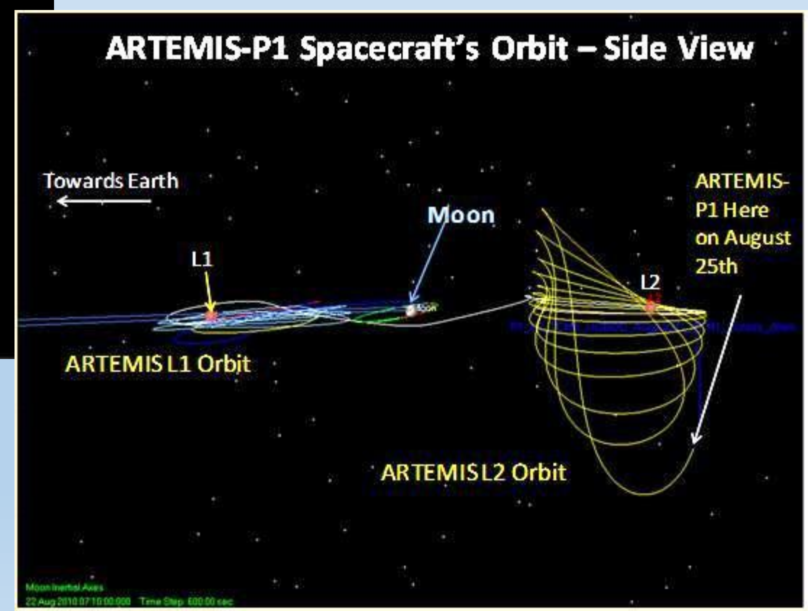
Themis/ Artemis Trajectory, first Earth-moon L1/L2 libration orbiters



Earth-moon Libration Orbit

- P1 captured into EML_2 Orbit
- Transferred to EML_1 Orbit
- Transferred from EML_1 to Lunar Orbit
- P2 s/c entered into EML1 via EML2 and transferred to lunar orbit

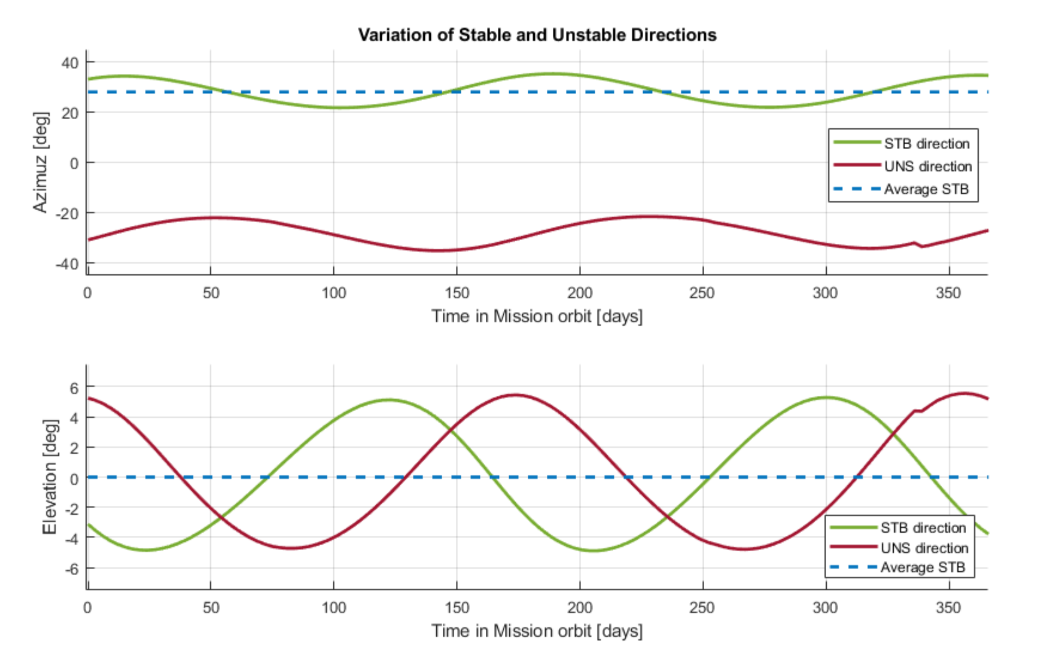


Credit: Folta, Woodward (GSFC), Artemis Mission Design

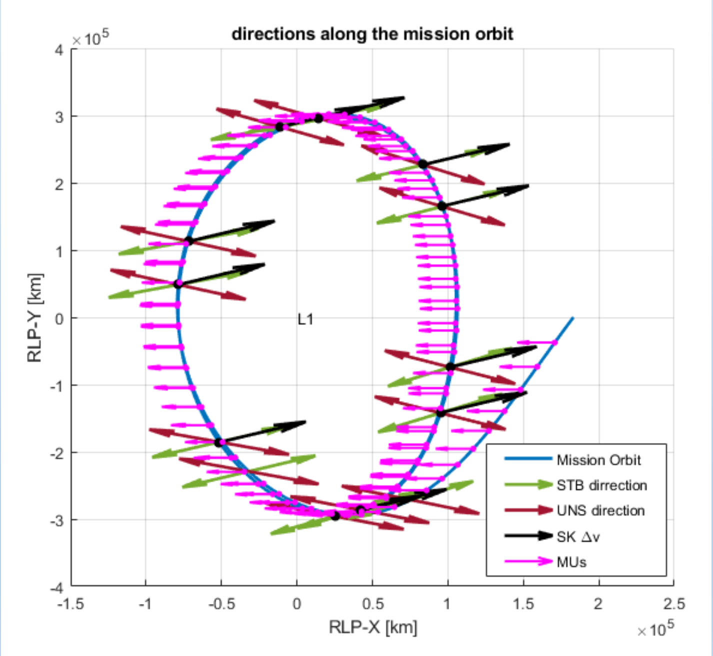
Sun-Earth L1 Applications: Space Weather Follow On-L1

- A SWFO-L1 study was undertaken to explore applied dynamics to determine an improved attitude that simultaneously meets momentum unloads and the Stkp needs
- Started as application of CR3BP dynamics to determine 'best' direction to point the Stkp DV
- Important due to weekly momentum unload (MU) sun-ward direction DV of ~ 6 cm/s
- Analysis to determine alternate attitude for momentum unload that would act as a Stkp DV
- Lead to the recent Stkp method of using a stable direction

Variation of the Azimuth and Elevation of the stable and unstable eigenvector for one orbital period



Variation of the stable and unstable directions

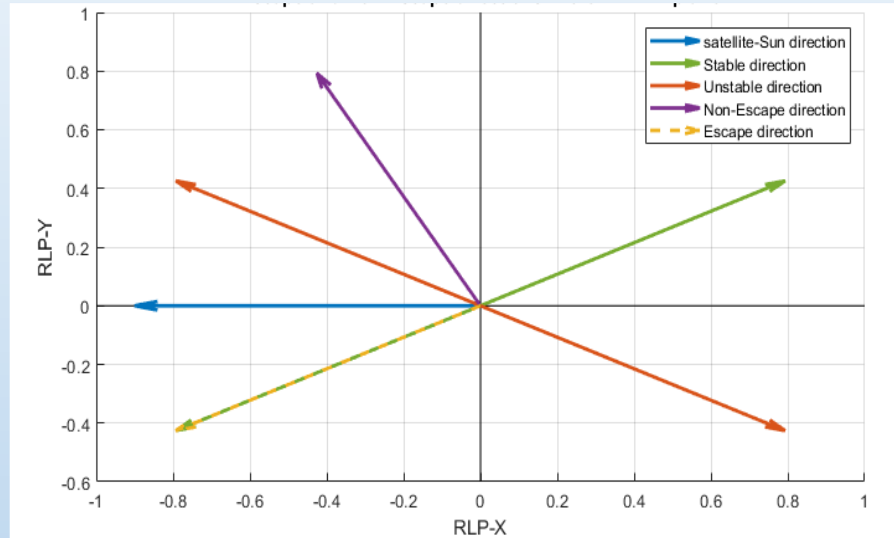


Credit: Ariadna Farres, Dave Folta (GSFC)

Sun-Earth L1 Applications: Space Weather Follow On-L1

- A proposed strategy to mitigate the impact of the momentum unloads on the Stkp DV budget uses the non-escape direction for MU, as these are frequent maneuvers to avoid deviating from the Lissajous pattern.
- Maximize the change along the unstable manifold to return to the Lissajous orbit with minimum delta-V.

Escape and Non-Escape Directions in the Sun-Earth XY-Plane Rotating Frame

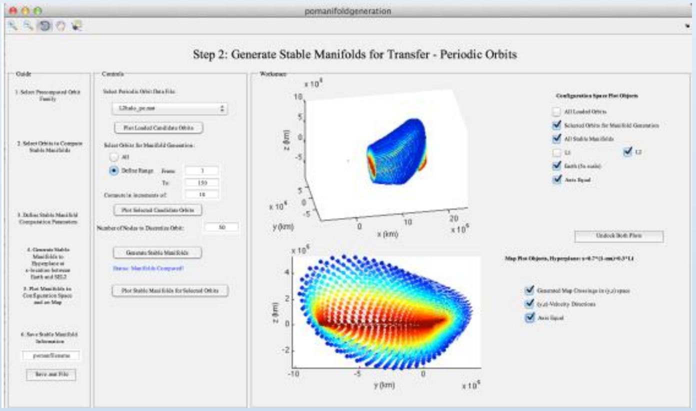


- Schematic representation of these two MU and DV sequences along the mission orbit. While moving along the Lissajous orbit, the stable and unstable directions vary and so do the escape and non-escape directions. To account for this direction variation, one can approximate the non-escape direction by a direction perpendicular to the stable eigenvector and contained in the ecliptic plane.
- Effort resulted in 90% decrease in the Stkp DV budget

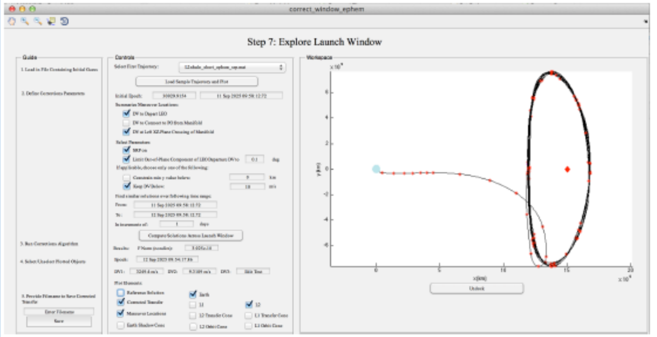
Credit: Ariadna Farres, Dave Folta (GSFC)

Sun-Earth L2 Applications: Roman Space Telescope

- A procedure was developed using various levels of CR3BP, ephems, and high-fidelity models to permit a user to design a complete RST orbit and its transfer
- Based on families of periodic orbits, stable manifolds that reach the Earth vicinity in negative time are generated for a user-specified range of candidate mission orbits
- Paths that depart the initial LEO are generated, integrated forward in time in the Sun-Earth CR3BP until piercing a selected hyperplane
- An initial guess is constructed using Poincaré mapping
- The constructed initial guess is corrected in the Sun-Earth CR3BP to ensure full state continuity, while also incorporating maneuvers
- The entire trajectory is corrected within a point-mass ephemeris model
- The corrected trajectory is used to generate similar solutions at various epochs across a user-defined launch window. The resulting trajectories are stored and GMAT scripts are automatically generated



Generation of stable manifolds associated with selected candidate mission orbits



Graphical user interface implementing, in Matlab

Credit: Natasha Bosanac (CU), Cassie Webster (GSFC)

Application of Dynamical Systems for Lunar Exploration

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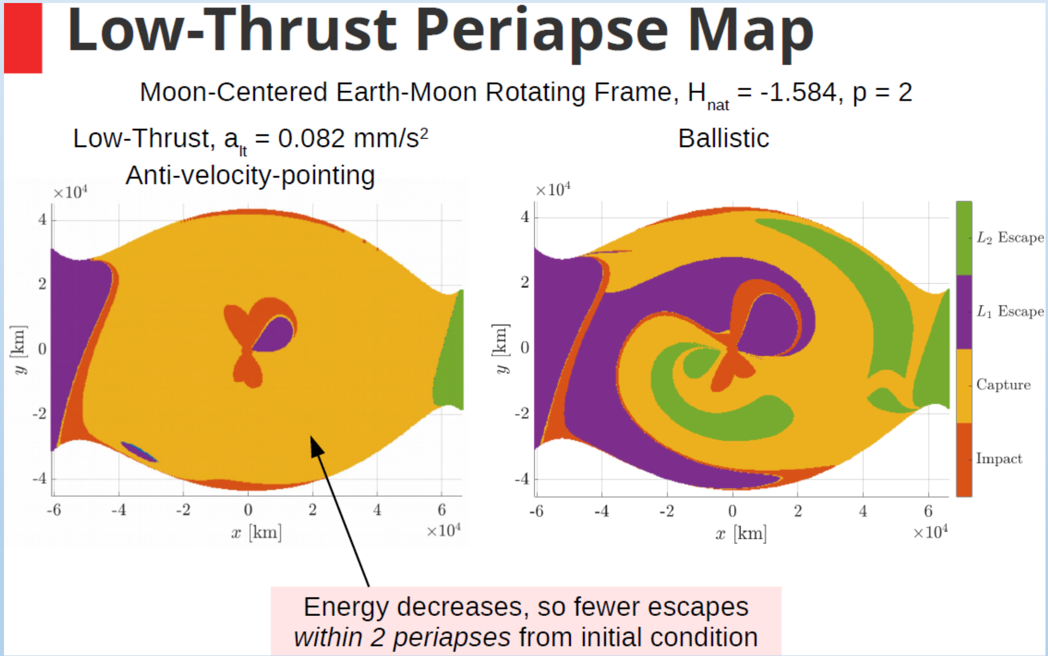
- Application to natural and low thrust lunar ballistic capture scenario
- One common visualization strategy for apse maps is to color the initial apse states by the behavior of the resulting arc
- The initial state of a trajectory that impacts the moon within the p = 2 map returns is colored red
- The initial states for trajectories that depart through the L_1 and L_2 gateways are colored purple and green
- Trajectories that remain in the lunar region (r < 115,500 km) are termed "captured," and the associated initial states are depicted in orange



Credit: Cox, Howell (Purdue)

Application of Dynamical Systems for Lunar Exploration

- Various lunar orbits can be implemented used these dynamics
- Near Rectilinear Halo Orbits (NRHO), Butterfly, and Vertical orbits are useful for lunar communication and observation coverage

Southern Halo Families

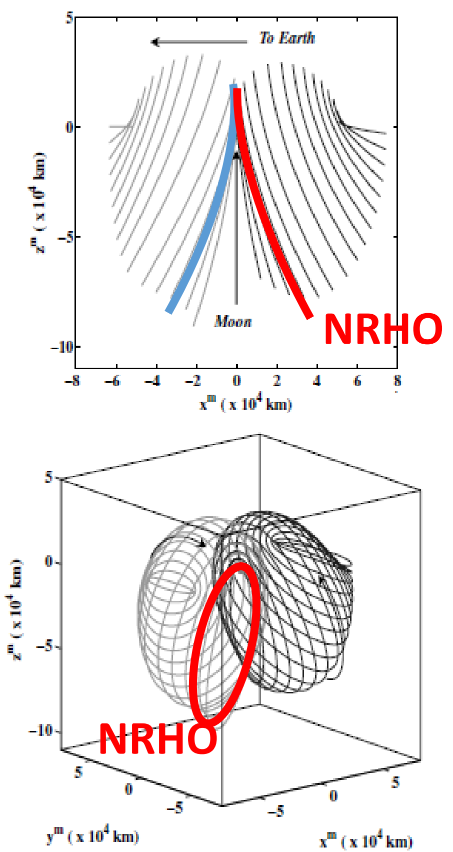


Fig. 1 Southern halo-orbit families: Earth–moon L_1 (left) and L_2 (right).

Southern Butterfly Families

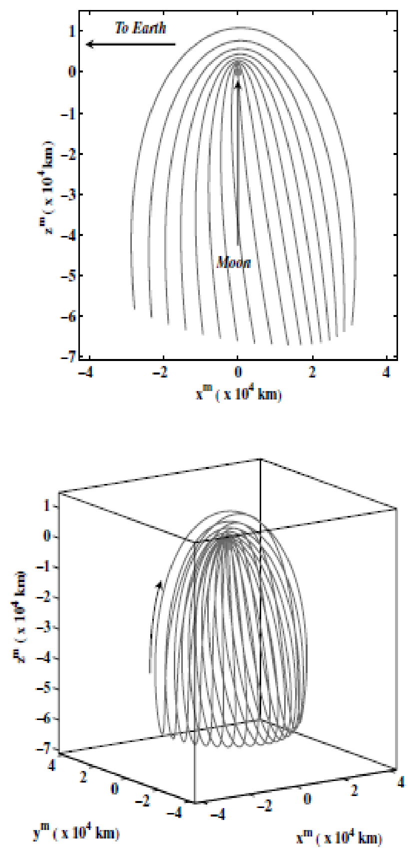


Fig. 3 Southern L_2 butterfly-orbit family.

Vertical Families

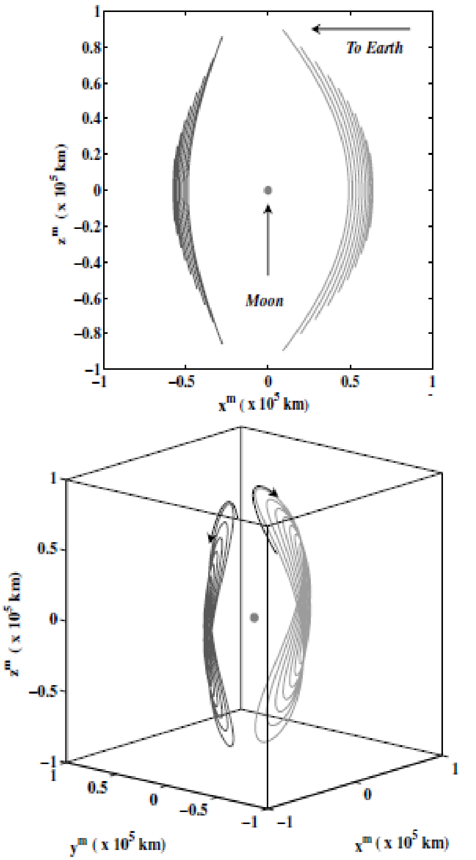


Fig. 2 Vertical-orbit families of interest: Earth–moon L_1 (left) and L_2 (right).

Credit: Howell (Purdue), Ozimek, Bosanac (CU), Davis (JSC)

The Past 50 Years

Over the past 50 years, astrodynamicsts and engineers at NASA centers, industry, and universities strived to determine innovative methods to not only achieve specialized Sun-Earth or Earth-Moon libration point orbits, but to also provide access from these unstable regions to distinctive orbits about the Moon and in its neighboring environment.

- Based on operational missions, environmental models have been proven and are at very high fidelity, e.g., gravity deg and order of 1200
- Optimization techniques are being applied for transfer design and for landing, ascent, and rendezvous
- High fidelity propulsion and maneuver modeling are being incorporated into the optimization and targeting simulations
- Sun-Earth and Earth-moon designs using multi-body dynamics are well understood and have been demonstrated for efficient transfers
- Use of direct and ballistic transfers for operationally constrained missions were demonstrated
- Applications for Lunar Missions, e.g., Gateway, ORION, and for more futuristic assembly and refurbishing missions

The Next 50 Years

- Continue research in the understanding of dynamical systems and their applications
- Use of AI, Neural Nets, Machine learning, combinatorics, may expand our design knowledge beyond the intuitive nature that we now hold
- Data mining and other extraction/cataloging methods will expand insights into numerically and dynamically generated trajectories
- Improvements in quantum computing and massive parallel systems will reduce (eliminate) integration times
- Visualization techniques to aid understanding the trajectory concepts
- New missions will always impose challenging and “impossible to achieve” constraints that need to be resolved – That’s the beauty of our work…

Looking for that *one new thing* that will once again, revolutionize astrodynamics

Thank You

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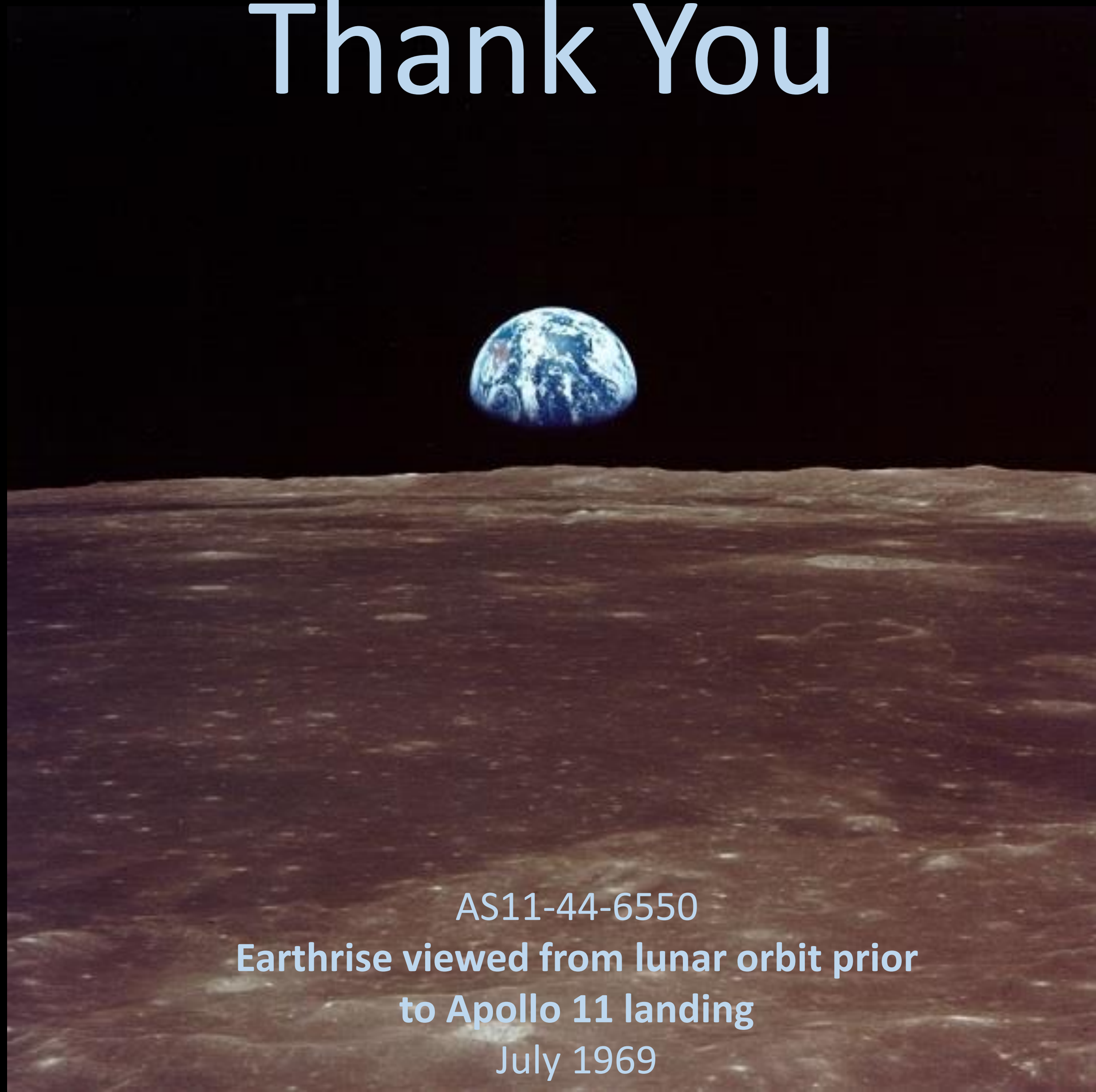
Thank You



AS11-44-6550
Earthrise viewed from lunar orbit prior to Apollo 11 landing
July 1969