Libration Orbit Mission Design: Applications Of Numerical And Dynamical Methods

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Libration Point Orbits and Applications
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Agenda

- NASA Enterprises
- Challenges
- Historical and future missions
- Libration mission design via numerical and dynamical methods
- Applications
  - Direct transfer
  - Low thrust
  - Servicing
  - Formations: Constellation-X and Stellar Imager
  - Conceptual studies
- Improved tools
- Conclusions
Recent SEC missions include ACE, SOHO, and the L₁/L₂ WIND mission. The Living With a Star (LWS) portion of SEC may require libration orbits at the L₁ and L₃ Sun-Earth libration points.

Structure and Evolution of the Universe (SEU) currently has MAP and the future Micro Arc-second X-ray Imaging Mission (MAXIM) and Constellation-X missions.

Space Sciences’ Origins libration missions are the Next Generation Space Telescope (NGST) and The Terrestrial Planet Finder (TPF).

The Triana mission is the lone ESE mission not orbiting the Earth.

A major challenge is formation flying components of Constellation-X, MAXIM, TPF, and Stellar Imager.
Future Libration Mission SSE and ESE Challenges

**Orbit**
- Biased orbits when using large sun shades
- Shadow restrictions
- Very small amplitudes
- Reorientation to different planes and Lissajous classes
- Rendezvous and formation flying
- Low thrust transfers
- Quasi-stationary orbits
- Earth-moon libration orbits
- Equilateral libration orbits: $L_4$ & $L_5$
- $L_3$ orbits

**Other**
- Servicing of resources in libration orbits
- Minimal fuel
- Constrained communications
- Limited ΔV directions
- Solar sail applications
- Continuous control to reference trajectories
- Tethered missions
- Human exploration
<table>
<thead>
<tr>
<th>Mission</th>
<th>Location / Type</th>
<th>Amplitudes (Ax, Ay, Az)</th>
<th>Launch Year</th>
<th>Total ∆V Allocation (m/s)</th>
<th>Transfer Type</th>
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<tr>
<td>ISEE-3</td>
<td>L1Halo/L2/Comet 1st mission</td>
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<td>WIND⁺</td>
<td>L1 – Lissajous</td>
<td>10000, 350000, 250000</td>
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<td>Multiple Lunar Gravity Assist</td>
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<td>SOHO</td>
<td>L1 – Lissajous</td>
<td>206448, 666672, 120000</td>
<td>1995</td>
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<td>ACE</td>
<td>L1 – Lissajous 1st small amplitude</td>
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<td>1997</td>
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<td>MAP</td>
<td>L2-Lissajous 1st L2 Mission</td>
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<td>Single Lunar Gravity Assist</td>
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<td>Genesis</td>
<td>L1-Lissajous</td>
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<td>Triana</td>
<td>L1-Lissajous Launch Constrained</td>
<td>81000, 264000, 148000</td>
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<td>Direct</td>
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<td>NGST*</td>
<td>L2-Quasi-Periodic Lissajous</td>
<td>290000, 800000, 131000</td>
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<td>Direct</td>
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<td>SPECs</td>
<td>L2-Lissajous Tethered Formation</td>
<td>290000, 800000, 131000</td>
<td>#</td>
<td>Tbd</td>
<td>Direct</td>
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<td>MAXIM</td>
<td>L1 – Lissajous</td>
<td>Large Lissajous</td>
<td>#</td>
<td>#</td>
<td>Direct</td>
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<tr>
<td>Constellation-X</td>
<td>L2 – Lissajous Loose Formation</td>
<td>Large Lissajaous</td>
<td>2010</td>
<td>150-250</td>
<td>Single Lunar Gravity Assist</td>
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<td>Darwin</td>
<td>L1-Lissajous Large Lissajous</td>
<td>300000, 800000, 350000</td>
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<td>#</td>
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<tr>
<td>Stellar Imager</td>
<td>L2 – Lissajous ~30 S/C Formation</td>
<td>Large Lissajous</td>
<td>2015</td>
<td>#</td>
<td>Direct</td>
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<tr>
<td>TPF</td>
<td>L2 – Lissajous</td>
<td>Lissajous</td>
<td>#</td>
<td>#</td>
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</table>

+ WIND was originally designed as an L1 orbiter, * NGST Concept only, # is tbd
Numerical Targeting

- High Fidelity Perturbation Theory Modeling
- Intuitive Numerical Targeting Via DC & Optimization
- Spacecraft Modeling for Attitude and Maneuvers
- Currently Single Trajectory Design
- Limited Set of Initial Conditions
- Operational Software
- Can perform Monte Carlo and parametric scan studies

GSFC’s Swingby Program
Astrogator

- Astrogator is a COTS mission design tool designed as an add-on module to Satellite Tool Kit by Analytical Graphics Inc.
- Astrogator was originally designed based upon Swingby mathematical specifications
- Astrogator combines the trajectory design capabilities of Swingby with the visualization and computational capabilities of STK
- MAP was the first LPO mission to use Astrogator operationally
Example of a Forward Shooting Method of a Libration Point Orbit Direct Transfer

- Initial escape trajectory towards a libration point with the Moon at the appropriate geometry
- Target the anti-Sun right ascension and declination at the appropriate launch epoch
- Target velocity of the Sun-Earth rotating coordinate x-z plane crossing condition to achieve a quasi-libration orbit, L₂ x-axis velocity ~ 0
- Target a second x-z plane crossing velocity which yields a subsequent x-z plane crossing, then target to a one period revolution
- Vary the launch injection C3 and parking orbital parameters
Example of a Forward Shooting Method of a Libration Point Orbit Lunar Gravity Assist

- Target the moon at the appropriate encounter epoch to achieve an anti-sun outgoing asymptote vector
- Target the lunar b-plane condition to achieve a gravity assist and a perpendicular sun-earth rotating coordinate x-z plane crossing
- Target x-z plane crossing velocities which yields a second x-z plane crossing and target to a one period revolution at L₂
- Re-target lunar b-plane conditions to achieve the correct orientation of the lissajous pattern with respect to the ecliptic plane

**Target goals may include:**
- Time
- B-plane conditions.
- Libration sun-earth line crossing conditions
- Mathematical computation (eigenvectors)
- Targets may be single event string, nested, Or branched to allow repeatable targeting
- Maneuvers can be inserted were appropriate
Numerical and Dynamical Targeting using Generator

Sample Generator Menus

- Qualitative Assessments
- Global Solutions
- Time Saver / Trust Results
- Robust
- Helps in choosing numerical shooting methods

<table>
<thead>
<tr>
<th>Utility</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase (Generic Orbit)</td>
<td>User Data</td>
<td>Control Angles For Lissajous</td>
</tr>
<tr>
<td>Lissajous</td>
<td>Universe And User Data</td>
<td>Patch Point And Lissajous Orbit</td>
</tr>
<tr>
<td>Monodromy (Periodic Orbit)</td>
<td>Universe And Lissajous Output</td>
<td>Fixed Points And Stable And Unstable Manifold Approximations</td>
</tr>
<tr>
<td>Manifold</td>
<td>Universe And Monodromy Output</td>
<td>1-Dimensional Manifold</td>
</tr>
<tr>
<td>Transfer</td>
<td>Universe, User Selected Patch Points, Manifold Output</td>
<td>Transfer Trajectory From Earth To L₁ Or L₂</td>
</tr>
</tbody>
</table>
NGST Mission Applications

• Mission: NGST Is Part of Origins Program
• Designed to Be the Successor to the Hubble Space Telescope
• Launch: ~2010, Direct Transfer
• Lissajous Orbit about L2: 
  400,000km > $A_y$ < 800,000km
• Spacecraft: Three Axis Stabilized, ‘Star’ Pointing
• Notable: Observations in the Infrared Part of the Spectrum
• Important That the Telescope Be Kept at Low Temperatures (~30K): Large Solar Shade/Solar Sail
Dynamical System Approach to Generate the Lissajous

- Input desired libration orbit parameters, e.g. 800,000 km y-amplitude liss orbit
- Class I configuration, epoch
- Provides invariant manifolds
- Select the manifold that best meets mission and parking orbit conditions, shadows, and minimum insertion $\Delta V$

Projections of All Invariant Manifolds for Time Interval
Application of Dynamical System Approach Results

- Input Into Numerical Targeting Scheme With Full Perturbation Modeling
- Direct Shooting Method to Meet Trajectory Goals Via DC
- \( \Delta V \) Corrections of 1 cm/s at Injection, 0.3 cm/s at LOI
NGST Transfer to Libration Orbit Via Low-Thrust

- Low thrust trajectory solutions exist for the collinear libration points
- No lunar gravity assist is used
- The trajectory generally consists of spiraling out to lunar orbit with periods of thrusting and coasting and targeting the post-lunar leg to insert into the periodic orbit using coast times
- The thrust can be along the velocity vector or at an angle to it to achieve maximum efficiency
- Results show possible extensive time-of-flight amplified by the mass
- A conceptual nuclear powered electric propulsion provides 1.2 N of thrust at an Isp of 4800 sec
- Transfer trajectory takes 510 days of continuous thrust followed by an 85-day coast
Servicing of Libration Missions

• Return to LEO to be serviced at the ISS.
• Unstable manifolds that pass near the Earth are used as initial estimates.
• The transfer is targeted to meet inclination and dynamic pressure constraints.
• Drag Mechanism would be used to aerocapture at the Earth.
• Retarget perigee to the original 107 km altitude at first apogee.
• After several perigees, altitude remains constant and the spacecraft is aerocaptured within 4 days.
• Challenge of placing 4 spacecraft into a formation in libration orbit

• Launch two spacecraft at a time

• Achieve a small Lissajous via a lunar gravity assist

• Targeted using DC with phasing loops and deterministic ΔVs to align both spacecraft in mission orbit

• Each spacecraft independently controlled

• Total Mission ΔV
  S/C #1 = 157m/s, S/C#2 = 151m/s

• B-plane Targets
  S/C #1: B.T = 13581km, B.R = 20894km
  S/C #2: B.T = 13838km, B.R = 20910km
Constellation - X

Spacecraft separation distances

Launch though libration orbit

Launch though gravity assist
Deeptail Conceptual Study

Trajectories derived from a standard libration orbit

Notes:
Launch C3 = -0.59
Total mission duration = 375 days
Total mission $\Delta V = 333 \text{ m/s}$ for mother ship

Red represents the trajectory in the Geotail region (0 to 20 deg)

$\Delta V$ increments of 10 m/s
Stellar Imager

- SI is a concept for a space-based, uv-optical interferometer. The leading concept for SI is a 500-meter diameter fizeau-type interferometer composed of 30 small drone satellites that reflect incoming light to a hub satellite.
- Focal lengths of both 0.5 km and 4 km are being considered. This would make the radius of the sphere either 1 km or 8 km.
- Perturbation models generate lissajous mission orbit monodromy matrix for accurate modeling and STM for propagation.
Stellar Imager

- Three different scenarios make up the SI formation control problem: maintaining the Lissajous orbit, slewing the formation, and reconfiguring.
- Using a LQR with position updates, the hub maintains an orbit while drones maintain a geometric formation.

The magenta circles represent drones at the beginning of the simulation, and the red circles represent drones at the end of the simulation. The hub is the black asterisk at the origin.

### SI Slewing Geometry

### Formation DV Cost per slewing maneuver

<table>
<thead>
<tr>
<th>Focal Length (km)</th>
<th>Slew Angle (deg)</th>
<th>Hub $\Delta V$ (m/s)</th>
<th>Drone 2 $\Delta V$ (m/s)</th>
<th>Drone 31 $\Delta V$ (m/s)</th>
</tr>
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<tbody>
<tr>
<td>0.5</td>
<td>30</td>
<td>1.0705</td>
<td>0.8271</td>
<td>0.8307</td>
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<td>0.5</td>
<td>90</td>
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<td>0.9395</td>
<td>0.9587</td>
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<tr>
<td>4</td>
<td>30</td>
<td>1.2688</td>
<td>1.1189</td>
<td>1.1315</td>
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<tr>
<td>4</td>
<td>90</td>
<td>1.8570</td>
<td>2.1907</td>
<td>2.1932</td>
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</table>
Improved Tools

- Utilize capabilities of numerical and dynamical methods. The idea being to merge the best of current targeting, optimizing, and control applications.
- Include search methods and optimization to numerical and dynamical approaches
- Additionally, these tools must be able to interface with one another
Conclusions

- Trajectory design in support libration missions is increasingly challenging as more constrained mission orbits are envisioned in the next few decades.

- Software tools for trajectory design in this regime must be further developed to incorporate better understanding of the solution space, improving the efficiency, and expand the capabilities of current approaches.

- Improved numerical and dynamical systems must offer new insights into the natural dynamics associated with the multi-body problem and provide to methods to use this information in trajectory design.

- The goal of this effort is the blending of analysis from dynamical systems theory with the well-established NASA Goddard software programs such as Swingby to enhance and expand the capabilities for mission design and to make trajectories more operationally efficient.