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TRAJECTORY DESIGN TOOLS FOR LIBRATION AND CIS-LUNAR ENVIRONMENTS

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Introduction

- Innovative tool development and selection is critical for multi-body mission design
  - Challenging multi-body regimes and complex dynamics
  - Uncertainty in modeling perturbations
  - Integration of propulsive influences
  - Undetermined level of modeling fidelity in general

- Solution
  - Leverage dynamical system techniques to design attainable trajectories that can achieve complex scientific goals
  - Incorporate tools which offer interactive access to a variety of solutions
  - Provide for flexibility in tool design and the level of fidelity

- Tools demonstrated which can provide these services
  - General Mission Analysis Tool (GMAT)
  - Adaptive Trajectory Design (ATD)

Tool and Trajectory Design Prerequisites

- Perturbation Models
  - Multi-body dynamical environments must be model accurately
  - Accelerations integrated precisely
  - Provide a wide range of integrators for numerical applications
  - Must show consistency in the design structure
- Choice of Targeting methods and parameters
  - Use of differential corrector and optimization techniques to meet goals
  - Target models in various frames and parameters
    - B-plane and Cartesian states
    - Energy levels and dynamical properties (modes)
- Tools should be capable of both prelaunch and operational use
  - Error analysis
  - Launch Windows
  - Maneuvers
  - Operational Support

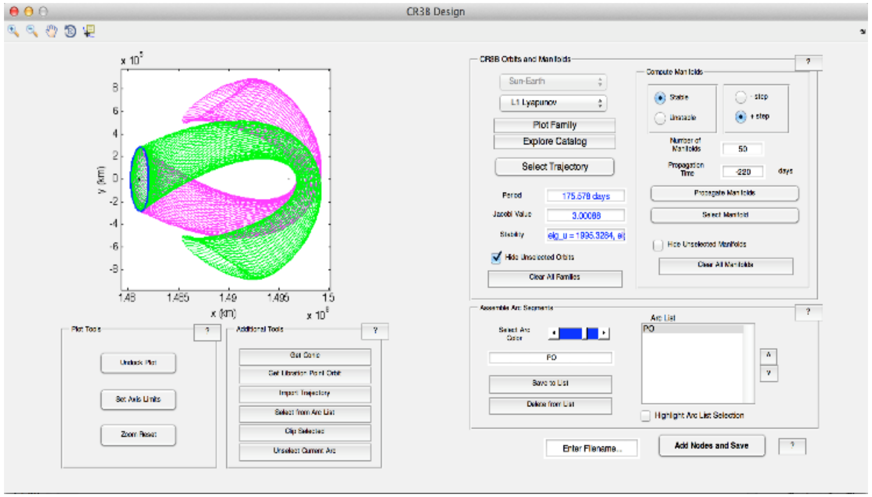
Libration and Lunar Encounter Numerical Trajectory Design

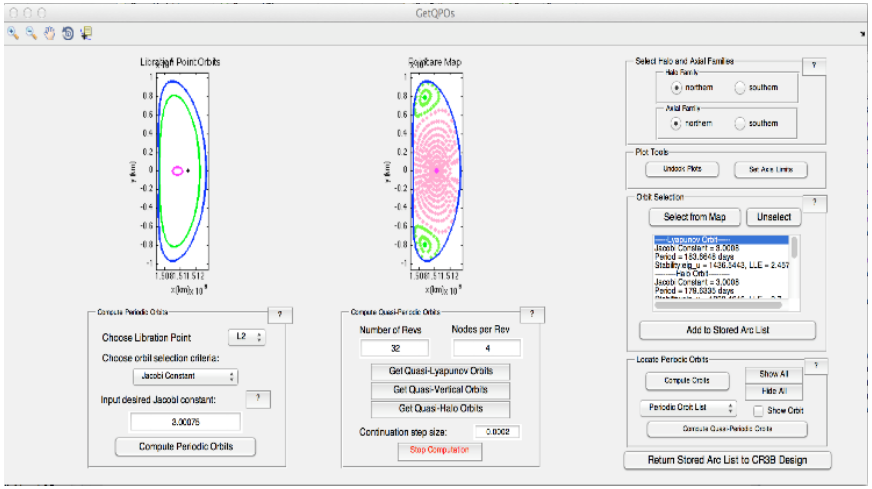
- Many previous lunar and libration missions have been designed with established numerical approaches
  - Numerical methods employing derivatives, finite difference, etc. for an interactive process
  - Additional constraints incorporated for corrections
  - A typical libration orbit numerical process includes
    - Escape trajectory energy with outbound asymptote
    - Solar directions at launch epoch
    - Solar rotating coordinate frame plane crossings
    - Variations of multiple orbit and injection initial conditions (C3, parking orbit, coast times)
    - B-plane targets for lunar gravity assist and outbound directions in a rotating frame
  - Target sequences can be nested, multiple goals, or branched to achieve a series of goals
- These schemes rely on knowing the underlying system dynamics

Adaptive Trajectory Design Tool

- Incorporates dynamical systems theory and techniques
  - Rapid and efficient exploration of complex solution space within chaotic multi-body systems
  - Trajectory design process exploits a better understanding of the design space
- An interactive design environment for constructing end-to-end trajectories
  - Models from CR3BP to full ephemeris
  - A Graphical User Interface (GUI), includes interactive and automated modules
  - Provides capability to select individual arcs, including periodic and quasi-periodic orbits, manifolds, and conics via on-demand trajectory generation and Poincaré mapping
  - Multiple frames (inertial, rotating, libration point) and models (two-body, restricted three-body, ephemeris)
  - Arcs are connected to exploit the underlying natural dynamics within various regions and transitioned to a higher-fidelity ephemeris model
  - The final trajectory can then be imported into GMAT for further analysis

Adaptive Trajectory Design Tool

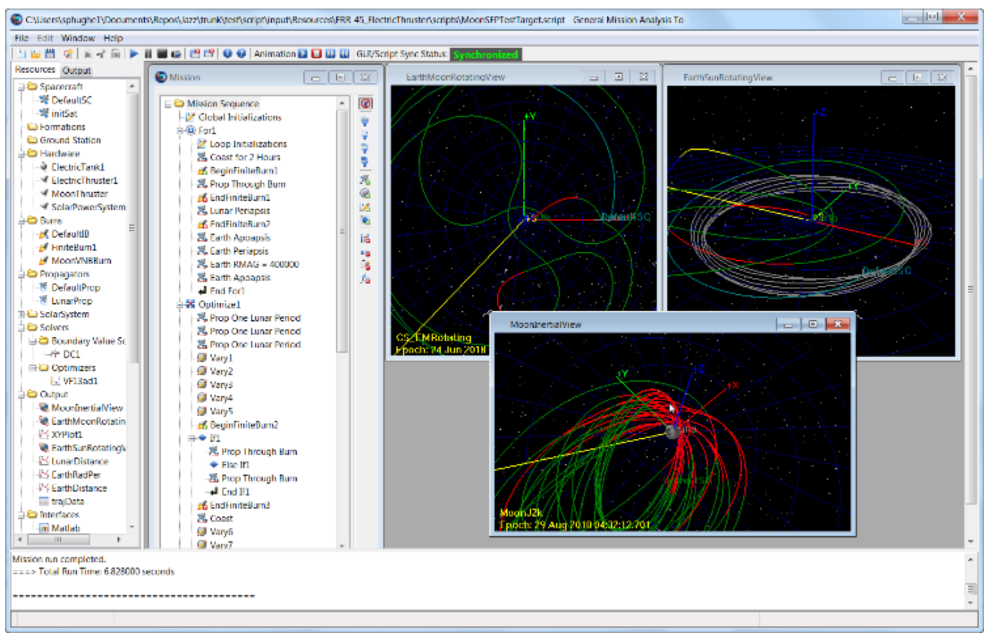




- Provide rapid design of libration, resonant, and body-centered orbits
- GUI shown with user-generated Sun-Earth L_1 Lyapunov orbit and associated stable (green) and unstable (magenta) manifolds
- Includes a module that employs Poincaré mapping to visualize and locate a wide variety of complex solutions near the libration points

General Mission Analysis Tool

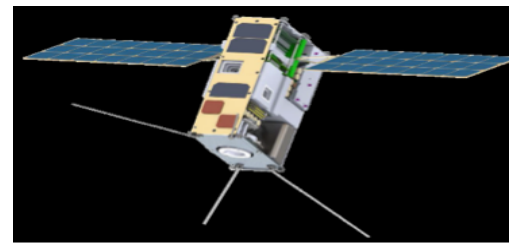
- Conceived and developed by an experienced team of aerospace engineers and software designers at NASA GSFC
  - Open-source high-fidelity space mission design tool
  - Operational tool for all orbit regimes, including cis-lunar
  - GUI or script interface
  - High fidelity perturbation models
  - Targeting and optimization algorithms
  - Spacecraft characters modeled (tanks, thrusters, finite maneuvers)



Mission Design Applications

- To demonstrate the use of ATD and GMAT, these tools are used by NASA GSFC to design trajectories for both the Lunar IceCube and WFIRST missions.

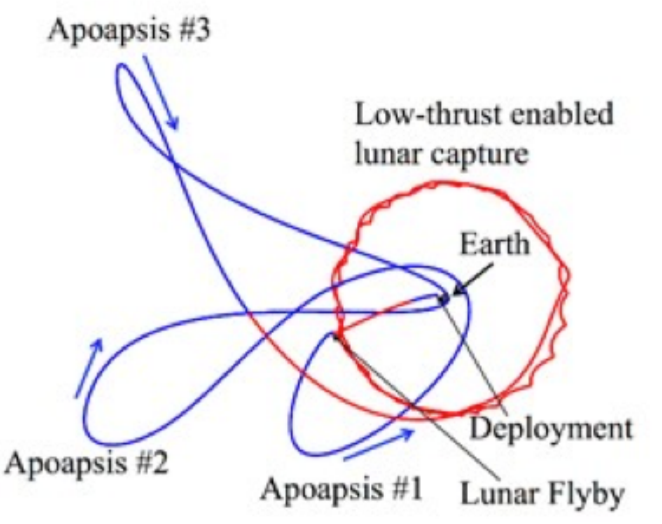
- Lunar IceCube mission
  - 6U Cubesat mission with a cis-lunar trajectory inserted into a lunar science orbit
  - Deployed as a secondary payload
  - High-energy departure trajectory dependent on NASA's SLS (EM-1) launch with constrained outbound departure and lunar gravity assist
  - Low thrust maneuver control using a Busek Ion Thruster (3-cm)



- WFIRST Mission
  - NASA led observatory currently in preliminary design stage
  - 2.4 meter telescope and wide field instruments
  - Science orbit employed is a Sun-Earth L2 quasi-halo orbit
  - Launch into a direct transfer

Lunar IceCube Application

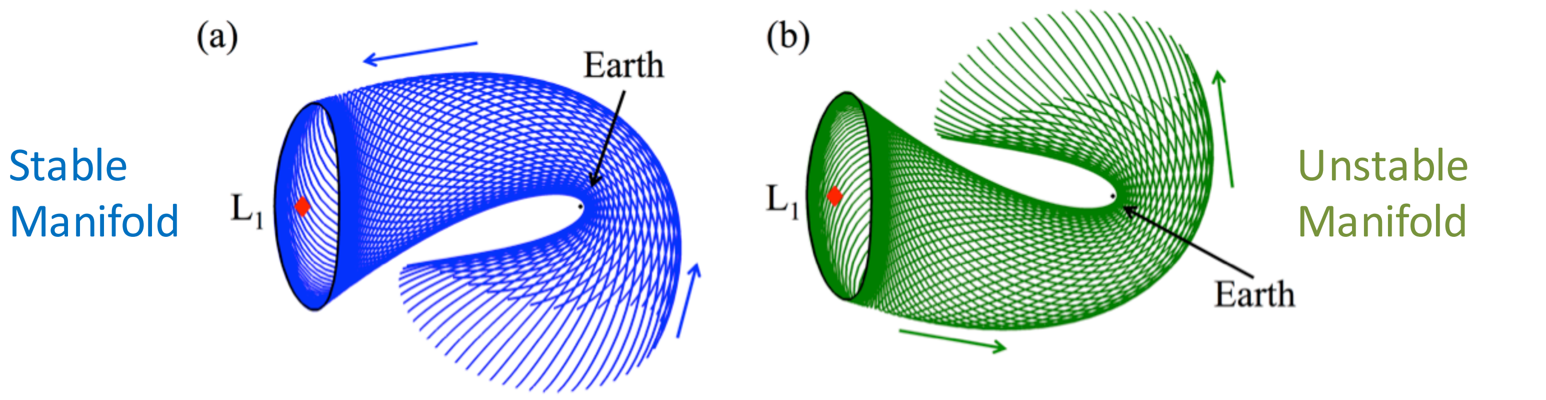
- Design incorporates combined dynamical system and numerical approach
- Leverage insight to transfer regions and geometries
- Point solutions sensitive to state uncertainties and models
- Using ATD, construct a framework for trajectory solutions
    - Post-deployment lunar encounter
    - Sun-Earth-Moon transfer
    - Lunar science orbit approach
    - DST concepts applied over each segment
- Mapping techniques employed to identify segment connections
- A patched fully designed trajectory is then passed into GMAT for reproduction with operational models



- Sample design characteristics
    - Long predominantly natural segment, resembles the Sun-Earth L_1 Lyapunov manifold structures
    - Initial low thrust outbound (red) segment can adjust the geometry of the natural segment prior to lunar encounter

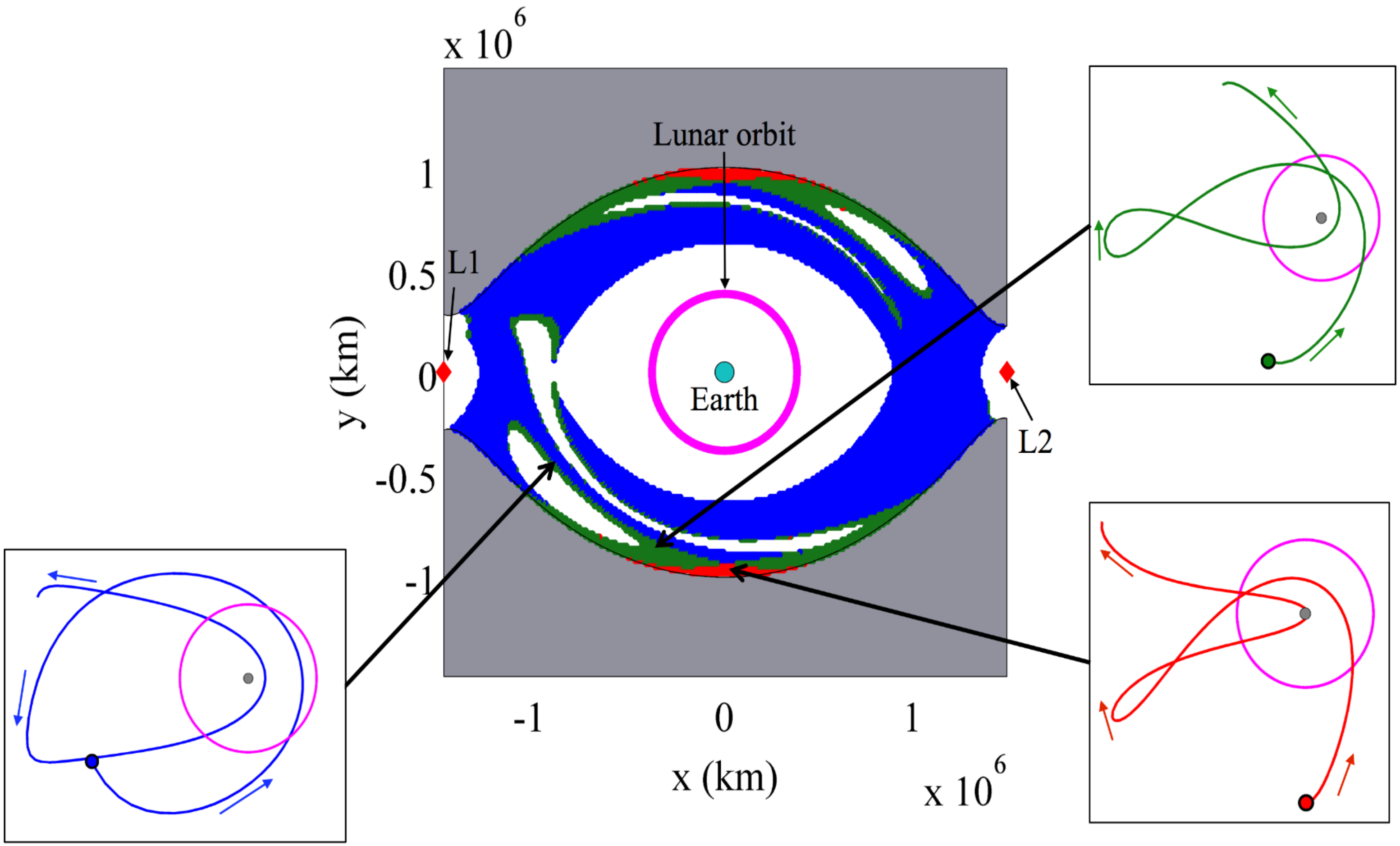
Manifolds of Periodic Orbits

- Trajectory design guided by underlying dynamical structures, including families of periodic orbits and associated manifolds within CR3BP
- Example in Sun-Earth: Lyapunov, halo and other orbit families near L_1 and L_2
- Periodic orbits may possess stable (blue) and unstable (green) manifolds with flow towards or away from the periodic orbit
- Lunar IceCube: stable and unstable manifolds supply approximate bounds on motion and influence transfer geometry
- Arcs from both manifolds are combined to construct a transfer from the outgoing EM-1 deployment trajectory to a return to a lunar encounter



Feasible Transfer Regions

- Apoapsis map in the CR3BP at $C = 3.00088$ for prograde initial conditions. Blue, red and green regions indicate initial apoapses of feasible trajectories that remain within the Earth vicinity for two revolutions, with each color corresponding to a different transfer geometry illustrated via the inset images.



Connections Between Transfer Segments

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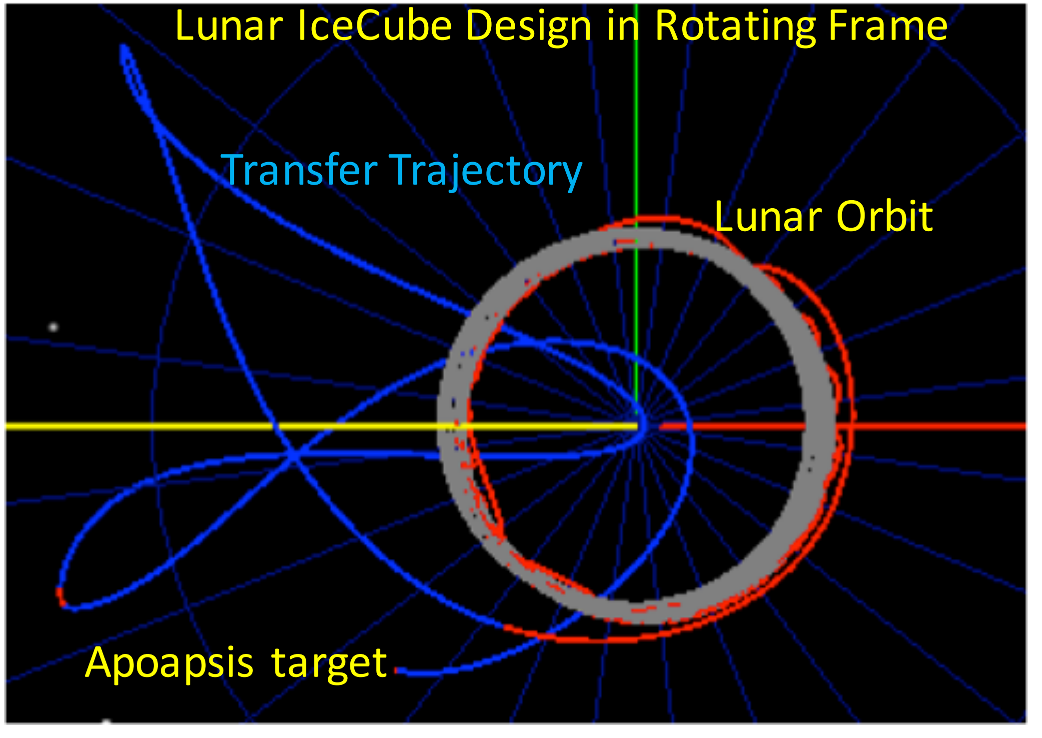
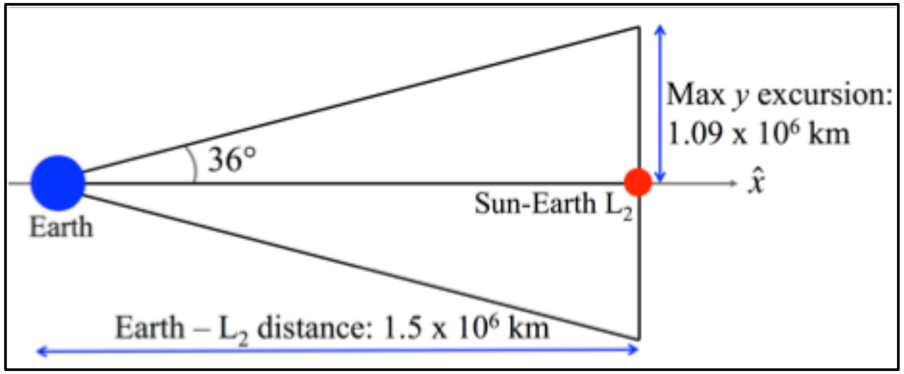
- Lunar IceCube trajectory can be constructed by directly selecting and assembling each of the three trajectory segments prior to corrections in an ephemeris model
- Solution can be approximately reconstructed by employing ATD apoapsis maps, which guide the trajectory design process
- Initial guess can then be corrected in an ephemeris model and exported to GMAT to produce a continuous transfer



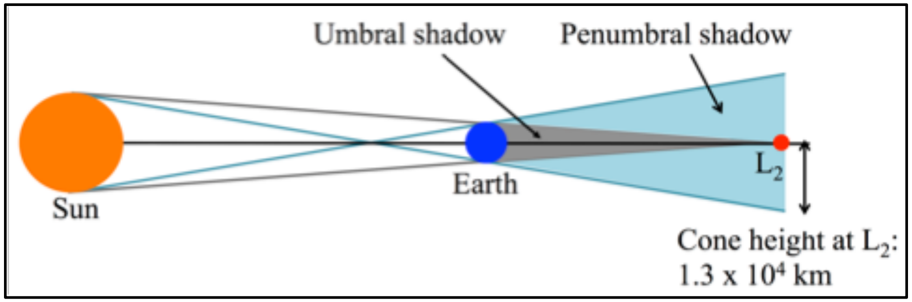
WFIRST Application

- WFIRST mission concept, a baseline scientific orbit in the Sun-Earth L_2 region
- Instrument thermal and geometrical constraints drive design
- Libration point orbit must continually avoid Earth shadow and maintain a Sun-Earth L_2 to vehicle (SEL2V) angle that is less than 36°
  - Approximated by constraint on maximum *y*- and *z*-amplitudes of the orbit
  - Shadow impacts libration orbit selection (Lissajous, axial, quasi-halo, etc.)
- These constraints are applied to candidate orbits in the Sun-Earth CR3BP within ATD to enable thorough orbit design space prior to higher-fidelity modeling

WFIRST Angle Constraint



WFIRST Shadow Constraint



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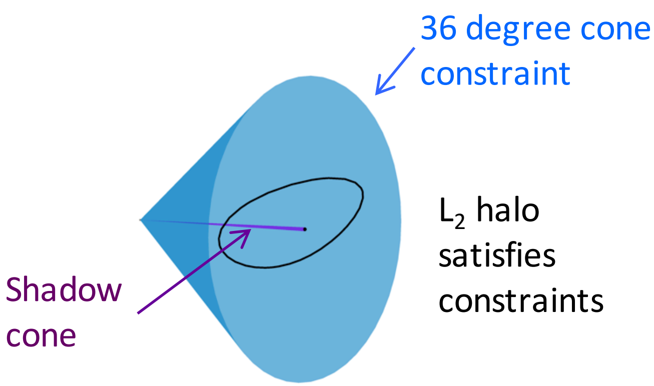
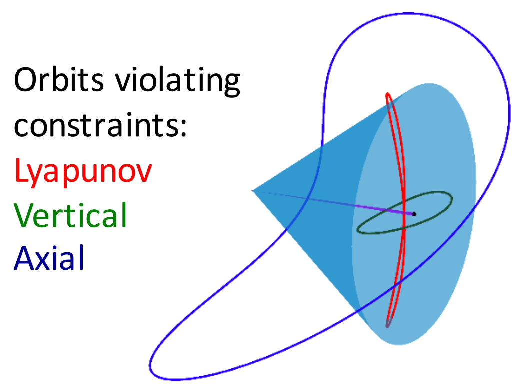
WFIRST Application

- Within ATD, libration point orbits in the Sun-Earth L_2 region can be generated and examined, along with their potential to satisfy geometrical constraints
- Directly examining families of periodic orbits from the CR3BP provides valuable guidance into the orbit selection process
    - Lyapunov, axial, and vertical orbits eliminated due to constraint violations
    - Halo orbits with low z-amplitudes or quasi-halo satisfy all constraints

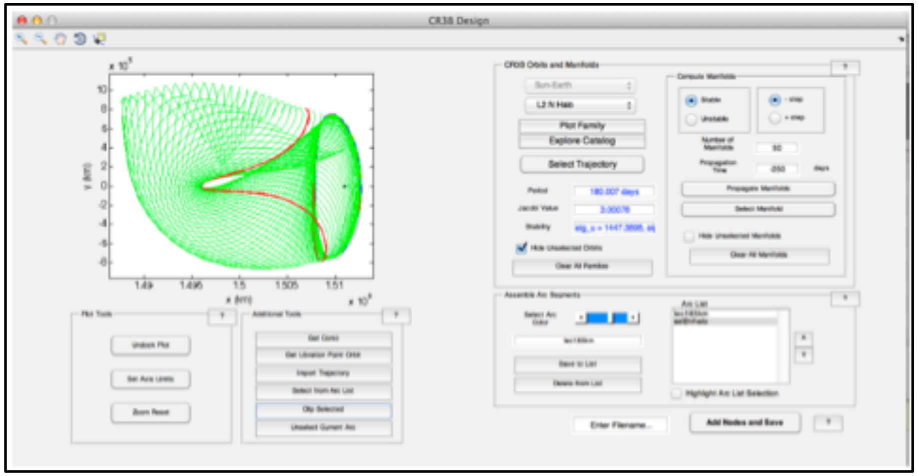


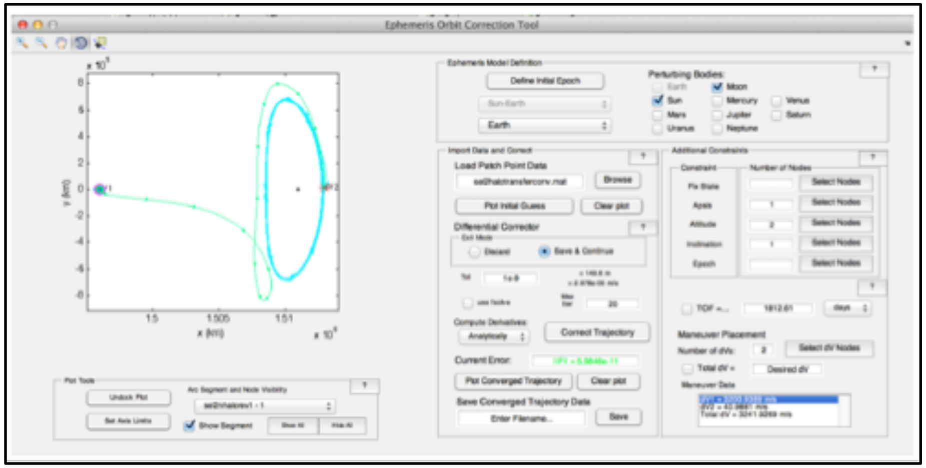


- ATD transfer design process
    - Trajectory segments are individually generated, clipped and ordered prior to connection using a corrections algorithm, including 185 km altitude and 28.5 degree inclination LEO, Sun-Earth L_2 orbit and associated manifold

WFIRST Application

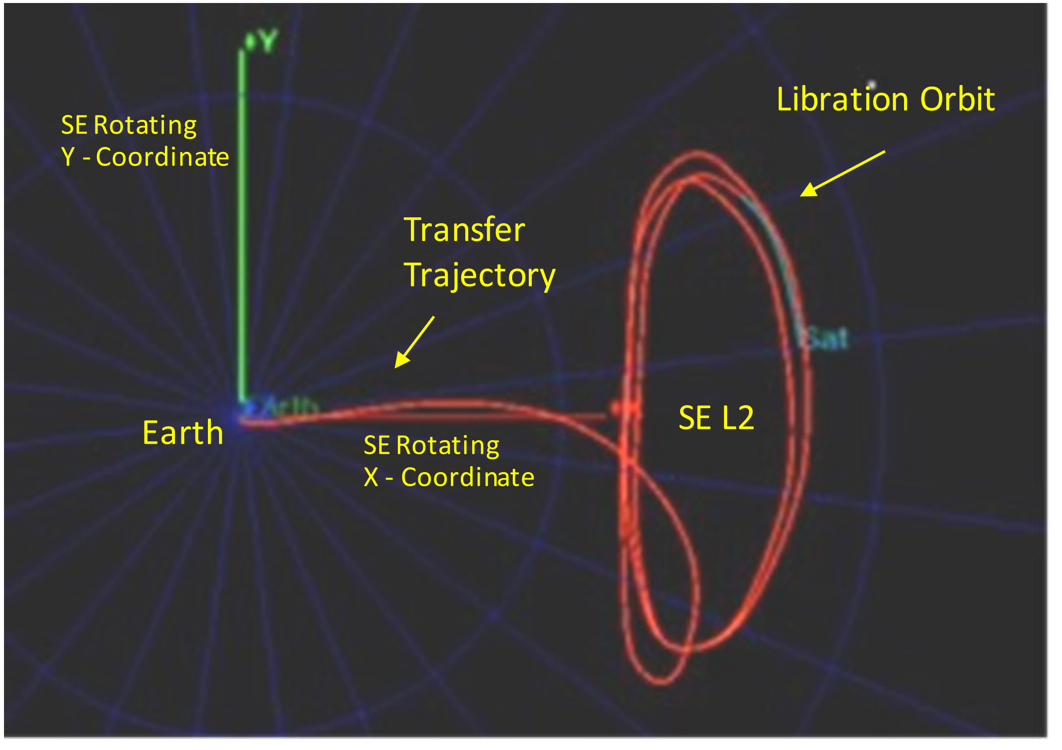
- Selected halo orbit is unstable and possesses stable and unstable manifolds that can be used for the transfer
- Using the manifold generation tool within the CR3BP Design module, 50 trajectories along the stable manifold are integrated backwards in time for a duration of 250 days
- A trajectory that passes close to the parking orbit conic is selected and clipped and additional halo orbit revolutions are then generated
- Selected segments are combined and discretized to form an initial guess for an end-to-end trajectory with allowable maneuver locations
- The resulting end-to-end trajectory that is continuous in the CR3BP is then loaded into the Ephemeris Orbit Corrections module





WFIRST Application

- Using the produced ephemeris data, along with a mission sequence and differential corrector, a similar trajectory is produced
- A trajectory for the WFIRST mission is rapidly designed using ATD to leverage known dynamical structures that satisfy geometrical mission constraints



ATD Transfer trajectory propagated and differentially corrected in GMAT

Concluding Remarks

- ATD, a graphical design environment developed by NASA GSFC and Purdue University, along with operationally-proven modeling software such as GMAT, provides the mission designer with the capability to design complex trajectories within multi-body systems
- An interactive design environment that leverages well-known solutions with the CR3BP enables an exploration of the trajectory design space, along with guidance into redesign for contingency studies
- The Lunar IceCube mission, which is subject to constraints and uncertainties in its deployment state and a limited propulsive capability, benefits from the use of techniques from dynamical systems theory
- WFIRST trajectory design process leverages ATD to accurately and efficiently generate a transfer and science orbit that satisfies the mission requirements
- The resulting trajectory is imported to higher-fidelity software such as GMAT for further analysis

ATD enables rapid and well-informed trajectory design that can provide solutions for further exploration in operational-level modeling tools such as GMAT

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Thank You