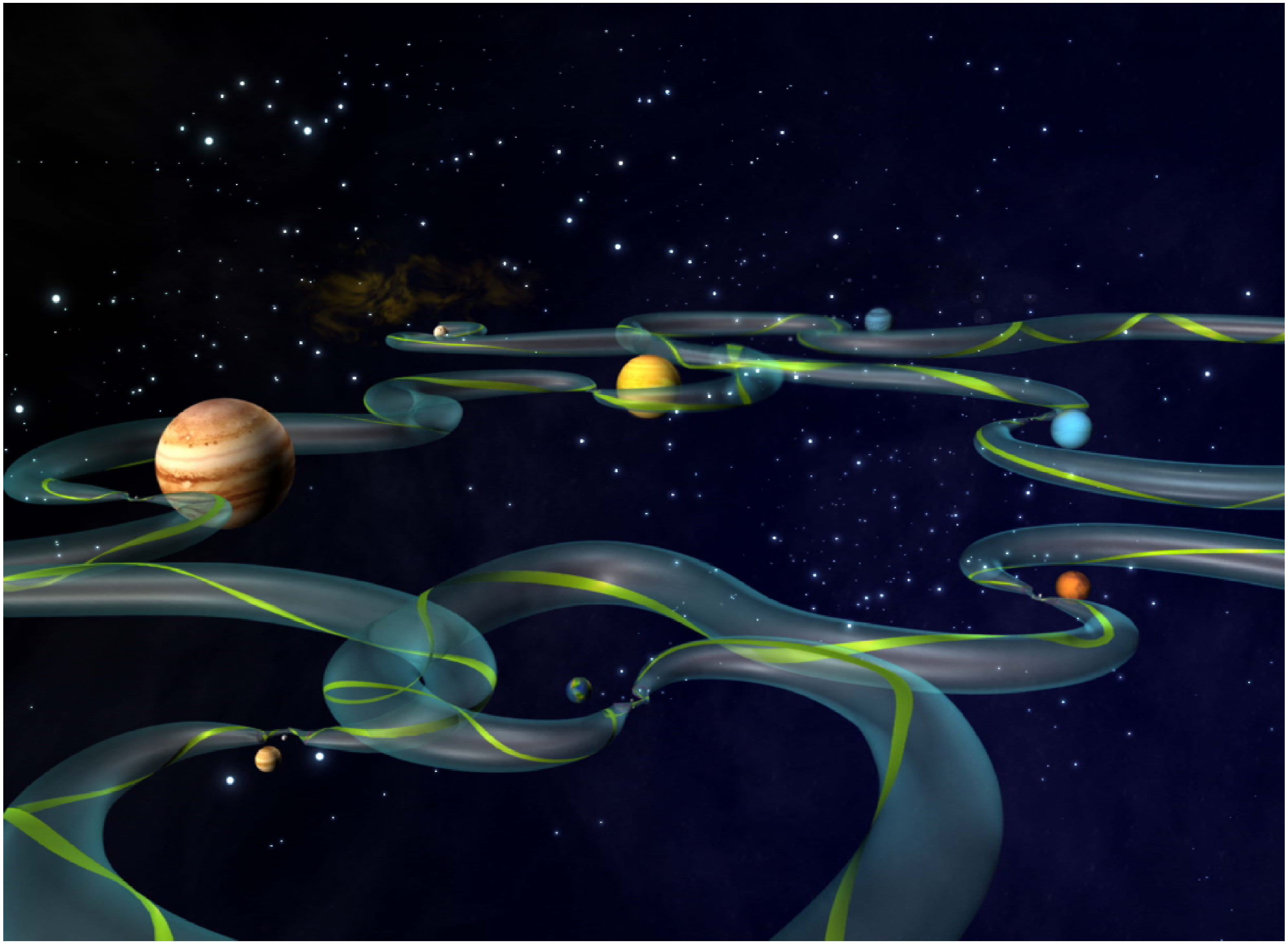
EPISODE: Software for Trajectory Generation and Mission Design



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Science Enabling Technologies in Trajectory Design

- Trajectory design in the past has been approached by solving a sequence of 2 body problems (I.e. Earth orbit, Lunar transfer, Voyager, etc.). **We are now entering a new era of mission design with interest in multi-body missions, where science orbits are established (not just fly-by's). Patched conic solutions are far to costly for these missions concepts, and require the inclusion of 3 and 4 body dynamics.**

- Example – the Jupiter Icy Moons Orbiter (JIMO) mission concept: Earth to Jupiter, Jupiter to Callisto, Callisto to Ganymede, and Ganymede to Europa. JIMO involves a sequence of low-thrust (ion propulsion) transfers and captures in maneuvering from one body to the next - inherently 3 or 4 body problems!

- Trajectory generation is a difficult constrained optimization problem: many local "minima" (bigger drawback for low-thrust trajectory design, with stringent constraints on feasibility of solutions), and consequently a good initial guess is required for convergence to near optimal solutions.

- Our Goal – to make the "initial guess" problem (semi) automated for preliminary mission design.

- Two key components to this approach are: 1) the ability to generate a large class of possible trajectories in a semi-automatic fashion utilizing the "interplanetary superhighway" (IPS) (a network of exact solutions of the 3 and higher-body dynamics which asymptotically wind on and off periodic orbits), and 2) the ability to evaluate a trial trajectory's "probability" of leading to an optimal solution with continued computing.

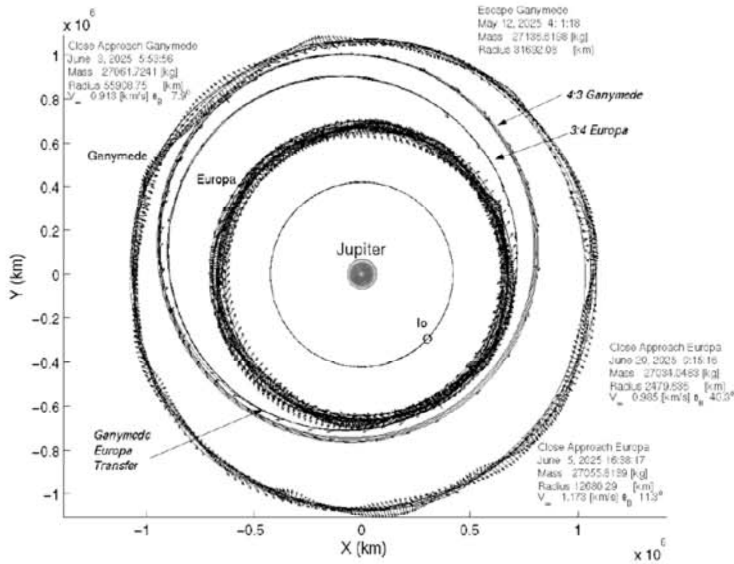
Low-Thrust Propulsion

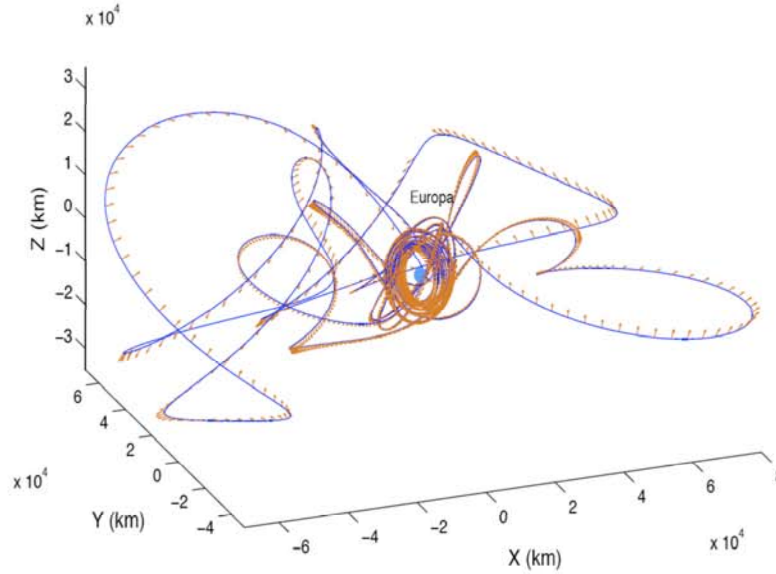
http://nmp.nasa.gov/ds1/

- Deep Space 1 provided successful flight validation of electric ion propulsion (low-thrust)
- Enabling for mission concepts such as JIMO, which is motivated by scientific interest in Jovian system, but requires DV of 25 km/sec to visit the moons of Callisto, Ganymede, and Europa.
- While low-thrust provides larger possible DV, corresponding trajectory design much more difficult due to potential instability and low control authority
- Example: JIMO reference trajectory VERY complex, and a very impressive computational feat accomplished by Whiffen and Lam using their high-fidelity design tool "Mystic".

JIMO Trajectory Segment: Ganymede to Europa

"The Jupiter Icy Moons Orbiter Reference Trajectory", Gregory J. Whiffen, Try Lam, AAS 06-186





Optimal Control as a Constrained Optimization Problem:

$$J = \underbrace{\left(\sum_i \nu_i \cdot x(t_i) \right)}_{} + \sum_j \int_{t_j}^{t_{j+1}} dt \left[\underbrace{L(x,u,t)}_{} + \lambda(t) \cdot \underbrace{\left(f(x,u,t) - \dot{x} \right)}_{} \right]$$

Boundary Conditions:
Start and End Science Orbits

Cost of control required

Dynamical Constraints

Solution! Compute:

$$0 = \dot{x} - f(x,u,t)$$

$$0 = \dot{\lambda} + \left(\frac{\partial f}{\partial x} \right) \lambda + \frac{\partial L}{\partial x}$$

$$0 = \frac{\partial L}{\partial u} + \lambda \frac{\partial f}{\partial u}$$

A two-point BVP: Computational Soln. NOT trivial for nonlinear systems!!

Computational Challenges in Trajectory Design

- Any convergent iterative algorithm to solve the DAE 1 optimal control problem requires a good initial guess of the entire path in configuration space.
- Many local “minima” of the objective that are not in the same “basin of attraction” as the globally optimal solution (bigger drawback for low-thrust trajectory design, as we have more stringent constraints on what solutions are feasible).
- There are potentially many feasible solutions “almost equally good” but with different flight times, stability, or other properties potentially impacting mission design (example - JIMO design study)
  - Some trajectories are much more unstable than others, leading to an increased risk of impact on the target body if loss of the ion engine occurs.
  - Some segments of a mission might place more emphasis on transit time for other hazards, such as radiation level (i.e. see the JIMO mission design problem in Whiffen and Lam, AIAA 06-186)

  - Motivates (or even requires) an initial survey of a wide class of trajectories in the early phase of mission design, and possibly the exploration of the entire “Pareto front” of multi-objective dominating solutions.

Approach Implemented in EPISODE

JPL

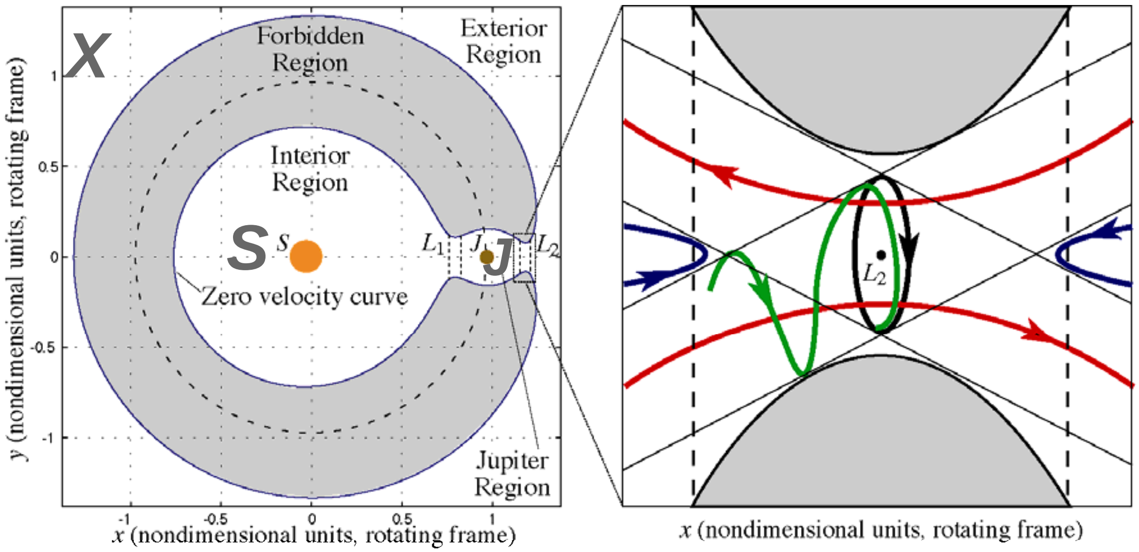
- Our Goal – to make the “initial guess” problem (semi) automated, and computationally as efficient as possible, enabling deterministic optimization algorithms to generate an increased number of feasible (and near optimal) solutions for fixed computational expense.

- The technical innovation explored in this project includes a probabilistic algorithm for trajectory generation (implemented computationally with the code EPISODE), which provably converges to globally optimal solutions.

- Two key components to this approach are:
  1) the ability to generate a large class of possible trajectories in a semi-automatic fashion utilizing the “interplanetary superhighway” (IPS) (a network of exact solutions of the 3 and higher-body dynamics which asymptotically wind on and off periodic orbits)
  2) The ability to evaluate a trial trajectory’s “probability” of leading to an optimal solution with continued computing.

- Key question - What is the connection between a probability on paths and the segments of “thrust-free” trajectories “shadowing” the invariant manifolds of the underlying dynamics?

Orbital Zoology Near the Lagrange Points



S: Sun Region

J: Jupiter Region

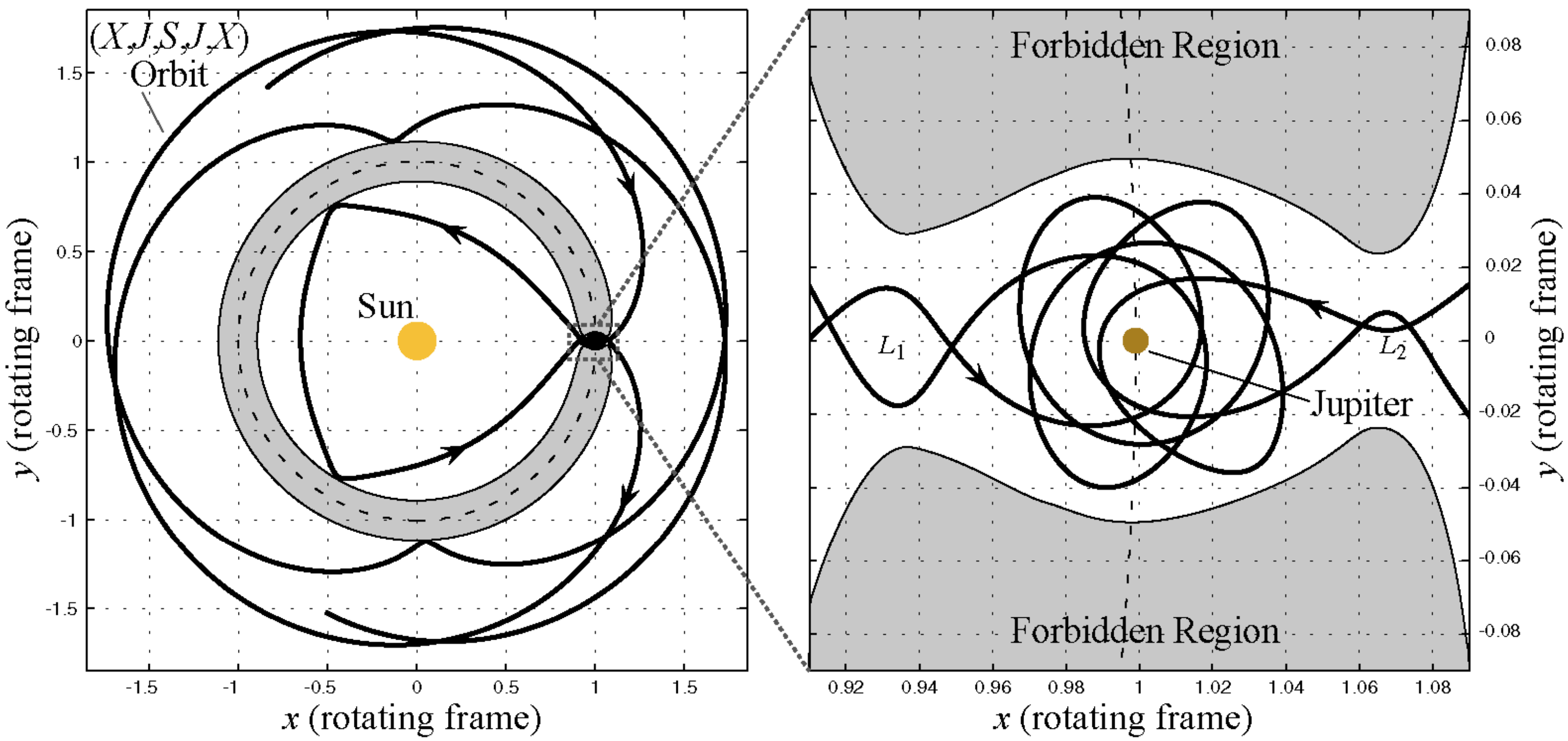
X: Exterior Region

(Outside Jupiter's Orbit)

Four Families of Orbits:

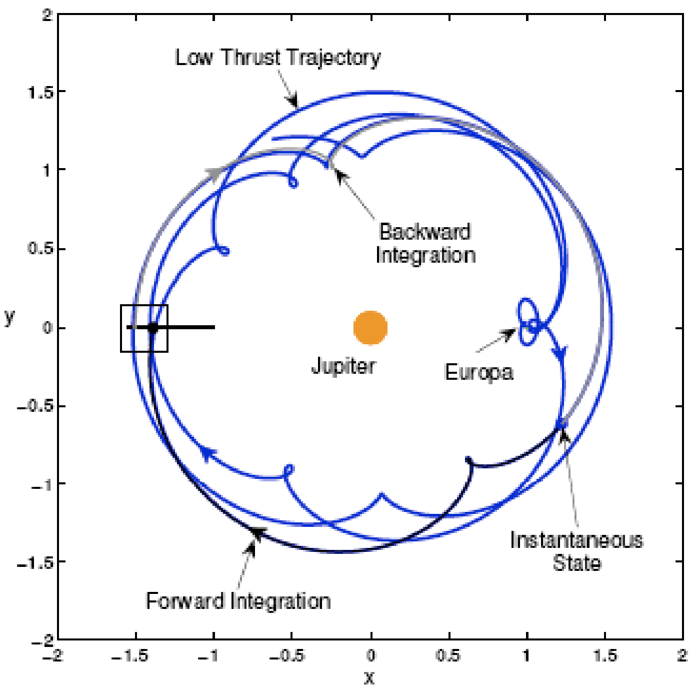
- Periodic Orbit (Planar Lyapunov)
- Spiral Asymptotic Orbit (Stable Manifold Pictured)
- Transit Orbits (*MUST PASS THRU LYAPUNOV ORBIT*)
- Non-Transit Orbits (May Transit After Several Revolutions)

Orbit with Itinerary (X,J;S,J,X)

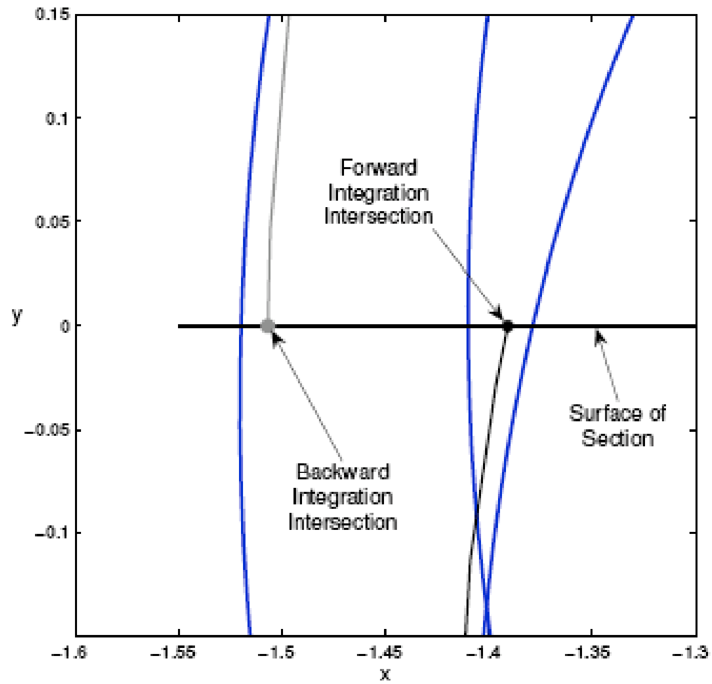


- Using Symbolic Dynamics Technique to Realize Complex Itinerary
- Capture Around Jupiter Multiple Revolutions (Specifiable)
- Note (2:3) to (3:2) Resonance Transition

Shadowing CR3BP Invariant Manifolds (1 of 2)



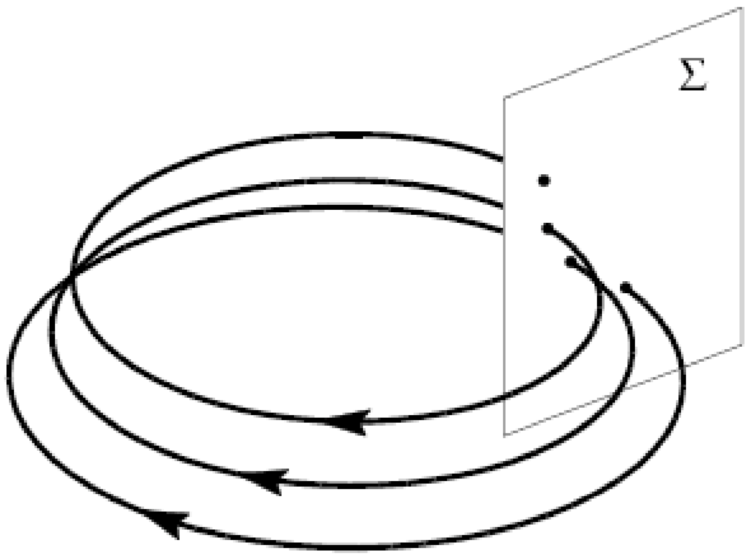
(a) Trajectory Overview

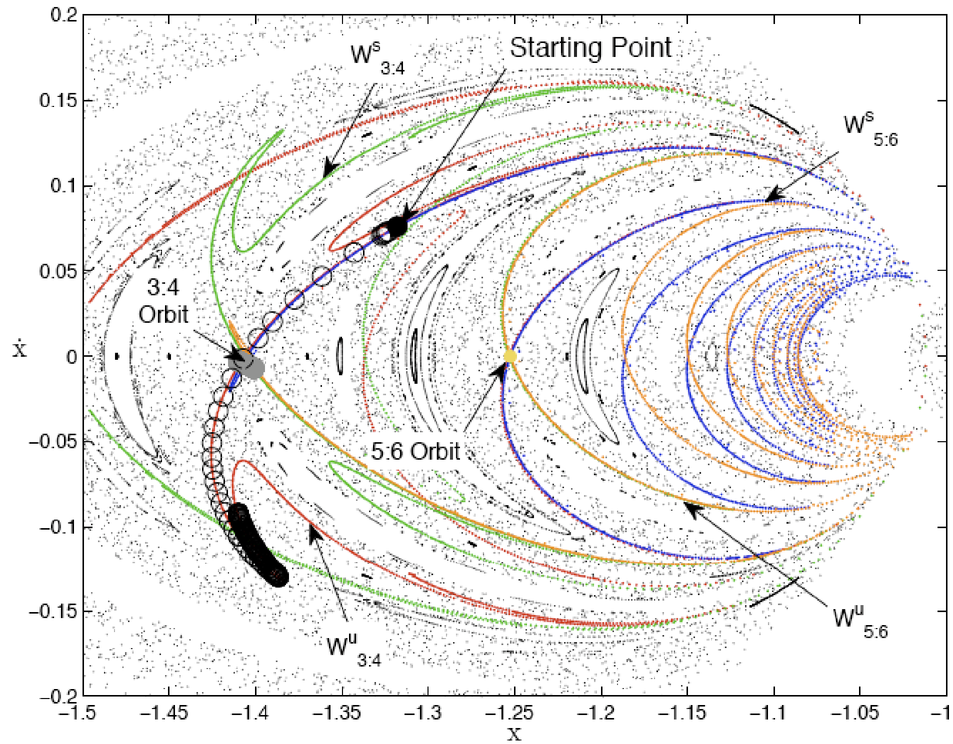


(b) Boxed Region

R.L. Anderson; M. W. Lo; "The Role of Invariant Manifolds in Low Thrust Trajectory Design", Journal of Guidance, Navigation, and Control, in press.

"Shadowing" CR3BP Invariant Manifolds (2 of 2)





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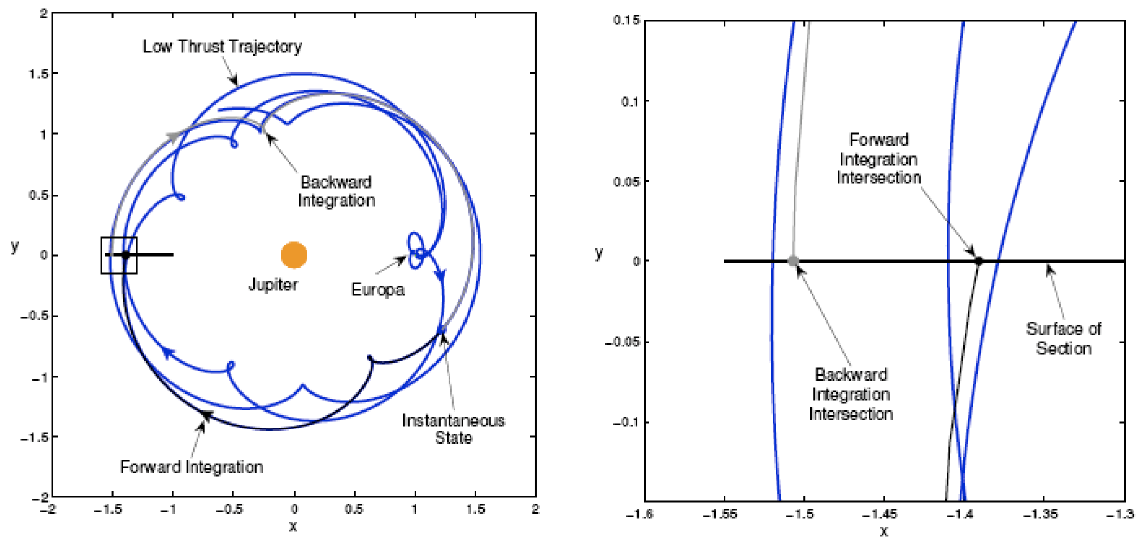
Relating the IPS and Feasible Solutions

- **The near optimal solutions “shadow” invariant manifolds (of varying energy) of the thrust-free dynamics.**
- **It is easy to generate thrust free trajectory segments on these (instantaneous) invariant manifolds – just integrate, for a selected point on the near optimal trajectory, the Hamiltonian equations forward and backward…**



(a) Trajectory Overview

(b) Boxed Region

$$\hat{y} = \min_y \left\| \acute{Y} - F \circ y \right\|_{L^q}$$

Optimal Solution

$$\max_j \left\| x_j - \hat{y} \right\| \leq \varepsilon$$

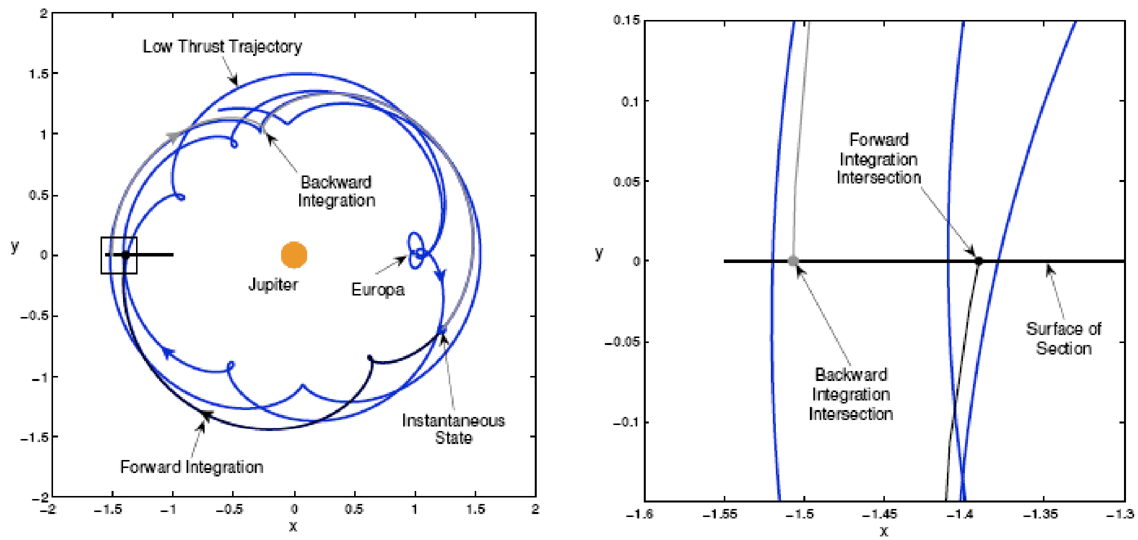
Thrust-free trajectory segments

$$-\log p(y) = \beta \left\| \acute{Y} - F \circ y \right\|^2 + \log Z(\beta) \qquad -\log p(x_j \mid y) = \theta \left\| x_j(t_j) - y(t_j) \right\|^2 + Z(\theta)$$

Relating the IPS and Feasible Solutions, continued…

-**Can generate thrust free trajectory segments given a feasible solution, or…**

- **Generate feasible solutions given thrust-free segments!**



(a) Trajectory Overview (b) Boxed Region

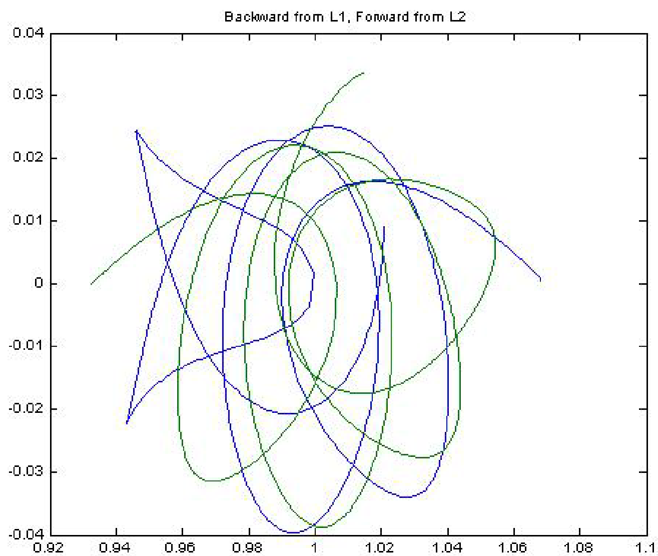
$$p(x_j, y) = p(x_j \mid y)\, p(y) = p(y \mid x_j)\, p(x_j)$$

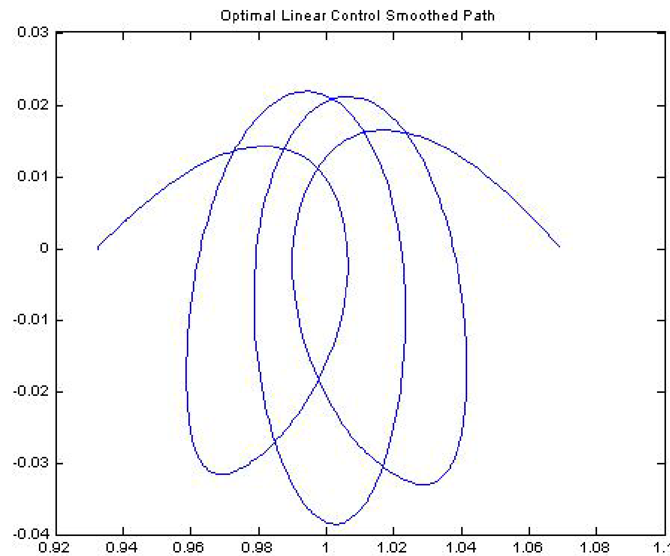
$$-\log p(y \mid x_{1:J}) \approx \sum_{j \le J} (y - x_j)\left[\partial_t + J \circ x_j\right]^T \left[\partial_t + J \circ x_j\right](y - x_j)$$

Example – Patching Thrust-Free Segments

$$-\log p(y \mid x_{1:J}) \approx \sum_{j \le J} (y - x_j)\left[\partial_t + J \circ x_j\right]^T \left[\partial_t + J \circ x_j\right](y - x_j)$$

- **Generate two thrust-free segments, one forward in time along an unstable L1 halo manifold, and the other backward in time along an (forward stable) L2 halo manifold.**
- **Maximize the (conditional) Gaussian – involves a linear problem with solution determined by the thrust-free segments, and the Jacobian (of the Hamiltonian dynamics) along the segments**





Summary, and On-Going Work

- **We are now entering a new era of mission design with interest in multi-body missions, which require the inclusion of 3 and 4 body dynamics (example – JIMO), utilizing low-thrust propulsion to achieve the required integrated delta V.**

- Trajectory generation is a difficult constrained optimization problem, with a good initial guess is required for convergence to near optimal solutions (important for low-thrust trajectory design!)

- Our Goal – to make the “initial guess” problem (semi) automated for preliminary mission design, using two key components: 1) the ability to generate a large class of possible trajectories in a semi-automatic fashion utilizing the “interplanetary superhighway” (IPS) (a network of exact solutions of the 3 and higher-body dynamics which asymptotically wind on and off periodic orbits), and 2) the ability to evaluate a trial trajectory’s “probability” of leading to an optimal solution with continued computing.

- Status and future work
  - Core collection of routines completed, integrating automatic differentiation libraries (for Jacobian computations along thrust-free segments), initial value problem solvers, and routines to solve the linear variational problems given thrust-free trajectory segments (tested with CR3BP problems).
  - MCMC driver routines written – now extending in a simulated tempering framework to improve mixing (important as our target path-probability is inherently multi-modal).
  - Completion of 3 body trajectory generation targeted for end of December 2009, and attempt at automatic 4-body solution generation by May, 2010.