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A PRELIMINARY INVESTIGATION OF THE JUPITER ICY MOON ORBITER TRAJECTORY

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NASA's initiative to send a single electric propulsion spacecraft to orbit Callisto, Ganymede, and Europa within a decade will require a very complex trajectory. Strong multi-body effects combined with low-thrust control of capture and escape will make trajectory design challenging. Multi-body phenomena that create mission risk and those that create opportunities need to be identified to improve the odds of success.

This paper describes a trajectory that begins in low Earth orbit and ends in low Io orbit. A spacecraft following this trajectory will orbit Callisto, Ganymede, and Europa in succession before orbiting Io. This trajectory highlights the complexity, some of the risks, and also some of the advantages that can be gained from using low-thrust in strong multi-body regimes. The trajectory includes an extended mission to Io. The NASA initiative does not include Io largely because the radiation environment near Io is too severe. Electric propulsion is enabling for this trajectory due to a ΔV requirement on the order of $30 \frac{km}{s}$ for reasonable flight times.

Optimizing low-thrust trajectories, and in particular, trajectories that include escape and capture is inherently difficult. The continuous operation associated with low thrust significantly increases the optimization complexity. In addition, multi-body force laws further compounds the optimization complexity. Finally, to fully optimize a trajectory from Earth to orbits around the Galilean moons, the interplanetary scale portion from Earth to Jupiter must be optimized simultaneously with the Jupiter centered spiral and at least the first of the of the moon-centered spirals. A trajectory involving an interplanetary leg, a Jupiter centered spiral, and a Galilean Moon centered spiral introduces several very different time and distance scales into mathematical formulation. Widely varying time and distance scales are well known to create difficulty for optimization.

The optimization algorithm called Static/Dynamic Control¹ (SDC) was used to design the complete trajectory. SDC is a general, gradient-based optimization method that is distinct from both parameter optimization and the calculus of variations. Trajectories are integrated with a multi-body force model and finite burns. Optimizing capture and escape trajectories with a multi-body force model results in a significant improvement in the flight time and mass delivered compared to patched two-body formulations². A strong point of the SDC approach is its ability to find and exploit multi-body phenomena³ and handle widely varying physical scales. It is not necessary to specify intermediate flyby bodies or multi-body interactions on input. This is in contrast to many other optimization methods.

The trajectory begins in low Earth orbit (2500 km altitude) with an initial mass of 9400 kg. The thruster specific impulse is 9000 seconds, the thruster efficiency is 74%, and the power available is 200 kW. Part of the complete optimal trajectory is illustrated by Figures 1, 2, and 3. These figures illustrate the trajectory from high Earth orbit to mid-level Callisto orbit. Figure 1 provides a solar system scale view of the trajectory. Figure 2 provides a view of the same trajectory in the vicinity of Jupiter. Figure 3 provides a view of the same trajectory in the vicinity of Callisto. Figure 3 is plotted using Jupiter-Callisto Lagrange point centered, rotating coordinates. The large lobe in the trajectory in Figure 3 is part of an unstable Distant Retrograde Orbit or DRO. The DRO is a multibody orbit similar to halo orbits. SDC optimization found DRO type captures on its own. DRO type captures are extremely efficient if the final target orbit is a low- or mid-level retrograde orbit around Callisto. It turns out that retrograde orbits around the Galilean moons are necessary for orbital stability.

There is an escape analogue to the DRO capture. The DRO escape showed up in the converged solution for the the escapes from Callisto, Ganymede, and Europa. The performance of the DRO capture/escape was compared to alternate types of capture/escape including capturing through a Jupiter-Moon halo orbit and direct spirals.

The transfers between Callisto, Ganymede, Europa, and Io were achieved in 95, 40, and 54 days respectively. The transfers required little propellant expenditure (mostly coasting) by using multi-

body effects and resonant flybys of the moons.

As an offshoot of this investigation, it was found that *stable* DRO orbits could be used to provide parking for the orbiter with no station keeping required for over a year or more. The stable DROs requires very little ΔV to depart to a higher or lower energy orbit around Jupiter.

This paper will conclude with a discussion of moon impact risk associated with the trajectory analyzed. The risk of moon impact is non-negligible due to the inherently low control authority of low-thrust near the escape and capture at each moon.

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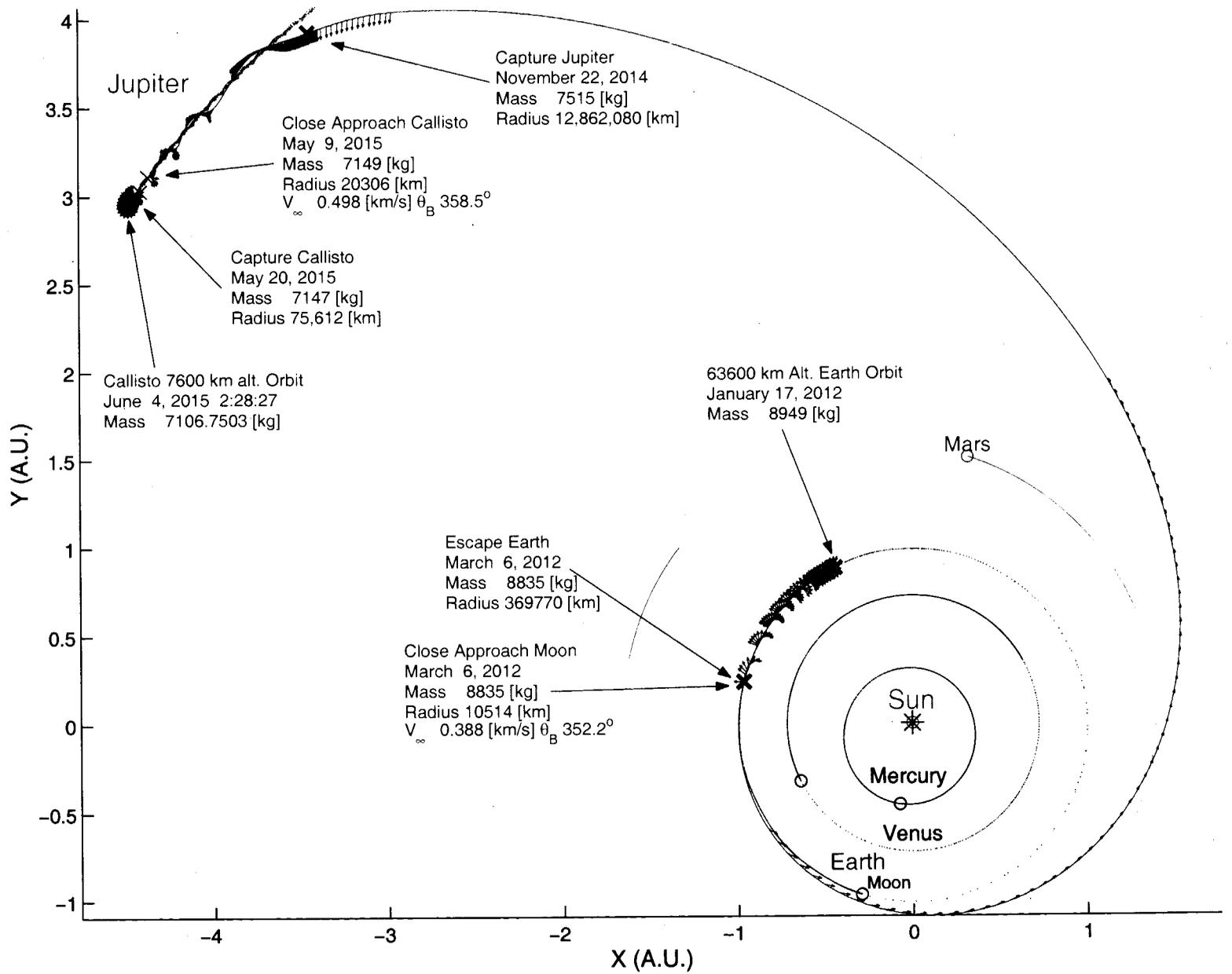


Figure 1: SDC Optimal trajectory from high Earth orbit to mid-level Callisto orbit. The trajectory includes flybys of both the Earth's moon and Callisto.

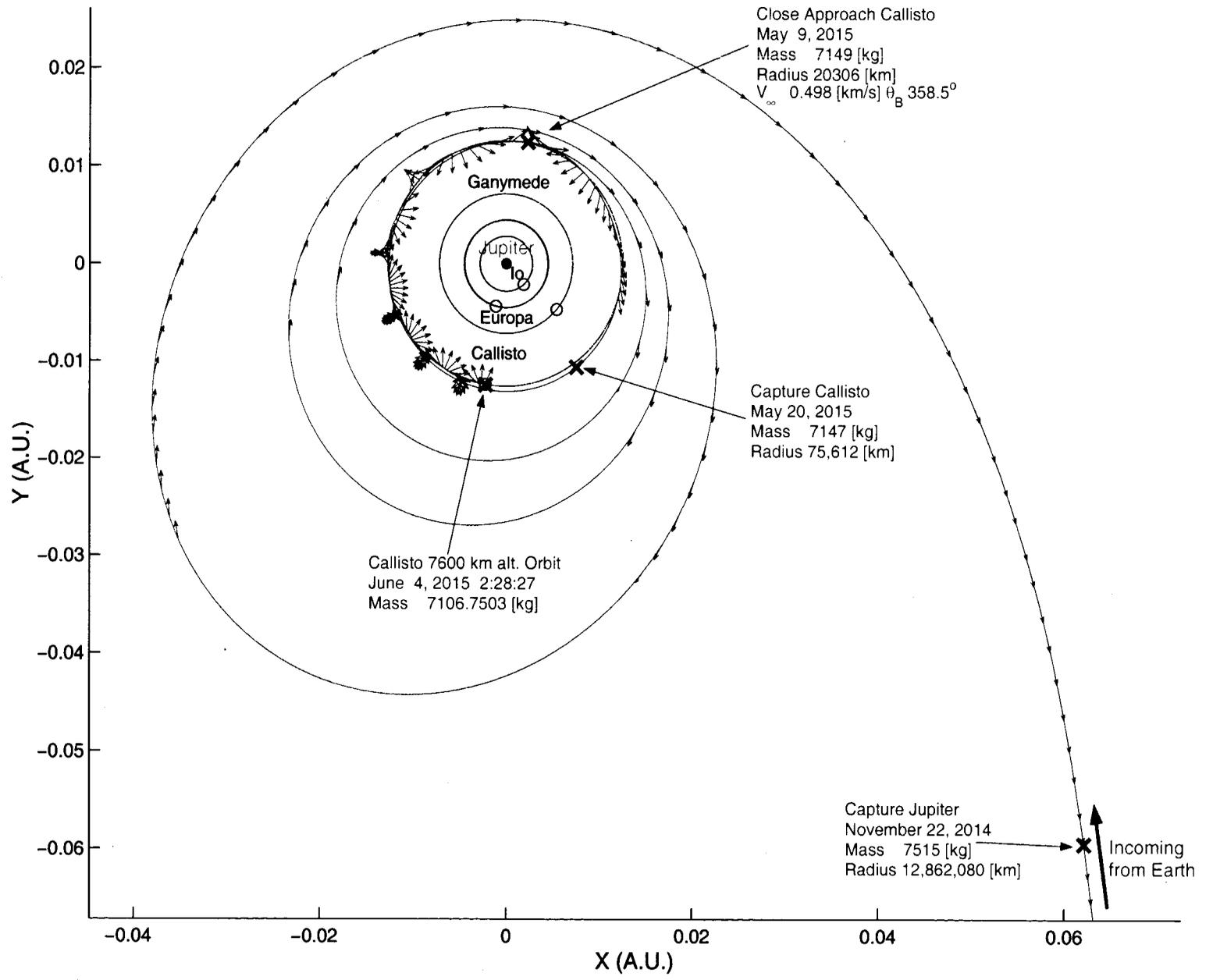


Figure 2: SDC Optimal trajectory from high Earth orbit to mid-level Callisto orbit highlighting the Jupiter capture spiral.

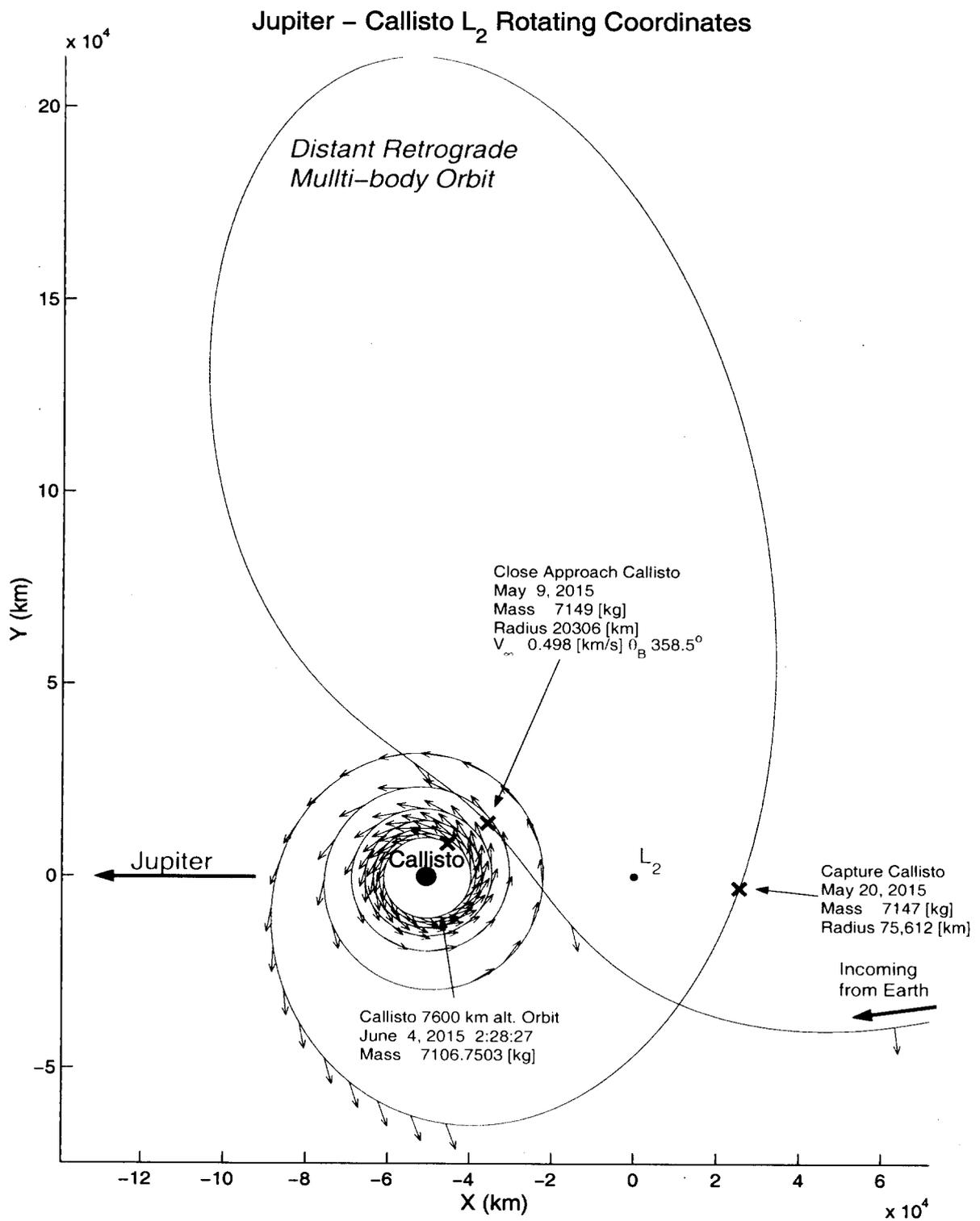


Figure 3: SDC Optimal trajectory from high Earth orbit to mid-level Callisto orbit highlighting the Callisto capture and spiral. This trajectory makes use of a Callisto flyby that inserts the vehicle in an unstable distant retrograde multi-body orbit. This type of capture is highly efficient in the Jovian system.