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Jupiter Icy Moons Orbiter Mission Design Overview

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JUPITER ICY MOONS ORBITER MISSION DESIGN OVERVIEW

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An overview of the design of a possible mission to three large moons of Jupiter (Callisto, Ganymede, and Europa) is presented. The potential Jupiter Icy Moons Orbiter (JIMO) mission uses ion thrusters powered by a nuclear reactor to transfer from Earth to Jupiter and enter a low-altitude science orbit around each of the moons. The combination of very limited control authority and significant multibody dynamics resulted in some aspects of the trajectory design being different than for any previous mission. The results of several key trades, innovative trajectory types and design processes, and remaining issues are presented.

INTRODUCTION

Europa is one of the highest priority targets for planetary science. The potential exists for a liquid water ocean under a crust of ice, and with liquid water comes the enticing prospect of life. Unfortunately, Europa is deep in the gravity well of Jupiter and within an intense radiation environment, making an extended mission at Europa extremely challenging. The Galileo mission flew by Europa several times and acquired evidence for the existence of an ocean. The Europa Orbiter project began in the late 1990s and neared completion of the formulation phase before being cancelled in 2001.

In 2002, NASA began seriously considering the use of nuclear reactors for planetary missions. The immense power available from the reactors would open up a new era in planetary exploration, enabling the use of high-power science instruments, high data rate communications, and advanced electric propulsion. Concept studies for a mission to three large moons of Jupiter, including Europa, were completed in 2002, and the Jupiter Icy Moons Orbiter (JIMO) project began Phase A in 2003. The objectives of JIMO were both technological (develop a safe nuclear reactor powered spacecraft) and scientific (explore the three icy moons of Jupiter). Several requirements were placed on the project, including the use of nuclear electric propulsion, accommodation of a large scientific payload, reaching the Jovian system by 2021, and achievement of low-altitude science orbits around Callisto, Ganymede, and Europa.

A mission transferring from Earth to Jupiter and into low-altitude orbits at three massive moons at Jupiter requires a large amount of ΔV. In order to make this mission feasible, an efficient propulsion system is required. With the large amount of power available from the nuclear reactor, nuclear electric propulsion was a logical choice.

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However, even though the power available for propulsion is substantial, the large mass inherent in a system using a nuclear reactor results in a low thrust-to-mass ratio for the spacecraft.

The dynamical environment at Jupiter is complex. The trajectories at Jupiter are governed by multiple gravitational fields and spend considerable time in regions of space in which more than one body is exhibiting significant influence on the spacecraft. With appropriate design techniques, we can find very efficient pathways by taking advantage of these intricate dynamics. An additional complexity results from the very low acceleration capability of the spacecraft. We are virtually being churned around by the ocean while using an oar for control. We must choose our strokes carefully and deliberately. The combination of very limited control authority and significant multibody dynamics results in some aspects of the trajectory design being different than for any previous mission.

A challenging aspect for low-thrust mission design in general is that the trajectory design is closely coupled with other project elements, even at an early stage. The trajectory depends on the launch vehicle capability, the mass of the spacecraft, characteristics of the power and propulsion subsystems, and capabilities of the attitude control. With JIMO being the first mission powered by a nuclear reactor, this coupling proved even more challenging since the system parameters had large uncertainties initially and significant external constraints as the design progressed.

This paper presents an overview of the mission design for the JIMO mission through the cancellation of the project in 2005. As has been described, there were many new and challenging aspects of the mission, requiring new tools and innovative techniques to be developed as we proceeded. We performed a wide variety of trades and developed fully integrated, high fidelity trajectories from interplanetary injection through the end of the mission. (The reference trajectory referred to later in this paper is the latest one that was completed.) Much of the work has been documented in papers. (See References 1-41.) This paper summarizes some of the key trades and results. More details are provided in the references.

INTERPLANETARY TRANSFER

An extensive database of direct interplanetary trajectories was created in order to be able to quickly perform broad trades in system parameters such as power, specific impulse, and mass. When coupled with subsystem mass models and potential launch vehicle capabilities, the database was used to explore a large trade space constrained by technological and other practical considerations. We could then focus on regions with reasonable system parameters and good mission characteristics.

Several options were considered for departure from Earth. The most appropriate option depends on the capabilities of the launch vehicles being considered. One option is

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to launch into an orbit about the Earth and use electric propulsion to gain energy and escape the Earth. Another option is to use the launch vehicle or a chemical transfer stage to escape the Earth. Spiraling out with electric propulsion provides more delivered mass or requires less launch vehicle capability but typically has a longer flight time. The project decided early on to escape the Earth using a chemical propulsion system. The requirement on arrival date forced a flight time that would have been difficult to meet with a spiral out option.

The project also had a guideline that JIMO would not require a significant new launch vehicle development. We baselined a launch vehicle that was a reasonable evolution from current launch vehicles, although we had to consider many different options. Using a chemical system to escape the Earth and relying on launch vehicle capability not much beyond the current level led to a scenario with three launches: one launch for the fully fueled JIMO spacecraft and two launches for two chemical propulsion transfer stages. The three vehicles would rendezvous and mate in low Earth orbit.

The reference interplanetary trajectory is a direct trajectory with no planetary gravity assists (Figure 1).[32] We performed an extensive analysis of a variety of gravity assist options with Earth, Venus, and Mars.[11,23,24] Results of one of these analyses are shown in Figure 2. The solid black line in Figure 2 is the direct case with optimized launch energy. All the other cases include at least one planetary gravity assist. There are many gravity assist options that both increase the delivered mass and decrease the flight time. Some of the Earth gravity assist options are particularly interesting because they are among the best performers and provide consistent performance at regular intervals of launch opportunities.
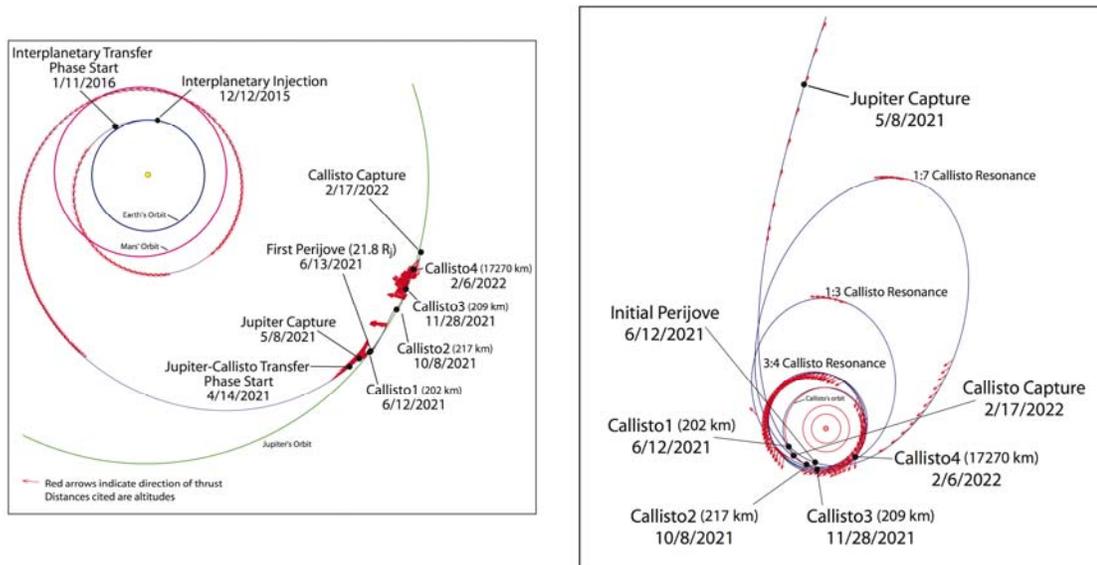

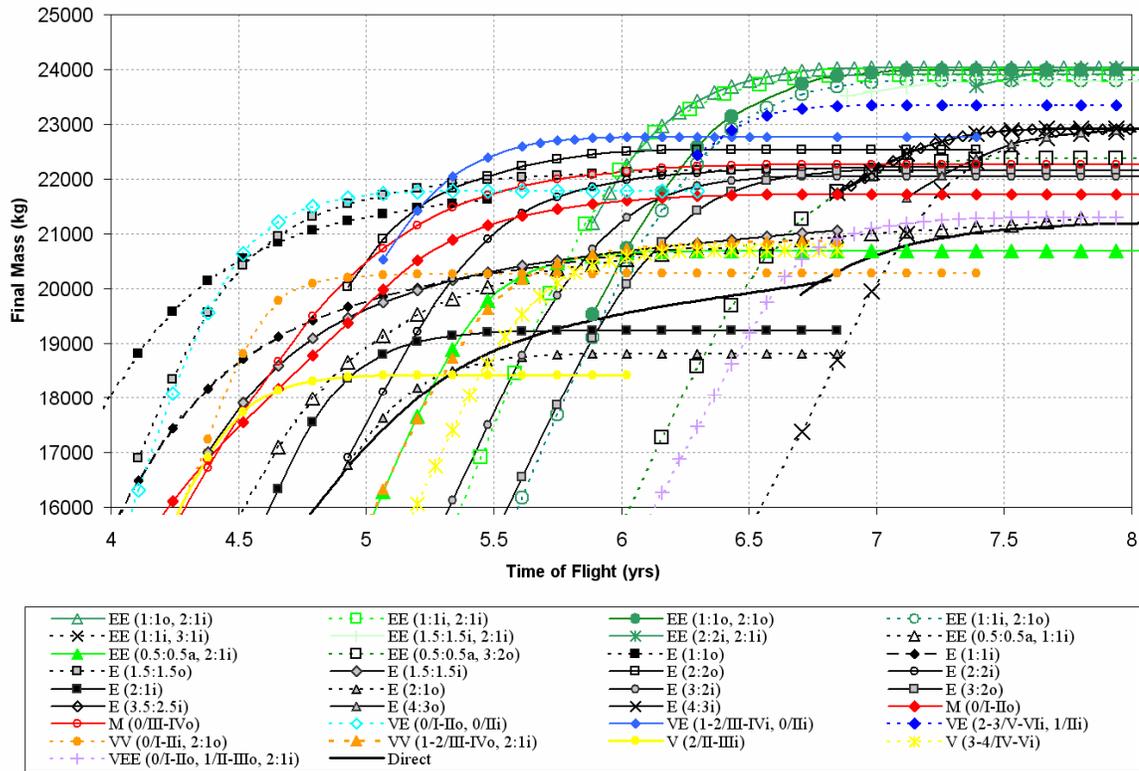**Figure 1 Reference Interplanetary Trajectory and Jupiter Arrival**

Figure 2 Gravity Assist Trajectories

The injection period for the reference trajectory can be quite long without sacrificing significant performance. For example, the injection period is potentially as long as 84 days at the cost of 0.3% of delivered mass to Jupiter. If we were to allow slightly longer transfer times for backup injection opportunities, the injection period could be extended indefinitely at a reasonable cost in performance. The mission is also extremely robust to injection vehicle delivery dispersions.[33]

TRAJECTORY NEAR JUPITER

The reference trajectory flies by Callisto on the initial approach to Jupiter and uses additional Callisto gravity assists prior to capture at Callisto (Figure 1). These gravity assists reduce the required propellant for this phase of the mission by about 80% and also decrease the flight time. We analyzed using Ganymede for gravity assists prior to capture at Callisto, but the results showed that Ganymede did not help when Callisto was to be the first moon orbited.

The reference trajectory orbits Callisto, Ganymede, and Europa, in that order. We also analyzed orbiting Europa first, then Ganymede, then Callisto. The delivered mass performance was very similar between the two cases. The Callisto first case has a slightly shorter flight time and lower radiation – potentially much lower radiation depending on the end-of-mission orbit.

Capturing at a body using low-thrust propulsion is different than for high-thrust missions. The reduction in orbital energy is necessarily slower; hence, a substantial amount of time is spent in a transition region between escaped from the moon and captured at the moon. During this transition, the multibody effects are significant, and in many cases an uncontrolled spacecraft would impact in a matter of days (Figures 3 and 4). This was particularly true when we tried to capture directly into near-polar inclination orbits. We did find very stable near-equatorial, retrograde orbits that we could capture into, but to avoid the unstable regions, we had to change the inclination at relatively low altitudes which is very costly in terms of propellant and flight time. At Callisto and Ganymede, we could follow paths to the science orbit that would not impact for at least a couple weeks; however, this is extremely costly at Ganymede since the relatively safe region is at a much lower altitude with Ganymede being closer to Jupiter. At Europa, the relatively safe region essentially disappears within about 45 deg of the poles. With the extremely high radiation environment at Europa, the decision was made to get to the science orbit as fast as reasonably possible, allowing the uncontrolled lifetime to be very short.
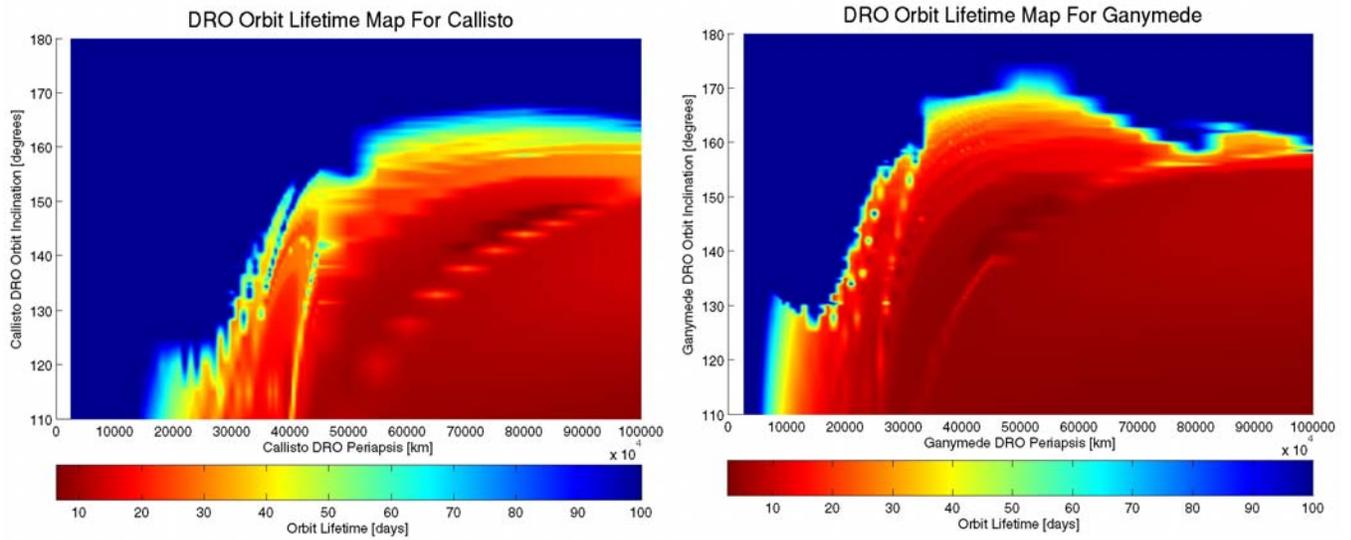
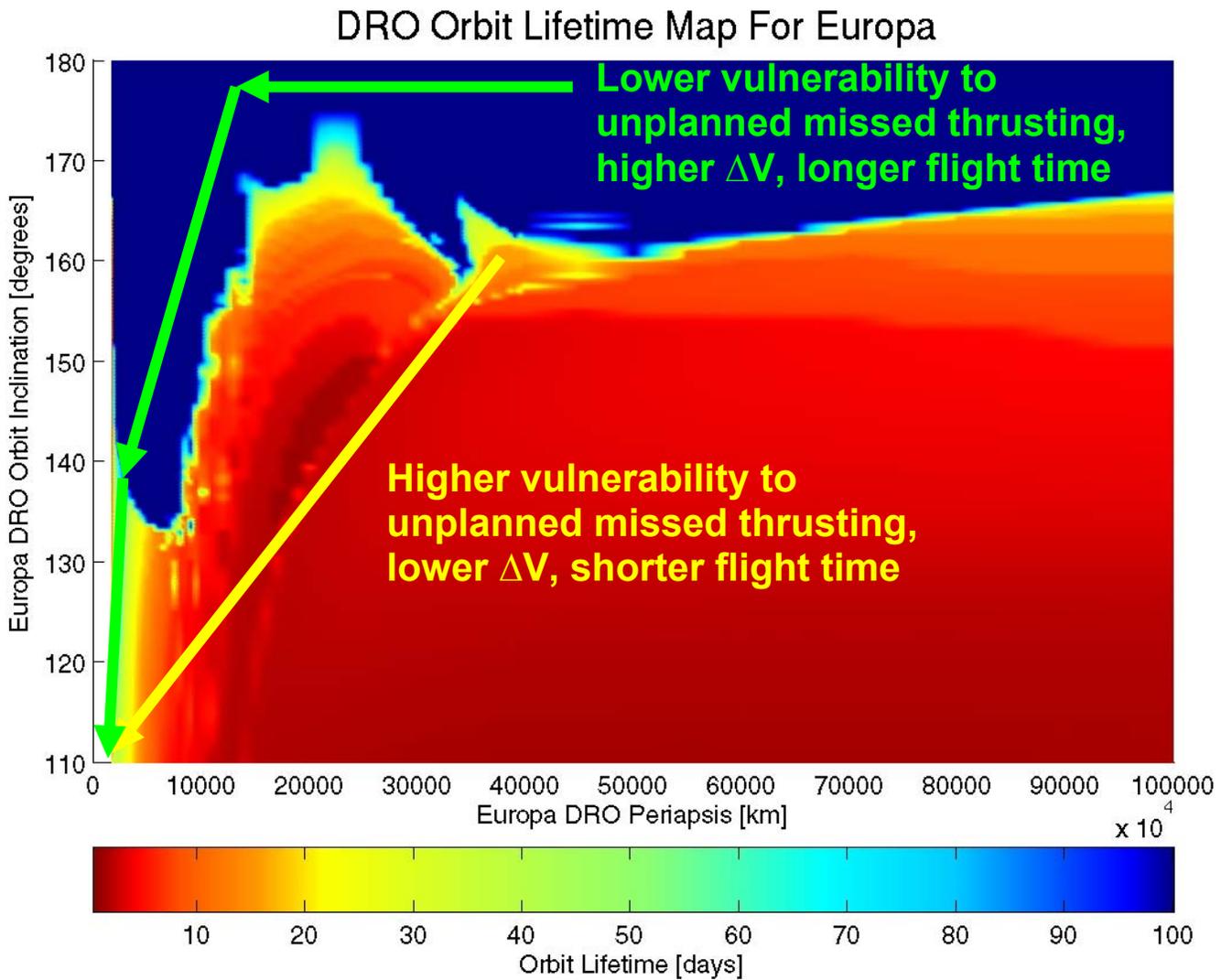**Figure 3 Orbit Lifetime Maps for Ganymede and Callisto**

Figure 4 Orbit Lifetime Map for Europa

We recently began exploring and discovering other types of captures that are very promising. These "manifold captures," as we referred to them, approach the moons along stable manifolds of unstable periodic orbits (of which there are many) near the moons. The manifold captures performed well in terms of propellant mass, flight time, and controllability with reasonable lifetimes.[34,35] These types of captures would have been explored more fully given more time. They may also be very useful for high-thrust missions.

Overall, significant trades are available between propellant mass, flight time, and stability for a variety of capture types. The requirements on trajectory lifetimes and acceleration levels (translational and rotational) will drive the design of the captures and, hence, many other aspects of the mission.

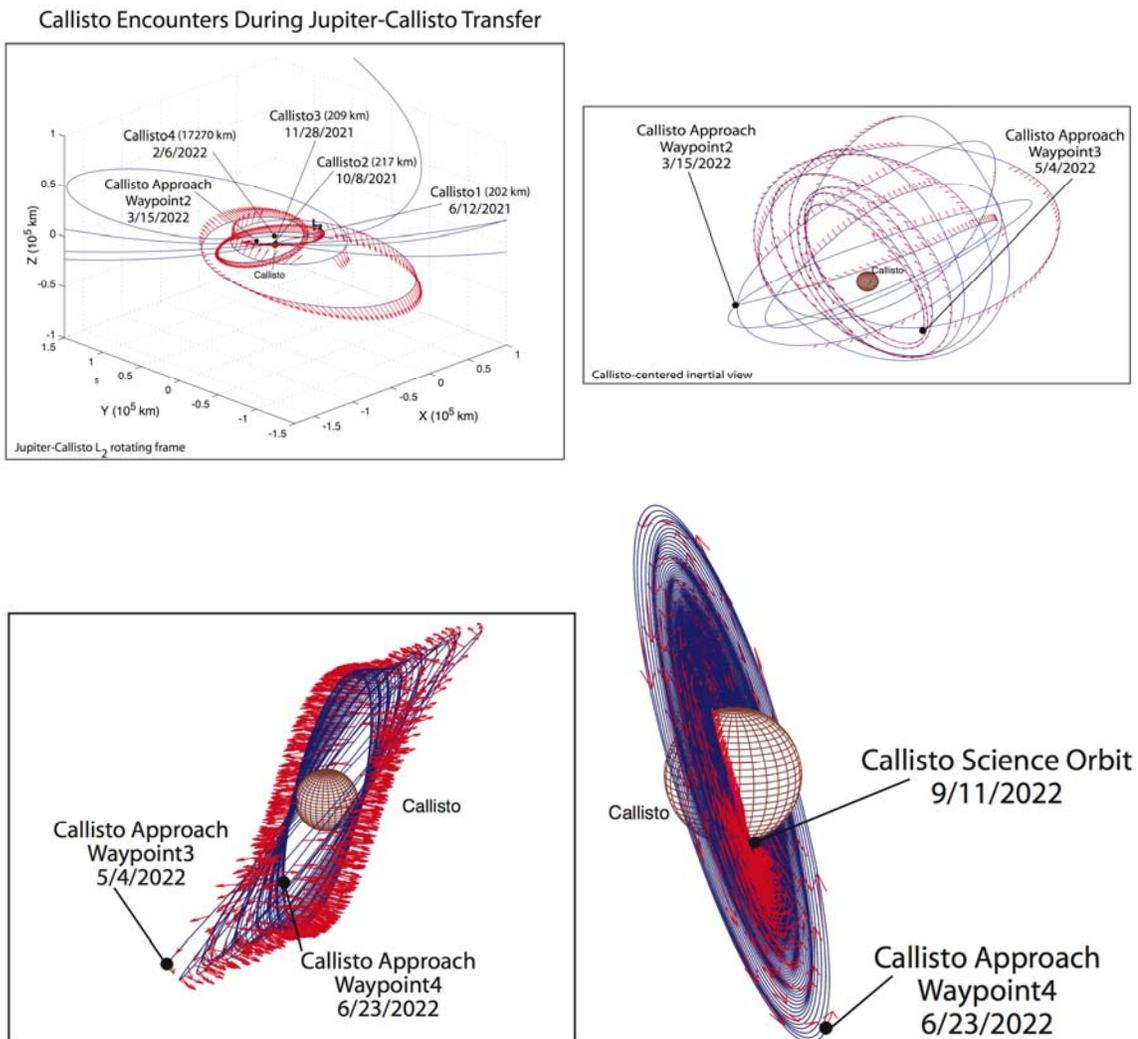Figure 5 illustrates the capture at Callisto and transfer down to the science orbit.

Figure 5 Capture at Callisto and Transfer to the Science Orbit

The transfers between the moons take advantage of multibody effects and gravity assists to reduce the required propellant for these phases of the mission by about 80%. We explored many different types of transfers, including various combinations of resonances with the moons. The best transfers depend on the type of escapes and captures used at the moons and the available level of acceleration. The transfer from Callisto to Ganymede for the reference trajectory is shown in Figure 6.
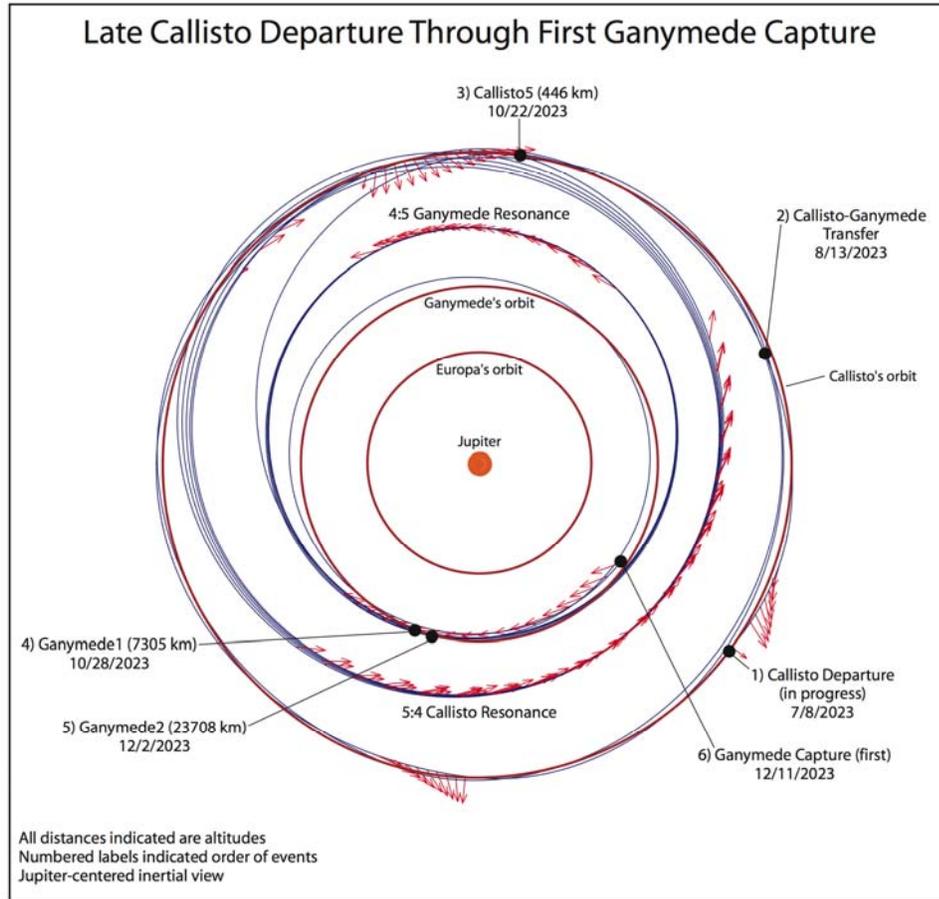

Figure 6 Transfer from Callisto to Ganymede

SCIENCE ORBITS

We knew from previous studies that low-altitude orbits around the moons with inclinations within about 45 deg of the poles are unstable due to the gravitational influence of Jupiter, that is, if left uncontrolled, they impact the moon in a relatively short time.[42] Since Europa is the closest to Jupiter of the icy moons and also the smallest, the time scale for this effect is the shortest at Europa with impact occurring on the order of 10s of days. The previous studies considered only a very simple gravity field for the

moons, including only the effect of J2. When we started considering more detailed gravity fields, we discovered that higher order terms can have a significant effect on the stability of the orbits. For example, a significant value for J3 makes orbits at essentially all inclinations unstable. We did discover very special cases of near polar "frozen orbits" that have relatively long lifetimes,[28] but the exact orbital conditions for these orbits depend on the details of the gravity field which we won't know until we have been at the moon for awhile.

Stability of the orbits also has a direct effect on the science orbit maintenance and, hence, the orbit determination. A trade exists between the frequency and total delta-V required for the maintenance maneuvers, with smaller, more frequent maneuvers potentially resulting in less ΔV overall. Lower total ΔV results in less total time interruption to the science, but the more frequent maneuvers may significantly degrade the orbit determination. So the selection of the precise elements for the science orbits and the orbit maintenance strategy are still unclear.

The mission ends with the spacecraft in the science orbit at Europa. We explored options for transferring to orbits that do not impact Europa for an extended duration (> 1000 years), but the transfers require more propellant and more time in the high radiation environment at Jupiter.

CONCLUSION

Designing the ambitious JIMO mission presented many interesting and new challenges. The spacecraft configuration and parameters placed severe constraints on the mission design, including a low thrust-to-mass ratio. The dynamical environment at Jupiter is complex, and the radiation environment is harsh. Even with all of these constraints and challenges, we were able to meet all of the high-level mission design requirements placed on JIMO.

A tremendous amount of innovative work was completed over the past three years. Many new tools and trajectory design techniques were developed and could play an important role when we return to seriously considering reactor powered missions of exploration. In addition, much of this work also applies to other types of missions, including low-thrust missions in a multi-body environment (e.g., the Earth-Moon system) or even high-thrust missions to any massive moon (e.g., Europa).

ACKNOWLEDGMENT

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