MIXING MOONS AND ATMOSPHERIC ENTRY PROBES: CHALLENGES AND LIMITATIONS OF A MULTI-OBJECTIVE SCIENCE MISSION TO JUPITER

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ABSTRACT

Current advanced mission concepts to explore the Jovian system target either Jupiter or its satellites. NASA's multi-billion-dollar "Jupiter Icy Moons Orbiter" (JIMO) advanced mission plan focuses only on orbiting Callisto, Ganymede, and Europa, using fission-based electric power for both propulsion and operations. Concurrently, concepts for Jupiter entry probe missions flown from a "New Frontiers" mission are being considered. It has been suggested that adding a Jupiter entry probe to JIMO might achieve the scientific objectives of both while costing less than the two implemented separately. Recently a small JPL team identified five combined-mission architectures that retain JIMO's post-capture mission design. JIMO's conceptual mission design, optimized for a given set of objectives, uses up all available degrees of freedom. Adding entry probe objectives adversely affects achieving the original objectives, or poorly achieves the probe objectives. We outline these five options in this paper, highlighting advantages and disadvantages of each. Also we describe a more recently conceived architecture that significantly alters JIMO's post-capture mission design, meeting both sets of objectives well, but adding time, complexity, and ΔV to the original JIMO mission. Options for adding entry probes to JIMO require careful evaluation to ensure the added science return is worth the additional effort.

INTRODUCTION

The quest to better understand our solar system and life within it drives the exploration of Jupiter and its moons. Galileo, the most recent of our missions to the Jovian system, vastly improved understanding of that system but raised further questions that call for new science missions there. Some advanced mission concepts focus on Jupiter's satellites while others would study Jupiter itself. As the first mission of Project Prometheus, the multi-billion-dollar "Jupiter Icy Moons Orbiter" (JIMO) mission would orbit Callisto, Ganymede and Europa, using fission-based electric power for spacecraft systems, instruments, and for Nuclear Electric Propulsion (NEP). As initially formulated, this mission focuses on the icy satellites only, searching for evidence of global subsurface oceans that may harbor organic material or even life.

At the same time potential investigators and mission implementers have discussed concepts for entry probe missions that might fit the ~$650M "New Frontiers" category. Science objectives for Jovian deep probes are assumed to be similar to those of the Galileo probe with two major distinctions. First, the probe should reach at least the 100-bar pressure level, since previous measurements to 20 bars did not answer high-priority questions about Jupiter's atmospheric structure and composition. Second, the probe's entry location should be selected to observe a representative sample of Jupiter's atmosphere. The Galileo probe entered a region dynamically different from most of Jupiter's atmosphere, a "5-micron hot spot", where down-welling air significantly depleted of the usual volatiles yield thin or absent clouds. Areas with normal vertical profiles of ammonia, hydrogen sulfide, and water have yet to be sampled in situ.

It was recently suggested that adding a Jupiter entry probe to JIMO might achieve the scientific objectives of both, while costing less than the two missions implemented separately. Recently a small team at JPL studied five such combined-mission architecture options. We outline those architectures here, highlighting the advantages and disadvantages of each. Based on a generic probe entry scenario, we demonstrate how distance between the probe and the JIMO spacecraft places telecommunications limitations on such missions. While most of these options were found unfeasible we describe one, which might allow for a combined mission without significantly impacting on the baseline JIMO mission. In addition we outline another option that yields a solution only if significant changes to the original mission architecture are allowed.

METHODOLOGY AND ASSUMPTIONS

In this section we outline the common elements used throughout the assessment, focusing on the sequence of events, the spacecraft, the entry probe and on telecommunications related issues. Trajectory calculations for the various mission architecture options are performed using the computer code Mystic[1,2], based on a preliminary JIMO spacecraft configuration. The S/C is launched on a Delta IV (4450) launch vehicle to a 2,500 km Earth orbit with a launch mass of 9,400 kg. From this orbit the S/C transfers to Jupiter on a low-thrust trajectory to complete the Icy Moons Tour, utilizing a 200 kWe NEP system, with a specific impulse (I_{sp}) of 9,000 s and a thruster efficiency of 74%. The trip time to Jupiter for all cases is ~3.7 years with identical Jovian approach parameters. The actual JIMO mission most probably will differ from this configuration. A Delta IV-Heavy (4050H) launch vehicle can deliver ~21.6 metric tons to a 1,000 km Earth orbit. This higher delivery capacity is needed to accommodate the nuclear fission reactor on-board. The reactor would provide 100 kWe power, with an I_{sp} of ~2,000 to 6,000 s. This would increase the trip time to ~6-7 years.

In-situ probe measurements cover atmospheric composition; temperature; pressure; wind speed; cloud particle composition, size and cloud bulk particle density; ortho-to-para H_2 ratio; and vertical flux of radiant energy. These measurements are performed with on-board instruments, such as a gas chromatograph / mass spectrometer, with an IR Spectrometer for ammonia; pressure and temperature transducers and accelerometers; a nephelometer for particle concentration; a net flux radiometer; a sound speed instrument (for ortho- to para-H_2 ratio); and an ultra-stable oscillator for Doppler wind experiments[3,4]. As derived from design studies, the probe mass is assumed to be around 160-250 kg without a propulsion system. For the option where onboard propulsion is required for the probe, the mass may increase to about ~350 kg. This is comparable to the Galileo probe (339 kg).

The envisioned probe mission follows a sequence of events similar to the Galileo mission, but with a deeper penetration into the Jovian atmosphere. After completion of its cruise phase, the spin stabilized probe performs an aerodynamic entry at hypersonic velocity in a region -7.5° from the equator. This latitude is chosen to avoid potential damage to the probe from passing through the equatorial ring. In addition, it provides an easy access from the preliminary baseline trajectory of the JIMO mission. A close equatorial entry supports science objectives and it benefits from Jupiter's rotation, resulting in an entry velocity of 48.1 km/s (for Option 1). This is comparable to the Galileo[3] and the Decadal Survey[4] missions with velocities reaching 47 km/s and 47.5 km/s, respectively. Atmospheric drag slows the probe by converting its kinetic energy that the heat shield dissipates. At ~0.01 bar pressure level the supersonic parachute – acting as a drogue – deploys then drops off with the aft cover at ~0.05 bar. The subsonic parachute opens, and at ~0.08 bar the heat shield is detached. The probe under the parachute descends to the 20 bar level in ~1.4 hours, during which data are collected and transmitted to the orbiter. The descent continues with the release of the deep probe. During its free fall to 100 bar, which takes ~0.6 hours[4,5], additional data are collected and sent to the orbiter. During this descent phase, the data transmitted to the orbiter are then relayed to Earth. In this assessment we are only concerned with the first telecom link, since the second link does not constrain the mission options.

If JIMO delivers a single probe, avoiding 5-micron hot spots will be important. In latitude bands where these hot spots occur, they grow, shrink, and move in longitude (and to a minor extent in latitude) on time scales of weeks. Adding a simple propulsion system to the entry probe allows some trajectory flexibility, particularly for adjusting entry longitude via entry timing, but the systems required to control the propulsion system add even more complexity, mass, and cost.

A telecommunication system sends the data to the orbiter. Its link performance is primarily determined by transmit and receive antenna sizes, transmit frequency and power, and distance. For similar telecom systems (similar receiver system noise temperatures, noise environments, same frequencies, etc.) data rates, R_{D2}, scale roughly as

$$R_{D2} = R_{D1}\left(\frac{P_{T2}}{P_{T1}}\right)\left(\frac{D_{T2}}{D_{T1}}\right)^2\left(\frac{D_{R2}}{D_{R1}}\right)^2\left(\frac{L_1}{L_2}\right)^2$$

Available space and heat shield dimensions limit the diameter of the probe's transmit antenna, D_{T2}, here assumed to be 0.35 m. Launch vehicle fairing considerations limit the orbiter's receive antenna diameter, D_{R2}, but with deployable primary reflectors the range of possible diameters is large. Here we use 3 m. We assume an effective radiated power, P_{T2}, of 30 W, similar to that of the Galileo Probe. For uplink through the Jovian radiation belts, L-band (~1.35 GHz) as used by the Galileo Probe is best: at higher frequencies, attenuation by ammonia and water vapor in the Jovian atmosphere reduce the effective power, while at lower frequencies the natural synchrotron radiation from the radiation belts greatly increases noise in the link. Atmospheric radio attenuation increases rapidly with depth below the 10 bar level. At the 100 bar level the supported data rate is only ~20% of that at 20 bars. The assumptions for power and antennae size yield a data rate of 33 bps at a communication distance, L, of 1 million km, with the probe at the 20 bar level.

The total data volume collected during the probe's descent is roughly 3.8 Mbits. Previous studies[4] indicate that each full sample obtained during probe descent consists of ~50 kbits of data, overwhelmingly mass spectrometer data. For the shallower levels, for pressures less than 20 bars, ~70 samples are collected for a total of ~3.5 Mbits. This sampling rate is based on the requirement of taking several samples per atmospheric scale height (~20-25 km) in Jupiter's upper troposphere, where a variety of processes can generate relatively steep gradients in important parameters. For the deeper levels, between 20 and 100 bar, atmospheric radio attenuation reduces the performance to a total of ~5-6 samples in that vertical range, yielding ~300 kbits of data. Finer sampling of simple parameters such as temperature and pressure would not significantly affect that data volume.

RESULTS AND DISCUSSION

In this section we address general telecommunication issues and summarize the six mission architecture options, one of which requires significant modifications to the baseline JIMO mission. Note that these six options are by no means an exhaustive treatment of all possible architectures.

Telecommunication

Previous studies[5] yielded estimates of data collection and transmission rates tailored to reasonable (and somewhat flexible) assumptions about transmit power, antennae sizes, and distances. These estimates provide performance goals for our telecommunications analyses. Descending under parachute to the 20 bar level in 1.4 hours, the probe should collect and transmit 3.5 Mbits of data at an average rate of ~700 bps. Given that performance, atmospheric absorption limits the data rate at the 100 bar level to ~140 bps, so in the 0.6 hours of free fall from 20 bars to 100 bars the probe collects and transmits ~0.3 Mbits. Transmitting almost 4 Mbits from the probe to the orbiter presents a formidable challenge when distances, time limitations, and other conditions are considered. Figure 1 shows data rates as a function of distance, scaled from the 1 million km point value. With our power and antennae size assumptions, the rate goals can be achieved at a distance of 216,000 km, similar to the Galileo Probe relay distance. Larger distances require more transmit power, a larger receive aperture, or both, though usefully larger transmit power places significant additional stress on the probe's thermal control system. For example, Fig.1 shows the data rate at 300,000 km to be unacceptably low using the initial assumptions and with resized components the data rate requirements are met. It should be noted that an orbiter trajectory with a perijove radius within 4 R_j risks undesirable mission impacts, such as exposure to more intense Jovian radiation and significantly increased mission duration.

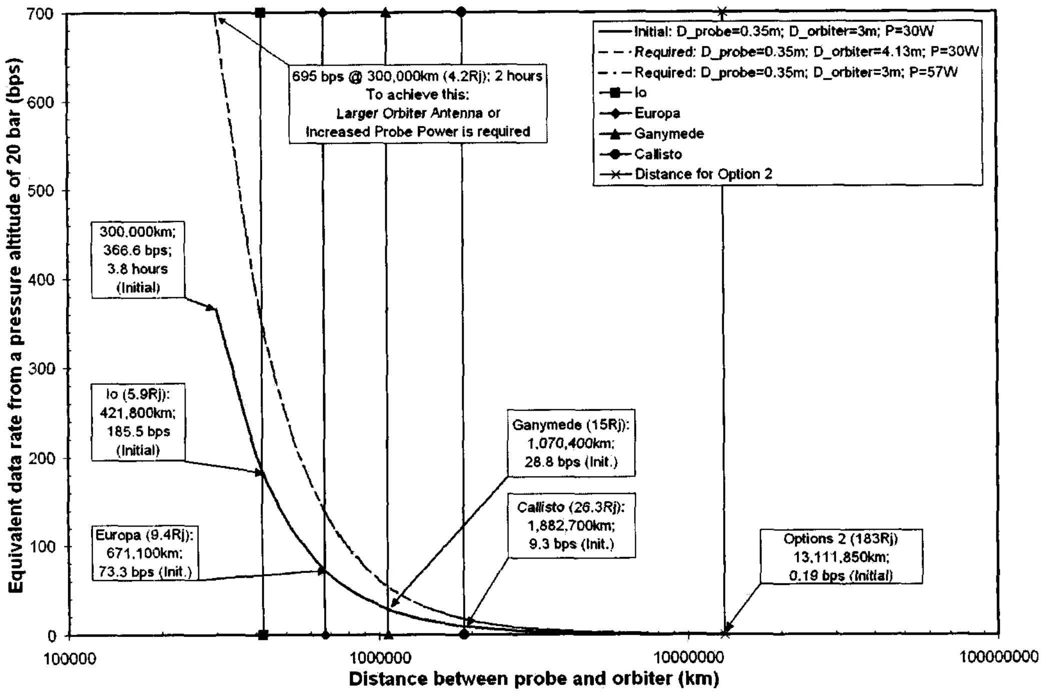

Figure 1: Telecommunication link budget

Mission Architecture Option #1

In this example the JIMO orbiter carries the probe on its NEP trajectory to Jupiter approach. The nominal JIMO approach trajectory is slightly altered such that 190 days before the orbiter reaches perijove, it releases the probe on a Jupiter-impact trajectory. With no additional ΔV the probe impacts Jupiter at latitude –7.5°, 142.4 days after separation. Since the approach is similar to that of the Galileo probe a comparison of the trajectory parameters between the two missions is given in Table 1.

Table 1: Comparison of JIMO and Galileo probe separation

Quantity	JIMO Probe	Galileo
Range	81,300,000 [km]	82,000,000 [km]
Range Rate	-530,072 [km/day]	-495,000 [km/day]
Probe Time from Impact	142.4 [Days]	150 [Days]

Following probe separation the JIMO spacecraft returns to its nominal (no-probe) trajectory in 302 days (see Fig.2). To do so the orbiter uses an additional 350 m/s of ΔV, slightly less than 1% of the total mission propellant load. These trajectory modifications are optimized for this feasibility study, without considering the probe-orbiter line of sight or telecommunication needs. In practice, rather than regaining the nominal flight path after the probe release, the entire trajectory would be re-optimized from that point forward, thus further reducing the upper limit on propellant penalty. Placing the probe on a ballistic trajectory removes the need for a dedicated probe propulsion system, reducing complexity and mass. The mission cost is also less than that for a probe with a propulsion system, even considering the cost of the additional propellant on the orbiter. However, a redesigned trajectory adds ~6 months flight time to the mission. Even if the orbiter achieves an acceptable line of sight to the probe at the time of entry, the distance between them is ~14.6 million km, yielding an unacceptably low estimated data rate of <0.2 bps (actually, the signal-to-noise ratio is too low to close the loop at all). Furthermore, the probe's lack of a propulsion system prevents it from maneuvering to avoid 5-micron hot spots. Finally, placing the spacecraft on an impact trajectory with Jupiter before the probe release, while a low probability event, could jeopardize the entire mission. Hence this option is considered undesirable.

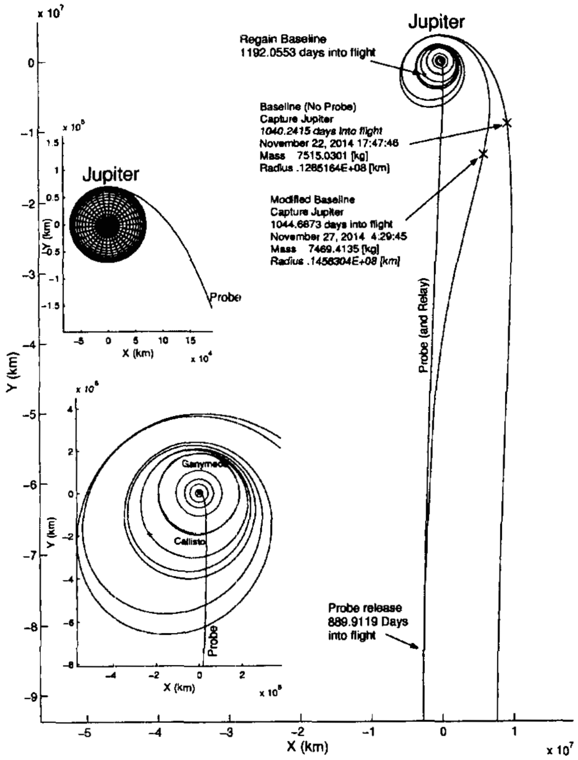

Figure 2: Ballistic probe trajectory followed by JIMO trajectory realignment

Mission Architecture Option #2

This option has the JIMO orbiter follow its nominal trajectory, modified only slightly by the added mass of the entry probe. The probe separates 190 days before the orbiter reaches perijove, and performs an 861.3 m/s maneuver whose direction is transverse to the pre-maneuver velocity vector. This places it on a ballistic Jupiter-impact trajectory, entering Jupiter's atmosphere 142.4 days after separation. When optimizing on both flight time and propellant mass, NEP trajectories capture into distant orbits with distant B-plane aimpoints, while entry probes require much closer aimpoints. The large maneuver magnitude reflects this disparity. Adding more ΔV to the propulsion system allows adding a retrograde component to the separation maneuver, slowing the probe's approach to Jupiter to yield smaller communication distances and proper line of sight. Without the retrograde component the relay geometry is very similar to that of Option 1, with the unacceptable sub-0.2 bps data rate. But the added ΔV is hundreds of m/s, and even without that addition the propulsion system mass is ~120 kg (optimistically assuming a bipropellant system with I_{sp}=325), possibly increasing the flight time to Jupiter. The propulsion system alone would add ~$10M to the cost. Systems to provide power and control to it add substantially more. Despite its advantages of minimal impact on the nominal JIMO mission design and avoiding Jupiter impact risk, this option is considered undesirable.

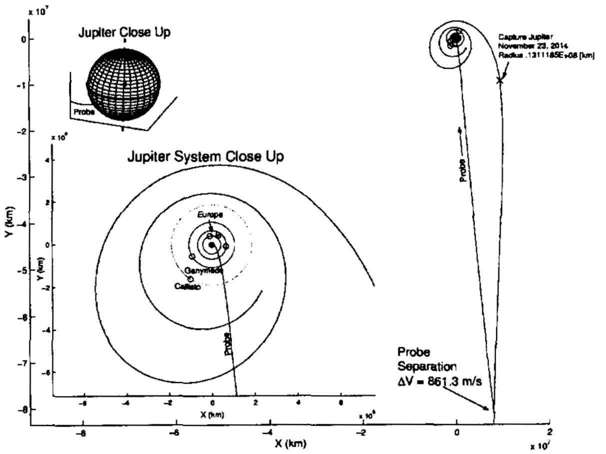

Figure 3: Probe release with a ΔV from nominal JIMO trajectory

Mission Architecture Option #3

In this option the probe is deployed during the JIMO moon tour. The velocity change (ΔV) needed for a ballistic probe entry to Jupiter from the orbit of a Galilean moon is shown in Table 2. The table also provides details on the moon's orbital distance, mean orbital velocity (V_{circ}), and the velocity for an elliptic orbit (V_{apo}), where the apojove and perijove are at the moon's orbit and at Jupiter's radius, respectively. Figure 4 gives an example of the probe deployment from Europa's orbit during the moon tour. (Note that a probe release from Callisto's orbit is more efficient.) If the probe is in a moon-orbiting phase it must exit the moon's gravity well. These large velocity changes cannot be achieved without a dedicated chemical or electric propulsion system on the probe. Both of these propulsion options add mass to the probe, but while an impulsive maneuver sends the probe on a ballistic approach, the electric propulsion system spirals it into Jupiter. Multiple passes increase radiation exposure, necessitating radiation protection and further increasing the mass. On a low thrust trajectory the probe also needs an on-board navigation system, a full-time telecommunication system, attitude sensing and control systems, etc. While the nominal JIMO mission remains unaffected, the added mass (>150 kg for the propulsion system, propellant and radiation protection), complexity and cost make this option the least desirable.

Table 2: Probe Delta V requirement to enter Jupiter

	Orbit [km]	V_{circ} [km/s]	Period [days]	V_{apo} [km/s]	ΔV [km/s]
Io	422,000	17.33	1.77	9.33	8.00
Europa	671,100	13.75	3.55	6.03	7.71
Ganymede	1,070,000	10.89	7.15	3.85	7.03
Callisto	1,883,000	8.21	16.69	2.22	5.99

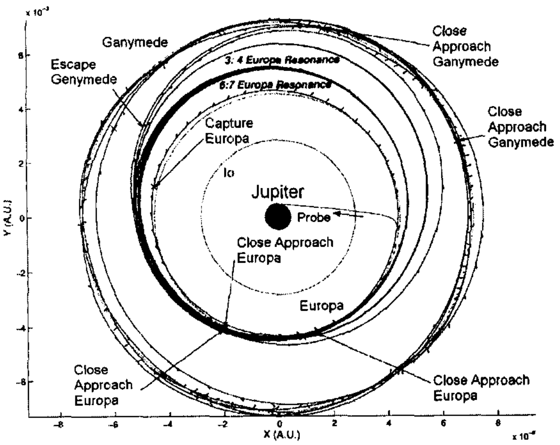

Figure 4: Probe deployment during moons tour

Mission Architecture Option #4

In this option the JIMO orbiter's initial perijove is lowered causing a much tighter capture and a more eccentric orbit around Jupiter. This lowers the probe's ΔV requirement to ~2.6 km/s during its apojove or pre-apojove separation. At the time of its impact into Jupiter the orbiter is still over 50 R_j away. The corresponding data rate is below 1 bps with no visibility between the probe and the orbiter, as shown in Fig.5. Although the velocity change of the probe is less than those for Option 3, it is still large enough to call for a sizable propulsion system. While this option permits multiple probes and reduces probe entry velocity, the redesigned eccentric orbit introduces a mission time penalty of several months. To make it work, the trajectory and the telecom system needs redesigning. This would include a periapsis of ~4-5 R_j on the return pass, better visibility, an increased antenna size on the probe and/or on the orbiter, and increased power to the probe's antenna. Hence this option is not recommended.

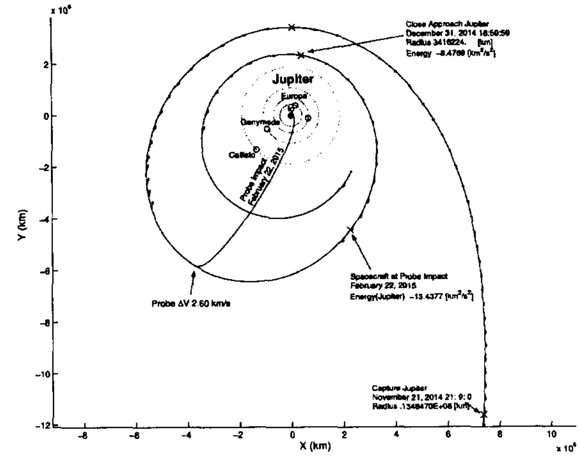

Figure 5: Probe release at apojove

Mission Architecture Option #5

This option merges the nominal JIMO mission with an add-on probe mission, which includes a data relay spacecraft (RSC). In one sub-case the JIMO orbiter follows its nominal trajectory. The add-on probe mission initiates 190 days before the JIMO orbiter arrives at perijove, as shown in Fig.6. Henceforth the JIMO mission is unswayed by the probe mission. The probe enters Jupiter's atmosphere at –7.5° from the equator, 142.4 days after separation from the JIMO orbiter, and shortly after it is released from the RSC, which passes Jupiter at a distance of ~4-5 R_j. This distance provides good visibility and data rate with the probe during its descent phase. However, the RSC must be designed to account for Jupiter's high radiation environment. (Following the Jupiter swing-by, the RSC proceeds on a trajectory out of the solar system.) Once the probe data is received, the RSC begins its transmission to Earth either directly or through a second relay link, utilizing the JIMO orbiter. This mission architecture option requires not only an atmospheric probe but also a RSC with navigation capabilities and a propulsion system providing a ΔV of ~860 m/s (see Option 2). The second sub-case is similar to that of Option 1. After uncoupling from the JIMO orbiter the RSC continues on a near-ballistic trajectory to Jupiter. A small propulsion system is installed only on the probe separating it before the RSC reaches perijove. This

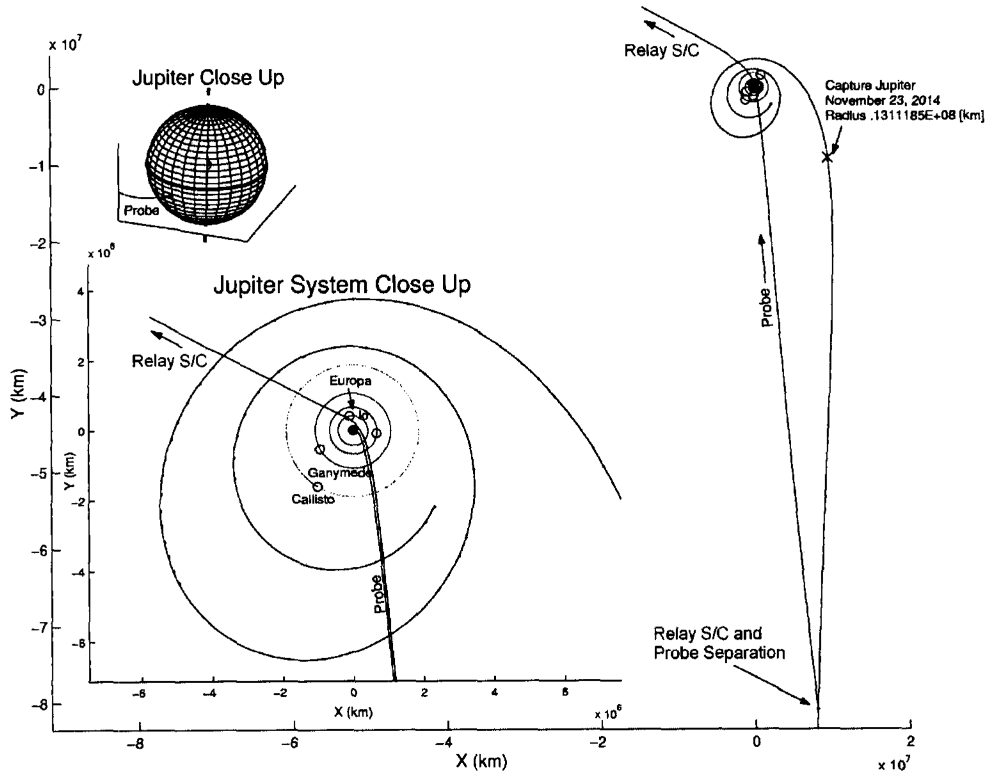

Figure 6: Nominal JIMO mission with add-on relay/probe S/C

high-risk architecture suffers the same problem as Option 1: it temporarily places the JIMO orbiter on a Jupiter impact trajectory. The probe mission sequence is similar to that of the Galileo mission and can be modified for multiple atmospheric probes. While out of the five examined options this one is the most sound from a mission architecture point of view, it is likely to cause an adverse impact on JIMO's mass budget. Furthermore, with such a significant increase in mission complexity the cost increase may be higher than having a separate "New Frontiers" class probe mission, independent from the original JIMO mission.

<u>Mission Architecture Option #6</u>

The five options above are based on the premise that the nominal Jupiter Icy Moons Orbiter mission architecture cannot be significantly altered by the addition of a Jupiter atmospheric deep probe. Nevertheless, if modifications to the JIMO architecture are allowed, then a novel mission can be envisioned with elements from Options 4 and 5. Here the JIMO orbiter releases the probe with a subsequent ΔV of 75.33 m/s, 150 days before impact. Both the orbiter and the probe coast towards Jupiter in close proximity. As shown in Fig.7, at the time of the probe's entry to Jupiter, the orbiter passes overhead at a distance of ~4.5 R_J. A day after passing perijove the orbiter initiates a maneuver, retrograde at first, in order to lower the apojove and to raise the perijove. This phase is similar to that of Option 5. On the return pass, this low thrust trajectory takes the orbiter outside of Callisto's orbit. It requires an additional 4 low thrust passes to spiral down to Callisto's orbit. From there the mission completes the science objectives of the icy moons tour. This mission architecture results in an ~16 months extension to the nominal JIMO mission. Telecommunication between the probe and the orbiter is achievable without significant changes to the assumed telecom system, as a consequence of good line of sight and distance. Radiation protection may marginally increase the mass of the orbiter. The trade space for this option is large, thus other optimization options can also be devised to reduce mission variables, such as time or propellant.

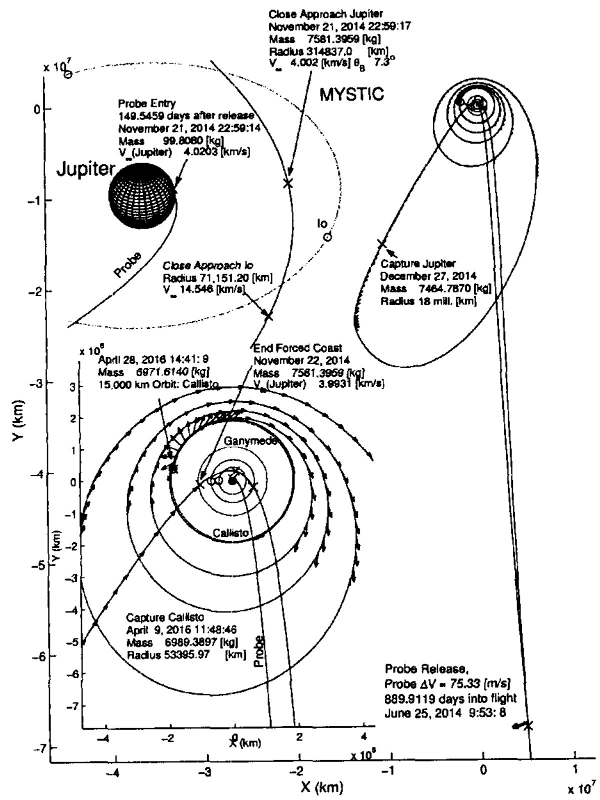

Figure 7: Probe drop from S/C during the 4-5 R_j perijove pass

CONCLUSIONS

In this feasibility study we examined five mission architecture options to add a Jupiter atmospheric entry probe to the baseline JIMO mission without significantly affecting the latter's mission design, and one option that did alter that mission design. Based on these options, we found that there is no simple or obvious way to merge these two missions without significant modifications to JIMO's nominal approach and capture strategy. In most cases telecommunication geometry prevents achieving the probe mission's scientific goals. For example, if the probe separates from the orbiter about six months before its arrival at Jupiter and performs no entry delay maneuver, then the large distance yields an unacceptably low data rate, and the orbiter is not in view during the probe's atmospheric entry anyway. If the probe separates during the moons tour, then the velocity change required to place the probe on a ballistic impact trajectory necessitates a sizable multi-stage high-thrust propulsion system. A low thrust trajectory is inadvisable due to collisions with Jupiter's rings and excessive exposure to the worst of Jupiter's radiation belts. Hence any feasible option from the "minimal alterations" category would add significant complexity, mass, time and cost to the mission, to the point where the relative benefits of such a combined mission become questionable.

If the baseline JIMO mission design is open to modification, then a viable architecture might be possible, but further detailed analysis should address trade options, cost and utility. The nominal JIMO mission design was optimized to accommodate all JIMO mission objectives identified to date by the project's Science Definition Team, and in doing so used all the available degrees of freedom. Additional mission objectives, such as entry probe objectives, that are not aligned with the original objectives necessarily impact the original mission objectives and architecture. This limits the freedom to modify the original mission architecture. Two ways to resolve this problem are to reduce the objectives for the original mission, allowing for more flexibility to carry out the new objective, or to redesign the entire mission with the combined set of objectives. Without an unanticipated and clever new mission architecture, it appears that any feasible option adds significant complexity, cost, and risk to the original JIMO mission, so such mission merger options must be carefully studied to fully understand their value and mission ramifications. We recommend further exploration of mission architecture options in order to find better solutions to this issue.

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