Riding the Banzai Pipeline at Jupiter: Balancing Low ΔV and Low Radiation to Reach Europa

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Europa's tantalizing allure as a possible haven for life comes cloaked in a myriad of challenges for robotic spacecraft exploration. Not only are the propulsive requirements high and the solar illumination low, but the radiation environment at Jupiter administers its inexorable death sentence on any electronics dispatched to closely examine the satellite. So to the usual trades of mass, ΔV, and cost, we must add radiation dose, which tugs the trajectory solution in a contrary direction. Previous studies have concluded that adding radiation shielding mass is more efficient than using ΔV to reduce the exposure time, but that position was recently challenged by a study focusing on delivering simple landers to the Europa surface. During this work, a new trajectory option was found to occupy a strategic location in the ΔV/radiation continuum – we call it the "Banzai pipeline" due to the visual similarity with the end-on view down a breaking wave, as shown in the following figures.

Nomenclature

C3	=	energy per unit mass, km^2/sec^2
EOI	=	Europa Orbit Insertion maneuver
JOI	=	Jupiter Orbit Insertion maneuver
krad	=	radiation dose, behind 100 mils of aluminum
LST	=	Local Solar Time
PJR	=	Peri-Jove Raise maneuver
Rj	=	distance in Jupiter radii (71,492 km)
V_∞	=	excess hyperbolic velocity, km/sec

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I. Introduction

The radiation environment at Jupiter ranges from trivial at the radius of Callisto, to 40 krad/day at Europa, with Ganymede occupying the middle (in a logarithmic sense) at 3.5 krad/day[1]. A low orbit of Europa sustains ~15 krad/day, due to the blockage of half the sky by the satellite, and the gyration radius of more than orbit altitude for the electrons that produce most of the dose. On parts of the Europa surface, the radiation is further reduced to as low as 2 krad/day due to the non-isotropic electron flux with respect to Europa.

The development of interplanetary trajectories to Jupiter is beyond the scope of this paper, but many examples exist[2] of 6-8 year flights arriving with a Jupiter V_∞ of ~5.6-5.8 km/sec, for a launch C3 of 10-15 km^2/sec^2. Clearly direct launches to Jupiter (C3= ~81) and 2-3 year ΔVEGA trajectories (C3=30 to 50, plus 900 to 300 m/s of spacecraft ΔV, respectively) are also available, but the shorter flight time is not worth the higher total ΔV for an already-challenging Europa mission. Once at Jupiter, the lowest-radiation approach possible is a direct insertion into Europa low circular orbit, but this costs ~5.3 km/sec and requires high thrust levels to achieve without incurring unacceptable gravity losses. Even this very quick and costly approach sustains ~20 krads during the final plunge to Europa.

On the other end of the spectrum, satellite tours have been developed[3-5] that arrive at a ballistic capture to a highly eccentric orbit at Europa, after a series of 4:3 and 6:5 Europa-resonant orbits with V_∞ leveraging, resulting in a Jupiter-system ΔV of ~1.5 km/sec and a tour length of ~1.3 years. However, the much longer time spent at Europa distances results in a radiation dose of ~1.1 Mrad before Europa arrival. This is a large (although acceptable) component of the total dose for missions with a 30-day design lifetime in Europa orbit (costing another ~0.4 Mrad), but it would be the dominant cost for a lander mission. In addition, while adding radiation-shielding mass is often cheaper than spending propellant to arrive more quickly, guaranteeing the reliability of the shielded electronics is likely to be expensive.

If the long Europa-resonant phase is deleted, the radiation dose drops markedly, but the ΔV increases noticeably, since the final leg is no better than a Ganymede-Europa Hohmann transfer, and generally worse – the V_∞ for such a trajectory at Ganymede is quite low, which requires a long tour with multiple Ganymede and Callisto flybys, or ΔV spent at apojove to reduce the Ganymede V_∞, somewhat defeating the overall goal. In addition, all the low-V_∞ Europa arrivals require multiple flybys at Ganymede to rotate the final V_∞ vector from prograde to retrograde, which incurs radiation costs on the intervening orbit (typically a Ganymede 1:1) with a periapsis substantially below Ganymede's orbit. Typical tours of this kind[6] have had performance ranging from radiation doses of ~150 krads with a ΔV of ~2.86 km/sec, to doses of ~600 krad with a ΔV of 2.16 km/sec. Exploiting multi-body dynamics without a long endgame results in a ΔV of 2.1 km/sec and a radiation dose of 130 krad[7].

For the recent lander study, there was a strong desire was to keep the radiation dose at Jupiter under 100 krads for cost reasons. The study also assumed the use of a Delta 4 Heavy class launch vehicle (which would include the Falcon Heavy vehicle (anticipated to have similar or higher performance) once it is developed) to investigate ways where additional launch mass (primarily propellant) could reduce the overall mission cost. Even so, the total ΔV remained a concern, due to the overall challenges of the mission. As it turned out, the Banzai pipeline was the endpoint in a series of trajectory designs (particularly for the last few orbits before arriving at Europa) in the <100 krad class, each with successively lower ΔV but about the same radiation. The intermediate approaches were not nearly as interesting or useful as the Banzai pipeline, so we will proceed forthwith to its detailed description.

II. Banzai Pipeline Description

Because of the radiation, the challenge of efficiently reaching Europa orbit is to perform the required flybys as close together as possible, while staying at the highest possible altitude for the longest time. This immediately suggests including multiple flybys in a single revolution, either of different satellites or of the same one. While using different satellites requires solving the problem of finding an acceptable relative phase, the rewards of doing so can make this worthwhile. Since the ultimate goal is to reach as near a rendezvous as possible with Europa, it is natural to think in terms of spacecraft orbits in the plane of the satellite orbits.

However, this shows insufficient imagination.[§] When the third author suggested[**] looking at out-of-plane options to the first author, an initial paper-and-calculator exercise quickly led to a patched conic script, and then to a full n-body solution with an optimizer (Cato). In the Jovian system, Ganymede is unique in that it can rotate a V_∞ vector between the Hohmann transfer from Callisto to the Hohmann transfer to Europa in a flyby-backflip-flyby

[§] As Spock said of Khan in the 2nd Star Trek film, "He's intelligent, but not experienced. His pattern indicates two dimensional thinking..."

[**] Thinking back, as he did so, to Ref. 8.

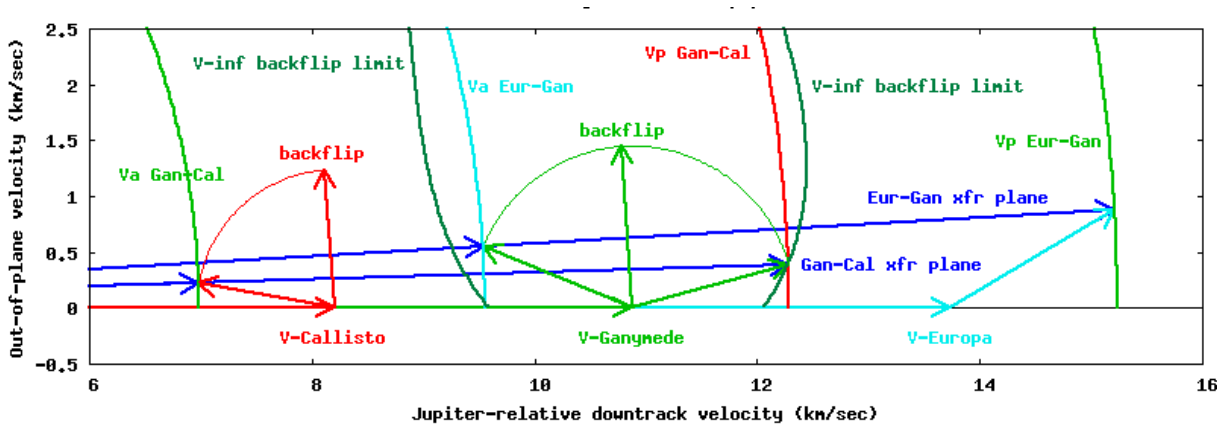

Figure 1. Velocity vector diagram of Banzai pipeline. *Satellite-relative V_∞ vectors are shown in the same color as the satellite Jupiter-relative velocity. 'Vp' and 'Va' are traces of the periapsis and apoapsis velocities of Hohmann transfers between the pair of satellites in each label. The dark blue vectors show the Jupiter-relative velocity at the endpoints of the Hohmann transfers that are actually utilized. 'V-inf backflip limit' is the trace of the Ganymede-relative V_∞ vectors that can be rotated into a backflip with a single 100-km altitude flyby. Note that the backflip limit coincides with the periapsis velocity for the Ganymede-Callisto Hohmann transfer at the Ganymede-relative V_∞ vector on the right (closest to the downtrack direction), which is the most limiting condition.*

sequence, with only minimal residual inclination on the surrounding trajectory segments. This combination of Hohmann transfers and backflips[††] forms the "Banzai Pipeline", and takes its name from the famous surf break on Banzai Beach, on the north shore of Oahu.

In the simplified world of patched-conic analysis with circular, co-planar satellite orbits, Fig. 1 illustrates a vector-diagram view of the Banzai pipeline. The origin (off-scale) is zero velocity with respect to Jupiter. The increasing orbital velocity of the satellites, from Callisto to Europa, is shown by the horizontal arrows, all lying in the satellites' orbit plane, with helpful color coding. Between each pair of satellites, the periapsis and apoapsis velocity of the Hohmann transfer traces an arc away from the orbit plane into the vertical velocity direction. As any inclined orbit between different radii must have a Jupiter-relative velocity that exactly lies on these arcs (to satisfy a 180-degree transfer angle), the satellite-relative spacecraft V_∞ from each satellite's own velocity must extend to these arcs as well. The Europa-relative V_∞ of 1.711 km/sec that makes an angle of just over 22 degrees with the satellite orbit plane (shown in the same light blue as the Europa velocity) is both one of many that satisfy the condition of reaching the Hohmann transfer velocity to Ganymede, and is also clearly not the smallest one possible. However, this particular V_∞ has the smallest magnitude that meets certain conditions, as discussed below.

Once the Europa-relative V_∞ is defined, so too is the Jupiter-relative inclination, as illustrated by the dark blue velocity vector extending from the origin to the Europa-Ganymede Hohmann transfer peripasis velocity. The arrival conditions at Ganymede must lie in this same plane, and so the left-most of the Ganymede V_∞ vectors extends from Ganymede's velocity to the apoapsis velocity of the same Hohmann transfer, at the same inclination. Since a single flyby must rotate this V_∞ into a Ganymede-Ganymede backflip using a flyby no lower than a specified minimum altitude (100 km in this case), it must lie on or inside the locus of acceptable maximum V_∞ endpoints, shown in dark green in Fig. 1. The V_∞ from Europa easily meets this condition, allowing a flyby altitude of several hundred km. The locus of accessible V_∞ vectors from a backflip also extends to the positive side of Ganymede's velocity, and in this case we see that the turn angle is at the backflip limit. The particular choice of the Europa V_∞ allows this condition to just barely be met at the transfer between Ganymede and Callisto. If Ganymede was somewhat smaller, then the necessary Europa V_∞ would grow markedly, such that this sequence would lose its attractiveness.

[††] A backflip (first discussed in Ref. 8) is a 180-degree transfer with an inclination difference from some reference orbit. For the purposes of this paper, the reference orbit is always a near-circular Galilean satellite orbit, but technically the inclined Hohmann transfers between different satellites could also be considered backflips.

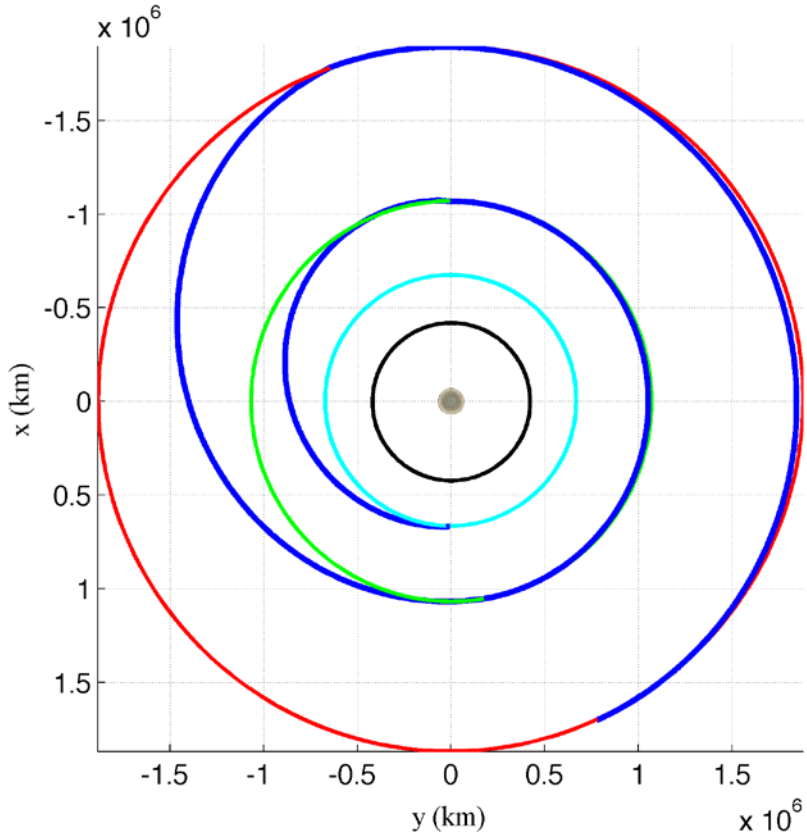

Figure 2. Banzai pipeline, normal view.

In a similar manner, Fig. 1 shows the V_∞ vector with respect to Callisto, at the intersection of the Jupiter-relative inclination and the apoapsis velocity of the Ganymede-Callisto Hohmann transfer. The Callisto-relative V_∞ allows a single flyby to switch the orbit into a Callisto-Callisto backflip, while remaining somewhat higher than the minimum altitude. An additional flyby (not shown) is sufficient to produce a near-equatorial 1:1 resonant orbit with Callisto, easily leading to flybys connecting longer orbits.

While the explanation of the Banzai pipeline started with Europa and ended with Callisto, this naturally should not be taken as the temporal direction of the trajectory. Time, like the third dimension, is our conceptual servant, and must take its direction at our bidding in the conceptual realm. So the Banzai pipeline, while most conveniently constructed backward in time, would almost always be flown forward in a final sequence of Callisto-Callisto-Ganymede-Ganymede-Europa, with a Europa orbit insertion maneuver at the end.[‡‡]

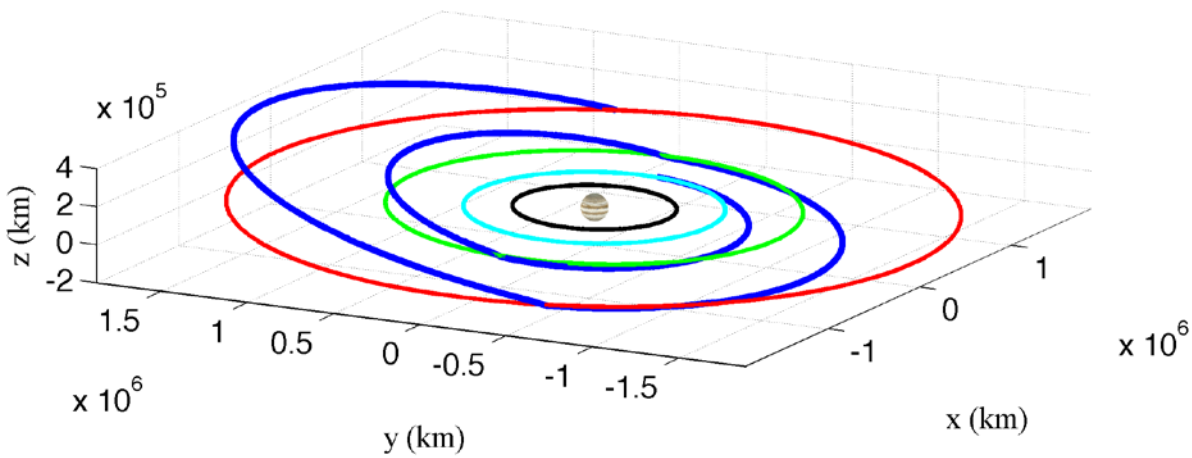

Figure 3. Banzai pipeline, perspective view.

[‡‡] Perhaps one day a Europa sample might traverse the pipeline in the opposite direction, but otherwise this is strictly a one-way descent.

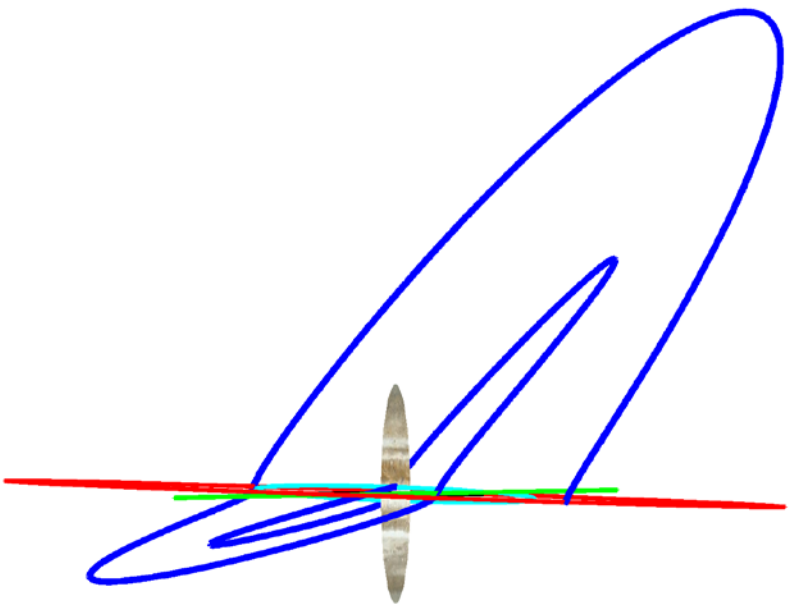

Figure 4. Banzai pipeline, side view, with stretched Z-axis.

Despite not revealing much of the detailed construction of this trajectory, the polar spatial view shown in Fig. 2 gives the Banzai pipeline its name. Spiraling down from Callisto's orbit (in red), Fig. 2 shows the alternating Hohmann transfer and circular orbit segments, ending at Europa. The visual similarity is most pronounced in this view, with the ecliptic –X component as the vertical axis, and +Y as the horizontal one. Fig. 3 provides a perspective view, where the inclination of the two backflip segments is clearly visible against their relevant satellites. Fig. 4 shows the same trajectory looking edge-on to the satellite orbit plane, with the Z-axis stretched, and displays some similarity with the inclinations in Fig. 1. Note too that the flyby locations are not completely aligned, since this trajectory is integrated using the real satellite ephemeris.

Placing a Banzai pipeline in the real world requires making pair of choices that do not arise meaningfully in the patched-conic, circular satellite orbit world. While not strictly necessary for a lander, polar orbits at Europa still hold some advantages[§§], and the analysis shown here always uses a near-polar Europa orbit, which depends on the first choice: North or South approach to Europa. To this choice is added the direction of the spacecraft orbit plane rotation out of the satellite orbit plane: either up or down, referenced on the leg from Ganymede to Europa, in a right-hand rotation sense.

These two choices can be made independent of each other, and all combinations may produce a minimum ΔV solution. In the real world, each flyby is offset from the satellite-center position used by the patched-conic, and the choice of North/South for the Europa arrival, coupled with up/down for the orbit plane rotation, produce preferred displacements away from co-linear in the location of the satellites at the moment of closest approach.[***] Some of these displacements will be a close match for the actual satellite locations, resulting in a Europa arrival V_∞ as low or lower than the ideal value. There is currently no consistent theory to determine which combination would be best *a priori* (a matter remaining for future study), but it is relatively easy to try all of them in the optimizer. Generally, for any date, one of the choices is really bad, two are passable, and one is really good, all in terms of minimizing V_∞ at Europa arrival. Three of the four combinations have been seen to produce minimum values for different dates, and doubtless the other combination would be beneficial in other cases.

For any polar-orbiting mission, the LST of the equator crossings is a key parameter for determining the available illumination, whether it be for remote sensing or to specify the LST at a landing. Since the natural Jupiter beta angle for any near-Hohmann arrival at Europa is near 90 degrees (face-on), the location of Europa in its orbit at the arrival epoch sets the LST. Any particular LST is therefore accessible at two points in Europa's orbit, separated by half a period, as long as the direction of travel (ascending or descending at the equator) is unimportant. (Generally the rotation direction also cannot be specified without cost if the North/South arrival choice is used to minimize V_∞ at arrival). Arrivals at relatively nearby epochs may be accommodated by performing a modest plane change at apoapsis in an initial longer-period orbit (with an argument of periapsis near 90 or 270 degrees), but this incurs both

[§§] And in fact the Banzai pipeline does not permit an equatorial orbit, arriving as it does at Europa with a non-equatorial inbound asymptote.

[***] Note that any flyby also advances or retards the spacecraft's progress around Jupiter, compared to that predicted by patch-conic analysis, due to the higher velocity at the hyperbolic periapsis of the satellite flyby. This effect combines with the three-dimensional effects to adjust the preferred satellite locations, but it is probably the smaller of the two.

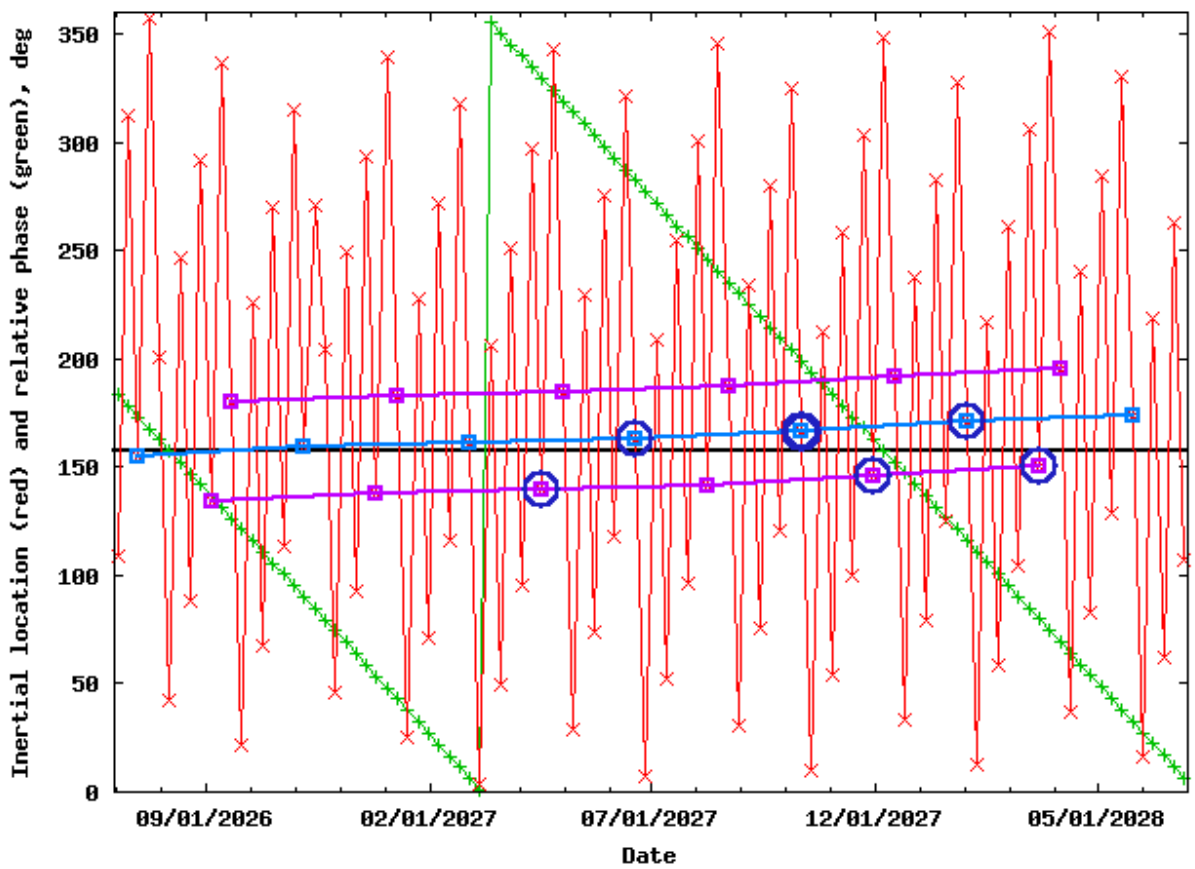

Figure 5. Satellite alignments. *Inertial location of final Ganymede flyby when Europa is correctly aligned is shown in green. Relative location of Callisto at that time shown in red. Black line is patched-conic ideal Banzai pipeline Ganymede-Callisto alignment. Nearby alignments occur on a 16-week cycle, with 3 opportunities spanning ~45 degrees, as shown by the magenta and blue lines. The circled opportunities have optimized Banzai pipelines with the full ephemeris, shown in Table 1. The trajectory shown in Figs. 2-4 is the one from October, 2027, marked with a heavier circle.*

ΔV and radiation costs. How often, then, can this Banzai pipeline be used to reach a particular polar orbit LST for an acceptable cost?

Since the Banzai pipeline uses the three outer Galilean satellites, all of them must necessarily be in the right alignment. Europa and Ganymede are nearly in a 2:1 resonance, with a -5.2 degree inertial offset at every repeat alignment, since Europa is slightly faster. This causes the inertial direction of a particular alignment to rotate

Table 1. Banzai pipeline alignment cases tested with optimizer. *The October 11, 2027 case is the one used in all the trajectory figures. Each case starts at Callisto and ends at Europa.*

Date of final Ganymede flyby	North or South polar arrival at Europa	Direction of orbit plane displacement (up/down for Ganymede-Europa leg)	V_∞ (km/s) at Europa	EOI magnitude to circular orbit, km/s (100 km altitude)	Ganymede-Callisto angle offset from nominal (deg)
Apr 18, 2027	S	down	1.703	1.211	-18.1
Jun 20, 2027	S	up	1.665	1.186	+5.1
Oct 11, 2027	N	down	1.701	1.209	+8.8
Nov 29, 2027	N	down	1.720	1.222	-11.9
Feb 1, 2028	N	down	1.695	1.206	+13.4
Mar 21, 2028	S	up	1.654	1.179	-7.7

through a full circle every ~487 days, as shown in Fig. 5 in green (for the alignment that allows the final Ganymede-Europa leg of the Banzai pipeline). Ganymede and Callisto are nearly in a 7:3 resonance, and when the relative Ganymede-Callisto alignment is evaluated at the time of the Ganymede-Europa alignment, the result is as shown in Fig. 5 in red. Starting from a particular alignment, there is a near-repeat in 16 weeks (moving an average of 3.15 degrees per cycle). At 7 and 9 weeks, the alignment matches to within +/- 22 degrees. As shown in Fig. 5, the black line is the ideal (patched-conic) Banzai pipeline alignment for Ganymede and Callisto, and the blue line and two magenta lines show the 16-week and 7- & 9-week patterns. The circled alignments have had optimized Banzai pipelines constructed with the real ephemeris, starting from the final Callisto flyby, with results shown in Table 1.

The most important result in Table 1 is that offsets of up to ~18 degrees from the nominal alignment do not change the cost significantly (in Europa V_∞). The sample size is not large, but there is no evidence that the upward knee in the cost curve has been reached. Clearly a larger range of offsets would be useful, but this data is enough to come to some conclusions about the accessibility of polar orbits with a particular LST. The slow regression of the Ganymede-Europa alignment is the most important factor, even when slightly hastened by evaluating it against the Sun (where it makes a full circle in 438 days). A particular sun-relative orbit plane can be entered at a Jupiter beta angle of 90 degrees twice in the full cycle, or every 219 days. However, the Callisto alignment only permits a Banzai pipeline arrival every 7-9 weeks, if a misalignment of ~22 degrees is acceptable. Table 1 strongly suggests that this is the case, even though the examples give only go out to 18 degrees.

Taking this to be true, then the worst-case arrival time error is 4.5 weeks, which works out to a Sun-relative orbit plane error of 26 degrees, or 1 hour and 44 minutes of LST. Perhaps such an error could be tolerated, especially since it will be smaller in all but the unlucky bounding cases. However, spacecraft with a discriminating taste in orbit LST could still be satisfied with a sequence of events as follows: 1) EOI into a 12-hour orbit polar orbit, with periapsis at the pole, 2) plane change maneuver of up to 26 degrees at apoapsis, and 3) circularization maneuver at periapsis. This would cost 146 m/s of ΔV at apoapsis, perhaps mitigated by reduced gravity losses from splitting the orbit insertion into two parts (of 793 and 415 m/s for this case, with periapsis at 100 km altitude). More seriously, a 12-hour orbit would incur an additional radiation penalty of ~10 krad, compared to the same duration in low Europa orbit. That is enough to motivate considering other options (including shorter orbit periods), but not enough to invalidate this approach as a viable final selection. Operationally, this would require performing 3 maneuvers, one every 6 hours, which is also a challenge (although still barely possible) if any ground interaction is necessary, so the robustness of the spacecraft would need to inform the selection of the strategy. A further discussion of options is found in a following section, but the existence of options suggests that finding a strategy should not present an insuperable problem.

While this concludes the discussion of the design of the Banzai pipeline portion of the trajectory, the radiation dose for the particular trajectory presented in the plots above has not yet been discussed. In this case, the total radiation from the last Callisto flyby to Europa arrival is 48 krads, which is in the expected range of about 45-50 krads (varying due to the phase of Jupiter's magnetic equator to the satellite orbit plane at Europa arrival). However, the radiation effect is best plotted as a cumulative dose over the whole tour, so it will be included in the discussion of the particular tour that was used for this study.

III. Connecting to a Banzai Pipeline

Like a figure skating competition, any Jovian satellite tour has a number of required elements (pursuant to the judging panel of Newtonian dynamics), but the artistry of their arrangement determines the potential beauty of the end result. Chief among these requirements are the date of arrival at Jupiter and at Europa, which despite being selectable at the start, form the frame for the rest of the tour in ways beyond merely setting the temporal boundaries.

Somehow, a combination of satellite flybys and ΔVs must connect the arrival from interplanetary orbit to the final Callisto flyby for the Banzai pipeline descent, with an acceptable amount of radiation, while not violating any other constraints[†††]. The possible arrival dates are relatively numerous, although the best one (for ΔV, C3, and arrival V_∞) will necessarily be unique for a potential programmatic launch period. As shown above, the final Banzai pipeline descent is available (to within minor variations) every ~7.5 months. Since it is hard to imagine a workable tour of this sort lasting less than a year, the practical tour durations are going to be at least 12 to 19.5 months, and it may well be that the minimum duration is closer to 18 months, leading to a maximum duration of 25.5 months for some arrival opportunities. The particular tour developed for this study was 20 months, and it had precious little extra time for everything that had to be included.

[†††] Fortunately the figure skating regulation prohibiting backflips in formal competition does not apply, or the Banzai pipeline would not be possible!

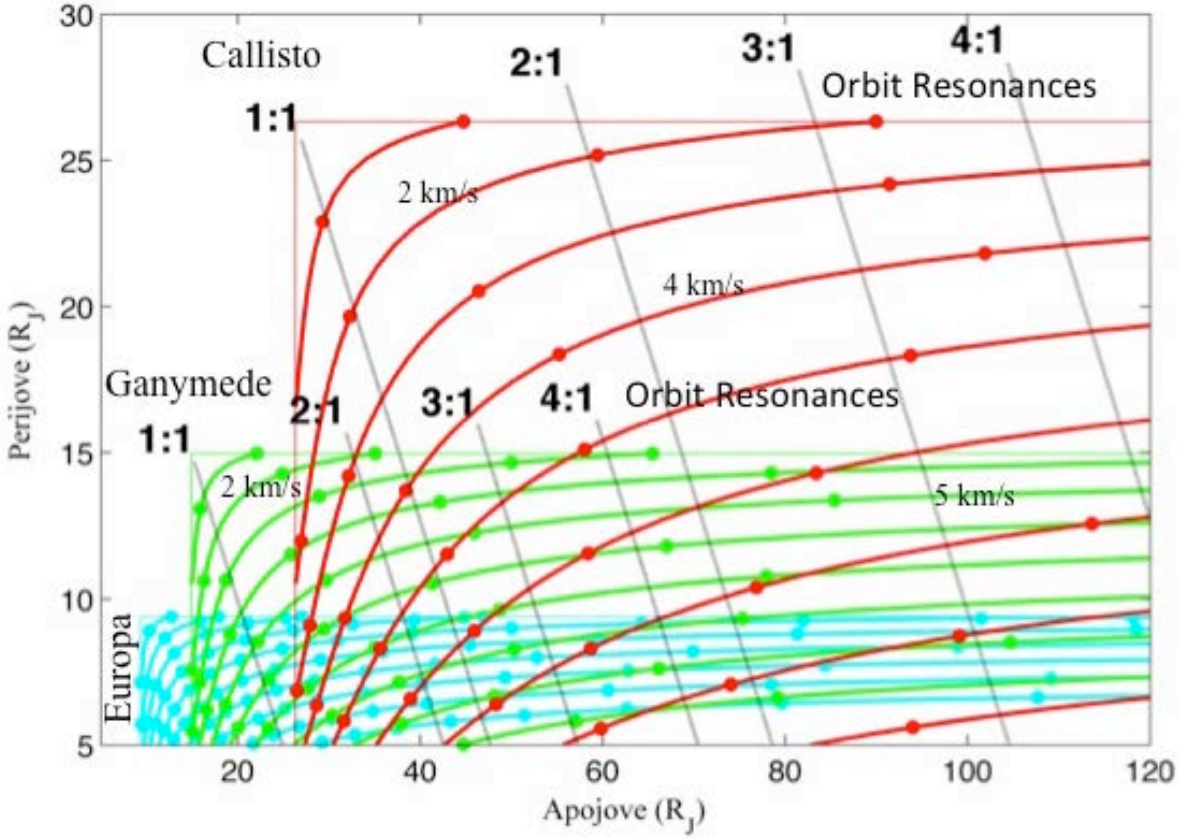

Figure 6. Tisserand plot for Callisto, Ganymede, and Europa. *Lines of constant V_∞ are shown for each satellite. Orbit resonance conditions are shown for Callisto and Ganymede. Dots on the V_∞ lines show the maximum change possible from a 100-km altitude flyby.*

What are these required elements? The general tour requirements have been extensively discussed in other papers, but clearly the spacecraft must be captured at Jupiter (typically by a Ganymede flyby followed with a large JOI, and the period of the orbit must be reduced by further flybys. In addition, solar perturbation lowers periapsis on the typical long first orbit (which would cause a noticeable radiation increase), and velocity leveraging is very efficient at such distances, so a substantial PJR is typically performed at the first apoapsis.

At the other end, the Callisto-relative V_∞ at the start of the pipeline descent is quite low, typically around 1.3 km/sec. Orbits with perijove distances close to Callisto have negligible radiation accumulation, and the low Callisto V_∞ keeps even in-plane 1:1 resonant orbits high enough to avoid significant radiation effects. However, as shown in the Tisserand plot[9-11] in Fig. 6, reasonable initial Ganymede V_∞ values of 4-5 km/sec do not even intersect with Callisto V_∞ values below 2 km/sec, and even that is with perijoves that approach Europa for resonances between 1:1 and 1:2 (causing many revolutions), all the while soaking up unacceptably high levels of radiation.

There are two ways to solve this problem: 1) apoapsis ΔVs (ie. V_∞ leveraging), or 2) alternating Ganymede and Callisto flybys. The former is straightforward, but comes at a propellant cost, and the latter may cost significant time (due to the difficulty of setting up transfers between the satellites) and radiation dose. Any Ganymede-altitude perijove or below has a noticeable radiation dose, especially as a component of a 100-krad allocation for the whole tour. A single transfer from Ganymede to Callisto is required by the starting conditions of the Banzai pipeline, but any additional transfers add significantly to the challenge. However, the relatively sharp intersection angle between the Ganymede and Callisto lines of constant V_∞ on Fig. 6, for the region just under Ganymede altitude, show that this approach would work well in principle.

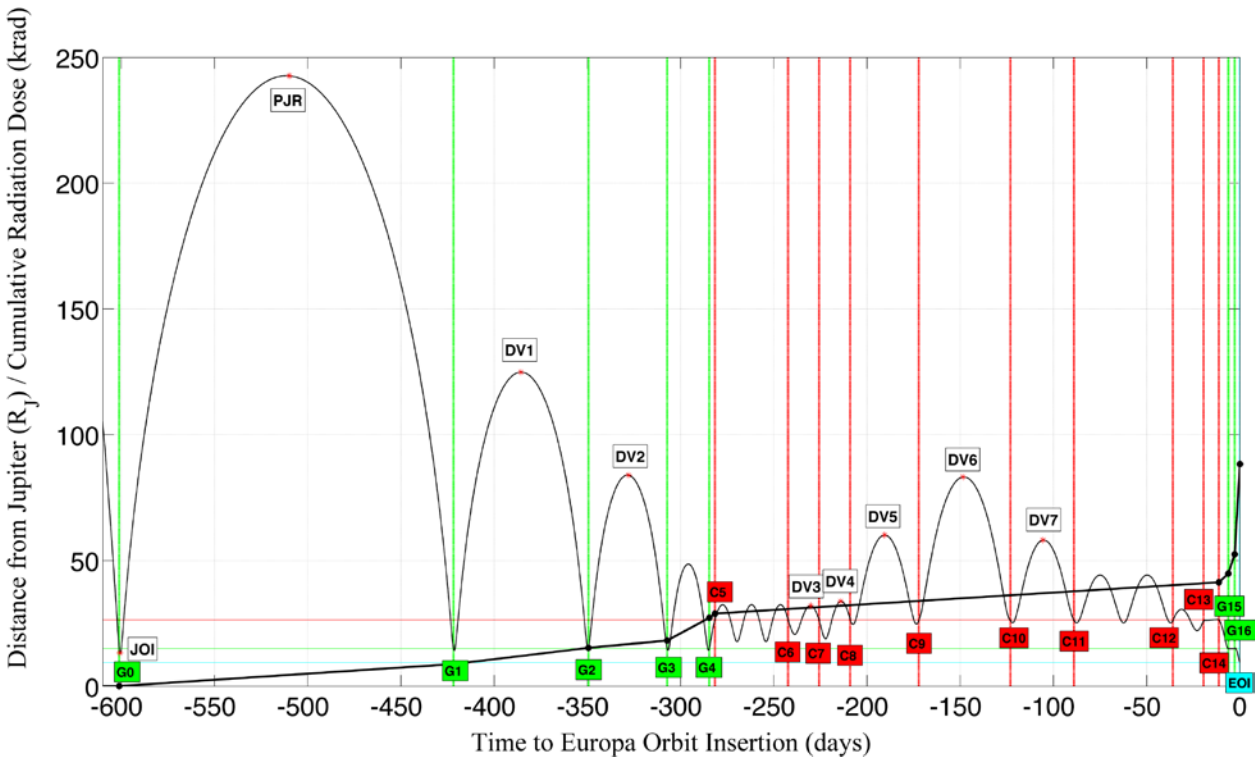

Figure 7. Full tour: distance and radiation vs. time. *The thin black line shows spacecraft radial distance, while the thick black line represents the radiation dose accumulated between reporting epochs indicated by black dots. Satellite encounters are shown by vertical colored lines, and labeled in boxes of the same color. Significant ΔVs are labeled in white boxes.*

The other challenge is that the location of the final Callisto flyby is at a particular point in the Callisto orbit, and the location of the initial Callisto flyby (however that happens, for the final Callisto-only sequence) is at some different point. Resonant Callisto flybys will never change their flyby location, so non-resonant flybys (and probably ΔVs) must be used to move the flyby point from the initial to the final location. All of this has the relatively long 16.69-day Callisto orbit period as the dominant frequency, requiring a long time to adjust the flyby location, or some luck.

The particular tour shown here is not necessarily the optimum approach, but it has the great virtue of: 1) working end-to-end with the real ephemeris for an acceptable cost, and 2) illustrating all the elements that might be used to generate other tours with similar requirements. The complete tour is shown in Fig. 7 in Jupiter distance vs. time format, with the radiation accumulation in black, and also shown in Fig. 8 in orbit-normal view. Most of the V_∞ reduction is accomplished by V_∞-leveraging maneuvers, with the exception of one Ganymede-Callisto transfer in the middle. The tour divides into a Ganymede sequence in the first half, and a Callisto sequence in the second half, with the Banzai pipeline tacked on at the end.

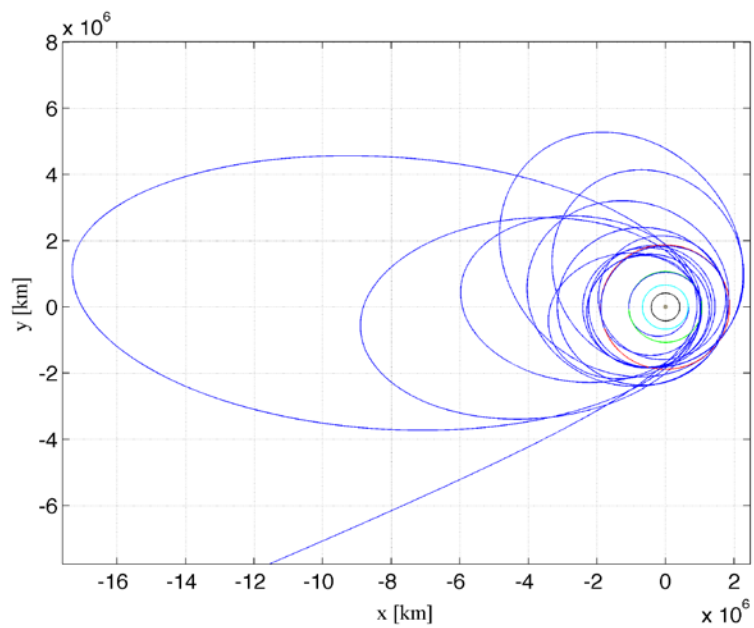

Figure 8. Full tour: normal view. *Trajectory starts before arrival at Jupiter.*

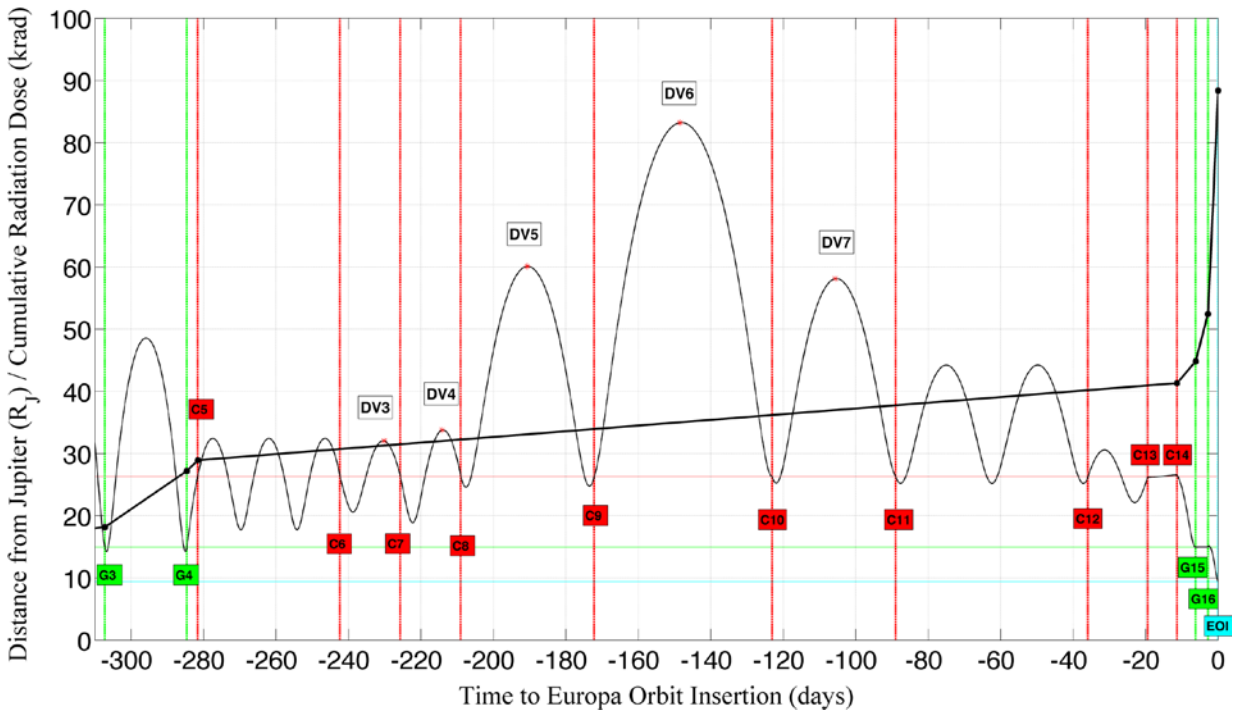

Figure 9. Second half of tour: distance and radiation vs. time. *The plot elements are the same as for Fig. 7.*

The Ganymede sequence includes 5 Ganymede flybys (G0 through G5), with a 805 m/s JOI and a 110 m/s PJR. The Ganymede V_∞ after JOI would be around 6 km/sec before solar gravitation perturbation, but that is reduced to around 4.8 km/sec by PJR, which comprises the first velocity-leveraging maneuver. Two-thirds of PJR is devoted to cancelling the solar-induced periapsis drop, or otherwise the PJR ΔV would have a bigger effect on this initial 25:1 orbit (with respect to the Ganymede period). After G1 and G2, the orbit period drops to 10:1 and 6:1 respectively, each with an apoapsis ΔV of a little over 40 m/s, to reduce the Ganymede V_∞ to 3.3 km/sec. The total ΔV on this sequence after PJR is 83 m/s, of which 55 m/s is due to various real-world effects (solar gravity perturbation, phasing) that would not be predicted by patched-conic analysis.

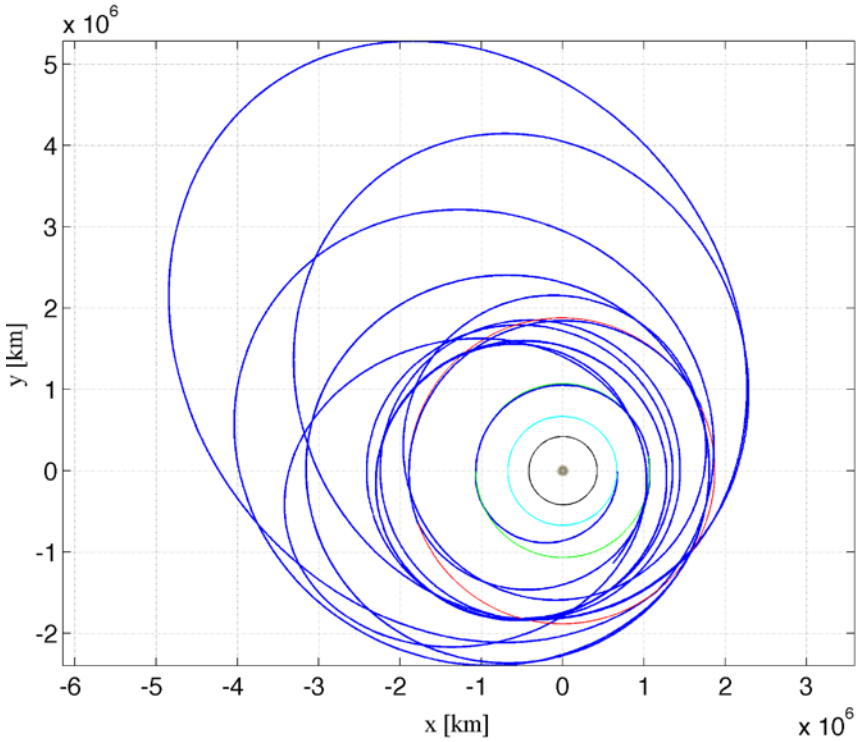

Figure 10. Second half of tour: normal view.

After the G3 flyby, the Ganymede sequence ends with a 3:1 orbit, and the final G4 outbound flyby knocks the period down to almost a 3:2 resonance, with a perijove radius of around 12.5 Rj, which would incur a significant radiation dose. However, just before the spacecraft falls to this doom, it is grabbed by the scruff of the neck by

Callisto (so to speak) and hauled up to a more-benign perijove of ~18 Rj. The timing of this G4-C5[‡‡‡] flyby sequence is a major constraint on the entire Ganymede segment, and requires particular choices of inbound or outbound flybys and orbit periods, without regard to radiation (which would otherwise always favor outbound flybys). The opportunities for a 3:1 Ganymede orbit leading to an outbound Ganymede flyby, and then a Callisto outbound or inbound flyby, leading into a Callisto 1:1 resonance, occur in offset pairs every 50 days, due to the 7:3 Ganymede-Callisto resonance. This is still less constraining in time than the Banzai pipeline opportunities, but more constraining in location, due to the slow progression of the Ganymede-Callisto alignments. Fortunately, small variations in the period after the final Ganymede flyby adjust the alignment to some degree, at the cost of modest Callisto-relative V_∞ changes. The total radiation dose to C5 is 30 krads, about one third of the total.

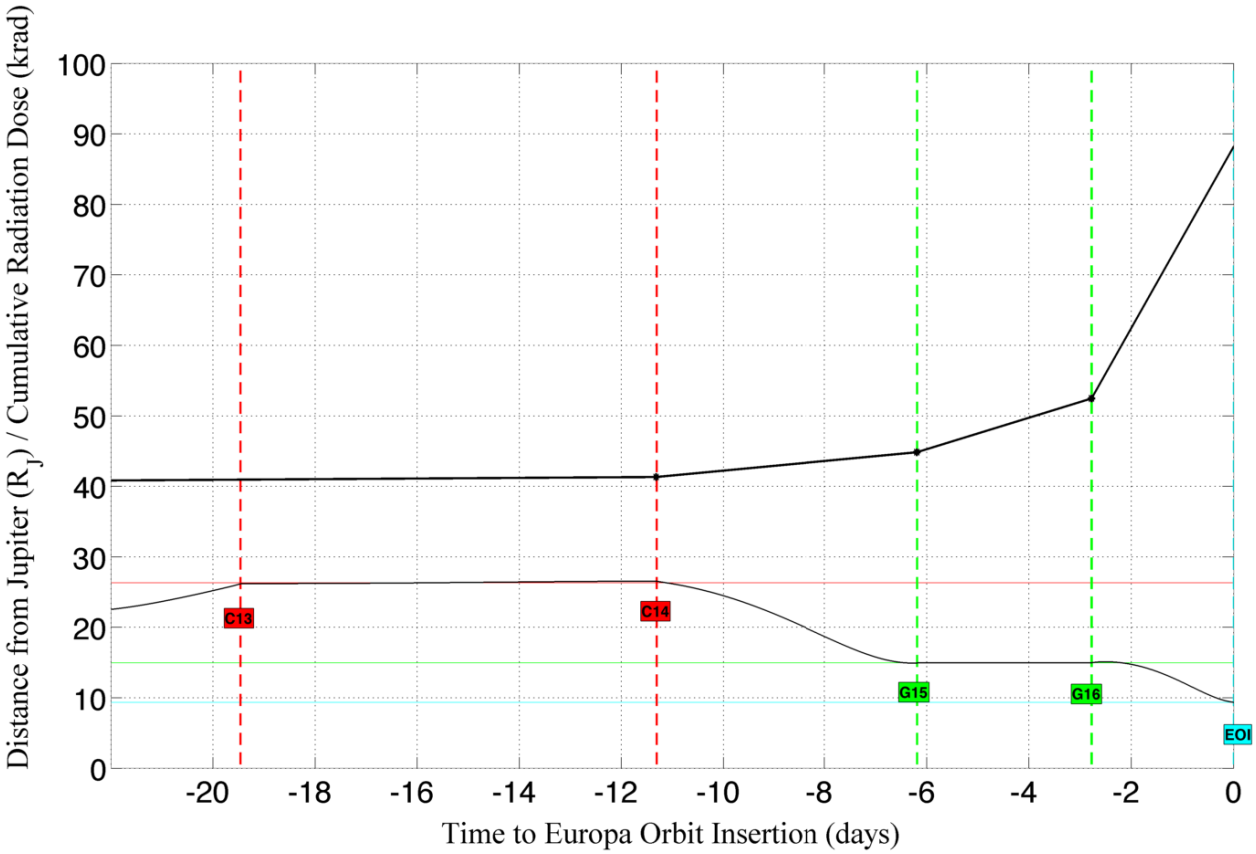

Figure 11. Banzai pipeline: distance and radiation vs. time. *The plot elements are the same as for Fig. 7.*

The Callisto sequence (including the Banzai pipeline at the end) is shown in Fig. 9 and 10. The initial V_∞ at C5 is 2.4 km/sec, far above the required final V_∞ for the pipeline. The strategy employed is to increase the period to a 3:1 resonance to perform a ΔV leveraging maneuver, followed by a 2:1 resonance and another ΔV leveraging, before dropping down through a 3:2 resonance on the way to the final 1:1 orbit, before the Callisto-Callisto backflip into the pipeline. Preceding this sequence are a series of near-1:1 orbits to adjust the phasing of the overall Callisto segment (in combination with non-resonant flybys in the longer-period orbits later) to align with the endpoints. The total phase-free ΔV for this segment is predicted to be 94 m/s, and the actual total required to connect this trajectory was 139 m/s, with most of the extra occurring in the ΔVs between C6 and C8. There are no doubt other flyby sequences that might yield a lower ΔV, but this is already the second in a series of attempts, each of which was quite resource-intensive to develop. The total duration of the Callisto sequence is 9 months, and the additional radiation accumulation is 12 krad, probably mostly from the low-altitude perijoves between C5 and C8.

The Banzai pipeline sequence is shown in Fig. 11, and of course also in Fig. 2 above. The two backflip segments are notable for their constant distance from Jupiter. The radiation accumulation is 4 krads from C14 to

[‡‡‡] Note that this paper uses the Galileo project nomenclature of consecutive flyby numbering, with the prefixed initial of the satellite involved, as behooves any mission to Jupiter, or elsewhere, possessed of more than a paltry single satellite with practical orbit-shaping efficacity.

G15, 8 krads from G15 to G16, and 36 krads on the final descent to Europa, for a total dose in the Jupiter system of 89 krads. The V_∞ at Europa is 1.71 km/s (slightly more than Table 1), but apart from the implicit maneuver at Europa arrival, this sequence is free of deterministic maneuvers. The total ΔV cost between PJR and EOI is 223 m/s, of which 100 m/s is necessary to convert from a phase-free patched-conic analysis into the real world.

IV. Optional Modifications and Other Considerations

The Banzai pipeline presented here is the lowest-radiation version of any related trajectory extending to Europa. However, additional orbits could be included with a perijove at Ganymede distance at a cost of ~8 krads per orbit. These could be additional revolutions in the Ganymede-Callisto Hohmann, or perhaps intermediate orbits between the first and second Ganymede flybys, allowing a modest reduction in the V_∞ at Europa. The additional orbits would also open up new options in the Europa-Ganymede-Callisto alignment space, and perhaps save on plane-change ΔV and post-EOI radiation costs (which are similar to an extra orbit). However, only a few additional revolutions could be added before the radiation cost would equal that of a more traditional approach (using a Ganymede-only sequence), which would be much easier to design.

Although currently Io does not hold nearly the same interest as Europa to the science community, it is natural to wonder if a Banzai pipeline could be extended past Europa to Io. With the simplest approach (no extra revolutions), the answer is no – the smaller Europa mass does not provide the turn angle needed to keep the V_∞ at Io low enough to be useful. Perhaps this could be revisited with extra revolutions at Ganymede, since the radiation there is not as severe. (Recall that Io is only 50% worse than Europa, but Europa is 10 times worse than Ganymede). It is interesting to note that the Uranian satellite system has many dynamical similarities to the Galilean satellites, but the absence of severe radiation makes a Banzai pipeline much less necessary.

Operationally, the close proximity of targeted flybys on the standard Banzai pipeline (most critically including the 3.5-day separation of the final two Ganymede encounters) would be enough to give any previous satellite tour Navigation Team the willies. Clearly the standard maneuver development timeline needs to be at least as short as the current Cassini timeline, which routinely executes maneuvers in less than a day from the data cutoff time. The most important navigation parameter (compared to current practice) would be the recovery time for missing a maneuver, either due to ground station problems or spacecraft contingencies. Although reporting the details would be beyond the scope of this paper, a recent study at JPL concluded that a recovery time of 12 hours makes flying this trajectory entirely feasible, and that perhaps a recovery time of 24 hours could just barely be tolerated. Fortunately, these recovery time scales are only necessary during the final 1.5 weeks before Europa arrival, and briefly for the G4-C5 transfer (separated by 3 days).

V. Conclusion

The Banzai pipeline trajectory permits very low radiation arrivals at Europa for very modest ΔV cost, and is particularly well-suited for Europa landers and short-duration orbital missions. The three-dimensional patched-conic analysis of the Banzai pipeline in the Galilean satellite system transfers with surprising flexibility into the real ephemeris world. While daunting at first, threading a trajectory through the shoals of multi-satellite alignments becomes practical by using the tools outlined herein, yielding substantial rewards in the difficult task of exploring Europa.

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