Preprint AAS-19-242

ON ALIGHTING DAINTILY AT JUPITER: INNOVATIVE METHODS FOR EFFICIENTLY ACHIEVING JOVIAN ORBIT

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Spacecraft bound for Jupiter orbit typically spend the majority of their ΔV in the capture process. The Galilean satellites provide myriad flyby opportunities to assist in the capture process. In addition, the relatively low solar range (compared to the other outer planets) and absence of significant rings add to the option space. Starting with typical single-flyby and Jupiter Orbit Insertion (JOI) maneuver sequences, we will walk through a range of capture options, including longer post-capture tours, double flybys (and their constraints), combined with solar-electric propulsion (SEP) usage, and finally the potential benefits of retrograde, "cloudtops" orbit insertion. In combination with a ΔV-EGA interplanetary trajectory, the cloudtops arrival saves over 500 m/s in the capture sequence.

INTRODUCTION

So far, there have been seven Jupiter flybys, but only two orbit insertions (Galileo and Juno). Both of these were different from each other, and the next two that are planned (Europa Clipper and JUICE) will be different from the earlier missions (though similar to each other). The wide variety of capture options utilized for these missions is indicative of the range of possibilities that are available for arriving missions. The radiation environment at Jupiter acts to constrain the option space, but the absence of a significant ring system is helpful, and the relatively low solar range makes SEP potentially useful. The four members of the Galilean satellite system comprise the most significant Jovian mission design feature, and most of them will inevitably be used for trajectory-shaping flybys by any spacecraft intending to study them further.

GENERAL MISSION DESIGN CONSIDERATIONS

Historically, most Jupiter missions focus significant attention on the Galilean satellite system. For this study, the ultimate target of the mission design is assumed to be Europa flybys (like Europa Clipper and to some degree Galileo) or efficient orbit insertion at Europa or Ganymede (like the proposed Europa Lander or JUICE, respectively). In all of these missions, the target orbit after the initial capture sequence can be defined in terms of a V_∞ at the next Ganymede flyby and

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a post-flyby period. In this paper, the Ganymede flyby that occurs at the first periapsis in Jupiter orbit (*i.e.* not the initial hyperbolic periapsis) is referred to as G1. (While other moons could in principle be used at this point in the mission, they are not typically used, so we will confine ourselves to a G1). Likewise, any flybys that occur around the initial hyperbolic periapsis are numbered zero, with G0 being a typical example. Multiple flybys may be used, but the first letter of the moons are unique, so the same orbit number is used, *i.e*. I0 and G0.

For current Europa Clipper tours, the G1 V_∞ needs to be 6.27 km/s, and we are largely adopting that value here for simplicity in comparing options, with exceptions noted as necessary. A typical post-G1 orbit period is 7 ~weeks/Ganymede periods, but in many cases the preceding orbit period is more important. Clipper uses an initial orbit period of 200 days, which we also use as a basis for comparison. Larger G1 V_∞ values imply significantly larger radiation Total Ionizing Dose (TID), since the spacecraft periapsis is necessarily lower initially, and drops further during the pump-down sequence.* However, larger G1 V_∞ values also correspond to lower spacecraft ΔV, so this option will be discussed below.

All of the trajectories considered here use two propulsive maneuvers to reach the G1 conditions above: Jupiter Orbit Insertion (JOI) and Peri-Jove Raise (PJR). The need for JOI is obvious – capture at Jupiter requires it (with very limited exceptions) – but the need for PJR warrants some discussion. There exist combinations of single flybys, initial periapsis radii, and JOIs that result in the desired period and G1 V_∞ without PJR, but these are typically not optimal. More importantly, the perturbation of the Sun's gravity in the initial long orbit changes the periapsis radius significantly, usually in an unhelpful direction. The initial orbit period is a trade-off between mission duration, JOI magnitude (versus taking more advantage of post-capture flybys to reduce the period), and PJR magnitude to counteract solar third-body perturbation effects. For a typical mission, periods in the 200-300 day range are potentially useful, but beyond that point, the PJR costs outweigh the JOI savings. The solar tidal effect will be quantified below.

SINGLE FLYBY ARRIVALS

The typical sequence of events for the first periapsis is a flyby of Ganymede or Io, followed by JOI. For Galileo, relay for the atmospheric probe required a low periapsis, making Io the natural flyby choice. Clipper plans to use Ganymede, to avoid significant radiation during JOI. Past studies[1,2] have shown that the total ΔV is nearly constant for either moon and for a broad range of altitudes (with Io being slightly more efficient), but that the magnitude of JOI and PJR individually change by ~300 m/s. Note that initial Callisto or Europa flybys are less efficient than Ganymede and Io.

In principle, JOI can occur before a satellite flyby, but that concept has never survived past the early concept stage of a mission, for the simple reason that any performance variation in JOI can easily cause a flyby altitude miss so severe as to either destroy the mission immediately (by impact) or significantly raise the cost (for a high flyby that does not provide the desired energy reduction). Ignoring these difficulties, a JOI-G0 sequence can save ~70 m/s. However, there is an additional small penalty due to the orientation change of the line of apsides with respect to the Sun-Jupiter line, and hence the solar tidal effect. Inbound flybys tend to reduce the PJR magnitude, and outbound flybys increase it. As far as JOI errors, we will show below that the required performance of inertial sensors seems feasible (perhaps neglecting radiation effects), but any in-

* Radiation flux increases over ten-fold between the orbits of Ganymede and Europa, with the sharpest increase slightly below the halfway point.

terruption in the maneuver would need immediate compensation, necessarily computed on-board the spacecraft. None of this seems worthwhile for such a small ΔV benefit, but may be useful for some double-flyby cases.

The altitude of a flyby directly affects its efficacy for energy reduction (or anything else). For airless moons, the overall navigation accuracy of the delivery is the primary factor driving the altitude limit. None of the Galilean satellites have atmospheres, but Io has volcanoes that have been considered a risk for low-flying spacecraft. However, current opinion is that this is not significant above perhaps 100 km.

Galileo's initial flyby of Io was targeted at 1000 km, primarily due to satellite ephemeris uncertainty, and the first Ganymede flyby was likewise limited to 500 km. Over the nearly 8 years that Galileo spent in the Jupiter system, the satellite ephemeris and related parameters were determined quite accurately. Galileo and subsequent spacecraft data have similarly greatly reduced the Jupiter ephemeris errors. Despite these improvements, the downtrack position knowledge of the satellites tends to drift, and of course downtrack errors map almost directly into flyby altitude. Fortunately, recent radar ranging of the Galilean satellites has measured the downtrack error to well below 10 km. By continuing these measurements and combining them with standard Earth-based radiometric tracking techniques, we believe that we can deliver a spacecraft to an initial satellite flyby with a 3-sigma error of no more than 10 km. If another spacecraft (such as Europa Clipper) had recently been navigated through satellite flybys at Jupiter, then the radar measurements would not be necessary to meet this sort of accuracy. Likewise, later flybys (for instance, during a pumpdown sequence) can safely achieve much lower flyby altitudes, by using data from earlier flybys to update the satellite ephemeris.

With this accuracy, a targeted altitude at the first flyby of 100 km seems conservatively reasonable, and will be adopted for all of the analysis presented here. For a typical G0-JOI sequence, the JOI magnitude increases by about 15 m/s per 100 km. The other cost results from needing to correct the orbit period some time after JOI, due to an initial altitude error (which is generally not known in time to adjust JOI magnitude). While much of the cost may arise from JOI errors, the flyby altitude can still contribute. The initial orbit period errors can be efficiently addressed by noting that Ganymede's period is ~7 days, and allowing some margin in the G1 altitude. If the initial orbit period error is a multiple of Ganymede's period (as happened for Galileo, with a -7 day error, resulting from a 100 km miss at Io), then no correction is necessary, other than moving the G1 date forward or backwards by the corresponding number of periods. The maximum period correction necessary is thus bounded by ~3.5 days, at the cost of no more than a few weeks of mission duration. Making this period change at one week after periapsis costs 9 m/s for a 200-day initial period.

All of the combinations of initial flyby(s) and JOI magnitude discussed in this paper are initially analyzed using patched-conics, with a circular, coplanar, phase-free model for the Jupiter satellite orbits. Experience has shown that this approach is a good starting point for everything except the solar perturbation effect. For the latter, we have produced results that give the PJR magnitude due to solar perturbations, shown in Figure 1. These were obtained by propagating an initial orbit period and initial apoapsis phase in a CR3BP model, from periapsis to periapsis, taking note of the apoapsis conditions. The periapsis drop is then compensated with an apoapsis maneuver, which is the solar perturbation cost. Figure 1 is plotted in terms of the osculating apoapsis angle at periapsis, but if the actual apoapsis angle is used, the maximum cost is very close to 45 degrees, which matches the analytic result. The cost increases with period for two reasons: 1) the longer time near apoapsis, and 2) the larger distance from Jupiter (which increases the solar perturbation). The initial apoapsis angle with the maximum cost moves earlier with in creasing period, since there is more time for Jupiter to move around the Sun (which is the main difference between initial and actual apoapsis angle for these periods).

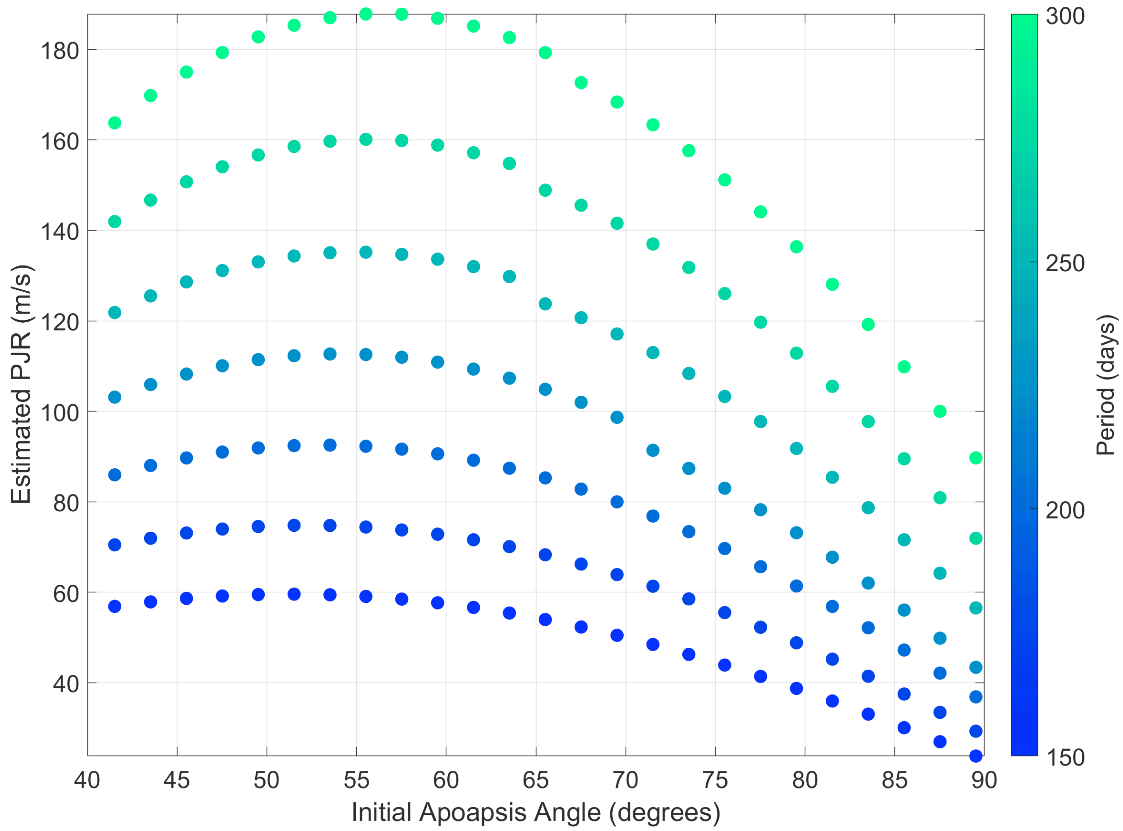

Figure 1: Estimated PJR Magnitude versus Initial Apoapsis Angle. Apoapsis angle starts at the anti-sunward point in the Sun-Jupiter rotating frame, and increases counter-clockwise.

Table 1 shows a variety of single-flyby capture cases (each comprising a choice of Jupiter V_∞, flyby body and altitude, JOI, PJR, initial orbit period, and G1 V_∞). The standard Ganymede and Io cases show how JOI and PJR trade off, ending up at a similar sum. While Ganymede changes the Jupiter periapsis location by a larger angle, the lower initial periapsis for Io results in a larger turn around Jupiter, such that the initial apoapsis angle is higher. (The worst-case solar perturbation for a 200-day period is at 53.5 degrees). A higher Jupiter V_∞ has a larger effect on a Ganymede flyby than an Io flyby, since the lower JOI is more efficient at compensating for the higher energy. The higher-altitude Ganymede flyby shows the 15 m/s per 100 km altitude partial. Putting JOI first produces a benefit of 74.5 m/s for Ganymede, but only 13.5 m/s for Io. If safety considerations require a higher Ganymede flyby after JOI (such as the 500 km altitude shown here), the benefit is largely removed. Finally, longer initial periods show very small benefits for Ganymede, but for Io the benefit is 28.5 m/s at 250 days, and perhaps a bit more for slight longer periods. Since the Io flybys have a large conic (periapsis raise) component, they benefit from a higher apoapsis, and that factor is not overwhelmed by the solar perturbation.

Table 1. Single-flyby Capture Cases.

Flyby Body and Case	Initial Periapsis (km)	JOI (m/s)	PJR (m/s)		Initial Apo Angle (deg)	Total (m/s)
			Conic	Solar		
Ganymede	928,000	808.8	13.6	79.2	61.5	901.6
Io	370,000	531.2	279.4	70.5	69.4	881.1
Ganymede, Jupiter V_∞ 6 km/s	904,000	941.1	23.7	80.5	59.4	1045.3
Io, Jupiter V_∞ 6 km/s	363,000	615.3	284.7	71.5	68.0	972.4
Ganymede, altitude 500 km	918,000	867.4	15.8	79.6	60.8	962.8
Ganymede, JOI first	965,000	748.3	1.1	77.7	44.2	827.1
Ganymede, JOI first, alt 500 km	962,000	812.9	0.1	78.8	45.3	891.8
Io, JOI first	376,000	513.6	275.8	78.1	62.8	867.5
Ganymede, 250d initial period	923,000	753.2	15.4	122.7	61.6	891.2
Ganymede, 300d initial period	919,000	713.7	16.1	174.7	61.8	904.5
Io, 250d initial period	368,000	496.0	244	112.1	69.3	852.6
Io, 300d initial period	367,000	471.4	218.6	163.0	69.3	853.0

Unless otherwise noted: 1) initial V_∞ with respect to Jupiter is 5.6 km/s, 2) flyby precedes JOI, 3) flyby altitude is 100 km, and 4) post-capture period is 200 days. Arrival solar phase angle is 90 degrees. Initial apoapsis angle has the same definition as in Figure 1. G1 V_∞ is 6.27 km/s. Initial periapsis is the periapsis radius before any flybys, and is optimal to the nearest 1000 km. The conic component of PJR is the osculating periapsis raise.

Extended Pump-down Considerations

By relaxing the G1 V_∞ constraint, the optimum JOI altitude for a G0 flyby drops, since PJR does not need to raise periapsis as far, and JOI is reduced. The lower periapsis leads to a higher flight-path angle at G1, and hence a higher V_∞ value. As an example, the cost of JOI+PJR for a G1 V_∞ of 10 km/s is about 135 m/s lower than with a G1 V_∞ of 6.3 km/s. The drawback for this ΔV savings is the longer pump-down sequence (typically including alternating Callisto and Ganymede flybys) required to arrive at the desired final Ganymede V_∞ value, leading to an increase in time-of-flight (TOF) and TID.

To quantify the penalties associated with an extended tour, we performed a broad search for pump-down solutions, beginning with a G1 V_∞ of 10 km/s and ending at Ganymede with a $V_\infty \leq$ 6.3 km/s. Four costs are used to evaluate each trajectory: total TID, TOF, ΔV*, and the final Ganymede V_∞ (which in these solutions varies between ~3.8-6.3 km/s). Any solutions that reach an advantageous extrema in one or more of these costs are retained. These are compared to a reference set of pump-down trajectories generated beginning from the typical Ganymede V_∞ of 6.3

* Resulting from estimates of solar perturbation on apoapses after the initial orbit.

km/s. Of these solutions, those near the knee in the TID/TOF/ΔV surface are selected for comparison with extended tour options. By comparing each extended tour option to the nearest solution in final Ganymede V_∞ from the selected standard tours, the penalties in TID and TOF can be obtained, in addition to estimated ΔV savings. Three example solutions are given in Table 2, with the totals for the extended tour given in the columns labeled "Absolute Values", and differenced values given as deltas from the selected nominal tour. For a total TID penalty under 500 krad, a savings of 100-110 m/s in deterministic ΔV* is achievable with a 250-275 day TOF penalty. For options with increased savings in ΔV, the TID penalty escalates quickly. More options for balancing TOF/TID and ΔV savings would likely be found by evaluating G1 V_∞ values between 9 and 10 km/s. For more details on the search and cost evaluation strategies, see Haapala et al.[3]

Table 2. Example Extended Pump-Down Results.

Solution Number	Absolute Values				Differenced Values		
	Tour ΔV (m/s)	Tour TID (krad)	TOF (days)	Final Ganymede V_∞ (km/s)	ΔV Savings (m/s)	TID Penalty (krad)	TOF Penalty (days)
1	42.2	482.9	496.5	5.2	107.5	471.5	250.9
2	42.1	473.6	494.4	5.3	99.2	460.4	277.7
3	23.9	624.6	423.5	4.5	116.7	590.8	228.3

ΔV savings is with respect to similar tours without an extended pump-down, and includes JOI, PJR, and solar perturbations (but not statistical costs due to additional flybys).

DOUBLE FLYBY ARRIVALS

Two factors are generally required for a double flyby to work: 1) the necessary in-plane alignment of two satellites with the direction of the incoming trajectory, and 2) the lack of a significant out-of-plane component to the incoming trajectory, with respect to the satellite orbit plane (which is very close to the Jupiter equator). The out-of-plane condition can be relaxed with a very specific satellite alignment that prevents the optimum JOI radius for energy reduction, but may be cheaper than arriving in-plane in many cases, as will be discussed below. In addition to these factors, the navigation errors from the first flyby and (if not the last element) JOI must be considered at the second flyby.

The Galilean satellites are in near-resonances with each other, but their slight offset from perfect resonance becomes useful in that any particular satellite-satellite alignment will occur at a different inertial point at its next instance. We are usually concerned with how an alignment progresses against the direction to the Sun, since that is also the reference for spacecraft arriving from the inner solar system. Jupiter moves about one degree in its orbit every 12 days, which is significant compared to the inertial change. Table 3 shows all of the possible pairs, with the angles all adjusted to be Sun-relative. Of particular interest are the number of alignments per synodic cycle – for example, Io and Callisto will align 25 times in just under 50 days, for an average spacing of 360/25 = 14.4 degrees. This pair's change with respect to the Sun per cycle is larger than that, and so the effective spacing becomes about 21 degrees, advancing about 3 degrees per two Callisto periods. By contrast, Ganymede and Callisto barely change over a cycle. The right-

* Statistical ΔV required for the additional flybys will slightly reduce the net savings.

hand column gives the time for the alignment to drift to cover the per-alignment spacing, which drives the mission timing flexibility needed to exploit that pair. The 438-day (14.5-month) value

Table 3. Galilean Satellite Resonances and Alignments.

Satellite pair	Resonance	Align-ments per cycle	Sun-relative change (deg)		Time to span alignment spacing (days)
			Per cycle	Per alignment	
Io-Europa	2:1	1	-2.900	-2.900	437.7
Io-Ganymede	4:1	3	-5.800	118.067	143.5
Io-Callisto	28:3	25	-16.928	42.523	124.3
Europa-Ganymede	2:1	1	-5.800	-5.800	437.6
Europa-Callisto	14:3	11	-13.728	96.934	350.4
Ganymede-Callisto	7:3	4	-3.603	269.099	1263.9

shows up for both Io-Europa and Europa-Ganymede, and is a driving factor for Europa mission studies.[4,5] Io-Ganymede and Io-Callisto offer the fastest alignment spans, and Ganymede-Callisto is the slowest, which makes it unlikely to be useful, despite offering the best performance of any pair. Examples of both Ganymede-Io and Callisto-Io trajectories will be provided below.

When discussing various sequences, it is useful to introduce a shorthand terminology where F is a flyby and M is the JOI maneuver. Two flybys followed by JOI would be a FFM sequence, *etc*. As before, there is some advantage to having JOI first in terms of energy reduction, but the PJR solar perturbation penalty may well overwhelm any benefit, depending on the initial apoapsis angle. The main advantage of permitting MFF or FMF sequences comes from the increased number of available alignments, which increases the likelihood of finding one at an acceptable time. The performance of several flyby pairs is given in Table 4. In all of these cases, the first flyby is set at 100 km, and the second at 300 km, as a way of allowing for navigation errors at the

Table 4. Double-flyby Capture Cases.

Capture Sequence	Initial Periapsis (km)	JOI (m/s)	PJR (m/s)		Initial apo angle (deg)	Total (m/s)
			Conic	Solar		
Ganymede-Io-JOI, in-plane	419,000	339.2	270.8	64.6	73.1	674.7
Callisto-Ganymede-JOI, in-plane	1,051,000	539.4	0.2	73.7	67.0	613.3
Callisto-Io-JOI, in-plane	439,000	417.3	273.9	64.8	73.0	755.9
Ganymede-JOI-Io, 180°-spacing	329,400	335.7	329.5	69.8	69.9	735.0
Callisto-JOI-Io, 180°-spacing	393,300	396.3	302.4	71.7	68.6	770.4

Unless otherwise noted: 1) initial V_∞ with respect to Jupiter is 5.6 km/s, 2) flyby altitude is 100 km for the first flyby, and 300 km for the second, and 3) post-capture period is 200 days. Arrival solar phase angle is 90 degrees. Initial apoapsis angle has the same definition as in Figure 1. G1 V_∞ is 6.27 km/s. Initial periapsis is the periapsis radius before any flybys, and is optimized for either total ΔV (in-plane cases) or required flyby spacing (180 degree cases).

first flyby. (This will be discussed in more detail below). For the in-plane cases, the initial periapsis radius is set for the optimum performance, but of course it could be adjusted to help with reaching the proper alignment.[6] The in-plane arrival constraint is significant, since the optimum declination of the incoming asymptote of Earth-originating trajectories can be as high as 8 deg. Correcting this with a pre-encounter maneuver can easily be as or more expensive than the savings from a double-flyby capture, but for now let us assume that the in-plane constraint is met.

The in-plane cases in Table 4 show almost 300 m/s of savings in the best case (C-G-JOI versus G-JOI), and over 200 m/s of savings in a more feasible case (G-I-JOI versus I-JOI). As with the single flybys, moving JOI before Io does not have much benefit. Despite having only 133 m/s of savings, the Callisto-Io-JOI case should be the easiest one to arrange. Longer initial periods behave similarly to the single-flyby cases.

For cases where the arrival asymptote is not close enough to the satellite orbit plane, a double flyby is still possible if the flyby locations are 180 degrees apart on the spacecraft trajectory, such that the flybys occur on the line of nodes. The 8-degree maximum arrival declination noted above is too small (with a cosine effect) to significantly affect the energy reduction from the two flybys. Since periapsis occurs between the flybys, the FMF sequence is the only one that allows JOI at periapsis, and it is consequently the most efficient sequence. The performance of various pairs of moons allowing an out-of-plane arrival is also given in Table 4. While these are worse than the best in-plane cases, their declination flexibility makes them more likely to be useful. However, the in-plane arrival direction needs to match the alignment of the two satellites rather closely since the 180-degree spacing must be met rather precisely. Adjusting the in-plane arrival direction seems likely to be less costly than adjusting the arrival declination, but determining to what degree that is true must be left for a future study.

An example of a Callisto-JOI-Io capture sequence in high fidelity is shown in Figure 2. The arrival declination is 7.5 degrees, and the Jupiter-relative V_∞ is 5.6 km/s. The arrival date of June 10, 2032 is potentially consistent with a 2027 2+ ΔV-EGA launch opportunity, but that was not determined in detail. The JOI magnitude found here is 420 m/s, which is reasonably close to the predicted patched-conic value of 396 m/s.

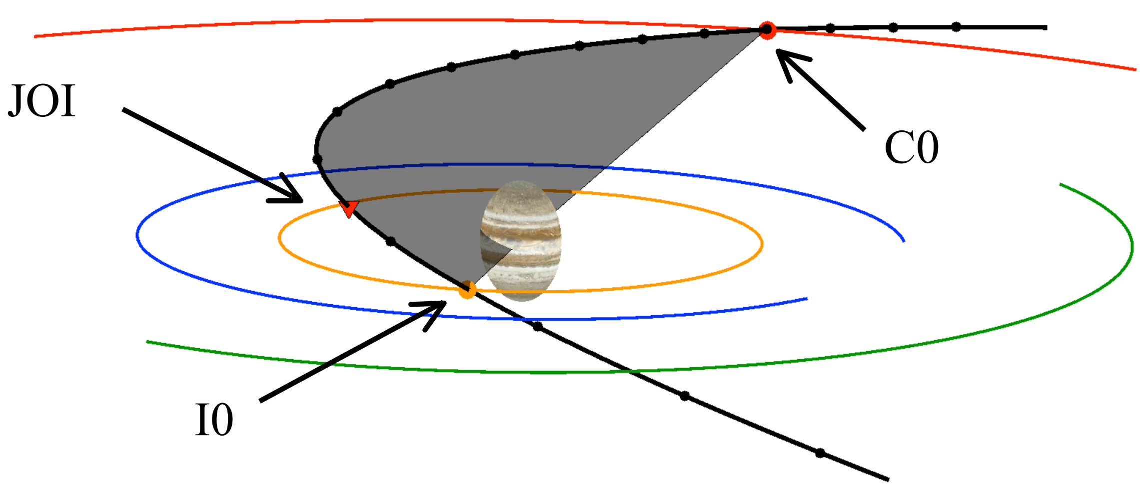

Figure 2: Example Callisto-JOI-Io out-of-plane capture sequence. Vertical dimension is exaggerated by about 50%. 4-hour time tics on the spacecraft trajectory.

Navigating Double-Flyby Arrivals

All of these double-flyby arrivals rely on limiting the navigation errors at the second flyby. As discussed above, the first flyby accuracy should be no worse than 10 km, which we can take (being slightly pessimistic) as an altitude error. For the Ganymede-Io-JOI sequence discussed in the SEP section below, this altitude error resulted in an 87-km altitude error at the Io flyby, which is easily tolerated by the nominal 300-km altitude. The resulting period error (assuming JOI is not adjusted) is 21 days, but allowing 3 more weeks after G1 accommodates this for the cost of 9 m/s one week after JOI (also noted earlier), plus a small cost (or savings) at PJR depending on the apoapsis radius. The time from the Ganymede flyby to JOI is about 17 hours, which isn't an impossibly short time in which to consider updating the JOI magnitude, based on Earth-based tracking, since the flyby altitude error at G0 becomes readily apparent at the flyby epoch.

For cases where JOI precedes a flyby, the JOI execution errors are important. These include errors in the direction or magnitude of the maneuver (based on inertial sensors) and potentially errors in timing due to system fault protection activities, which may halt the burn for some period of time. If the time history of the maneuver can be maintained during any fault, then the remaining part of the maneuver could be adjusted onboard to compensate for the outage, as was implemented on Cassini for Saturn orbit insertion. However, avoiding that complexity would be preferable.

The out-of-plane Callisto-JOI-Io case shown in Figure 2 and described above can be used as a test of the acceptable level for JOI errors (and also for the acceptable Callisto flyby errors). Table 5 shows the effect of selected JOI errors at Io and in the post-capture period (nominally 200 days). The effect of these JOI errors is small, largely because JOI starts only 3.7 hours before the Io flyby epoch. While this puts a lower limit on the thrust level (lest the burn still be proceeding during the flyby, or need to start earlier than would be optimal), the overall effect of keeping a low duration from JOI to the final flyby seems advantageous.

Callisto flyby altitude errors produce a large change in Io altitude and post-capture period, even after the 10 km delivery error discussed above was reduced to 5 km. The Callisto flyby is 38 hours before the Io flyby, which allows time for the flyby errors to grow significantly. Perhaps the 3-sigma delivery error at such a Callisto flyby could be reduced to 5 km. However, the 34.5 hours from C0 to JOI suggest that a JOI adjustment could reasonably be performed after the C0 flyby, using Earth-based tracking. The last row on Table 5 shows the effect of adjusting the

Table 5. Effect of JOI and C0 Errors on I0 Altitude and Post-capture Orbit Period

Parameter	Input perturbation	I0 altitude change (km)	Post-capture period change* (days)
JOI magnitude	0.5%	8.3	1.26
JOI right ascension	0.5 deg	55.5	11.03
JOI declination	0.5 deg	1.1	1.30
JOI start time	86.4s	21.3	2.64
C0 altitude	5 km	233.8	34.6
C0 theta	0.1 deg (4.5 km)	9.8	1.51
C0 altitude + JOI RA	5 km, 2 deg	12.7	7.29

For Callisto-JOI-Io out-of-plane arrival sequence shown in Figure 2.

**The post-capture period would only need to be adjusted by ±3.5 days to reach a G1 flyby.*

direction of JOI to approximately adjust for an altitude error. The actual value of the direction adjustment would be modified to achieve the post-capture period more precisely, but this example shows the feasibility of this approach in general.

SOLAR ELECTRIC PROPULSION ENABLED ARRIVALS

Advances in solar array technology now enable solar-powered spacecraft to operate effectively at Jupiter. The large TIDs required for missions to Europa cause significant degradation of the array output by the end of the mission. When this is accounted for in the array sizing, there is often a surplus of power early in the mission. Additionally, the array output at lower solar ranges on the way to Jupiter is much higher. All of these factors suggest that using solar electric propulsion (SEP) for Jupiter-bound solar-powered spacecraft would be a good match.

Previous studies have shown that Jupiter ballistic capture can be achieved for a still-substantial V_∞ of ~3.5 km/s, using Callisto and Ganymede flybys.[7,8] SEP thrusting can be used to adjust the arrival plane and timing with very little penalty, and it may be the only way to reliably enable in-plane double flybys. However, reducing the typical arrival V_∞ of 5.6 km/s to 3.5 km/s requires a significant ΔV (at least 1 km/s) to be delivered at Jupiter range, which drives solar array sizes much beyond what is typically needed at Jupiter. While this potentially removes the need for a chemical propulsion system altogether, the cost trade suggests that this is not advantageous. In addition, when there are large velocity-leveraging maneuvers in the future, and/or satellite orbit insertions, the high-thrust chemical system will be required anyway.

A more reasonable approach is to use SEP to modestly reduce the arrival V_∞ and set up a favorable double flyby opportunity. The JOI magnitude can easily be reduced to well under 300 m/s with a Ganymede-Io-JOI sequence, and those opportunities are accessible every ~145 days, as discussed above. The SEP system can provide part of PJR, with the rest performed chemically, although this could be traded against dropping the SEP thrusters and tanks before JOI, in terms of launch mass and/or cost. The high-thrust propulsion system only needs to provide ~400 m/s for Jupiter arrival, and if the remaining ΔV requirements are modest (no more than perhaps about 500 m/s), a less-expensive monopropellant system may suffice.

While it is beyond the scope of this paper to discuss in detail, the large power levels available in the inner solar system enable smaller launch vehicles to deliver the same mass to Jupiter orbit. The array size, SEP thrusters & propellant load, and trip time can be adjusted to accommodate a particular launch vehicle, with much more flexibility than for a chemical system. Of course, this is only a good trade if the difference in launch vehicle cost is accounted for, since the flight system cost is more likely than not to increase, despite the typically lower launch mass.

The other benefit of large power levels is to reduce the flight time on larger launch vehicles, particularly if the launch vehicle does not quite have enough performance to use a direct trajectory, but must utilize a ΔV-EGA, with a 2-year increase in duration. As an example, consider the results of a study into SEP-aided direct trajectories to Jupiter using a SLS Block-1B launch vehicle, for a possible Europa Lander mission. With a chemical-propulsion mission, the SLS had excess performance for the ΔV-EGA (with a C3 of $\leq$ 30 km^2/s^2), but not nearly enough to go direct (requiring a C3 of at least 80 km^2/s^2), even accounting for the lower spacecraft mass due to the lower ΔV requirements (no DSM). In the SEP case, the optimum launch C3 is 66 km^2/s^2, using all of the launch vehicle performance*, and SEP thrusting does the rest, as shown in Figure 3. The SEP thrusting also adjusts the arrival time to use a Ganymede-Io-JOI capture sequence, as shown in Figure 4.

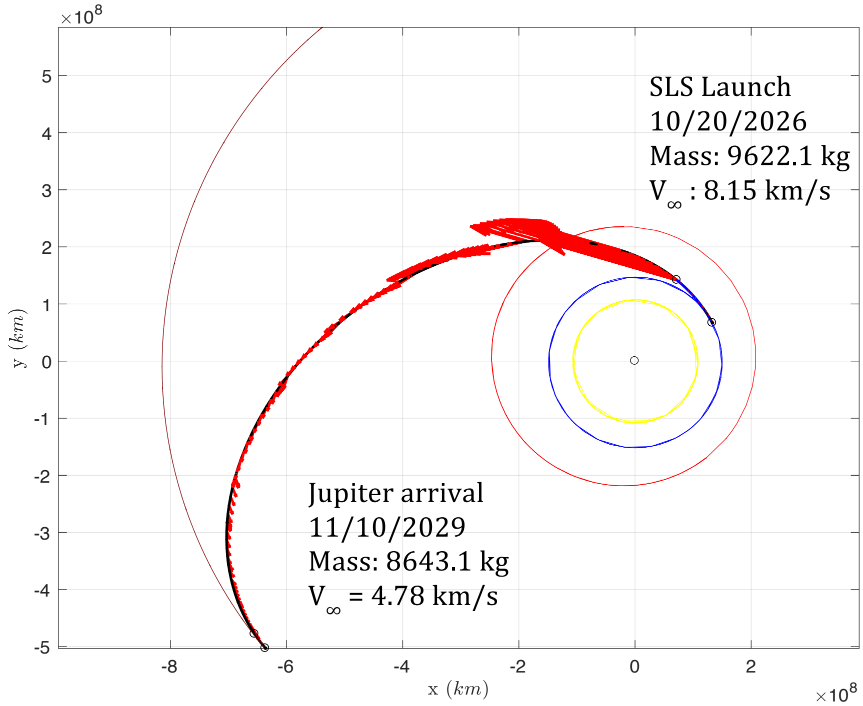

Figure 3: SEP Interplanetary Trajectory Example. Red arrows indicate SEP thrust direction and magnitude.

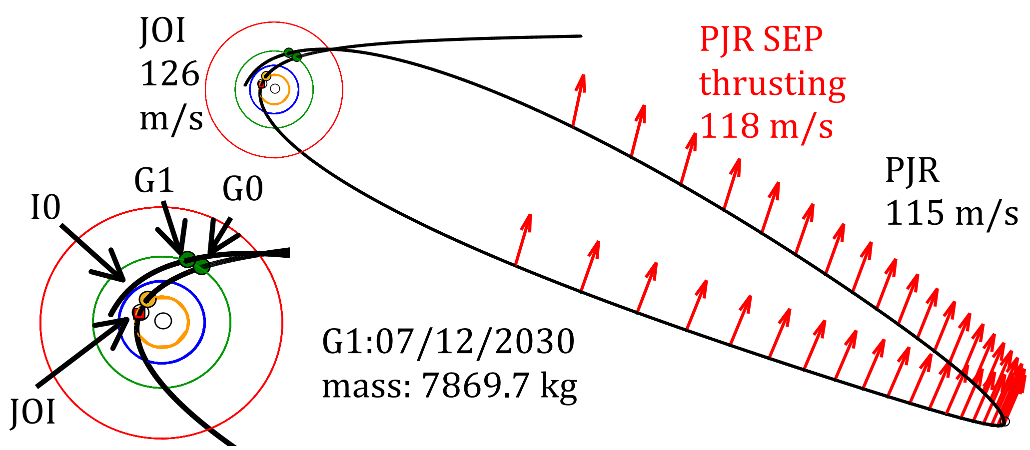

Figure 4: SEP Trajectory Example at Jupiter.

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* Another SEP benefit is that all of the launch vehicle performance can be used, with the usual trajectory step functions being smoothed over by spacecraft low thrust.

After JOI, part of PJR is performed on the SEP system, and the rest is completed with the chemical system. Table 6 gives some of the representative spacecraft parameters used for this study. The mass performance for this arrival date (November 2029) and an earlier one (May 2029, corresponding to the preceding Ganymede-Io opportunity) are very similar for this set of assumptions, which suggests that better performance may be possible for some other Earth-Jupiter transfer opportunities, where the timing of the satellite alignments is more favorable. Jupiter was near aphelion for these arrival dates, which also limits the performance. Nonetheless, this example illustrates the potential benefits of a SEP-aided transfer.

Table 6: Parameters Used in SEP Example

Parameter	Value
Solar array power for engines	20 kw @ 1 AU, 1 kw @ 5.33 AU (due to higher efficiency at low temperature)
SEP engines	Four BPT-4000s, Max Isp: 1850s, Max thrust per engine: 280 mN
Acceleration level	9.1 m/s/day @ 1 AU, 0.63 m/s/day @ 5.33 AU
Duty cycle	90%
Chemical ISP	300s
G1 V_∞	9 km/s (utilizing a longer tour)

CLOUDTOPS ARRIVALS

Considering the Jupiter arrival space can be frustrating – low altitude JOIs are very effective at reducing the arrival V_∞ and capturing, because of the enormous Jupiter mass, but the PJR magnitude is correspondingly large. Increasing the initial period fails to significantly reduce the PJR magnitude, due to solar tidal perturbations, as shown above. If only there was some way to get the solar perturbations to help!

Fortunately, there is. With a retrograde arrival, apoapsis is now in the leading, sunward quadrant in the Sun-Jupiter rotating frame, such that the solar perturbation increases the (prograde) periapsis altitude. JOI can efficiently be performed as low as possible, hence a "cloudtops" arrival. The period can now be increased, such that apoapsis is high enough to keep the conic part of PJR magnitude reasonable, especially since a large fraction of PJR is due to solar perturbation, even accounting for the extra cost for switching from retrograde to prograde (effectively starting the periapsis raise from a radius of negative 75,000 km).

The effect of solar perturbation on retrograde cloudtops arrivals can be calculated in the same way as for prograde arrivals (as was shown in Figure 1). Figure 5 shows the ΔV required at PJR to transfer from a retrograde arrival at 75,000 km to a prograde periapsis at 1 million km, as a function of the initial apoapsis angle. For periods of ~18 months or longer, the solar perturbation alone is enough to accomplish this transfer for larger angles.

The first cloudtops trajectory computed is shown in Figure 6, compared to the standard approach. The Jupiter arrival solar phase is 73 degrees, which puts the initial apoapsis angle at 61 degrees solar phase (or 119 degrees in Fig 5), where it receives significant solar perturbation help with the prograde switch and periapsis raise. The period of the initial loop ended up being 20.5 months, and the sum of JOI and PJR is 574 m/s, which was enough to validate the savings potential of this concept.

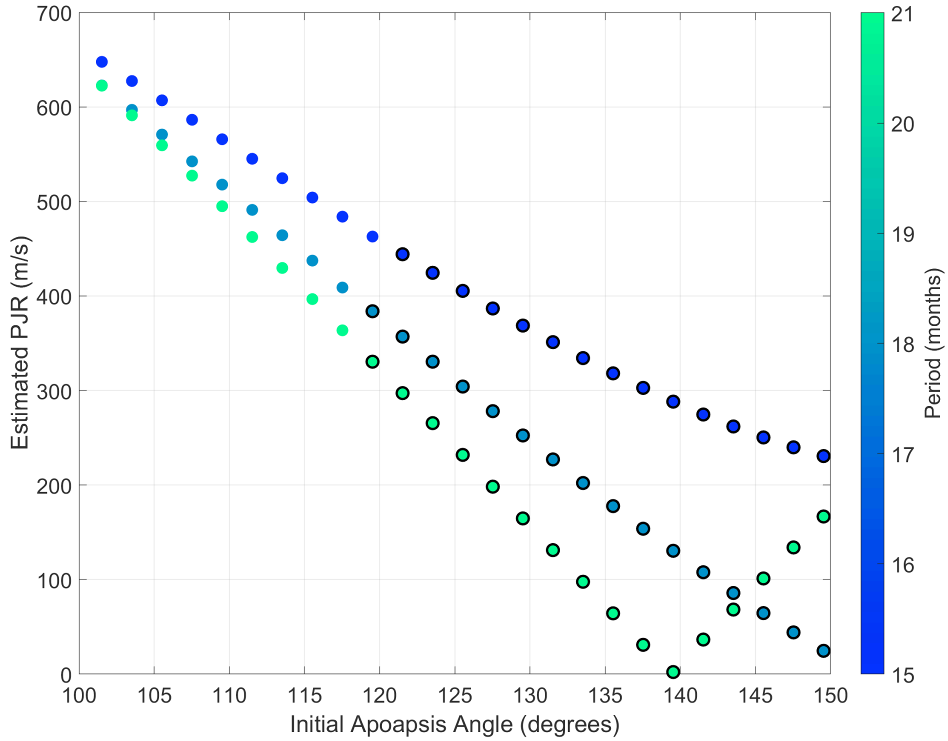

Figure 5: PJR Cost for Retrograde Orbits. Initial periapsis is 75,000 km, final periapsis is 1 million km, prograde. Black-circled cases become prograde without any ΔV.

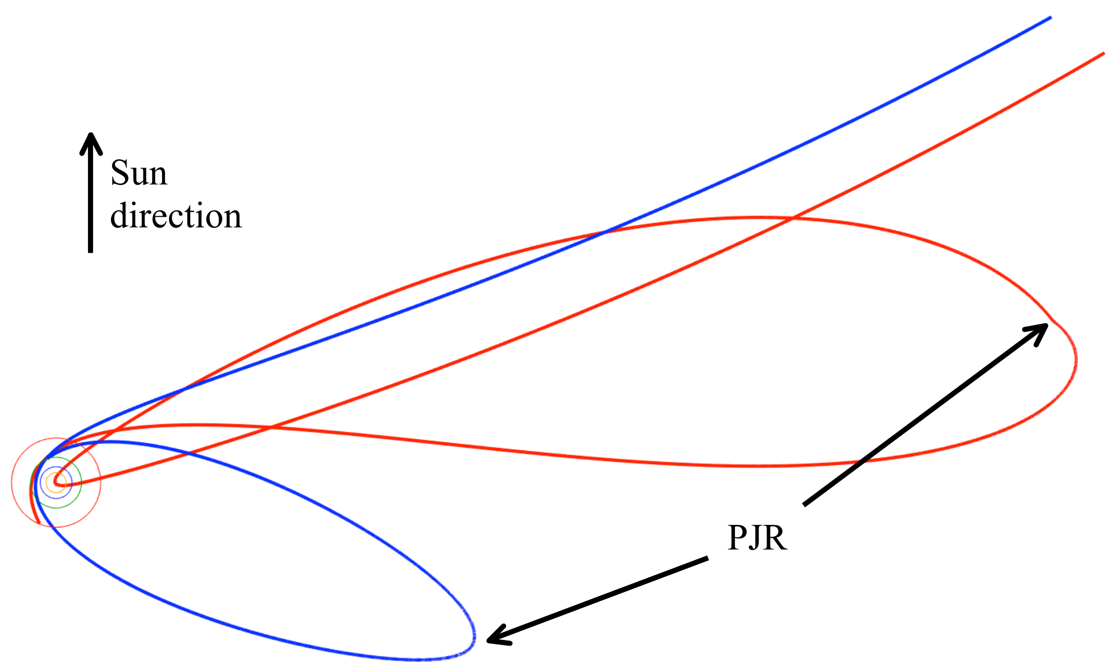

Figure 6: Cloudtops versus Standard Jupiter Arrival. Cloudtops trajectory is in red, standard trajectory is in blue. Both are from the same Earth-Jupiter trajectory. Shown in the Sun-Jupiter rotating frame, with the Sun at the top.

With further optimization, we will show that a cloudtops arrival can save more than 500 m/s, significantly better than any double flyby arrival (aside from SEP-aided cases). The flight time increase is a little under one year, which seems tolerable for such a benefit. The other drawbacks are: the necessity of avoiding Jupiter's modest ring system, a modestly higher required acceleration level, and a higher TID, each of which will be discussed below. The benefit of the cloudtops approach is particularly strong with a ΔV-EGA trajectory to Jupiter, and we will conclude with detailed analysis of a pair of such trajectories.

Jupiter possesses a modest ring system below the orbit of Thebe. All of it appears to be very fine dust except for the main ring, which extends 6500 km below Adrastea (and Metis). The main ring has a vertical extent of only a few hundred km, which makes it easy to avoid. However, the halo ring covers radii of 92,000 to 122,500 km, and extends as far as perhaps 10,000-20,000 km from the equatorial plane. The brightness falls off quite rapidly in the out-of-plane direction, so it may not be necessary to avoid the full extent of the halo ring. In fact, the dust particle size and density may be low enough to ignore the halo ring entirely. However, for the purpose of this paper, a minimum out-of-plane distance of 7000 km at the mid-point (~107,000 km radius) was imposed.

Ring avoidance would not be a problem were it not for a desire to still make use of a satellite flyby to aid in Jupiter capture. With a retrograde flyby en route to a low perijove, the most effective satellite for this purpose is Ganymede, but the savings from this flyby are only about 45 m/s. That is worth pursuing at >10% of the JOI cost, but it is not a large value in an absolute sense. Analysis shows that for inbound asymptotes with declination magnitudes below 2.5 degrees (with respect to the Jupiter equatorial plane), it is not possible to avoid the halo ring (as defined above) and still perform a Ganymede flyby. For magnitudes as low as 1.5 degrees, a Callisto flyby is still possible, and the flyby benefit drops to 37 m/s. For those cases where the Jupiter-relative arrival declination is below these levels, the trajectory must forgo the benefit of a flyby. In all of these cases, the small inclination resulting from ring avoidance should easily be accommodated at PJR and during the subsequent flybys.

The largest impulsive JOIs contemplated for a cloudtops arrival are ~440 m/s (corresponding to a Jupiter V_∞ of 7 km/s with a G0 flyby), and in many cases they may be closer to 300 m/s. Figure 7 shows the performance of acceleration levels around 0.1 m/s^2, in terms of Jupiter V_∞. Even at 7 km/s and 0.08 m/s^2, the gravity loss is not quite 12%, and for the higher acceleration levels the gravity loss is 6% or less. While not explicitly calculated, the better cases (with a duration as low as ~33 minutes) can probably withstand a thrust interruption (due to some fault condition) of a few minutes without undue penalty. Figure 7 results are for anti-velocity thrusting (which will be very similar to a constant-rate pitch over), but constant-attitude thrusting should be tolerable for the larger acceleration levels. Achieving these acceleration levels does not appear unduly difficult – for the proposed Europa Lander (currently under study), the arrival mass would be around 15 metric tons, and four 400N bi-prop engines (which are readily available) would provide enough thrust. Even if such a spacecraft had a complete redundant set of main engines (as befits a flagship-class mission), the total mass of the thrusters (and their cost) would not be unreasonable. For the lower acceleration levels, JOI extends to radial distances well above the halo ring, which makes using a protective spacecraft attitude mode against dust impact impossible, and suggests that higher thrust levels are a better risk/cost trade.

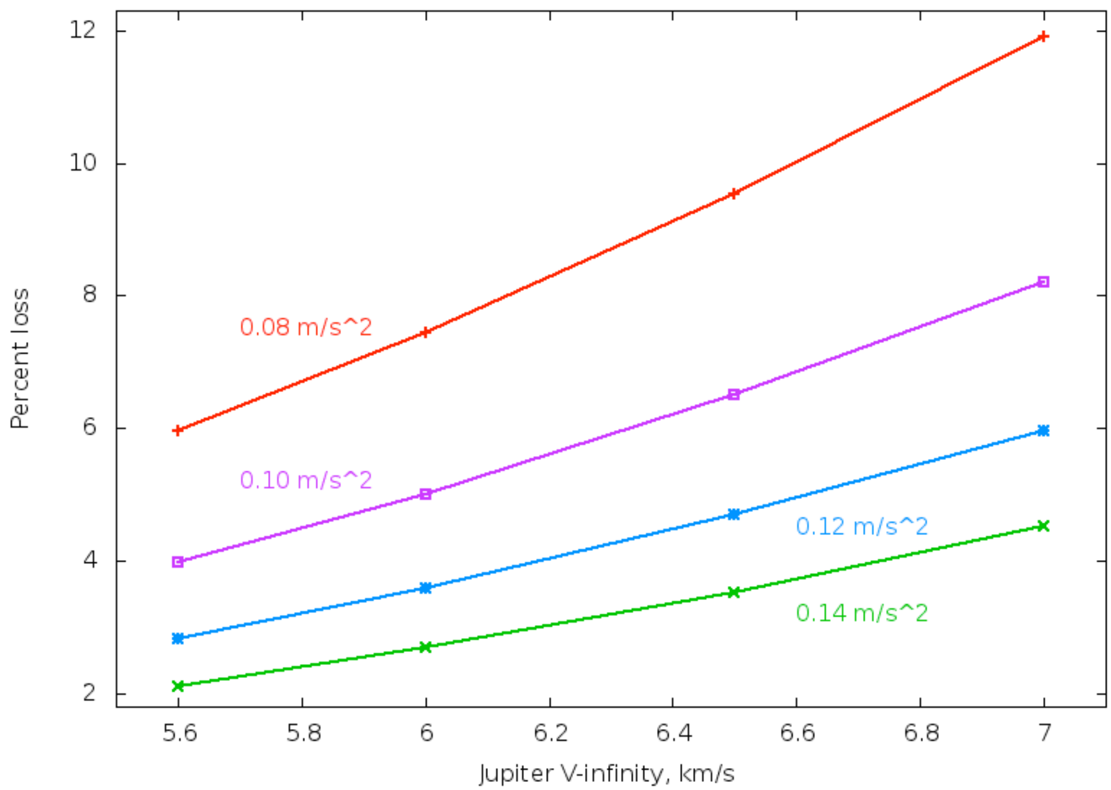

Figure 7: Gravity Loss versus Acceleration Level at Jupiter. Minimum altitude during burn is 5000 km. Thrust direction is anti-velocity. Acceleration level is at JOI start, and Isp is assumed to be 315s.

The Jupiter radiation flux has peaks at about 143,000 km and 243,000 km, dropping off by more than a factor of two in between, and above 290,000 km, when modeled in Grav2p.[9] The radiation region is aligned with the magnetic equator, offset by 10 degrees from the rotational equator. During the 4.7 hours spent at or below 290,000 for a cloudtops arrival, phasing periapsis as far out of the magnetic equator as possible provides a significant benefit, since the periapsis pass duration is significantly less than the 9.9-hr Jupiter rotation period. For a minimum-declination, G0 arrival, the TID from the initial periapsis varies from 110 krad to 246 krad, depending on the phasing, when modeled in GRID2P.[10] The Ganymede orbit period is about 14.25 Jupiter revolutions, so a 1- to 2-week arrival time adjustment would allow arrival during the lowest quartile of TID values, which would be limited to 150 krad*. By comparison, velocity-leveraging trajectories to Europa add over 1000 krad for a (similar) benefit of 500 m/s, and Europa Clipper is designed for 3000 krad. Consequently, accepting the additional radiation dose for the large ΔV savings (and accepting the TOF penalty) seems like favorable trade. A bigger concern may be performing a critical maneuver in (or shortly after passing through) a high radiation flux. Even so, the savings should make this worthwhile for some missions. After all, Galileo

* The inclination can be freely increased by giving up the benefit of an inbound flyby (~45 m/s), and doing so should significantly reduce the TID, if that was deemed a favorable trade. Note that there could be some time or ΔV cost for reducing the inclination later in the pumpdown sequence. For a standard prograde arrival, an initial Io flyby costs ~55 krad, and an initial Ganymede flyby costs ~9 krad.

managed to perform JOI and probe relay during relatively high flux levels (below Io), so it can certainly be accomplished again.

Having addressed the various drawbacks of a cloudtops arrival, we turn to the benefits, especially in combination with the transfer from Earth to Jupiter. Figure 5 showed that for a long enough period, and the right initial apoapsis angle, PJR is entirely accomplished by the Sun. Increasing the apoapsis angle implies a steeper heliocentric flight-path angle (equivalent to a lower solar phase angle) approaching Jupiter, with a higher Jupiter-relative V_∞ and an earlier arrival date. The cost of the higher V_∞ is rather modest: an increase of 1 km/s only costs about 120 m/s for a cloudtops JOI, and the earlier arrival helps mitigate the longer initial orbit. For a ΔV-EGA trajectory, the arrival phase angle change is accomplished by increasing the Earth-relative V_∞ at the flyby, which is in turn produced by a larger Deep Space Maneuver (DSM) at the preceding apoapsis. The DSM is very efficient at increasing the Earth-relative V_∞ and so rather low phase angles (compared 90 degrees for a Hohmann transfer) become reasonable. The optimized total spacecraft ΔV takes into account the increases in the DSM and JOI values, and the decrease in PJR, as shown in Figure 8* for a fixed first-orbit duration of 18 months, and expressed in terms of arrival date. The values for DSM and JOI slowly decrease for later arrival dates, but since the PJR magnitude has the steepest slope, the PJR minimum defines the minimum for the total.

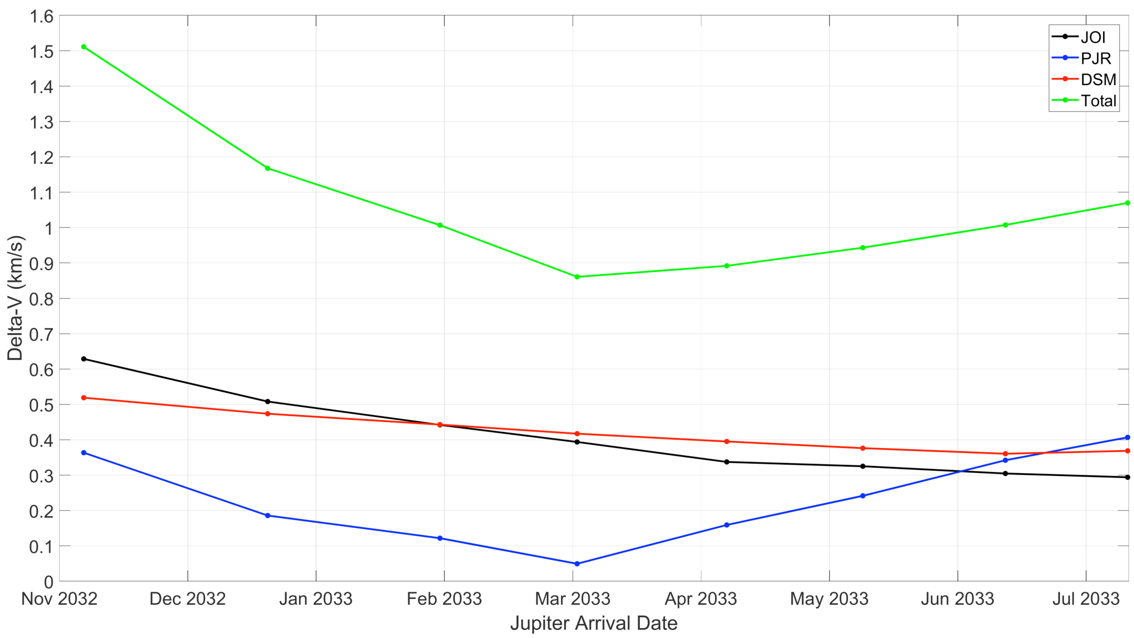

Figure 8: Maneuver Magnitudes versus Arrival Date. 18-month period from arrival to G1, and G1 V_∞ is 6.27 km/s. 2028 ΔV-EMGA trajectory. JOI at 75,000 km radius. DSM and JOI magnitudes are for the maximum across the launch period.

The initial period can also be varied to find the optimum balance of ΔV and TOF, as shown in Figure 9 in terms of the G1 arrival date. Later arrival dates have too high an arrival phase to ben-

* The interplanetary trajectory used here has a Mars flyby after the Earth flyby, which reduces the DSM by about 200 m/s. However, the DSM and JOI trends are similar to pure ΔV-EGAs.

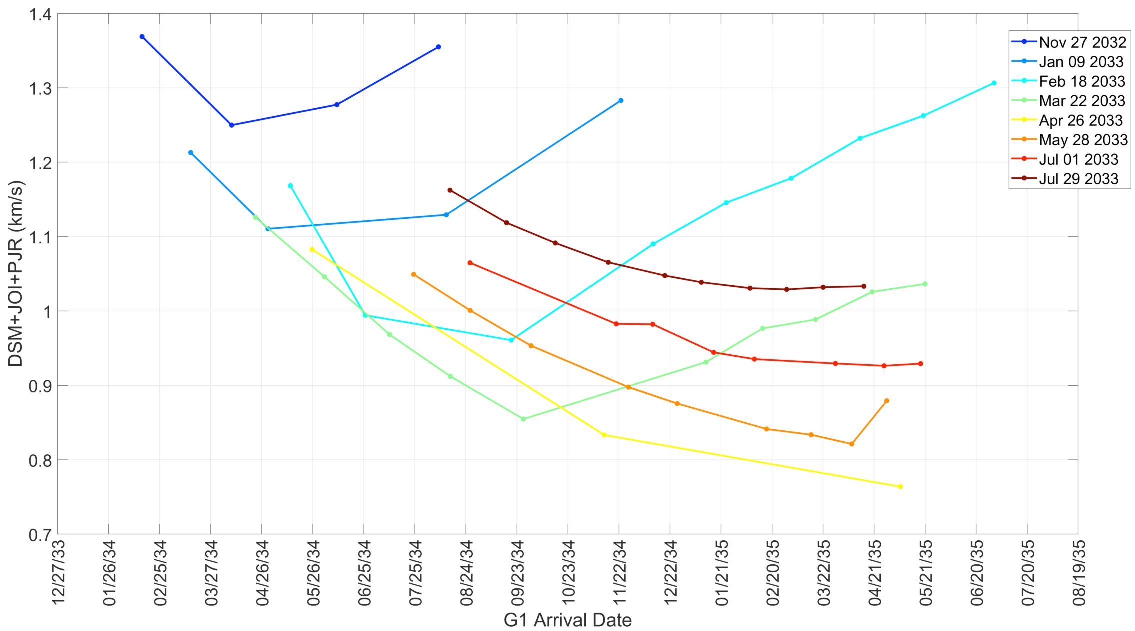

Figure 9: Cloudtops Total ΔV versus Arrival Date and G1 Date. For 2028 ΔV-EMGA trajectory. JOI at 75,000 km radius. G1 V_∞ is 6.27 km/s. Jupiter arrival date is stepped in 30-day increments, and the post-JOI orbit period is stepped in 1.5-month increments.

efit much from solar perturbation. We can imagine a Pareto front surface in Figure 9, trading total ΔV and the G1 arrival data (or TOF). Mid-range dates (March and April) occur at the knee in this Pareto surface, reaching some of the minimum values, and even earlier arrival dates start to pay too much in DSM and JOI. The ideal point appears to be a March 22, 2033 Jupiter arrival, with an 18-month initial orbit reaching G1 on September 26, 2034. However, even lower total ΔV cases are available with later arrival G1 dates, for an April 26, 2033 Jupiter arrival.

The results in Figures 8 and 9 are from a medium-fidelity interplanetary model, combined with a high-fidelity model for the Jupiter phase. As a verification, the entire trajectory for the March 2033 arrival/September 2034 G1 combination was run in a high-fidelity model, for the maximum spacecraft ΔV across the launch period, both for the Mars gravity assist (MGA) and for the regular ΔV-EGA trajectories. These cases were then compared to high-fidelity modeling of a standard prograde arrival into a 200-day orbit, using the corresponding interplanetary trajectory type. Figures 10 and 11 show the Jupiter arrival for the cloud-tops MGA trajectory, in the Sun-Jupiter rotating frame. The arrival solar phase is 55 degrees, noticeably steeper than the earlier example in Figure 6, which corresponds to an initial apoapsis angle on Figure 5 of 139 degrees (after accounting for the effect of the G0 flyby and JOI).

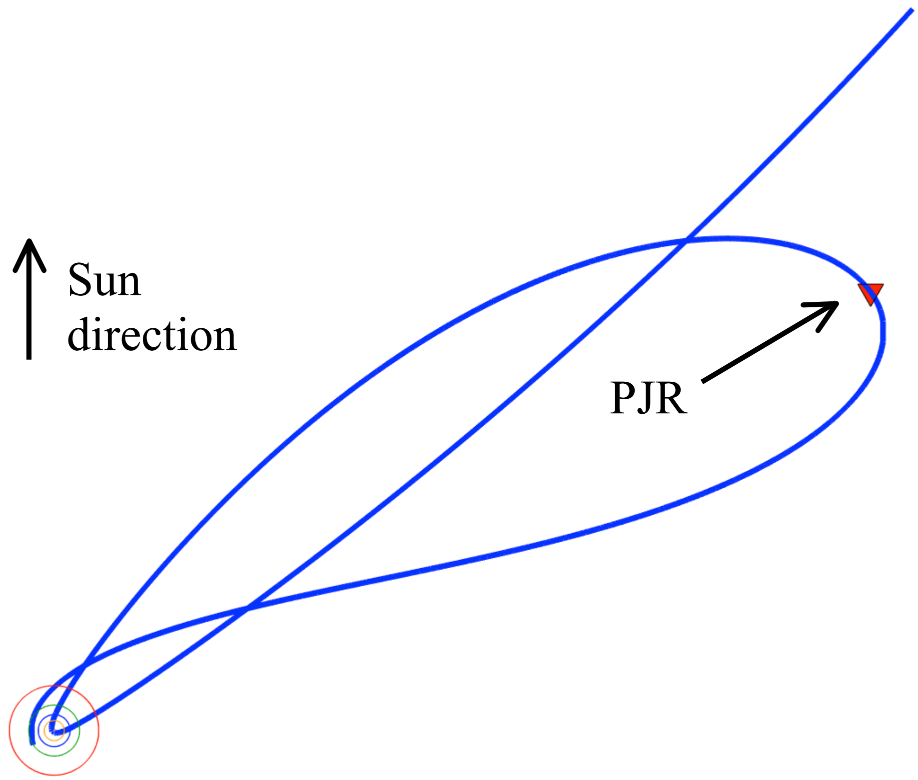

Figure 10: High-fidelity Cloudtops Trajectory at Jupiter. Sun-Jupiter rotating frame. 2028 ΔV-EMGA case.

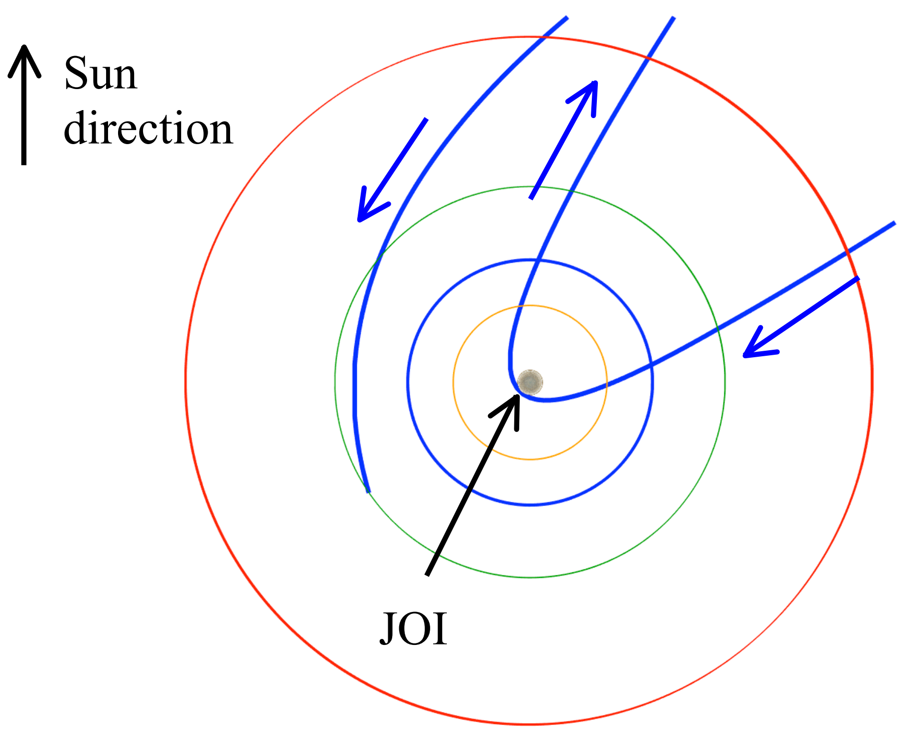

Figure 11: Zoomed View of High-fidelity Cloudtops Trajectory at Jupiter. Sun-Jupiter rotating frame. 2028 ΔV-EMGA case. Blue arrows show direction of motion.

Trajectory plots are fun to look at, but how do these trajectories compare in ΔV? The remarkable benefit of combining a ΔV-EGA and cloudtops trajectory jumps out of Table 7. For the ΔV-EMGA trajectory, the total savings is 504 m/s, and the ΔV-EGA 2+ trajectory's advantage of 577 m/s is even larger. Some of that difference is due to the universal use of a 500 km minimum flyby altitude, which penalizes the standard cases by 60 m/s, versus 6 m/s for the cloudtops arrivals. Both cloudtops arrivals utilize the higher Jupiter V_∞ values that we would expect from the discussion above, and have very slightly higher DSM magnitudes. Most of the ΔV difference between the standard and cloudtops trajectories accrues at JOI. The delay in G1 date is less than 8 months for the ΔV-EGA cloudtops trajectory, although there may be some additional delay during the post-G1 pumpdown due to the larger initial period and inclination (which has not yet been optimized). The performance of the ΔV-EGA trajectories across the Earth-Jupiter synodic cycle is not addressed in this paper*, but the general benefit of a cloudtops arrival should be similar at each opportunity. For direct trajectories, a cloudtops arrival would require higher launch C3s, but the reduced spacecraft ΔV requirements at Jupiter might make that a favorable tradeoff.

Table 7: Cloudtops versus Standard Arrivals, in High Fidelity.

Trajectory type		Launch date in 2029	JOI date in 2033	G1 date in 2034	Launch C3 (km^2/s^2)	Jupiter V_∞ (km/s)	ΔV (m/s)			
							DSM	JOI	PJR	Total
ΔV-EMGA	Regular	Jan 13	Jul 29	Feb 13	26.4	5.67	372	895	85	1352
ΔV-EMGA	Cloudtops	Jan 5	Mar 20	Sept 26	26.7	6.68	401	400	47	848
ΔV-EGA	Regular	Jan 17	Jul 14	Jan 30	27.1	5.97	560	1013	92	1665
ΔV-EGA	Cloudtops	Jan 14	Mar 20	Sept 26	27.2	6.80	573	439	76	1088

For all cases, the G1 V_∞ is 6.27 km/s, the JOI radius is 75,000 km, and the G0 periapsis altitude is 500 km. Both cloudtops approaches have a declination magnitude larger than 2.5 degrees, so the halo ring avoidance happens naturally.

SUMMARY AND CONCLUSIONS

The variety of capture options presented here allow mission designers the flexibility to trade ΔV, time-of-flight, radiation TID, and spacecraft propulsion capabilities to optimize their missions to Jupiter. For single-flyby captures, Ganymede has lower TID but Io allows slightly lower ΔV, especially for longer initial orbit periods. An extended pump-down sequence provides modest ΔV savings for a higher TID and TOF. Double flybys provide significant ΔV savings, but are difficult to arrange. However, placing the flybys at the nodes of an inclined arrival may make

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* Gentle readers beset with insatiable curiosity on this subject are encouraged to complete this aspect of the study themselves, and to elucidate our esteemed community with the results.

obtaining some of the double-flyby benefit easier. Navigation of flybys after JOI (or after other flybys during a capture sequence) is challenging, but appears feasible. SEP trajectories can provide significant benefits for solar-powered missions to Jupiter, especially when combined with a double-flyby arrival.

Finally, the retrograde, cloudtops arrival is a new and powerful option that can save over 500 m/s, and we hope that further study of it will lead to its adoption for some future mission to Jupiter. If nothing else, the view from the spacecraft during JOI, as it emerges from eclipse a few thousand km above the Jupiter cloudtops, stirs the imagination even now.*

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, and the Johns Hopkins University Applied Physics Laboratory under a contract with the National Aeronautics and Space Administration. The motivation for this work was NASA's proposed Europa Lander mission. The information presented about such future Europa and Jupiter mission concepts is pre-decisional and is provided for planning and discussion purposes only.

REFERENCES

[1] Kloster, K. W., Petropoulos, A. E., Longuski, J. M. (2010). "Europa Orbiter tour design with Io gravity assists". *Acta Astronautica*, *68*(7), 931–946.

[2] Johannesen, Jennie R, D'Amario, Louis A. "Europa Orbiter Mission Trajectory Design", AAS Paper 99-360, AAS/AIAA Astrodynamics Specialist Conference, Girdwood, AK, August, 1999.

[3] Haapala, Amanda, Siddique, Fazle, McElrath, Timothy P., "Mars Gravity Assist Options to Reduce Mission ΔV for Europa Lander", AAS Pre-print Paper 19-295, AAS/AIAA Space Flight Mechanics Meeting, Ka'anapali, HI, January 14-17, 2019.

[4] McElrath, T. P., Campagnola, S., Strange, N. J. "Riding the Banzai Pipeline at Jupiter : Balancing Low ΔV and Low Radiation to Reach Europa". AIAA/AAS Astrodynamics Specialist Conference, August 13-16, 2012, Minneapolis, Minnesota, paper AIAA 2012-4809.

[5] Campagnola, S., Buffington, B. B., Petropoulos, A. E. (2014). ""Jovian tour design for orbiter and lander missions to Europa". *Acta Astronautica*, *100*, 68–81.

[6] Lynam, Alfred E., Kloster, Kevin W., Longuski, James M. "Multiple-satellite-aided capture trajectories at Jupiter using the Laplace Resonance", Celestial Mechanics and Dynamical Astronomy (2011) 109:59084, DOI 10.1007/s10569-101-9307-1

[7] Landau, Damon, Strange, Nathan J., Lam, Try, "Solar Electric Propulsion with Satellite Flyby for Jovian Capture," AAS Paper 10-169, AAS/AIAA Space Flight Mechanics Meeting, San Diego, CA, February 14–17, 2010.

[8] Vasile, M., Campagnola, S. (2009). "Design of Low-Thrust Multi-Gravity Assist Trajectories to Europa". *Journal of the British Interplanetary Society*, *62*(1), 15–31.

[9] Campagnola, S., Buffington, B. B., Lam, T., Petropoulos, A. E., Pellegrini, E. (2018). "Tour Design Techniques for the Europa Clipper Mission". In 69th International Astronautical Congress, Bremen, paper IAC18-C1.9.11x44026.

[10] Evans, R. "A new GRID program, GRID2p, for quick estimates of Jupiter trapped particle fluences", Interoffice Memorandum 5132-15-032." Technical report, Jet Propulsion Laboratory, 2018.

* Admittedly, visualizing Juno's JOI provides a similarly striking view.