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GLOBAL SEARCH OF RESONANT TRANSFERS FOR A EUROPA LANDER TO CLIPPER DATA RELAY

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Following its prime mission Europa Clipper becomes a potential asset to relay data from a proposed Europa Lander back to Earth. To this end, we describe an efficient method to globally search for trajectories that repeatedly fly over the same location of Europa. Different families of trajectories emerge with different flyby geometries that satisfy a convoluted set of landing constraints. Here, the landing location and local solar time must match a limited set derived from expected Clipper observations, while providing multiple opportunities to land in a given season. We include estimates for data volume and radiation dose associated with these resonant trajectories.

INTRODUCTION

Europa has long been a tantalizing destination to search for conditions suitable to life outside of Earth.[1–9] As recommended by the 2011 Planetary Science Decadal Survey,[10] NASA is developing the Europa Clipper mission with a planned launch in 2023 to investigate the icy moon through a series of 45–50 flybys with altitudes ranging from 25–3000 km.[11] A separate study of a Europa Lander mission concept is also underway to investigate the feasibility of landing a science package on the surface.[12,13] As currently envisioned, the Europa Clipper prime mission would end before a Europa Lander would reach the surface, providing a potential asset to relay data from the surface of Europa through Clipper to Earth. A complementary study has shown that Jupiter Orbiter (e.g. Clipper after its prime mission) and Europa Lander tours can be designed concurrently to arrive at Europa at the same time.[14] We build upon this possibility with a global search for families of Jupiter Orbiter trajectories that not only arrive at Europa simultaneously with Lander, but also maximize the datalink capabilities over a wide region of potential landing locations. These trajectories begin in a Callisto-crossing orbit to preserve Clipper from Jupiter's radiation until a Lander arrives, then fly by Europa on consecutive resonant orbits that are visible from a single location on the surface.

PROBLEM STATEMENT AND MODEL

The baseline scenario for a potential Lander mission on Europa is to transmit data directly to Earth via a (pointable) high-gain antenna.[13] To maximize the probability of mission success it would be prudent to explore contingency options to return such valuable data back to Earth. One option is to relay the data via the Lander (fixed) low-gain antenna to an asset in the Jovian system. To this end we seek trajectories that enable large volumes of data (on the order of Gbits) to be

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transmitted from a low-gain antenna on the surface of Europa to a medium-gain antenna on a spacecraft in Jupiter orbit (e.g. Europa Clipper) on multiple flyovers. The design drivers for this problem are summarized in Table 1. Because the lifetime of a Europa Lander is expected to be limited (we assume a baseline of 3 weeks) the flyby repeat time should be short in order to accommodate as many opportunities to transmit data as possible. The total ionizing dose (TID) of radiation to the relay spacecraft should also be limited to lower the risk of failure before the data could be transmitted back to Earth. Because landing on Europa is a critical event, the first flyover must coincide with the landing time to collect data during this critical sequence. The landing time could occur any time between June and November 2033 when Earth is within 5 AU of Jupiter, enabling direct-to-Earth communication as the baseline option. Moreover, the local solar time (LST) at landing must coincide with the local solar time of the landing site reconnaissance (e.g. by Europa Clipper) in order to preserve lighting conditions for the landing navigation system. The preferred lighting conditions typically occur between 9AM and 3PM local solar time. In our global search we consider the entire globe of Europa for potential landing sites, but pay special attention to locations within 30 deg of the anti- and sub-Jovian points. These regions are especially attractive because they are heavily sampled during the Clipper prime mission,[11] and they provide better Earth visibility than at the poles. (We note the sub-Jovian point experiences frequent occultations by Jupiter.) The data relay architecture should therefore be resilient to a landing that could occur at any time (of day) anywhere on the surface of Europa.

Table 1. Design Constraints for a Europa Lander.

Constraint	Range	Notes
Lander location	Anywhere on the surface Additional detail within 30deg of sub- and anti-Jovian points	Global search Likely sites of Clipper reconnaissance
Landing Time	June 1 to Nov. 1, 2033 9AM–3PM LST	Viable link to Earth Good lighting conditions
Mission duration	22 days	Limits cost and risk of a Lander mission[12]
Data volume	Minimum 1 Gbit per encounter, optimized to maximize the minimum across all flybys	Surface mission threshold of 1.5 Gbit with 4.5 Gbit for contingency[15]

The initial conditions for the trajectory begin with Clipper parked in a parking orbit that intercepts Callisto. We then use a single Callisto flyby to drop perijove to intercept Europa and transition to either a 3:1 or 2:1 resonance with Europa (orbit period of 3.55 days). In the assumed three-week window, a 2:1 resonance encounters Europa four times over three orbits. A 3:1 resonance only encounters Europa three times during the same Lander window, but accrues less radiation over only two orbits as seen in Figure 1 using the GIRE2 radiation model.[16] There are significantly fewer opportunities to enter a 2:1 resonance than 3:1 from a Callisto transfer, but a Ganymede flyby en route to Europa provides additional opportunities to achieve the shorter resonance. Europa close approaches are limited to between 50 km altitude and 14,000 km (approximately 1 Hill) radius, and the maximum range for data relay is 42,000 km. Moreover the data rate is limited to a maximum of 1 Mbit per second (Mbps) by the telecommunications system. The data rate for a low-gain antenna decreases as the line-of-sight travels away from the boresight following the curve of Figure

2. We assume that the low-gain boresight is pointed at zenith to maximize coverage and simplify Lander design. The data rate achievable by our assumed Lander low-gain to Clipper medium-gain link is depicted in Figure 3, where we note that a 1 Mbps link can transmit 1 Gb of data in under 20 minutes. The antenna performance assumes a design point of 600 kbps at 10,000 km range and 30 deg from boresight with an inverse square dependence on distance.

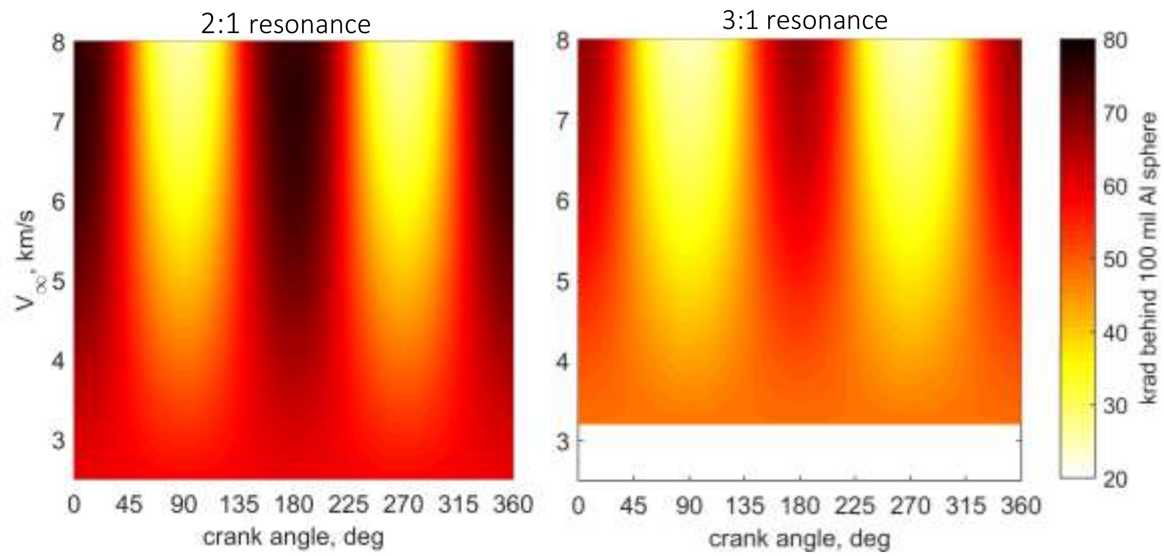

Figure 1. The total ionizing dose per orbit is significantly higher for 2:1 versus 3:1 resonances or for in-plane versus inclined transfers.

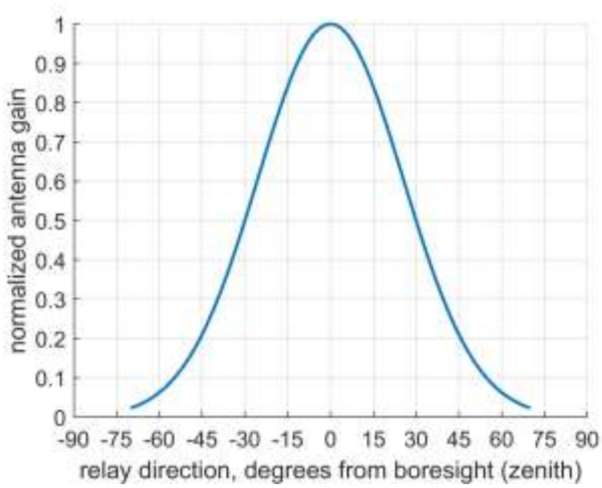

Figure 2. The low-gain antenna pattern for a Lander is modeled as a Gaussian with a 30-deg half-gain angle.

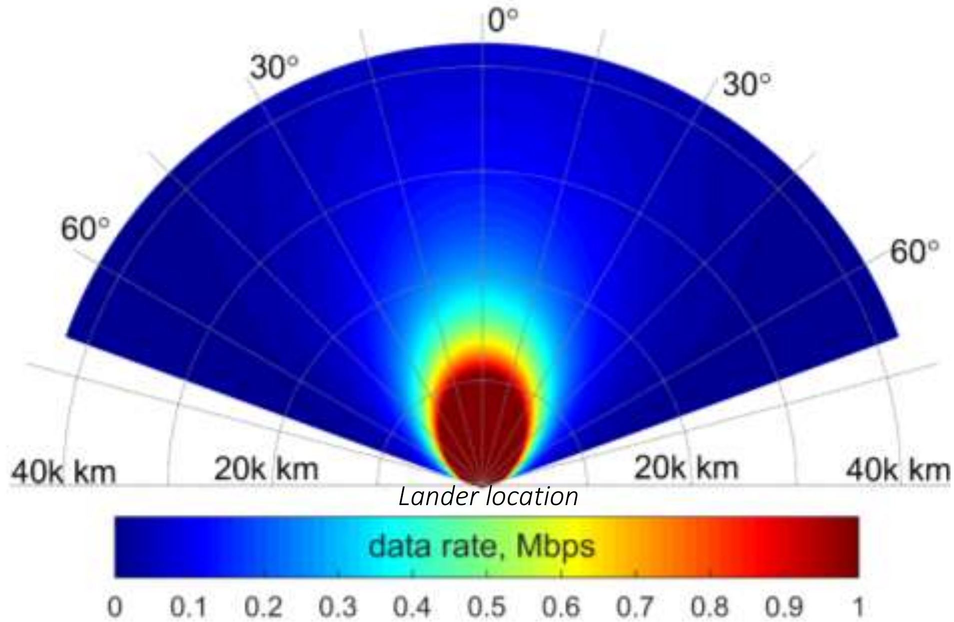

Figure 3. Relay data rate of 1 Mbps is achievable up to 10,000 km and 20 degrees from zenith boresight.

The trajectories are modeled as patched-conics with hyperbolas during the flybys. During the resonant flyby phase, the precessing eccentric orbit of Europa is fixed to a circle and the orientation of Europa remains fixed relative to its velocity. These assumptions eliminate time as one of the search dimensions during the resonance phase. For a given V_∞ speed and resonance period the locus of V_∞ directions is confined to a ring around the orbital velocity as depicted in Figure 4. During each flyby the V_∞ travels along this fixed ring through a quantity known as the crank angle, where close flybys crank the orbital orientation more than distant ones. Because there is no change in the V_∞ component relative to orbital velocity, the periapsis direction remains orthogonal to Europa's velocity along the prime (or anti-) meridian in our circular model. As the V_∞ speed increases the V_∞ ring moves farther from the orbital velocity by an amount dubbed the pump angle, with smaller changes in crank angle for a given flyby altitude. Thus the periapsis direction also travels less along the meridian for each flyby. A critical design trade becomes apparent when considering the data-rate performance: we desire low and slow flybys directly above the Lander to maximize data rate, but the following periapse will necessarily move away from zenith and degrade subsequent relay opportunities. Moreover, if we try to crank in the opposite direction, the periapse moves to the opposite side of Europa, potentially eliminating an entire data pass from the mission. It is also not apparent what to do about scientifically interesting areas located away from the prime meridian, since periapse cannot be placed over these sites.

The hyperbolic flyby geometry depicted in Figure 5 provides some guidance. The arrival and departure V_∞ directions define the flyby plane, where the groundtrack traverses from the trailing to leading hemisphere by an angle primarily driven by pump (see reference 18 for a set of useful equations). While opposing crank directions place periapsis on opposing hemispheres, the hyperbolas cross above the initial V_∞ direction before they asymptote out in Figure 5. Considering the relatively distant ranges that our communication system can transmit (Figure 3), it is possible to relay large data volumes even when the relay periapsis is occluded from the Lander. A range of landing locations are thereby accommodated by selecting Callisto-to-Europa transfers with different arrival V_∞ speed and crank angles. For this transfer phase we employ integrated ephemerides from JPL's HORIZONS system* to exhaustively search for patched conic trajectories from Callisto to Europa with an optional gravity assist of Ganymede. While the preponderance of transfers are nearly equatorial, we also seek half-rev (pi-) transfers to initiate high crank angle sequences with a deterministic (broken-plane) maneuver ΔV less than 20 m/s.

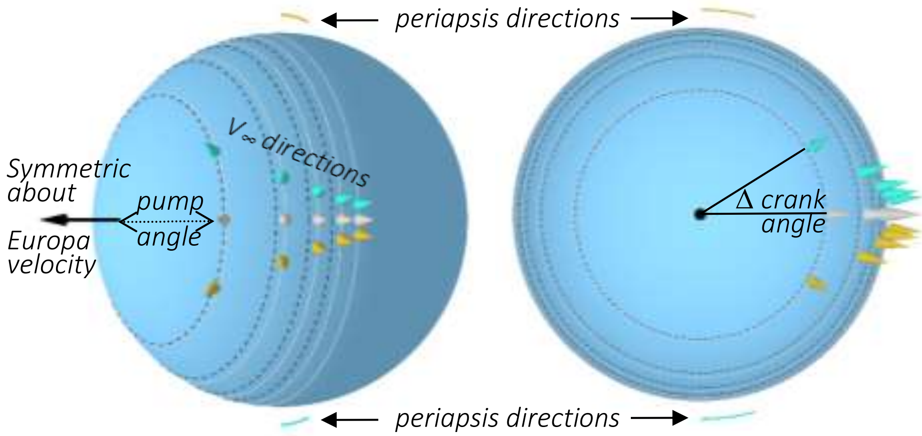

Figure 4. V∞ globe[17] with direction of periapsis confined orthogonal to Europa's velocity.

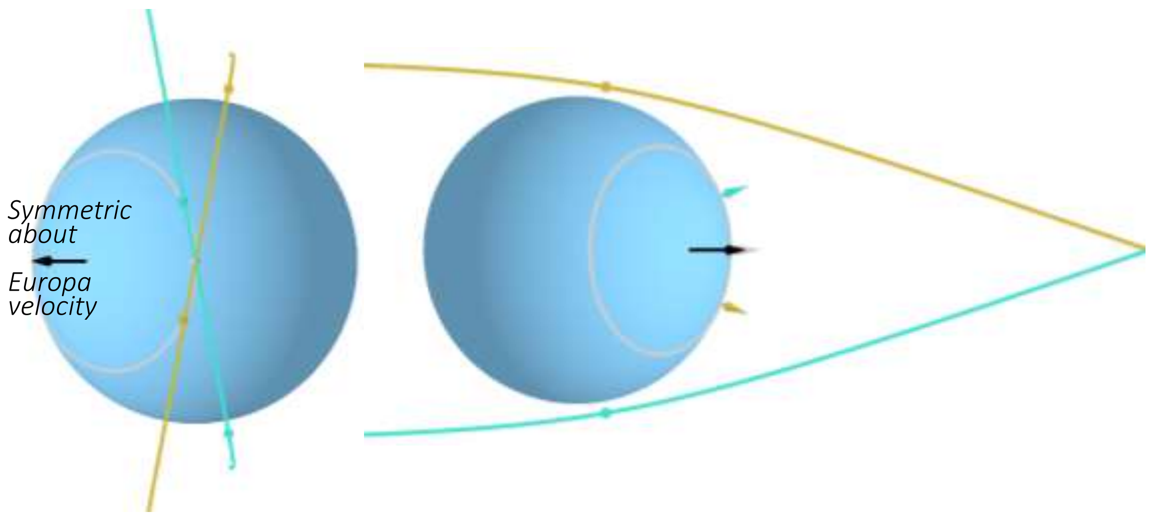

Figure 5. Flybys traverse the globe at an azimuth determined by the pump angle.

SEARCH METHOD

To further explore the trade space, we optimize two different objectives: 1) maximize the minimum data volume over all passes with no consideration for radiation, and 2) minimize total radiation dose with the constraint that each pass must relay at least 1 Gb. For a given Lander arrival time and location with n relay passes, the optimization space comprises n+1 dimensions: 1 for the Callisto departure time (which combined with the Europa arrival time provides the arrival V_∞) and n Δcrank control variables. (The first Europa flyby also achieves the required Δpump angle.) Optimization of a single Lander design point would be relatively straightforward, but a global search grows to n+4 dimensions if we are to exhaustively map each potential arrival time and location. A

* https://ssd.jpl.nasa.gov/?horizons

brute-force search over 7 or 8 dimensions (3 or 4 flybys) appears computationally intractable, but our earlier circular-orbit assumption permits the *n* flybys to be optimized sequentially in a dynamic programming problem with reduced dimension. The dynamics programming algorithm is as follows, with a visual representation presented in Figure 6.

1) For a given lander location and V_∞ speed (pump angle), create a 2-dimensional function of orbit crank angle (the state, 0–360 deg) and flyby Δcrank angle (the control, bounded by max and min altitude constraints) to the objective function. This provides a global map of how each additional orbit (radiation) and flyby (data) affects the mission objective and changes the state.
2) Begin at departure of the final flyby and record any cost associated with the disposal phase as a function of the state. For the minimum radiation objective this is the radiation of the terminal orbit (e.g. Figure 1), and is undefined for the maximin data objective. This is the map of the objective value at flyby $i = n$.
3) Step back one orbit/flyby to the departure of flyby $i-1$ and apply the map from Step 1 to increment the state and objective from flyby $i-1$ to i. Read the objective values of each new state at flyby i (recorded on previous step), and combine with the objective values from the map of Step 1. Record the control that optimizes this combined objective value and record the optimal value at each state. This is now the objective value at flyby $i-1$.
4) Repeat Step 3 until departure of the first flyby is reached. This gives a global map of how to either minimize radiation of the entire tour or maximize the minimum data volume of any pass as a function of departure crank angle. The optimal control (Δcrank) at each flyby can either be recovered by propagating forward using the recorded values from Step 3 at each flyby (feedback control), or by appending the previous control (for the updated state) to the current control at each iteration of Step 3.
5) Collect the set of arrival velocities from the Callisto-to-Europa trajectory search that match (with low ΔV tolerance) the current V_∞ speed. For each of these arrival V_∞ calculate the radiation dose and sample the reachable set of departure crank angles and record the data volume. Combine this value for radiation or data objective with the flyby tour objective values (from Step 4) for the reachable crank-angle set, and select the control at flyby 1 that optimizes the combined objective (same principle as Step 3). Replace this optimal value for each arrival date compatible with the current V_∞ speed if there's an improvement.
6) Repeat Steps 1–5 for different V_∞ to sample every possible arrival in Step 5, completing the search across Europa arrival dates.
7) Repeat Steps 1–6 for different lander locations to globally search the trade space.

We choose to sample V_∞ speed instead of the Europa arrival velocity in Step 5 in order to take advantage of the time independence of the circular-orbit model for Europa. The Europa arrival velocity is effectively a two-dimensional search (Callisto and Europa encounter dates) that we replace with a single V_∞ search. The "missing" V_∞ dimension is recovered by mapping the entire state space of crank angles, while keeping the Callisto-to-Europa phase independent of the Europa-flyby phase. This dynamic programming approach is particularly efficient because it transforms a single n+4 dimension problem into n sequential 5-dimensional searches (of crank, Δcrank, V_∞, lander longitude,latitude for each flyby). In fact, because the integration of data rate during the flybys is the most expensive calculation, the computational burden is closer to searching only two 5-D spaces during Steps 1 and 5. Thus the solution time as number of flybys increase doesn't grow geometrically or even linearly, but is effectively static.

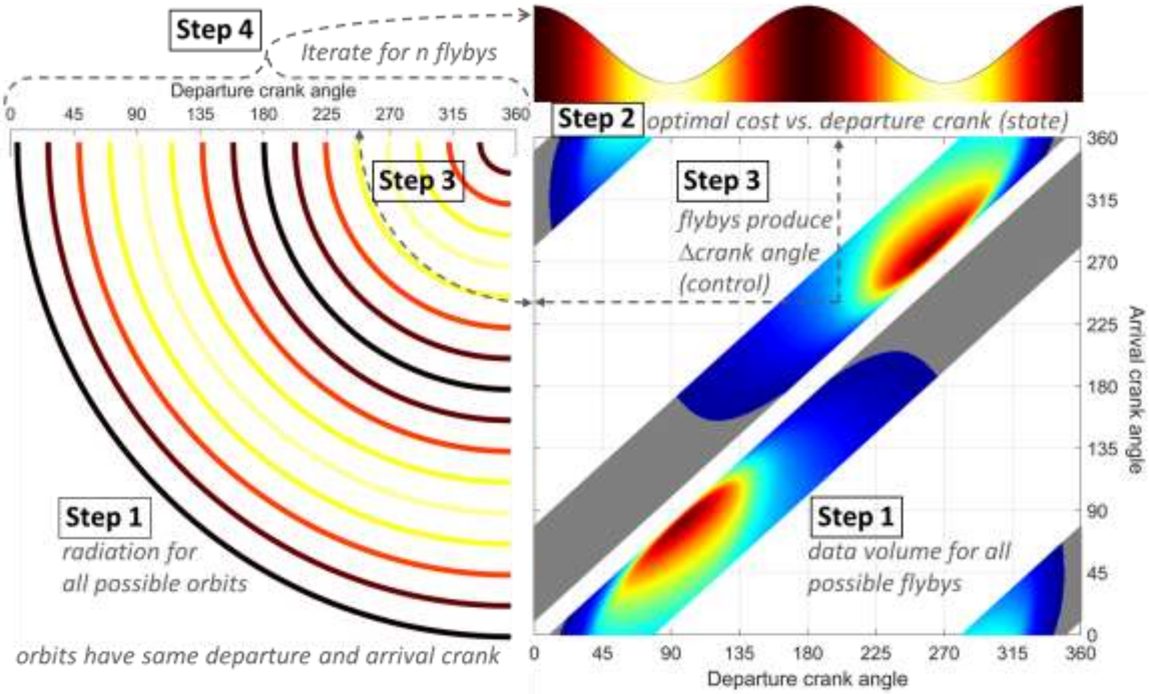

Figure 6. Optimization over *n* flybys can be treated as a dynamic programming problem.

RESULTS

The trade space of available Europa arrival V_∞ is depicted in Figure 7, where Europa's velocity is out of the page, and 0-deg crank is defined where the in-page V_∞ component points toward Jupiter. The loci of V_∞ are clustered along 0- and 180-deg crank for in-plane transfers, but out-of-plane arrivals are also available through half-rev transfers. High crank angles also occur near the minimum achievable V_∞ for a given resonance (3.2 km/s for 3:1 or 2.3 km/s for 2:1 resonance) where the V_∞ is nearly aligned with Europa's velocity and the crank-plane component is small.

As indicated by Figure 1, the higher crank angles minimize total ionizing dose to the spacecraft. In Figure 8, a half-rev transfer from Callisto to Europa initiates a high-inclination tour that minimizes radiation dose. In this example, a Lander is situated on the sub-Jovian point and periapsis is situated above the landing site as in Figure 9, where high data rates are achievable for short periods of time. The maximum achievable data volume for this geometry is about 2.5 Gb. Figure 10 highlights an alternative approach where an in-plane transfer initiates four communication passes, but accrues a TID of 240 krad. With the flyby asymptotes placed over the Lander site in Figure 11, high data rates persist for longer durations, where all four passes transmit a minimum of 4.6 Gb of data with a total of more than 18.6 Gb for the mission. We find that a preponderance of trajectories converge on the strategy of Figure 11 to maximize data volume. Additional analysis is required to determine the ΔV cost of these trajectories in a high-fidelity model, where the ΔV cost to reverse crank is expected to be on order tens of m/s.

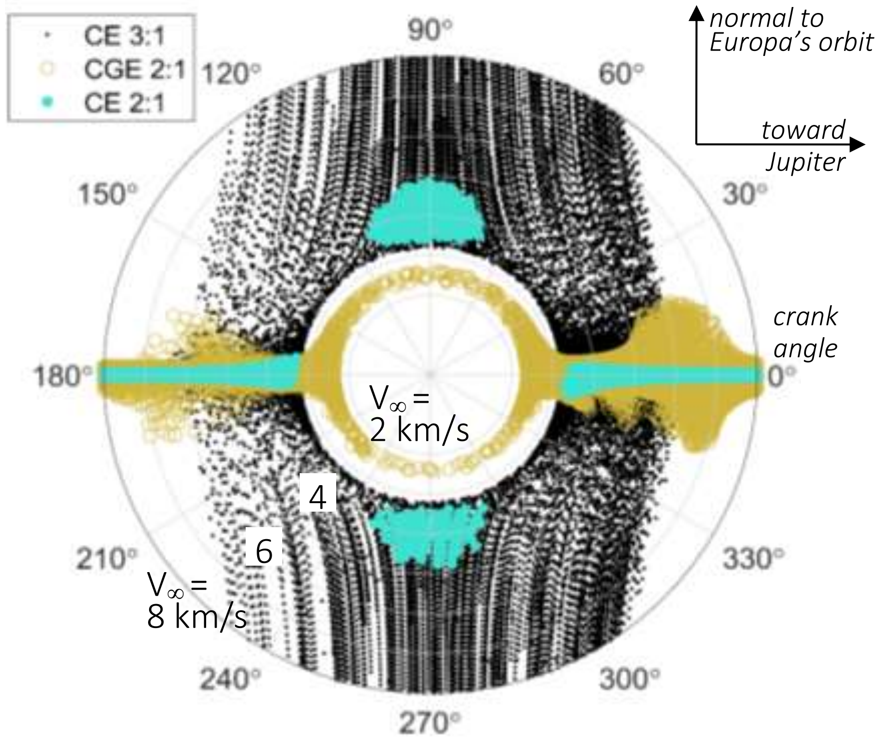

Figure 7. A variety of crank angles following transfers from Callisto (C) and Ganymede (G) are available to initiate resonant orbits with Europa (E).

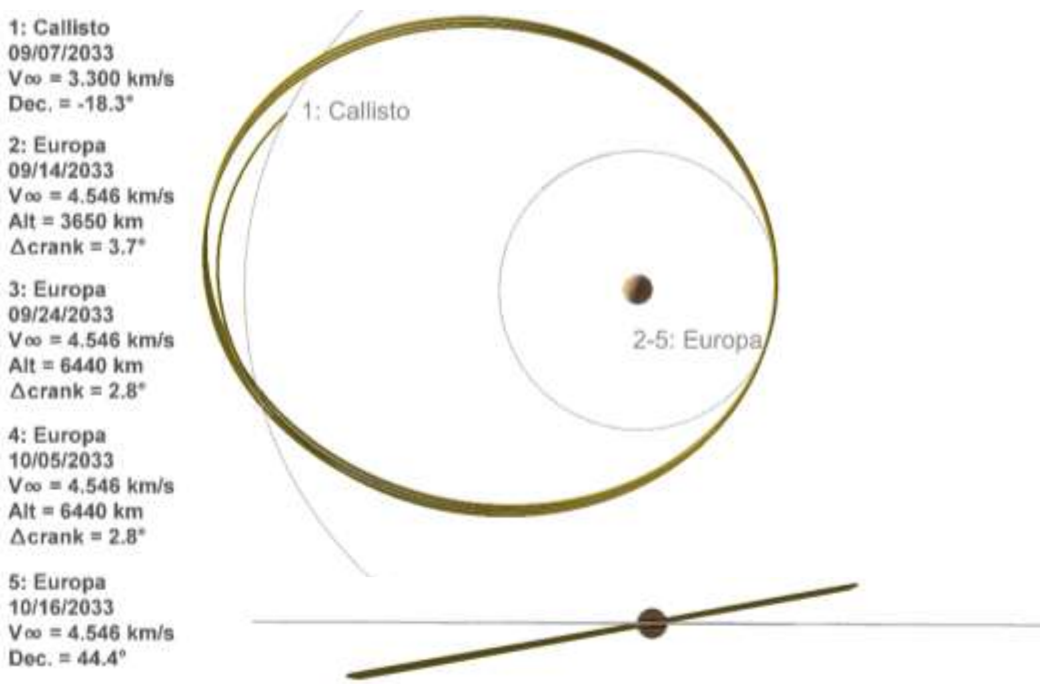

Figure 8. A high-inclination transfer from Callisto sets up two 3:1 resonant orbits with a TID less than 150 krad.

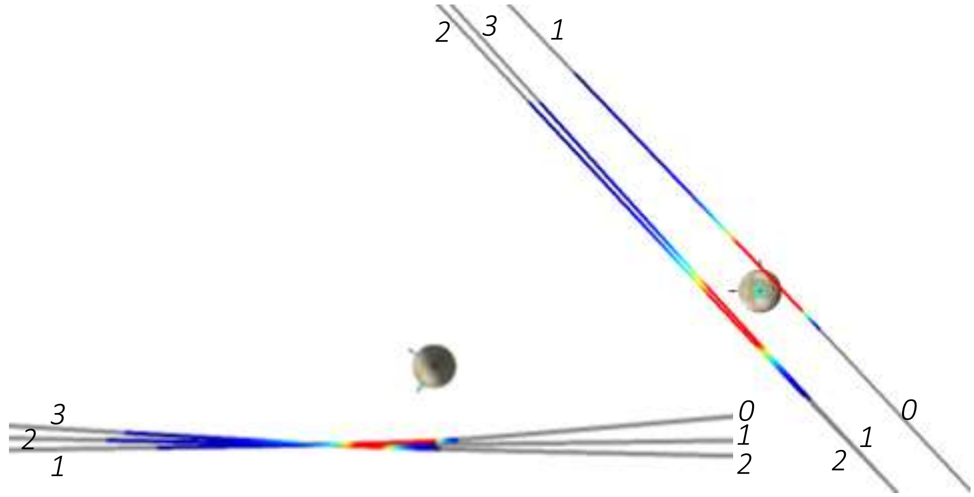

Figure 9. Landing sites directly sub- (or anti-) Jovian typically transfer less than 2.5 Gbit of data per flyby with periapsis near zenith (where red indicates data rates of 1 Mbps).

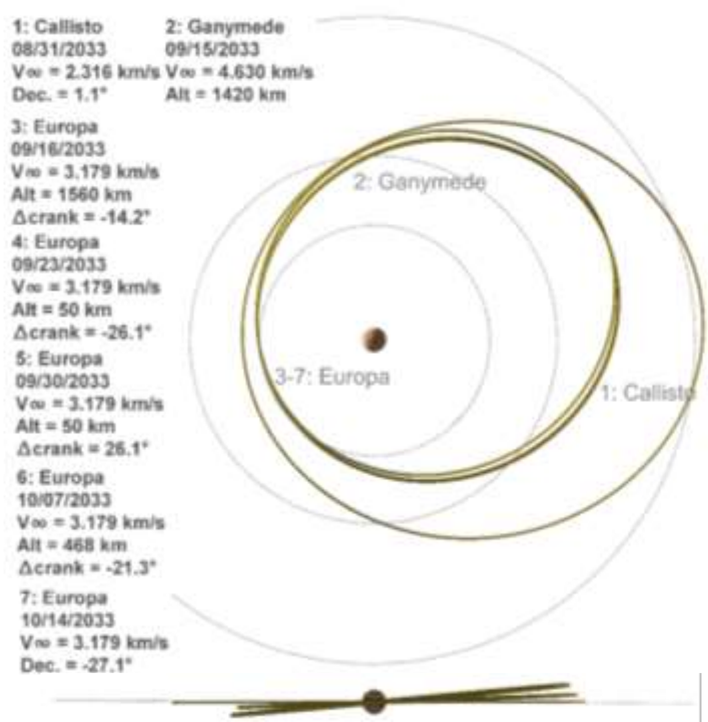

Figure 10. A tour of Ganymede followed by four communication passes of Europa accrues at least 230 krad of radiation (equivalent behind 100 mil Al sphere).

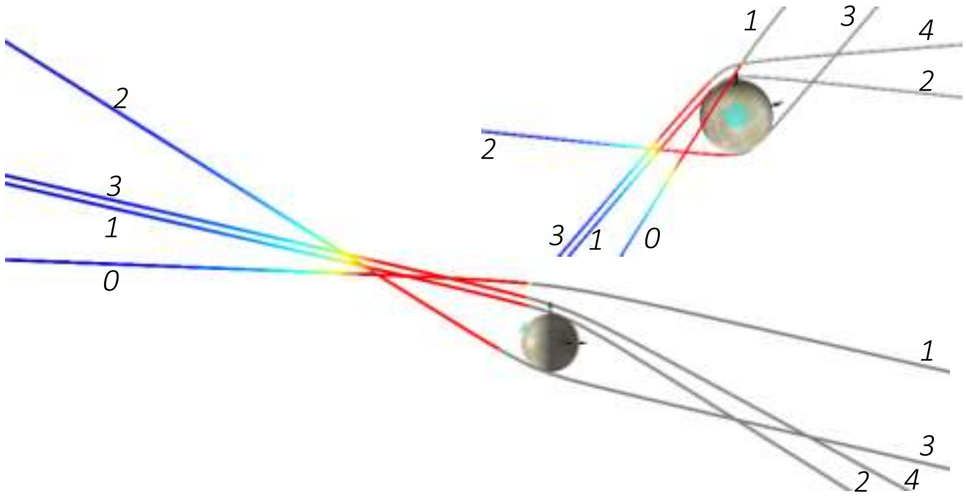

Figure 11. Data rates up to 1 Mbps (indicated by red) are sustained by placing the flyby asymptotes above a landing site's zenith. Each pass transmits in excess of 4.6 Gbit of data.

The example design points in Figure 8-Figure 11 demonstrate different approaches on how to relay large data volumes, but do not address the resiliency of this contingency option. A Jupiter Orbiter must be available to relay data for a variety of scenarios for it to be a viable alternative relay path. Moreover, each data pass should transmit a significant amount of data so that no opportunity is missed. A set of 18 lander locations situated near 30 deg of the anti- and sub-Jovian points on Europa with local solar times between 9AM–3PM are represented in Figure 12. For each location we are interested in how often Clipper could be used to relay a threshold amount of data, where we have maximized the minimum data volume over the set of 3 or 4 relay passes. In general we find that there are more opportunities to relay data from a 3:1 resonance than from a 2:1, and that a Ganymede flyby significantly increases the percent of landing times compatible with a 2:1 orbit. The addition of a Ganymede gravity assist also enables an excess of 4 Gb of data to be relayed on each pass for many locations. Lander locations along the prime (0°E) and anti- (180°W) meridians typically provide the most opportunities for lower data volumes, but fade away for a threshold above 2.5 Gb for 3:1 or 3 Gb for 2:1 resonances. Conversely, a Lander located closer to the leading or trailing edge of Europa can meet a threshold of 3 Gb per pass at least 25% of the time. The percentage of opportunities is derived from the database of trajectories generated during the broad search and represented in the Appendix, where Europa landing dates are sampled at every half hour of local solar time from June 1, 2033 to November 1, 2033.

The curves in Figure 12 represent trajectories that maximize the minimum data volume per pass, but do not account for radiation. In Figure 13 we present trajectories that minimize total ionizing dose with the constraint that each pass relays a minimum of 1 Gb. The 3:1 resonant trajectories are available for much lower radiation thresholds than the 2:1 primarily because they have one less orbit around Jupiter. Also from Figure 1 each 3:1 orbit accumulates less TID than each 2:1 orbit, providing a clear radiation advantage. For many locations the percent of opportunities to relay at least 1 Gb of data increases from 25% at 150 krad to 50% at 200 krad. No relay opportunities exist for a 2:1 architecture with less than 250 krad TID, but 25% of landing times are viable at 300 krad, and up to half of the potential opportunities to land on Europa within 9AM–3PM local solar time are available if 350 krad is acceptable. For comparison, Europa Clipper accumulates 90–230 krad for its different disposal options out of a total of 2.6–3.1 Mrad TID.[11] Again, the addition of a gravity assist from Ganymede dramatically increases the frequency of opportunities to achieve four relay passes in a 2:1 resonance with Europa.

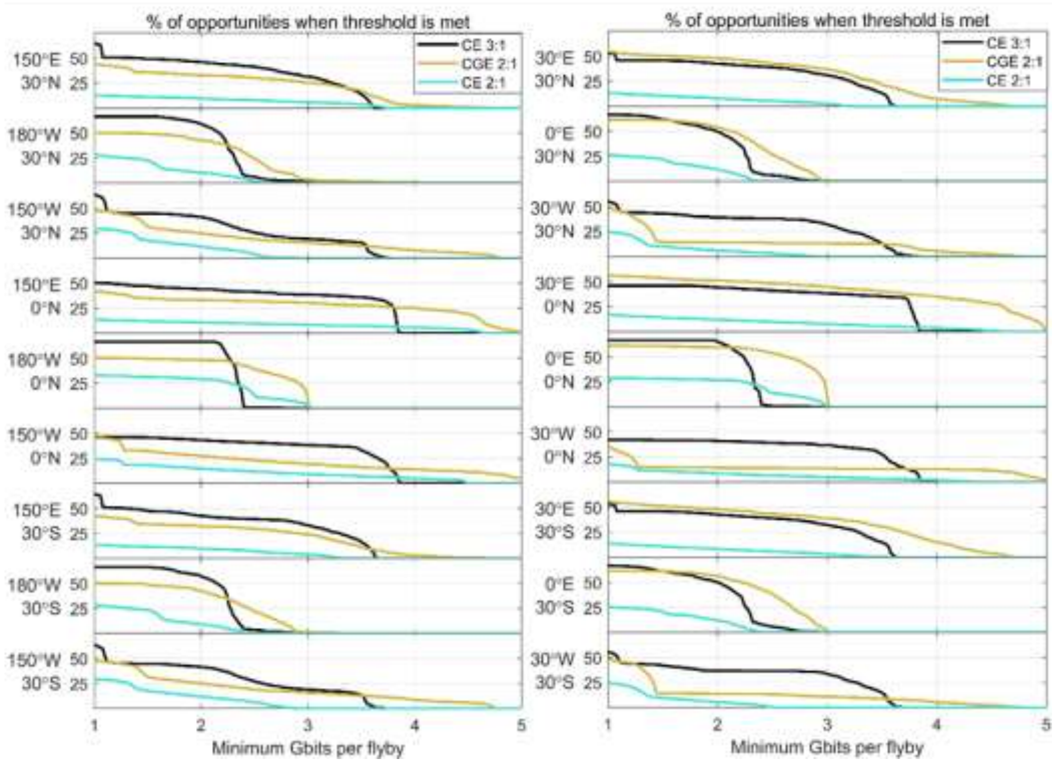

Figure 12. Higher data volumes are achievable towards the leading and trailing hemispheres versus near the prime meridian.

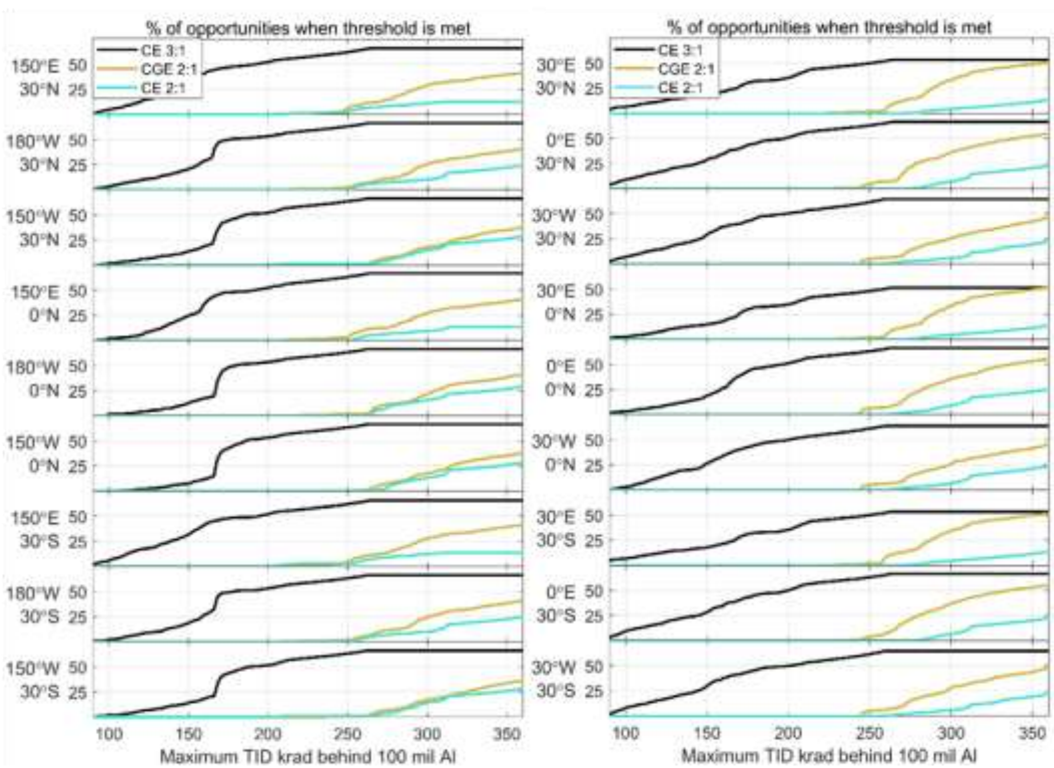

Figure 13. There are significantly more opportunities for a 3:1 versus 2:1 resonant sequence for a given radiation threshold.

A global perspective of how frequent a potential landing site on Europa is viable for a given data threshold or radiation TID is presented in Figure 14 and Figure 15, respectively. As anticipated from Figure 12 high data-rates are not available with 3:1 resonances along the prime and anti-meridian but become a viable option toward the leading and trailing regions. High data volumes are also available for 2:1 resonances with Ganymede flybys, but are mostly limited to the trailing hemisphere of Europa. The landing sites with most frequent relay capability for 2:1 resonance without Ganymede flyby are near the sub- and anti-Jupiter regions with a preference for the leading hemisphere, albeit with lower data threshold per pass. In contrast to the data-volume results, the landing sites with lowest TID with 3:1 resonances in Figure 15 are not near the leading and trailing regions, but are skewed on a 45-deg azimuth from leading sub-Jovian to trailing anti-Jovian. The high-frequency regions for lowest TID with 2:1 resonances are more aligned with the data-volume results of Figure 14, suggesting a general compatibility for landing sites in the trailing hemisphere for transfers with Ganymede gravity assist, or leading hemisphere for transfers direct from Callisto. We note that the TID threshold for 2:1 resonances is double that of 3:1 resonances in Figure 15 .

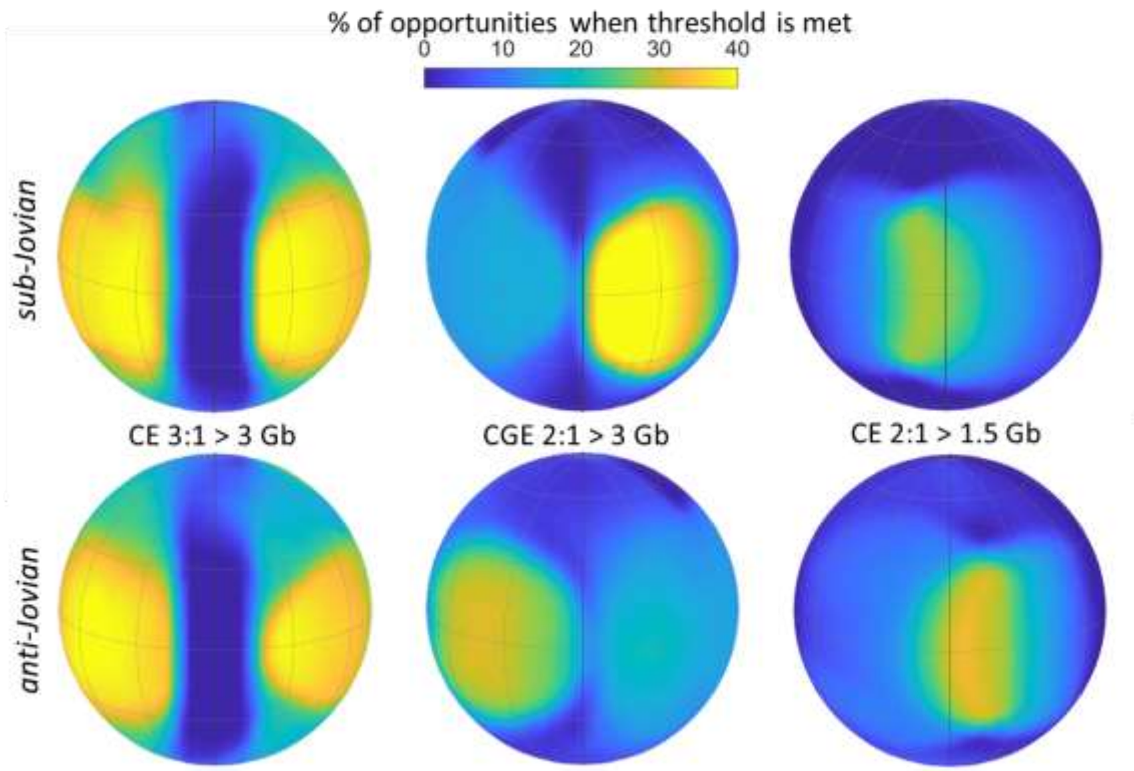

Figure 14. Global view of how often a data-volume threshold per pass can be met.

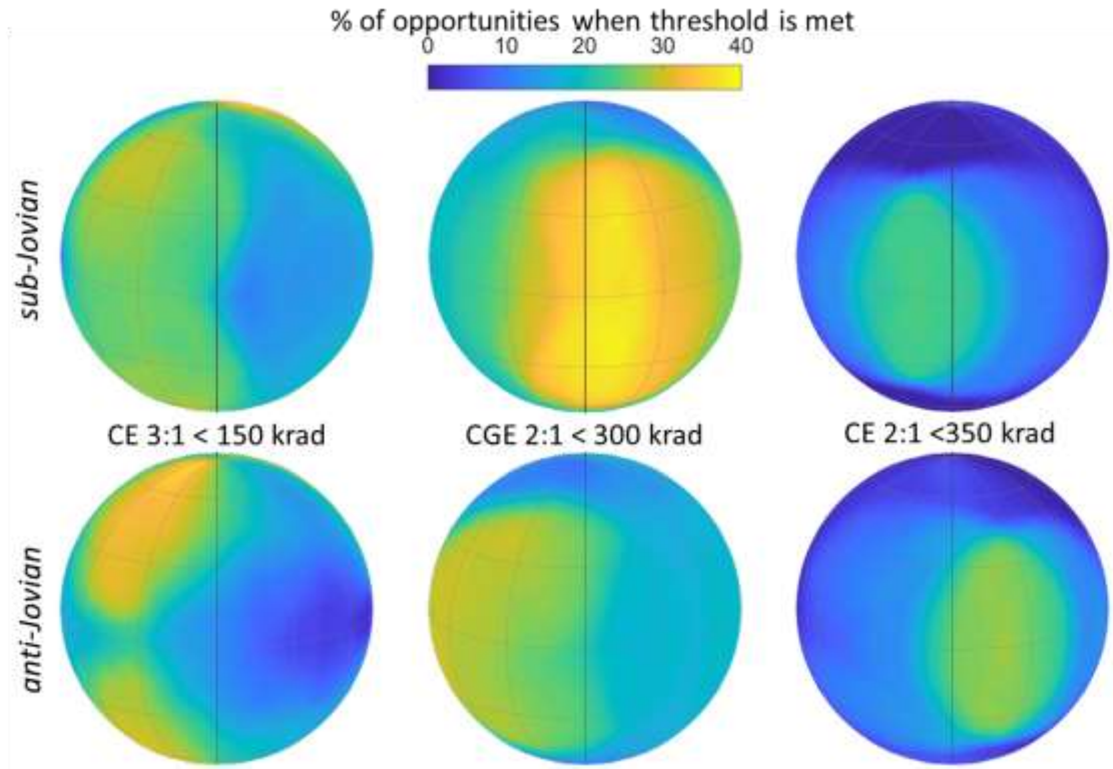

Figure 15. Global view of how often a radiation-TID threshold can be met.

CONCLUSIONS

Should a communication contingency occur during a Lander mission on Europa where the baseline path is direct-to-Earth, a Jupiter-orbiting asset such as Europa Clipper could be used to restore the data link back to Earth. The Jupiter Orbiter would loiter in a Callisto-crossing orbit then fly by Callisto at a pre-determined time to target Europa at a coordinated arrival epoch. This backup strategy is not viable for every anticipated landing date, but a minimum of 1 Gb per fly by is possible at least 50% of the time for desirable locations near the sub- and anti-Jovian points. Data volumes up to 3 Gb per flyby are available 25% of the time for Landers located at least 30 deg from the prime or anti-meridian (i.e. towards the leading and trailing hemispheres). The total ionizing radiation dose is 350 krad (behind a 100 mil Al sphere) to provide 4 data passes during a three-week mission, but can be reduced to 200 krad with only 3 data passes for 50% coverage of landing opportunities. A 100 krad radiation threshold limits this coverage to below 10%. A coordinated effort between a potential Europa Lander mission and any planned Jupiter Orbiter mission could significantly retire risk of transmitting precious data from the surface of Europa to Earth.

ACKNOWLEDGMENTS

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APPENDIX: DATA VOLUME FOR EVERY RELAY OPPORTUNITY

The frequency of opportunities in Figure 12 (or Figure 13 for minimum radiation) are derived from the database of trajectories generated during the broad search. Each dot in Figure 16–Figure 18 represents an entire relay mission as portrayed by the trajectories in Figure 8–Figure 11. This database comprises Europa-landing opportunities at any local solar time, while the opportunity percentages in Figure 12 and Figure 13 are filtered for landing time between 9AM and 3PM. We calculate the percentage of opportunities by noting that each desired local solar time occurs once per Europan day, then summing all opportunities that meet the filtering criteria over the approximately 43 Europan days during the timeframe of interest.

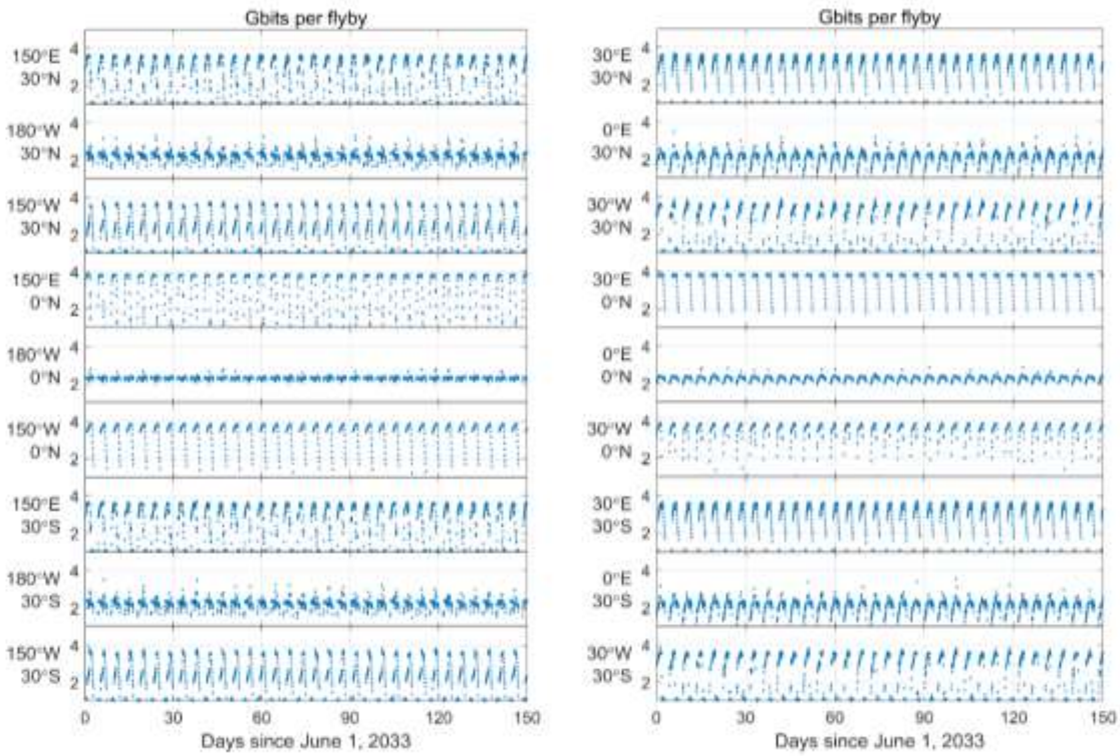

Figure 16. Minimum data volume per pass for every relay mission with Europa landing 6/1/33–11/1/33 and CE sequence into a 3:1 resonance.

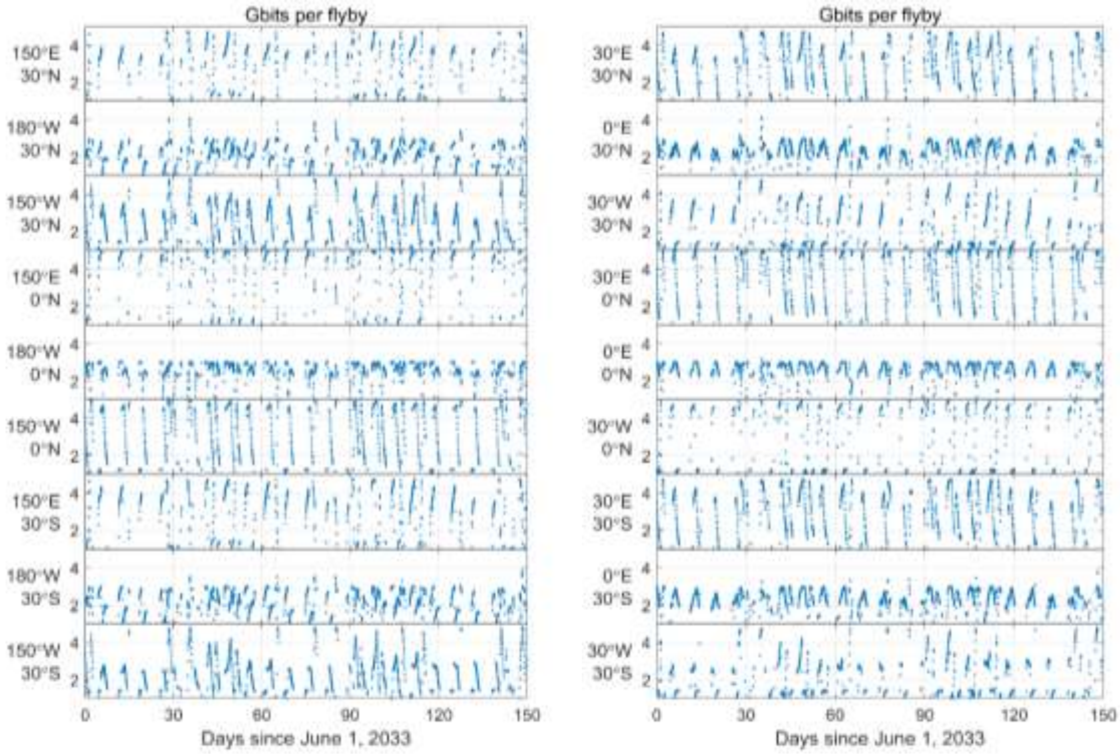

Figure 17. Minimum data volume per pass for every relay mission with Europa landing 6/1/33–11/1/33 and CGE sequence into a 2:1 resonance.

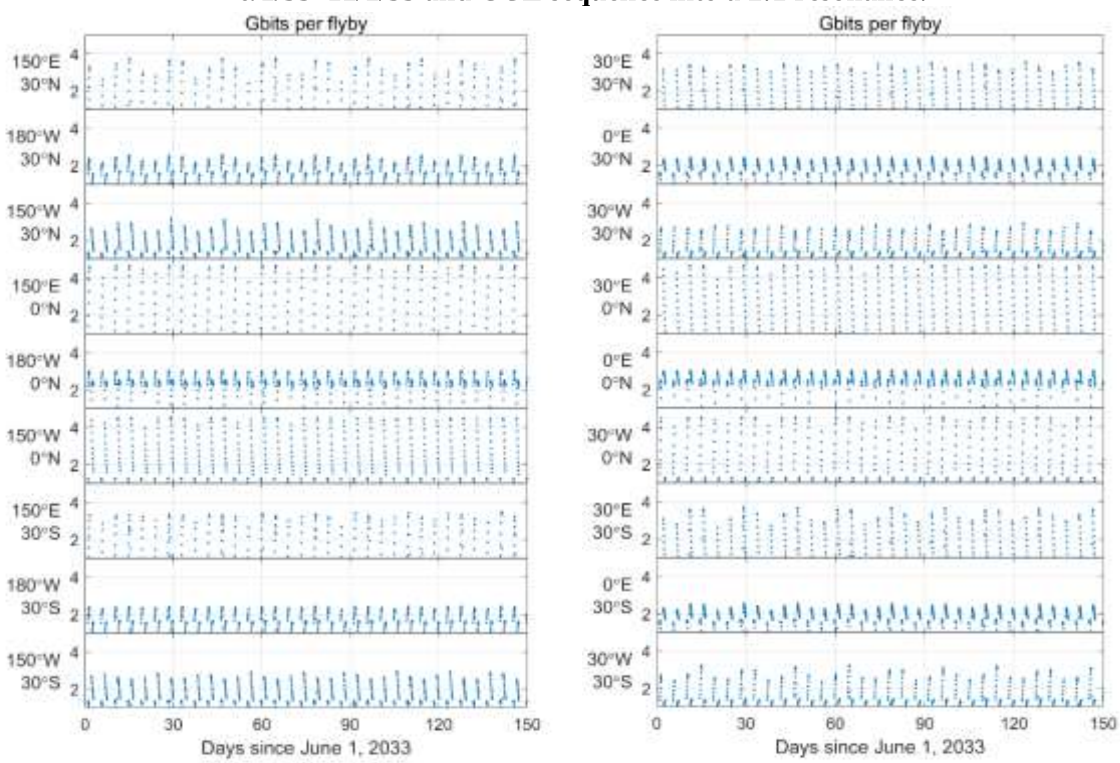

Figure 18. Minimum data volume per pass for every relay mission with Europa landing 6/1/33–11/1/33 and CE sequence into a 2:1 resonance.