Families of Io-Europa-Ganymede Triple Cyclers

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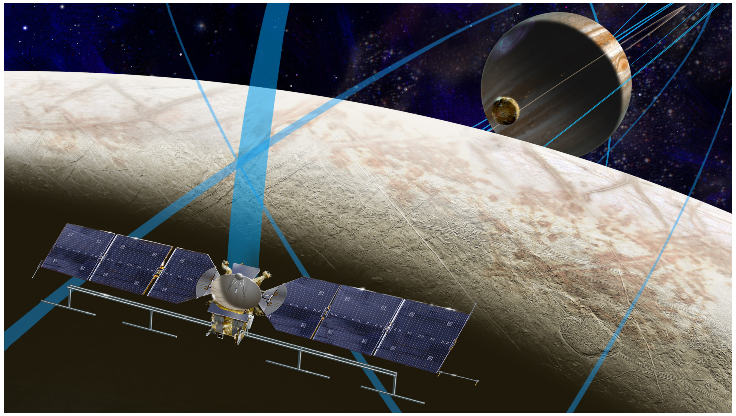
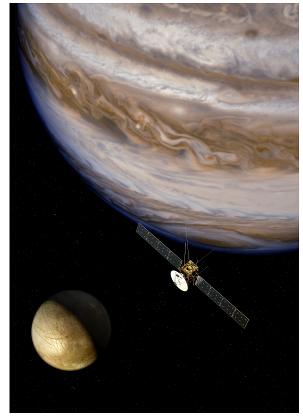
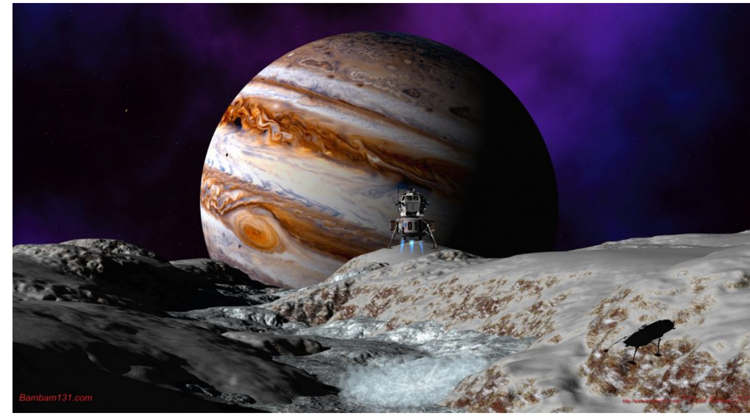
Introduction

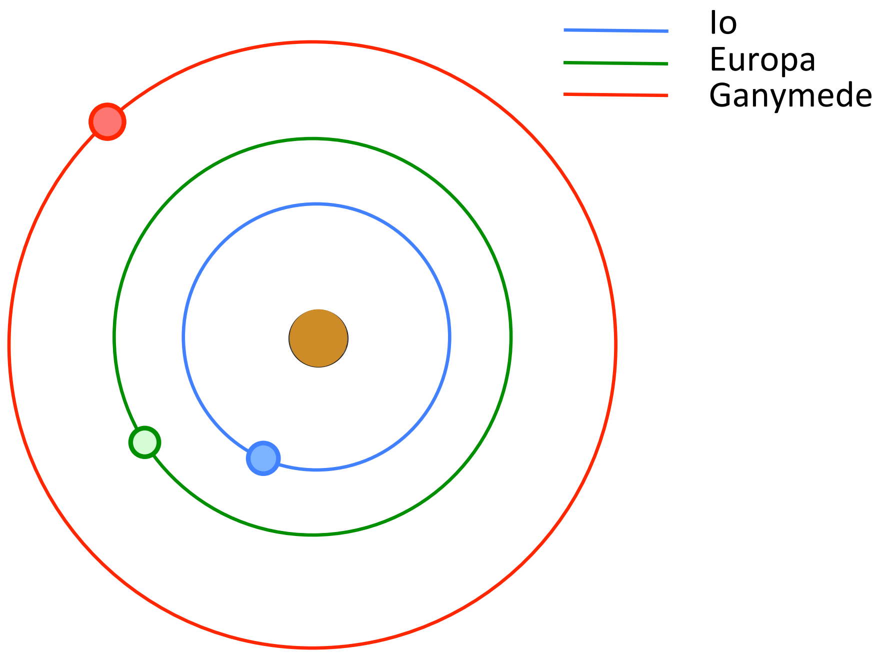
- The Jovian system is a fascinating world, with missions planned in the near future to visit two of Jupiter largest moons: Europa and Ganymede
- A spacecraft on a ***cycler trajectory*** uses gravity assists to ***return to the starting body*** after a flight time commensurate with the celestial bodies' ***synodic period***
- The non-propulsive ***repeatability*** of these trajectories makes them of interest to human and robotic exploration applications.
    - Cycler trajectories could be used for sending crew and cargo to/from Earth and Mars
    - Inter-moon cycler trajectories for robotic tour missions could, in an ideal environment, flyby several moons for an ***indefinite amount of time***

In the past cycler trajectories have been focused on gravity assist from two planets/moons. We discuss ***triple cyclers***, trajectories flying by three planets/moons

Io, Europa, Ganymede System

Triple cycler trajectories: spacecraft repeatedly flies by three moons

- Ganymede, Europa, and Io are in ***1:2:4*** orbital resonance
- Synodic period is time it takes to repeat a given angular alignment of the three bodies: $\boldsymbol{T_{syn} = 7.05}$ ***days***
- After one synodic period, all the moons return to their initial relative configuration; however, an ***angular shift*** in their inertial location of 5.2° occurs



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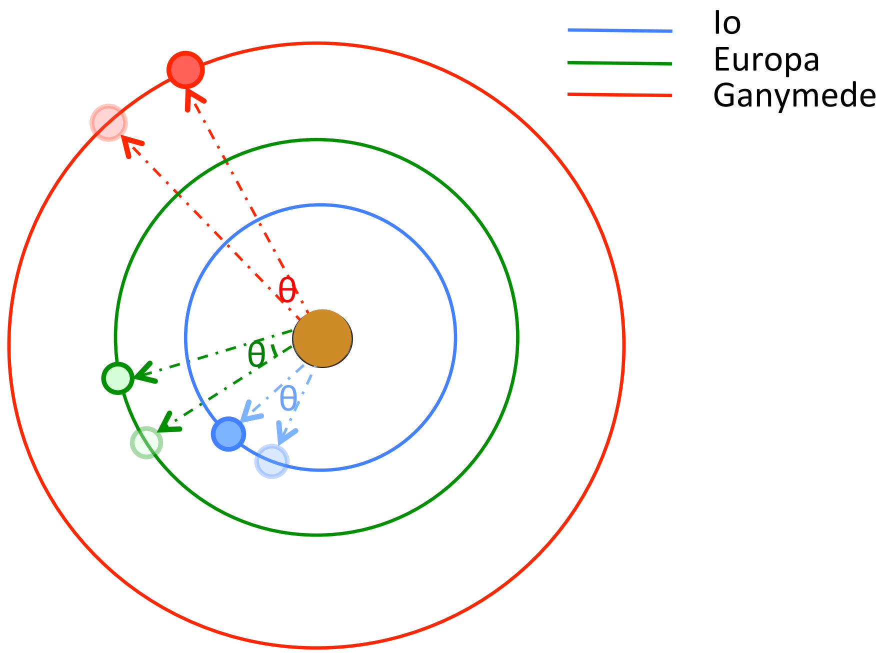

Understanding Triple Cyclers in Jovian System

Triple cycler trajectories: spacecraft repeatedly flies by three moons

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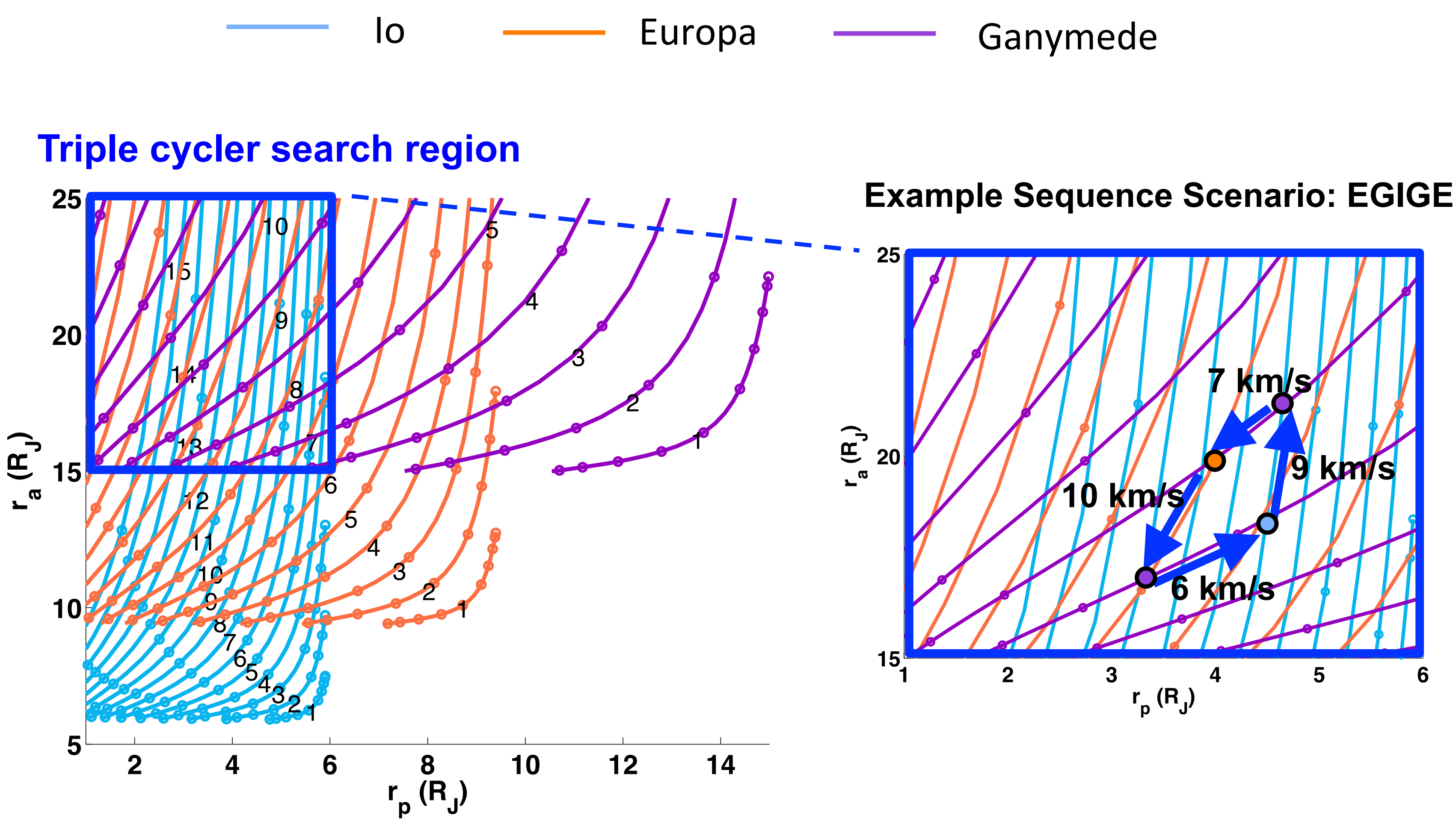
- ***Cycle:*** Portion of trajectory with flight time equal to an integer number of T_{syn}, that starts and ends at the same body, and flies by at least once through each of the bodies (Io, Europa, Ganymede)
- A ***cycler*** trajectory is one that completes one or more cycles.
- Categorize into families based on integer number of synodic periods in a cycle, and the itinerary of flybys.
- Example:
  - 1 synodic: EGIE, EIGIE,
  - 2 synodic: EGIE, EIGIE, GEIIEIG, IEIGIEI
  - 3 synodic: EGIE, EIGIE, GEIIEIG, IEIGIEI, EIGIGEIGE

Tisserand Graph



The plot indicates possible gravity assist connections from a purely energy perspective (phase free)

Strategy to Find Triple Cycler Solutions

- Possible sequences based on number of encounters: $\boxed{s(n) = 3^{n-1} - 2^n + 1}$

Number of encounters	Sample Sequence	Possible Sequences
3	EIGE, EGIE	2
4	EEIGE, EEGIE, EIEGE, ...	12
5	EIGGIE, EEGIGE, EIEEGE, EIIGEE, ...	50
6	EEIGIGE, EGEGGIE, EIIEGEE, EEIIEGE, ...	180

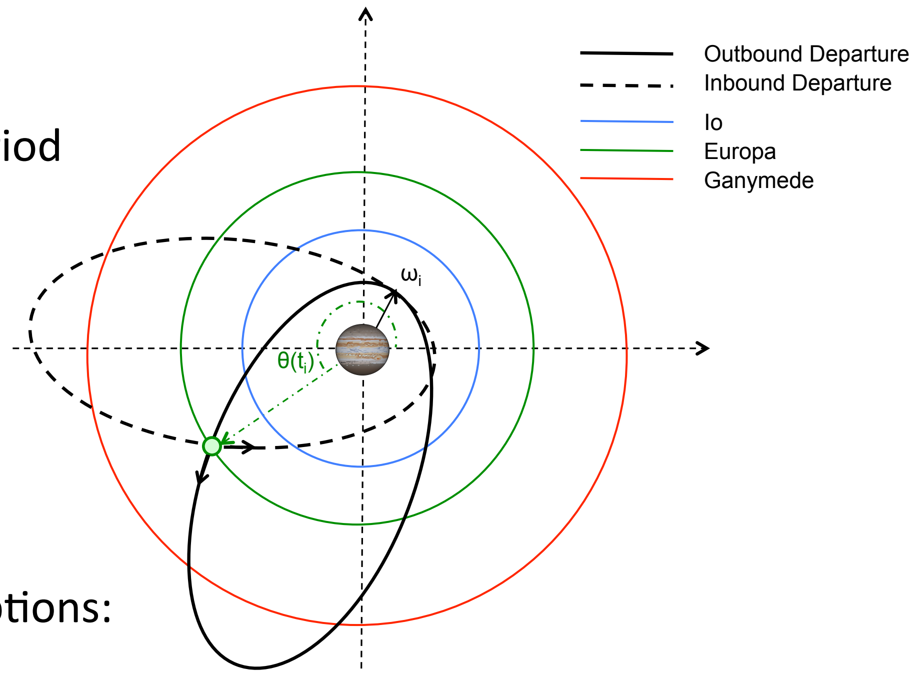
- The number of possibilities increases very quickly as number of encounter bodies increases

Need good ***initial guess strategy*** to reduce search space

1. ***Reduce the large phase-space*** search through a preliminary analysis based on two-body dynamics, where geometries that can potentially allow triple cycler solutions are selected.
2. Potential geometry includes a ***sequence of close flyby*** encounters, and an approximate ***time of flight*** between them
3. Patched conic gravity model and ***Lambert's problem*** is solved to determine the legs connecting consecutive encounters
4. Optimize using Monte Carlo

Conic Search Initial Guess Tool

- Approximate cycle solution by ***conic orbit that intersects all three flyby bodies***



1. Semi-major axis

Period is integer multiple of synodic period

$$n_{rev}T_i = n_{syn}T_{syn}$$

2. Eccentricity

Bounded by conic intersecting three moons

$$r_{p_{min}} = R_{Jup} \quad \text{and} \quad r_{p_{max}} = a_{Io}$$

$$r_{a_{min}} = a_{Gan} \quad \text{and} \quad r_{a_{max}} = \infty$$

3. Argument of periapsis

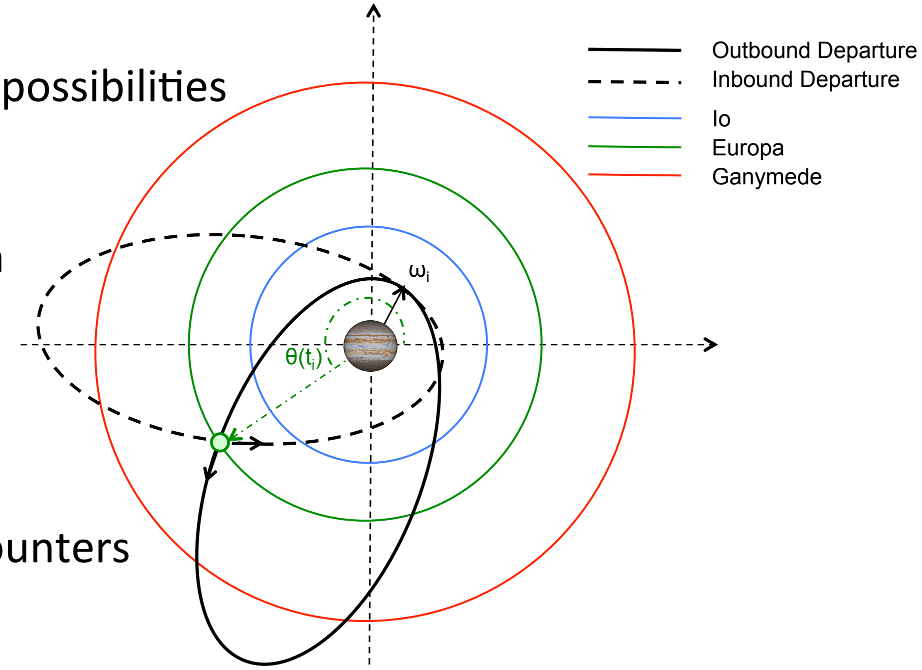
For given departure phase there are 2 options:

ω_1 (outbound) and ω_2 (inbound)

syn. per. \ s/c revs	1	2	3	4	5	6	7	8	9
1	1:1	1:2							
2	2:1	–	2:3	–	2:5				
3	3:1	3:2	–	3:4	3:5	–	3:7		
4	4:1	–	4:3	–	4:5	–	4:7	–	4:9

Conic Search Initial Guess Tool

- Approximate cycle solution by ***conic orbit that intersects all three flyby bodies***
- 3 independent variables are looped over all possibilities
- ***Search*** if the three flyby bodies are within a specified distance from the spacecraft when it crosses each satellite's orbit.
- For each synodic period cycle:
  - ***- Sequence*** of close flyby encounters
  - - Approximate ***time of flight*** between encounters



Potential ***sequence of flybys is predetermined***, greatly ***reducing the exhaustive search*** that would be needed otherwise

Initial Guess to Lambert

- Using initial guess for TOF: pair of flybys is connected via ***Lambert*** arcs using a ***zero-sphere-of-influence patched conic gravity model***, and allowing for a velocity impulse (ΔV) if needed at periapsis of the flyby.
  - The number of revs is predefined by the time of flight between encounter bodies, and the type of arc is chosen so as to minimize the ΔV at the flyby
  - ***Input***: n_{syn}, flyby sequence, tof between encounters
  - ***Output:*** ΔV, r_p
- ***Monte Carlo Lambert Optimization*** (find min ΔV)

EIGE Sequence Example

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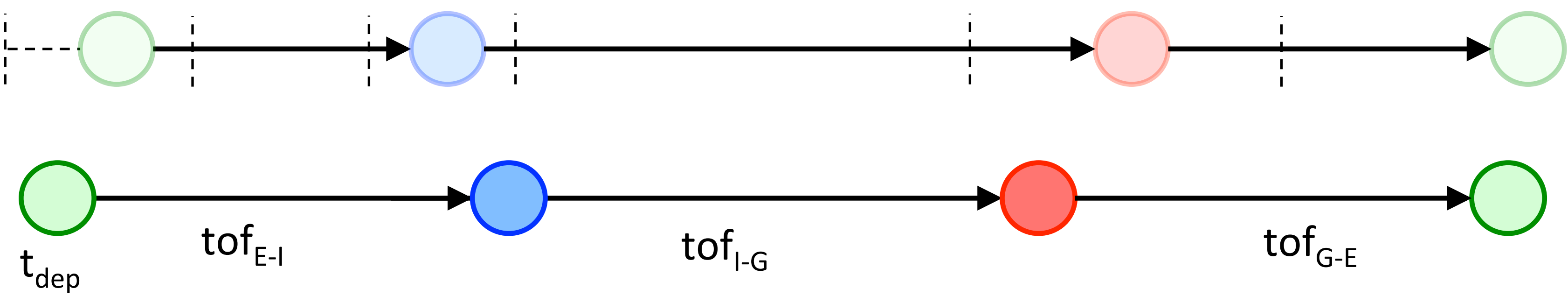
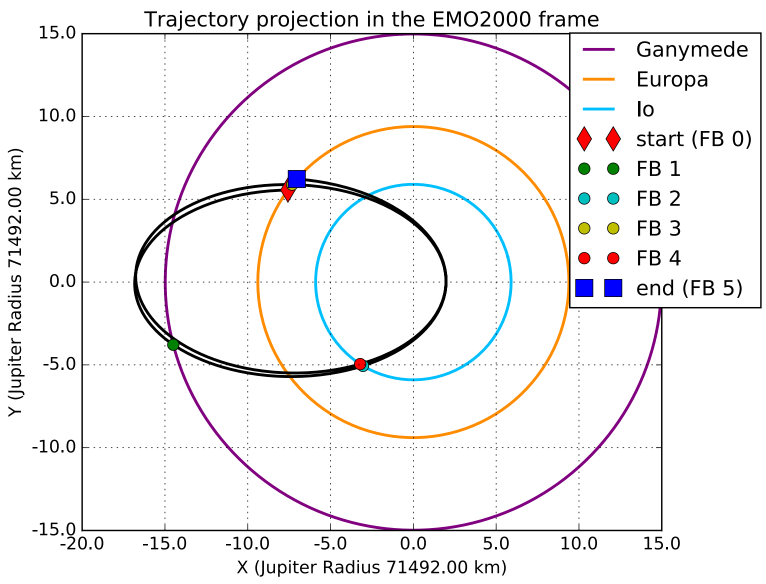
EIGE Sequence Example

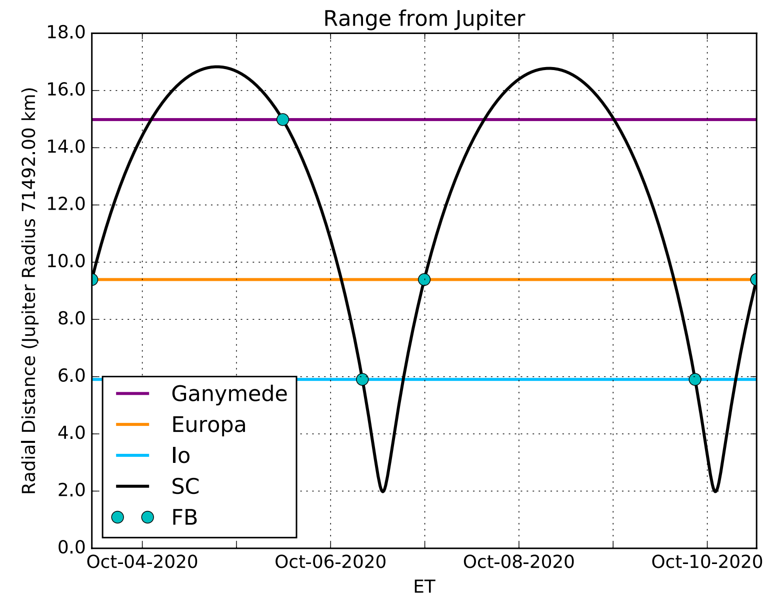


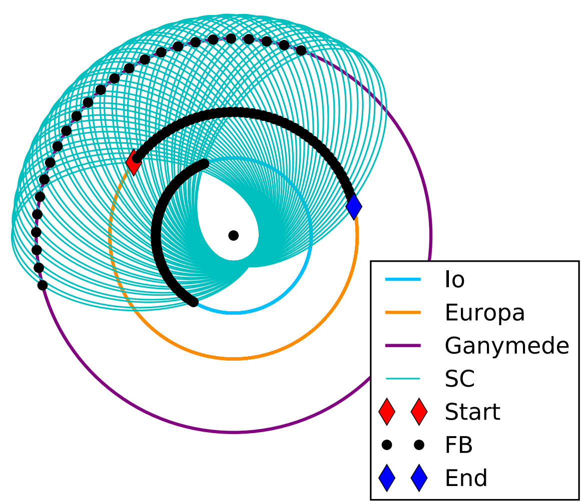
- Fixed parameters: Sequence and $T_{cycle} = tof_{E-I} + tof_{I-G} + tof_{G-E}$
- 3 parameters to vary: t_{dep}, tof_{E-I}, tof_{I-G} and tof_{G-E} solved for from fixed period

n parameters to optimize for n sequence cycle

One Synodic Period: EGIEIE Cycle

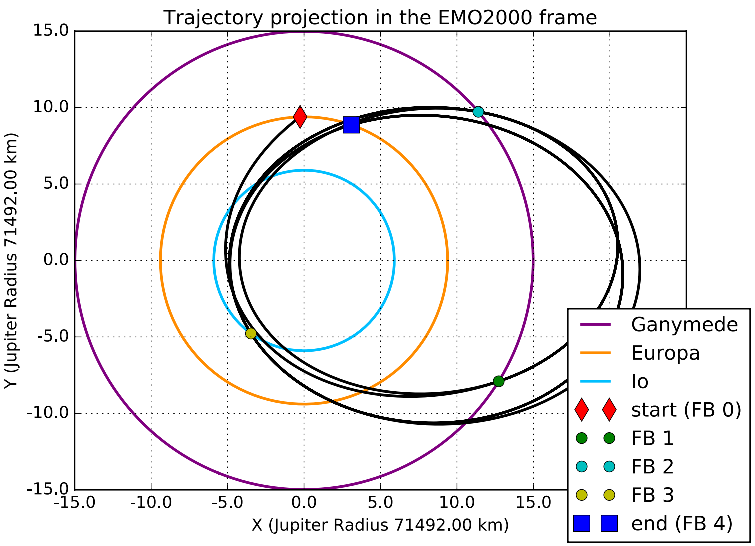


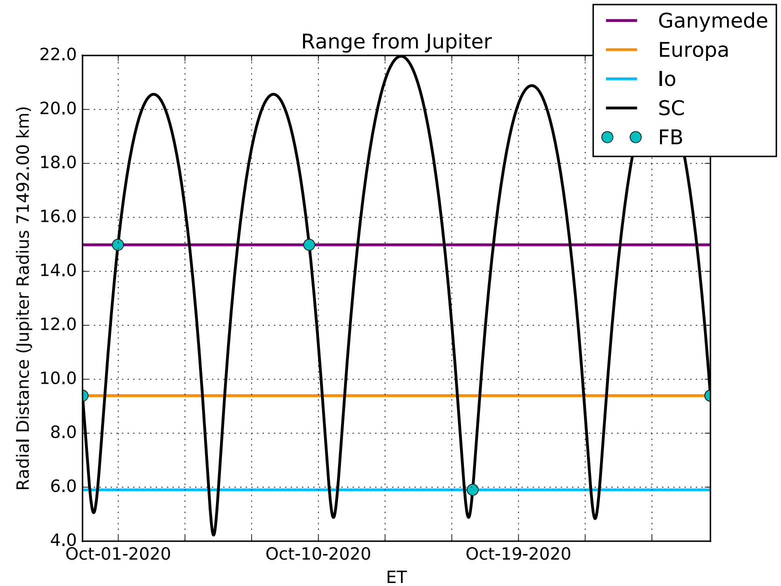


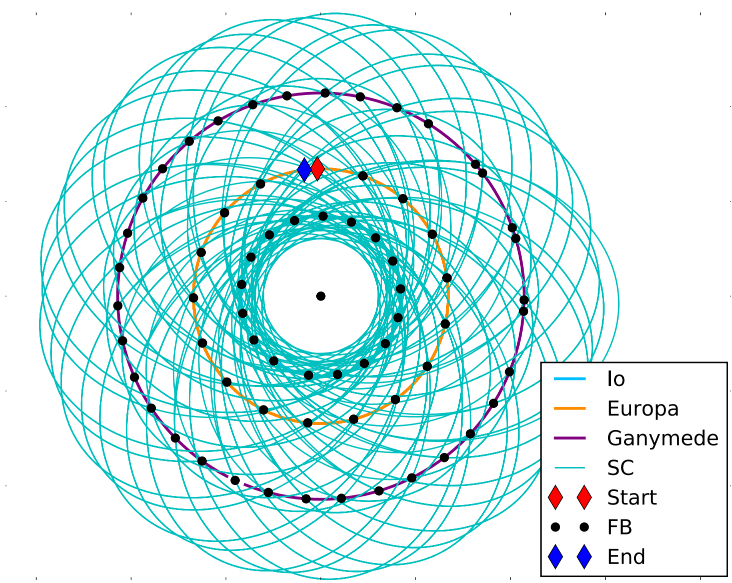


Flyby Body	Time of Flight (days)	Excess Speed (km/s)	Flyby Altitude (km)	ΔV (m/s)
Europa	–	12.27	9,260	1.8
Ganymede	2.03	7.29	69,990	0.1
Io	0.85	15.77	3,176	4.4
Europa	0.66	12.15	2,259	0.6
Io	2.87	15.86	494	0.0
Europa	0.65	–	–	–
Total	7.06	–	–	6.90

Four Synodic Period: EGGIE Cycle



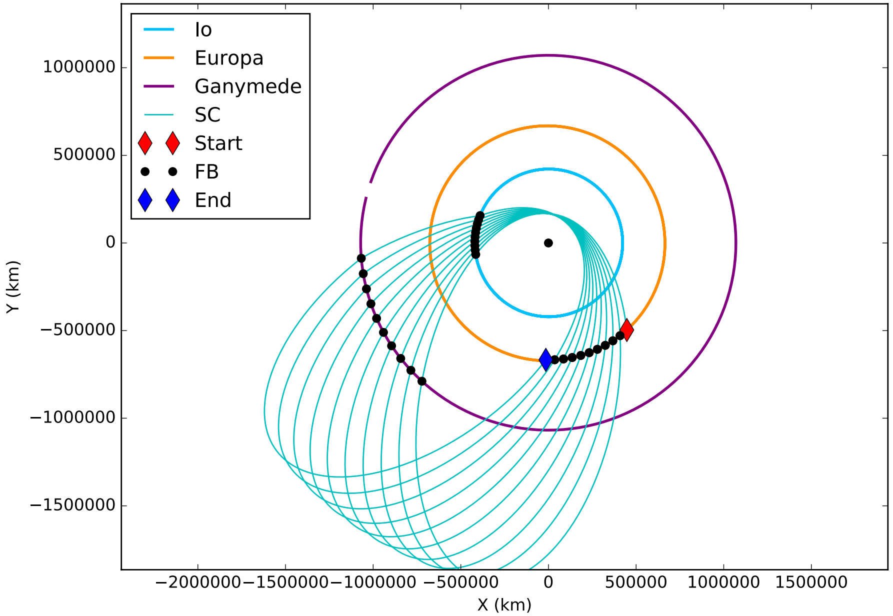




Flyby Body	Time of Flight (days)	Excess Speed (km/s)	Flyby Altitude (km)	ΔV (m/s)
Europa	–	9.12	1,444	0.00
Ganymede	1.59	7.07	2,155	0.60
Ganymede	8.60	7.07	6,263	0.00
Io	7.34	8.38	653	0.10
Europa	10.69	–	–	–
Total	28.22	–	–	0.70

High-Fidelity Solutions

- In real ephemeris, the repeatability of the solution is not exact due to the fact that the relative geometry of the encounter bodies changes over time
- Maintenance of the cycler will be required by implementing an adaptive algorithm that can compute a new cycle at each repeat period
- Two level approach
  1. Lambert in the real ephemeris
  2. Full optimization in a high-fidelity gravity environment



- 1 Synodic Period EIGE Sequence
- Ideal model:
  - $\Delta V = 0$ m/s
- Real ephemeris:
  - 10 repeat cycles: $\Delta V = 30$ m/s
  - Increasing ΔV after that
- Optimization high-fidelity:
  - Ballistic for 2 cycles
  - Large ΔV to maintain afterwards

Conclusion

- ***Triple cyclers*** around Jovian moons Ganymede, Europa, and Io are possible due to 1:2:4 orbital resonance

- ***Initial guess strategy*** is important to reduce the large phase-space search
  - Approximate a desired cycler trajectory with a two-body
  - Check at what phase the encounter bodies intersect the orbit
  - Families are classified by
    1. Integer number of synodic periods in one cycle
    2. Integer number of revolutions around Jupiter

- Once a good initial guess is known, ***Lambert*** is used along with a zero-radius sphere-of-influence patched conic gravity model
  - Due to fast computation time of solving Lambert's problem, a Monte Carlo analysis allows for fast ***optimization*** to reduce any ΔV discontinuities
- ***Future work:***
  - Jupiter-centered energy remains approximately constant
  - Initial guess strategy can be expanded to allow conic orbits that do not intersect three flyby bodies and then patch consecutive conics together
  - Allow cyclers with more complex itineraries, sequences that cover a wider range of energy levels