Global Mapping of the Galilean Moons

... a preliminary analysis of the second ranked trajectory in the GTOC6 competition ...

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Introduction

The 6th Global Trajectory Optimization Competition required participants to design a trajectory to map the Galilean moons, as fully as possible, given 4 years time and a spacecraft of 2000kg with low-thrust propulsion. The objective is to maximize a coverage index, which measures the diversity of the different areas visited on a moon. A mass penalty depending on the perijovian distance is applied at each revolution.

Methodology

We use self-adaptation in evolutionary algorithms to expand the nodes of a search tree by solving ΔV gravity-assist global optimization problems. The tree is then searched by our Lazy Race Tree Search algorithm which hybridizes depth and breadth search. We apply simple linear algebra to detect which face we are visiting. The resulting trajectory (mainly ballistic) is then transformed into a low-thrust trajectory without losing scores.
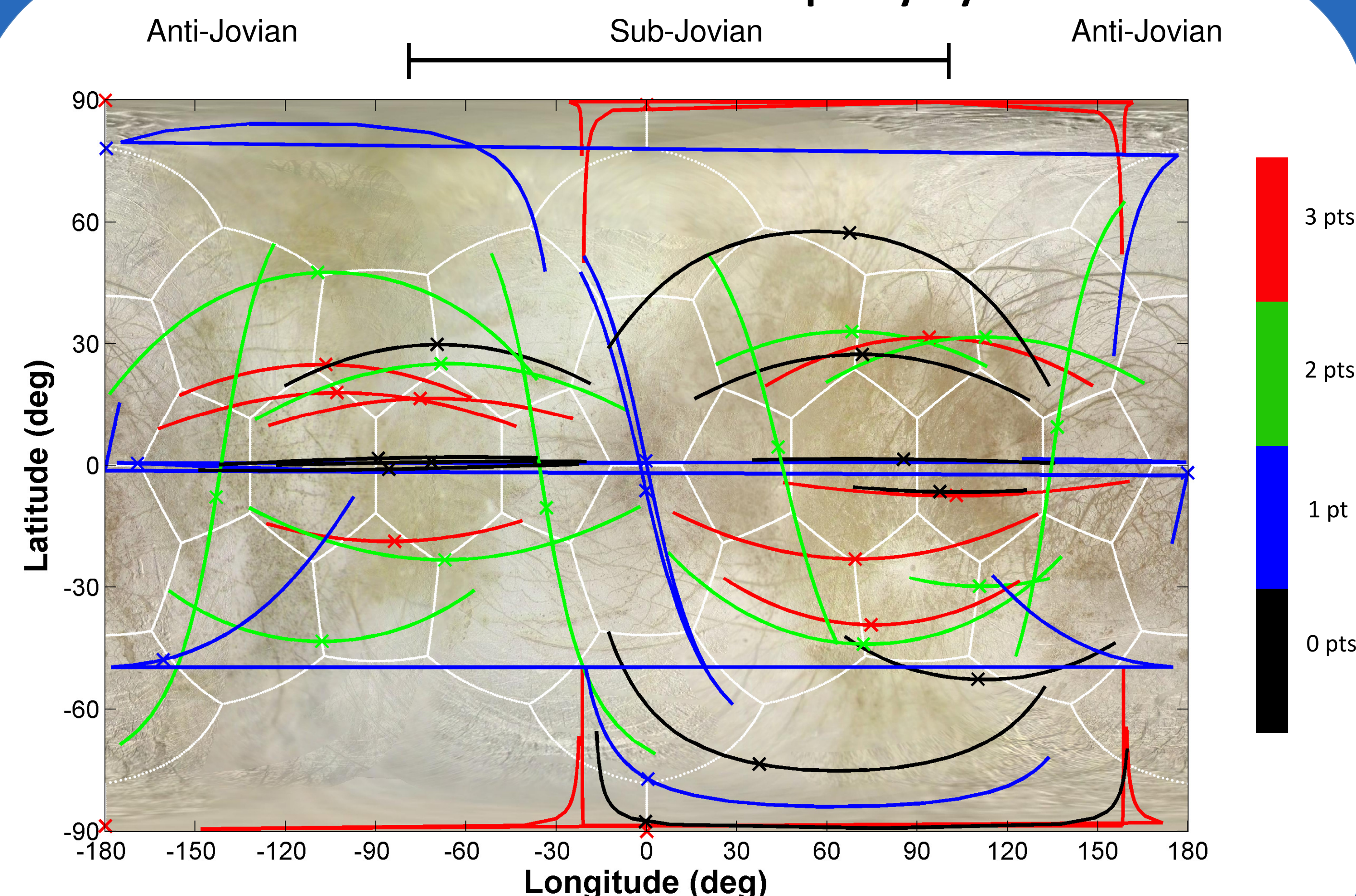
Coverage Index

The moons are overlaid by a truncated icosahedron. At each fly-by 1-3 points are awarded based on which face the closest approach falls on. Europa, the scientifically most interesting moon, gives double points. Revisits to a face give zero points.

| 3 pts | 2 pts | 1 pt |
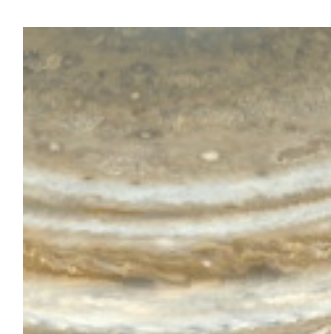
The closest approach falls on a face that awards 3 points

Ground Tracks of Europa Fly-bys

Ground tracks of altitude less than 2000km of all Europa fly-bys. Closest approaches are marked with the cross sign.

Detecting the Visited Area

At the point of closest approach, we find the closest vertex to our spacecraft $\vec{e_0}$ by taking the dot product of our position vector $\vec{R_p}$ and the vertex vectors $\vec{e_n}$, then defines a plane $\vec{R_p} \times \vec{e_0}$ with a normal vector $\vec{n}$. We then define the neighboring vector $\vec{e_n}, \vec{e_n}, \vec{e_n}$. If $\vec{n} \cdot \vec{e_1} > 0$ and $\vec{n} \cdot \vec{e_3} < 0$, we are on F_{23}. If this is not the case, $\vec{n} \cdot \vec{e_2}$ will uniquely determine the face.
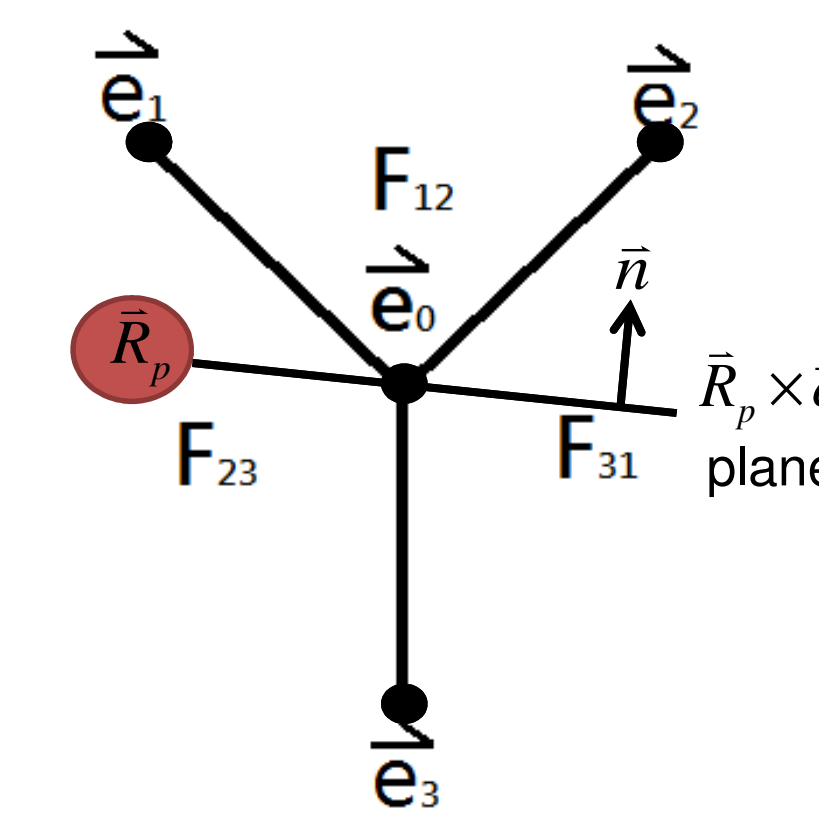

Improving the Coverage

Some fly-bys revisit faces. Many of these fly-bys happen near the edges of a polygon, so that the point of closest approach can be moved a small distance to a new face to score a higher coverage index. To do so, we iterate a number of random combinations of incoming and outgoing relative fly-by velocities. The new ones only perturb slightly around the original value to prevent using too much propellant.
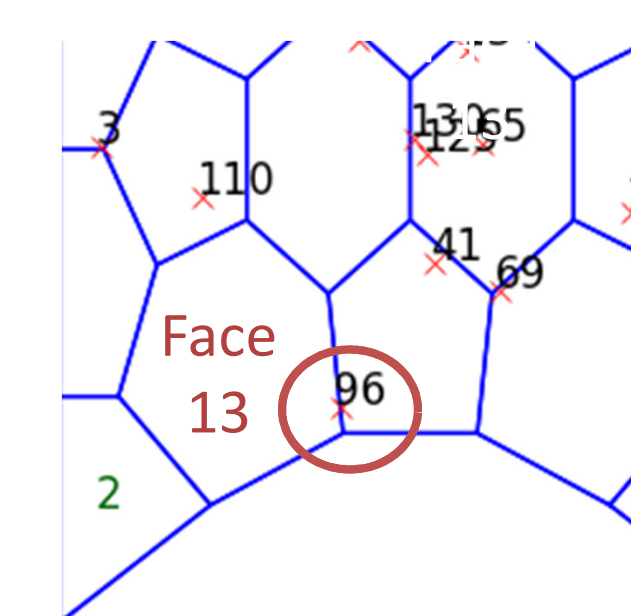
The 96th fly-by is easy to move into face 13 to improve coverage

The Four Phases of the Trajectory
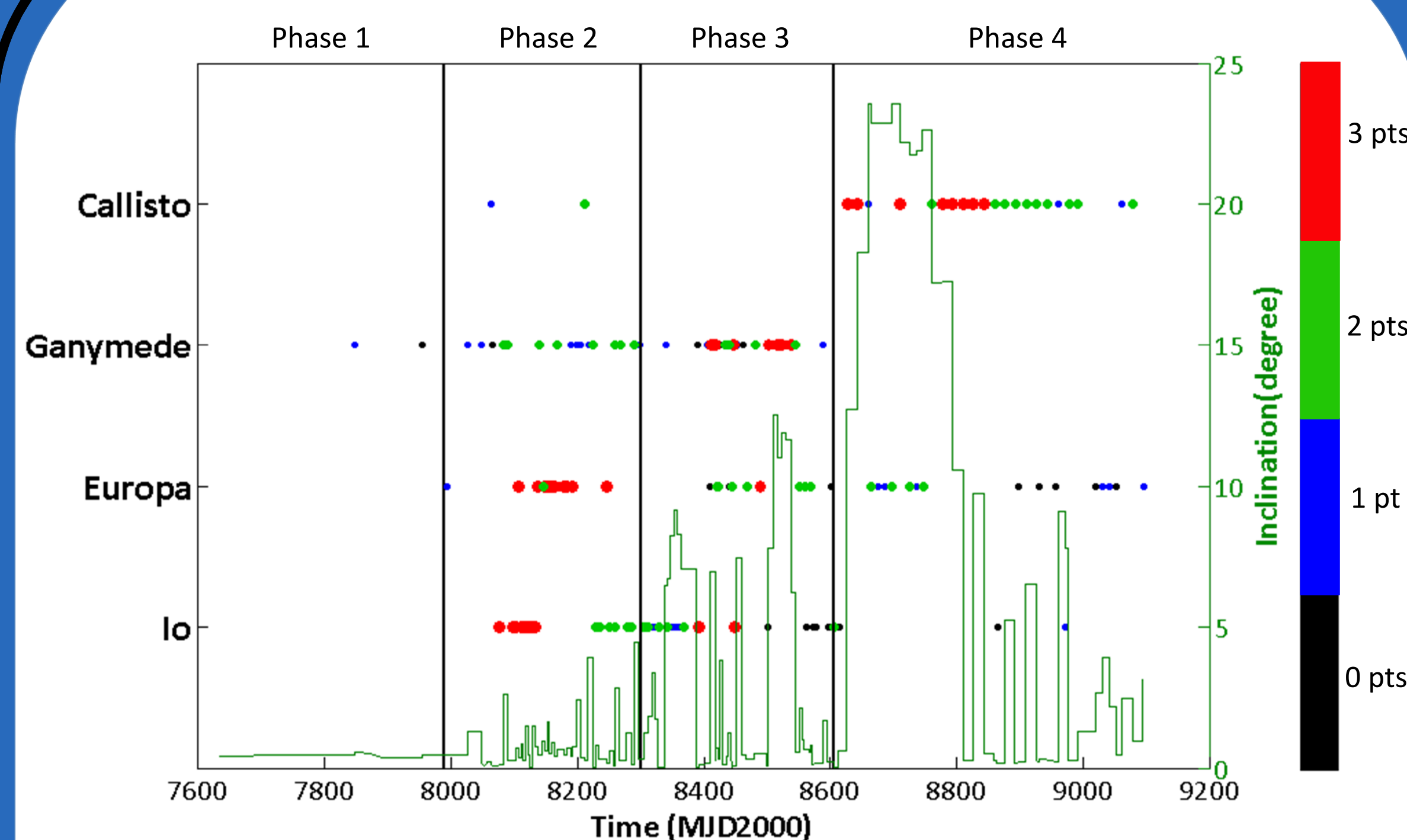
Our trajectory makes 141 fly-bys and scores 308 out of the maximum possible 324. The fly-by sequence is found in a fully automated manner by our Lazy Race Tree Search. Nodes (trajectories) are expanded by performing a global optimization over a one leg trajectory with deep space maneuver. At each step we branch over the next possible moon and the face we target on the current moon. Trajectories with the smallest cumulative time of flight are then ranked by ΔV and expanded further.

Phase 1: Pump Down

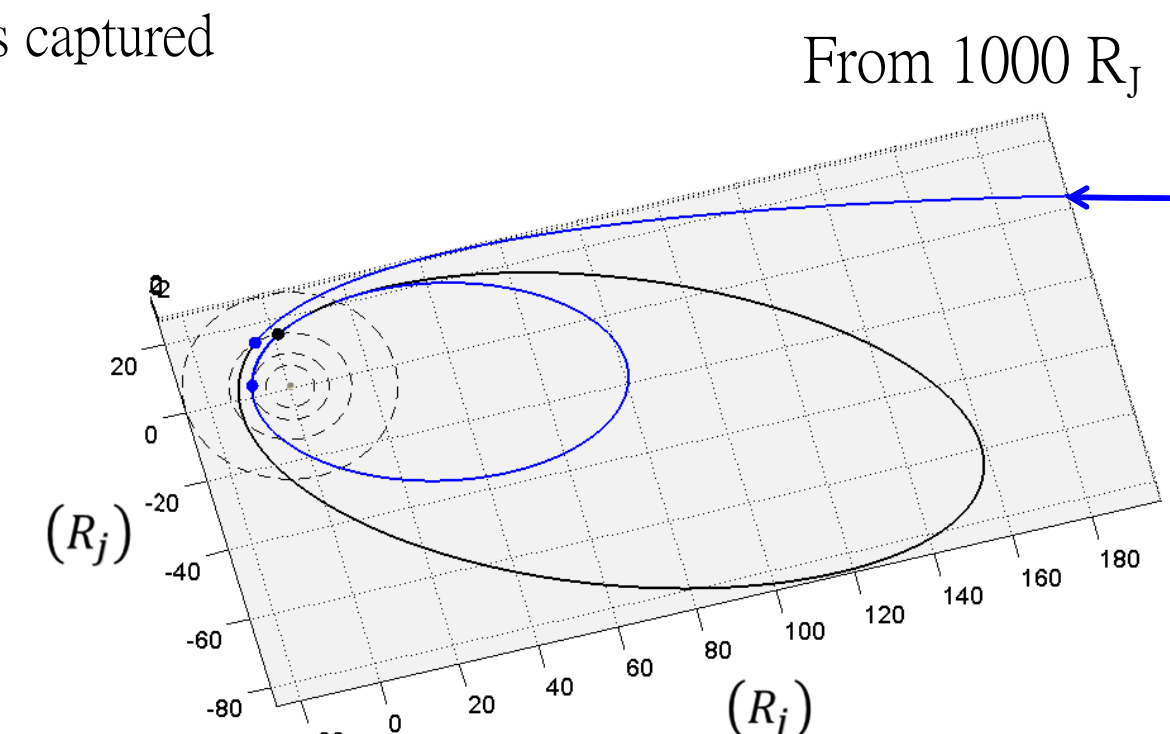Starting at 1000 R_J, the spacecraft is captured in the Jupiter system

Departure date: Dec 2020

Time of flight: 358 days

Final mass: 1895 kg

3 fly-bys: 1E, 2G

Score: 3

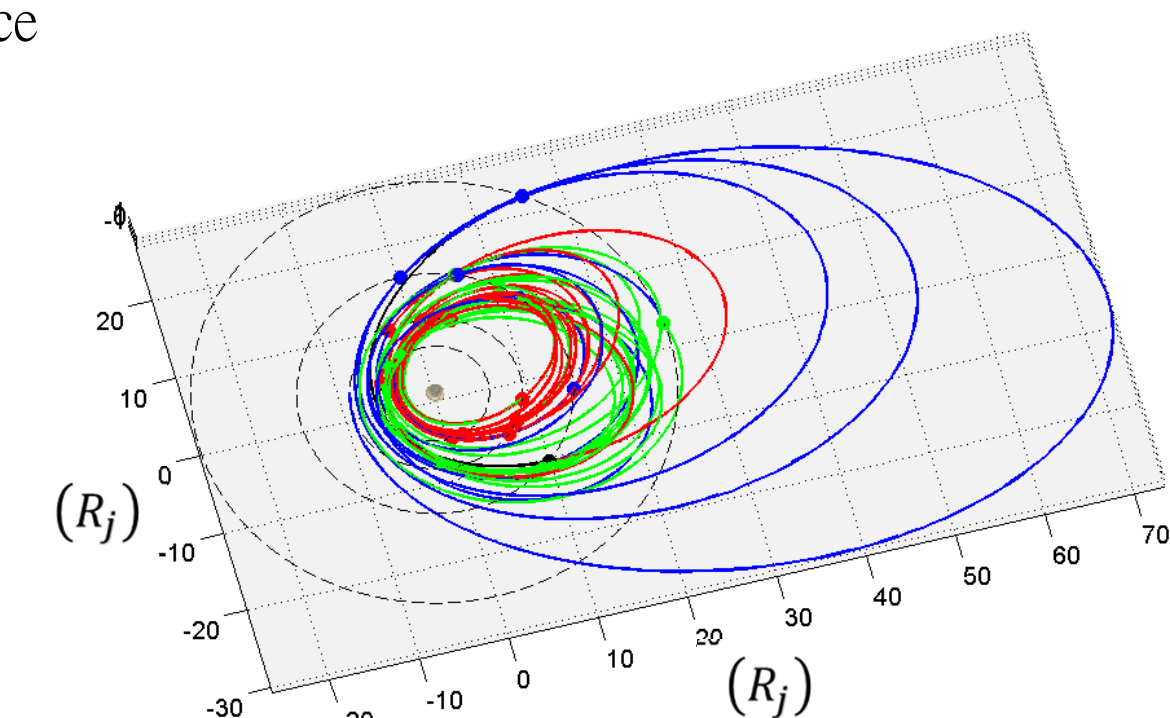From 1000 R_J

Phase 2: Inner moon tour

Io and Europa are visited by resonance transfers. The fly-bys score high.

Time of flight: 303 days

Final mass: 1653 kg

46 Fly-bys: 16I, 12E, 16G, 2C

Score: 138

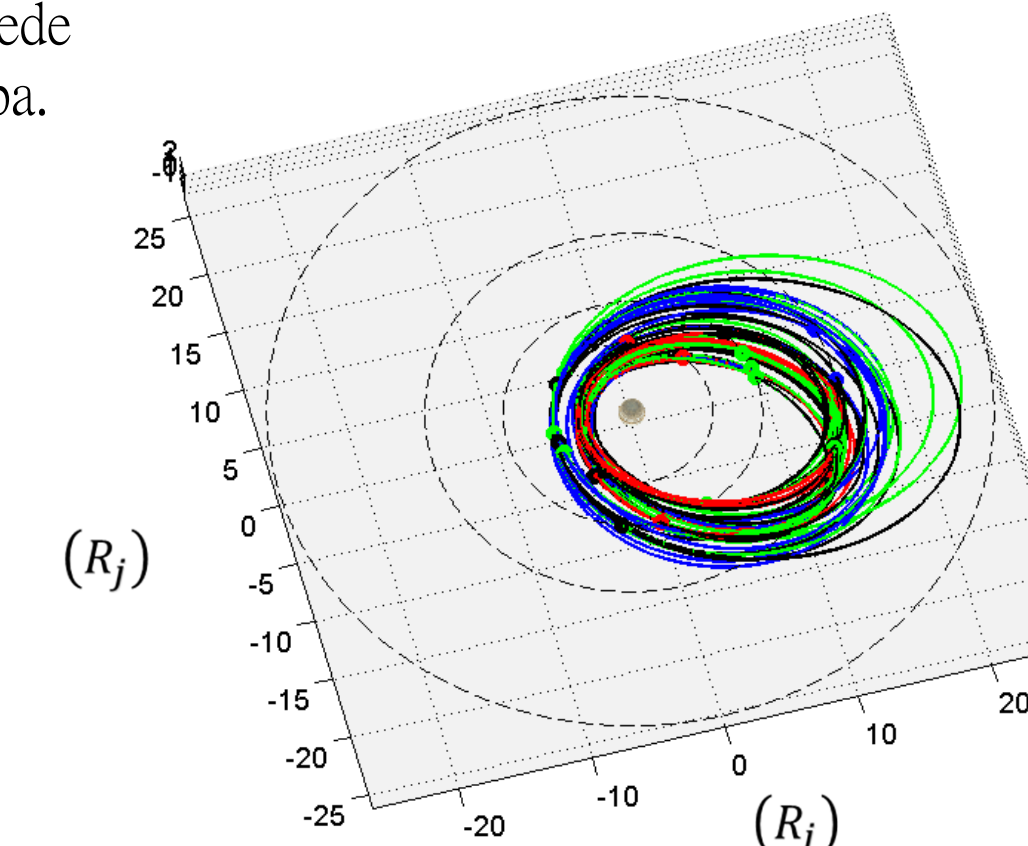## Phase 3: Ganymede and Inner Moons

Visiting high scoring faces on Ganymede and low scoring faces on Io and Europa.

Time of flight: 317 days

Final mass: 1252 kg

54 fly-bys: 20I, 14E, 20G
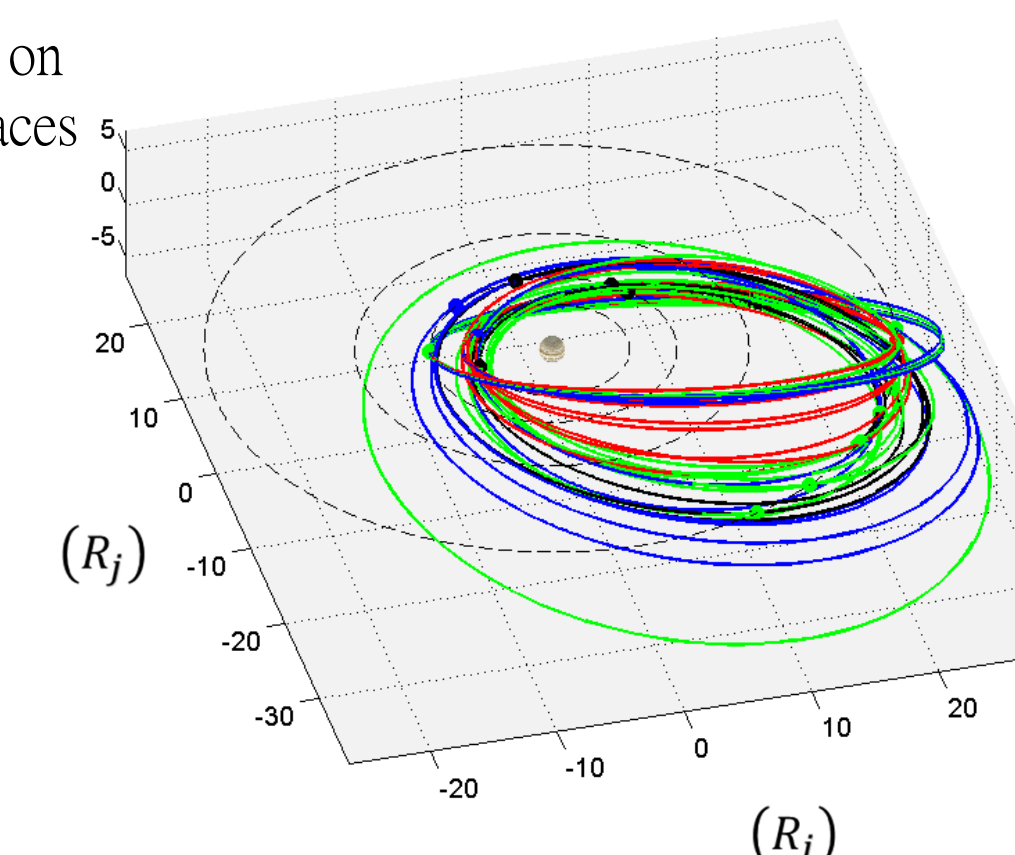
Score: 91

Phase 4: Crank up and Callisto

Inclination is increased to focus mapping on high-score faces of Callisto. Low-score faces of Europa are also mapped.

Time of flight: 418 days

Final mass: 1000 kg

54 fly-bys: 2I, 15E, 21C

Score: 76

Conclusions

Our trajectory successfully visits 115 out of 128 possible faces in 141 fly-bys, which gives us good coverage of all four moons. Europa, the most interesting moon, has very good coverage from the -50th to the 50th latitude and the polar regions. The total score is 308 out of 324, placing us 2nd in GTOC6. Our trajectory can be divided into 4 phases mapping distinct moons and have varying inclinations. The artificial intelligence algorithm came out with the final design with no human in the loop.

Contact Information