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PRELIMINARY MISSION ANALYSIS FOR A JUPITER ENTRY PROBE MISSION

Michael Khan, Paolo de Pascale
ESA – ESOC European Space Agency, European Space Operations Centre
Robert-Bosch-Strasse 5, D-64293 Darmstadt, Germany
(E-mail : Michael.Khan@esa.int)

Abstract

Mission analysis results for an ESA study into a Jupiter entry probe mission are presented: transfer of one or two entry probe(s) to Jupiter, sequential targeting and deployment, entry conditions and atmospheric descent profiles, data relay, and a possible post-entry mission of the carrier, comprising Jupiter orbit insertion and a tour of the Galilean moons. The parametric results provided are useful as reference for future Jupiter mission design tasks.

1. Mission Framework

A carrier spacecraft shall transport one or two Jupiter entry probes to Jupiter, target and deploy them from hyperbolic approach, perform data relay during the at least one-hour entry phase(s) (which will take the probes to the 100 bar level, i.e., approximately 240 km depth) and then may continue on an add-on mission.

2. Transfers to Jupiter

Case	VEEGA2017	VEEGA2020
Launch	2017/1/1	2020/3/9
Dep. Vel. [km/s]	3.434	3.17
Decl. [°]	-32	43
Venus GA	2017/5/17	2020/9/9
Earth GA 1	2018/3/20	2021/7/15
Earth GA 2	2020/3/15	2023/7/16
DSM [m/s]	110	32
Arrival	2022/11/20	2026/6/6
Arr.Vel [km/s]	6.09	5.704

Table 1: VEEGA2017/2020 Summary

Typically, the best transfer from Earth to Jupiter is of the Venus-Earth-Earth-Gravity-Assist (VEEGA) type. The launch windows in 2017, 2018, 2020 and 2022 were analyzed. 2017 is the most, 2020 the least demanding case in that time frame.

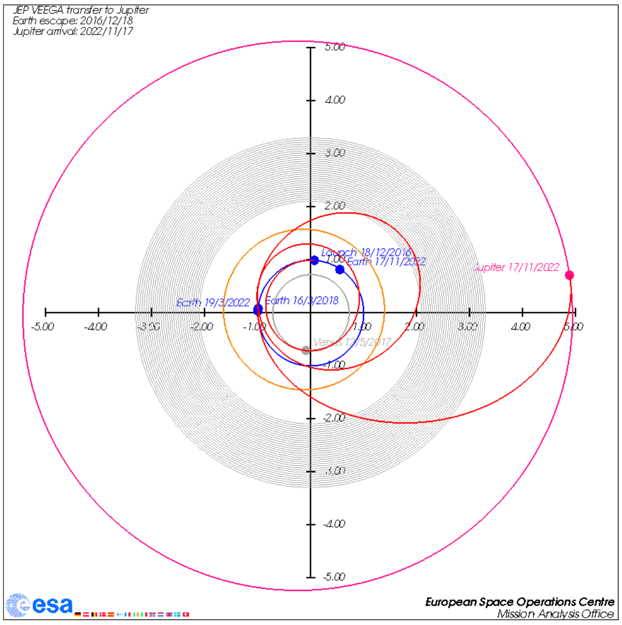

Figure 1: VEEGA 2017 Transfer to Jupiter

3. Probe Targeting and Deployment

Probe deployment is performed long before arrival to limit the size of the carrier deflection maneuver (ODM). This retargets the carrier to a safe perijove radius so it can relay the entry probe data. This radius is obtained through a trade-off.

A close approach limits the useful relay time but also reduces communications range, ODM and JOI. The carrier is exposed to a harsh radiation dose. We chose a perijove radius of 4 Jupiter radii (RJ) (4 x 71,492 km = 285,968 km).

3.1 Entry Accuracy Considerations

The targeting accuracy critically depends on the velocity error at deployment, which is a combination of uncertainties in the orbit determination/control and in the deployment mechanism.

Table 2 shows the mean and maximum possible errors in the entry flight path angle (FPA) due to 1 m/s residual velocity error (all sources) at probe deployment. With a given entry corridor width and known residual velocity uncertainties, the deployment epoch is thus constrained.

Deployment prior to arrival	FPA Error through 1 m/s Velocity Uncertainty	
	Mean	Maximum
-30 d	0.24 deg	0.5 deg
-90 d	0.56 deg	1.2 deg
-150 d	0.97 deg	2.0 deg

Table 2: Deployment Date and Entry Accuracy

3.2 ODM Cost Considerations

The ODM raises the carrier trajectory from an entry course to the chosen perijove radius and also delays the carrier arrival by a given amount required to optimize relay conditions. Table 3 lists typical ODM sizes as function of the epoch (immediately after probe deployment) and the target perijove radius.

ODM prior to arrival	ODM to Perijove Radius of:	
	4 RJ	5 RJ
-30 d	220 m/s	278 m/s
-90 d	85 m/s	106 m/s
-150 d	53 m/s	66 m/s

Table 3: ODM Epoch and Typical Size

ODM is a large manoeuvre; there is a strong incentive to deploy the probe early. This sizes the probes' batteries and the autonomy capabilities of its avionics.

4. Probe Entry and Descent

4.1 Probe Entry Conditions

For any near-ballistic transfer from the Earth, the hyperbolic arrival velocity will be around 6 km/s and the inertial velocity at entry almost 60 km/s. As Jupiter rotates with a period of less than 10 h, the atmospheric rotation at the equator is almost 12.6 km/s. For a prograde entry, this subtracts from the probe velocity, still inevitably yielding a relative entry velocity of ca. 47.3 km/s.

4.2 Trajectory Profile and Loads

The entry conditions are specified at a reference altitude of 450 km over the 1 bar level. Table 4 summarizes only three of the many sample cases with near-equatorial entry analyzed in the course of the study.

	Entry latitude [°N]		
	-1.2	+4.4	-7.4
Inclination [°]	1.3	+15	-15
Azimuth [°]	91	108	74
FPA [°]	-8.6	-10.1	-8.4
Desc. lat. [°]	-1.2	+3.7	-6.8
Rel.vel. [km/s]	47.1	47.6	47.6
Peak decel. [g]	213	192	214

Table 4: Trajectory Profiles for 3 Sample Cases

4.2.1 Higher-Latitude Entry

Entry latitudes far from the equator require high inclinations, lead to increase relative entry velocities and steep entry and exact a heavy penalty in terms of deceleration and thermal loads.

	Entry latitude [°N]		
	-15.4	-15.7	-16.1
Inclination [°]	25	30	35
Azimuth [°]	65	58	51
FPA [°]	-16.1	-12.5	-10.2
Desc. lat. [°]	-15		
Rel.vel. [km/s]	48.7	49.2	49.8
Peak decel. [g]	480	370	300

Table 5: Trajectory Profiles for -15 deg Latitude

Table 5 summarizes results for three cases leading to descent at 15 deg S latitude. Either entry velocity or the entry FPA are penalized, massively increasing thermal and structural loads.

5. Probe Data Relay

As the perijove radius is already set to 4 RJ, the only free parameter available to optimize the relay conditions is the carrier arrival delay, the time difference between probe entry and carrier perijove pass. The mission scenarii involving one and two probes are regarded separately.

5.1 One-Probe-Mission

The deployment sequence is fairly simple. The carrier deploys the probe onto an impact trajectory and then performs the ODM to raise its own perijove to 4 RJ, simultaneously setting the arrival delay. The desired relay conditions were defined as having a range of less than 300,000 km and a carrier elevation of at least 70 deg over the local horizon, as seen by the entry probe.

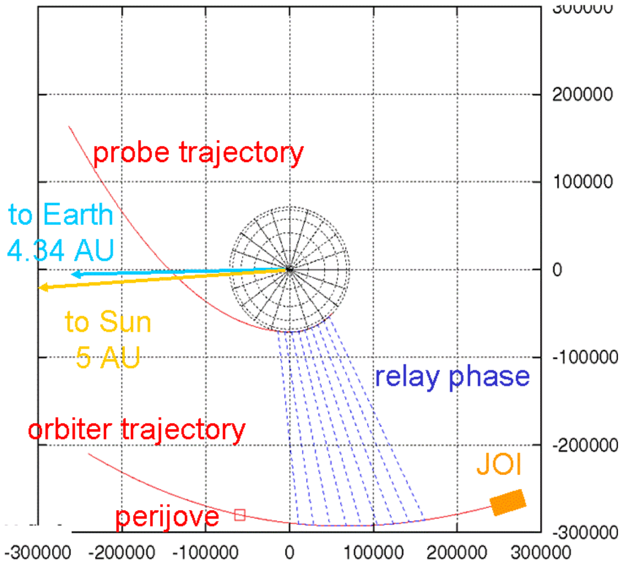

Figure 2: One Probe Relay Geometry

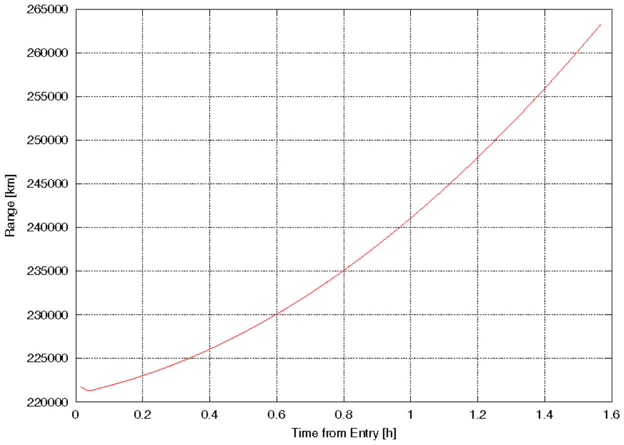

Figure 3: Range for 90 Minute Case

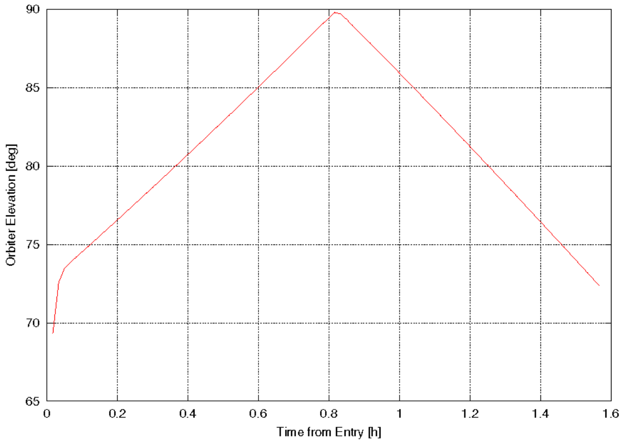

Figure 4: Elevation for 90 Minute Case

Two cases were analyzed. For 90 minutes of relay, the optimal carrier perijove time is 45 minutes before the entry probe's "virtual perijove pass" (VPP) (The probe is targeted at an imaginary perijove within the Jupiter atmosphere. This is never reached because the probe decelerates to sub-orbital velocities before).

To achieve 2 hours of relay, the carrier perijove time is 75 minutes before the entry probe VPP.

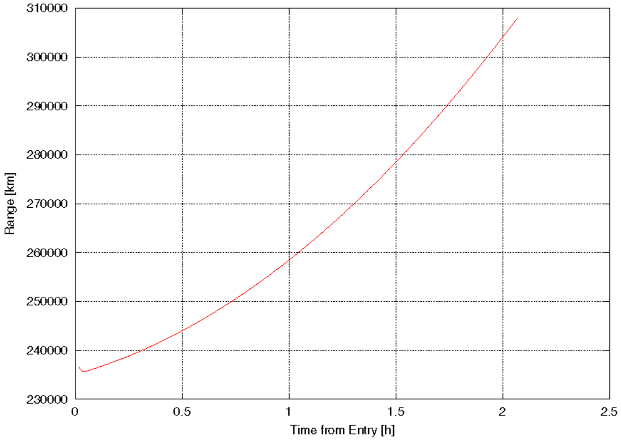

Figure 5: Range for 2 Hour Case

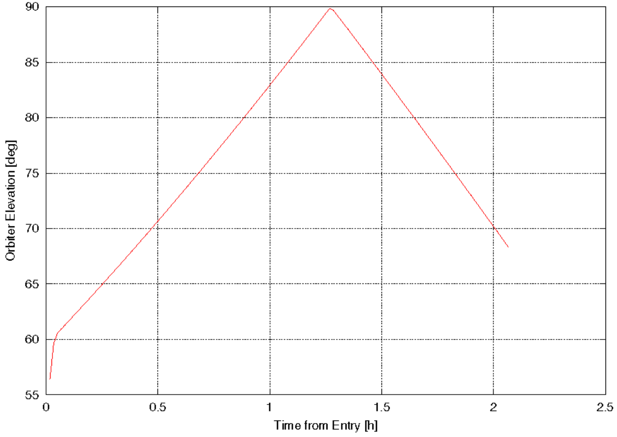

Figure 6: Elevation for 2 Hour Case

For the 90 minute case, the elevation and range requirements can be fulfilled. For the 2 hour case, this is not possible; the range requirement is violated toward the end and the elevation constraint toward the beginning of the pass. The carrier trajectory was designed such that the two constraints are not violated simultaneously.

The radiation dose absorbed by the carrier during the relay pass was assessed as over 50 krad (electron dose, 4 mm Al shielding).

5.2 Two-Probe-Mission

The two-probe mission is considerably more complex. It was assumed that the entry probes are deployed 90 and 70 days prior to arrival. They are also placed on trajectories with different inclinations so that entry takes place at latitudes of +4.4 and -7.4°, respectively.

The survival time (and relay duration) of each probe is assumed as 60 minutes. As the single carrier performs relay for two entry probes, the two entry missions must take place at distinctly separate times. 15 minutes are allowed for carrier retargeting between entry missions 1 and 2, so the time delay between subsequent entries is 75 minutes. With this delay, the longitude separation of the entry points will be 45°, leading to a distinct spatial separation of the atmospheric descent locations.

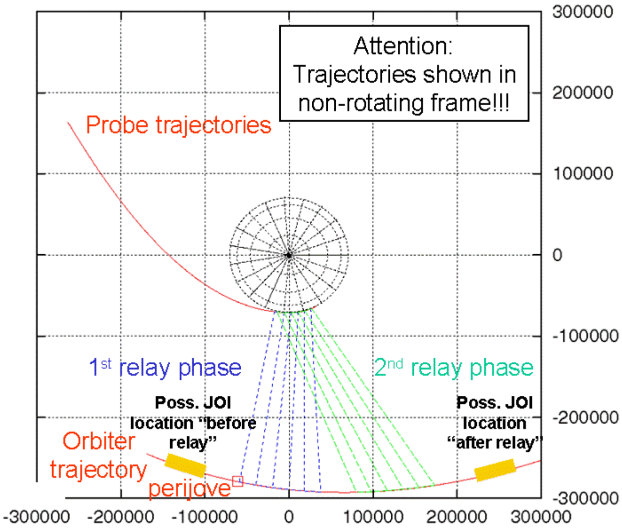

Figure 7: Two Probe Relay Geometry

In addition to the targeting of each entry probe and the setting of the two entry times, the carrier must perform inclination changes, first after the deployment of probe 1, in preparation for the deployment of probe 2, then after the deployment of probe 2, going back to a near-equatorial inclination. ODM raises the perijove and sets the orbiter perijove delay to the optimum value of -7 minutes. The budget for this sequence of manoeuvres is 120 m/s.

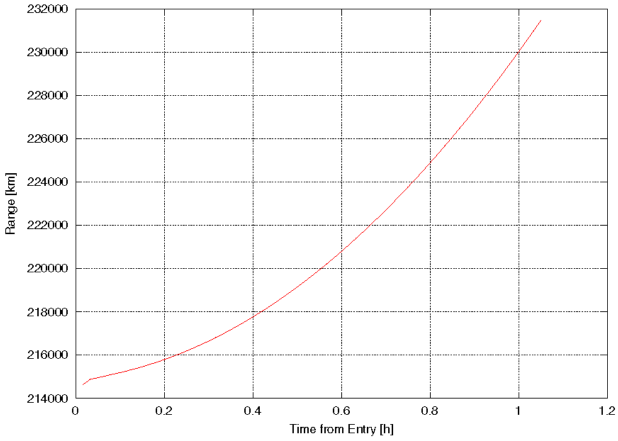

Figure 8: Range for Probe 1

Figure 7 displays the entire geometry for the two-probe mission. As the view is inertial, both entry phases appear to take place in the same location. However, apart from the latitude difference, taking into account the planet rotation and time difference, the entry locations have a large spatial separation.

For probe 1, the obtained carrier range profile remains well below 300,000 km, the elevation requirement if fulfilled until near the end of the entry phase. For probe 2, the elevation requirement is violated at the beginning of the phase, when the range is still lowest.

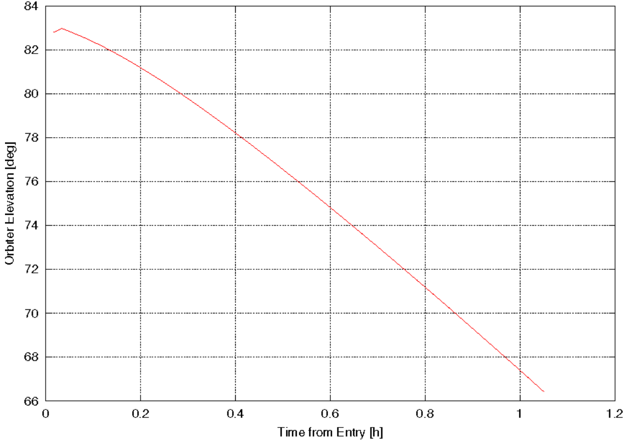

Figure 9: Elevation for Probe 1

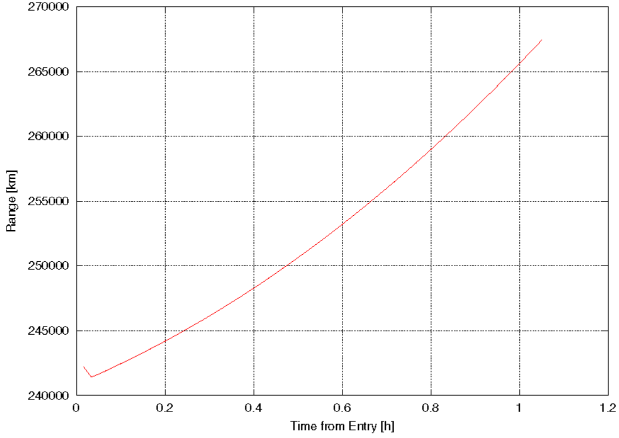

Figure 10: Range for Probe 2

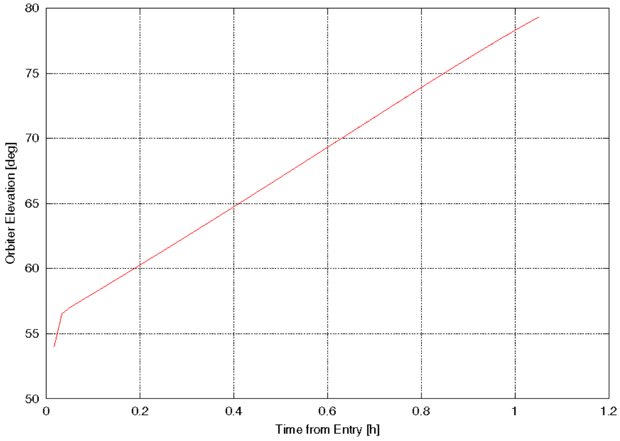

Figure 11: Elevation for Probe 2

6. Add-on Mission Possibilities

The carrier vehicle can continue unchecked on its hyperbolic trajectory. For the studied 2017 case, this Jupiter swingby at a radius of 4 RJ would inject the carrier spacecraft into a trajectory that escapes from the solar system at a final hyperbolic velocity of 6 km/s.

Alternatively, the carrier can be inserted into orbit around Jupiter and perform a scientific mission. This option was studied in some detail.

6.1 Jupiter Orbit Insertion – JOI

A mission around Jupiter requires insertion into a jovicentric orbit. In the following, the options for JOI are highlighted. Typically, the initial orbit is still highly eccentric, with a long period (> 6 months) and a high apojove. Then, a tour with multiple swingbys at the Galilean moons follows to achieve the final orbit.

In the following, impulsive JOI values only are given. However, with typical propulsion systems and spacecraft masses, gravity losses are negligible. The JOI size will however be adversely affected if JOI cannot be performed directly at perijove to avoid interfering with the probe data relay.

6.1.1 Impulsive JOI without Gravity Assist

Figure 12 shows the cost of JOI for hyperbolic approach velocities from 5 to 7 km/s, target apojove radii of 200 and 300 RJ (14.3 and 21.4 million km) and the perijove ranging from 2 to 12 RJ. Obviously, the most effective way to reduce the JOI is by choosing a lower perijove. In our case, the perijove radius is already fixed by the probe relay requirements. Some added reduction is available by raising the target apojove, increasing the initial insertion orbit period.

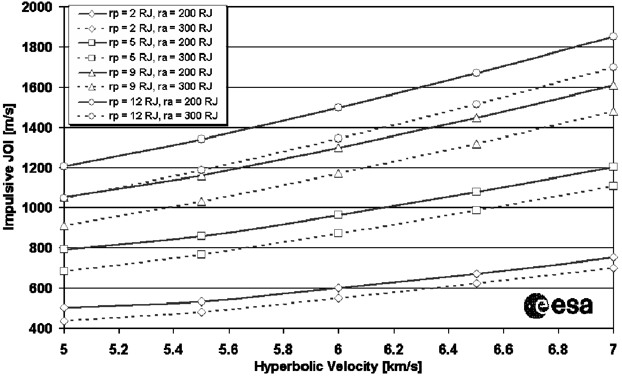

Figure 12: JOI Cost without Gravity Assist

6.1.2 Io Gravity Assist

Gravity assists at Io or Ganymede are useful options to reduce the JOI. An Io GA can be used only if the target perijove radius is less than around 5 RJ, which is the case here. For an arrival velocity of 6 km/s and a target perijove of 4 RJ, JOI can be reduced by more than 20%. The actual values depend on the chosen initial apojove radius and the allowed swingby altitude at the moon, which we constrained to 300 km.

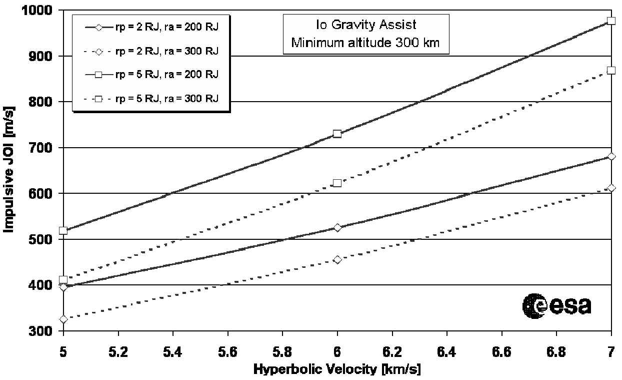

Figure 13: JOI Cost with Io GA

6.1.3 Ganymede Gravity Assist

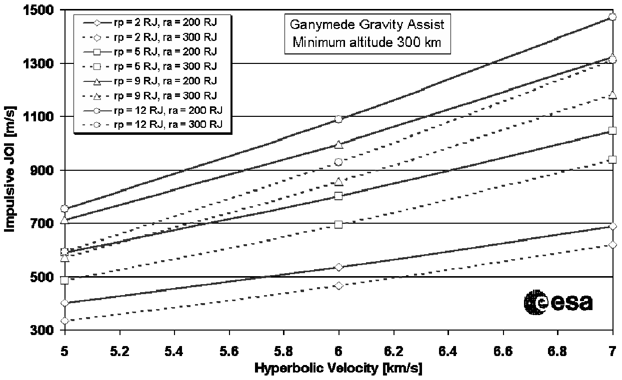

Figure 14: JOI Cost with Ganymede GA

Ganymede gravity assists are slightly less efficient than Io ones but have the advantage that more time remains for any spacecraft operations necessary between swingby and probe relay phase: ca. 16 hours for a Ganymede GA against 4 hours for an Io GA.

6.1.4 Effect of Off-Perijove JOI

Although the most efficient location for JOI is perijove, with the given mission scenario, this time will be reserved for probe relay, so JOI must be performed after the end of the relay phase, possibly several hours away from perijove. In the given scenario, a JOI delay of 2 or 3 hours increases the cost by around 8 and 15%, respectively.

6.2 Tour Example

In the given study case, the regarded add-on mission option was for a Jovian magnetospheric orbiter. The mission objective was to rotate the line of apsides clockwise by more than 45° such that they would be aligned with the current magnetotail (i.e., the apojove pointing away from the Sun. Additionally, the final orbit is to be 15 x 200 RJ.

These modifications are achieved with a perijove raising maneuver of 500 m/s, performed at the first apojove in order to raise the perijove to 1,000,000 km, almost the Ganymede orbit radius. Then, 5 Ganymede swingbys follow which first contract and then expand the orbit, while rotating the line of apsides. No further deterministic maneuvers are required, only small adjustments. The entire tour lasts 9 months, including 4 months for the initial post-JOI orbit. As Figure 15 shows, the final alignment and orbit size are exactly as required.

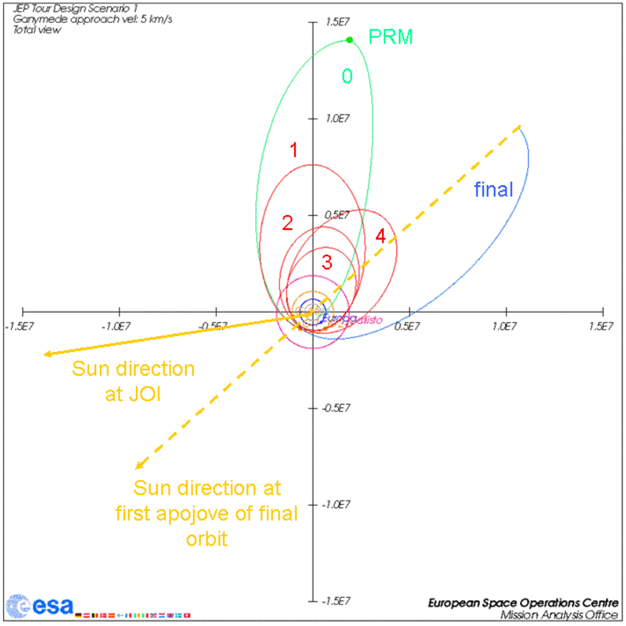

Figure 15: Sample Tour to Reach Target Orbit

7. Conclusions

This paper summarizes mission results for a Jupiter entry probe mission. It focuses on the task of transporting and deploying one or two entry probe(s) and of relaying their data. The probes' actual atmospheric flight is not described in detail in the present paper; the complexity and difficulty involved warrant a dedicated discussion. The post-entry mission options for the carrier are also detailed. The present work was performed in the context of a study conducted by the European Space Agency, which found the mission to be feasible with a low cost Soyuz-Fregat launch vehicle.

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