Jupiter Magnetospheric Orbiter trajectory design: reaching high inclination in the Jovian system

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Abstract

This paper presents the trajectory design for the Jupiter Magnetospheric Orbiter (JMO) in the Jovian system. JMO is JAXA's contribution to the Europa Jupiter System Mission, and its science objectives include in-situ exploration of different regions of the magnetosphere and the remote sensing of the plasma torus from high latitudes. For this reason the spacecraft is initially captured into low-inclination, high-apojove orbits, and gradually increases the inclination and reduces the apojove using gravity assists. In order to minimize the mission cost and complexity, JMO avoids the high-radiation regions. At the same time, the trajectory minimizes the transfer time and the propellant mass, and maximize the final inclination to the Jupiter equator. This work analyzes the solution space of this complex multi-objective optimization problem and discusses the trade-offs by comparing two representative solutions on its Pareto front. The design approach is also presented.

Keywords: *Jupiter Magnetospheric Orbiter, Jovian system, multiple gravity assists,orbit plane change*

1 Introduction

In the last years the scientific community has become increasingly interested in the Jovian system. The scientific return from a mission devoted to the exploration of Jupiter and its environment would be enormous, addressing fundamental questions on the plasma science, and on the presence of water - and possibly life - below the surface of the moons Europa and Ganymede.

In February 2009, the European and American space agencies ESA and NASA announced their plan for a joined Europa Jupiter System Mission to be launched in the 2020s. NASA will provide the Jupiter Europa Orbiter (JEO) and ESA will provide the Jupiter Ganymede Orbiter (JGO). In addition to JGO and JEO, a third spacecraft, the Jupiter Magnetospheric Orbiter (JMO), will be launched by JAXA. The three missions will share data and a tight collaboration is expected to provide the maximum scientific return from their mutual interaction. The JMO in particular will study the plasma interaction with the highly energetic and complex magnetosphere of Jupiter[1].

This paper presents the design of the JMO trajectory in the Jovian system. The design is particularly challenging because JMO must reach orbits with high inclination and low apojove, while minimizing the Δv, the time of flight, and the exposure to the radiation. Because these objective are conflicting, an analysis of the solution space is important to assess potential trade-offs. In particular this paper focuses on solutions with very low radiation exposure to enhance low-complexity and low-cost options.

The first section presents the JMO mission and the scientific objectives. The second section introduces the models and the design tools. The third section describes the design approach and presents the solution space with its the Pareto front, which is the main result of this paper. One example solution (option A) is used to support the discussion. The last section presents the details of two representative solutions (option A and B) on the Pareto front.

2 Jupiter Magnetospheric orbiter

Currently two mission scenarios are under investigation [2]. In the *shared-launch* option, JMO is a payload of the Trojan Asteroid Exploration Mission, and will be jettisoned some time before the Jupiter flyby. In the *dedicated-launch* option, the spacecraft is launched separately with a *H-IIA* launcher. Depending on the scenario and on the interplanetary transfer, the wet mass of JMO at Jupiter ranges from a few hundreds kg to more than two tons. Previous studies[3] determined the arrival velocity of 6.5 km/s opposite to Jupiter's velocity, with zero declination on Jupiter's equator, while the arrival date changes with the option and is considered free in this work. Figure 1 shows the direction of the v_∞ and the definition of local time in the rotating frame centered in Jupiter.

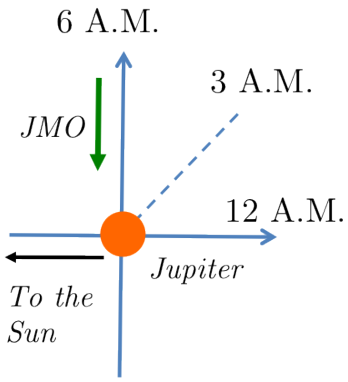

Figure 1: Arrival v_∞ and definition of the local time in the rotating reference frame.

2.1 Trajectory requirements in the Jovian system

At Jupiter the science phase is split in two parts [1, 4]: in the first part (phase I), the spacecraft orbit lies on the equatorial plane to better explore the magnetodisk. The apojove of each orbit falls around 12 A.M. to 3 A.M. local time, where scientists expect to find an emitter of hot plasma clouds. In the second part (phase II), the spacecraft orbit reaches high inclination (up to 30° or more) to measure the magnetosphere far from the equator, and to allow the remote sensing of the plasma torus from high latitudes. The apojove is reduced below 40 R_J at 3 A.M. to 6 A.M. local time, to better measure the plasma cloud that propagates radially and starts rotating eastward as it approaches the moons. Phase II starts around the second half of 2028 to allow synergistic, three-point investigations with JEO and JGO. Table 1 summarize the trajectory requirements.

	Phase I	Phase II
Initial date	-	second half of 2028
Final inclination	$\sim 0°$	$\geq 30°$
Final apojove	-	$\leq 40\ R_J$
Local time of the apojove	12 A.M. - 3 A.M.	3 A.M. - 6 A.M.

Table 1: Trajectory requirements for Phase I and Phase II.

3 Models

In this work the orbits of the moons are circular and coplanar. The spacecraft trajectory is computed with the linked-conics model (zero-radius sphere-of-influence, patched-conics model), except for the first large orbit around Jupiter where the Sun perturbation is included. In this paper the resonant ratio $n : m$ is used to indicate the spacecraft energy relative to a moon[5]: n is the number of moon revolutions and m is the number of spacecraft revolutions before two consecutive gravity assists.

3.1 Radiation dose

Jupiter has a large magnetic field that rotates very fast and traps many charged particles. For this reason, spacecraft in the Jovian system are exposed to high radiation and carry heavy shielding to protect special radiation-hardened instruments capable to absorb 100-150 krad (against 10-15 krad for typical space-qualified instruments). A simple way to estimate the radiation dose R_{8mm} for a spacecraft with an 8mm Aluminum shielding is to integrate the *radiation dose rate* F along the spacecraft trajectory

$$R_{8mm} = \int F_{8mm}(r, \phi)dt \tag{1}$$

where F is function of the distance r and of the latitude on the equator ϕ, and is found by averaging the instantaneous radiation dose rate over a Jupiter day. The model is explained in detail in [6].

Figure 2 shows the radiation dose rate on a plane perpendicular to the equator. For $r > 16\,R_J$ no data are available, but the amount of radiation is considered negligible [7]. The figure shows that even with the 8 mm shielding, the radiation dose rate in krad per day at Io, Europa or Ganymede is very high. In fact, JEO and JGO are exposed to very severe radiation because they orbits Europa and Ganymede during their science phase.

JMO however can avoid the high-radiation regions. One objective of the trajectory design is then to minimize R_{8mm}, possibly below 10-15 krad, corresponding to 100-150 krad outside the shielding [8]. With such low radiation exposure, JMO can varry radiation-hardened instruments without any shielding - a mass saving of 50 -100 kg - or still carry a shielding to protect lower-cost instruments.

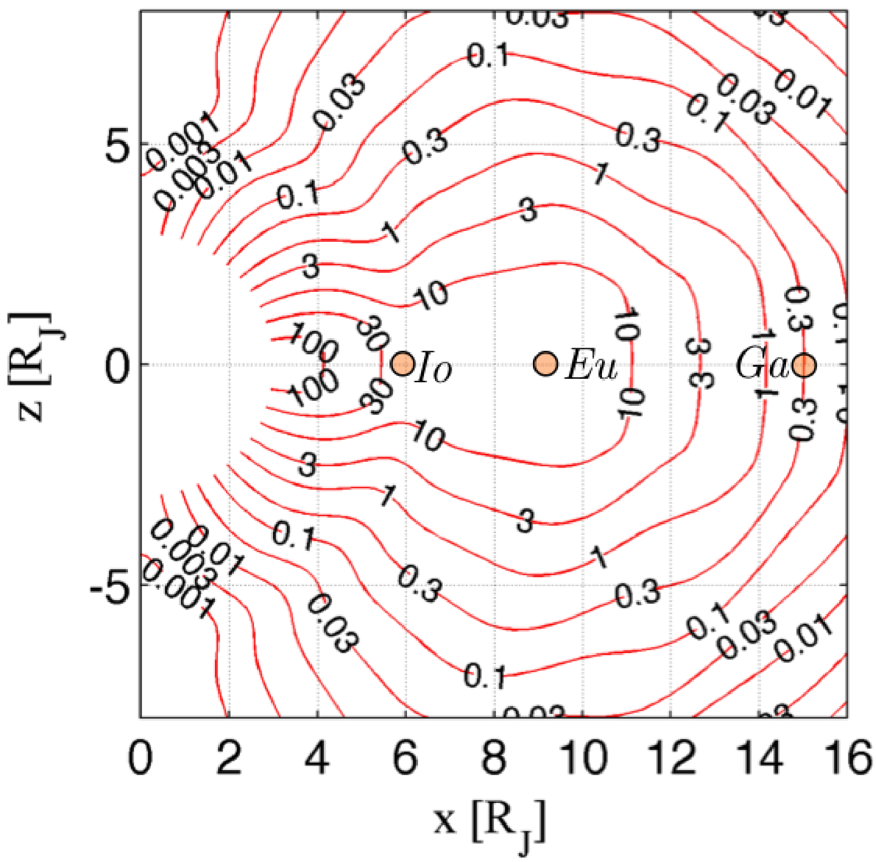

Figure 2: Averaged radiation dose rate in krad/day on a plane perpendicular to the (geographic) equator.

3.2 3-D resonant hopping

JMO trajectory implements a 3-D resonant hopping, a technique adopted by several missions (SOLO, Solar C, Cassini) to increase the spacecraft inclination using repeated gravity assists at one body. In this section we recall some formula and design tools for 3-D resonant hopping that were introduced in [9].

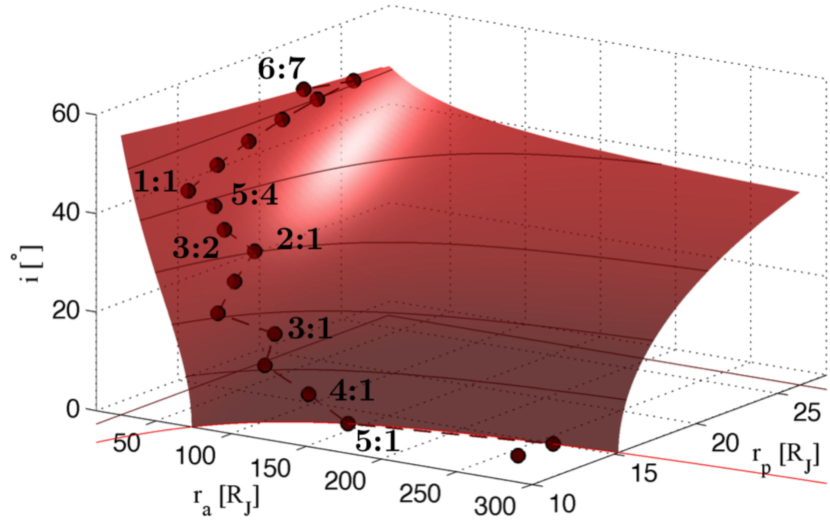

Figure 3: 3-D Tisserand graph with one v_∞ level set at Callisto. Each point on the surface represents an orbit. The sequence of orbits is a 3-D resonant hopping solution for JMO (the solution A discussed in the last section).

The Tisserand graph [10, 11] is a two-dimensional graph where every point represents a planar orbit of a spacecraft around Jupiter. For each moon, the graph shows the level sets of relative velocity v_∞ between the spacecraft and the moon. A gravity assist at one moon is represented with a shift along a v_∞ curve.

The 3-D Tisserand graph[9] is an extension of the Tisserand graph to inclined orbits; a convenient representation uses r_a, r_p, i as the Cartesian coordinates, as shown in Fig. 3. In this graph the v_∞ sets are two-dimensional surfaces; using the Tisserand criterion [12], the surfaces can be expressed explicitly as

$$i(r_a, r_p; v_\infty) = \arccos\left(\left(\frac{3 - v_\infty^2}{2} - \frac{a_M}{r_p + r_a}\right)\left(\frac{a_M(r_p + r_a)}{2r_p r_a}\right)\right) \tag{2}$$

where a_M is the semi-major axis of the moon. A 3-D resonant hopping is represented by a sequence of dots climbing up the surface, as shown in Fig. 3.

The maximum inclination is reached when the v_∞ vector is perpendicular to the spacecraft velocity and to the orbital plane of the moon, with

$$i_{max} = \arccos\left(\frac{v_\infty}{v_M}\right) \tag{3}$$

where v_M is the velocity of the moon. Eq. 3 shows that v_∞ level set are also i_{max} level sets.

An important tool for JMO design is the section $i = 0°$ of the graph, which is shown in Fig. 4 for the Jupiter moons with the i_{max} level sets replacing the v_∞ level sets.

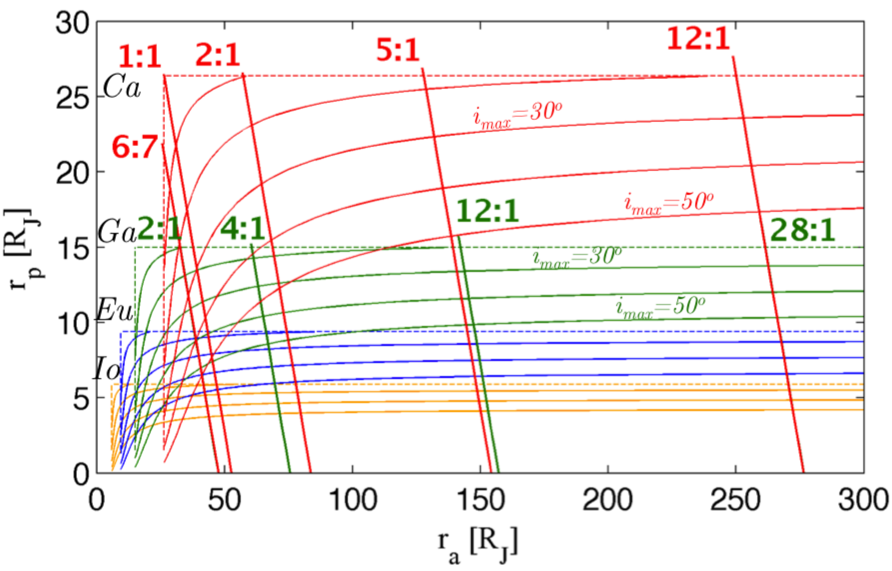

Figure 4: i_{max} level sets in the $i = 0°$ section of the 3-D Tisserand graph.

4 Trajectory in the Jovian system

For design purposes, the trajectory in the Jovian system is split in four phases (see Fig. 5). The capture phase starts with the spacecraft approaching Jupiter, and ends with the second gravity assist. Phase I includes low-inclination orbits and overlaps with the capture phase and with Phase II. Phase II starts around mid-2028 and ends when the trajectory requirements in Table 1 are met. The extended Phase II increases the inclination further and ends with a an orbit that is 6:7 resonant with Callisto and 2:1 resonant to Ganymede.

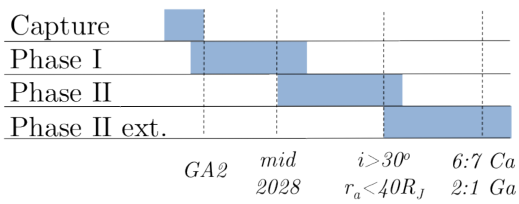

Figure 5: Phases of the JMO trajectory in the Jovian system.

The objectives of the trajectory design are (1) minimize the radiation dose, (2) minimize the total Δv, (3) minimize the transfer time, and (4) maximize the final inclination on Jovian equator, while satisfying the trajectory constraints summarized in Table 1. To mitigate the propellant mass requirements for the entire missions, Phase I and II do not include any deterministic maneuver, exploiting instead the gravity of the Galilean moons through repeated gravity assists.

This section presents the trajectory design in the Jovian system and an analysis of the solution space and its Pareto front. The capture phase is studied separately in the first part of this section, while the other three phases are designed jointly and are presented in the second part.

4.1 Capture phase

The capture is an important part of any mission to Jupiter and was analyzed in many feasibility studies [13, 14, 15, 16, 17]. The phase is schematically represented in Fig. 6. As the spacecraft approaches Jupiter, a gravity assist at one of its moons is used to reduce the velocity. The minimum altitude is 500 km in case of Callisto, Ganymede or Europa gravity assist, and 1000 km in case of Io gravity assist. Around the first closest approach at Jupiter (r_{pJOI}), the Jupiter Orbit Insertion (JOI) maneuver places the spacecraft into a closed orbit of approximately 200-day period (corresponding to a 12:1 resonance at Callisto and to

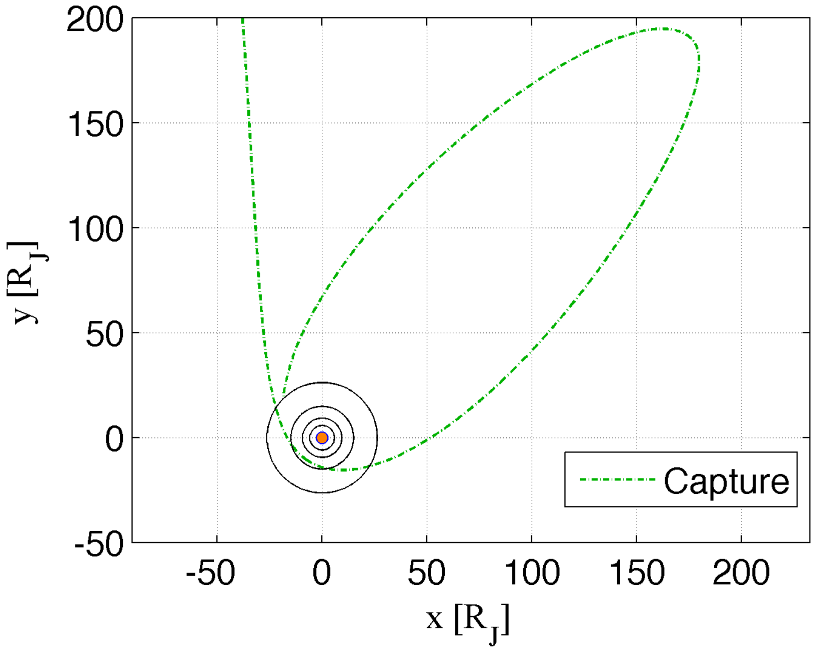

Figure 7: Capture phase in the rotating frame for option A.

a 23:1 resonance at Ganymede). At the first apojove $r_a = 260R_J$, the Perijove Raise Maneuver (PRM) increases the perijove to r_{pPRM} to counteract the effect the Solar gravity and to mitigate the exposure to radiation. The phase ends with a gravity assist just before the second closest approach. Once a capture phase is designed, similar capture opportunities exist every synodic period of the gravity-assist moon.

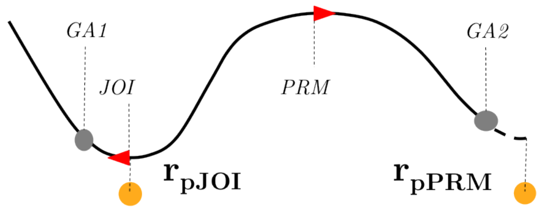

Figure 6: Capture phase (schematic).

Figure 7 shows the capture phase for option A in the rotating frame. To allow low relative velocities with respect to the moons, the incoming hyperbola is direct and the first gravity assist occurs around 12 P.M. The JOI then follows at around 3 P.M. and the first local apojove is at 3 A.M. From this time on, the local time of the apojove is changed by two factors. The apparent motion of the line of apsides in the rotating frames decreases the local time of the apojove, while the gravity assists can increase or decrease the longitude of the apojove depending on whether they occur in the incoming or outgoing leg of the spacecraft orbit [3]. As the local time of phase II must be greater than the local time of Phase I, we place all the gravity assists in the incoming leg of each orbit. Then the two design parameter for the capture phase are r_{pJOI} and r_{pPRM}, which affect both the Δv and the radiation dose.

The radiation dose is first estimated integrating the radiation dose rate on closed orbits with different perijoves r_{pJOI} and a fixed apojove $r_a = 260R_J$. Figure 8 plots the radiation dose as function of r_{pJOI}, and suggests to choose $r_{pJOI} \geq 12$ to limit the radiation dose to a few krad.

The Δv is initially estimated without solving the phasing and using linked-conics. Assuming $r_{pPRM} \geq r_{pJOI}$, Δv_{PRM} is

$$\Delta v_{PRM} = \sqrt{\frac{2\mu_{Ju}}{r_a}}\left(\sqrt{\frac{r_{pPRM}}{(r_a + r_{pPRM})}} - \sqrt{\frac{r_{pJOI}}{(r_a + r_{pJOI})}}\right)$$

and decreases with r_{pJOI} while increases with r_{pPRM} . Δv_{JOI} is a more complex function of r_{pJOI} only (monotonically increasing) and depends on the choice of the gravity assist moon.

Figure 8 shows the total Δv as function of r_{pJOI} and for three different choices of r_{pPRM} (solid curves) . For each r_{pJOI} and r_{pPRM}, the figure shows only the solution with the best moon for the gravity assist, revealing that Europa is never a good choice. The Δv includes some 70 m/s penalty to model the effects of the Sun gravity, which always decreases the perijove because the apojove is in the first quadrant. The figure suggests to choose $r_{pJOI} \leq 13\ R_J$. The total Δv increases with r_{pJOI} because Δv_{JOI} increases more than Δv_{PRM} decreases. This trend changes at lower v_∞: Fig. 9 shows that at $v_\infty = 5.5$ km/s a minimum Δv exists at around 13 R_J, in agreement with other studies in literature [18].

Then $r_{pJOI} = 13\ R_J$ was chosen as a design value because is a good compromise between radiation dose and Δv, and is robust to changes of v_∞.

The most interesting options are re-computed with a dedicated software that minimizes the total Δv and restores the phasing constraint, taking into account the Sun gravity perturbation. The optimization parameters are the times of the gravity assists , and the times and Δv vectors of the JOI and PRM maneuvers. Table 2 shows the total Δv for different choices of r_{pPRM}, assuming $r_{pJOI} = 13\,R_J$. The values are in good agreement with the estimated ones of Fig. 8.

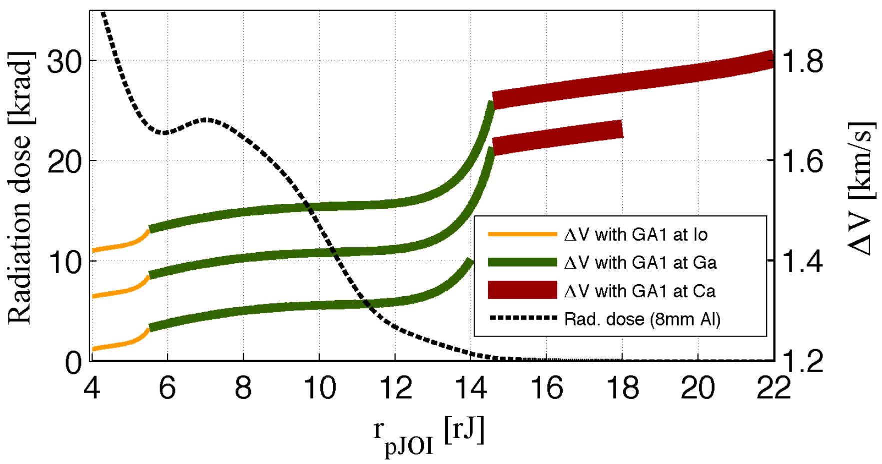

Figure 8: Δv and radiation dose in the capture phase ($v_\infty = 6.5$ km/s) .

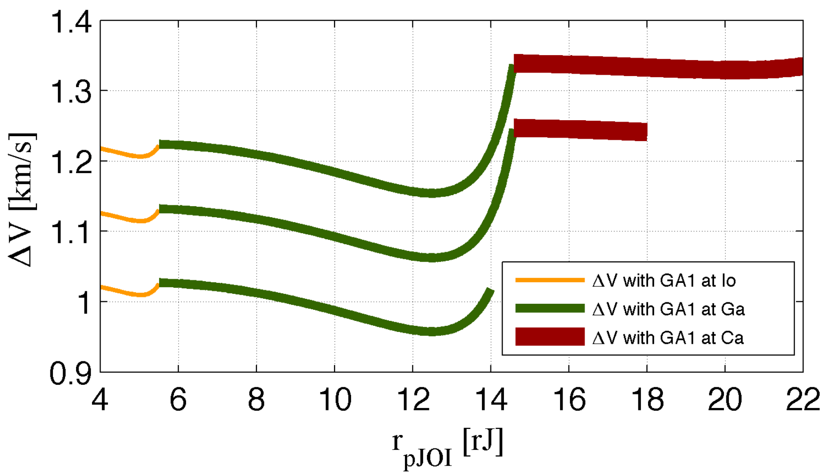

Figure 9: Δv in the capture phase for a lower arrival v_∞ (5.5 km/s) at Jupiter.

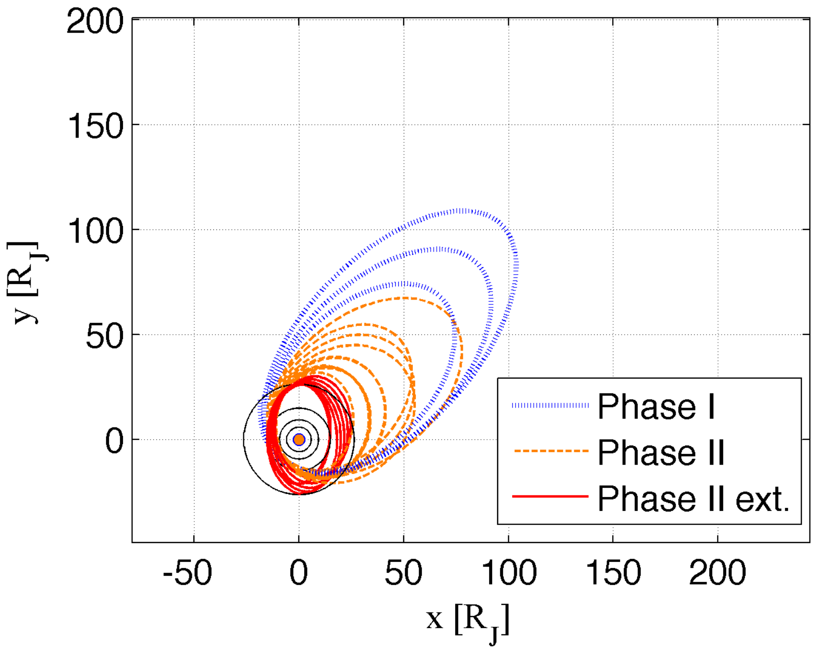

Figure 10: Phase I, Phase II, and extended Phase II in the rotating frame for option A.

r_{pPRM} $[R_J]$	15	16	17	18	19	20	21	22
Δv [km/s]	1.36	1.39	1.42	1.44	1.47	1.49	1.51	1.53
m_p [kg] - *shared*	75	76	78	79	80	81	82	82
m_p [kg] - *dedicated*	874	887	900	912	927	937	948	958

Table 2: Total Δv and propellant mass for the shared (~200 kg) and dedicated (~2300 kg) option, for different r_{pPRM}. The Δv are the results of the optimization.

4.2 Phase I and Phase II

After capture, no deterministic maneuver is applied[1] and the apojove and the inclination are changed by a sequence of gravity assists. Such trajectories are typically called "moon tours" [20, 13, 21, 16] as they include gravity assists at different moons.

The initial condition for Phase I is the orbit following the PRM; r_{pPRM} is a free parameter and uniquely determines the total Δv (see Table 2), but it is assumed $r_{pPRM} \geq 13\, R_J$ to limit the radiation exposure[2]. For the same reason we do not include any Europa and Io gravity assists. Figure 4 shows that at $r_a = 260\ R_J$ and $r_p \geq 13\ R_J$, only Callisto can be used to pump the inclination above 30°. Then a simple solution for JMO is the *Callisto-only* strategy, where a 3-D resonant hopping at Callisto gradually increases the inclination and decreases the apojove. As an example of Callisto-only solution, Fig. 10 shows Phase I, Phase II and the extended Phase II for option *A* in a rotating reference frame.

A more general strategy would include Ganymede gravity assists before the inclination pumping, or using π-transfers. However, π-transfers only exists at very low perijove [4], while including Ganymede gravity assist has proved not sufficiently effective for the following reasons.

First, Ganymede gravity assists tend to increase the radiation dose. Callisto-only solutions absorb very little radiation, because at Callisto the radiation dose rate is negligible. As the spacecraft reduces the apojove energy and increases the inclination, the perijove will often be below Callisto's orbit but will also be outside the equatorial plane (with the equator crossing at Callisto distance).

[1] Although some 10 m/s per gravity assists must be added for trajectory correction.[19]

[2] The second closest approach is at a lower distance then r_{pPRM} as an effect of the second gravity assist.

Second, Ganymede gravity assists make the solution much less robust to non-equatorial arrival v_∞ at Jupiter. In fact solutions using Callisto and Ganymede must lie on Jupiter equator to allow inter-moon transfers. Because only two or three gravity assists at Ganymede can be used before the v_∞ at Callisto (hence the i_{max}) becomes too low, only very small out-of-plane components of the velocity can be corrected ballistically.

Third, a Callisto-only solution repeats every synodic period of Callisto (~two weeks) and can be easily modified anytime, because it does not rely on the relative phasing between the moons. The scientist can then choose the best epoch for synergistic measurements with JEO and JGO, even after the nominal trajectory of these spacecraft are re-defined.

For these reasons, we adopt the Callisto-only strategy and compute trajectories that reach $i \geq 30°$ and $r_a \leq 40\ R_J$ in less than two years, and reach the $6:7$ orbit in less than three years. The minimum altitude for the gravity assists is now 100 km, because the orbit determination data collected during the capture phase will reduce the uncertainties on the moon ephemerides [19]. With these assumptions, we loop through a set of r_{pPRM} and use the algorithm explained in [9] to explore the solution space. Having fixed r_{pJOI}, the choice of r_{pPRM} also determines the total Δv as shown in Table 2 . The algorithm computes hundred thousands feasible solutions in a few hours.

The Pareto-front is plotted in Fig. 11, where the different performance indeces are compared by alternatively plotting one against the other (as done in [22]). The minimum radiation dose is ~2 krad, which is the dose accumulated in the capture phase. The markers represent different r_{pPRM} .

The graph on the top-left plots the radiation dose against the final inclination. High inclination is achieved with a high v_∞ at Callisto, i.e. with a low r_{pPRM} (i.e. a small Δv_{PRM}) that exposes the spacecraft to high radiation.

The graph on the top-right plots the radiation dose against the time of flight from JOI. For a fixed r_{pPRM}, a decrease of radiation dose results in longer transfer time. In fact, a lower exposure to radiation is possible if the inclination pumping starts when the apojove is still high (increasing the perijove and the latitude to the equator, see Fig. 3), and the transfer time increases accordingly.

Finally the graph on the bottom-right provides important information about the solution space of JMO. In fact it shows that an increase of 5° on the final inclination costs 3 additional months of transfer time, but saves around 50 m/s in Δv because r_{pPRM} is reduced by 2 R_J.

5 Baselines

This section presents the details of the two solutions circled in the Pareto front of Fig.11.

Option A is a long-transfer time, low-Δv, and high-inclination solution. The spacecraft completes Phase II in less than 2 years, reaching more than 45° in inclination. The extended mission further increases the inclination to 55° with some additional 6 months. The trajectory in the rotating frame (projected on the equator) was shown in Fig. 7 and Fig. 10. The trajectory in the inertial reference frame is shown in Fig. 12.

Option B is a fast, high-Δv, and low-inclination solution, where the nominal Phase II conditions are met in around one year, while the extended mission reaches 35° and is completed in less than 1.5 years. Because of the higher r_{pPRM} than in option A, the Δv increases of 150 m/s, and the v_∞ at Callisto decreases of 2 km/s less, and the final inclination is also reduced (from Eq 3) . Details of the trajectory are presented in Fig. 13 and Fig. 14.

Figure 15 shows the inclination history for both options. Thick lines represent legs of the transfer below 40 R_J. Tables 3 and 4 shows the time and altitude of the gravity assists, and the resonance ratio following each. Because only Callisto gravity assists are used, similar solutions exists every synodic period of Callisto. The table shows that only the second and the last gravity assists occurs at altitude higher than the minimum. In fact, the orbit following the second gravity assist is constrained to be on the equatorial plane, while the last gravity assist is used to jump to a 6:7 orbits. In the rest of the trajectory, however, every gravity assist can change the inclination or the apojove or a combination of both, while bringing the spacecraft to the next resonance. In such cases the most efficient sequence always include minimum-altitude gravity assists only [9].

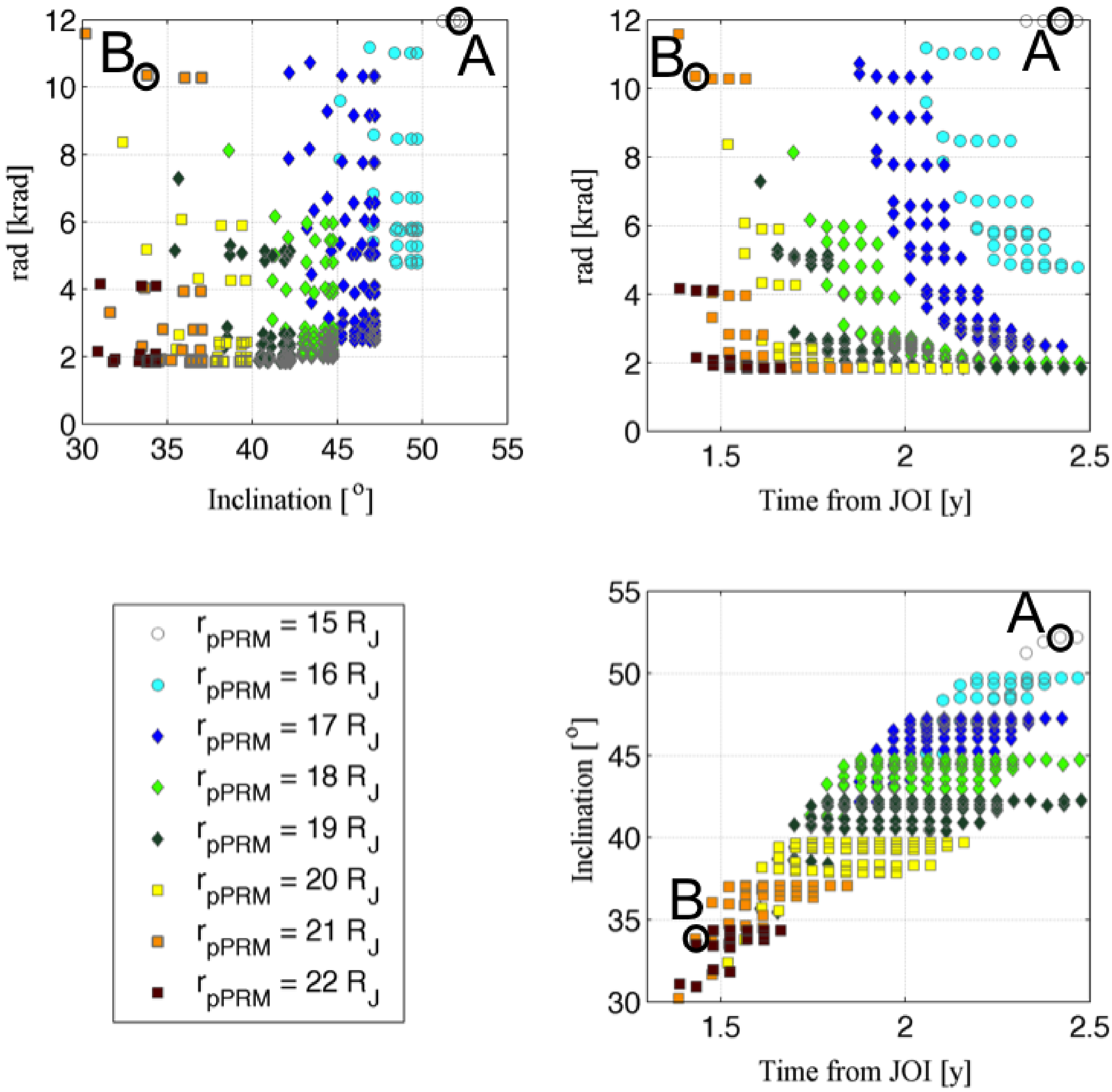

Figure 11: Pareto front for the JMO trajectory design problem in the Jovian system.

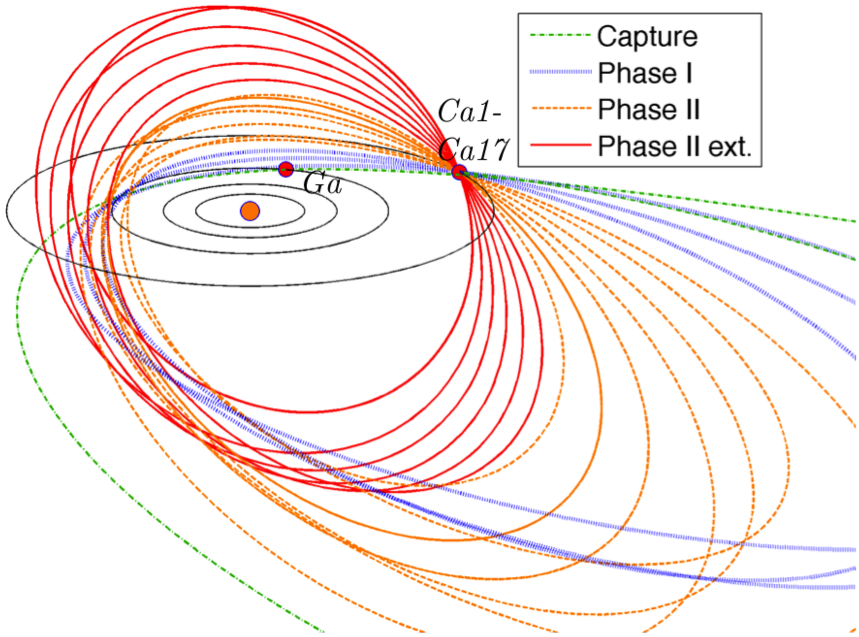

Figure 12: Solution A in an inertial reference frame.

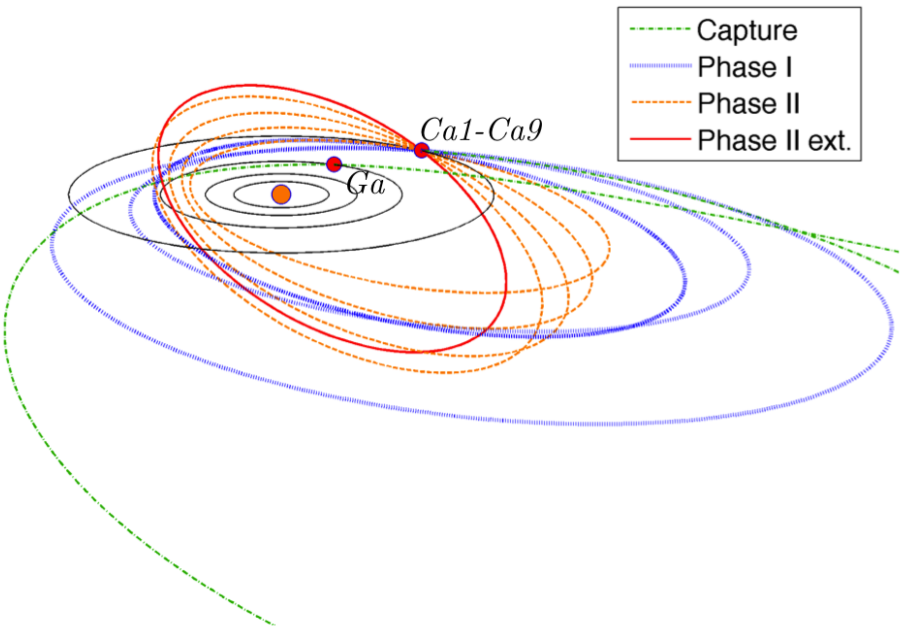

Figure 13: Solution B in the inertial frame.

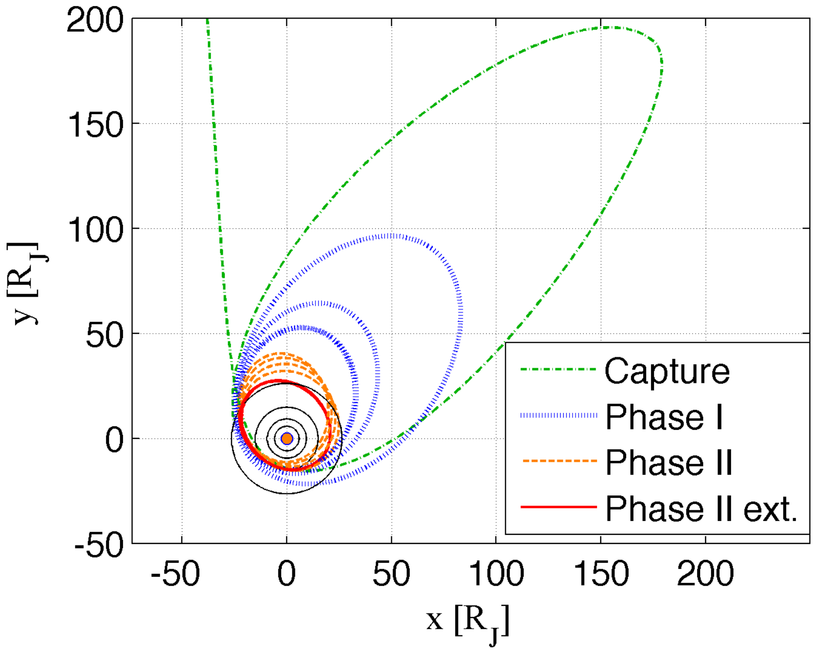

Figure 14: Option B in the rotating frame

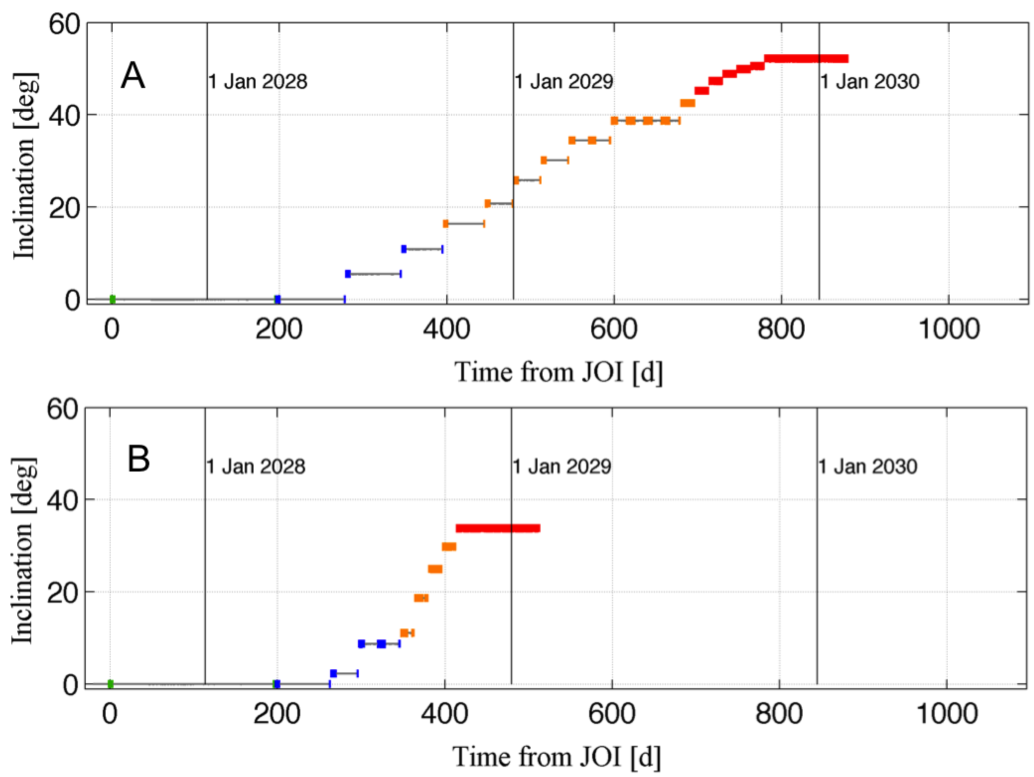

Figure 15: Inclination history for option A (top) and B (bottom).

Moon	G.A. epoch	v_∞ [km/s]	altitude [km]	Next res.
Ga	08 Sep 2027	7.476	500	12:1
Ca 1	22 Mar 2028	7.028	764.8	5:1
Ca 2	13 Jun 2028	7.028	100	4:1
Ca 3	19 Aug 2028	7.028	100	3:1
Ca 4	08 Oct 2028	7.028	100	3:1
Ca 5	27 Nov 2028	7.028	100	2:1
Ca 6	30 Dec 2028	7.028	100	2:1
Ca 7	02 Feb 2029	7.028	100	2:1
Ca 8	07 Mar 2029	7.028	100	3:2
Ca 9	26 Apr 2029	7.028	100	5:4
Ca 10	19 Jul 2029	7.028	100	1:1
Ca 11	04 Aug 2029	7.028	100	1:1
Ca 12	21 Aug 2029	7.028	100	1:1
Ca 13	07 Sep 2029	7.028	100	1:1
Ca 14	23 Sep 2029	7.028	100	1:1
Ca 15	10 Oct 2029	7.028	100	1:1
Ca 16	27 Oct 2029	7.028	100	6:7
Ca 17	04 Feb 2030	7.028	-	-

Table 3: Summary of gravity assists and following resonances for option A.

Moon	G.A. epoch	v_∞ [km/s]	altitude [km]	Next res.
Ga	08 Sep 2027	7.476	500	12:1
Ca 1	23 Mar 2028	5.085	500.2	4:1
Ca 2	29 May 2028	5.085	100	2:1
Ca 3	01 Jul 2028	5.085	100	3:2
Ca 4	20 Aug 2028	5.085	100	1:1
Ca 5	06 Sep 2028	5.085	100	1:1
Ca 6	23 Sep 2028	5.085	100	1:1
Ca 7	09 Oct 2028	5.085	100	1:1
Ca 8	26 Oct 2028	5.085	100	6:7
Ca 9	03 Feb 2029	5.085	-	-

Table 4: Summary of gravity assists and following resonances for option B.

6 Conclusions

This paper discusses the solution space of trajectories in the Jovian system for the Jupiter Magnetospheric Orbiter. For typical arrival conditions at Jupiter, the best strategy for capture consists of a Ganymede gravity assist followed by the JOI maneuver at the first perijove at 13 R_J. This strategy is a good compromise between transfer time, radiation dose and Δv, and is robust toward changes of arrival v_∞. For the rest of the mission, a strategy consisting of resonant orbits and gravity assist at Callisto provides a large number solutions that satisfy all the requirements and that repeats every Callisto period (an important feature to allow synergistic investigation with JEO and JGO) . Hundred thousands of low-radiation trajectories are evaluated with four performance indexes: the total Δv, the total transfer time, the final inclination, and the total radiation dose. The Pareto-front is the main result of this work, and shows the possible trade-offs between these conflicting objectives.

7 Aknowledgement

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