PRELIMINARY ORBIT DESIGN OF JUPITER SYSTEM TOUR FOR JOVIAN MAGNETOSPHERIC SCIENCE MISSION

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Abstract

The Jupiter system tour for Jovian orbiter is discussed. The orbiter for a magnetospheric observation mission in Jupiter system requires a wide passage area to be swept on the equatorial plane. In this paper, the efficient orbital transfer to establish such magnetospheric mission orbits is designed, using the Jovian moons multiple swing-by technique. In general, the highly efficient swing-by uses inner moons. But in such orbits, the spacecraft is exposed to the strong radiation environment of Jovian system. The Jupiter system tour which relieves the effect of the radiation is also mentioned in this paper.

木星磁気圏探査ミッションのための木星系ツアー軌道設計

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摘要

木星系ツアーのための軌道設計について考察する. 木星磁気圏を探査するミッションを想定した場合, オービターは赤道面上の幅広い領域を通過することを要求される. 木星周回軌道を確立するためには木星衛星群を利用したスイングバイは欠かせないが, ここでは効率よく磁気圏観測のための観測軌道を確立する軌道計画について考察する. 特に, 軌道変更の観点からは効率のよい内側の衛星を利用したスイングバイ軌道では, 木星の強い放射線帯の影響を強く受けるため, 放射線の影響を出来るだけ小さくする木星系ツアー計画について言及する.

1. Introduction

The multiple swing-by trajectory in Jupiter system is investigated. It is denoted as “Jupiter Tour” and was first performed by NASA in Galileo mission.

To establish the orbit around Jupiter with a practical orbital period, the Jupiter moons multiple flyby is absolutely required, to keep the required deterministic delta-V (i.e. amount of fuel) to the practical amount.

The analyses in this paper have been done for the preliminary design of the Jupiter Magnetospheric Orbiter (JMO), which is a part of what is proposed as the JAXA/ESA joint mission toward Jupiter in the Cosmic Vision framework.

This paper focuses on flyby with two large Galilean satellites, Ganymede and Callisto, and designs the orbital sequence to establish the required Jupiter orbiting conditions required by JMO.

In general, the highly efficient swing-by uses inner moons. But in such orbits, the spacecraft is exposed to the strong radiation environment of Jovian system. The strategy to relieve the effect of radiation is taken into account in the orbital sequence design. Also the plane change transfer without using deterministic delta-V is discussed.

2. Basic Properties of Multiple Swing-by Trajectory

2.1. Basic Consideration of Jovian Moons Swing-by

Table 1 provides a summary of important physical and orbital data for each of the Galilean satellites. These satellites are all in near-ecliptic orbits, and the inner three satellites' orbital periods are locked in 1:2:4 resonance. There are more than 12 additional satellites, all of which are much smaller than the Galilean satellites. Because these satellites have very low masses, their gravitational influence on the spacecraft's trajectory is negligible. These smaller satellites are, therefore, not used for orbit transfers.

Table 1: Galilean Satellite Physical and Orbital Data [1]

Satellite	GM, $km^3 s^{-2}$	Radius, km	Orbital radius		Eccentricity	Inclination, deg	Period, days
			10^3 km	R_J			
Io	5934	1815	422.2	5.91	0.003	0.037	1.769
Europa	3196	1569	671.4	9.40	0.009	0.418	3.551
Ganymede	9885	2631	1071.1	15.00	0.001	0.254	7.155
Callisto	7172	2400	1883.4	26.38	0.008	0.163	16.689

Notes:
GM = Newton's gravitational constant times satellite mass.
1 R_J = 1 Jupiter radius = 71 492 km.

Ganymede, the most massive satellite, is effective for changing orbital period and inclination. It is particularly effective at accomplishing large reductions in orbital period.

Callisto, the outermost Galilean satellite, is less massive than Ganymede and orbits at a greater distance from Jupiter. Therefore, Callisto is less effective than Ganymede in changing orbital period. However, because Callisto orbits further from Jupiter than Ganymede, a given period change at Callisto results in a greater change in perijove distance and a greater apsidal rotation than at Ganymede. Also, the smaller radiation effect is expected than Ganymede flyby. Although not as massive as Ganymede, it can be more effective in changing inclination because the Orbiter's velocity is lower at the greater distance from Jupiter at which Callisto is encountered.

Europa, the least massive of the Galilean satellites, is least effective in changing orbital period and inclination. Since the Orbiter's perijove cannot be much closer to Jupiter than the distance at which Europa orbits due to radiation considerations, targeted flybys with Europa must occur close to perijove. Therefore, the amount of change in perijove distance and rotation of the line of apsides caused by energy changes at Europa is small.

Consequently, in this paper, the resonance orbits of Ganymede and Callisto are synthesized. The patched-conics analysis is performed, in which the orbits are connected one by the next by satisfying the swing-by conditions at Ganymede and Callisto.

2.2. Parameters Change Before and After Swing-by

The multiple swing-by technique uses the orbits which have the integer ratio of that of a Jovian moon. In this paper, such resonance orbits are utilized. The spacecraft is supposed to transfer from one resonance orbit to another, satisfying swing-by conditions.

Flybys that change the orbital period also rotate the line of apsides and change the perijove distance. For a given orbital period change, a flyby that occurs far from the spacecraft's perijove rotates the line of apsides and changes perijove distance more than a flyby occurring close to perijove. A flyby occurring exactly at perijove changes orbital period with minimal changes to the line of apsides and perijove distance. The direction in which the line of apsides is rotated depends on whether the orbital period is increased or decreased and whether the satellite flyby occurs before perijove (“inbound”) or after perijove (“outbound”). The inbound flyby rotates the apsides counter-clockwise for energy reducing flyby, while the outbound flyby rotates the apsides clockwise for energy reducing flyby. These characteristics can be used to control the shape and the direction of the spacecraft’s orbit without using the active orbit transfer maneuver using RCS.

Consider hereafter the coplanar energy reducing orbit transfer. Denoting orbital energy, angular momentum, velocity, radius, gravity constant and inplane flight path angle as E,h,v,r,μ,β, then the following relations are satisfied;

$$E = \frac{1}{2}v^2 - \frac{\mu}{r} \quad (1)$$

$$h = rv\sin\beta \quad (2)$$

$$e=\sqrt{1+\frac{2Eh^2}{\mu^2}}=\sqrt{1+\frac{r^2\sin^2\beta}{\mu^2}\left(v^2-\frac{2\mu}{r}\right)v^2} \quad (3)$$

Suppose the change in the inplane flight path angle at flyby with reference to the central body (Jupiter) is very small. This assumption is valid when the orbit energy is sufficiently high compared with that of the moon to be used for swing-by. Then the change in the eccentricity can be written as follows;

$$\delta e=\frac{4v}{e}\left[\frac{r^2\sin^2\beta}{\mu}\left(\frac{1}{r}-\frac{1}{a}\right)\right]\delta v \quad (4)$$

where a is the semimajor axis. Because the flyby occurs at the perijove side, r<a can be assumed. Therefore,

$$\delta v<0 \Leftrightarrow \delta e<0 \quad (5)$$

is satisfied.

Also from the relation;

$$\tan\beta=\frac{1+e\cos\theta}{e\sin\theta} \quad (6)$$

(θ :true anomaly) the following derivative can be performed;

$$\delta(\tan\beta)=-\frac{1}{e^2\cos\theta}\delta e-\frac{\sin\theta}{e\cos^2\theta}\delta\theta \quad (7)$$

Then,

$$\delta\beta=0 \Rightarrow \delta e=-e\tan\theta\delta\theta \quad (8)$$

which leads to the following relations;

$$\begin{cases}\theta>0; & \delta\theta>0\\ \theta<0; & \delta\theta<0\end{cases} \quad (9)$$

The inequations (9) support the aforementioned relations; the inbound flyby rotates the apsides counter-clockwise, and the outbound flyby rotates the apsides clockwise.

From the relation between perijove radius r_p and e,. θ and from equation (9),

$$\delta r_p=\frac{-1+\cos\theta}{(1+e)^2}\delta e-\frac{e\sin\theta}{1+e}\delta\theta=\frac{-1+(2+e)\cos\theta}{(1+e)^2}\delta e \quad (10)$$

is obtained. (10) implies that the any flybys performed at -60<θ<60deg reduces the perijove radius, which is the general case of the Galilean satellites high energy flybys.

In summary, it can be said that the energy reducing high-energy flybys

- always reduce the eccentricity (from eq (5))
- rotate the apsides (from eq.(9))
- always reduce the perijove radius (from eq.(10))

3. Jupiter Tour Trajectory Design

3.1. Ganymede Swing-by Trajectory

The patched-conics analyses are performed to obtain the multiple swing-by trajectories. The initial orbit must be a resonance orbit with the moon to be used for the first swing-by. Therefore, at Jupiter orbit insertion (JOI) from the interplanetary orbit, the spacecraft is assumed to be inserted to the 1:50 Ganymede resonance orbit or 1:22 Callisto resonance orbit, both of which have the orbital periods of about 360 days.

The requirements for the final (mission) orbit of JMO are as follows;

- Perijove is 15 Rj (1Rj=71492km). The time to stay within 13 Rj distant from Jupiter should be short to avoid the severe radiation environment.
- Apojove is around 50 to 80 Rj.
- The orbital plane is near ecliptic, and can be slightly inclined to avoid long eclipse if needed.

This subsection exclusively uses Ganymede for orbit transfer. In this preliminary study, the following conditions are imposed to obtain the Jupiter tour trajectory.

- The initial orbit is 1:50 Ganymede resonance orbit with 13 Rj perijove, and the orbital plane aligns with the ecliptic plane.
- The epoch for the first swing-by is MJD=58849.
- The final orbit is 1:3 Ganymede resonance orbit.
- The total flight time from JOI to the final swing-by must be less than 800days.
- The minimum swing-by altitude limitation is 500km.
- Only the orbital sequences which require no deterministic delta-V is considered.

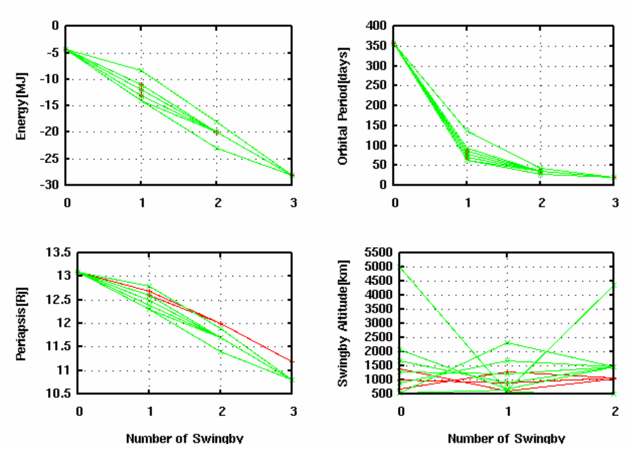


Figure 2: Orbit Properties Changes in Ganymede Multiple Swing-by

(The horizontal axis is the number of swing-by for the right bottom figure, and the number of orbital node for other three figures)

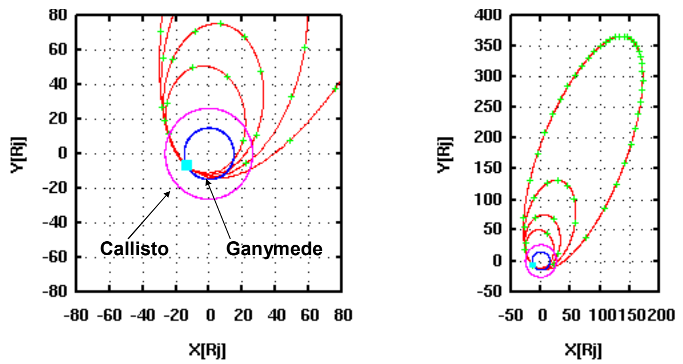


Figure 1: Example of Ganymede Multiple Swing-by Trajectory (G50-G11-G05-G03)

All the possible orbital sequences are searched and consequently, 10 solutions are obtained (Table 2), which are all composed of 5 orbit nodes (i.e. 3 swing-bys). In Table 2, G50-G12-G05-G03 means that each orbit is Ganymede-resonant with the resonance ratio of 50, 12, 5 and 3. The character '-' means inbound flyby, while '+' means outbound flyby. The example trajectory is shown for the orbit sequence (2) (G50-G11-G05-G03) in Figure 1.

Figure 2 provides the orbit properties changes as results of swing-bys. The orbital energy and the period smoothly decreases at one swing-by to anther, and at the same time, the perijove distance decreases monotonically as is suggested by equation (10).

To effectively take advantage of Ganymede gravity, the initial perijove of the spacecraft is sufficiently small than the 15 Rj Jupiter to Ganymede distance.

Table 2: Orbit Sequence of Ganymede Multiple Swing-bys

No.	Orbital Sequence	Flight Time [day]
(1)	G50-G12-G05-G03	500.8
(2)	G50-G11-G05-G03	493.7
(3)	G50-G10-G05-G03	486.5
(4)	G50+G19+G06+G03	558.1
(5)	G50+G13+G05+G03	508.0
(6)	G50+G12+G05+G03	500.8
(7)	G50+G11+G05+G03	493.7
(8)	G50+G10+G05+G03	486.5
(9)	G50+G09+G05+G03	479.4
(10)	G50+G09+G04+G03	479.2

The 13 Rj initial perijove in this analysis is selected by this reason, and that makes it inevitable for the spacecraft to fly with the considerably low perijove during the Jupiter tour.

3.2. Callisto Swing-by Trajectory

The same analysis is performed for Callisto swing-by case.

Figure 3 provides the result analyzed with the following conditions;

- The initial orbit is 1:22 Callisto resonance orbit with 13 Rj perijove, and the orbital plane aligns with the ecliptic plane.
- The final orbit is 1:2 Callisto resonance orbit.

The other conditions are the same as section 3.1.

The resulting sequences require 4 Callisto-flyby, and the flight time ranges from 630 to 750 days, which is longer than the Ganymede siwng-by cases.

Because Callisto is further than Ganymede from Jupiter, the true anomaly at which the swing-by occurs is larger for Callisto swing-by. It leads to the larger perijove variation at each swing-by, and consequently, the final perijove is even worse (around 7 Rj) compared with the Ganymede swing-by case.

The merit of using Callisto for swing-by can be brought out by choosing larger initial perijove. Figure 5 shows the results of Callisto swing-by sequences with the initial perijove set to be 23 Rj. In this case, the flight time ranges from 530 to 690 days, and the final orbit perjove is 18 Rj, which is sufficiently high as long as the radiation effect is concerned.

If one wants to establish the perijove of 23 Rj from

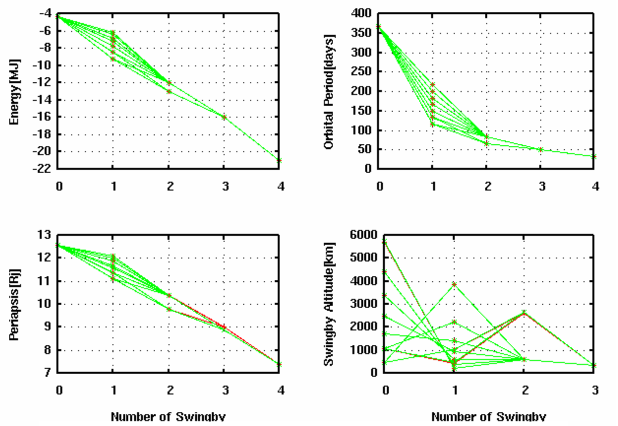


Figure 3: Orbit Properties Changes in Callisto Multiple Swing-by (R_p=13Rj)

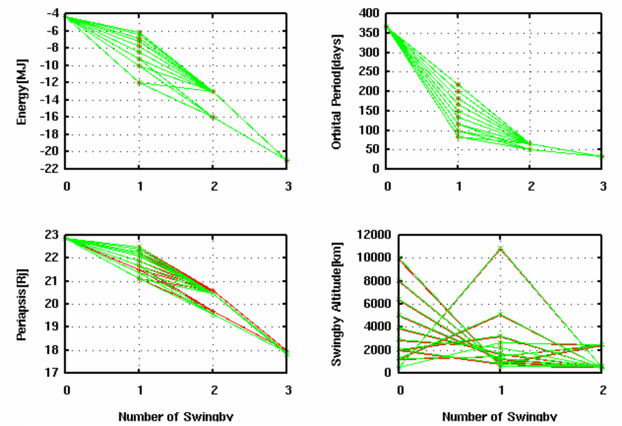


Figure 5: Orbit Properties Changes in Callisto Multiple Swing-by (R_p=23Rj)

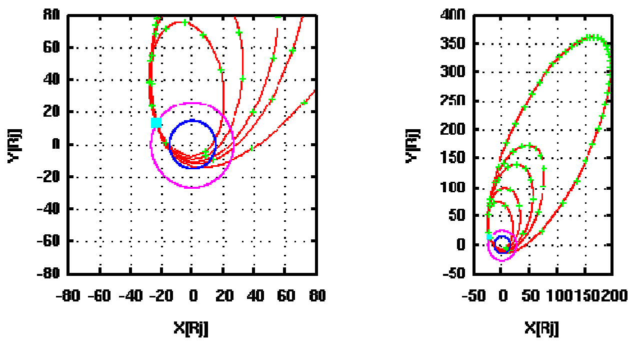


Figure 4: Example Trajectory for Callisto Multiple Swing-by (R_p=13Rj) (C22-C07-C05-C03-C02)

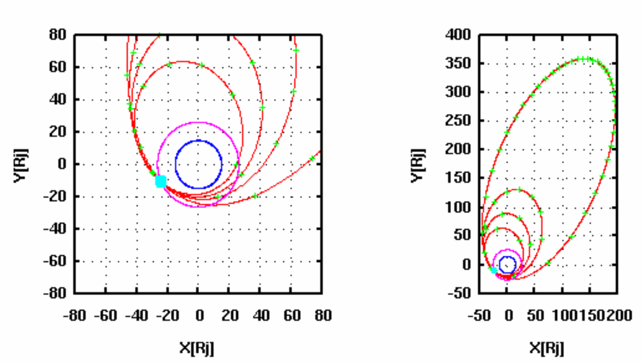


Figure 6: Example Trajectory for Callisto Multiple Swing-by (R_p=23Rj) (C22-C05-C03-C02)

13 Rj perijove orbit after JOI, 200m/s delta-V apojove maneuver is required.

3.3. Ganymede/Callisto Swing-by Trajectory

The Ganymede and Callisto combined flyby sequence is investigated. The solution for this case is much sensitive to the initial time, because it depends on the relative phase around Jupiter between Ganymede and Callisto, so the analysis was done with a particular initial time. Also it should be noted that the first priority of this case is the timing to accomplish flybys, so that the orbital energy may be increased after flybys.

The conditions for analysis are as follows;

- The initial orbit is 1:50 Ganymede resonance orbit with 13 Rj perijove, and the orbital plane aligns with the ecliptic plane.
- The final orbit is 1:2 Callisto resonance orbit.
- One transfer from Ganymede resonance orbit to Callisto resonance orbit is allowed.

The other conditions are the same as section 3.1.

Figure 7 shows the result of Ganymde/Callisto swing-by case. The number of swing-by in this case is 5, and the flight time ranges from 530 to 640 days. Even though the initial perijove is set to be 13 Rj, several solutions with larger than 13 Rj perijove are obtained.

4. Plane Change Strategy in Jupiter System

The ecliptic plane orbit generally has a long eclipse time, and it is undesirable because it makes the design of spacecraft system and mission operation more complicated.

Figure 9 provides the basic characteristics of the eclipse of the ecliptic plane orbit. The apojove eclipse does not have to be taken into account, because practically it cannot occur when considering the JOI direction condition. The other cases can occur during Jupiter tour. This is inevitable because the Jupiter's moon multiple swing-by impose the spacecraft's orbital plane to be aligned to the ecliptic plane (Galilean satellites' orbital plane).

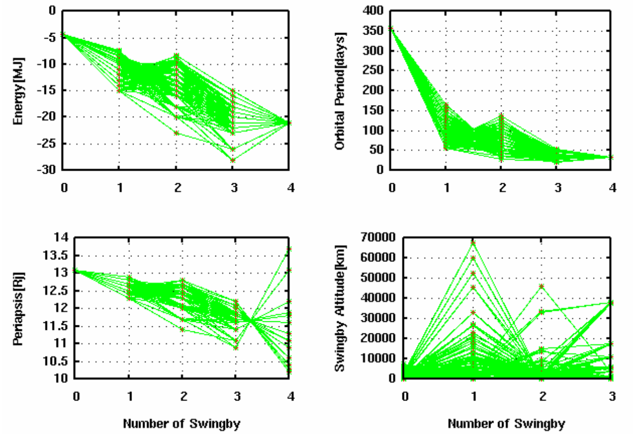
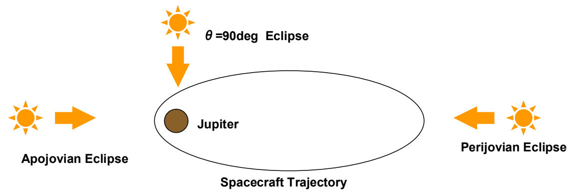


Figure 7: Orbit Properties Changes in Ganymede/Callisto Multiple Swing-by



Orbit	Perijovian Eclipse	θ =90deg Eclipse	Apojovian Eclipse	Orbital Period
5RJ x 300RJ	1.5hr	2.9hr	—— (very long)	232.6days
12.7RJ x 27RJ	2.9hr	3.9hr	6.1hr	10.9days
15RJ x 27RJ	3.2hr	4.2hr	5.8hr	11.9days
15RJ x 50RJ	3.0hr	4.5hr	(9.8hr)	22.9days

Figure 9: Basic Eclipse Characteristics of Ecliptic Plane Orbit around Jupiter

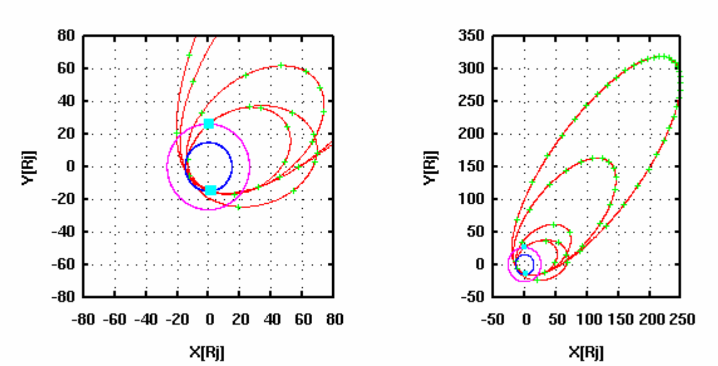


Figure 8: Example Trajectory for Ganymede/Callisto Multiple Swing-by (G50+G20+G06+C-C02)

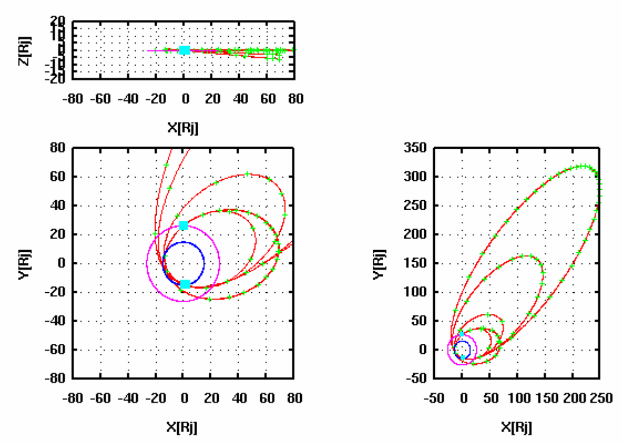


Figure 10: Example Jupiter Tour with 5 deg Inclination Final Orbit (G50+G20+G06+C-C02-C02-C02)

After the Jupiter tour ends, on the other hand, the orbital plane of JMO is free to be chosen. A small inclination can reduce the eclipse time drastically. (Even 0 eclipse time is possible)

The swing-by to change the orbit plane can be done with one selected Jupiter moon. As mentioned in section 2.1., Callisto is preferable for this objective. On the contrary with energy reducing swing-by, the inclination change swing-by requires the spacecraft to pass the polar region of Callisto.

The example trajectory is shown in Figure 10. The two additional swing-bys are added to the example trajectory provided in Figure 8. As a result of these additional two swing-bys, 5 degree inclination is established. Because the ascending and descending nodes of the finally established orbit are sufficiently far from the Sun direction, in this case, the eclipse time for the final orbit is accomplished to be zero.

5. Conclusion

The multiple swing-by trajectory in Jupiter system was investigated.

This paper focused on flyby with two large Galilean satellites, Ganymede and Callisto, and designed the orbital sequence to establish the required Jupiter orbiting conditions required by Jupiter Magnetsphric Orbiter (JMO), which had been proposed as the JAXA/ESA joint mission in Cosmic Vision framework.

The major results obtained in this study are listed as follows;

- Ganymede multiple swing-by can establish the final objective apojove of 50 to 70 Rj, but the final perijove is lower than required, which makes the spacecraft to be exposed in the severer radiation environment.
- Callisto multiple swing-by with the same initial orbit conditions is inadvisable, because it results in even lower perijove than Ganymede swing-by trajectories.

- Callisto multiple swingby can establish the final objective apojove and perijove, when the initial orbit perijove after JOI is tuned to be as high as around 23 Rj.
- Ganymede and Callisto combined multiple swing-by broadens the possible orbital sequence solutions, although it is more dependent on the JOI epoch.
- Additional a few Callisto swing-bys sufficiently provide the inclination change to reduce the eclipse time.

Reference

[1] Louis A. D'amario, Larry E. Bright and Aron A. Wolf, "Galileo Trajectory Design", Space Science Reviews, vol. 60, no. 1-4, May 1992, pp. 23-78.