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Conceptual Analysis of Japan's Jovian System Exploration: Interplanetary Orbits and Aeroassistance in the Jovian Atmosphere*

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The Galileo spacecraft exploration has shown a probability that Europa has a large amount of water under its icy surface, as well as that some kinds of life may be present on Europa. In the present study, feasibility analysis for Japan's Europa exploration is carried out in terms of interplanetary and Jupiter atmospheric flight trajectories. First, three types of interplanetary trajectories from the Earth to Jupiter, i.e. direct, Mars gravity-assisted, and Venus-Earth gravity-assisted, are calculated and the case of the minimum Jovian insertion energy, i.e. the maximum deliverable mass, is selected in each type of the trajectories. Second, flight trajectories in the Jovian atmosphere for decelerating and deploying spacecraft to Europa are calculated and the required mass of the ablator is evaluated. It is clearly shown that aerobraking is much more advantageous for enhancement of deliverable mass than applying chemical propulsion alone, and that the combination of H-IIA Augmented Launch Vehicle, gravity assists, and aerobraking will enable Europa biological explorations.

Key Words: Planetary Exploration, Feasibility Analysis, Orbital Design, Aeroassistance, Europa

Nomenclature

c_{abl}: specific heat of the ablator
C_{D}: drag coefficient
$\vec{F}_{\mathrm{g\_Sun}}$: gravitational force given by the Sun (vector)
$\vec{F}_{\mathrm{g\_planet}}$: gravitational force given by a planet (vector)
$\vec{F}_{\mathrm{g\_Jupiter}}$: gravitational force given by Jupiter (vector)
$\vec{F}_{\mathrm{D}}$: drag force (vector)
g_0: standard gravitational acceleration
I_{sp}: specific impulse
m_{abl}: mass of the ablator
m_{f}: mass of the spacecraft after retrofiring
m_{i}: mass of the spacecraft before retrofiring
m_{s}: mass of the spacecraft
$\dot{q}$: aerodynamic heating rate on the unit surface
$\vec{r}_{\mathrm{s}}$: position of the spacecraft (vector)
r_0: nose radius of the spacecraft
R_{J}: radius of Jupiter
S: projected area of the spacecraft
s_{abl}: thickness of the ablator
t: time
$\vec{u}$: spacecraft's velocity relative to the atmosphere (vector)
V_{e}: effective exhaust velocity
α: safety factor for ablator thickness estimation
Δm: required propellant mass
ΔV: velocity increment
ρ: density of the atmosphere
ρ_{abl}: density of the ablator
θ: angle measured along the nose surface from the stagnation point
π: the ratio of the circumference of a circle to its diameter

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1. Introduction

From the reports of NASA's Galileo Prime Mission and Galileo Europa Mission, it has been predicted that Europa has a large amount of liquid water under its icy surface as illustrated in Fig. 1.[1] Future explorations focusing on Europa are being planned by JPL. One of them is the Europa Orbiter Project whose image is illustrated in Fig. 2. In this project, investigation on the presence of water, mapping of the whole surface of Europa, etc. are to be carried out.[2]

Additionally, there is a hypothesis that Europa may have some kinds of life in its ocean, because liquid water is essential to the creation of life. Although it is far from the Sun and the amount of solar energy available is very small, it is predicted that some submarine volcanoes are supplying suffi-

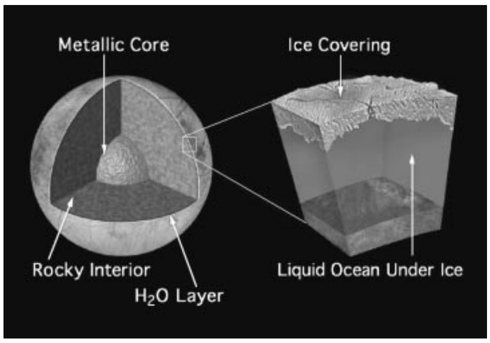

Fig. 1. An artistic of the Europa interior.[1]

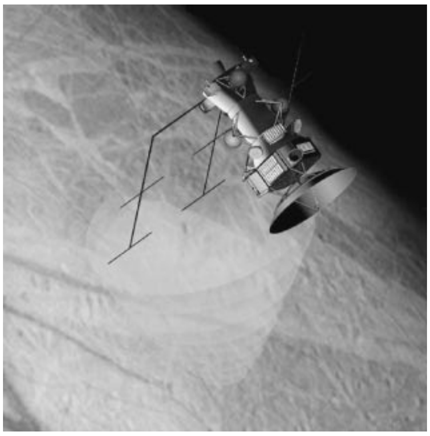

Fig. 2. An artistic of the Europa Orbiter.[2)]

Fig. 3. An artistic of the H-IIA Augmented Type.[4)]

cient geothermal energy to create life.[3)]

Exploration of life on Europa will give us the chance to discover biological life forms beyond Earth, and deepen our understanding of the origin of life.

In such a situation, the present study investigates the feasibility of the Jovian system exploration missions, especially focusing on the Europa exploration. A series of flight trajectories from the Earth to Jupiter are calculated and the deliverable mass is estimated. The feasibility and effectiveness of aeroassisted maneuvers are analyzed by calculation of flight trajectories through the Jovian atmosphere and by estimation of the mass of the thermal protection system. Overall feasibility of the missions is assessed by comparison between the estimated mass deliverable into the Jovian/Europa orbits and the assumed spacecraft mass required to the biological missions.

For such analysis, mission design tools for two-body orbital design, multi-body orbital design, and atmospheric flight calculation are constructed in the present study.

2. Assumptions for Mission Design

Mission requirements and conditions are assumed as follows:

1) The launch vehicle is the H-IIA Augmented Type (H2A212), in which a liquid rocket booster is added to the H-IIA Standard Type as shown in Fig. 3. It can carry a payload of 17,000 kg into a low Earth orbit at an altitude of 300 km.[4)]
2) The launched payload is injected once into the low Earth orbit at 300 km altitude. Thus the maximum payload mass on the orbit is 17,000 kg, as is determined from the above launch vehicle's performance. It consists of a spacecraft and an upper stage motor.
3) The spacecraft escapes from the Earth's gravitational field using the upper stage motor.
4) For the upper stage motor, a combination of liquid oxygen and liquid hydrogen is selected as the propellant. Its specific impulse is 455 seconds. The ratios of its structural and propellant mass are 16% and 84%, respectively. It is jettisoned immediately after the injection into a hyperbolic departure orbit.
5) Launch days between 2008 and 2030 are selected.
6) For scientific missions, a Europa biological exploration with a lander and Jovian atmospheric observation with multi-probes are the objectives.
7) For an engineering mission, a flight demonstration in the Jovian atmosphere with aerocapture or aerobraking is the objective.
8) The spacecraft consists of an orbiter, a few probes, and a biological observation lander. Their masses are assumed as listed in Table 1. The orbiter mass including scientific instruments ranges from 800 to 1,200 kg in accordance with the types of the exploration. The probes are assumed to be about 340 kg including scientific instruments and a thermal protection system, and to be separated before the closest approach to Jupiter, similar to the Galileo probe. The mass of the lander is assumed to be about 750 kg including scientific instruments and propellants for landing, on the basis of the Viking Mars Lander. The total mass to be injected into a Jovian/Europa orbit is 1,550–1,950 kg. These values will be used not as conditions given for flight calculations, but as criteria for feasibility assessment through comparison with the estimated mass deliverable into the Jovian/Europa orbits.
9) Propellants of the spacecraft propulsion system are nitrogen tetroxide (NTO) and hydrazine (N_2H_4).
10) The following three types of interplanetary trajectories are assumed:
   a) Direct trajectories on which the spacecraft flies from the Earth directly to Jupiter without any plane changes. These are, in other words, 2-impulse ballistic trajectories.
   b) Mars Gravity-Assisted trajectories (MGA) on which a

Table 1. The assumption for the spacecraft mass.

Module	Mass (kg)	
Orbiter	800–1,200	Injected into the Jovian/Europa orbit.
Probes	340	Separated before the Jovian C/A.
Lander	750	Injected into the Jovian/Europa orbit.
Total	1,890–2,290	

Mars swing-by is carried out in order to reduce the required departure energy. The periapsis altitude at the swing-by is assumed to be 2,000 km.

c) Venus-Earth Gravity-Assisted trajectories (VEGA) on which both a Venus and an Earth swing-by are carried out in order to reduce the required departure energy. The periapsis altitudes at the Venus and the Earth swing-by are assumed to be 2,000 km and 1,000 km, respectively.

11) The following two ways of injection into orbits around Jupiter are assumed:

a) Retrofiring of the spacecraft propulsion system. In this case, it is assumed that the spacecraft is injected to an elliptic orbit of a periapsis altitude of 300,000 km (about $4R_J$) and an apoapsis altitude of 15,000,000 km (about $210R_J$). The mass of the spacecraft after the injection, m_f, is evaluated by Tsiolkovskii's formula

$$\Delta V = V_e \ln\left(\frac{m_i}{m_f}\right) \tag{1}$$

$$\Delta m = m_i - m_f \tag{2}$$

where m_i and Δm are the mass of the spacecraft before the retrofiring, and of propellants, respectively. ΔV is the velocity increment required for the injection, and V_e is the characteristic exhaust speed, i.e. the product of the specific impulse and the standard gravitational acceleration, $I_{sp}\, g_0$. Here I_{sp} is 344 seconds, in accordance with the selection of propellants.

b) Aeroassisted maneuvering, that is, aerocapture or aerobraking. In this case, the drag force is used for deceleration of the spacecraft. Ablation cooling is assumed for the thermal protection against aerodynamic heating during the hypersonic atmospheric flights.

3. Construction of Analysis Tools

The following three numerical tools are constructed in the present study:

1) A calculation tool for two-body interplanetary orbits: Orbital calculation is carried out as a two-body problem using the patched conic approximation and Lambert's theorem. This tool is applied to initial designs for the interplanetary trajectories.

2) A calculation tool for multi-body interplanetary orbits: The spacecraft motion equation is solved directly by considering positions of the solar system planets. The equation is described by

$$m_s \frac{d^2\vec{r}_s}{dt^2} = \vec{F}_{g\_Sun} + \sum_{Mercury}^{Neptune} \vec{F}_{g\_planet} \tag{3}$$

where m_s and $\vec{r}_s$ are the mass and the position of the spacecraft, respectively. $\vec{F}_{g\_Sun}$ and $\vec{F}_{g\_planet}$ are the gravitational forces given to the spacecraft by the Sun and a planet, respectively. This equation is integrated by a six-step, fifth-order Runge-Kutta-Fehlberg formula with automatically adjusted time steps. In addition, VSOP (Variations Seculaires des Orbites Planetaires) of Bureau des Longitudes, France, is used for ephemeris calculation where orbital parameters of the planets are evaluated at an arbitrary time.[5)]

3) A calculation tool for atmospheric flights: Flight trajectories in the Jovian atmosphere and aerodynamic heating rates are solved. The spacecraft is considered as a symmetric body at a zero angle of attack and the aerodynamic force is the drag alone. Its three-degree-of-freedom motion is described by

$$m_s \frac{d^2\vec{r}_s}{dt^2} = \vec{F}_{g\_Jupiter} + \vec{F}_D \tag{4}$$

where m_s and $\vec{r}_s$ are the mass and the position of the spacecraft, respectively. $\vec{F}_{g\_Jupiter}$ is the gravitational force given by Jupiter to the spacecraft, and $\vec{F}_D$ is the aerodynamic drag evaluated by

$$\vec{F}_D = -\frac{1}{2}\rho|\vec{u}|\vec{u}C_D S. \tag{5}$$

The shape of the spacecraft is assumed to be a hemisphere with a radius of 0.648 meters. Then its projected area is $S = 1.32\,\mathrm{m}^2$ and its hypersonic drag coefficient is $C_D = 1.00$. Equation (4) is integrated using a six-step, fifth-order Runge-Kutta-Fehlberg formula with automatically adjusted time steps.

The nose temperature in the case without ablation is evaluated on the assumption of the equilibration of aerodynamic heating onto and radiation from the surface of the spacecraft. The aerodynamic heating rate can be evaluated using a semi-experimental formula for the Jovian atmosphere.[6)] Such a procedure requires temperature, density, and average molecular weight of the atmosphere data. Those acquired by the Galileo probe[7)] are used (see Fig. 4).

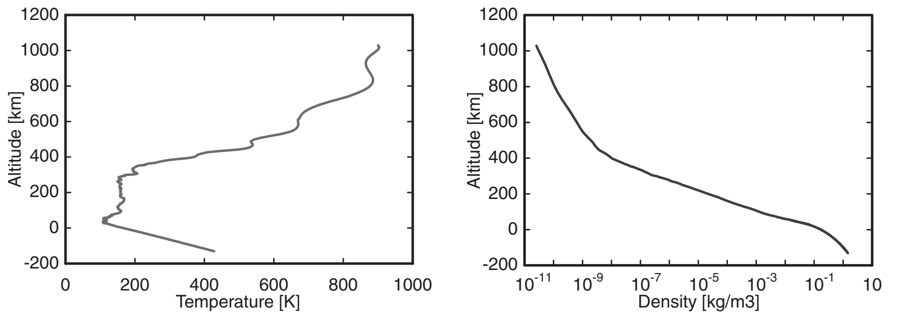

Fig. 4. The temperature and the density distribution in the Jovian atmosphere, measured by the Galileo probe.[7)]

Table 2. Parameters of direct trajectories from the Earth to Jupiter, with the minimum value of the departure C3.

Parameters	Case I-A	Case I-B	Case I-C	Case I-D	Case I-E
Given					
Date of departure from LEO	2007/02/14	2008/03/21	2009/04/27	2010/06/07	2011/07/11
Date of arrival at Jupiter	2009/03/30	2010/03/21	2011/04/16	2012/08/16	2013/12/02
Time of flight [days]	775.0	730.0	719.0	801.0	875.0
Mass on LEO [kg]	17,000	17,000	17,000	17,000	17,000
Predicted					
ΔV at departure from LEO [km/sec]	6.36	6.49	6.54	6.51	6.4
C3 at departure from LEO [km^2/sec^2]	78.9	82.7	84.4	83.3	80.2
Mass after the departure [kg]	1,641	1,496	1,436	1,476	1,591
Hyperbolic excess speed relative to Jupiter, $V_{\infty J}$ [km/sec]	6.86	7.12	6.99	6.12	5.72
ΔV at injection to the Jovian orbit [km/sec]	1.09	1.15	1.12	0.92	0.84
Propellants required for insertion into the Jovian orbit [kg]	358	333	308	272	277
Mass deliverable into the Jovian orbit [kg]	943	823	788	864	974

Table 3. Parameters of MGA trajectories from the Earth to Jupiter, with the minimum value of the departure C3.

Parameters	Case II-A	Case II-B	Case II-C
Given			
Date of departure from LEO	2009/10/25	2013/12/28	2016/04/06
Date of the Mars swing-by	2010/06/09	2014/07/24	2017/06/16
Date of arrival at Jupiter	2012/12/07	2026/09/12	2019/11/23
Time of flight [days]	1,139	4,641	1,326
Mass on LEO [kg]	17,000	17,000	17,000
Predicted			
ΔV at departure from LEO [km/sec]	3.91	3.60	5.61
C3 at departure from LEO [km^2/sec^2]	16.1	8.99	58.5
Mass after the departure [kg]	5,191	5,795	2,525
ΔV given by chemical propulsion during the Mars swing-by [km/sec]	7.46	1.91	0.00
Mass after the Mars swing-by [kg]	571	3,287	2,524
Hyperbolic excess speed relative to Jupiter, $V_{\infty J}$ [km/sec]	5.77	11.14	5.82
ΔV at injection to the Jovian orbit [km/sec]	0.85	2.35	0.86
Propellants required for insertion into the Jovian orbit [kg]	52	1,477	492
Mass deliverable into the Jovian orbit [kg]	179	1,470	1,692

In the case with ablation, the thickness of the ablator is estimated by the following equation:

$$s_{\mathrm{abl}} = \frac{\alpha}{\rho_{\mathrm{abl}} c_{\mathrm{abl}}} \int_{\text{flight time}} \dot{q}\,\mathrm{d}t \tag{6}$$

where $\dot{q}$ [J/m^{2}sec] is the aerodynamic heating rate on the unit area of the spacecraft surface, and ρ_{abl} and c_{abl} are the density and the specific heat of the ablator, respectively. An appropriate value for the safety factor α is about 2.0 according to the experience of the Jovian atmospheric entry of the Galileo probe. The ablator is assumed to be carbon-phenolic with $\rho_{\mathrm{abl}} = 1763.6\,\mathrm{kg/m^3}$ and $c_{\mathrm{abl}} = 30\,\mathrm{MJ/kg}$.[8] The total mass of the ablator on the hemispherical nose of the spacecraft with a radius r_0 is evaluated by

$$m_{\mathrm{abl}} = 4\pi r_0^2 \rho_{\mathrm{abl}} \int_{-\pi/2}^{\pi/2} s_{\mathrm{abl}} \cdot \sin\theta \mathrm{d}\theta. \tag{7}$$

4. Results for Interplanetary Trajectories

The dates of the departure, arrival, and swingbys if used, are specified as the initial conditions for calculation, by trial and error. An orbit with the minimum value of the departure C3 is selected for each departure date. The parameters of the orbit selected for the case of direct trajectories are listed in Table 2. Those for Mars and Venus-Earth gravity-assisted trajectories are shown in Tables 3 and 4, respectively. Shapes of some of these are illustrated in Figs. 5, 6, and 7, respectively. Note that the velocity increments are given by chemical propulsion alone.

In comparison between the evaluated mass deliverable into the Jovian orbits shown in Tables 2 through 4 and the assumed spacecraft mass listed in Table 1, it is found that the H-IIA Augmented Launch Vehicle has a sufficient capability to send the spacecraft to Jupiter, and to carry out some scientific observation missions. The direct and Mars gravi-

Table 4. Parameters of VEGA trajectories from the Earth to Jupiter, with the minimum value of the departure C3.

Parameters	Case III-A	Case III-B	Case III-C
Given			
Date of departure from LEO	2008/12/14	2009/01/22	2015/06/10
Date of the Venus swing-by	2009/06/28	2009/06/25	2015/12/06
Date of the Earth swing-by	2010/05/21	2010/05/15	2016/11/26
Date of arrival at Jupiter	2013/01/29	2013/06/02	2019/03/03
Time of flight [days]	1,507	1,592	1,362
Mass on LEO [kg]	17,000	17,000	17,000
Predicted			
ΔV at departure from LEO [km/sec]	4.01	4.13	3.76
C3 at departure from LEO [km^2/sec^2]	18.4	21.2	12.6
Mass after the departure [kg]	5,006	4,788	5,480
ΔV given by chemical propulsion during the Venus swing-by [km/sec]	0.09	0.04	0.00
Mass after the Venus swing-by [kg]	4,862	4,730	5,480
ΔV given by chemical propulsion during the Earth swing-by [km/sec]	0.00	1.05	0.00
Mass after the Earth swing-by [kg]	4,862	3,462	5,480
Hyperbolic excess speed relative to Jupiter, $V_{\infty J}$ [km/sec]	5.87	6.23	6.76
ΔV at injection to the Jovian orbit [km/sec]	0.87	0.95	1.06
Propellants required for insertion into the Jovian orbit [kg]	1,030	763	1,390
Mass deliverable into the Jovian orbit [kg]	3,492	2,359	3,750
Mass deliverable into the Europa orbit at an altitude of 500 km [kg]	125	112	184

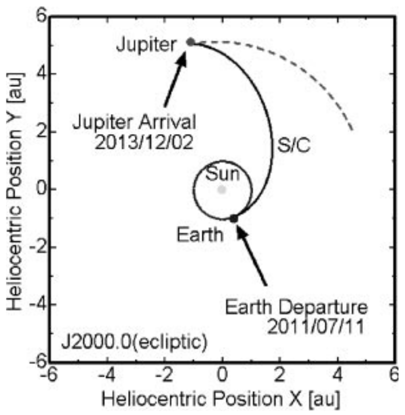

Fig. 5. A direct trajectory: Case I-E.

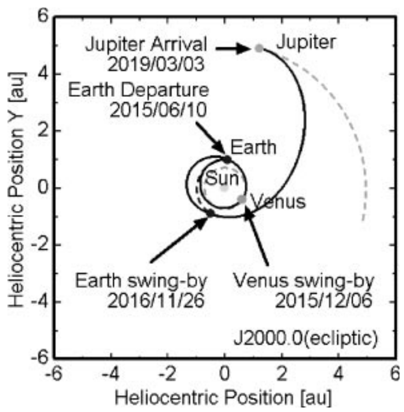

Fig. 7. A Venus-Earth gravity-assisted trajectory: Case III-C.

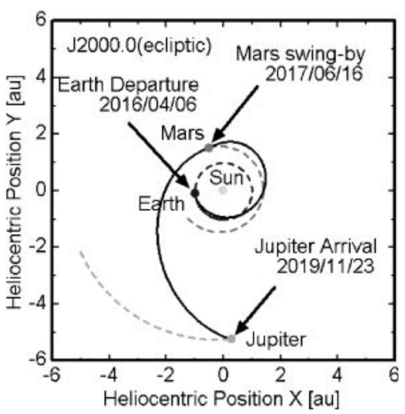

Fig. 6. A Mars gravity-assisted trajectory: Case II-C.

ty-assisted trajectories will enable an exploration with the assumed orbiter and probes, except for Case I-C and II-A. Note that the probes are assumed to be separated before the Jovian closest approach. In addition, the Venus-Earth gravity-assisted trajectories (CASE III-A, -B, and -C) will enable the insertion of all of the assumed orbiter and biological observation lander into the Jovian orbits.

For the Europa biological exploration, a part of the spacecraft mass must be delivered into a low orbit around Europa. The mass deliverable into such an orbit at 500 km altitude is evaluated for Case III as shown in Table 4. Its small values of less than 200 kg imply that the Europa biological exploration with a lander will not be feasible by means of chemical propulsion alone for Jovian orbit insertion. Another method of insertion, i.e. aeroassisted maneuvering is indispensable for such a mission.

5. Jovian Atmospheric Flights

Jovian atmospheric flights are calculated using the approach conditions predicted by the interplanetary trajectory

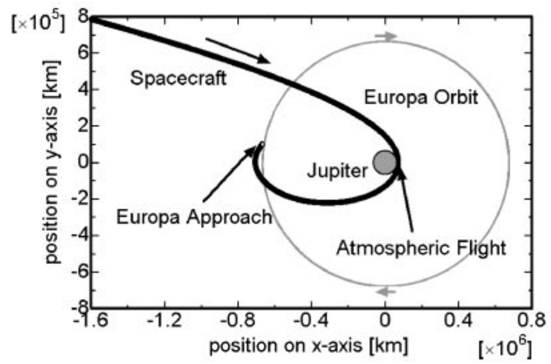

Fig. 8. An aerocapturing trajectory with an approach condition of Case III-A.

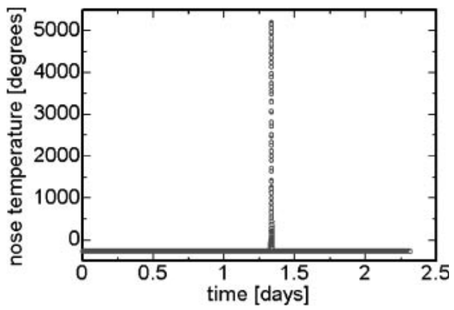

Fig. 9. A history of the nose temperature (centigrade) during the aerocapturing flight.

analysis described above. The results for the approach condition of Case III-A are shown in Figs. 8–11.

Figure 8 shows the aerocapturing flight trajectory whose periapsis altitude is 225 km from the Jovian surface. Note that the surface is defined as that of 71,492 km radius. As shown in Fig. 9, the nose temperature of the spacecraft reaches 5,100°C. Figures 10 and 11 show the history of acceleration and velocity, respectively, during the aerocapturing flight.

In this case, the required ablator mass is evaluated to be 420 kg and the mass deliverable into the Jovian orbit is 4,102 kg. On the other hand, if the chemical propulsion is used alone for insertion, the mass deliverable is 3,492 kg as shown in Table 4. From these results, it can be noted that aeroassisted maneuvering reduces the required propellant mass and enhances deliverable mass effectively.

The spacecraft passes near the orbit of Europa after the aerocapture, as shown in Fig. 8. For insertion into the low orbit at 500 km altitude around Europa, the required propellant mass is estimated to be 3,109 kg and the mass deliverable into the Europa orbit is 993 kg. This result indicates that aeroassisted maneuvering will enable some Europa biological exploration missions with an orbiter and a lander somewhat smaller than assumed. Such a smaller orbiter and lander can be developed easily using the recent downsizing technology in electronics. In conclusion, aeroassisted maneuvering is far more advantageous than applying chemical propulsion alone.

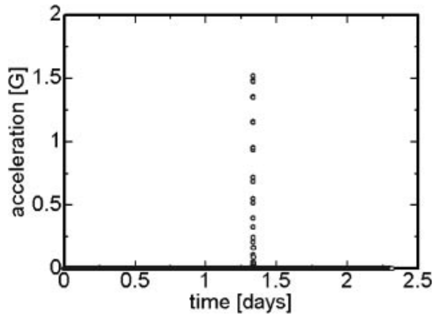

Fig. 10. A history of the acceleration during the aerocapturing flight.

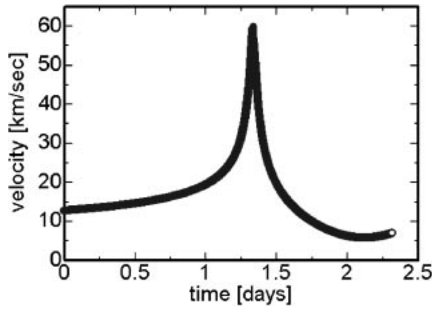

Fig. 11. A history of the velocity during the aerocapturing flight.

6. Conclusions

Feasibility analysis for Japan's Europa exploration was carried out in terms of interplanetary and Jupiter atmospheric flight trajectories. Three types of interplanetary trajectories from the Earth to Jupiter, i.e. direct, Mars gravity-assisted, and Venus-Earth gravity-assisted, were calculated and the case of the minimum Jovian insertion energy, i.e. the maximum deliverable mass, was selected in each type of trajectory. In addition, flight trajectories in the Jovian atmosphere for decelerating and deploying spacecraft to Europa were calculated and the required ablator mass was also evaluated. It was clearly shown that aerobraking is much more advantageous for enhancement of deliverable mass than applying chemical propulsion alone, and that the combination of H-IIA Augmented Launch Vehicle, gravity assists, and aerobraking will enable Europa biological explorations.

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