LOW COST MISSION DESIGN IN JOVIAN SYSTEM IN A FULL EPHEMERIS MODEL WITH TWO COUPLED RTBP ENGAGING

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Abstract *The reduction of the spacecraft's (SC) asymptotic velocity and the radiation hazard are really main problems for low-Delta V cost Jovian moons missions: orbiters and landers. Algorithm to overcome the "obstruction of solo disturbances" for one-body flybys around some Jovian moon with using full ephemeris with two coupled RTBP engaging has been implemented. The region where the total received radiation dose (TID) exceeds is skirted along the upper section of Tisserand-Poincaré graph. Withal low-cost reduction of the SC asymptotic velocity is required for rendezvous with small body. It became possible to find such scenarios when restricted three body problem is transformed into the two-coupled RTBP models and full ephemeris model. New Multi-Tisserand coordinates has been made for parametric passage into this region. With their help it is shown that the "cross" gravity assists at the early stage of reduction of the orbital period are required. As a result, a reasonable increase in the duration of the mission can be exchanged on a sharp decline TID and found "comfortable" (in TID) rounds scenario in the system (less than 70 krad for standard SC protection 8-10 mm Al). This will provide significant gains in the payload for spacecraft missions in Jovian system and systems of other outer planets and improving the reliability of their scientific instruments.*

Keywords: *Adaptive Mission Design, TID, Gravity Assists, Beam of Trajectories, Jovian System.*

1. Introduction

Mission design of low-Delta V cost gravity assists tours in Jovian system for the landing on the Galilean moon is considered, taking radiation hazard into account [1]. Limited dynamic opportunities of using flybys require multiple gravity assists. Relevance of regular creation of optimum scenarios – sequences of passing of celestial bodies with definition of conditions of their execution is obvious. This work is devoted to the description of criteria for creation of such chains. New Multi-Tisserand coordinates [2] for this purpose are introduced for the best study of features for the radiation hazard decrease and the spacecraft asymptotic velocity reduction.

2. Strategy of Mission Design in the Jovian system

One of main problems of the Jovian system mission design is that the reduction of the asymptotic velocity $V\infty$ of the spacecraft with respect to the satellite for the capture of the moon is impossible. A valid reason is consist in the invariance of the Jacobi integral and the Tisserand parameter in a restricted three-body model (RTBP) [3-5]. Furthermore, the same-body flybys sequence on the Tisserand-Poincaré graph [3-4] falls according the V∞-isoline to the extra radiation zone. Formalized algorithm to overcome this "obstruction of solo disturbances" with using full ephemeris model and with two coupled RTBP engaging has been implemented. The region of exceeding of the total received radiation dose (TID) can be bypassed along the upper section of the Tisserand-Poincaré graph. Withal low-cost reduction of the spacecraft asymptotic velocity required for the capture of the moon. For this purpose classes of "crossed" gravity assists from one small body of first CRTBP ("Ganymede") to the second CRTBP (with small body "not Ganymede"- mostly Callisto) and then – in the opposite direction are demanded. The corresponding numerical scheme was developed with using Tisserand-Poincaré graph and the simulation of tens of millions of options. The Delta V-low cost searching was utilized also with help of the modeling of the multiple rebounds of the beam of trajectories. The techniques developed by the authors specifically to the needs of the mission "Laplas P" RSA [6].

3. Specific features of gravity assist maneuvers

In the first approximation, the spacecraft trajectory in the represented jovicentric coordinates can be represented as a flyby hyperbola [7]. The ascent to orbit of an artificial satellite of Jupiter requires a braking impulse JOI (Jovian Orbit Insertion) in its pericenter. After this, the spacecraft ascends to a highly elongated elliptical orbit in the Jovian system.

Both interplanetary and intersatellite (Jovian) flights can be designed using the following step-by-step algorithm.

(1) Before approaching a target satellite, the current GAM is planned by specifying the next GAM based on the chosen method of the target passage.

(2) At the perijove preceding the current GAM, after choosing the parameters of the subsequent GAM, the patched conics method [7] is initially used to calculate the correction of the spacecraft's orbit providing the implementation of the current GAM due to the flight of a target satellite at a given height calculated from the solution of the Euler–Lambert problem.

(3) Newton's method is used to refine the correction according to the model of precise ephemeris (PEMs). Then, the corresponding solution is called the refined solution of the Euler–Lambert problem.

(4) The spacecraft motion is calculated (using PEMs) to the perijove preceding the next GAM.

We introduce the term of beam trajectory. We assume that in the first approximation, the pulse execution of arbitrarily small orbit corrections before the GAM corresponds to the formation of a "tube" of virtual trajectories (in other words, to a "paraxial beam of trajectories"). Under a certain choice of small impulses maintained by a given indicatrix, this produces a corresponding set of possible longitudinal and lateral flyby heights of the target satellite. The model evolution of this set using PEMs until leaving target satellite's sphere of influence leads to the formation of a trajectory beam.

The scenarios of gravity assist maneuvers in the Jovian system must contain (after JOI) the following two main stages [1-2,8-12]. The first stage (P1) is used to decrease the orbital energy of the spacecraft relative to Jupiter after JOI and provide conditions for more frequent encounters with Jupiter's natural satellites by reducing the period of spacecraft revolution down to values of the order of a few orbital periods of the satellite (for example, the period of Ganymede is approximately 7.155 Earth days). Before each flyby of Jupiter's satellite that serves for a gravity assist, the spacecraft orbit should be corrected to ensure the given parameters of the flyby of this satellite of Jupiter; according to the PEMs, these parameters guarantee a new encounter with it. In the second stage (P2), one should use the "frequent" series of GAM (with a decreased period of spacecraft revolution) to approximate the orbital velocities of the spacecraft and a target satellite (for example, Ganymede) to provide the conditions for the formation of a prelanding orbit. Here, one has to avoid the technique of resonance GAM using only a single target satellite because they do not allow one to reduce the asymptotic velocity of the spacecraft relative to this satellite down to the desired value. This is conditioned by the features of spacecraft trajectories in the restricted three-body problem. In the class of low-cost (quasi-inertial) gravity assist maneuvers near a fixed target satellite, the invariants are the Jacobi integral, the Tisserand parameter [5], and the asymptotic velocity relative to the target satellite (the "obstruction of solo perturbations" [3-4]).

The implementation of P1 is sufficiently clear: it is required to perform the correct refinement of the solution of the Euler–Lambert problem from the condition that the spacecraft goes to Ganymede after the JOI and for providing opportunity of solution of the next series of similar P1 tasks, such that the orbital period of the spacecraft at the exit from the zone of the subsequent gravity assist maneuver is a multiple of the orbital period of the chosen maneuvering partner satellite (quasi-resonance property). The fact that the periods of the spacecraft and the Jupiter's satellite ("small body") are quasi-resonant provides a new encounter with the partner in a time period that is a multiple of the spacecraft period at a vicinity of true anomaly of the last encounter (Fig. 1). To this end, it will suffice to perform a small correction of the flyby height of the target satellite immediately before the upcoming planned GAM.

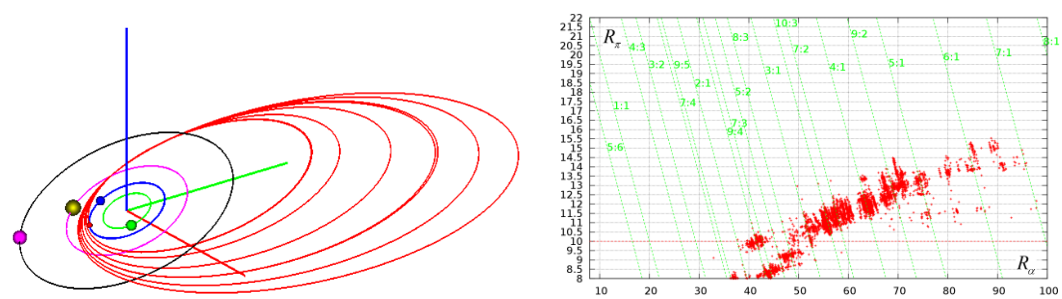


Figure 1. Quasi-resonant orbits of the spacecraft in the projection on Ti graph

Fig. 1 shows the results obtained from mapping the sequence of quasi-resonant orbits after a GAM to the Tisserand graph (Ti graph). The *x*-axis is the distance R_α of the apocenter of the spacecraft's orbit and the vertical axis is the distance R_π of the pericenter (in Jupiter radius R_J). One can see that the resonant isolines of the spacecraft's orbital period are blurred by thickness as a result of the fact that the PEM is used instead of patched conics model.

The problem of the search for GAM chains in the P1 stage is solved as conjunctions (encounters of the spacecraft with a target satellite *G* (for example, Ganymede) computed using PEM).

The P2 stage cannot be implemented in a way similar to P1 [1-2]. However, there is another possibility. The asymptotic velocity of the spacecraft relative to a small body can vary when another small body is used [1-4,8-12] (multibody GAMs). This property is a dynamic feature of the model of the restricted four-body problem (R4BP) and its reduced modification (double bond of restricted circular three-body problems). In terms of a restricted circular three-body problem (RCTBP), this modification can be written as 2-RCTBP. At a fixed time, we consider the osculating 2-RCTBP for the spacecraft in the Jovian system for which there exist both the Tisserand number τ_{Γ} [5] for the main target satellite (for example, Ganymede) and the Tisserand number for an auxiliary small body τ_{K} (for example, Callisto). Each of them becomes dominant when entering into the sphere of influence of a given satellite. The corresponding reduction of the asymptotic velocity has already been considered earlier (for example, by NASA during the use of multibody GAMs in the Galileo and Cassini-Huygens missions, as the analysis of ballistic scenarios shows). In addition, this technique proves to be irreplaceable in terms of saving the characteristic velocity ΔV and implementing the required maneuver of the pericenter uplift almost "free of charge" [1-2,13].

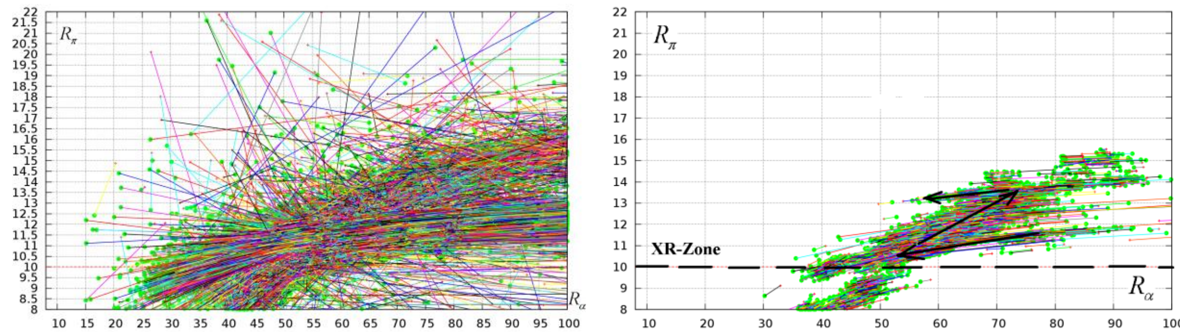
Thus, at the P2 stage after the P1 stage, one should use special correcting maneuvers to "enable" other small bodies of the Jovian system. This will provide a transition of another RCTBP to the line of the Tisserand invariant [1-5, 8-10]. These are "cross" GAMs such that the spacecraft after the reflection from the sphere of influence of the main target satellite G (for example, Ganymede) approaches another satellite $\bar{G}$ (Non_Ganymede). After this, it is necessary to choose a conjugate cross maneuver with a reverse change of the participants. By turning from the search for solutions in the simplest RCTBP model to the 2-RCTBP and R4BP problems that are more adequate to PEM, one can overcome the ballistic determinism of RCTBP imposed by the Jacobi integral.

For mass computing (tens of millions of variants with PEM are simulated), we formalize the invariant technique of asymptotic velocity reduction:

$$G_1 \wedge \ldots \wedge G_k \wedge \bar{G}_m \wedge \ldots \wedge \bar{G}_{m+n} \wedge G_{k+1} \wedge \ldots \qquad (1)$$

This makes it possible, using PEM, to solve the problem of GAM chains synthesizing as a special automatic selection of the spacecraft's trajectory beams in the class of conjunctions (1) of the encounters with satellites. To this end, the authors developed a semianalytic technique for constructing adaptive scenarios based on Tisserand graphs (Ti-graphs) [14-15] carrying the results of the numerical search for only structurally suitable low-cost reflections and rereflections of trajectory beams (in the PEM-formulation [16-17]).

At the revolution before the GAM, the spacecraft's orbit is slightly corrected. To fully reveal its dynamic capabilities, we use a four-parametric small correction to the spacecraft's velocity vector, chosen from the indicatrix (three parameters are responsible for the orientation and the correction magnitude and the fourth parameter controls its place in the orbit). The indicatrix is a uniformly "seeded" sphere of virtual supplements for each of the sufficiently densely distributed points of the spacecraft's orbit. As a result, the given vector of the spacecraft's velocity is replaced by a thin cone of virtual velocities and the single trajectory is replaced by a beam of trajectories (a large number of trajectories dynamically implementable using a single-impulse correction of the variants). The calculations within the RCTBP show that after the GAM is conducted relative to any satellite, the points for a new orbit of the spacecraft remains on the isolines of the corresponding Tisserand invariant [5]. For the calculations using PEM the corresponding points of the trajectory beam turn out to be close to the isolines. To investigate a multiparameter family of the trajectory beam subjected to gravitational scattering on the GAM, one needs a large number of trajectories in the beam. During tests of millions of variants we choose only those GAM chains that contains closed cycles of Ganymede flybys on the Tisserand graph provided that Callisto is passed intermediately. This reduces the analysis of the number of possible GAM variants by three orders of magnitude.



a) **b)**

Figure 2. Image of the beam of spacecraft trajectories passed through the sphere of influence of Ganymede (primary G-reflections) on the Ti-P graph (a); Image of the beam of spacecraft trajectories passed through the sphere of influence of Ganymede after the application of formulas $G \wedge C \wedge G$ on the Ti-P graph (b).

Fig. 2 a) shows the set of resulting possible GAM variants of the beam of trajectories near Ganymede (primary G-reflections). The secondary points are marked by circles. To avoid missing the required solution, we should ensure that their quantity is sufficiently large. Fig. 2 a) shows around $3 \cdot 10^6$ primary variants. Fig. 2 b) shows a beam of primary trajectory reflections chosen using cross-GAMs for Callisto. The dotted-dashed line roughly indicates the level of Ganymede's pericenter. The number of resulting variants is around $3 \cdot 10^3$. The arrows mark the general direction of moving points during a cross maneuver. It can be seen that their number is significantly reduced.

Now, we obtain a criterion allowing the technique corresponding to formula (1) to conduct cross maneuvers. This criterion should choose the bifurcation time T_{Bif} for restructuring the trajectory beams of solo GAMs. This is done based on the requirements of reducing the maximum level of TID, with a reasonable increase in the mission time and the costs of the characteristic velocity.

4. Methods for lifting the pericenter of the spacecraft orbit and the Bi-Ti-coordinates

The zone of impermissible radiation *XR* on the Ti-graph (Fig. 2 b), which is represented by the horizontal stripe $XR\{R_\pi \leq 10\, R_J\}$, where R_J is the radius of Jupiter, is bounded above by the dashed line $R_\pi = 10\,R_J$. For this boundary, the ionizing dose received per revolution can be approximately 30 krad, depending on the elongation of the spacecraft's orbit in the Jovian system. Inside the *XR*-zone, the ionizing dose will be even higher. The pericenter of the spacecraft orbit can be lifted from the zone of impermissible radiation to the upper section in different ways depending on the problem formulation. Next, we consider a "standard" tour with respect to radiation (the TID does not exceed the JUICE norm of 300 krad), which implies a lift in the upper section directly at the P2 stage in one or more steps, and a "comfort" tour with respect to radiation (the TID is less than 100 krad), which implies a lifting of the pericenter at an earlier stage. For each tour, its specific bifurcation time T_{Bif} is determined.

We can use the dimensionless Tisserand parameters $\tau_\Gamma, \tau_\mathrm{K}$ for Ganymede and Callisto in the corresponding "local" 2-RCTBP. For simplicity, we assume that the dimensionless gravity parameters of these bodies in the Tisserand formula [11, 20] are negligible. Then, we have

$$\tau_\Gamma(a,e,i) = T(\frac{a_{sc}}{a_\Gamma}, e, i)\ ,\ \tau_\mathrm{K}(a,e,i) = T(\frac{a_{sc}}{a_\mathrm{K}}, e, i)\ ,$$

$$T(\xi,e,i) = \frac{1}{\xi} + 2\sqrt{\xi(1-e^2)}\cos i\,, \tag{2}$$

where i is the inclination of the spacecraft's orbital plane to the median plane of the corresponding small body, e, a_{sc} and are the eccentricity and major semi-axis of the spacecraft's orbit relative to Jupiter, and a_Γ, a_K are the major semiaxes of Ganymede and Callisto, respectively. T_{Bif} can be efficiently determined by introducing a new graph with the axes of $\tau_\Gamma, \tau_\mathrm{K}$. Let us call this the ***Bi-Ti-graph***, and $\tau_\Gamma, \tau_\mathrm{K}$ we will call ***the Bi-Ti-coordinates*** (Fig. 3).

We can argue, that [10]:
1. The solo conduction of the quasi-resonant GAMs near Ganymede generates vertical (both upward and downward) vectors on the Bi-Ti-graph. The solo conduction of GAMs near Callisto produces a chain of horizontal vectors (both to the right and to the left).
2. The isolines of the spacecraft's orbital periods T_{sc} for RCTBP on the Ti-graph are represented by straight lines $R_\pi = c_1 - R_\alpha$, $c_1 = \mathrm{const}$, where c_1 depends on the gravitational parameter of the main body.
3. The isolines of the spacecraft's revolution periods on the Bi-Ti-graph will also be represented by straight lines.

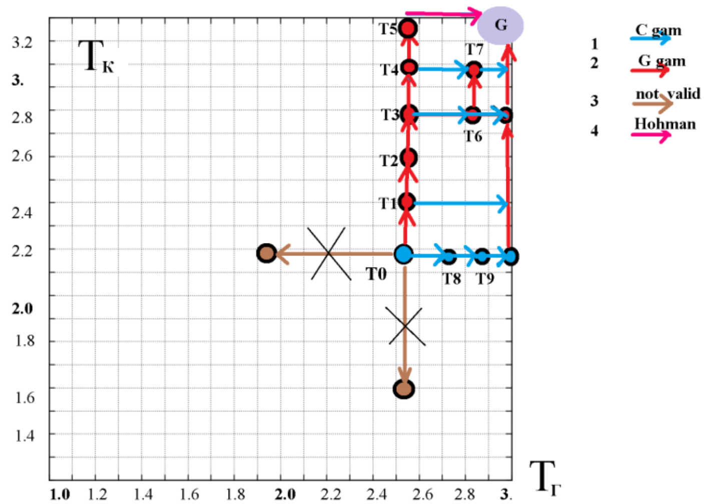


Figure 3. Bi-Ti-graph for tours in 2-RCTBP

The Bi-Ti-graphs help us to classify the possible tours and project them on specific space mission tasks. Their use allows for a clear classification of the two-way elements that generate efficient tours. We can identify the following elements among them: “Solo with Callisto” {→ →} (maneuvers with Callisto),“Solo with Ganymede” {↑↑} (maneuvers with Ganymede),and cross maneuvers: {→↑},{↑→}. The combination of a pair of two-way elements [{→↑},{↑→}] produces a three-way element {→↑→}. This is a symbolic record of a key technique: the pericenter’s lifting maneuver, which can be said to be a bond of cross maneuvers of reflections and rereflections. This technique is a cost-effective tool for penetrating the upper section of the Ti-graph.

Specifically, the choice of the time for this operation is a key problem: an excessively early start leads to long times and a late implementation is correlated to an increase in the total ionizing dose accumulated by the spacecraft. The adaptive scenario of landing on a satellite of Jupiter implies mixed tactics of using the elements with alternating solo and bonds of conjugate cross maneuvers.

5. Isolines of accumulated ionizing dose (“isorads”)

It can be suggested that the increase in radiation at the revolution of a given orbit of the spacecraft entirely depends on its coordinates on the Ti-graph. In this paper, we calculate the TID using NASA’s flat Galileo model [18], which depends on the apocenter and pericenter of the spacecraft. The general consideration with respect to reducing the radiation hazard for space missions of the JUICE class (8 mm Al, TID < 300) is that the spacecraft’s orbit pericenter should not be reduced for a long time below the “danger threshold” (the zone of impermissible radiation $XR\{R_\pi \leq 10\, R_J\}$ [8-9]; see the horizontal dashed line on the Ti-graph (Figs. 2 b). The numerical simulation shows that along an elliptical orbit the spacecraft receives the highest radiation dose in the pericenter almost quasi-singularly because most of the revolution (by the property of the area integral) is beyond the dangerous vicinity of the pericenter [8-10]. This is correlated to the localization of the *XR* region on the Ti-graph [8] for the elongated elliptical orbits that are typical for the initial stage of the mission to the Jovian system. However, with a decrease in the eccentricity of the spacecraft's orbit during the reduction of its orbital energy, there appear classes of almost circular spacecraft orbits for which the interval of maximum dosing at the revolution begins to be enlarged. This necessitates the calculation and application of more accurately derived isorads (the isolines of radiation exposure) on both the Ti- and Bi-Ti-graphs, numerically integrating the radiation dose per revolution for all orbits [1,10].

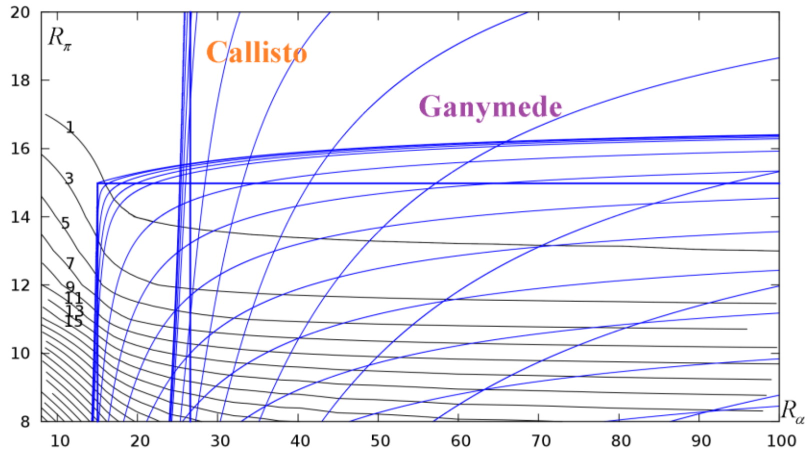


Figure 4. Isorads for single-revolution orbits with an increment of 2 krad on the Ti graph.

Fig. 4 shows isorads that make it possible to estimate the radioactive hazard of each gam and a series of gams. The main isorads are marked by the values of radiation doses in Krad.

6. Advanced Bi-Ti-graph

Let us consider an advanced variant of the Bi-Ti-graph. To obtain this, we apply the following curves on the Bi-Ti-graph:
(a) the isorads calculated earlier (the isolines of the ionizing dose (ID) received at the revolution);
(b) the isolines of the spacecraft revolution period (according to Proposition 2, these isolines will obviously be straight lines in these coordinates).
Fig 5 shows the advanced Bi-Ti-graph for the Ganymede/Callisto-2-RCTBP model. The isorads (the isolines of ID accumulated on the revolution with indicated doses in krad) and the isolines of the spacecraft's revolution period in Earth days are applied (dashed lines). The abscissa and ordinate axes of the Bi-Ti-graph indicate the Tisserand numbers for Ganymede and Callisto.

The advanced Bi-Ti-graph shows that the downward tracks on the Bi-Ti-graph do not improve the quality of the tour and lead only to a further increase in the period. The leftward tracks lead to a sharply increased TID and therefore are likewise inefficient.

It should be noted that the condition of landing on Ganymede require that the value of τ_Γ be very close to 3, which corresponds to a zero asymptotic velocity of the spacecraft relative to Ganymede [1-2,8-10]. The "solo with Ganymede" chain generates vectors vertically upward on the Bi-Ti-graph. In the course of this process, the scenario track leans to the isorad corresponding to the model value of the limiting TID (or crosses it at the next GAM).

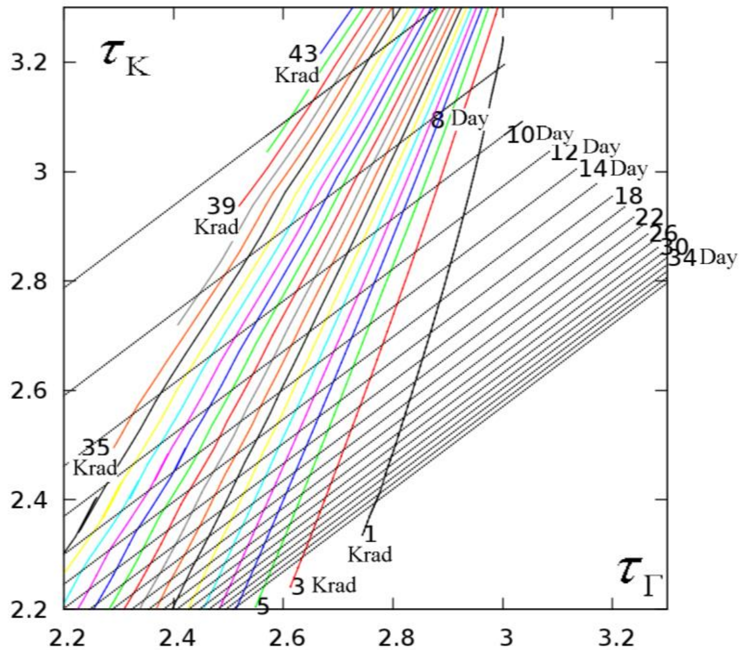


Figure 5. Advanced Bi-Ti-graph for the Ganymede/Callisto-2-RCTBP model

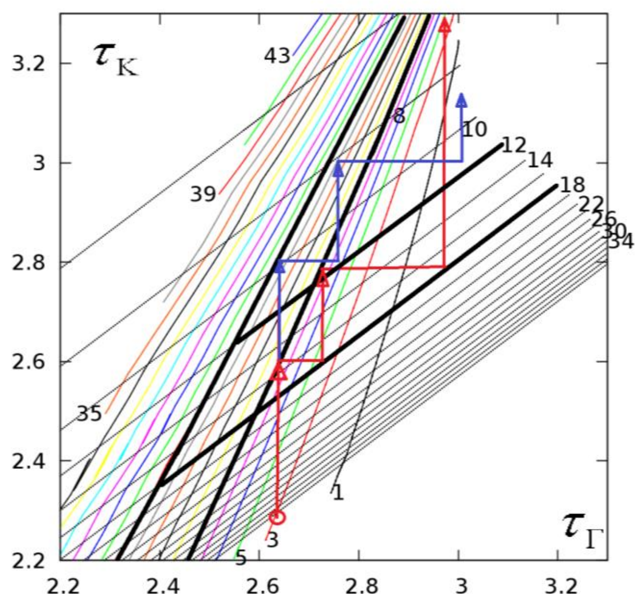


Figure 6. Ballistic scenarios on the advanced Bi-Ti graph. The isorads (isolines of ID accumulated on the revolution and isolines of the spacecraft period of revolution) are shown

It is this that serves as a criterion for changing the current local RCTBP and restructuring the regular solo-scenario by a bifurcation maneuver of going to a horizontal "solo with Callisto" (maneuvers with an exchange of ID with time). Further, when the horizontal chain solo with Callisto reaches the isoline of time limit, one should search for the continuation in the dissection of the phase flow of the reverse exchange. Fig 6 shows the restructuring of solo-scenarios. For completeness, the limiting values of ID are chosen to be the pair of model values 21 and 11 krad and the limiting orbital periods of the spacecraft are taken to be 12 and 18 Earth days, respectively.

7. Connection of Poincaré section to the Bi-Ti-graph

The scenarios of the ascent to a near-satellite orbit and landing on the satellite may vary substantially. On satellite orbits located below the orbit of Callisto, the GAMs with Callisto become unreasonable due to the large cost of the characteristic velocity. At the same time, the standard GAMs with Ganymede lose their efficiency. Although most of the excess asymptotic velocity of the spacecraft for approaching to Ganymede can be already suppressed, the further attempts of full-fledged GAMs lead to a sharp decrease in the value of the spacecraft's pericenter from values close to Ganymede. The modern methods of ballistic design [19] imply the use of the technique of high-altitude GAMs at this stage utilizing the properties of the corresponding solutions of restricted three-body problems and the PEM for this stage. These GAMs should be performed at the boundary and above the sphere of influence of the small body (Ganymede) due to the effect of the large body; under certain conditions, they reduce the apocenter of a spacecraft's orbit without reducing the height of its pericenter [3,12,19]. In fact, the spacecraft maneuvers in the vicinity of the Lagrangian points of libration in the Jovian–Ganymede system [3,9,19-23]. Formally, this is expressed in the flybys over a partner satellite at large heights of 20000–50000 km. On the standard Ti-graph, this motion corresponds to the set of Tisserand invariant isolines located beyond the area bounded by the respective separatrices, which are to be reached through regular GAMs. On the advanced Bi-Ti-graph, we mark this section as a vertical layer with a built-in target—the phase state of Ganymede on the Ti-graph. We call it the Poincaré section of Ganymede for the Bi-Ti-graph [2,10]. As a result, we obtain the Bi-Ti-P-graph (Fig. 7). In the vertical layer of the Poincaré section containing the G (Ganymede) marker, the relation for the Jacobi integral $J \cong 3 - v^2 \approx 3$ is satisfied and chaotic motions are typical [23].

The Poincaré section of Callisto is accordingly a horizontal layer with a built-in position marker for Callisto. The immersion into the Poincaré section of Ganymede requires an eventual leftward move of the pericenter of the spacecraft's orbit above $15\,R_J$, which can be rationally used applying the regular GAMs with Callisto. Evidently, these GAMs are possible only for heights of the apocenter of the spacecraft's orbit larger than the Callisto orbit radius ($26\,R_J$), i.e., before the chain of GAMs passes through the Poincaré section of Callisto. Further, to approach Ganymede now within the Poincaré section, it is necessary to move up towards position G of Ganymede using the above-mentioned special-purpose techniques for constructing trajectory flows with high-altitude flybys of a small body and a final weak gravitational capture [23].

In Fig. 7, the intersection of the vertical (for Ganymede) and horizontal (for Callisto) sections corresponds to the intersection of the horizontal (for Ganymede) and vertical (for Callisto) separatrices of local RCTBPs. In the Jovian system, this intersection is a low-energy transfer channel of the Interplanetary Transport Network [20,23] (also called the Interplanetary

Superhighway [21-22]), which allows for low-cost quasi-ballistic flights to other small bodies in the Jovian system.

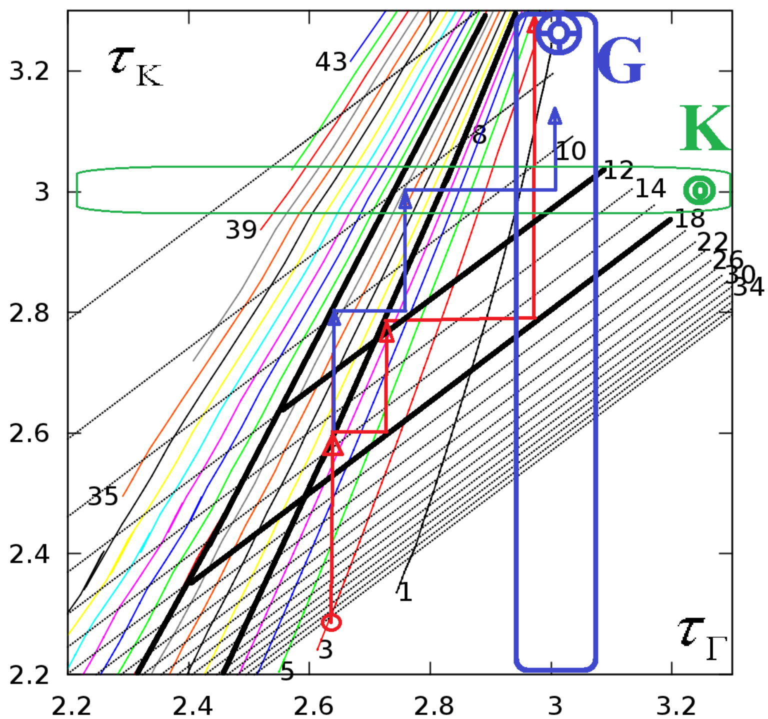


Figure 7. Final advanced Bi-Ti-P-graph (with the Poincaré sections for Ganymede and Callisto)

8. A technique for synthesizing trajectory beams with high-altitude flybys over a small body

We note the following factors.
(1) The limiting minimum height of the spacecraft flyby over Ganymede does not exceed 20000 km.
(2) The search is extended to heights that are formally higher than the sphere of influence of Ganymede: 60000 km.
(3) The classes of high-altitude flybys of Ganymede are sought "on the rebound" such that the next high-altitude encounter of the trajectory beam with Ganymede is followed by another encounter with it. Thus, the initial beam of trajectories is substantially filtered to compensate the gravitational scattering at GAM.

These requirements make it possible (in the RCTBP and then in the PEM-formulation) to reveal the modes of the flyby of trajectory beams over a small body, allowing for a very close approach to Ganymede due to the action of Jupiter, reducing the apocenter's height without decreasing the pericenter of the height of the spacecraft's orbit [19].

Before the ascent to orbit of an artificial satellite of Ganymede, one can additionally reduce the mission's budget through a weak gravitational capture by the gravity field of Ganymede [3,23].

The search can be based on both a direct integration of the trajectory beams and a reverse-time integration of the trajectory beams emitted from the orbit near Ganymede.

This criterion for determining T_{Bif} was numerically implemented by the authors in the Ballistic Center of the KIAM of the Russian Academy of Sciences, using its operational Earth Space ToolKit (ESTK) software and the JPL NASA ephemeris data in the NAIF format. On the example of a mission in the Jovian system, we revealed and synthesized scenarios of flights with the spacecraft's ascent to the orbit of Ganymede that were considerably more comfortable in terms of radiation than the earlier known ones. The TID does not exceed 70 krad for the standard protection of 8–10 mm Al (or 200–300 krad for a protection of 4 mm Al). These scenarios make is possible to obtain substantial gains in the spacecraft's payload in designing future real space missions, as well as enhance the reliability of the scientific equipment.

A typical fragment of spacecraft maneuvering before landing on Ganymede synthesized with the help of the techniques described is shown in Fig. 8. Here, one can note the initial series (labeled as $\boxed{\mathbf{1}}$) of GAMs with Ganymede (the GAM location is labeled as $\boxed{\mathbf{2}}$) with an almost constant line of apsides and decreasing (from one revolution to another) sizes of the major semiaxes.

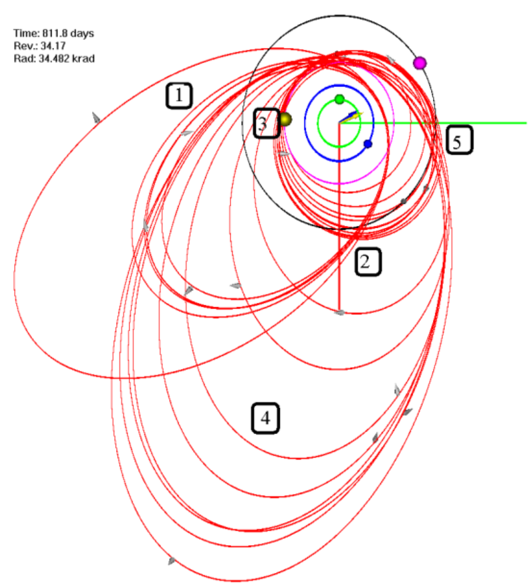


Figure 8. Typical fragment of the resulting comfortable (with respect to accumulated ID) scenario of spacecraft approaching Ganymede

After the cross maneuver with Callisto (labeled as $\boxed{\mathbf{3}}$), the spacecraft enters a new contracting series of quasi-resonance GAMs with Ganymede with a turned line of apsides (labeled as $\boxed{\mathbf{4}}$). Label $\boxed{\mathbf{5}}$ marks the series of high-altitude GAMs with Ganymede, slowly reducing the height of the apocenter of the spacecraft's orbit, thus pushing the spacecraft's orbit to Ganymede.

9. Illustration of the algorithm of synthesizing a comfortable tour by TID (with the passage of the upper section) on the Bi-Ti-P graph

In most cases of organizing missions to Jupiter and other giant planets, as well as expeditions to the Sun, it is of special importance during choosing from "pilot chart" to ensure that the scenario is comfortable with respect to the accumulated ID. The design of strong (with respect to the accumulated ID) tours in the "tank"-style [24] simplifies the choice and evidently expands the geometry of the "pilot chart" to satellites that are closer to Jupiter and simultaneously weights its characteristic velocity budget. Aimed, in contrast, at constructing a maximally favorable (in terms of TID) scenario of the tour to Ganymede, we used an advanced Bi-Ti-P graph and assumed that the resulting ID received at a revolution is limited from above by a low isorad that still fits (during the reflection) the maximum required time of the orbital period (a limit of 70 Earth days was used). The calculation using tens of millions of variants allowed us to synthesize a comfort-tour (with respect to TID) (see Fig. 2). Its mapping on the Bi-Ti-P-graph is shown in Fig. 9. The crosses mark the phase jumps on GAM. The numbers of the main stages of the tour are encircled. Numbers 1 to 5 correspond to two series of regular GAMs near Ganymede, separated by a cross GAM near Ganymede and Callisto. Stage 6 uses a GAM with Callisto to ensure that the Poincaré section of Ganymede is reached. Here, at stage 7, a final approaching to Ganymede is accomplished with the help of a series of high-altitude GAMs.

Additionally, we note stage 6 takes into account the Poincaré section for Callisto on the Bi-Ti-P-graph (rather than the ID level) to allow regular encounters of the spacecraft with Callisto.
The corresponding form of the same tour on the Ti-graph is shown in Fig. 10.

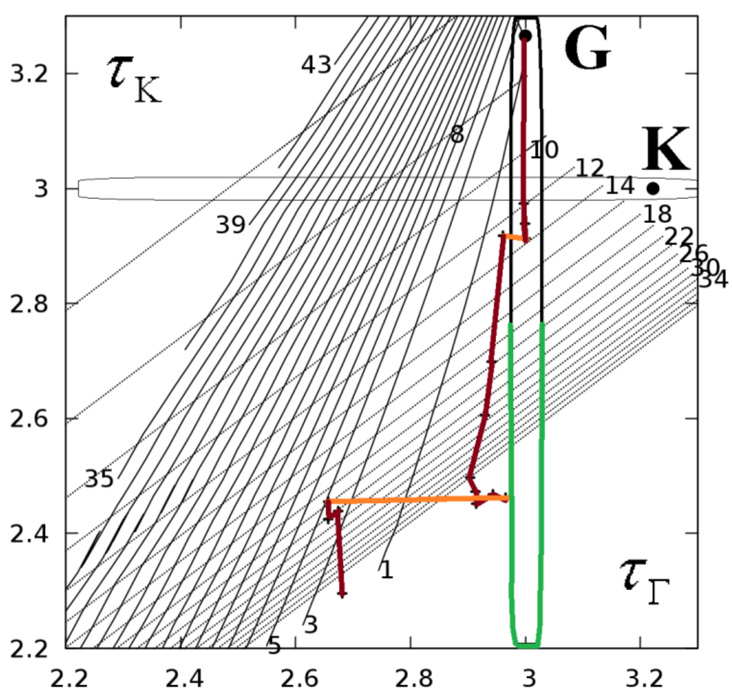


Figure 9. Scenario of a comfortable (with respect to accumulated ID) tour on the Bi-Ti-P-graph

In the Jovian system, the resulting variants of comfortable flights (with respect to ID) correspond to values of 70 krad, which is obtained by using the standard protection of the Galileo spacecraft of 8–10 mm Al (or, alternatively, 200–300 krad for light spacecraft with a thickness of the protective cover of 4–5 mm Al).

10. Conclusions

The beam algorithm to overcome the "obstruction of solo disturbances" of one-body flybys with using real ephemeris model and with two coupled RTBP engaging has been implemented for the capture of the moon. The region of exceeding of the total received radiation dose (TID) skirted along the upper section of multibody Tisserand-Poincaré graph. New Multi-Tisserand coordinates has been made for parametric passage into this region. With their help it is shown that the "cross" gravity assists at the early stage of reduction of the orbital period are required. Withal low-cost (within 0.5 km/s) reduction of the spacecraft asymptotic velocity required for approaching. As a result, a reasonable increase in the duration of the mission can be exchanged on a sharp decline TID and found "comfortable" (in TID) tours scenario in the system (less than 70 krad for standard SC protection 8-10 mm Al, or less than 200-300 Krad for the “light” SC with the 4-5 mm Al shield). The execution of the scenario takes 2.5–3 years.

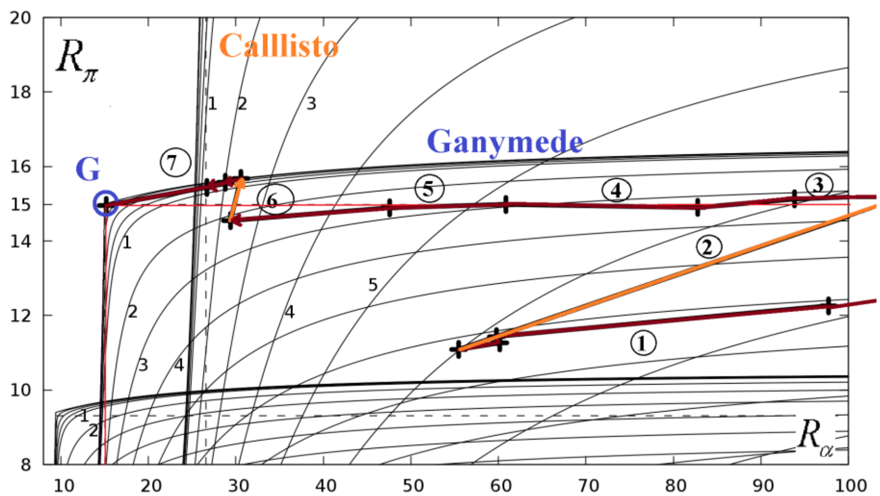


Figure 10. Scenario of a comfortable (with respect to accumulated ID) tour on the Ti-P graph

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