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THE ANALYSIS OF COMPLETED, ONGOING AND POTENTIAL MISSIONS TO THE JUPITER SYSTEM

E. S. Gordienko, I. V. Platov*, A. V. Simonov

Lavochkin Association
24, Leningradskaya Str., Khimki, Moscow region, 141400, Russian Federation
*E-mail: aia@laspace.ru

In the next decade, a significant increase in the intensity of the Jupiter system and its satellites studying with the help of spacecraft is expected. The two Galilean moons – Europe and Ganymede – are particularly interesting since the potential life is possible on these objects, even in a primitive form. Such missions are being developed by ESA ("Jupiter Icy Moon Explorer" (JUICE)), NASA ("Europa Clipper" and "Europa Lander"), Roskosmos ("Laplace-P") and others.

The final goal of the European and Russian projects is the detailed study of Ganymede – the largest satellite both in the Jupiter system and in the entire Solar system. The Russian perspective project "Laplace-P" assumes the creation and launch of two spacecrafts in one launch window. At the heart of the first mission spacecraft is an orbiter. One of its tasks is mapping the surface of Ganymede from the orbit of an artificial satellite and collecting data for selecting a landing site of the second spacecraft – a landing satellite. The project should be based on the launch of a spacecraft from the Baikonur cosmodrome with the help of the Angara-A5 launcher and the KVTK upper stage. When developing the flight scheme it is assumed that in 8 years the spacecrafts should be put into the orbit around Ganymede. The flight trajectory to Jupiter is formed with the help of gravitational maneuvers near the Earth and Venus. The mission of "JUICE" involves the study of Ganymede only from the orbit of an artificial satellite.

The article is devoted to comparison of completed, carried out and perspective expeditions to the Jupiter system. If the first mission – "Galileo" – was mainly focused on Jupiter itself, the future missions are aimed at investigations of its satellites. Based on the analysis of the reviewed projects, recommendations are given to improve the efficiency of the Russian "Laplace-P" project.

It is established that to improve the efficiency of the Russian mission "Laplace-P" it is recommended both further structural improvement of space vehicles and the development of a trajectory in the Jupiter system based on modern methods of ballistic design.

Keywords: spacecraft, Jupiter investigation, Europa, Ganymede, orbiter, lander, flight profile.

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АНАЛИЗ МИССИЙ В СИСТЕМУ ЮПИТЕРА: СОСТОЯВШИЕСЯ, ОСУЩЕСТВЛЯЕМЫЕ И ПЕРСПЕКТИВНЫЕ

Е. С. Гордиенко, И. В. Платов*, А. В. Симонов

АО «НПО им. С. А. Лавочкина»
Российская Федерация, 141400, г. Химки, Московской области, ул. Ленинградская, 24
*E-mail: aia@laspace.ru

В ближайшее десятилетие ожидается значительное увеличение интенсивности изучения системы Юпитера и его спутников с помощью космических аппаратов. Особенно интересны две галилеевы луны – Европа и Ганимед. На этих объектах потенциально возможна жизнь, пусть даже и в примитивной форме. Такие миссии разрабатываются ЕКА (Jupiter Icy Moon Explorer, JUICE), НАСА (Europa Clipper и Europa Lander), Роскосмосом («Лаплас-П») и др.

Финальной целью европейского и российского проектов является детальное изучение самого большого спутника как в системе Юпитера, так и во всей Солнечной системе – Ганимеда. Российский перспективный проект «Лаплас-П» предполагает создание и запуск в одно стартовое окно двух космических аппаратов. В основе первого КА миссии лежит орбитальный аппарат. Одной из его задач является картографирование поверхности Ганимеда с орбиты искусственного спутника и сбор данных для выбора места посадки второго КА – посадочного. Проект должен быть разработан исходя из запуска космического аппарата с космодрома Байконур при помощи ракеты-носителя «Ангара-А5» и разгонного блока КВТК. При разработке схемы полёта предполагается, что через 8 лет аппараты должны выйти на орбиту вокруг Ганимеда. Траектория перелёта к Юпитеру формируется с помощью гравитационных маневров у Земли и Венеры. Миссия JUICE предполагает изучение Ганимеда только с орбиты искусственного спутника.

Представлено сравнение состоявшихся, осуществляемых и перспективных экспедиций в систему Юпитера. Если первая миссия «Галилео» в основном исследовала сам Юпитер, то разрабатываемые миссии нацелены на исследование его спутников. На основании анализа рассмотренных проектов приводятся рекомендации по повышению эффективности российского проекта «Лаплас-П».

Установлено, что для повышения эффективности российской миссии «Лаплас-П» рекомендуется как дальнейшее конструкционное совершенствование космических аппаратов, так и разработка траектории в системе Юпитера на основе современных методов баллистического проектирования.

Ключевые слова: космический аппарат, исследования Юпитера, Европа, Ганимед, орбитальный аппарат, посадочный аппарат, схема полёта.

Introduction. One of the most attractive goals of the Jupiter system research is life detection on its satellites – Europa and Ganymede. Mars and Titan (a Saturn satellite) are always considered to be potentially habitable objects in Solar System as well.

In the next decade the intensive studying of the Jupiter system and its satellites with the help of spacecrafts is expected. Such missions are being developed by ESA (“Jupiter Icy Moon Explorer” (JUICE)), NASA (“Europa Clipper” and “Europa Lander”) and Roskosmos (“Laplace-P”). The final goal of the European and Russian projects is the detailed study of the largest satellite both in the Jupiter system and in the entire Solar system – the Ganymede. The project “Laplace-P” includes two spacecrafts: an orbiter “Laplace-P1” and a lander “Laplace-P2”. The “JUICE” mission is assumed to study Ganymede only from the orbit of an artificial satellite. The expedition “Europa Clipper” carries out the investigation of Europa from the jovicentric orbit by spacecraft-satellite rendezvous procedure. “Europa Lander” is an independent spacecraft and it is expected to be launched in the next launch window shortly after “Europa Clipper”.

It should be noticed that about 10 years ago it was planned to realize a joint project “Europa Jupiter System mission – Laplace (EJSM/Laplace)” instead of those mentioned above. It included NASA and ESA with their own spacecrafts: “Jupiter Europa Orbiter” (USA) and “Jupiter Ganymede Orbiter” (Europe). Later on Japan’s National Aerospace Agency (JAXA) with the spacecraft “Jupiter Magnetospheric Orbiter” and Roskosmos with the “Jupiter Europa Lander” joined the project [1].

In 2011 NASA withdrew from the joint project because of the reduction of budget. ESA decided to work out a spacecraft for the Jupiter system investigation and in 2012 announced the independent mission JUICE with the launch in 2022 [2]. The American project was substantially reduced due to cutbacks of funding. At first it was named “Europa Multiply-Flyby Mission” [3] and assumed only several Europa proximity missions. However, it was even considered to realize the ascent to its orbit but this idea was abandoned later. The project was renamed as “Europa Clipper”. This spacecraft is to be launched in 2021 [4]. In 2016 it was decided to improve the mission with an additional independent spacecraft with the “Europa Lander” module [5]. It is planned to be launched in 2025.

JAXA is not actively engaged in the Jupiter system studying mission so far.

The Russian part of the mission has been revised as well. It supposed to create a lander originally designed for the surface data transmission by means of “JEO” spacecraft used as a retransmission station. An orbiter has been included in the project whose priorities are selecting a landing site for the lander and data transmission. Both spacecrafts are to be launched in one launch window in 2026 [6–8]. Because of high radiation intensity at a distance from Jupiter equal to the Europa orbital radius Ganymede has become the final goal of the Russian project “Laplace-P” because the level of radiation on this satellite is noteworthily lower.

The three above mentioned projects are based on the experience of the Jupiter first artificial satellite – the “Galileo” spacecraft. Its task was to analyze the chemical compound and physical characteristics as well as to perform close-look photography of Jupiter satellites. The spacecraft consisted of a long term monitoring orbiter and a special atmospheric research probe. The spacecraft was launched on 18 October, 1989; in 1995 it entered the Jupiter orbit and was in operation till 2003. It provided more than 30 GB amount of data including 14 000 planetary and satellites’ images as well as unique information about the planetary atmosphere. The spacecraft was named after Galileo Galilei who made a discovery of four Jupiter satellites in 1610. Nowadays the spacecraft “Juno” which was launched on the 5th of August 2011 investigates this giant planet and its magnetosphere. It entered the orbit of the Jupiter artificial satellite on the 5th of July 2016. “Juno” is expected to be in operation till February 2018. The mission is entirely focused on the study of the giant planet, not on its satellites. To supply power three higher-rated solar batteries with radiation damage stability were installed on “Juno” as distinct from the previous research spacecrafts equipped with radioactive thermoelectric generators. In this paper the characterization of Jupiter and its moons research efficiency is presented and the mission effectiveness according to the analyzed criteria is evaluated.

Mission profiles. The Jupiter and its planetary system were studied by means of only spacecrafts with Jupiter gravity-assist trajectory up to 1995. They were “Pioneer-10” (1973), “Pioneer-11” (1974), “Voyager-1” and “Voyager-2” (1979), “Ulysses” (1992 and 2000). “Cassini” (2000) and “New Horizons” (2007) also passed by this planet. Heliocentric flight phase of all these spacecrafts except “Cassini” was a direct flight to Jupiter and did not include gravity-assist (GA) maneuvers.

In 1995 “Galileo” became the first Jupiter artificial satellite. It had been launched in 1989, six years before [9]. Its interplanetary trajectory included three gravity assists: once near the Venus and twice near the Earth (VEEGA). In eight years of studying the Jupiter system the spacecraft accomplished 35 orbits having passed close all its large satellites. The jovicentric phase of the flight trajectory was mainly in equator plane [10].

In 2016 the spacecraft "Juno" entered the Jupiter orbit. This spacecraft covered the distance to the giant planet by a faster profile than "Galileo". The flight lasted one year less and included only one Earth gravity assist (EGA). However, the implementation of such a flight scheme is a higher-energy mission than the Venus-Earth-Earth one. The Jupiter orbit of the spacecraft is to be rotated at a larger angle to the equator – up to 35°. It was initially planned that the spacecraft would enter the elliptical polar orbit with the period about 53 earth days and with the pericenter altitude less than 5000 km. Later on the orbital period was to be lowered till 14 earth days [11]. Because of power plant problems it was decided to keep the spacecraft on the 53 days orbit. It wasn't anticipated that the spacecraft would execute any gravity-assist maneuvers to change the orbit period

The basic characteristics of heliocentric flight phase of the mission to the Jupiter system are shown in tab. 1.

The perspective JUICE, "Europa Clipper / Lander" and "Laplace-P" missions are to enter the orbits of the Galilean moons (Europa and Ganymede) orbital vehicles in the final phase of the mission. Interplanetary flight phases include a number of gravity-assist maneuvers near the Venus and Earth: according to the VEEGA scheme applied for "Galileo" and for the Russian expedition as well and to the EVEEGA one applied for the European missions. Heliocentric trajectory of the "Europa Lander" spacecraft performs only one gravity assist maneuver near the Earth ("EGA" scheme) like the "Juno" spacecraft does. To date "Europa Clipper" will fly to the Jupiter performing no maneuvers in case of the perspective superheavy "SLS" booster launch and according to the VEEGA scheme in case of the "Atlas V 551" booster launch.

Before the launching phase of the "JUICE" and "Europa Clipper / Lander" spacecrafts to enter the Jupiter initial orbit the gravity assist maneuver is performed near Ganymede. This allows saving about 400 m/s of characteristic speed [12]. Nevertheless, such GA maneuver is out of the profile of Russian "Laplace-P" missions because of its complex implementation. It is required to synchronize the spacecraft trajectory with Ganymede very precisely.

After entering the Jupiter initial orbit the flight profile of all the three missions follow the similar patterns. The main task of the Jupiter mission early stage is the orbit energy attenuation (being determined by its period) by GA maneuvers sequence near the largest Jupiter satellite – the Ganymede. At the second stage "Callisto" or "Europa" also performs GA maneuvers to reduce asymptotic speed by approaching to the satellite which is the final goal of the mission [13; 14]. The comparison of trajectory schemes is shown in tab. 2. The cumulated dose is estimated for an aluminum shield 1 cm in thickness.

In terms of the complex approach (an acceptable dose of radiation by the characteristic speed lower input) the implementation of the scheme with the GA maneuvers near the Ganymede, the Callisto and the Europa is the most favourable option.

The JUICE spacecraft trajectory has two additional phases as compared to the "Europa Lander" and "Laplace-P" missions. The first phase is studying the Europa by flying around two times (the process time is approximately 36 earth days). The second one is a high-latitude phase of studying the Jupiter with the orbital plane change at about 22° to the equator which is available from GA maneuvers near the Callisto. The process time is approximately seven months.

"Europa Clipper" jovicentric phase is a little different from the "orbital" missions. After the first required phase of energy orbit reduction in a period of 11 months the main phase of the mission starts which goal is to study the Europa by 35 approaches in a period of one year and a half.

Quality characteristics of Jupiter missions. The main characteristics of spacecrafts and their flight profiles for the completed and perspective Jupiter system missions are shown on tab. 3. Energy-mass characteristics and spacecraft profiles primarily define flight time and proper technology mass.

Table 1

Comparative characteristics of heliocentric flight phase options concerning to the Jupiter mission

Parameter	Path			
	Straight	EGA	VEEGA	VVEGA
Characteristic deorbiting acceleration speed of an earth artificial satellite, km/s	6.8	4.4	3.8	3.8
Asymptotic departure speed, km/s	9.5	5.2	3.5	3.5
Mandatory maneuvers, km/s	–	0.6	–	–
Asymptotic arrival speed, km/s	6	6	6	6
Flight duration, year	2–3	4–5	6–8	6–8
Return period, year	1	1	2–4	2–4

Table 2

Comparative characteristics of the Jupiter mission paths

Scheme	Flight duration, year	Characteristic speed input, km/s	Cumulated dose, Mrad
Straight entering the satellite orbit	0	more than 5.5	0
GA maneuver near Callisto	0.5	3	0
GA maneuver near Ganymede and Callisto	1	2.5	0.1–0.5
GA maneuver near Ganymede, Callisto and Europa	1.5	1.5	0.8–1.2
GA maneuver near Ganymede, Callisto, Europa and Io	2.5	1.3	1.7

Table 3

The main spacecraft characteristics for studying the Jupiter system

Parameter / mission	“Galileo”	“Juno”	“Europa Clipper”	“Europa Lander”	JUICE	“Laplace-P1”	“Laplace-P2”
Original mass of a spacecraft, kg	2333	3625	3200	7100	2300	7000	6800
Launch year	1989	2011	2021	2025	2022	2026	
Flight profile	VEEGA	EGA	VEEGA	EGA	EVEEGA	VEEGA	
Flight duration, year	6	5	6.4	4.7	7.6	6.1	6.1
Launcher, upper stage	«Atlantis», «IUS»	«Atlas V 551»	«Atlas V 551»	«SLS», «Block 1»	«Ariane-5», «ESA»	«Angara-A5», the KVTK	
Entering Ganymede (G) / Europa (E) satellite orbit (1) or landing (2)	no	no	no	2	1	1	2
Number of GA maneuvers in the Jupiter system before entering the (G) / (E) satellite orbit	– (24)	– (0)	– (42)	16	15+2+10	10	13
Duration of jovicentric phase before entering the (G) / (E) satellite orbit	– (2844)	– (596)	– (874)	641	767+208	758	804
Studying time, year	8	2	3.5	2+20 days (the lander)	3.5	3	2+1 days (the lander)
Power source	2 RITEG	3 SP	4 RITEG	2 SP	2 SP	4 SP	2 RITEG
Technology mass, kg	118	173.7	127	42.5	104	50	50
Spacecraft thrust loading, N							
Orbital maneuvering engines	400	645	890		424	4×390	1×8428 2×590
Vernier thrusters qty×drive	12×10	12×–	4×90 16×4		8×22	12×13 4×55	12×6 4×50

Remarks:

1. EGA is a scheme with one GA maneuver near the Earth.
2. VEEGA is a scheme with three GA maneuvers near the Venus (one time) and the Earth (two times).
3. EVEEGA – is a scheme with four GA maneuvers near the Earth – the Venus – the Earth – the Earth.
4. SP is a solar panel.
5. (–) means that the characteristic is unavailable.

In accordance with the mission history and above mentioned scientific tasks the main quality characteristics for the comparative analysis of Jupiter system studying efficiency were estimated:

– duration of heliocentric phase $T_\text{С}$;

– duration of jovicentric phase $T_\text{Ю}$;

– a number of GA maneuvers in the Jupiter system before entering the (G) / (E) satellite orbit $N_\text{ГМ}$;

– studying time $T_\text{И}$;

– technology mass $m_\text{ПН}$;

– remote (from the orbiter) and contact (from the lander) studying $J_\text{П}$.

Hence, it is required to solve a task of complex technical system optimization upon the vector criterion to compare mission effectiveness and to make the valid decision [15]. It can be solved by systems analysis methods.

In this paper a method of convolution from the vector to the scalar criterion is used. Thereat, the optimized functional is a linear combination of control criteria which value is defined by the weight coefficients of linear convolution assignment.

For reference and spacecraft design selection the following composed function is used:

$$F = k_{t\text{С}} T_\text{С} + k_{t\text{Ю}} T_\text{Ю} + k_N N_\text{ГМ} + k_m m_\text{ПН} + k_\text{И} T_\text{И} + k_\text{П} J_\text{П}, \quad (1)$$

where $k_{t\text{С}}$, $k_{t\text{Ю}}$, k_N, k_m, $k_\text{И}$, $k_\text{П}$ are weight coefficients which formulate the priority of each quality characteristic.

Taking into consideration that the values of quality characteristics included in the composed function (1) must be regulated they are to be estimated in the following way:

– for duration of heliocentric and jovicentric phases of the flight and for the number of GA maneuvers (which larger values decrease the mission reliability) as dependency of a current mission value to the maximum value of all missions;

– for the payload mass and duration time of scientific investigation (whose larger values increase the mission effectiveness) as dependency of a current mission value to the maximum value of all missions;

– the value of “orbiting/landing” functional $J_\text{П}$ is equal to 1,0 when landing on a Jupiter satellite (“Europa Lander” and “Laplace-P2)”; 0,5 when studying from the orbit (JUICE и “Laplace-P1”); 0,2 from the GA trajectory (“Europa Clipper” and “Galileo”); 0,1 without any GA maneuvers (“Juno”).

Table 4

The values of the Jupiter mission effectiveness criteria

Mission	$F_С$	$F_Ю$	$F_{ГМ}$	$F_{ПН}$	$F_И$	$F_П$	F
"Galileo"	0.040	0.023	0.021	0.200	0.170	0.070	0.522
"Juno"	0.048	0.108	0.050	0.042	0.250	0.035	0.532
JUICE	0.031	0.088	0.033	0.088	0.149	0.175	0.565
"Europa Clipper"	0.037	0.073	0.012	0.061	0.122	0.070	0.376
"Europa Lander"	0.050	0.100	0.031	0.046	0.118	0.350	0.696
"Laplace-P1"	0.039	0.085	0.050	0.079	0.079	0.175	0.506
"Laplace-P2"	0.039	0.080	0.038	0.082	0.079	0.350	0.668

The values of weight characteristics expressing the particular quality parameters mustn't be defined exactly and are subjective. As a rule these values are chosen in accordance with the expert evaluation method in such a way to reflect the priority of each quality characteristic [16]. In this case one of the most important scientific effectiveness criteria may be the technology mass and the inclusion of landing on the Jupiter satellite into the mission scheme. The flight duration and the number of GA maneuvers influence mainly the mission reliability not its scientific value. That is why these coefficient values must be lower. According to the outlined logic the following weight coefficient values may be taken: $k_{tС} = 0.05$, $k_{tЮ} = 0.10$, $k_N = 0.05$, $k_m = 0.25$, $k_И = 0.20$, $k_П = 0.35$.

In accordance with the values of the partial criteria of mission effectiveness mentioned above the functional value for the outlined missions for the Jupiter system studying (1) were estimated. The results are shown in tab. 4. The final value of effectiveness is in the last column. When calculating the criteria $F_Ю$ and $F_{ГМ}$ for the JUICE project the phases of high-latitude studying the Jupiter and the Europa investigations by two-time orbiting are neglected as these phases increase the scientific effectiveness of the mission and are not to low the functional final value.

It must be mentioned that the "Laplace-P" mission is complex because it consists of two coordinated spacecrafts operating simultaneously. That's why the arithmetic mean value for two spacecrafts may be taken as the final functional value (1) for the "Laplace-P" project. It is equal to 0.587. Data analysis from tab. 3 shows that the "Europa-Lander" mission demonstrates the maximum effectiveness in accordance with the specifications stated. This mission seems to be more attractive due to the landing availability by high technology mass. The relatively short period from the ground take-off to the reaching the Jupiter satellite orbit is also essential. This is achieved by using the super-heavy launcher "SLS".

Recommendations for "Laplace-P" mission further elaboration. To improve the "Laplace-P" mission effectiveness the mass of targeted spacecraft payload and power system capacity may be updated without increasing the total mass of the spacecraft. Thereto several options are considered, for example a configuration with the substitution of four SP (with the complex multiple opening and closing system) for 2 RITEG units. The possibility of life-extension for the lander should be taken into consideration. It is assumed to improve the spacecraft structure in terms of the mass and the desired degree of the dose buildup protection. The lander structure [6] may be improved in terms of the frame and the fuel tank unit integration. Such decision is dictated by the need to displace the spacecraft mass center closer to the surface formed by landing pads. Based on the results of the preliminary engineering the load-carrying construction for the lander propulsion system is a welded frame which has a form of a frustum with four peaks on the top and eight those on the bottom. Landing pads, fuel tanks, spherical tanks, compensator tanks, bars and carriers for engine assembly and structural components (8) are set up on the frame. The usage of a lower thrust (mass) propulsion engine is optionally recommended.

The more effective trajectories of two spacecrafts should be elaborated which may provide less duration time of the flight to the Jupiter system, less total dose of radiation and waste of fuel. Decisions may be found with the help of the high-altitude GA maneuvers in a restricted three-body problem [17] and it requires a high level of qualification in the field of dynamical astronomy and a creative approach from decision makers.

In spite of the high complexity the above mentioned problems can be solved at the following stages by the detailed in-depth analysis by reference of the experimental data described in this paper.

Conclusion.

1. This article presents completed, ongoing and perspective missions to the Jupiter system carried out by Russian and world specialists. The flight schemes in Earth-Jupiter and Jupiter system phases are described. The analysis of spacecraft main characteristics is made.

2. Mission quality criteria for remote and contact the Jupiter system studying are defined and the functional of effectiveness is estimated. According to the achieved results the perspective "Europa Lander" (NASA) expedition is considered to be the most effective one. It is based on the facts that the spacecraft is to be placed into orbit with the help of the super-heavy "SLS" booster and that it has a more advanced flight scheme which allows carrying a great amount of technology mass on the Europa.

3. To improve the effectiveness of the Russian perspective "Laplace-P" mission it is suggested both further structure development of spacecrafts and improvement of the Jupiter mission schemes in terms of up-to-date ballistic engineering methods.

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