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RUSSIAN EXPLORATION OF VENUS: PAST AND PROSPECTS

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Summary. Secure methods of the cost-effective flights to Venus and the passage of its gravity sphere are necessary to increase the amount of scientific and service equipment on board spacecraft and effectively exploration of the solar system. The results of the modern methods of ballistics design using for interplanetary flights to Venus are given with the purpose of entering the Venusian satellite orbit and for the landing on its surface. The main attention devotes to the construction of the launch windows and to the calculation of the reachability areas of the descent vehicle on the surface of Venus.

1 INTRODUCTION

Domestic space missions to Venus traditionally dominated in the world research of Venus, and the bulk of the fundamental knowledge about the planet by the Soviet missions in 1961-1985 was obtained. In those years, Venus was launched 18 automatic stations and made 10 landings – all successful [1]. NASA also carried out two successful orbital projects, the “Pioneer-Venus” and later - the “Magellan”.

After a long break, Venus was studied only from orbit, for example, by the European Venus Express project (2005-2015).

The Venus-D project is the next step after the successful series of Venus and VEGA missions in the 1970s and 1980s. The qualitative difference between modern landing craft from the programs "VEGA" is equipped with the knowledge of the geology of the surface according to the results of radar studies of the spacecrafts "Venera 15,16" and the "Magellan" spacecraft. The lander will land not blindly, as before, but in an area with a known geological context.

The development of cost-effective ballistic schemes of spacecraft’s flights to Venus and the passage of its scope is relevant and necessary to increase the payload of the spacecraft by reducing the mass of fuel [2, 3]. Ballistic design of such schemes, in particular, is an essential part of the promising domestic project "Venus-D", providing for the landing of the descent module on its surface in a given area.

The paper presents the results of the use of modern methods of ballistic design of interplanetary flights for planning flights to Venus (the mission of delivery and, in particular, to land the spacecraft on its surface in a given area), analyzes the methods of implementation of Hesperian projects and improve their efficiency. The main attention is paid to the construction of the launch windows and the method of construction and direct calculation of the reachability areas of the descent vehicle on the surface of Venus.

2010 Mathematics Subject Classification: 70E55, 70M20, 70Q05.
Key words and Phrases: mission design, Venus, descent module, target region of accessibility, gravity assist, “Venera-D” mission

2 THE SHORT HISTORY OF THE HESPERIAN MISSIONS

The Soviet automatic interplanetary probe Venera-3 was the first to reach the Venus surface on March 1, 1966. The USA accomplished the successful mission Pioneer Venus in 1978. This mission included the launch of two spacecraft—the first one was an orbital module and the second one included one large and three small descent modules. They acquired a lot of data concerning the atmosphere, but the landing was not planned, and the descent modules stopped making measurements at the altitude of 12 km. Thus, only Soviet probes have successfully worked on the Venus surface. A number of Soviet space projects aimed at approaching Venus and landing on its surface have been accomplished (Tab. 1 and Fig. 1).

By contrast with the preceding missions, the modern projects of Venus exploration using landing modules plan to land at a given landing point on the Venus surface, which is impossible without using a high-quality Venus maps.

In the middle of October of 1983, Venera-15 and Venera-16 were inserted into orbits around Venus. These satellites were equipped with a radar system for mapping the Venus surface. Later, an atlas of Venus [4] was created based on these data. The radar mapping started by Veneras was continued by the NASA Magellan mission, which did not plan to land on the Venus surface. To help plan the survey, the NASA researchers used the data acquired by Venera-15 and Venera-16. In 1990–1993, Magellan mapped the Venus surface at a higher

Automatic interplanetary probe	Date		Landing coordinates (degrees)		Remark
	launch	arrival	latitude	longitude	
Venera-1	1961/02/12	1961/05/19	—	—	Flyby at a distance of~100 thousands of km
Venera-2	1965/11/12	1966/02/27	—	—	Flyby at a distance of~100 thousands of km
Venera-3	1965/11/16	1966/03/01	—	—	Reached the surface
Venera-4	1967/06/12	1967/10/18	19.0	38.0	
Venera-5	1969/01/05	1969/05/16	-3.0	18.0	
Venera-6	1969/01/10	1969/05/17	-5.0	23.0	
Venera-7	1970/08/17	1970/12/15	-5.0	351.0	
Venera-8	1972/03/27	1972/07/22	-10.0	335.0	
Venera-9	1975/06/08	1975/10/22	31.7	290.8	Venus satellite
Venera-10	1975/06/14	1975/10/25	16.0	291.0	Venus satellite
Venera-11	1978/09/09	1978/12/25	-14.0	299.0	
Venera-12	1978/09/14	1978/12/21	-7.0	294.0	
Venera-13	1981/10/30	1982/03/01	–7.5	303.5	
Venera-14	1981/11/04	1982/03/05	-13.0	310.0	
Venera-15	1983/06/02	1983/10/10	—	—	Venus satellite
Venera-16	1983/06/07	1983/10/14	—	—	Venus satellite
Vega-1	1984/12/15	1985/06/11	7.9	176.7	Halley's Comet

Table 1. Soviet projects aimed at Venus exploration.

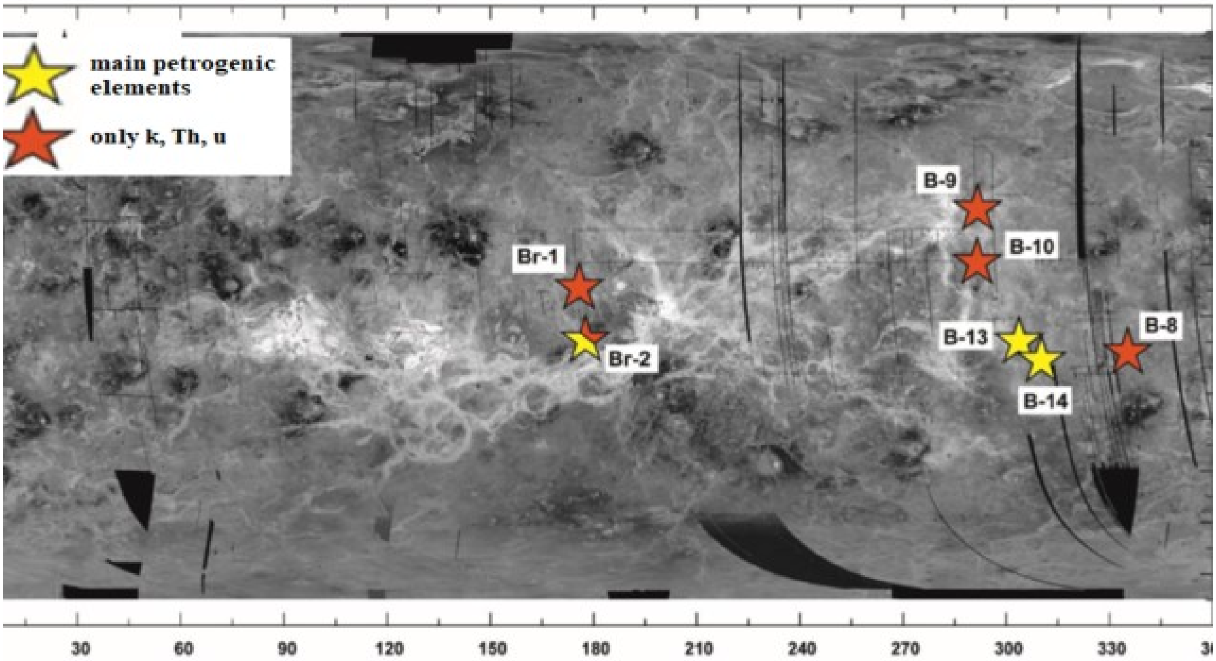

Figure 1. Landing regions of Soviet descent modules of the series Venera (B) and Vega (Br) on the Venus surface (borrowed from [5]).

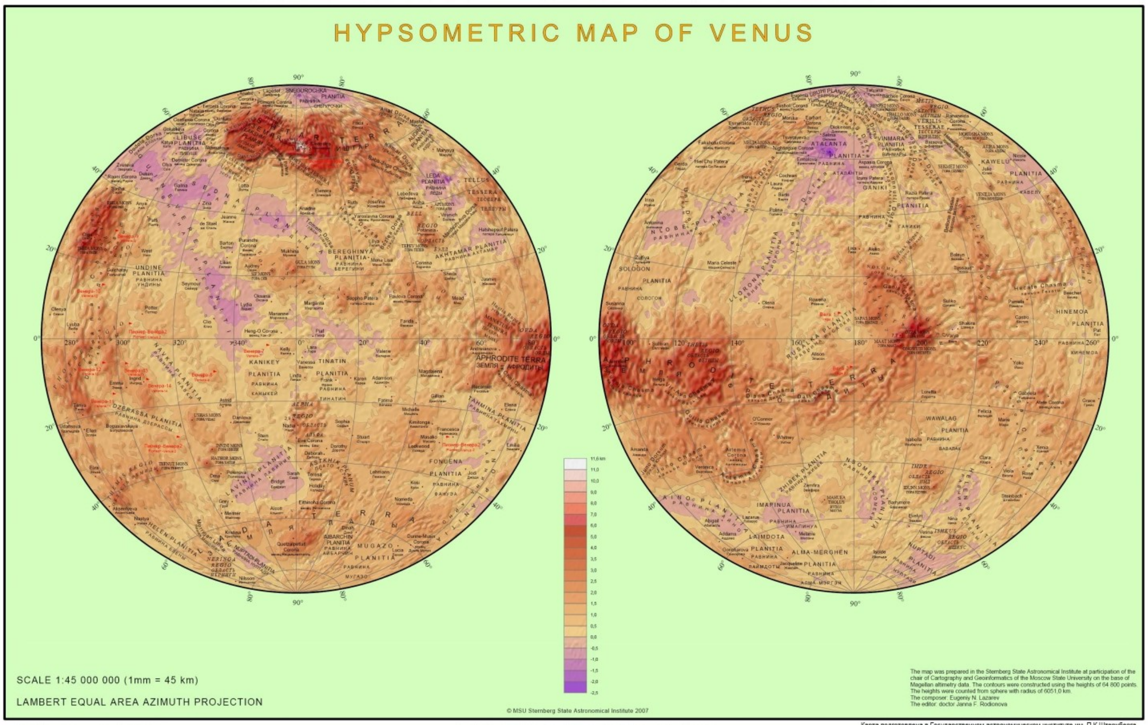

Figure 2. Hypsometrical topographic map of Venus.

spatial resolution.

Later, more accurate hypsometrical topographic and geological maps of Venus were created based on the data collected by Magellan (in particular, the hypsometrical topographic map of Venus (Sternberg State Astronomical Institute, 2006), see Fig. 2.

Nowadays, Venusian landing missions are planned based on the analysis of ballistic reachability regions for specific launch dates; the reachability regions are put on maps of terrain priority types, which intensively use the available morphological and geological data (Fig. 3, [5, 6]). The reachability regions are shown by grey and white circles in this figure. The lander is able to land in a region whose geological characteristics are known in advance [7].

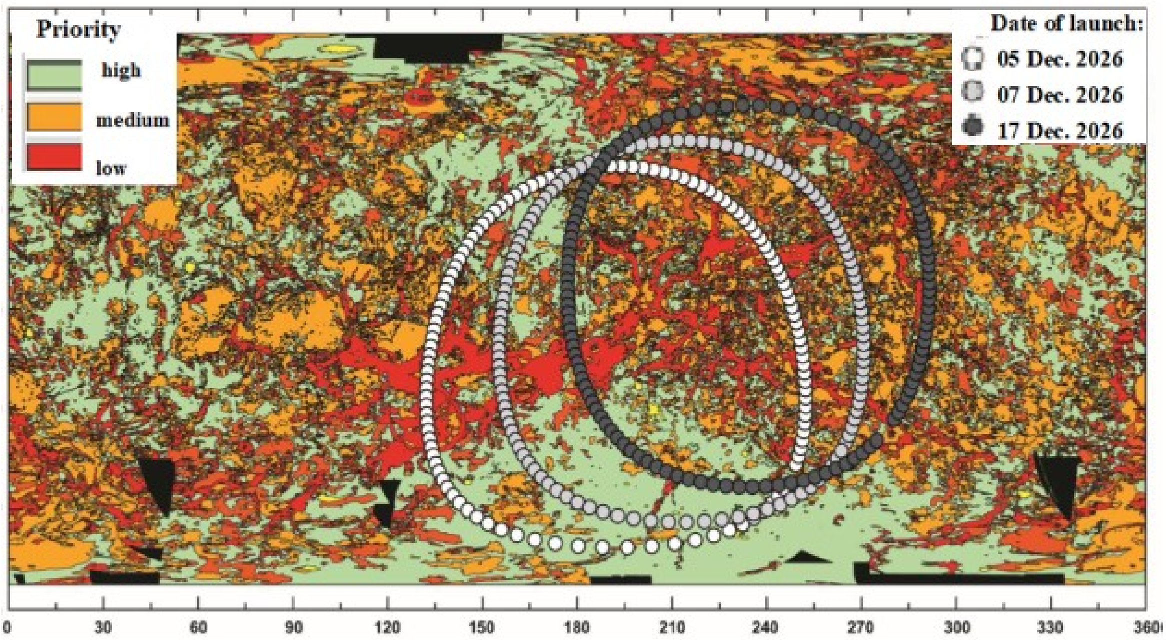

Figure 3. Priority map of Venus corresponding to the geological map of Venus with ballistic reachability regions. Borrowed from [5, 6].

2. DESIGNING LAUNCH TIME WINDOWS

Procedures for calculating launch windows for interplanetary flights are thoroughly described in the literature [8-11]. Since the flight to Venus is energy consuming, the priority in designing flight trajectories is to minimize the characteristic velocity.

The possibility to reach a planet with the minimum possible energy consumption repeats periodically. First of all, the cyclicity is determined by the synodic period T_{syn} of repeated configuration of mutual arrangement of two planets. The period T_{syn} is almost fixed relative to the stars [9], and it is expressed in terms of the revolution periods of these planets T_1 and T_2 by the rule

$$T_{\mathrm{syn}} = T_1 T_2 / |T_2 - T_1|.$$

In the classical astronomy, oppositions are the configurations in which Earth is on the same straight line with Sun and another planet, and the direct ascent of Sun and the second planet differ by 180°. The time interval between two events when Earth and an outer planet are closest to each other is called the period of their favorable oppositions. In modern astrodynamics [9], this concept is generalized to the case of two planets; the period of their mutual configuration in the heliocentric frame of reference is approximately determined as the least common multiple of the sidereal periods of these planets and their synodic period.

The opportunity of transfer to Venus with minimum energy consumption occurs every eight years at the time of favorable oppositions. A slightly greater characteristic velocity for the transfer to Venus is required every 1.6 years.

The preliminary approximate evaluation of the optimal launch dates is determined using the Hohmann transfer orbit in the circular model of planetary motion in the Solar system. The initial approximation of the launch dates is then improved taking into account the eccentricity of the planets' orbits and their noncoplanarity. A grid of departure and arrival dates is formed, the Lambert problem about the transfer in the central field of Sun is solved for them, and the departure and arrival velocities are found. The sum of these velocities gives the characteristic velocity required for the transfer. Based on these calculations, the isolines of the characteristic velocity in the coordinate plane are constructed. The departure dates are plotted on the horizontal axis, and the transfer time is plotted on the vertical axis [3].

Next the distance of the pericenter the hemisphere through which the asymptotic axis of the arrival hyperbola passes, and the inclination to the equatorial Venus plane are specified. The transfer from the near-Earth orbit to the trajectory ensuring the arrival with the prescribed parameters is then determined. The grid of departure and arrival dates and the range of transfer durations were calculated with the accuracy up to one earth day.

3. OPTIMAL LAUNCH DATES FOR THE VENUSIAN MISSIONS DELIVERING PAYLOAD

Tab. 2 summarizes the launch dates that are best from the viewpoint of characteristic velocity expenditure for the period 2021–2028. The best launch dates to Venus are in May 2023 and in December 2024.

Date		Flight duration, days	Velocity, km/s		
launch	arrival		departure	arrival	sum
2021/10/27	2022/04/05	160	2.80	4.76	7.56
2023/05/26	2023/10/27	154	2.56	3.71	6.27
2024/12/06	2025/05/15	160	3.27	2.70	5.97
2026/06/09	2026/12/09	183	3.86	2.98	6.84
2028/01/11	2028/07/24	195	4.63	3.49	8.11

Table 2. The best launch dates to Venus in 2021–2028.

The launch window in 2024 requires the minimum characteristic velocity expenditure, and the launch window in 2028 requires the maximum characteristic velocity expenditure. The difference between the maximum and minimum values is about 2 km/s. Fig.4 illustrates the characteristic velocity expenditure for Earth–Venus transfer in the launch windows 2021–2028. The characteristic velocity expenditure is plotted on the vertical axis in km/s for the central point of the window.

In Fig. 4,5 we give the plots of launch windows for the period 2021–2028 for interplanetary Earth–Venus transfers.

Each figure shows the level lines of the characteristic velocity needed for the transfer (they are called porkchop plots in English and seashells in Russian [12]. The launch dates (in days) are plotted on the horizontal axis. The zero point corresponds to the first of January of the year indicated in the figure caption. For example, for Fig. 4 this is January 1, 2021. The transfer time is plotted on the vertical axis (in days). The maximum value of the characteristic velocity for these figures is 10.5 km/s. The cursor (in the shape of a cross) is at the point with the minimum total characteristic velocity (its value is printed nearby). The cross bars are extended to the intersection with the coordinate axes. Near these intersection points, the departure date and time (on the horizontal axis) and the arrival date and time (near the vertical axis) are shown.

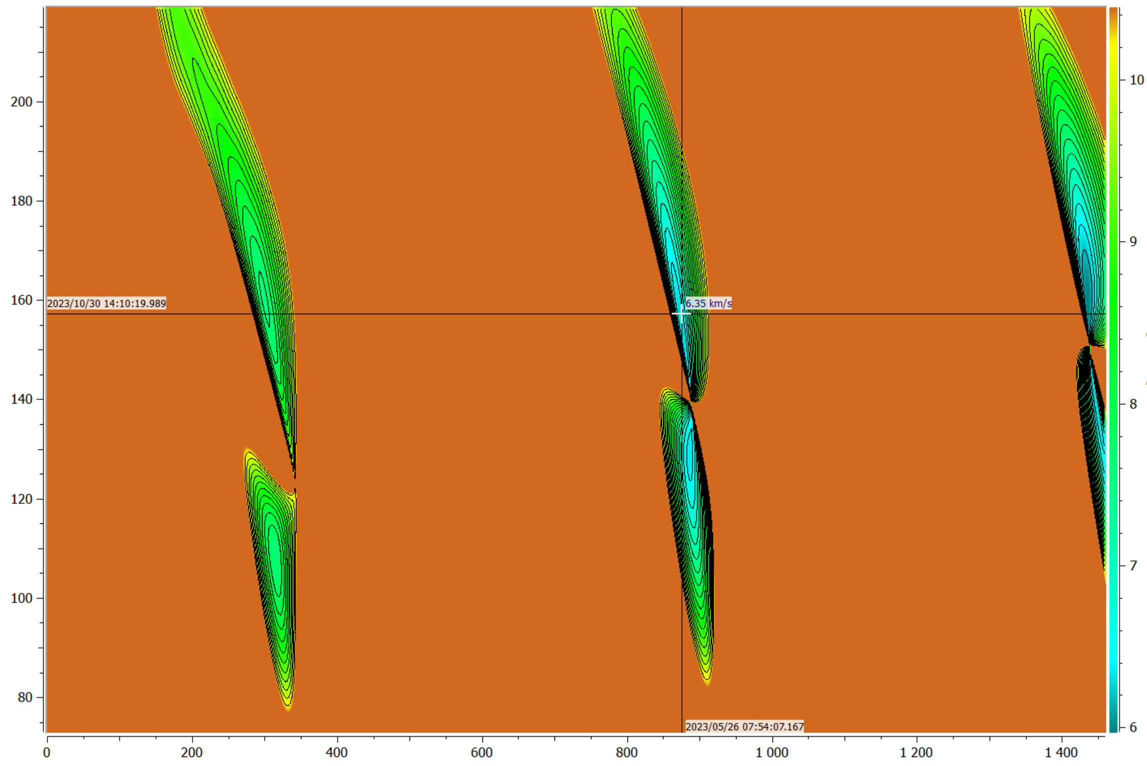

Figure 4. Earth–Venus transfer for 2021–2024. Total characteristic velocity.

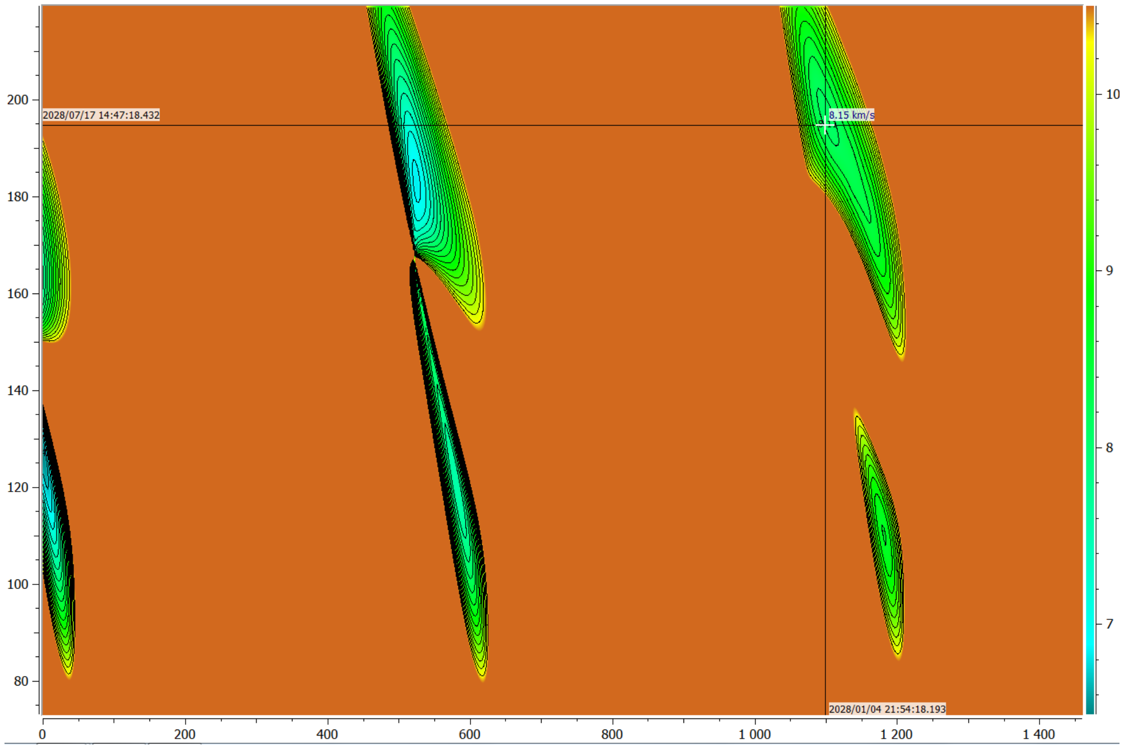

Figure 5. Earth–Venus transfer for 2025–2028. Total characteristic velocity.

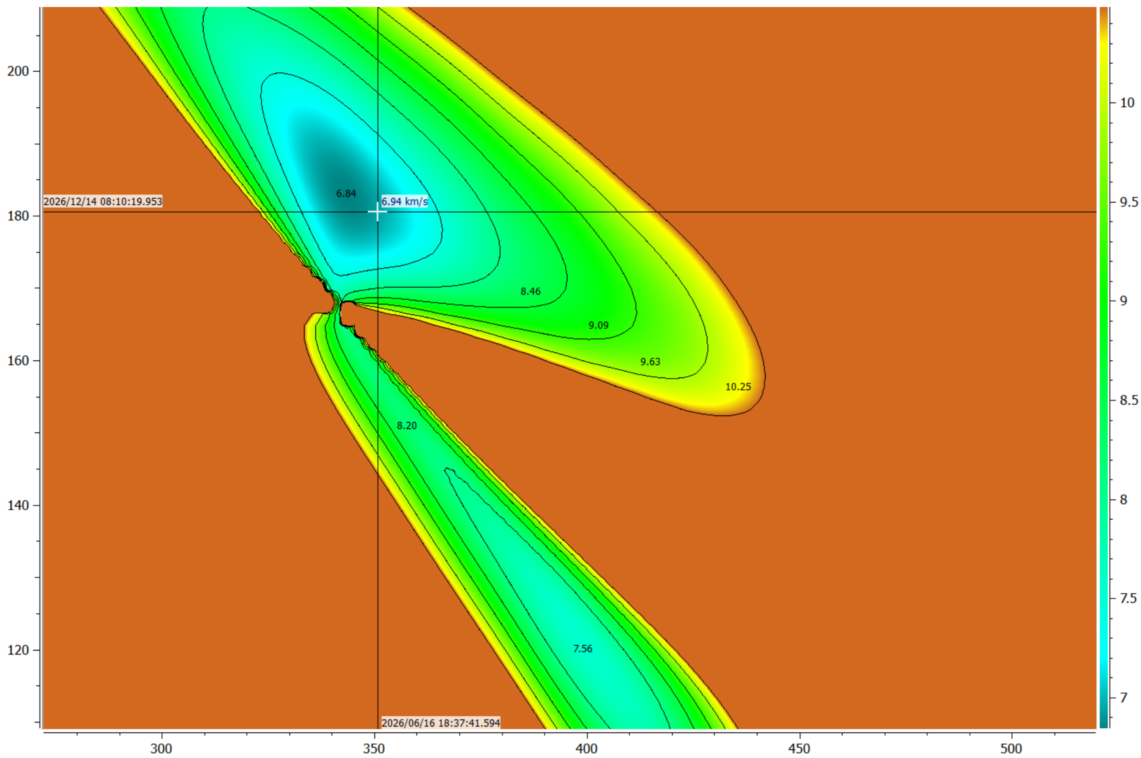

Figure 6. Isolines of characteristic velocity for the launch window in 2026.

4. OPTIMAL LAUNCH DATES FOR THE VENUSIAN DELIVERING PAYLOAD: TECNIQUE

The numerical scale is represented by the fraction 1/M, in which the denominator M is the number showing the factor by which the dimensions in the map are decreased (1:M). When different numerical scales are compared, the scale with a greater denominator M is smaller.

Let us describe in more detail the launch dates found above. Fig. 6,7 show the isolines of the total characteristic velocity (*porkchop plots*) for the launch dates presented in Table 3 on a greater scale [12]. The launch dates are plotted on the horizontal axis, and the transfer time is plotted on the vertical axis (in days). The numbers show the total characteristic velocity in km/s. For the second part of the eight-period cycle (including the launch windows in 2026, which is most probable for the implementation of space missions), the detailed isolines of the characteristic velocity are shown. They were constructed interactively using the software package BalCalc developed in the Ballistic Center of the Keldysh Institute of Applied Mathematics.

The probable early launch date for the Venera-D project is 2026 (the launch window is 2026/05/13–2026/07/08). However, the dates up to 2032 are also considered. In Fig. 8 show the isolines of the total characteristic velocity for the additional launch windows 2029–2032 of the Venera-D project.

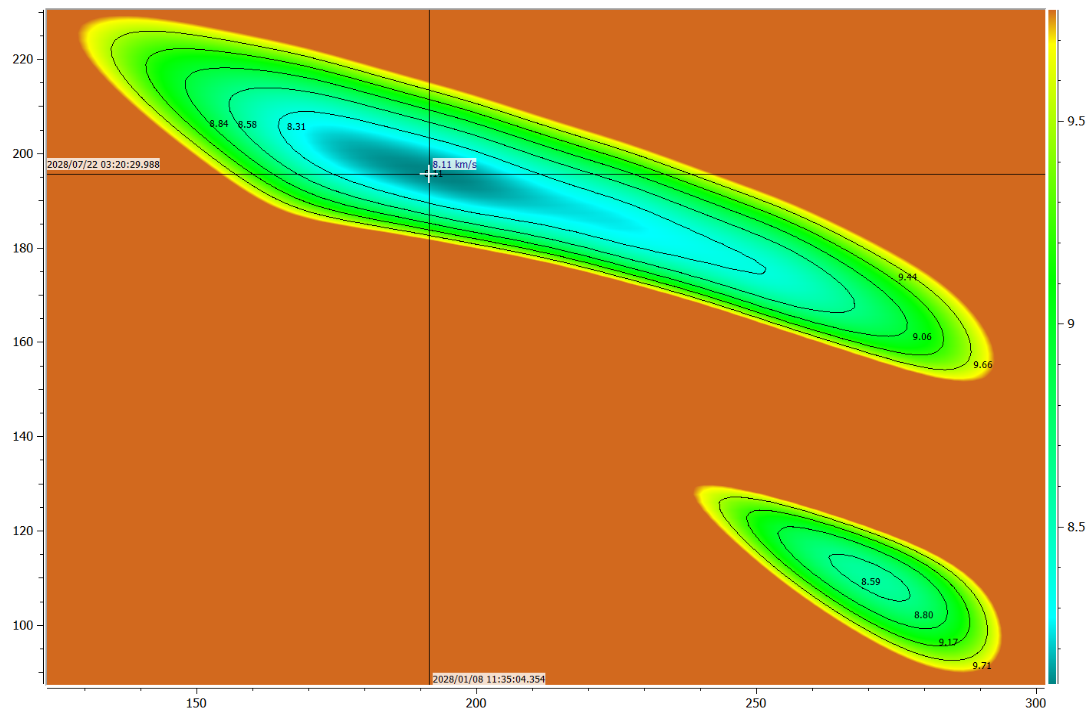

Figure 7. Isolines of characteristic velocity for the launch window in 2028.

5. SPECIFIC FEATURES OF THE PROBLEM OF GUIDING DESCENT MODULES TO THE PRESCRIBED VENUSIAN REGIONS

The problem of guiding descent modules to the prescribed regions of Venus and the problem of forming Venus-centric orbits with given parameters was studied, e.g., in [13], where Pioneer–Venus 1, 2 ballistic missions was designed; this mission was launched on August 8, 1978 with the goal of examining the Venus atmosphere. The solutions found in that research are still useful for designing new missions. As a preparation for designing this mission, reachability regions on the Venus surface depending on the coordinates and the entry angle of the descent module into the Venus atmosphere were mapped.

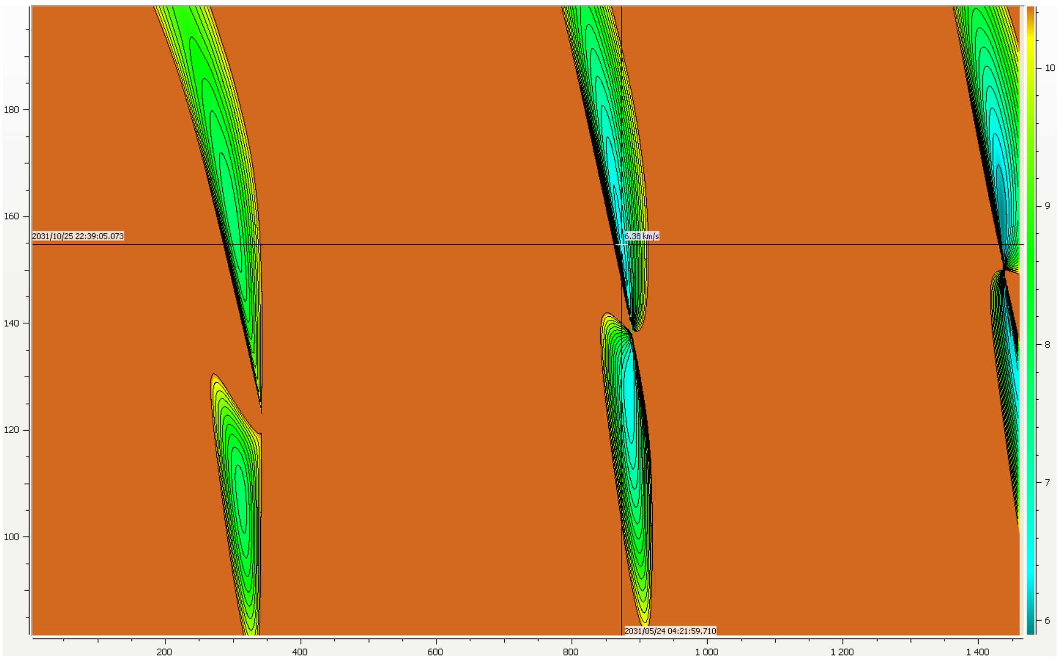

Figure 8. Earth–Venus transfer for 2029–2032. Total characteristic velocity.

More detailed exploration of Venus (e.g., within the Russian project Venera-D [5]) require not only the transfer to the planet but also the formation of an orbital subsatellite and a descent module at the given point of the flyby trajectory. The orbital subsatellite is designed to fly in the Venus atmosphere at an altitude of 50 km, and the descent module must investigate the causes of water loss from Venus. In one version of the project, the subsatellite separates from the main SC after the braking impulse accomplished when the spacecraft approaches Venus on a hyperbolic trajectory. After the subsatellite separation, the SC goes into a circular orbit around Venus. On this orbit, the descent module separates from the SC and lands on the Venus surface. Another project version assumes landing without injecting the SC into a Venus orbit.

The Venera-D project concept is based on the experience gained in preceding successful missions to Venus [5, 12]. The descent module, which includes a lander and maybe other atmospheric modules, separates from the SC near Venus. The SC goes into a Venus orbit and becomes its satellite. It is used for communication with Earth, with other modules, receives data from the lander, coordinates the investigations, and transmits data to Earth.

6. CALCULATION OF THE REACHABILITY VENUSIAN SURFACE FOR THE DECENT MODULE

In this section, the procedure for constructing reachability regions on the Venus surface for the landing mission scheme is described in which the landing is planned from the transfer trajectory without the SC becoming a Hesperian satellite. If the entry angle into the atmosphere is too small, the SC can bounce from the atmosphere; if the entry angle is large, the SC can burn. In this paper, we use the nominal entry angle of –15°±1°. Different points on the Venus surface can be reached by varying the SC orbit inclination.

For calculations, we use the picture plane (ξ,η) [10, 12]. The initial data for finding the reachability regions on the Venus surface are the departure date and time, the starting velocity V_∞, the inclination of the transfer orbit, and the distance of the pericenter for the arrival hyperbola. For the given orbit inclination, the coordinates (ξ,η) are used to solve the corresponding boundary value problem for ensuring the prescribed atmosphere entry angle. As a result of the calculation, the launch time and V_∞ are refined, and the coordinates (ξ,η) that unambiguously correspond to the given entry angle are found. Additionally, for the time when the descent module enters the Venus atmosphere, the angles Earth–descent module–Venus and Sun–descent module–Venus are determined. By varying the orbit inclination, we can obtain a band of reachability points on the Venus surface. The parameter of this band is the launch date. Thus, we find the reachability region for landing on Venus without creating an intermediate Venus satellite.

In [3], for each launch date given in Tab. 2, a combination of according figures for the case when the asymptotic axis of the arrival hyperbola passes through the northern hemisphere is presented (for the southern hemisphere, the configuration is symmetric). The first figure shows the locus of landing points in the plane longitude–latitude. The same locus of points is marked at the second figure on the sphere depicting the Venus surface. The arrow shows the Venus rotation axis (the arrow is directed to the North); the equator and the meridians for 0^0 and 180° are also shown. The segment in this figure connects the Venus center with the point (0°,0°).

For launch window in 2026, which is the most favorable for space projects, Fig. 9 depicts the reachability regions on the Venus surface on a greater scale. They were constructed interactively using the software package BalCalc mentioned above. The union of these regions (the "reachability region" on the Venus surface) in the entire arrival window 2026/05/14 – 2026/07/03 is also shown.

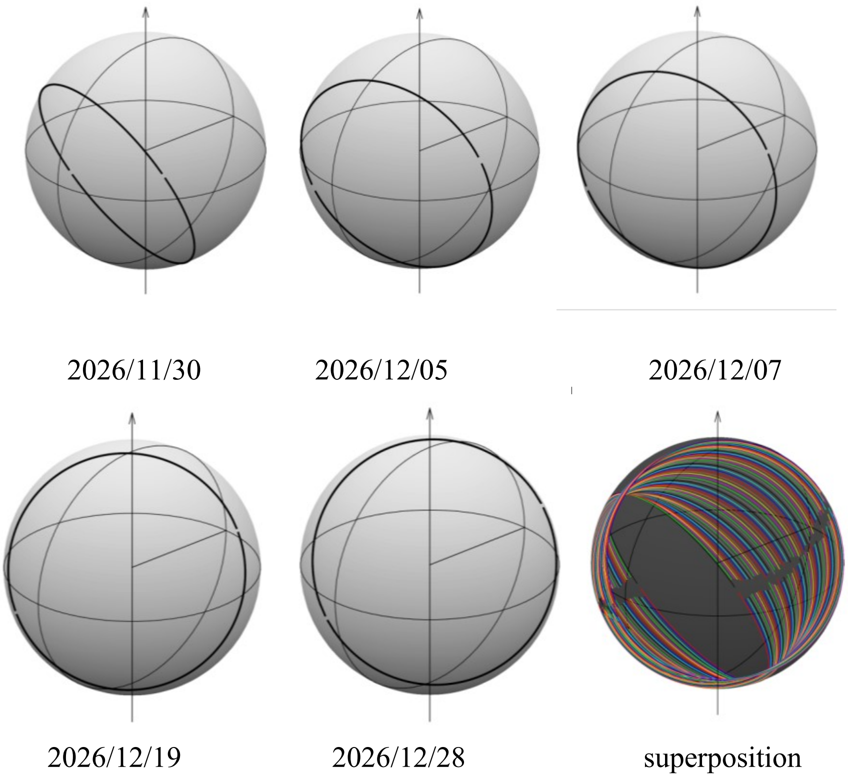

Figure 9. Dependence of the latitude and longitude of the landing point (deg.) for the launch window in 2026 for different launch dates for the arrival through the northern of southern hemisphere and their union over the entire arrival window 2026/05/14 – 2026/07/03.

CONCLUSIONS

Methods of ballistic mission design adapted for future exploration of the near-solar space and Venus are presented, and the following main results are obtained.

For planning Venus missions, which requires trajectories for the delivery (in particular, for landing) spacecraft on the Venus surface in a prescribed region, launch windows in the period 2021–2032 are found. For these launch windows, the total characteristic velocity, the departure (from Earth) asymptotic velocity, and the arrival (to Venus) asymptotic velocity are calculated.

An efficient procedure for constructing the reachability regions corresponding to these launch dates for the descent module on the Venus surface for the landing transfer scheme is described.

It is found that the launch window in 2024 requires the minimum expenditure of characteristic velocity. The launch window in 2028 for the orbital– landing transfer ballistic scheme requires the maximum expenditure of characteristic velocity, which is over 8 km/s. The difference between the maximum and minimum expenditures is about 2 km/s.

The implementation of the transfer trajectory requiring the maximum expenditure of characteristic velocity is questionable for the available Russian rockets. For this reason, some reachability regions on the Venus surface can be actually unreachable. The reachability regions evolve with time. To overcome the difficulty due to large energy expenditure, missions to Venus can be planned once in eight years or more energy efficient ballistic schemes can be used [14].

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