

Research Article

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Gravity assists maneuver in the problem of extension accessible landing areas on the Venus surface

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Abstract: This study discusses the usage of Venus gravity assist in order to choose and reaching any point on Venusian surface. The launch of a spacecraft to Venus during the launch windows of 2029 to 2031 is considered for this purpose. The constraints for the method are the re-entry angle and the maximum possible overload. The primary basis of the proposed strategy is to use the gravitational field of Venus to transfer the spacecraft to an orbit resonant to the Venusian one – with the aim of expanding accessible landing areas. Results of the current research show that this strategy provides an essential increase in accessible landing areas and, moreover, may provide an access to any point on the surface of Venus with a small increase in ΔV required for launch from the Earth and in the flight duration. The comparison with the landing without using gravity assist near planet is also given.

Keywords: Venus, Venera-D, landing, accessible landing area, gravity assist maneuver, resonant orbit.

Nomenclature

ΔV characteristic velocity, km/s;
 r_p periapsis distance, km;
 r_{pmin} minimal periapsis distance to the planet during its flyby, km;
 r_{pvirt} virtual periapsis distance, i.e. the parameter required for calculating landing points on the planet surface, km;
 r planetocentric distance at the point of spacecraft re-entry into the atmosphere, km;
 ψ angular radius of landing circle, deg;

φ angular radius of the circle of possible pericentres, deg;
 ϑ module of the true anomaly of the spacecraft at the point of re-entry, deg;
 θ horizontal flight path angle (re-entry angle), deg;
 e eccentricity of the incoming hyperbolic orbit;
 p the parameter of the incoming hyperbolic orbit, km;
 μ gravitational constant of the Venus; $\mu = 324859 \text{ km}^3/\text{s}^2$;
 V_{ai} heliocentric velocity of the spacecraft, km/s; $i = 1, n$;
 V_p Venus orbital velocity, km/s;
 V_r relative velocity of the spacecraft after Venus gravity assist (also asymptotic velocity of the spacecraft), km/s; $V_r = V_{ri} = V_\infty$; $i = 1, n$;
 V_{r0} relative velocity of the spacecraft before Venus gravity assist, km/s;
 α_{min} minimum turning angle required to obtain relative velocity V_r , deg;
 α_{max} maximum turning angle required to obtain relative velocity V_r , deg;
 α^* maximum turning angle on which the V_r can be turned by gravity field of the planet, deg;
 δ angle between Venus orbital velocity and V_{r0} , deg;
 γ angle between pole of the Venus and projection of the V_{r0} on the plane perpendicular to V_p , deg;
 A area accessible for landing, % of Venus surface.

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1 Introduction

Venera-D is a Russian-American project with international involvement aimed at studying the surface and atmosphere of Venus (Senske *et al.* 2017a,b; Eismont *et al.* 2019; Zasova *et al.* 2019). The project is expected to send several space missions to Venus during the launch windows starting from 2029. The spacecraft will include a lander and an orbital module. The lander is intended to be used with and without roll control capability. The lander will also include a long-lived (about 1 month) and a short-lived (a few hours) scientific station (Zasova *et al.* 2019).

In the past, there have been several missions to study Venus launched from 1960-1986. Mariner 2 was the first spacecraft to fly at approximately 34,000 km from the surface of Venus in 1962, transmitting data on the planet's hot atmosphere and the absence of its own magnetosphere. Venera 7 was the first spacecraft to land on the surface of Venus in 1970 and transmit scientific data on the surface and lower atmosphere. The last successful missions to Venus were Soviet Vega 1 and 2 launched in 1984. The last mission to Venus, however, was Akatsuki (JAXA), the purpose of which was to study the planet's atmosphere and surface using an orbiter.

An important part of a mission to study Venus surface is the selection of the most valuable landing sites in order to obtain scientific information. The choice of such sites is primarily related to geological and geochemical surface features, as well as the ability to make a safe landing on the planet (Ivanov *et al.* 2017). However, the possibility of choosing such places is limited, first of all, by the level of permissible maximum overload, which the spacecraft is able to withstand during the descent. Another factor is the duration of the launch window. Due to the short duration of the launch window, which is traditionally accepted of about two weeks, it is impossible to ensure landing in any selected area on the surface of Venus. To expand the available areas on the surface of Venus an exit to the intermediate near Venusian orbit can be used (Senske *et al.* 2017a,b; Eismont *et al.* 2019; Fedyaev *et al.* 2019; Zasova *et al.* 2019; Eismont *et al.* 2021a). Expansion of the available landing regions in this case will depend on the near-Venusian orbit of spacecraft, to ensure landing in any given region can be achieved by entering the intermediate circular orbit of the spacecraft. However, this approach would require a high cost of ΔV to perform maneuver to transfer to such orbit. The easiest way to increase reachable surface is to broaden the windows of departure from the Earth and arrival to the Venus dates. However, our studies have shown that such approach is not effective enough to solve the problem. Another quite

obvious method supposes to use different maximum allowed overloads for different regions of Venus for landing. In this case in order to withstand the increased overloads one needs to use stronger structures and instruments which increase mass and cost.

Current research is intended for the problems connected with Venera-D project which includes landing on Venus surface. Now the project is in the phase of development when the landing site is not chosen. So, it is quite natural to demand from scientific experiments, the trajectory design scenario and mission parameters to secure the maximum possible area of the Venus surface accessible for spacecraft landing (Eismont *et al.* 2021b). To satisfy these requirements means allowing maximum freedom for optimizing landing site for fulfilling explorations. But reachable flight dynamics characteristics put very strong constraints on standard approach when parameters of transfer trajectory to Venus are chosen in such a way to maximize simultaneously payload mass to be delivered onto Venus surface. So, in the article we propose to use the own Venus gravitational field to transfer the spacecraft to a resonant orbit for expansion of accessible landing areas on the planet surface.

The use of the gravitational fields of celestial bodies to obtain a resonant orbit of spacecraft for reducing velocity is well known. The first to perform such a maneuver was Mariner-10, which used a gravity assist maneuver near Venus in 1974 for moving to an orbit with a period equal to twice the orbital period of Mercury. A paper (Strange *et al.* 2008) has proposed methods for obtaining resonant orbits at Saturn's satellite Titan. A similar technique for putting a spacecraft to a resonant orbit has also been used in (Uphoff *et al.* 1976), which describes gravity assist maneuvers in the Jovian system to reach Europa and Ganymede.

The current paper takes research of using gravity assist maneuvers leading to transfer spacecraft from initial Venus flyby trajectory to another one belonging to the Venus resonant heliocentric orbit having spacecraft-Venus periods ratio one to one. It means that after this Venus flyby, the spacecraft returns to Venus one-Venus year later with relative trajectory parameter allowing to land on most part of the Venus surface.

Notice, if generally accepted methods are to be used, leading to reaching a given landing point on the surface of Venus, these require the use of a deep-space maneuver on the flight path, but this approach would require additional fuel consumption, which may become unacceptable when it is necessary to provide a landing at any point on the surface. Therefore, this paper considers the replacement of such a maneuver by a gravity assist maneuver near Venus,

but at the cost of this is an increase in the time of reaching the landing point on the Venus surface.

2 Landing to the Venus surface from the incoming hyperbolic trajectory of the spacecraft

In order to simplify the calculation and optimization of trajectories of the flight to Venus, the method of patched conic approximation is used (Prado 2007), in which the spacecraft trajectory is separated into planetocentric and heliocentric sections. In this approach the n -body problem is split into n two-body problems. Spheres of influence of planets are reduced to a point in heliocentric sections and are considered to have infinite dimensions at calculation of the spacecraft motion in planetocentric sections. In view of this, the spacecraft velocity at the boundary of the planet's influence sphere is assumed to be equal to V_∞ . The trajectory of the spacecraft within the planetary sphere of influence is calculated according to the Keplerian theory. The heliocentric part of the trajectory, connecting two planetocentric sections is determined by solution of the Lambert problem, which consists of determining the trajectory by two given initial positions of celestial bodies, between which the flight is made, and the duration of such a flight. In this paper, the Lambert problem is solved by the Sukhanov method (Sukhanov 1989).

Let us analyze landing on the surface of Venus with hyperbolic approach trajectory. When the spacecraft enters the sphere of influence of Venus, a bunch of incoming hyperbolic trajectories is formed (Figure 1), which form a cylindrical surface with a diameter equal to the small semi-axis of the incoming hyperbolic trajectory (Hintz 2015). Each of the trajectories shown in Figure 1 is accessible to the spacecraft by using a small deviation of the spacecraft approach velocity vector at the boundary of the sphere of influence of Venus. At the same time, any of these trajectories provides entry into the atmosphere of Venus at an angle of 25 degrees to the local horizon. The model of atmosphere can be obtained from (Petropoulos 1988; Zasova *et al.* 2007). Accepted re-entry angle of 25 degrees, according to (Senske *et al.* 2017a,b; Eismont *et al.* 2019; Zasova *et al.* 2019), was used as the main one for the ballistic scenario of the Venera-D project mission. The angle of entry into the atmosphere of 25 degrees corresponds to approximately 180 units in terms of maximum overload (Eismont *et al.* 2019, 2021a).

The geometry of the approach part of the trajectory is shown in Figure 1 for one of the possible choices of velocity

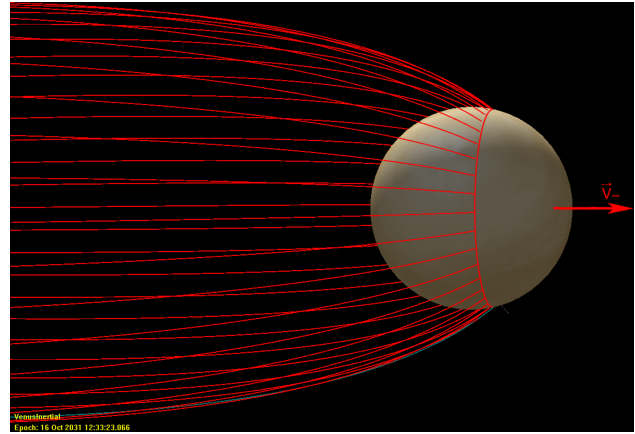


Figure 1. Bunch of incoming hyperbolic trajectories of the spacecraft, where each trajectory is possible for spacecraft by small impulse on the border of Venus sphere of influence.

vectors at infinity. It is assumed that this vector is a free one, *i.e.*, is not attached to any point in space. In the picture it is shown as a vector passing through the center of Venus and corresponds to a set of hyperbolic trajectories with asymptotes going along the formations of a circular cylinder along this vector. Intersections of these trajectories with the surface of Venus form the mentioned landing circle with angular radius ψ to which corresponds the circle of virtual pericenters.

The angle ψ is calculated according to the (Battin 1999; Hintz 2015):

$$\psi = \varphi + \vartheta, \quad (1)$$

The angular radius of the circle of possible virtual pericenters and the modulus of the true anomaly can be calculated as follows (Hintz 2015):

$$\cos \varphi = \frac{1}{1 + r_{pvirt} V_\infty^2 / \mu}, \quad (2)$$

$$\operatorname{tg} \theta = \frac{e r \sin \vartheta}{p}, \quad (3)$$

The landing circle obtained according to (1)–(3) in projection on the Venus surface map is presented in Figure 2.

For each launch and arrival window, we obtain a set of landing circles (rings). Expanding these windows, we correspondingly expand the accessible landing areas on the surface through a corresponding increase of the set of possible for realization centers of circles, in other words, the set of vectors of relative arrival velocities at infinity.

However, as the researches carried out so far (Eismont *et al.* 2021a) show, an expansion of areas of Venus surface reachable by such method has appreciable restrictions, including the fact that it entails growth of necessary characteristic velocity.

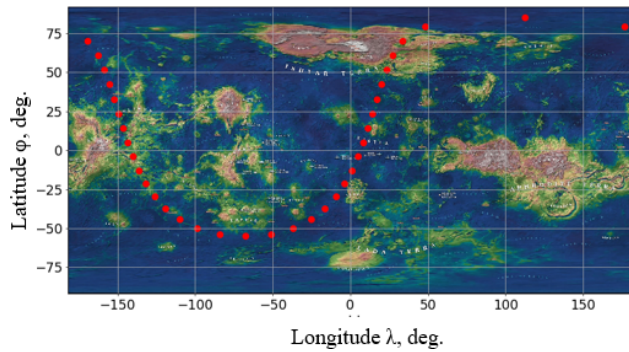


Figure 2. Circle of landing points on the surface map of Venus. Each red spot represents a landing point. The center of the circle corresponds to incoming velocity vector of spacecraft.

The obvious way to partially solve the problem is to perform an intermediate braking maneuver, delivering the vehicle to a satellite's orbit, followed by transferring the descent vehicle to the re-entry trajectory (Vorontsov *et al.* 2011). But, as in the previous case, this is an expensive method in terms of losses in the payload.

Therefore, a scenario is proposed, the basis of which is the performance of gravitational maneuvers near Venus.

3 Gravity assist maneuver in the problem of obtaining a resonant spacecraft orbit

A general concept of the proposed scenario involving the use of a gravity assist to control the choice of the landing area is shown in Figure 3. The main idea is to use the gravitational field of Venus to transfer the spacecraft into the orbit, that would be resonant with Venus in a ratio of 1:1, so that would be orbit with a period equal to the Venusian one. The purpose of this maneuver is to re-fly to Venus through the orbital period. In this case, because we can choose the new landing point by controlling the spacecraft trajectory periapsis relative to Venus during flyby Venus than after return to the Venus landing would be in chosen point. Note that there is no additional consumption of the fuel for the nominal flight, *i.e.* the gravity assist remains unpowered.

The essence of the gravity assist is to change the heliocentric velocity vector of the spacecraft by turning the vector of its relative velocity using the gravitational field of Venus. The operations required for using the gravity assist maneuver near Venus to transfer the spacecraft on an orbit which is resonant 1:1 to Venusian orbital period can be found in (Eismont *et al.* 2021b). In Figure 4 the geometry

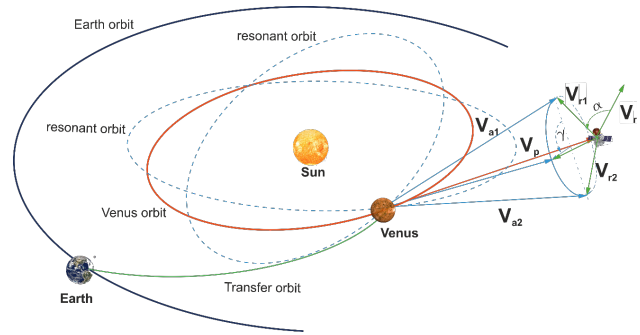


Figure 3. The concept of using the gravity assist maneuver near Venus to expand accessible landing areas on the planet's surface.

of gravity assist is shown. Let us describe some important basic steps of algorithm of obtaining resonant velocity according to (Eismont *et al.* 2021b).

At first let us consider the use of a simple geometry equation that connects the $\mathbf{V}_a$ and $\mathbf{V}_r$ near the planet:

$$\mathbf{V}_a = \mathbf{V}_p + \mathbf{V}_r, \quad (4)$$

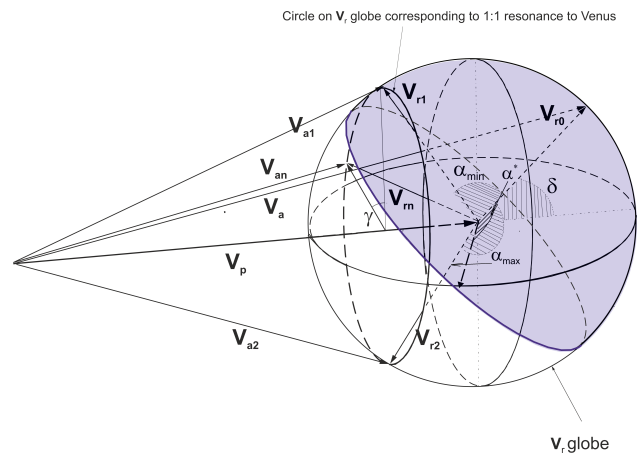


Figure 4. Geometry of a gravity assist maneuver with the spacecraft transfer to an orbit resonant in a 1:1 ratio to the Venusian one.

The vector $\mathbf{V}_p$ defines the first sphere with the center at the beginning of this vector and a radius equal to its magnitude. Next, we define a second sphere with a radius equal to the length of the vector $\mathbf{V}_{r0}$, and the center at the endpoint of the vector of Venus orbital velocity. The intersection of these two spheres determines the positions of relative velocities that are required to obtain a resonant heliocentric velocity of the spacecraft using Eq. (6).

The angle on which V_{r0} can be turned by the planet gravity field, is determined as follows (Battin 1999; Hintz 2015):

$$\sin \frac{\alpha^*}{2} = \frac{1}{(1 + r_{p \min} V_\infty^2 / \mu)}, \quad (5)$$

The required value of the rotation angle α^* is achieved by choosing the radius of the pericenter.

The condition for the availability of the entire set of vectors, the ends of which lie on the circle of intersection of the spheres (see Figure 5) and, accordingly, provide the heliocentric velocity of the spacecraft equal to the Venus velocity, can be written as

$$\alpha_{\max} \leq \alpha^* \quad (6)$$

If the entire set of resonant velocities can be reached through gravity assist of Venus, then landing can be performed at any desired point of the Venusian surface.

4 Landing areas received by using the proposed method

As an example, let us consider a flight to Venus at launch in 2029 or in 2031. Figure 5 shows the inaccessible landing areas, which are only inaccessible for a single launch date. However, since the launch window consists of at least 14 days, there are no unreachable regions on the surface of Venus for the whole launch window, in any of the cases considered.

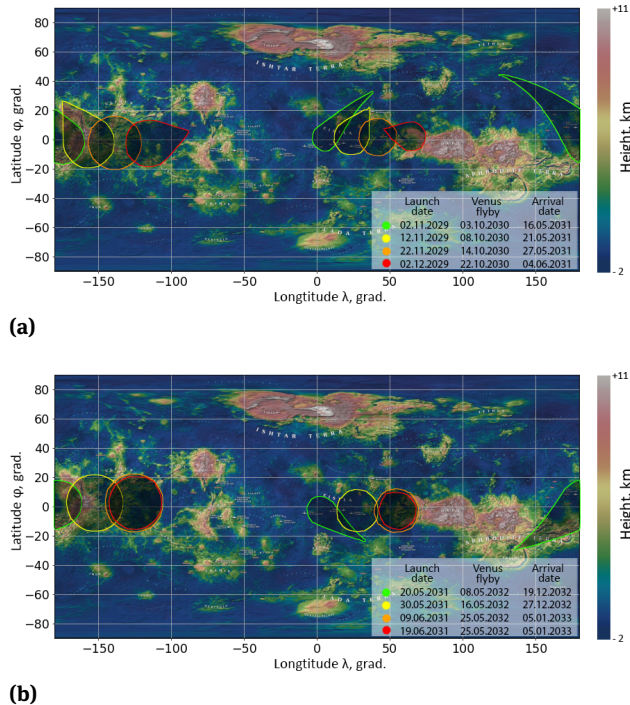


Figure 5. Landing inaccessibility areas (shown in dark color) for launch dates; (a) – 24.11.2029; (b) – 01.06.2031; with landing through a turn after a gravity assist.

This significant increase of accessible landing areas compared to the usage of the standard approach (i.e., without gravity assist) as shown in Figure 6 is explained by the option of controlling the spacecraft motion using gravity assist maneuver.

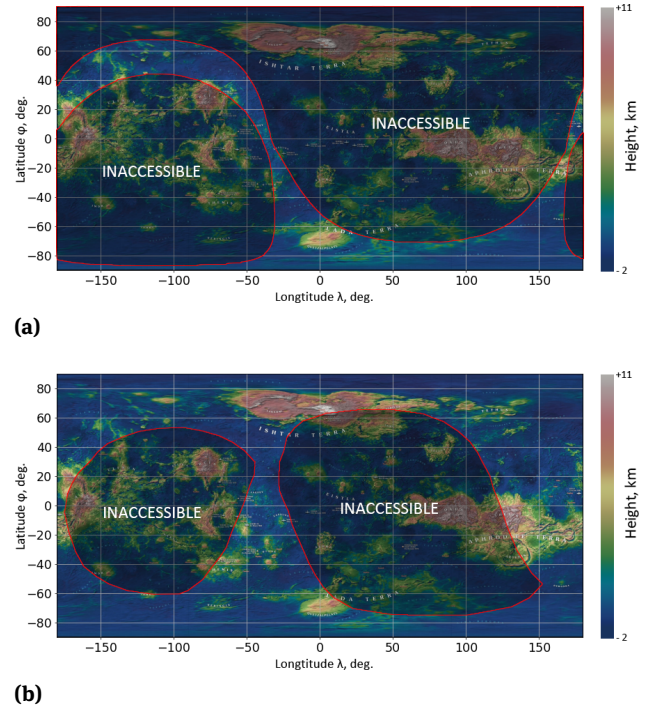


Figure 6. Landing inaccessibility areas (shown in dark color) for launch windows in 2029 (a) and 2031 (b) without Venus gravity assist. The launch windows include 30 launch dates (extended launch windows).

Note that the application of the method is limited by the accepted level of maximum overload that the lander can withstand during descent. Because of this, areas of inaccessible landing points appear in the form of circles. It is also possible that the region of inaccessible landing points extends beyond the circle. These points correspond to the case when constraint (6) is not fulfilled.

As the results show (see Figure 5) the application of the method makes it possible to reach any point on the surface of Venus during the spacecraft launching within the launch window. The only limitation is the allowable level of maximum overload, which is directly related to the chosen entry angle, since $n_{\max} \sim \sin(\theta)$. The analysis carried out in this paper for an input angle of 25 degrees corresponds to an accepted maximum overload level of about 180 units. If it is necessary to decrease the maximum overload level, the area of achievable landing areas will also be decreased. It is also possible that the region of inaccessible landing

points extends beyond the circle. These points correspond to the case when constraint (6) is not fulfilled.

The inaccessible areas can be compensated by shifting the arrival date by several days from the optimal one (Figure 7). In this case, due to the rotation of Venus, it will be possible to get access to previously inaccessible areas. Let us give an example of how to solve this problem (Eismont *et*

al. 2021b). In the mentioned research examples were given for launch windows from 2029 to 2034. Here we show only examples for considered cases in 2029 and 2031.

As shown in Figure 7, if the gravity assist maneuvers date is shifted by five days, it allows reaching the whole surface of Venus at launch on designated dates. The increase of launch ΔV for the flight with the shift of dates of

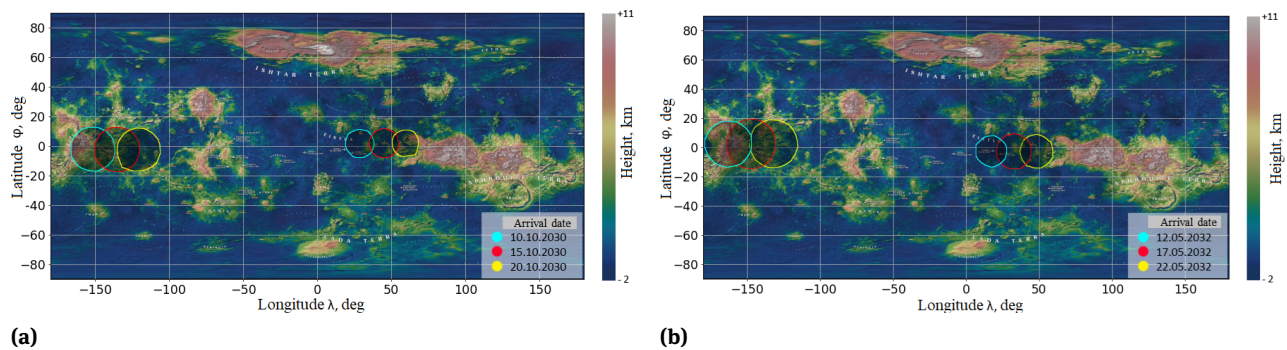


Figure 7. Inaccessible areas for landing (shown in dark color) for launch dates 24.11.2029 (a) and 01.06.2031 (b) with a landing after a gravity assist (Eismont *et al.* 2021b).

Table 1. Characteristics of the spacecraft trajectory during the transit of Venus at launch in 2029.

Launch date dd.mm.yyyy	Transit date dd.mm.yyyy	Landing date dd.mm.yyyy	α_{min} , deg	α_{max} , deg	α^* , deg	δ , deg	γ , deg	ΔV , km/sc	V_{∞} , km/s	A, %
22.11.2029	04.03.2030	14.10.2030	75.4	109.9	111.3	17.3	94.7	4.32	3.23	94.5
23.11.2029	04.03.2030	14.10.2030	76.2	109.1	111.0	16.5	94.6	4.35	3.25	94.9
24.11.2029	05.03.2030	15.10.2030	76.7	108.6	110.6	15.9	94.5	4.39	3.27	95.1
25.11.2029	06.03.2030	16.10.2030	77.0	108.4	110.2	15.7	94.4	4.42	3.29	95.2
26.11.2029	06.03.2030	16.10.2030	76.8	108.6	109.6	15.9	94.3	4.46	3.32	95.9

Table 2. Characteristics of the spacecraft trajectory during the transit of Venus at launch in 2031.

Launch date dd.mm.yyyy	Transit date dd.mm.yyyy	Landing date dd.mm.yyyy	α_{min} , deg	α_{max} , deg	α^* , deg	δ , deg	γ , deg	ΔV , km/sc	V_{∞} , km/s	A, %
31.05.2031	05.10.2031	16.05.2032	72.6	112.3	115.5	19.9	78.8	3.78	3.00	95.1
01.06.2031	06.10.2031	17.05.2032	75.3	109.5	116.2	17.1	78.9	3.78	2.97	95.0
02.06.2031	07.10.2031	18.05.2032	78.1	106.7	116.7	14.3	79.1	3.78	2.94	95.7
03.06.2031	08.10.2031	19.05.2032	80.9	103.8	117.1	11.4	79.2	3.78	2.92	95.8
04.06.2031	09.10.2031	20.05.2032	83.7	101.0	117.4	8.7	79.4	3.78	2.9	95.9
05.06.2031	09.10.2031	20.05.2032	86.2	98.5	117.5	6.1	79.5	3.79	2.90	95.9
06.06.2031	10.10.2031	21.05.2032	87.8	96.9	117.5	4.6	79.7	3.79	2.90	95.7
07.06.2031	11.10.2031	22.05.2032	87.4	97.4	117.3	5.0	80.0	3.79	2.91	95.6
08.06.2031	12.10.2031	23.05.2032	85.4	99.4	116.9	7.0	80.3	3.79	2.93	95.6
09.06.2031	13.10.2031	24.05.2032	83.0	101.8	116.4	9.4	80.7	3.80	2.95	95.8
10.06.2031	13.10.2031	24.05.2032	80.8	104.1	115.9	11.6	81.3	3.80	2.98	96.0
11.06.2031	14.10.2031	25.05.2032	79.1	105.8	115.3	13.4	82.0	3.81	3.01	95.7
12.06.2031	14.10.2031	25.05.2032	77.9	107.1	114.8	14.6	82.7	3.83	3.04	96.1
13.06.2031	14.10.2031	25.05.2032	76.9	108.1	114.2	15.6	83.4	3.84	3.07	96.2
14.06.2031	14.10.2031	25.05.2032	76.1	109.0	113.7	16.4	84.0	3.86	3.10	96.2
15.06.2031	14.10.2031	25.05.2032	75.4	109.7	113.2	17.2	84.5	3.88	3.13	95.8
16.06.2031	13.10.2031	24.05.2032	74.7	110.4	112.6	17.8	85.0	3.90	3.16	95.8
17.06.2031	13.10.2031	24.05.2032	74.1	111.1	112.0	18.5	85.4	3.92	3.19	95.9

Venus flyby does not exceed 50 m/s (Eismont *et al.* 2021b), the gravity assist maneuver remains unpowered. The dates given correspond to approximately average dates from Tables 1 and 2. In these tables, the parameters of only those flight trajectories to Venus for which it is possible to obtain any of the 1:1 resonant orbit are given.

Note that the data in the Tables 1 and 2 show that 2031 is the most preferable launch year in terms of applying the proposed methodology. Because in any date within the 14-day launch window in 2031 it is possible to perform the required gravity assist.

5 Conclusions

In this paper, we consider the application of a gravity assist maneuver near Venus to transfer the spacecraft to a 1:1 resonant orbit to Venus to expand the achievable landing areas on the planet's surface. The limitations were the parameters of landing, namely, the maximum overload or the angle of entry into the atmosphere, which were assumed to be 180 units, or 25 deg accordingly. The parameters of the flyby trajectory at Venus depend on the value of the relative velocity of the spacecraft at the time of the flyby and the radius of the pericenter of the flyby hyperbola. The calculations showed that the entire surface of Venus becomes accessible for landing (Figure 5, Tables 1–2), except for two circles with an angular radius of about 15 degrees. Such areas of inaccessibility appear due to the value of the angle of entry into the atmosphere that we have chosen. According to (1), the radius of the landing circle will be about 75 degrees. To eliminate this limitation, a method is considered, which consists of shifting the date of the gravity assist at Venus by ± 5 days, in order to ensure a shift of the circle by ± 15 degrees on the surface of Venus (Figure 5). Thus, it can be argued that the proposed method allows one to provide an access to any point on the surface of Venus within the range of dates considered.

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