Investigation of Reachable Landing Sites in the "Venera-D" Mission for Various Types of a Lander

A.V. Kosenkova

Bauman Moscow State Technical University, Moscow, 105005

Corresponding author: Kosenkova.AV@yandex.ru

Abstract. This paper presents the investigation of reachable landing areas on the Venus surface taking into account the expected dates and launch windows as a part of the "Venera-D" project for various types of a lander: traditionally used ballistic type of a lander and "lifting body" type of a lander capable of maneuvering during the descent in the atmosphere of the planet. It is shown that the use of a maneuverable "lifting body" type of a lander allows to increase the area of reachable landing sites and to reach the required area, while reducing the overload if using this type of a lander compared to the ballistic type. The evaluation of the range of lateral maneuver for the "lifting body" type of a lander is presented as well as the comparison of the longitudinal range for the "lifting body" and ballistic types of a lander.

INTRODUCTION

The exploration of Venus have a great interest in terms of comparative planetology. The Venus is close to the Earth, they have the similar values of the size, density and amount of energy received from the Sun (Venus is closer to the Sun, but its clouds reflect 75% of the incoming solar energy). Everything this mentioned above earned for Venus the title of "twin of the Earth". Covered with a layer of clouds 20 km thick of 75% sulfuric acid, the planet's surface has been inaccessible to remote observations for a long time.

And despite the success of numerous orbital spacecraft and landers in the past [1-6] and some orbital spacecraft in present, such as the "Venus Express" and "Akatsuki" missions [7, 8], the fundamental issues related to the origin and evolution of Venus , its atmosphere and climate (and, consequently, the Earth climate) remain unresolved [9], and they cannot be solved on the basis of observations only from the orbit. Direct measurements are needed in the atmosphere and on the surface of the planet using landers and atmospheric probes.

Nowadays to continue the Venus exploration various fundamental space research programs are being considered in Russia and abroad [10, 11, 12], including the international project "Venera-D" [13, 14, 15, 16]. At the same time, the issues of creating a lander that would be capable of not only landing on the planet's surface, but also reaching the specified areas that are most interesting for scientists to study, become relevant [17]. In particular, it seems promising to consider the possibility of using new configurations of landers [18, 19], which have the ability to maneuver during the descent in order to increase the area of possible landing sites and reach the most interesting landing areas for studying.

RELEVANCE AND INNOVATION OF THE RESEARCH

At the moment for the "Venera-D" project it is considered the design of a lander, analogous to the Soviet landers of the "Venera" and "Vega" series, which have a spherical form and relate to the ballistic type of a lander that do not have the ability to make maneuvers during the descent, the possible landing sites are quite limited by the dates and launch windows and parameters when entering the atmosphere.

The spacecraft landing areas are determined primarily by the relative velocity vector at infinity of its arrival to Venus. This vector changes depending on the launch dates and the achievement of the planet's surface. An important parameter affecting the position of the available landing site is also the permissible maximum overload when entering the atmosphere, which depends on the entry angle into the atmosphere and its characteristics.

In this connection to expand landing sites, it is promising to consider landers capable of making maneuvering descent to the surface of the planet. Landers with some lift-to-drag ratio at hypersonic range of velocities have this capability. However, ensuring a required lift-to-drag ratio entails the complication of the design and mass increase of the lander. A trade-off solution to this problem may be using the "lifting body" type of a lander [19, 20], which, with an acceptable design complexity, have lift-to-drag ratio sufficient for solving the existing maneuvering tasks in the atmosphere of the planet.

This paper presents the investigation of possible reachable landing sites on the Venus surface taking into account the expected dates and launch windows for the "Venera-D" project for various types of a lander: traditionally used ballistic type of a lander and "lifting body" type of a lander. The paper also shows the possibilities of increasing the achievable landing areas on the planet's surface when using a maneuverable "lifting body" type of a lander.

CALCULATION MODEL OF THE DESCENT

The calculation of the descent for the landing to the Venus surface of is carried out using the developed program which optimize the trajectory by solving the system of differential equations of motion for the lander as a material point in the velocity coordinate system multiple times by using classic Runge-Kutta method. In this case, we accept the following assumptions:

– the lander descends in the atmosphere without turning on the propulsion system ($g_{en}=0$);

– the lander is controlled only by changing the angle of roll γ, sideslip angle $\beta = 0$.

Then the system of differential equations of motion for the lander as a material point in the velocity coordinate system will be as follows [21]:

$$\begin{cases} \dfrac{dV}{dt} = -\dfrac{1}{2\cdot Px}\cdot\rho\cdot V^2 - g\cdot\sin\theta + \omega_V^2\cdot R\cdot(\cos^2\varphi\cdot\sin\theta - \cos\varphi\cdot\sin\varphi\cdot\sin\varepsilon\cdot\cos\theta), \\ \dfrac{d\theta}{dt} = \dfrac{1}{2\cdot Px}\cdot\rho\cdot V\cdot K_\delta\cdot\cos\gamma + \left(\dfrac{V^2 - g\cdot R}{V\cdot R}\right)\cdot\cos\theta + 2\cdot\omega_V\cdot\cos\varphi\cdot\cos\varepsilon + \\ \qquad + \dfrac{\omega_V^2\cdot R}{V}\cdot\cos\varphi\cdot(\cos\varphi\cdot\cos\theta + \sin\varphi\cdot\sin\theta\cdot\sin\varepsilon), \\ \dfrac{d\varepsilon}{dt} = \dfrac{1}{2\cdot Px}\cdot\rho\cdot V\cdot\dfrac{K_\delta\cdot\sin\gamma}{\cos\theta} - \dfrac{V}{R}\cdot\cos\theta\cdot tg\varphi\cdot\cos\varepsilon - \dfrac{\omega_V^2\cdot R}{V}\cdot\sin\varphi\cdot\cos\varphi\dfrac{\cos\varepsilon}{\cos\theta} + \\ \qquad + 2\cdot\omega_V\cdot(\cos\varphi\cdot\sin\varepsilon\cdot tg\theta - \sin\varphi), \\ \dfrac{d\varphi}{dt} = \dfrac{V}{R}\cdot\cos\theta\cdot\sin\varepsilon, \\ \dfrac{d\lambda}{dt} = \dfrac{V}{R}\cdot\cos\theta\cdot\dfrac{\cos\varepsilon}{\cos\varphi}, \\ \dfrac{dR}{dt} = V\cdot\sin\theta \end{cases} \tag{1}$$

where V – velocity of a lander, m/s; θ – angle of inclination of the trajectory (angle between the velocity vector and the local horizontal plane), *rad*; ε – angle of yaw (angle between the local parallel and the projection of the velocity vector on the local horizontal plane), *rad*; ϕ – latitude, *rad*; λ – longitude, *rad*; $R = R_V + H$ – distance from the center of the planet, *km*; R_V – average radius of the planet (for Venus R_V = 6051.8 *km*); H – height above the surface of the planet, *km*; m – current mass of a lander (during the descent it is assumed constant and equal 1 600 *kg*); ρ – density of the unperturbed flow, kg/m^3; *t* – flight time, *s*; *g* – acceleration of gravity on the planet (on the Venus surface g_o = 8,84 m/s^2); ω_V – angular velocity of rotation of the planet (for Venus $\omega_V = 2.9926\cdot10^{-7}\ rad/s$); γ – angle of roll, *rad*; $K_\delta = \dfrac{Cya}{Cxa}$ – lift-to-drag ratio for the lander; Cya – lift coefficient in the velocity coordinate system; Cxa – drag coefficient in the velocity coordinate system; $Px = \frac{m}{Cxa \cdot S}$ – load on master cross section, *kg/m²*; S – master cross section of the lander, m^2.

The expression to evaluate the overload is:

$$n = \frac{\sqrt{1+K_\delta^2}}{2 \cdot Px \cdot g_0} \cdot \rho \cdot V^2$$

The initial conditions are: $V(0) = V_0,\ \theta(0) = \theta_0,\ \varepsilon(0) = 0,\ \varphi(0) = 0,\ R(0) = R_0$, where $R_0 = R_V + H_{ent} = 6051.8 + 130 = 6181.8\ km,\ H_{ent} = 130\ km$ – atmospheric boundary (Venus atmosphere model VIRA-30 [22, 23]).

In the course of the solution for the landing vehicle capable of maneuvering, the task is to find the maximum lateral maneuver

For the maneuverable “lifting body” type of a lander while solving the system of equations(1) the task is to find the maximum lateral maneuver $L_{lat} = \varphi_k \cdot R_V$ by getting the optimal program of changing the angle of roll $\gamma(t)$.

ALGORITHM OF THE SOLUTION

The process of solving the task consists of several stages (See Figure 1). Firstly, all the necessary parameters of the solving task need to be set: the lander parameters (mass and dimensions of the lander, its aerodynamic characteristics [19,20]), parameters of the planet (parameters of the atmosphere and the planet itself), trajectory restrictions (restrictions on height H_{final}, in the lower atmosphere there is no significant increment in lateral maneuver, and maximum overload, as well as maximum descent time if necessary) and initial conditions (velocity, angle and height of entry into the atmosphere), and also all settings of the solution process should be determined (step and accuracy of integration, the number of optimized sections of the trajectory, etc.). Then, after setting the parameters of the solving task, its solution follows - each section of the trajectory (step) includes search of all possible variants for the roll angles and integration of the system of equations (2) using the Runge-Kutta method and checking all restrictions to be implemented for the trajectory, after that the value of the lateral maneuver is determined for the final landing point, for each acceptable combination of roll angles, a combination of roll angles with a maximum lateral maneuver is selected. As a result of the program, the parameters of the selected descent trajectory are output in the form of a table: for each moment of descent time, the values of the descent velocity, height, overload, inclination of the trajectory, lateral maneuver range, longitudinal range and roll angle are given.

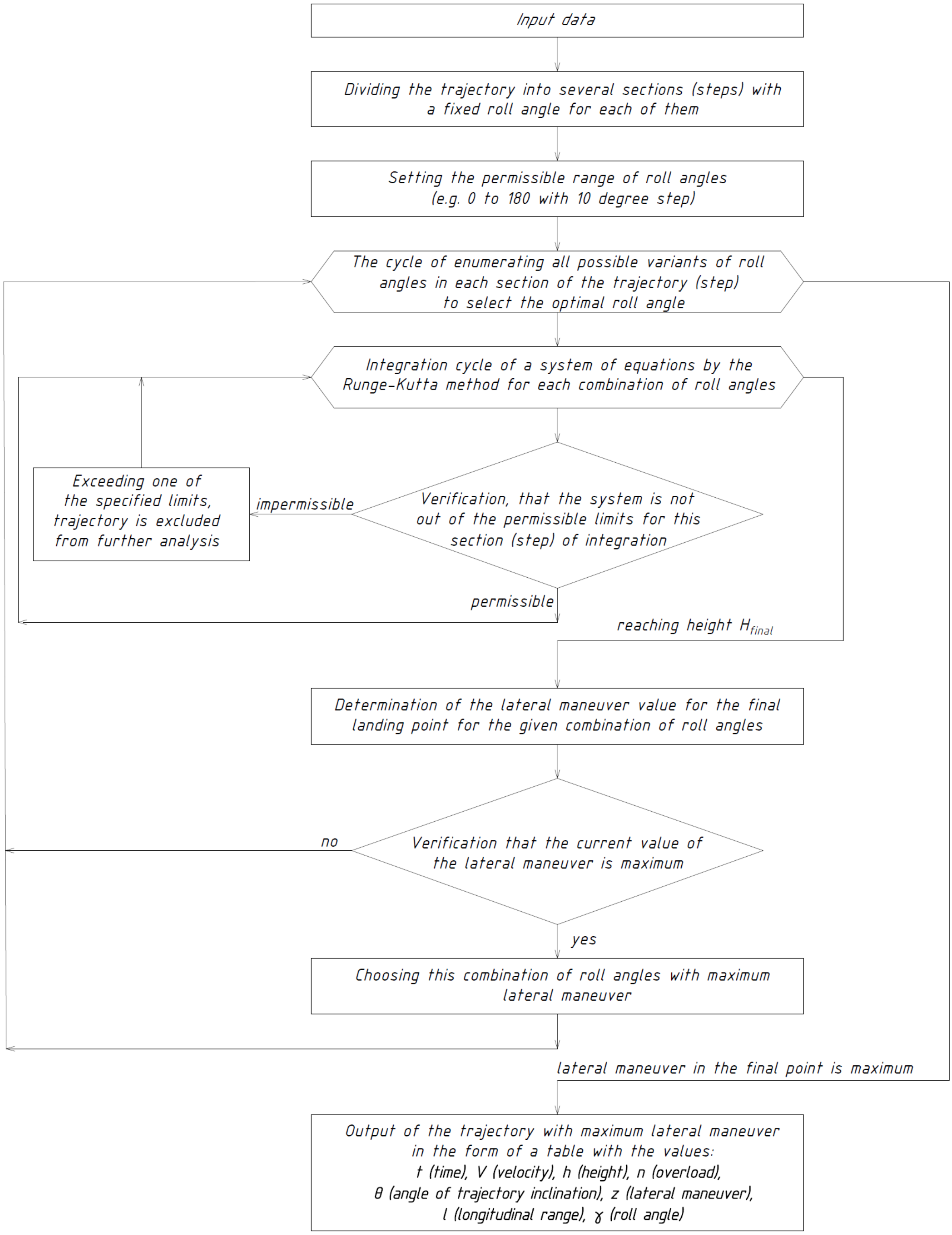

FIGURE 1. Block diagram of a program for calculating the descent trajectory parameters

RESULTS. REACHABLE LANDING SITES ON THE VENUS SURFACE

The problem of choosing a landing site is a complicated and complex issue that must take into account many requirements both from a scientific and a technical point of view, at the same time a number of requirements and restrictions imposed by the ballistic flight scheme, radio visibility zones for the lander, as well as terrain features, must be taken into account.

The calculation results of reachable landing sites for various types of a lander are shown in the Table 1 and Figure 2.

The estimation of the displacement relative to the entry point for the ballistic type of a lander, assumed in the “Venera-D” mission, shows that the longitudinal range is not more than 150..300 km for entry angles of -20 ° ..-10 °, respectively (See Table 1), while the overload for the same range of angles is 150..100 units, respectively, and for the currently assumed angle of -15 ° in the framework of the Venera-D mission [5, 6] it is ~ 122 units .

Calculation for the “lifting body” type of a lander shows that the range of lateral maneuver can be up to 5,000 km, and the longitudinal range - up to 8,000 km in the case of using the simplest control program for the angle of roll, when the value of the roll angle is different from zero and is not changed for a predetermined time of making lateral maneuvers. Herewith, the overload for the “lifting body” type of a lander is lower in comparison with the ballistic type of a lander (See Table 1).

The results of the descent trajectories calculation for both types of a lander are presented in Table 1, while taking the following restrictions - the descent time is no more than 2000 s, the overload no more than 150.

TABLE 1. Comparative table of some parameters of the descent trajectory for the ballistic and “lifting body” type of a lander

Entry angle θ, degrees	**Longitudinal range, km**		**Range of lateral maneuver, km**		**Overload**	
	Maneuverable	**Ballistic**	**Maneuverable**	**Ballistic**	**Maneuverable**	**Ballistic**
-8	7,831	310	4,972	-	57	90
-9	7,825	305	4,970	-	65	94
-10	7,824	304	4,960	-	68	98
-11	7,774	281	4,950	-	72	101
-12	7,724	260	4,943	-	79	107
-13	7,691	240	4,881	-	82	113
-14	7,682	219	4,770	-	92	116
-15	7,542	200	4,754	-	94	122
-16	6,983	186	4,637	-	103	128
-17	6,535	169	4,338	-	116	134
-18	5,969	152	4,243	-	126	140

As a result of all calculations you can see Figure 2 which shows the landing sites for the three launch windows in 2028, which is proposed as one of possible launch dates of the “Venera-D” mission [13], for the ballistic type of a lander (the region is indicated in red) and for the “lifting body” type of a lander (the region is indicated in yellow).

It should be also marked that while using the “lifting body” type of a lander, if necessary, a program of changing the roll angle can be selected in such a way as to obtain the required range within the highlighted yellow area, unlike the ballistic type of a lander that does not have this capability.

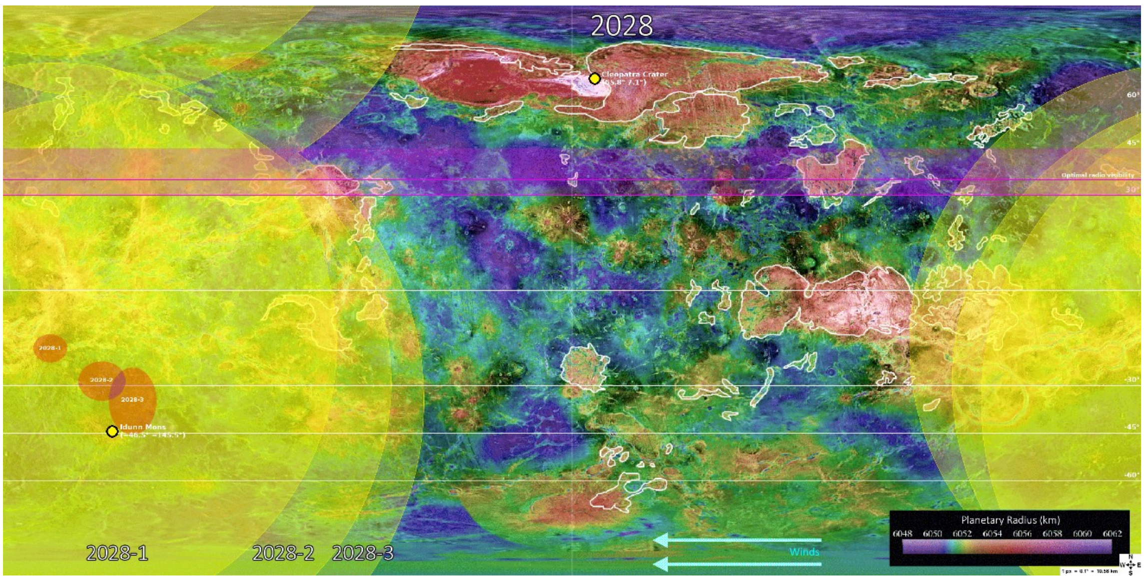

FIGURE 2. Reachable landing areas on the Venus surface for the ballistic type of a lander (red regions) and for the "lifting body" type of a lander (yellow areas)

CONCLUSION

The paper shows the investigation of reachable landing sites taking into account the expected dates and launch windows in the "Venera-D" mission for the ballistic type of a lander which is proposed at the moment for the "Venera-D" project, and the possibilities for increasing these zones when using the "lifting body" type of a lander capable of controlled descent and landing on the Venus surface, which will help to expand the selection of potentially interesting zones for research. In addition, the "lifting body" type of a lander is characterized by a decrease in maximum overloads while entering the atmosphere compared with the ballistic type of a lander, what in fact ensures the integrity of the equipment during descent in the atmosphere of the planet.

Moreover, such landers with some lift-to-drag ratio at hypersonic range of velocities can make long planning descent if necessary, which will expand the range of scientific tasks that can be carried out during the descent in the atmosphere until reaching the planet's surface.

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