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Aerial Platforms for Exploration Under Extreme Conditions in the Venus Atmosphere

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Conflicts of interest

The authors declare that there is no conflict of interest.

Abstract. This paper explores various aerial platforms for in-situ atmospheric exploration of Venus, emphasizing their potential integration into future missions. Platforms under consideration include fixed-altitude balloons, variable-altitude balloons, aircraft-like vehicles with three-dimensional maneuvering capabilities, and others. Design configurations of descent vehicles and deployment strategies for these platforms in Venus' atmosphere are discussed. Specific deployment mechanisms for balloons are detailed. The study also models the dynamics of spherical descent vehicles equipped with balloons, analyzing trajectory parameters during different phases. Results confirm the parameters remain within acceptable limits throughout descent.

Keywords: atmospheric descent, balloon probe, descent vehicle, deployment, trajectory modeling

Authors' contribution

Vorontsov V.A. — analysis of the data obtained, approval of the final version; *Quispe Mendoza M.V.* — developing the concept, conducting research, writing

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Воздушные платформы для исследований в экстремальных условиях в атмосфере Венеры

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Заявление о конфликте интересов

Авторы заявляют об отсутствии конфликта интересов.

Аннотация. Рассмотрены различные воздушные платформы для исследования атмосферы Венеры на месте, подчеркивается их потенциальная интеграция в будущие миссии. Рассматриваемые платформы включают аэростаты с фиксированной высотой полета, аэростаты с переменной высотой полета, летательные аппараты, подобные самолетам, с возможностью трехмерного маневрирования и др. Обсуждаются конструктивные конфигурации спускаемых аппаратов и стратегии развертывания этих платформ в атмосфере Венеры. Подробно описаны конкретные механизмы развертывания аэростатов. Исследование также моделирует динамику сферических спускаемых аппаратов, оснащенных воздушными шарами, анализируя параметры траектории на разных этапах. Результаты подтверждают, что параметры остаются в допустимых пределах на протяжении всего спуска.

Ключевые слова: атмосферный спуск, аэростатный зонд, спускаемый аппарат, развертывание, моделирование траектории

Вклад авторов

Воронцов В.А. — анализ полученных данных, утверждение окончательной версии; *Киспе Мендоза М.В.* — разработка концепции, проведение исследования, написание текста.

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Introduction

Venus exploration programs rely on remote sensing and in-situ approaches, with the latter offering more accurate and reliable scientific data. To facilitate remote and contact exploration, a Venus mission typically comprises two main modules:

Orbiter: Operates around Venus to relay data back to Earth.

Descent Vehicle: a capsule able to carry scientific payloads and aerial platforms into Venus' atmosphere.

More than 40 Spacecrafts have been sent to Venus, but its extreme conditions (high temperatures, pressures, and clouds of sulfuric acid) limit the operational life of the probes to a few hours. The Soviet Union's *Vega* balloons in 1985 demonstrated the scientific potential of aerial platforms (APs), providing critical date of over two days at altitudes of 51–54 km, where conditions were moderate. These balloons carried a modest payload of 7 kg, including 1–2 kg of scientific instruments [1–4].

Future aerial platforms with large payloads, longer operational life, and variable operating altitudes could significantly enhance Venus exploration. Such advancements are pivotal for comparative planetology and habitability studies, especially given the discovery of Earth-like exoplanets with Venusian characteristics. Current General Circulation Models (GCMs) fail to fully capture Venus' atmospheric dynamics, underscoring the need for improved data acquisition [5].

Increasing the number and diversity of aerial platforms is essential to address these challenges, requiring enhanced payload capacities and innovative mission architectures, in particular, aerial platforms, to expand the fields of the fields of study of the planet atmosphere and surface, as well as to obtain updated scientific information about the phenomena studied.

1. Aerial Platforms for Venus Exploration

The aerial platforms are designed to operate in the Venusian atmosphere where conditions are Earth-like, collecting data on atmospheric components and phenomena. This paper classifies these platforms based on altitude and positional control, evaluating them against three key criteria: scientific capability, complexity, and technological readiness.

Three primary categories of aerial platforms are discussed:

Fixed-Altitude Balloons: Passive platforms that drift with wind currents at a stable altitude.

Variable-Altitude Balloons: Platforms capable of adjusting altitude to exploit atmospheric wind patterns for trajectory control.

Three-Dimensional Maneuvering Vehicles: Active platforms offering lateral and vertical mobility, including aircraft.

1.1. Fixed-Altitude Balloons

High-pressure balloons, such as those used in the Vega project, are ideal for stable operations in Venus' atmosphere. Despite turbulence-induced fluctuations, these platforms have proven effective for long-duration data collection. The Vega balloons, with a diameter of 3.5 m and a payload capacity of 7 kg, covered 11,000 km over 46 hours (Figure 1) [1; 2; 6–8].

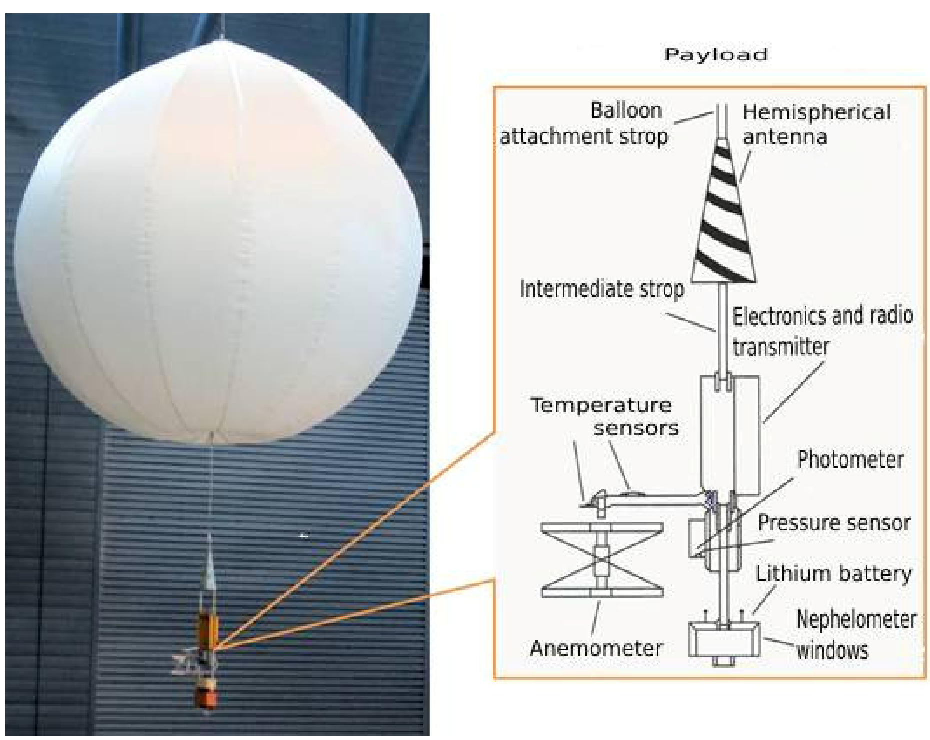


Figure 1. Balloons with variable altitude
Source: by M.Ya Marov, U.T. Huntress [6]

Figure 2. Balloon probe with payload of the Vega project
Source: by Glaze et al. [20]

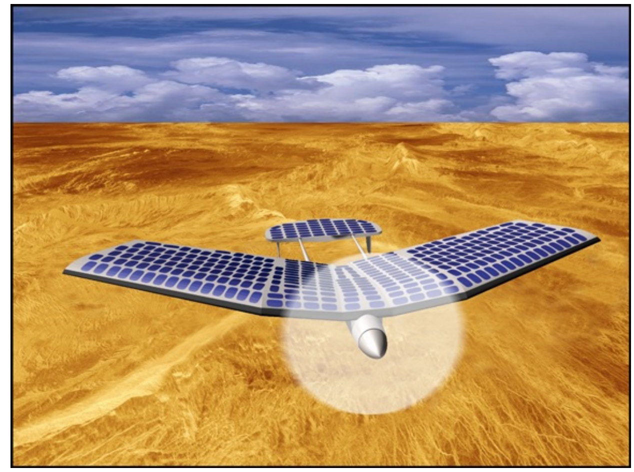


Figure 3. Solar powered aircraft
Source: by Glaze et al. [20]

1.2. Variable-Altitude Balloons

Variable-altitude systems utilize mechanisms such as helium compression (mechanical or pump-based) to adjust buoyancy. These platforms can leverage vertical wind patterns, such as those identified by Venus Express, to navigate meridional wind currents, enabling controlled latitudinal movement (Figure 2) [5; 9; 10].

1.3. Three-Dimensional Maneuvering Vehicles

Fixed-wing aircraft powered by solar panels can fly high in the cloud layer using the intense solar flux on Venus. Instead of "floating" around the planet in the field of super-rotating atmospheric currents, a solar-powered aircraft must remain on the sunlit side of Venus, and this requires flying at speeds approaching 100 m/s, in an easterly direction opposite to the atmospheric flow. Compared to balloons, a solar-powered aircraft has the advantage of precise position control. However, dependence on electric propulsion also has limitations in the latitudes that can be observed. In addition, with existing and planned opportunities in the field of energy storage technologies, a solar-powered aircraft will not be able to cross the night side. It is also limited in how deep it can penetrate into the atmosphere, as dense clouds block the sunlight needed to power the device (Figure 3) [5; 10].

Figure 4. Venus Atmospheric Maneuverable Platform (VAMP) — Inflatable airplane
Source: by G. Lee et al. [12]

Venus Atmospheric Maneuverable Platform — An aircraft-type maneuverable aircraft with the weight of 450 kg, which is capable of independently entering the atmosphere of Venus from a low orbit at a speed, and is designed to survive under conditions of thermal pressure and hypersonic entry. During the flight phase, VAMP will move with minimal energy use at speeds of about 50–70 km/h in the upper and middle layers of the clouds of Venus and collect scientific data for transmission to Earth. VAMP is also quite stable and able to cope with the strong atmospheric winds of Venus, and can orbit the planet for up to a year (Figure 4) [5; 11; 12].

Next, we will examine in detail the related issues to the deployment and activation of aerial platforms (using aerostats as examples) as technical tools for research within the framework of integrated missions aimed at studying the atmosphere of Venus.

2. Deployment of Aerial Platforms

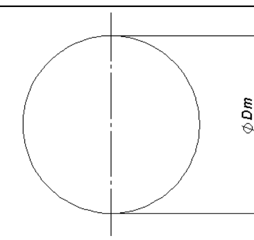
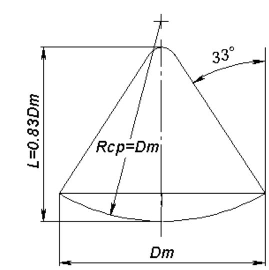
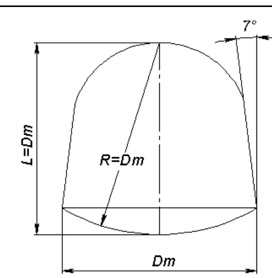
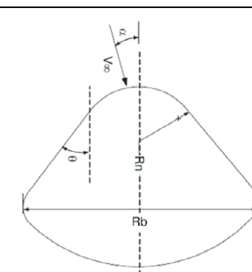
Descent Vehicles (DVs) serve as carriers and deployment systems for aerial platforms. This paper reviews DV configurations and strategies for releasing balloons in Venus' atmosphere.

In practice, the following types of DVs have been utilized in various missions to explore the planets of the Solar System — Table 1 [1; 7; 16–17].

Designs for integrating aerial platforms within DVs are detailed, including configurations for spherical, conical, and segmental-conical vehicles. Deployment mechanisms for balloons are illustrated, emphasizing reliability during atmospheric entry — Table 2 [2; 7; 18].

Table 1

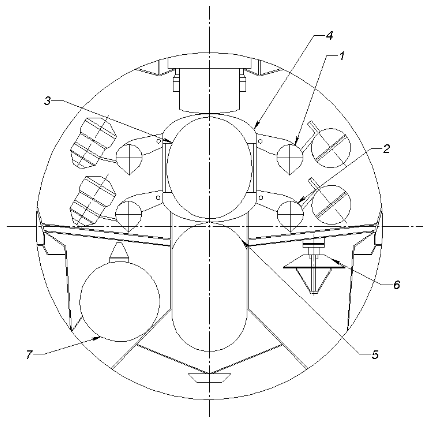
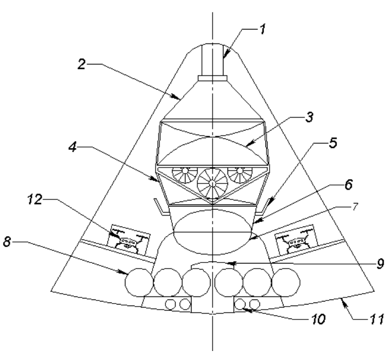
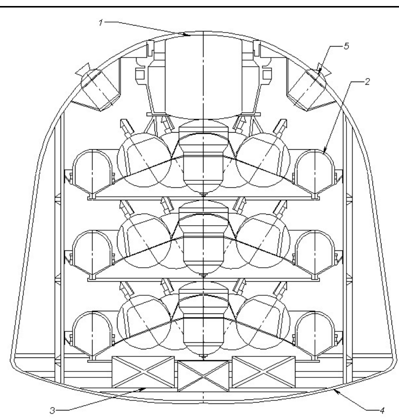
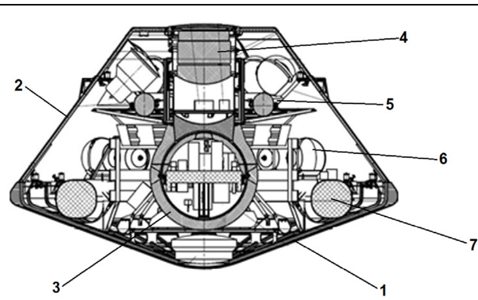
Types of Descent Modules and Their Characteristics

Shape of the DM	Description	Dimensions
Spherical	Ensures stability and compact payload arrangements.	
Conical	Accommodates elongated payloads, such as cameras, for high-altitude missions.	
Segmental-Conical	Optimized for aerodynamic efficiency and high-speed atmospheric entry.	
Venus-D Type	Features a sphere-cone shape for enhanced drag and stability.	

S o u r c e: by V.V. Efanov et al. [21]

Table 2

Layout Configurations of DVs with Aerial Platforms

Shape of the DM (Descent Modul)	Components
	**Spherical-Type DV:** 1 – Aerostat Probe (AP 1) 2 – Aerostat Probe (AP 2) 3 – Gliding Probe (GP) 4 – Service and Scientific Equipment Compartment of GP 5 – Drifting Probe / UAV Container 6 – Radar 7 – Landing Probe
	**Conical-Type DV:** 1 – Drogue Parachute 2 – Braking Parachute 3 – Descent Module 4 – Truss 5 – Communication Antenna with Orbital Module 6 – Main Parachute 7 – Aerostat Envelope 8 – Aerostat Envelope Inflation System 9 – Aerostat Gondola 10 – Aerostat Guide Rope 11 – Aerodynamic Shield 12 – Second Aerostat
	**Segmented-Conical-Type DV:** 1 – Parachute Container 2 – Aerostat Power Cone, containing the aerostat probe envelope 3 – Instruments 4 – Fore Screen 5 – Delta-V in the entry from orbit
	**Venera-D" Type DV** 1 – Fore Screen 2 – Envelope 3 – Landing Module 4 – Parachute Container 5 – Aerostat Power Cone No. 1, containing the aerostat probe envelope 6 – Aerostat No. 2 7 – Aerostat No. 3

S o u r c e: by V.V. Efanov et al. [21]

The deployment of aerostats in the atmosphere of Venus occurs following the descent module's entry into the atmosphere during its descent phase. The configurations for the spherical and segmented-conical descent modules are illustrated in Figures 5, 6.

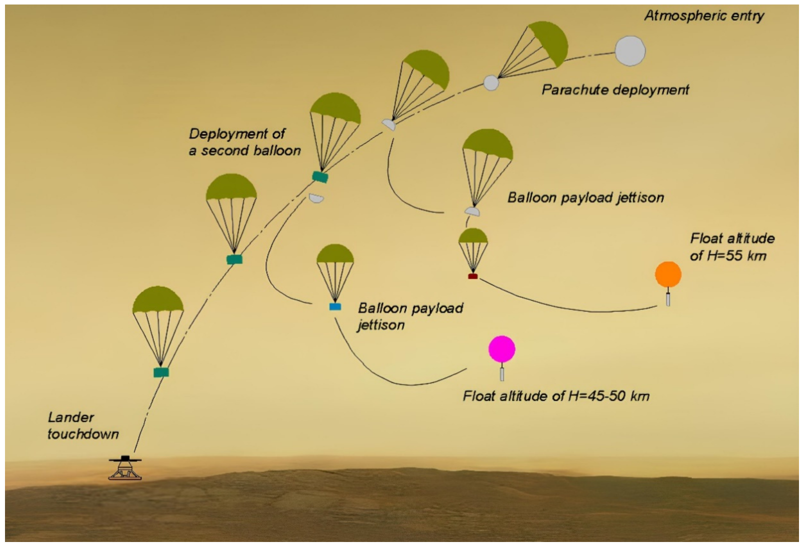


Figure 5. Commissioning of balloons in the atmosphere of Venus from a spherical descent vehicle
S o u r c e: by V.V. Efanov et al. [21]

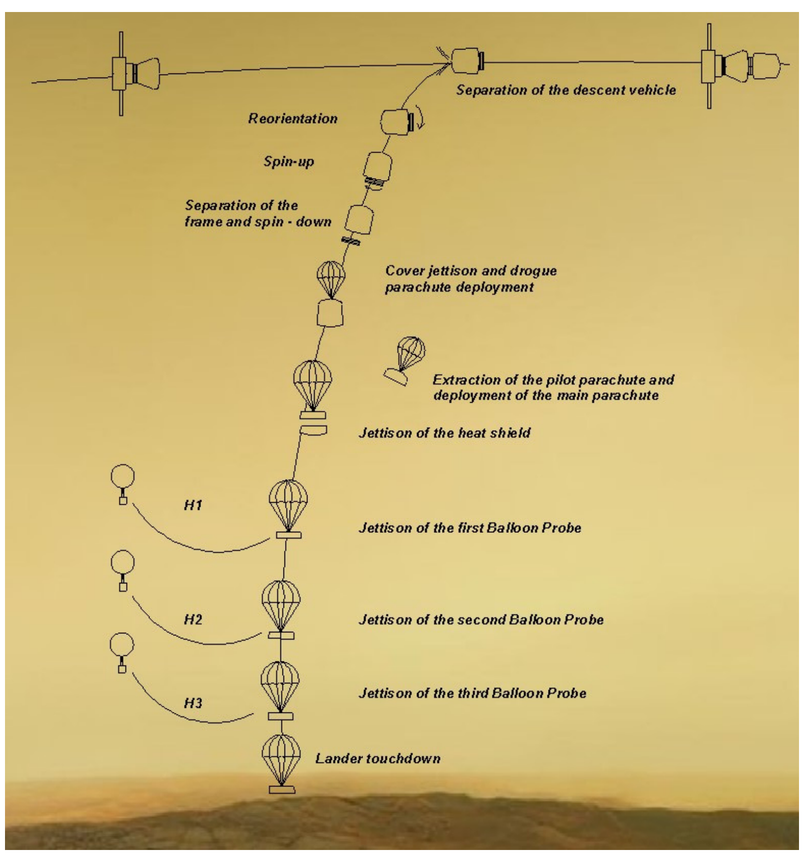


Figure 6. Commissioning of balloons in the atmosphere of Venus from a segmental-conical descent vehicle
S o u r c e: by V.V. Efanov et al. [21]

Table 3

Drag coefficient and application of different parachute parameters

Type	Drag coefficient	General application (Mach number, M)
Conical	0.75–0.90	Airdrop (M < 0.5M < 0.5M < 0.5)
Biconical	0.75–0.92	Airdrop (M < 0.5M < 0.5M < 0.5)
Disk-gap-band	0.52–0.58	Airdrop (M < 0.5M < 0.5M < 0.5)
Ring-slot	0.56–0.65	Extraction deceleration (0.1 < M < 0.50.1 < M < 0.50.1< M <0.5)
Ribbon	0.30–0.46	Supersonic deceleration (1 < M < 31 < M < 31 <M < 3)
Conical ribbon	0.50–0.55	Airdrop, deceleration (1 < M < 31 < M < 31 < M < 3)

S o u r c e: by S.C.G. Torres, V.A. Vorontsov [19]

3. Modeling the Motion of a Descent Vehicle in Venus' Atmosphere

The motion of a descent vehicle (DV), consisting of aerostats in Venus' atmosphere is analyzed using the example of a spherical-type DV. The process can be divided into the following stages[1] [7].

3.1. Stage One: Ballistic Motion of the DV in the Atmosphere

During this stage, the vehicle's velocity changes according to the laws of motion for a body falling through the air without a parachute (aerodynamic deceleration), transitioning from the second cosmic velocity to a near-sonic speed.

The equations of motion for the DV can be simplified and expressed as follows:

$$\begin{cases} \dot{V} = -\dfrac{\rho V^2}{2P_x} - g\sin\theta; \\ \dot{\theta} = -\cos\theta\left(\dfrac{g}{V} - \dfrac{V}{R_v + H}\right); \\ \dot{H} = V\sin\theta; \\ \dot{L} = \dfrac{V R_v \cos\theta}{R_v + H}, \end{cases} \tag{1}$$

where V — vehicle flight velocity, m/s; θ — trajectory inclination angle relative to the local horizon (angle between velocity vector and local horizontal plane), rad/deg.; H — altitude above the planet's surface, m; L — distance, m; R_v — average planetary radius (for Venus, R_v = 6051.8 km); ρ — undisturbed flow density, kg/m³; g — gravitational acceleration at the DV's location, m/s²; P_x — ballistic parameter, kg/m².

3.2. Stage Two: Deployment of a Deceleration Parachute and Descent Using the Deceleration Parachute Until the Main Parachute is Deployed

The drag coefficient of the parachute depends on the canopy design, fabric type, permeability, flight speed, etc. Table 3 presents drag coefficient values for various parachute canopy types [19].

3.3. Stage Three: Separation of the Deceleration Parachute, Detachment of the Upper Hemispherical Heat Shield Containing Two Aerostats

Subsequently, the upper hemisphere descends on a parachute, followed by activation of the aerostats. For this stage, the equations of motion can be expressed as:

$$\begin{cases} \dot{V} = \dfrac{\rho g U \sin\theta - mg\sin\theta - \frac{1}{2}\rho V^2\left(C_x S_m + C_P F_P + C_a F_a\right)}{\left(m + k\rho U\right)}; \\ \dot{\theta} = \dfrac{\rho g U\cos\theta - mg\cos\theta + \dfrac{mV^2}{R_v + H}}{\left(m + k\rho U\right)V}; \\ \dot{H} = V\sin\theta; \\ \dot{L} = \dfrac{V R_v \cos\theta}{R_v + H}, \end{cases} \tag{2}$$

[1] Ivanov NM, Dmitrievsky AA, Lysenko LN. *Ballistics and navigation of spacecraft*. Bustard Publ.; 2004. ISBN 5-7107-7085-X

where: m — mass of the DV (or its components), kg; C_x — DV drag coefficient (or its components); S_m — characteristic area of the DV; C_P — parachute drag coefficient; F_P — parachute area; C_a — aerostat drag coefficient; F_a — aerostat area; k — added mass coefficient; U — aerostat shell volume, m³.

3.4. Stage Four: Deployment of the Main Parachute, Descent, and Deceleration in Venus' Atmosphere

The simulation yielded trajectory parameter variation graphs over time (Figures 7–11).

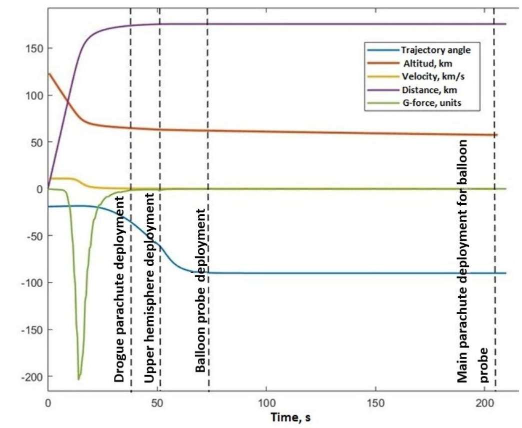


Figure 7. Trajectory parameters of a spherical DV during motion in Venus' atmosphere (Stages 1–4)
Source: by M.V. Quispe Mendoza

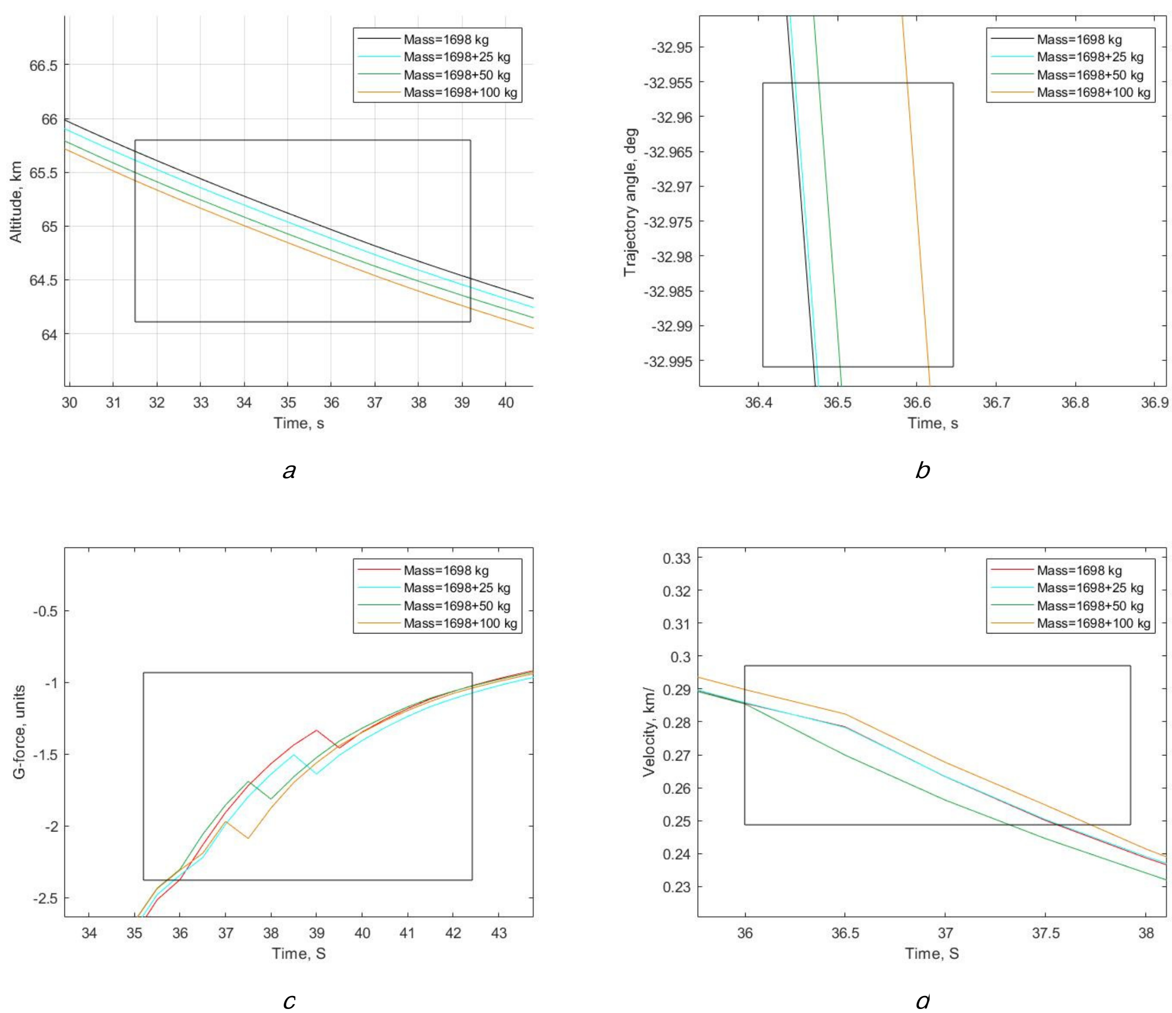


Figure 8. Parameters during parachute deployment with variable masses:
a — altitude, km; *b* — trajectory angle, deg; *c* — overload, units; *d* — velocity, km/s
Source: by M.V. Quispe Mendoza

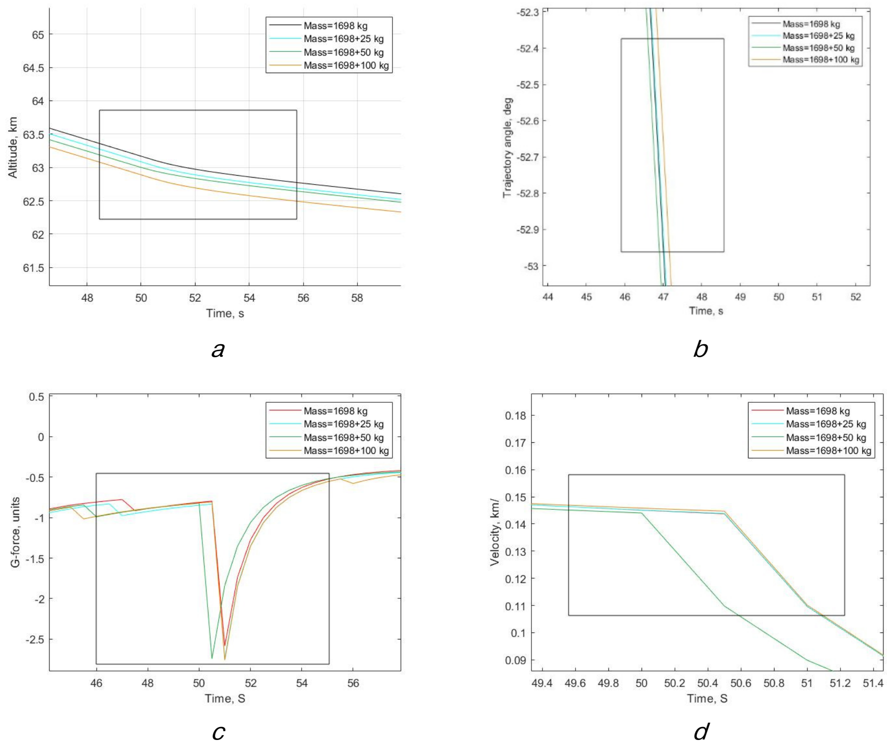


Figure 9. Parameters during upper hemisphere detachment:
a — altitude, km; *b* — trajectory angle, deg; *c* — overload, units; *d* — velocity, km/s
S o u r c e: by M.V. Quispe Mendoza

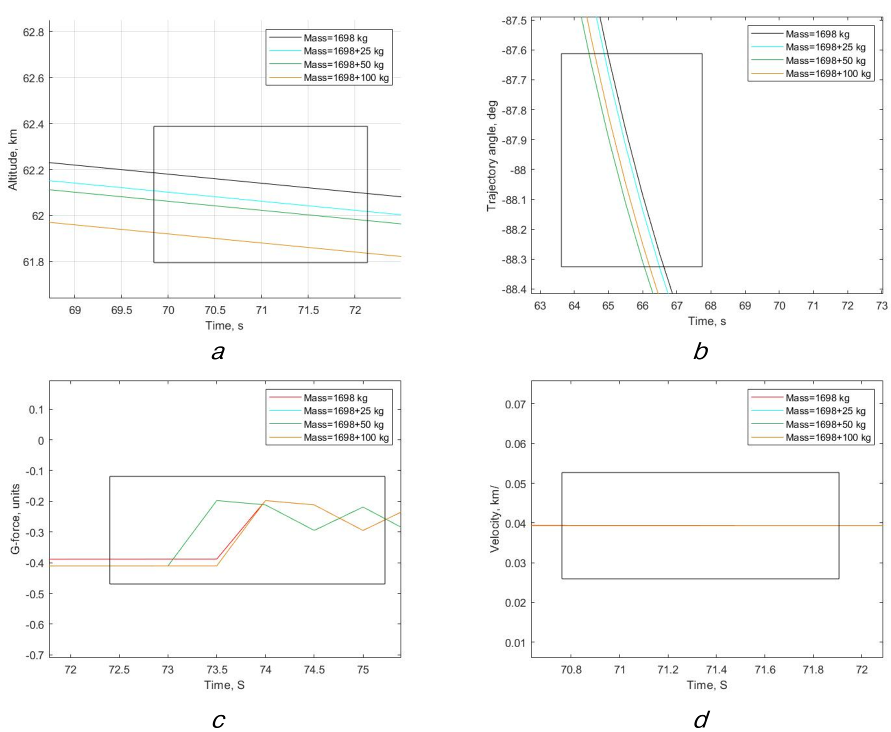


Figure 10. Parameters during aerostat probe deployment:
a — altitude, km; *b* — trajectory angle, deg; *c* — overload, units; *d* — velocity, km/s
S o u r c e: by M.V. Quispe Mendoza

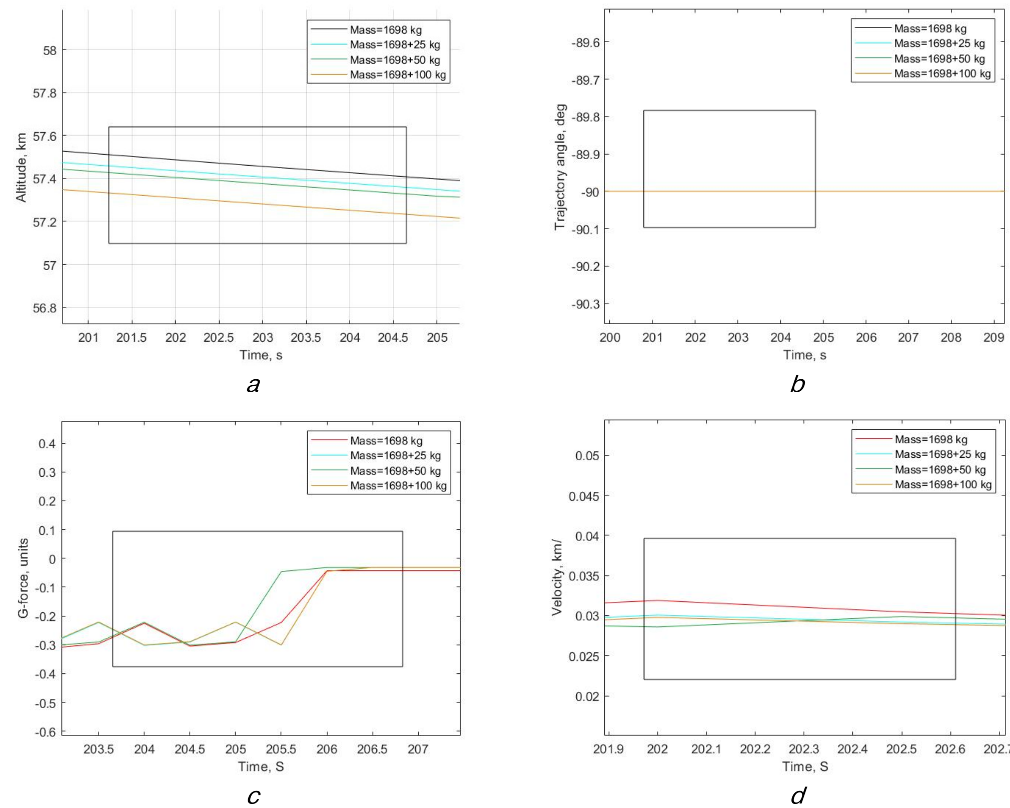


Figure 11. Parameters during aerostat parachute deployment:
a — altitude, km; *b* — trajectory angle, deg; *c* — overload, units; *d* — velocity, km/s
Source: by M.V. Quispe Mendoza

Conclusion

This study examines various aerial platforms carrying payloads for the contact and remote investigation of Venus' atmosphere and surface. The analysis of these platforms demonstrates enhanced potential for achieving scientific objectives in future missions.

Due to the extreme atmospheric conditions of Venus, prolonged contact-based studies are infeasible, emphasizing the importance of increasing the number of aerial platforms deployed to the planet, which necessitates a higher payload capacity for descent vehicles.

Simulation results confirm that trajectory parameters of a spherical descent vehicle with payloads up to 100 kg remain within acceptable limits across all motion stages, enabling the integration of advanced technical systems, such as aerial platforms, into the baseline design.

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