Jet Propulsion Laboratory
California Institute of Technology

Aerial Platforms for the Scientific Exploration of Venus

Summary Report
by the
Venus Aerial Platforms Study Team

JPL D-102569

October 2018

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Cover Illustration by Tibor Balint: Artist concepts for a variable altitude Venus balloon circling the planet in the powerful winds of the upper atmosphere. This study concluded that variable altitude balloons are the optimal choice among aerial platform design concepts considered here for advancing the scientific exploration of Venus. Other aerial platform concepts that appear in the illustration and considered in the study are a hybrid airship and a solar airplane.

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Foreword

In 1985, two balloons were inserted into the atmosphere as elements of the Venus-Halley (VeGa) mission, the last mission to Venus conducted by the Soviet Union. In two Earth days, each balloon travelled approximately 11,500 km in the superrotating winds at an altitude of about 54 km, tracked by a global array of twenty radio observatories. Observations by instruments on the balloons and from radio tracking of their motion provided unique information on the circulation of the Venus atmosphere.

Now, almost 35 years later, the time is ripe to resume the exploration of Venus by once again deploying aerial platforms that can investigate the Venus environment in situ, yet avoid the extreme temperatures of the surface. Aerial platforms much more capable than the VeGa balloons can now be designed to be equipped not only to investigate the structure of the atmosphere and its circulation, but also to determine the chemical nature of the gaseous atmosphere and the Venus clouds. A platform high can also be used to investigate the surface and interior in a way that is neither possible from orbit, nor from short duration landed missions feasible with current technology.

The Venus Aerial Platforms study involved 52 participants with expertise in Venus science, planetary mission engineering, and aerial platform technology. A process developed by the Keck Institute for Space Studies (KISS) was used to perform the study, which was conducted at the KISS conference facilities at Caltech. A range of possible Venus aerial platform concepts were considered and evaluated with a methodology which included the merits of the science that could be performed, the size and complexity of the platform, and the maturity of the technology.

We would like to thank all the participants in the study for the commitment of their time and creative efforts at the study's two face-to-face meetings and for their continuing engagement through the completion of this report. We would also like to thank Prof. Tom Prince, Director, and Michele Judd, Executive Director, for permission to use the KISS facilities for this study. The support of Dr. Adriana Ocampo, Program Executive for Venus Studies, and Dr. James L. Green, Director of the Planetary Science Division, at the inception of the study, and now NASA Chief Scientist, provided the impetus and resources for carrying out the study. Finally, we would like to acknowledge Dr. Lori Glaze for her leadership as a study participant and her continued support since becoming Acting Director of the Planetary Science Division at NASA.

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Co-leaders of the Venus Aerial Platforms Study

VENUS AERIAL PLATFORMS

Assessing Venus environment with robust scientific aerial platforms

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1 Introduction

The *in situ* exploration of Venus is seriously hampered by the severe environment (T=460°C and P=90 bars) of the Venus surface. Extending the lifetime of landers equipped with conventional electronics to more than a few hours poses formidable challenges. Development of high temperature systems to survive for months in this environment is one alternative that NASA is pursuing. Another option is aerial platforms that float or fly in regions of the Venus atmosphere where temperatures and pressures are Earth-like. NASA commissioned this study to explore the potential of aerial platforms for the scientific exploration of Venus. Aerial platform concepts were classified in terms of their degrees of control over altitude and location on Venus. Each concept was then evaluated in terms of three key metrics: the science that it could accomplish, the size and complexity of the platform, and the maturity of the technology required. The study found that aerial platforms that can control altitude occupy the sweet spot in the trade space and that there are no technology show stoppers to their adoption for future NASA missions. This narrative summary report is one of three reports planned on the study findings. A PowerPoint presentation with additional details on the scientific and technical analyses (Venus Aerial Platforms Study Team, 2018a) is being released contemporaneously with this report. A complete narrative report with scientific and technical Appendices is in preparation (Venus Aerial Platforms Study Team, 2018b).

2 Background

2.1 Venus Aerial Exploration

The aerial exploration of Venus began in 1985 when two Soviet-era VeGa superpressure balloons were successfully deployed at Venus at an altitude of 54 km in the cooler regions of the Venus atmosphere. The VeGa balloons were smaller than those contemplated in this study and had a very modest scientific payload. However, each was successfully tracked from Earth for about 46 hours before their batteries were exhausted. Since the VeGa mission there have been U.S.-led studies of fixed-altitude Venus aerial platform missions implemented with much larger superpressure balloons, balloons capable of changing altitude, and solar powered airplanes and hybrid airships with some degree of control in three dimensions. While no mission has yet occurred, aerial platforms for Venus have been identified as key mission elements in the Venus Climate Mission (VCM), (Planetary Science Decadal Survey, 2011), in a number of NASA and ESA competitive proposals as well as a potential U.S.-contributed element to the Russian Venera D mission concept. Balloons were also recommended as a candidate concept in the Venus Bridge Study conducted by the Venus Exploration Assessment (VEXAG) in the spring of 2018 (Grimm & Gilmore, 2018).

2.2 Nature and scope of this study

This study involved two 3½-day workshops, 15 teleconferences and an extensive on-line interaction by a team of 52 experts, drawn from a variety of disciplines, listed in the Appendix. An initial task for the study team was to determine the range of aerial platforms to be considered. Prior studies have included platforms that operate exclusively in the upper atmosphere (where temperatures are Earth-like), platforms that can descend to the surface and operate there, and platforms that can retrieve samples from the surface and deliver them to the upper atmosphere.

Since the main focus of the study was on capabilities that were already mature or could be implemented in the time period of the next Planetary Science Decadal Survey (2022 to 2032), it was determined that the focus should be on aerial platforms that operate nominally within the “temperate zone” on Venus between 50 and 65 km where the temperature is below 77°C. However, the feasibility of platforms that would make brief excursions down to the cloud base at 47 km (100°C) using passive thermal control to limit temperature rise of electronic systems was also addressed. An alternative approach to probing deeper in the atmosphere, also considered here, is the use of probes or sondes that could be deployed from the aerial platform and could acquire data on the atmospheric column and potentially obtain surface images relaying that data through the aerial platform.

3 Venus Aerial Platform – Candidate Concepts

Three broad categories of aerial platforms were considered in detail: fixed-altitude balloons that would travel on trajectories determined by the wind speed and direction, variable altitude balloons with control over one of the three degrees of freedom and vehicles with control in three dimensions. The variable altitude balloon category proved to be of great scientific interest and four different implementations were examined. Two approaches to control in three dimensions were examined (a solar airplane and an airship using both aerodynamic lift and buoyancy) which had very different levels of control authority. Except for the solar airplane, all of these concepts circumnavigate the planet every four or five days in the super-rotating atmosphere flow.

3.1 Fixed Altitude Balloons

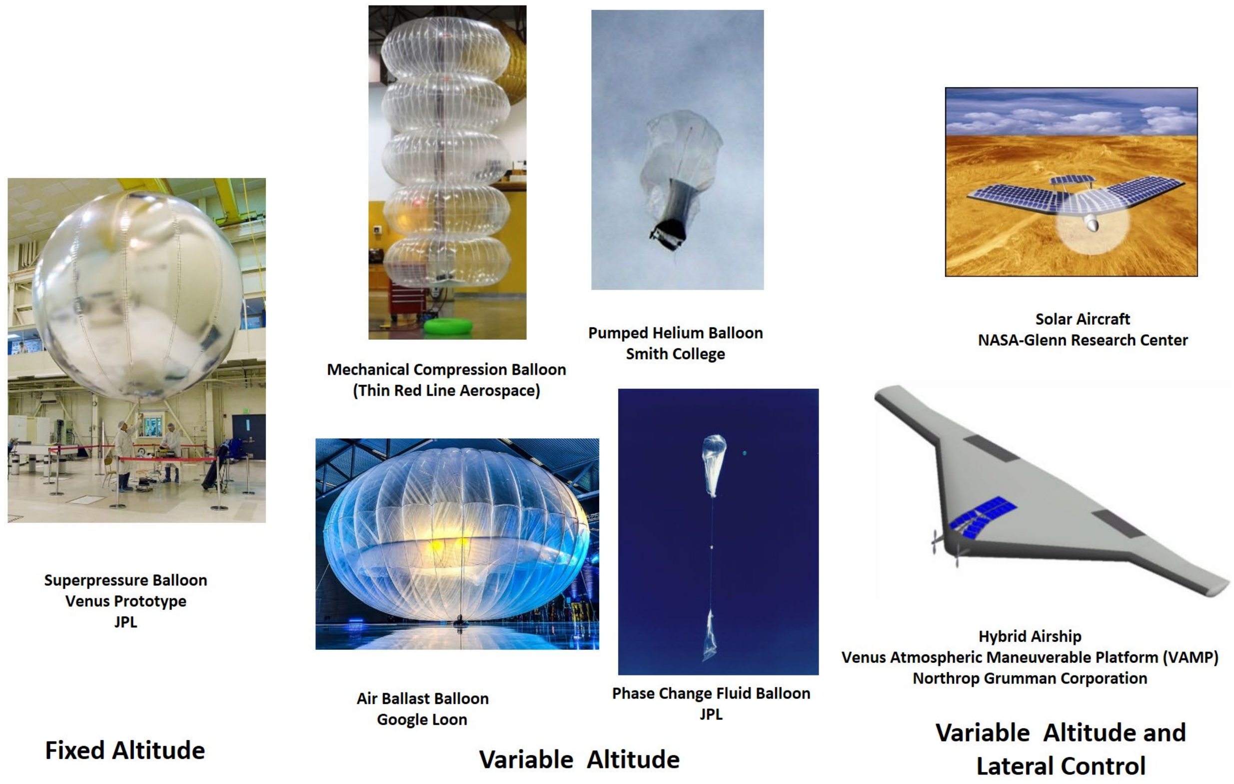
The most mature of the concepts studied is the super-pressure (SP) balloon which operates at a fixed density altitude although turbulence will cause fluctuations in that altitude. SP balloons have been widely used on Earth for long-duration flights because of their ability to tolerate temperature changes caused by the day/night cycle. The VeGa SP balloons were 3.5 m diameter with a 7 kg gondola module. They were tracked for 46 hours and had travelled 11,000 km when their batteries were exhausted. SP balloons designed for an altitude of 54 km and tolerant to the acidic Venus environment have been built at JPL, although they have not yet been demonstrated as surviving the Venus diurnal cycle. A balloon of 7.4 m diameter can support a gondola module with a mass of 110 kg including a science payload of 25-30 kg.

3.2 Variable Altitude Balloons

Over the last five years, there have been major advances in the technology of long-lived terrestrial balloons capable of controlling altitude in a systematic way and navigating using the variations of wind speed magnitude and direction with altitude. For instance, balloons developed in the terrestrial Google Loon program, using an air ballast approach, have operated for up to 190 days at up to 20 km altitude (equivalent to 70 km on Venus) and demonstrated impressive levels of guidance (Google_Loon, 2018). The Venus environment creates some new possibilities for altitude control at Venus as well as new challenges. Phase Change Fluid balloons—independently conceived in Russia and Japan in the 1980s and pursued at JPL in the 1990s as “Venus aerobots”—offer one pathway. Two types of helium compression balloon (mechanical compression and pumped compression) are more recently identified alternatives. All four concepts were considered in this study. The study focused on platforms with an altitude range of 50 to 60 km referred to as “nominal range”. The feasibility of an extended range capability of 40 to 60 km where was also assessed. As with terrestrial balloons, variable altitude balloons on Venus can use wind variations with altitude to modify their trajectories. In particular, the Hadley cell circulation identified from Venus Express data that causes the meridional component of wind to reverse near 60 km (Khatuntsev, 2017) may enable these platforms to control their latitude within certain latitude ranges.

3.3 Solar Airplane

Fixed wing solar powered aircraft can fly high in the cloud layer exploiting the intense solar flux at Venus. Instead of being carried around the planet in the super-rotating atmospheric flow field, the solar airplane must remain on the sunlit side of Venus and this requires flight at airspeeds approaching 100 m/sec in an easterly direction opposite to the atmospheric flow. Compared to balloons, the solar airplane has the advantage of positive control of position. However, the dependence on powered flight also comes with limitations in the latitudes that can be observed. In addition, with current and projected capabilities in energy storage technology, the solar airplane cannot traverse the night side. It is also limited in how deep it can penetrate into the atmosphere because the dense clouds block the sunlight needed to power the craft. Limitations in access to different times of day, latitudes and altitudes will constrain the science that can be accomplished. Solar powered airplanes have been built on Earth with extended range. Solar airplane concepts have been developed for both Venus and Mars that could be packaged in an aeroshell and deployed after atmospheric entry. Concepts for Venus solar airplanes that would exploit convection and shear flow to extend the domain of operation are being studied by NASA. These studies, which will not begin until the Fall of 2018, will be an addendum to this study.



Superpressure Balloon
Venus Prototype
JPL

Mechanical Compression Balloon
(Thin Red Line Aerospace)

Pumped Helium Balloon
Smith College

Solar Aircraft
NASA-Glenn Research Center

Air Ballast Balloon
Google Loon

Phase Change Fluid Balloon
JPL

Hybrid Airship
Venus Atmospheric Maneuverable Platform (VAMP)
Northrop Grumman Corporation

Fixed Altitude

Variable Altitude

Variable Altitude and Lateral Control

Figure 3-1 Venus Aerial Platform Concepts considered in this study are subdivided into three categories: Fixed Altitude platforms, Variable Altitude platforms as well as Platforms with both Variable Altitude and Lateral Control.

3.4 Hybrid Airship

The Venus Atmosphere Maneuverable Platform (VAMP) is a hybrid craft which uses both buoyancy and aerodynamic lift to maintain and control altitude. It also differs from all other concepts considered in this report in that it is deployed and inflated in space before entering the atmosphere at hypervelocity. After entry, VAMP uses solar power on the day side to rise to altitudes of 60 km while at night it is unpowered and sinks to 50 km. VAMP does not have the control authority to station keep on the sunlit side of Venus but it can maneuver in latitude as it is carried around the planet in the super-rotating flow. The dual functionality of the inflated hull as both an entry system and a buoyancy system provides for potential mass savings. In addition, since the vehicle would become subsonic much higher in the atmosphere than conventional entry systems, it would provide new measurement opportunities. Vehicles with buoyancy and aerodynamic lift have been built for terrestrial commercial applications. However, no hybrid vehicles that can also survive entry have yet been built. Hybrid vehicles which enter using conventional aeroshells were not considered as part of this study.

4 Aerial Platform Trade Study

The trade study conducted by the study team examined three key attributes of the aerial platforms being considered for Venus as a function of the degree of mobility: the science that could be accomplished, the size and complexity of the aerial platform, and the maturity of the technology. Increasing mobility generally requires a larger and more complex vehicle to deliver the same sized scientific payload. Increasing mobility also requires less mature technologies. The fixed altitude concept was quite mature with a fairly clear path to application on a mission. Adding vertical and horizontal mobility involves technical hurdles, implying significant investment needs and, in some cases, questions about feasibility. In the study, we compared all three attributes and looked for a “sweet spot” where a high science return could be accomplished with a vehicle of acceptable size and complexity and achievable technology compatible with a mission realizable in the decade 2023 to 2032.

4.1 Scientific Assessment

The Venus Exploration Assessment Group (VEXAG) established a set of Goals, Objectives and Investigations (GOI) for Venus Exploration (VEXAG, GOI, 2016) that provided this study with a valuable framework for assessing the scientific potential of aerial platforms.

4.1.1 Initial Science Assessment

During the first study team meeting in May 2017, the study team methodically examined each of the priority investigations identified by VEXAG and determined the contribution that could be made by aerial platforms and whether there were any discriminators between the different types of platform. It was determined that Aerial Platforms would make the largest contributions to addressing Goal I – Atmospheric Formation, Evolution and Climate History, established by VEXAG. Significant contributions would also be made to investigations of Goal II – Evolution of the Surface and Interior; and to Goal III – Interior-Surface-Atmosphere Interaction. An initial finding was that the variable altitude platforms provided a significant gain in science over the constant altitude platforms and that any additional gains that might be achieved from full three-dimensional control balloon (vs. 1-D control model) were modest--given the currently anticipated (~100 Earth-day) lifetime of the aerial vehicles.

4.1.2 Science Instrument Assessment

A key issue identified at the first study meeting was the feasibility of making the needed measurements with instruments that would be compatible with the limited scientific instrument payload capabilities of an aerial platform. Scientific instruments needed to carry out the investigations to meet the VEXAG goals were grouped into five broad categories (Table 4-1), and the current state of the practice and the opportunities for applying new techniques and technologies were assessed.

Atmospheric Gas Composition: This category of investigation requires a highly capable survey instrument such as the Quadrupole Mass Spectrometer used on the Mars Curiosity rover. Recent advances in mass spectrometer technology may enable similar capabilities with substantial reductions in power and mass. UV/IR spectrometers and MEMS-based chemical sensors were also considered.

Cloud and Haze Particle Characterization: To characterize the cloud and haze layers, it is necessary to determine optically the size, number density and scattering properties of the aerosol particles both in bulk and individually. In addition, several investigations in the VEXAG's GOI require determining their chemical composition using mass spectrometry of either individual cloud or haze particles or aggregates filtered from the atmosphere.

Atmospheric Structure: Characterizing the dynamical and thermal structure of the atmosphere and radiation fields within it involves measurements that are made with instruments on the platform as well as by precise tracking of the platform. Deployments of sondes would augment these measurements by providing an atmospheric temperature and pressure and multi-spectral radiation profiles all the way down to the surface.

Geophysical Investigations: Various geophysical techniques were examined for determining information about the surface and interior of the planet. For some measurements (e.g. gravity field, remanent magnetism, electromagnetic sounding) the aerial platform vantage point offers advantages over orbital observations because of proximity to the surface of the planet. In another cases, seismology, the location within the atmosphere enables the detection of infrasound signals.

Table 4-1 Scientific Instruments identified as candidates for deployment on the aerial platform or on probes/sondes released from the aerial platform

Instruments	Abbreviation	Measurement Type/Objectives
ATMOSPHERIC GAS COMPOSITION		
Mass Spectrometer	MS or GCMS	Atmospheric species including noble gases and their isotopes. Survey instrument
Tunable Diode Laser Spectrometer	TDL	Trace species including isotopic abundances. Targeted on a few species
UV/IR Spectrometer	UVS, IRS	Atmospheric species from their spectal signatures. Survey instrument
Chemical Sensors (MEMS based)	ChemSens	Chemical species. Small low power instrument targeted on a few species
CLOUD AND HAZE PARTICLES		
Nephelometer	Neph	Size, scattering properties and abundance of cloud and haze particles in bulk
Light Optical Amospheric Counter	LOAC	Size, scattering properties and abundance of cloud and haze particles individual
Imaging Microscope	Mic	Images larger cloud particles captured on a filter.
Aerosol Mass Spectrometer	AMS	Chemical composition or biological nature of aerosols (individual or bulk)
ATMOSPHERIC STRUCTURE		
Atmospheric Structure Instrument	ASI	Temperature, pressure and vertical wind speed.
Net Flux Radiometer	NFR	Upward and downward flux of radiation in multiple spectral bands
Ultra Stable Oscillator	USO	Wind velocity from Doppler signatures from DSN and orbit
Lightning Detector	Lightning	Transient EM, optical and acoustic signals indicative of lightning
GEOPHYSICAL SENSORS		
Magnetometer	Mag	Remanent magnetic fields indicative of early Venus dynamo
Electromagnetic Sounder	EM Sounder	Crustal thickness and conductivity
Gravimeter or Gradiometer	Grav.	Gravity anomalies at high resolution
Infrasound Sensor	Infrasound	Infrasound from Venus quakes and volcanoes
SURFACE OBSERVATIONS		
NIR Imager	NIR	Thermal emission from the surface viewed from below base of clouds
Visible Imager	VIS	Surface imaging at high resolution (sub-meter). Probe or sonde instrument only

Surface Imaging: Observing the surface at both high contrast and high spatial resolution requires observations from beneath the clouds. Approaches were examined for both visible and near infrared imaging from the aerial platform and from probes or guided sondes deployed from an aerial platform and relaying data through the platform.

Previous studies of Venus balloon missions with more limited objective than those envisaged here have had science payloads of about 30 kg. However, we believe that the broader objectives can also be accomplished with a scientific payload allocation of 30 kg. This will require miniaturizing some existing instrument concepts, introducing some entirely new design concepts that are inherently more compact, low-power and share functionality. For instance, magnetometers are needed in three of the instruments identified and there is a potential for integrating several functions into a single instrument. A focused investment in instrument technology for aerial platforms is needed to accomplish these objectives. An effective way to validate many of these instrumental techniques for use at Venus is to conduct deployment of them on aerial platforms in appropriate Earth analog environments (see recommendation in Section 6.3).

4.1.3 Updated Science Assessment

With the benefit of knowledge of what instrumentation might realistically be placed on an aerial platform, the study team updated its initial assessment of the science potential of the different aerial platform options as well as probe/sonde options. The key assumptions in this assessment are the 30 kg payload discussed in the last section and an aerial platform lifetime of at least 30 days. The assessment of probes/sondes was included but does not play a role in the comparative assessment of the aerial platforms. The capabilities of variable altitude platforms have been considered as a group for two separate altitude ranges: nominal (50 to 60 km) and enhanced (40 to 60 km). The results of this assessment appear in Table 4-2.

4.2 Platform Size and Complexity

In this section, the size and complexity of the platform required to deliver a scientific payload to Venus with the specified level of mobility are addressed.

4.2.1 Platform Size

A key metric for comparing aerial platform concepts is the size of the scientific payload that each concept would deploy at Venus. In this study, we established a science instrument payload of 10 kg as a reference point and determined both the Arrival Mass – that is the mass of the system that approaches Venus - and the Floating or Flying Mass needed to support this 10 kg payload. Smaller or larger scientific payloads such as the 30 kg considered in our science instrument assessment can be scaled from this result although the scaling is not linear in all cases.

The results are summarized in Figure 4-1. The super-pressure (fixed altitude) balloon was determined to be the lowest mass option with respect to both metrics and consequently supports the largest science payload fraction. However, the altitude-controlled balloons can be implemented with an addition of 30% to 50% in Arrival Mass. The fixed and variable altitude balloons are also scalable to larger and smaller sizes without a major impact on science payload fraction. The hybrid airship (VAMP) requires the largest Arrival Mass and Floating or Flying Mass of all the options considered. Larger versions of VAMP will have an improved payload fraction but reducing the scale has the adverse effect. The solar airplane is intermediate in both of the mass parameters to the hybrid airship and the balloon platforms.

Arrival Mass for both the SP balloon and the altitude-controlled balloon are believed to scale roughly linearly to larger sizes than those for the 10 kg payload. Hence for a super-pressure balloon with a 30 kg payload we would need approximately 750 kg arrival mass and for the Variable Altitude Platform approximately 1200 kg. Both are readily achievable in currently feasible delivery and entry systems.

4.2.2 Platform Complexity

The complexity of the platform concepts examined in this study tracks with the size differences. The super-pressure balloon is by far the simplest. It consists of a single envelope that is inflated after entry and deployment at Venus. The variable altitude concepts are more complex because they involve pumped or mechanical compressions systems or, in the case of the phase change balloon, heat exchangers. The solar airplane requires multiple wing folds to package it in the aeroshell, a deployment system that ensures a smooth transition from entry to flight, and a capable propulsion system for sustained flight. The VAMP concept requires a sophisticated system for controlling the rigidity of the airframe and managing the level of pressurization of the hull in the transition from inflation in space through the severe heating of entry and descent to its operating altitude range.

Table 4-2 Science Assessment of Aerial Platforms, probes and sondes. The color codes represent the science team's judgments on what could be accomplished with a science payload with miniaturization reflecting current technology

VEXAG Goals, Objectives and Investigations				**Venus Aerial Platform and Sonde Types with Altitude Range (km)**							
Goals	**Objectives**	**Investigations**	**GOI Code**	**Constant Altitude**	**Variable Altitude Aerobot**		**3D control**		**Probes/Sondes**		
				SP Balloon	**Nominal Range**	**Enhanced Range**	**Solar Airplane**	**Airship VAMP**	**Large Probe**	**Targeted Sonde**	**Shallow Sonde**
				55	**50 to 60**	**40 to 60**	**66 to 75**	**50 to 60**	**65 to 0**	**55 to 0**	**60 to 40**
Atmosphere	Atmospheric Evolution	Solar Nebula/noble gases	I.A.1	🟦	🟦	🟦	🟦	🟦	🟩		
		Atmospheric Escape	I.A.2	🟩	🟩	🟩	🟩	🟩	🟩		
	Radiative balance, climate and superotation	Global circulation	I.B.1	🟨	🟩	🟩	🟨	🟩	🟨	🟨	🟨
		Radiative Balance	I.B.2	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩
		Vertical motions	I.B.3	🟨	🟩	🟩	🟨	🟩	🟨	🟨	🟨
	Clouds and Haze characterization	Cloud chemistry	I.C.1	🟩	🟦	🟦	🟨	🟦	🟨	🟨	
		Greenhouse /Cloud physics	I.C.2	🟩	🟦	🟦	🟨	🟦	🟨	🟨	🟨
		Role of lightning	I.C.3	🟩	🟦	🟦	🟩	🟦	🟨		
		Biologically relevant chemistry	I.C.4	🟩	🟦	🟦	🟨	🟦	🟨	🟨	
Surface and Interior	Geodynamics	Stratigraphy/deformation	II.A.1						🟨	🟦	
		Radiogenic He_4 Ar_{40} in atmos	II.A.2	🟦	🟦	🟦	🟦	🟦	🟩		
		Geophysical studies	II.A.3	🟩	🟩	🟩	🟨	🟦			
		Active volcanism and tectonism	II.A.4	🟩	🟩	🟩		🟩			
		Absolute rock ages	II.A.5								
	Differentiation	Elemental composition	II.B.1.								
		Large scale composition variations	II.B.2			🟦			🟦	🟦	
		Structure of crust	II.B.3	🟩	🟩	🟩		🟩			
		Core and mantle structure	II.B.4	🟨	🟨	🟨		🟨			
		Radiogenic crustal elements	II.B.5								
		Subsurface layering	II.B.6	🟩	🟩	🟩					
Interior Surface Atmosphere	Liquid water and the greenhouse effect	History of water from Isotopes	III.A.1	🟦	🟦	🟦	🟦	🟦	🟩		
		Role of water in tessera	III.A.2			🟩			🟩	🟦	
		Hydrous minerals and sediments	III.A.3								
	Interactions of interior-surface and atmosphere over time	Elemental composition-noble gas	III.B.1	🟩	🟩	🟩	🟩	🟩	🟩		
		Rock weathering investigations	III.B.2			🟩			🟩		
		Altitude profiles of reactive species	III.B.3	🟨	🟩	🟦		🟩	🟦	🟩	
		Sulfur outgassing from surface	III.B.4	🟨	🟩	🟦	🟩	🟩	🟩	🟩	
	Other	Solid Body Atmosphere Ang Mom	NA								

🟦	Necessary and sufficient to address the investigation in the GOI
🟩	Necessary but not sufficient
🟨	Complementary to a primary measurement

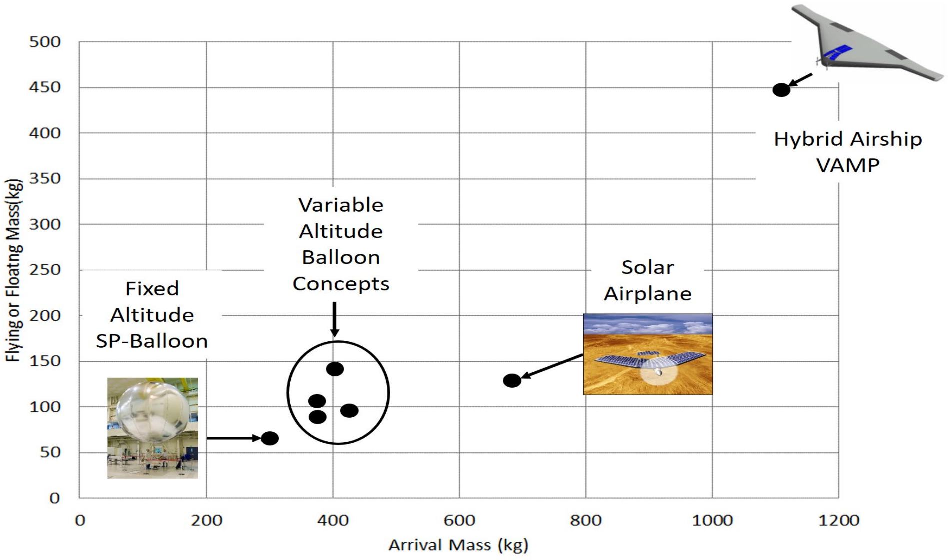


Figure 4-1 Arrival Mass and Flying or Floating Mass for aerial platforms capable of supporting a 10 kg science payload. The super-pressure balloon requires the smallest values of both metrics. The four variable altitude concepts deemed suitable for a Venus mission require about 30 to 50% more arrival mass. The data presented here apply only to the nominal altitude range (50 to 60km) platform. The solar airplane has a similar flying mass to the variable altitude balloon but requires a larger arrival mass because of deployment complexity. The hybrid airship has the largest flying mass. The arrival mass is driven in this case by the need for a propulsion system to orbit Venus in order to reduce entry velocity to an acceptable range

4.2.3 Access to Deeper Regions in the atmosphere

Two approaches were examined for using aerial platforms designed for operation in the temperate zone for acquiring data from deeper in the atmospheric column. In the first approach, sondes designed to survive the severe environment are released from the aerial platform and fall towards the surface acquiring data and relaying it through the aerial platform. The study determined that sondes as small as 5 kg could carry a useful payload of 1 kg and survive and operate all the way to the surface enabling close up imaging of the surface. The other approach is for the balloon to descend to regions of higher temperatures. This requires that electronics and sensors that would be rendered inoperable or damaged by the high temperatures be protected. For relatively short excursions (several hours) to the base of the clouds this could be accomplished with passive techniques. Active cooling of some components such as near infrared sensors may be required to meet the science objectives. Any systems which are exposed to this harsher environment, such as the balloon envelope and solar arrays, must be designed to assure survival under these conditions.

4.3 Technology Maturity

The aerial platform concepts examined here represent different levels of technology maturity. The three mission phases considered for determining technology maturity are entry; descent and deployment; and the operational phase, where aerial mobility is exercised. The standard TRL nomenclature has not been used in this assessment, since it implies a degree of rigor that was not practical for this study. Instead we have used a five-level assessment: Very High, High, Moderate, Low-Moderate, and Low similar to that used in VEXAG's Venus Technology Plan (VEXAG, Tech Plan, 2014). These assessments appear in Table 4-3.

4.3.1 Entry Technology

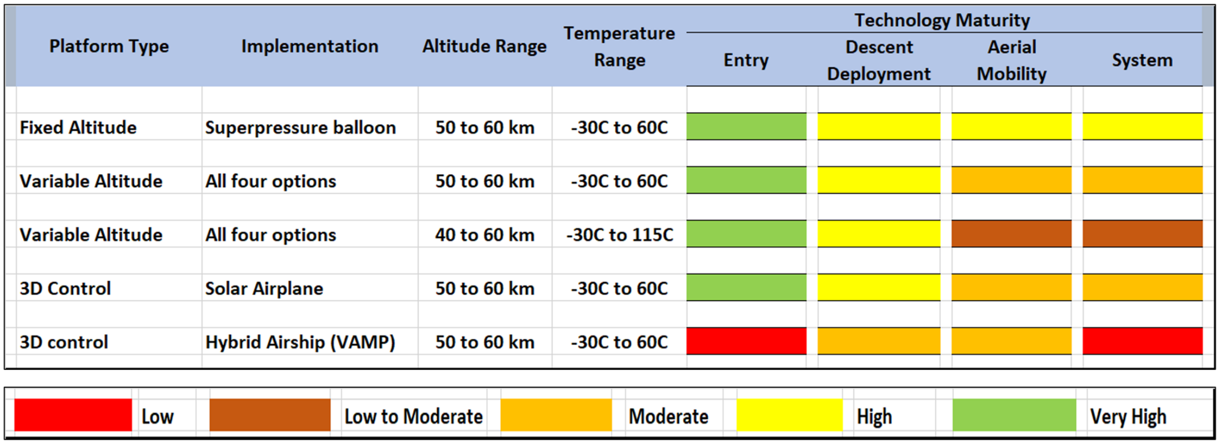
Four of the concepts considered here use a rigid aeroshell which is jettisoned after use; the fifth concept uses an inflatable entry system which also provides aerial mobility.

Rigid Aeroshell: The rigid aeroshell (Figure 4-2, left) is a well-established approach used in prior U.S. probe missions to Venus. In the last five years, NASA has also invested in an advanced Thermal Protection System (TPS) called Heatshield for Extreme Entry Environment Technology (HEEET) which will replace carbon phenolic, which is no longer produced, and also provide more design flexibility including trajectories with shallower entry angles than feasible with the older technology. The entry performance for this approach is well understood from the standpoint of structural design, aerodynamics and aeroheating and its maturity is deemed Very High.

Figure 4-2 Comparison of entry systems used for Venus Aerial Platforms. The rigid aeroshell, a relatively mature concept (left) is used for all of the concepts except VAMP. The entry configuration for VAMP is considered low TRL and is a much larger vehicle.

Semi Buoyant Air Vehicle: This concept is unique to the hybrid vehicle VAMP. The vehicle is inflated in space to form a winged entry vehicle with a ballistic coefficient two orders of magnitude lower than the rigid aeroshell just described. The performance for this concept during entry is not well understood and there are major uncertainties in structural design, aerodynamics and aeroheating. Based on NASA experience with inflatable entry systems (e.g., Hypersonic Inflatable Aerodynamic Decelerator (HIAD), the development life cycle for this vehicle will be protracted. Doubling the linear scale of the vehicle at each development step is the maximum that is realistic for such a technically advanced vehicle. To scale up to a vehicle with scientific value will require four or five successful development cycles for the entry system behavior which must be coupled to similar validation for operation as an aerial vehicle. Its maturity is considered low.

Table 4-3 Technology Maturity of five different aerial platform concepts. The maturity was separately assessed for entry, descent, deployment, and aerial mobility. System maturity generally cannot exceed the rating with the least maturity in these three categories



Platform Type	Implementation	Altitude Range	Temperature Range	Technology Maturity			
				Entry	Descent Deployment	Aerial Mobility	System
Fixed Altitude	Superpressure balloon	50 to 60 km	-30C to 60C	🟩	🟨	🟨	🟨
Variable Altitude	All four options	50 to 60 km	-30C to 60C	🟩	🟨	🟧	🟧
Variable Altitude	All four options	40 to 60 km	-30C to 115C	🟩	🟨	🟫	🟫
3D Control	Solar Airplane	50 to 60 km	-30C to 60C	🟩	🟨	🟧	🟧
3D control	Hybrid Airship (VAMP)	50 to 60 km	-30C to 60C	🟥	🟧	🟧	🟥

🟥	Low	🟫	Low to Moderate	🟧	Moderate	🟨	High	🟩	Very High

4.3.2 Descent and Deployment

The first four of the platform concepts in Table 4-3 are deployed after descent through the atmosphere to an altitude at or even below where the operational phase will be conducted. The fixed altitude superpressure balloon is most mature with respect to descent and deployment since some development has been completed (Hall, et al., 2017). The variable altitude balloons and solar airplane are more complex and are deemed to have moderate maturity. For the hybrid airship (VAMP) concept the order of entry descent and deployment is inverted with deployment taking place in space. Following entry, the inflated vehicle descends through tenuous regions of the atmosphere until it reaches a level where buoyancy will support its mass. Because of this, maturity for both the deployment and descent phases of the hybrid airship is deemed moderate.

4.3.3 Aerial Mobility

The fixed altitude superpressure balloon is deemed the most mature of the concept considered here since prototypes designed for the Venus environment have been built and tested. Neither of the four Variable Altitude balloon concepts have been designed or built for the Venus environment and are therefore of lower maturity. Those designed for the nominal altitude range (50 to 60 km) were determined to be of moderate maturity; those designed for the enhanced altitude range (40 to 60 km) were deemed to be of low to moderate maturity a result of not only the altitude range but also accommodating the high temperatures. A thermal control system will be needed to protect temperature-sensitive electronics, sensors and batteries during excursions into the high temperature regions. The solar airplane and hybrid airship, neither of which need to handle these higher temperatures, are deemed to be of moderate maturity in terms of aerial mobility technology readiness.

4.3.4 System Level Maturity

The system level technology maturity is a composite of the maturity of the three components. System maturity cannot be higher than the least mature of the three component elements. None of the concepts examined here are deemed Very High and ready for flight. The VAMP concept is deemed least mature, an assessment driven by the challenges of entry technology and compounded by the fact that this is a multifunctional vehicle that has to meet requirements in all three flight domains. Development of maturation plans for each of the platform types was beyond the scope of the study.

4.4 Trade Study Findings - The Sweet Spot

The assessments presented in Sections 4.1 to 4.3 have been consolidated in Figure 5-1. The science merit of each of the five platform concepts is depicted on the vertical axis drawing on information from Table 4-2. Size and complexity, which is a composite measure derived from the analysis presented in Figure 4-1 and Section 4.2, is plotted along the horizontal axis. Technology maturity at the system level as depicted by a color code and is derived from Table 4-3. Based on these analyses, Variable Altitude platforms with nominal altitude range were determined to offer a significant increment in science value over fixed altitude platforms without incurring a major increase in size or complexity or requiring major advances in technology. The Variable Altitude−Enhanced Range platforms provide a still higher science value but involve greater size and complexity and more advanced technology. This more detailed analysis confirms the initial finding of the science team that Variable Altitude Platforms occupy the sweet spot in the option space. The solar airplane was considered to be of moderate maturity but with significantly lower science than Variable Altitude Balloons. NASA-sponsored studies of solar airplanes currently underway may lead to an upgrading of science potential but are unlikely to change the overall assessment. The hybrid airship inflated in space was deemed to be of low technology maturity. A hybrid airship deployed from within a conventional aeroshell was not studied but would be unlikely to change the overall assessment.

5 Synergies with Orbital Spacecraft

An orbital spacecraft can provide vital support for an aerial platform by providing relay communications, tracking and synergistic science observations. These capabilities may not be necessary for some mission concepts with highly targeted science. For example, the VeGa balloons communicated directly to Earth (at a very low rate) and were tracked from Earth but required an extensive network using Very Long Baseline Interferometry (VLBI). However, orbital spacecraft will be required for the comprehensive science investigations described in this report.

5.1 Relay Telecommunications

Although it is possible to communicate data from the platform directly to the Earth, much greater data rates can be achieved with power economies for the platform if data is relayed through an orbiter. Unlike Mars, there is no established communications relay network at Venus although the protocols and technology developed for Mars can be applied at Venus. Key challenges are that the platform would be in continuous motion in the superrotating atmospheric flow and its positions would be much less predictable than for a stationary lander or near-stationary rover. A relay orbiter in a circular equatorial orbit appears to be the best choice with the altitude depending on a trade between data rate and tolerance for excursions to higher latitudes. Except for mission concepts where imaging is acquired from below the cloud base (see next section), data return requirements are modest and many of these concepts would be compatible with relay to a SmallSat as contemplated in VEXAG's Venus Bridge study (Grimm & Gilmore, 2018).

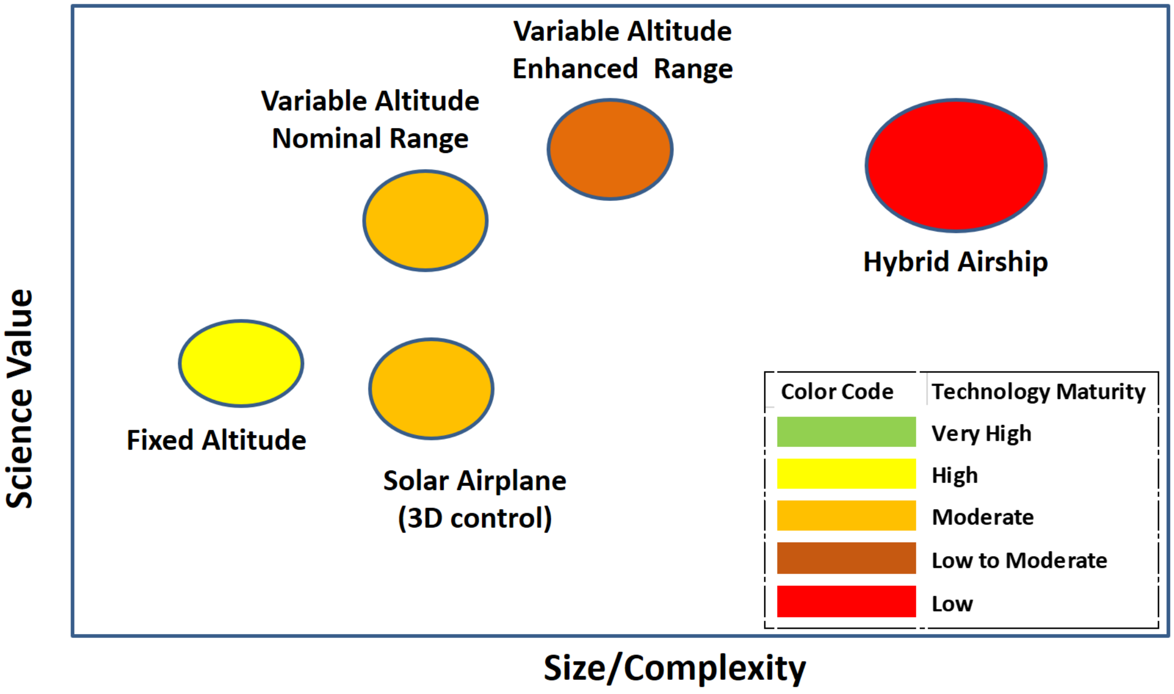


Figure 5-1 Comparison of aerial platform options with respect to the metrics of Science Value, Size/Complexity and Technology Maturity. Variable Altitude/Nominal Range (50 to 60 km altitude) balloons occupy the sweet spot. For a modest increase in size and complexity over the fixed balloon and accepting a moderate degree of technology maturity, there is a significant gain in science. The Variable Altitude Enhanced Range balloon provides a further gain in science but are more complex and less mature because of enhanced range and the extreme temperatures they must tolerate.

5.2 Guidance Navigation and Control (GN&C)

Determining the location of the aerial platform and the attitude of its instrument module presents many challenges. Viewing stars optically from within the Venus cloud deck appears infeasible. Locating the Sun to better than 10 degrees accuracy may be impractical as well. There is no permanent magnetic field on Venus that would be an alternative means of determining platform attitude. Localization of the platform when it is on the Earth-facing side of Venus should be feasible to better than 100 m, but because of radio link atmospheric losses, this may be only practical for 30% of the time. Variable altitude platforms exploiting meridional wind velocity component reversals to change latitude will require accurate positional tracking because of uncertainties in the circulation but not platform attitude. Further work is needed to determine how a relay orbiter could be used to determining platform position and attitude where that is required for science.

5.3 Orbital Science

Orbital science missions including most recently the ESA Venus Express and JAXA Akatsuki missions have provided a vast amount of information about the Venus atmosphere. Although important measurements can be made at Venus without the need for simultaneous orbital observations, it is clearly desirable to have orbital observations to provide context for the in situ observations of an aerial platform. The platform can provide “ground-truth” to calibrate orbital observations so that they are more useful. VEXAG’s Venus Bridge study (Grimm & Gilmore, 2018) concluded that important synergistic science could be conducted with SmallSats and even CubeSats that also provide relay communications. In addition, power, telecommunications and other electronics technologies used in SmallSats and CubeSats may be directly applied to aerial platforms which have similar restrictions on power and mass.

6 Technology and Infrastructure Development Needs

The primary focus of the development activities described below is for a capable aerial platform as a NASA contribution to the Venera D mission or for the aerial platform in a NASA led Flagship mission similar to Venus Climate Mission recommended by the 2011 Planetary Science Decadal Survey. However, these capabilities are also relevant to future opportunities for competitive missions (Discovery and New Frontiers class) and for a class of smaller missions including Venus Bridge.

6.1 Aerial Platform Development

Fixed Altitude balloons up to 5.5 m in size currently have a high level of technology maturity and are ready for targeted science missions today. Scaling to larger sizes will present additional challenges and further work is needed to assure extended life. Variable Altitude balloons have the potential for a substantial enhancement of the science over fixed altitude balloons without a commensurate increase in size and complexity of the platform, but will require some new technology largely adapted from terrestrial examples. A competitive technology program funding several different concepts would be an effective way to determine the most promising approach to a Variable Altitude Aerial Platform. The program should include designing and building subscale prototypes followed by laboratory and flight tests. Following an independent evaluation of the different options a full-scale prototype of the selected option should be built.

6.2 Science and Instrument Development

Aerial platforms enable investigations addressing all three major goals established by VEXAG: for Atmosphere, Surface and Interior, as well as Surface-Interior-Atmosphere Interaction. Development of new experimental techniques and miniaturization of existing ones are needed in order that aerial platform missions can deploy rich and diversified scientific payloads and fully exploit the promise of aerial exploration of Venus. NASA’s PICASSO and MATISSE technology development programs provide opportunities for advancing these capabilities.

6.3 Earth-Based Flights for Engineering and Science

Aerial platform flight tests and experiments should be implemented not only for engineering purposes but also to demonstrate and develop scientific techniques. A dedicated test bed program would be an effective way to validate the performance of these instruments in operational environments, as well as to train scientists and engineers in the unique challenges of aerial platform missions.

6.4 Modeling and Simulation

Computer models with sufficient fidelity to describe the flight of aerial platforms in the Venus environment are a vital part of developing Venus Aerial Platform capabilities. They will play a role in the design, development and operation of aerial platforms at Venus

6.4.1 Venus Environment Models

These models must incorporate representations of the atmospheric environment of the planet including the velocity fields, the cloud structure, and the solar and thermal radiation fluxes which are the primary parameters influencing the behavior and performance of aerial platforms. The Venus environment models should both incorporate the best data that is available from the Venus Express and Akatsuki missions, as well as the best physics for integrating these data into a concise but reliable representation of the Venus environment. These models should describe both average behavior and the dispersions in key parameters.

6.4.2 Models of the Aerial Platforms

Models are also needed to describing the behavior of different aerial platform concepts in the Venus environment. The environmental modeling should be accessible to the developers of these aerial platform concepts so they can be used in evaluating and refining those concepts. Validation of model predictions with Earth flights of Venus aerial platform prototypes can ensure that model results can be extrapolated with greater confidence to Venus.

6.4.3 Models of Sensors and Experimental Techniques

These models would use information from Venus environment models to predict the performance of sensors in that environment. For instance we need to determine at what altitude quality images of the surface can be obtained in the visible and infrared as a function of time of day. We also need to know how well we can locate the sun and stars as a function of platform altitude, viewing conditions and spectral region.

6.4.4 Aerial Platform Operations – Autonomy

A capable simulation environment will be important for developing and validating controls systems that build resilience and expand the operational envelope of an aerial platform concept. The platform may be out of contact with ground controllers for periods in which the vehicle travels thousands of kilometers and encounters unpredicted atmospheric conditions. An autonomous control system will ensure that the platform remains in a safe zone constrained by temperature and the solar radiation environment and executes timely scientific operations including deployment of probes and sondes.

6.5 Synergies with SmallSat and CubeSat Technologies and Systems

Miniaturized systems for providing relay and direct-to-Earth communications, guidance navigation and control and autonomous operations are needed to exploit the scientific potential of aerial platforms. There are important synergies with the technology needs of interplanetary SmallSats and CubeSats. SmallSats and CubeSats are also a cost-effective way of conducting science at Venus and providing relay communications, continuous tracking and attitude determination to the aerial platform.

7 Programmatic Opportunities

Opportunities for aerial platforms in NASA's planetary science program include opportunities for Flagship class missions (such as Venera D and a NASA-led Venus Flagship mission) which were a primary focus of this study. There are also opportunities in the competitive New Frontiers and Discovery programs as well as for low cost missions such as those contemplated in the Venus Bridge study (Grimm & Gilmore, 2018).

7.1 Flagship Class Missions

The primary focus of the recommendations made here related to a Flagship class mission. Currently, there are two possible avenues that might be considered for such a mission: as a U.S.-provided aerial platform for the Venera D mission as a NASA contributed element as recommended by a Joint Science Definition Team (JSDT); and as an element of a U.S. led Venus Flagship mission.

A U.S.-Russia Joint Science Definition Team (JSDT) has been studying a mission concept in which Russia would furnish a lander and orbiter and the U.S. would contribute other flight elements. An aerial platform was identified as one of those elements (Venera D Joint Science Definition Team, 2017). The Venera D mission is not yet an approved mission and it is anticipated that there would be several years available for technology development of any U.S.-funded elements. Mass allocations for an aerial platform were originally made in this report in anticipation that the VAMP technology could be ready for this mission. A variable altitude balloon with the comprehensive science payload is compatible with the mass allocations that Russia has made for a U.S. contribution (Venera D Joint Science Definition Team, 2019).

NASA will also be studying a Venus Flagship mission in the fall of 2018 in preparation for the next Planetary Science Decadal Survey (PSDS). For the last PSDS in 2011, a Venus Climate Mission was recommended which included an orbiter, a superpressure balloon, a miniprobe and two drop sondes. In the new study the variable altitude balloon should be considered and the broadening of the science to include geophysical observations and surface imaging should be evaluated.

7.2 Discovery and New Frontiers

Aerial Platforms may also be considered for future Discovery and New Frontiers opportunities. There have been prior proposals of Venus superpressure balloon missions and, at this time, only superpressure balloons are viewed as sufficiently mature technologically for a future proposal. An investment in variable altitude balloon technology could also make that technology mature enough for a future proposal.

7.3 Venus Bridge

In April 2018, NASA's Planetary Science Division completed a study of Venus Bridge, a concept for a very low-cost mission to Venus consisting of two linked elements, an orbiter and an in situ element. The study included a balloon as the in situ element with an orbiter that provided data relay, balloon localization and synergistic science observations. Venus Bridge may provide an opportunity for demonstrating new types of in situ system at Venus in NASA Class D projects for which cost/schedule are considered equal or greater considerations compared to mission success risks. Although the baseline studied for Venus Bridge was a superpressure balloon comparable in size to the VeGa balloons, variable altitude balloons might be an alternative candidate. At this time, Venus Bridge is still a concept and NASA has not indicated how it plans to implement the recommendations of the study.

8 Summary

This study concluded that not only are Venus Aerial Platforms feasible, but they offer a rich menu of scientific opportunities for studies of the Venus atmosphere, its surface and interior as well as their mutual interaction. However, to realize these benefits, a set of technology investments are needed including new science instrumentation and modeling tools to characterize the behavior of vehicles in the Venus environment. However, there are no technological show-stoppers to impede the development of these capabilities. Flight tests using the Earth environments as an analog for Venus will be needed to optimize both the vehicles and science experiments. There are several programmatic opportunities that should be explored including U.S.-contributed elements for Russia's Venera D mission, a U.S.-led Venus Flagship Mission, missions in NASA's competitive Planetary Science programs (Discovery and New Frontiers) and even smaller missions exploiting SmallSat and CubeSat technology.

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