Venus Bridge

Examining a Low-Cost Renewal of American Exploration of Earth's Divergent Sibling

Summary Report

Prepared for the
Associate Administrator
NASA Science Mission Directorate

Prepared by the
Venus Exploration and Analysis Group (VEXAG)

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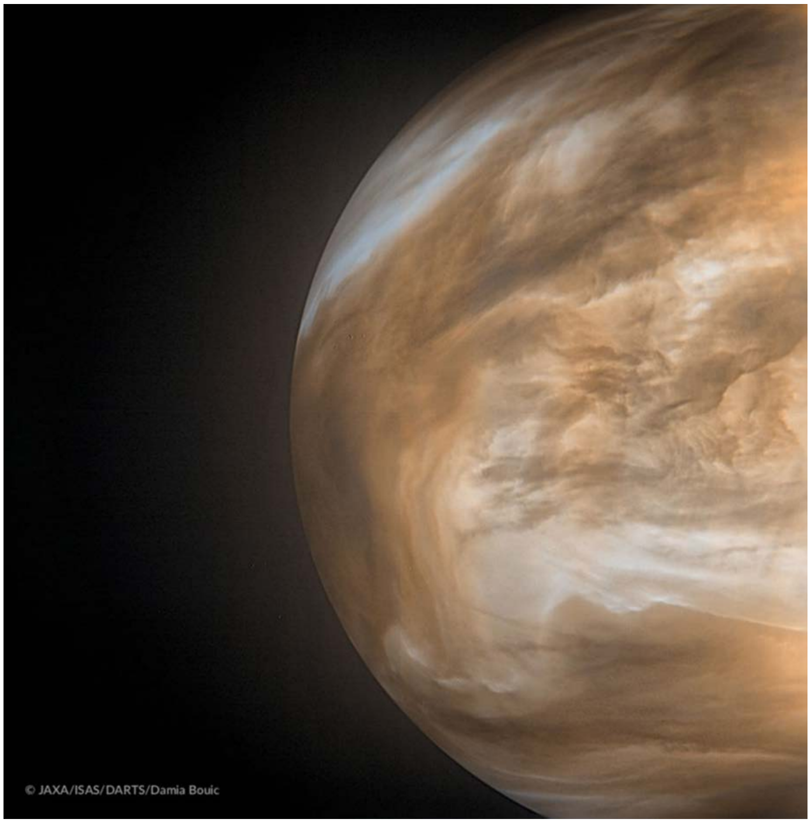

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Executive Summary

In early 2017, the NASA SMD AA posed the question to VEXAG leadership “What can you do for $200M?” VEXAG chartered a “Venus Bridge” Focus Group to solicit and evaluate ideas on architectures, technology, and science goals that could be pursued with small satellites launching in the early-to-mid 2020s. The moniker emphasizes that one or more low-cost missions could bridge the gap between the 1989 Magellan mission and larger, more capable missions flying in the late 2020s to early 2030s.

Given that several awards by the Planetary Science Deep Space SmallSat Studies (PSDS3) program were expected to produce concepts for Venus smallsat missions for $100M or less, the $200M target naturally suggested multiple flight elements. In order to maximize value, mission-design teams at GRC and JPL were directed by the Focus Group to emphasize one orbital and one in situ element (probe, balloon, lander) that were linked via science and telecom and did not consider a single mission with a $200M cap. GRC produced a detailed point design (Concept Maturity Level or CML = 4) for an orbiter carrying a small lander that demonstrates new technology for long life on the hot surface of Venus. Telecom relay is required due to the minimal resources of the lander. In addition to measuring atmospheric properties at the surface and mapping surface composition from orbit, the two elements jointly determine infrared radiance.

JPL executed 8 architecture studies (5 orbital, 3 in situ, CML 2−4) that drew on several funded PSDS3 concepts. Several complementary mission pairs can be formulated (skimmer and orbiter assess atmospheric composition and loss, probe and orbiter investigate the mysterious ultraviolet absorber, balloon and orbiter seek Venus quakes). Due to larger and more complex in situ elements, they found that separating the aggregate into two components that fly independently to Venus was preferred. All missions from both centers address one or more VEXAG investigations, which in turn trace to the Decadal Survey.

GRC used a conservative approach to cost estimation assuming major aerospace providers. They priced their two-element mission at $201M, including 25% reserves on Phases A-D but not including some technology development to TRL 6 nor launch and operations. JPL’s single-element concepts were typically <$100M including ~30% reserves, launch, and operations, but assumed cost control by outsourcing to university or smallsat providers. These differences in cost-estimating assumptions make it difficult to determine definitively whether a two-element Venus Bridge Class D program can be carried out for a total $200M cost to NASA, but the results probably have enough fidelity to continue feasibility investigations to CML 5 (e.g., Step 1 proposals).

VEXAG continues to advocate for a balanced program of US exploration of Venus (see Finding #1 from VEXAG Meeting #15) consisting of elements drawn from Flagship, New Frontiers, Discovery, and smallsat missions. A Venus Bridge program can reinvigorate the US Venus community for the mid-2020s and serve as pathfinders for larger, more capable missions for flight in the late 2020s to early 2030s.

1. Introduction

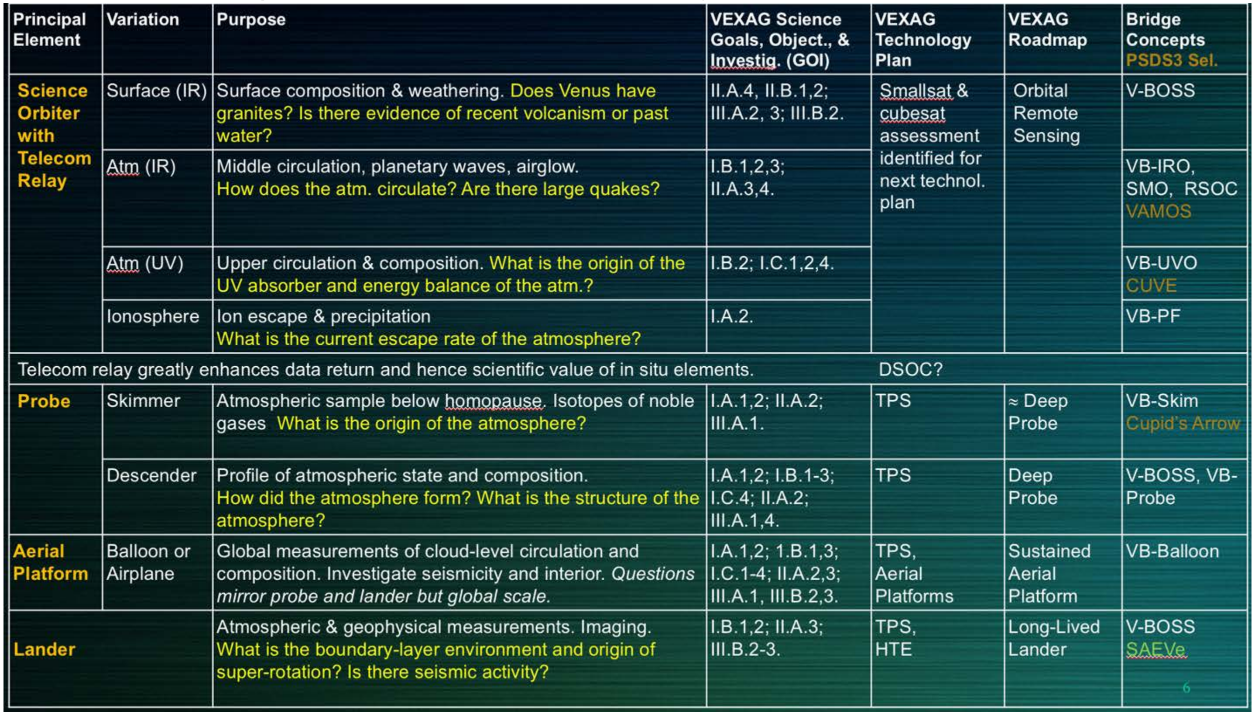
Venus is the cornerstone of comparative planetology and is the key to understanding where an Earth-sized planet elsewhere in the galaxy might be Earth-like. In spite of being called Earth's twin, the fundamental questions about Venus are unique: what is the origin and evolution of is massive atmosphere? Why is the geology of Venus—its expression of internal heat loss—different than any other world? What was the fate of its water and history of its habitability? The first-ever successful interplanetary mission was Mariner 2 to Venus in 1962 and the US continued with additional Venus-specific missions culminating in Magellan in 1989. Since then no there have been no US Venus missions. Smallsats may provide a means to attain new Venus science pending larger and more capable missions.

Venus Bridge was started in response to a query from the NASA SMD AA "What can you do for $200M?" The term "Bridge" was deliberately selected by analogy with NASA IceBridge, as a gap-filling program between larger efforts—for Venus, between Magellan and a subsequent Discovery or New Frontiers mission. The Venus Bridge Focus Group (**Appendix 1**) was chartered to consider ideas on architectures, technology, and science that could be pursued within framework of multiple small missions totaling <$200M using rideshare opportunities. A key aspect was to consider science and communications linkage between elements, e.g., an orbiter relay from an in situ element (probe, balloon, or lander). The multi-element and linked framework was envisioned to distinguish Venus Bridge from the ongoing PSDS3 program, which selected several single-element Venus concepts to study feasibility at <$100M cost.

More than a dozen concepts were received from the community and Focus Group members. These were edited and organized for study by mission-design teams at GRC and JPL. Note that the sum of funding for the entire Venus Bridge study ($330K) was significantly less than that provided for a single PSDS3 ($500K). Funding was provided for engineering whereas the scientific contributions were, as usual, on a volunteer basis. Fortunately, the Venus PSDS3 concepts could be significantly leveraged for Venus Bridge.

Differences in the interests and cultures of the two participating NASA centers dictated separate studies. GRC performed a detailed point design (CML 4) complementing the SAEVe PSDS3 long-lived lander with a dedicated carrier/science orbiter/telecom. (SAEVe relies on an unspecified carrier and telecom). Their final report numbers nearly 300 slides (submitted separately by GRC) detailing trades, launch, cruise, and landing configuration, science, technology, CONOPS, mission design, EDL, systems, C&DH, telecom, power, structures and mechanisms, thermal, ADCS, propulsion, and cost. A 6-page executive summary (also submitted separately by GRC) is summarized below. JPL took a different approach, drawing on two in-house PSDS3 awards for Venus (Cupid's Arrow in situ and VAMOS orbiter) as well as information from other PSDS3 concepts. This provided the basis for architecture studies (CML 2) on several additional missions as well as expressing the two PSDS3 concept studies (CML 4) on the same footing. JPL's ~30-page report is also submitted separately. We summarize the GRC and JPL efforts and then consider joint findings and assess the path forward. Generalized (**Table 1**) and mission-specific (**Table 2**) science traceability matrices are presented.

Table 1. Venus Bridge Generalized Science Traceability



Principal Element	Variation	Purpose	VEXAG Science Goals, Object., & Investig. (GOI)	VEXAG Technology Plan	VEXAG Roadmap	Bridge Concepts PSDS3 Sel.
Science Orbiter with Telecom Relay	Surface (IR)	Surface composition & weathering. Does Venus have granites? Is there evidence of recent volcanism or past water?	II.A.4, II.B.1,2; III.A.2, 3; III.B.2.	Smallsat & cubesat assessment identified for next technol. plan	Orbital Remote Sensing	V-BOSS
	Atm (IR)	Middle circulation, planetary waves, airglow. How does the atm. circulate? Are there large quakes?	I.B.1,2,3; II.A.3,4.			VB-IRO, SMO, RSOC VAMOS
	Atm (UV)	Upper circulation & composition. What is the origin of the UV absorber and energy balance of the atm.?	I.B.2; I.C.1,2,4.			VB-UVO CUVE
	Ionosphere	Ion escape & precipitation What is the current escape rate of the atmosphere?	I.A.2.			VB-PF
Telecom relay greatly enhances data return and hence scientific value of in situ elements.				DSOC?		
Probe	Skimmer	Atmospheric sample below homopause. Isotopes of noble gases What is the origin of the atmosphere?	I.A.1,2; II.A.2; III.A.1.	TPS	≈ Deep Probe	VB-Skim Cupid's Arrow
	Descender	Profile of atmospheric state and composition. How did the atmosphere form? What is the structure of the atmosphere?	I.A.1,2; I.B.1-3; I.C.4; II.A.2; III.A.1,4.	TPS	Deep Probe	V-BOSS, VB-Probe
Aerial Platform	Balloon or Airplane	Global measurements of cloud-level circulation and composition. Investigate seismicity and interior. *Questions mirror probe and lander but global scale.*	I.A.1,2; 1.B.1,3; I.C.1-4; II.A.2,3; III.A.1, III.B.2,3.	TPS, Aerial Platforms	Sustained Aerial Platform	VB-Balloon
Lander		Atmospheric & geophysical measurements. Imaging. What is the boundary-layer environment and origin of super-rotation? Is there seismic activity?	I.B.1,2; II.A.3; III.B.2-3.	TPS, HTE	Long-Lived Lander	V-BOSS SAEVe

Table 2. Detailed Science Traceability for Selected Venus Bridge Mission Concepts. Green = significantly addresses investigation, yellow = partially addresses investigation.

Goals	Objectives	Investigations	GOI Code	Atmospheric Element			Orbital Element					V-BOSS
				VB-Skim	VB-Probe	VB-Balloon	VB-PFO	VB-UVO	VB-IRO	VB-SMO	VB-RSO	
Atmosphere	Atmospheric Evolution	Solar Nebula	I.A.1	🟩								
		Atmospheric Escape	I.A.2	🟩			🟩					
	Radiative balance, climate, and superrotation	Global Circulation	I.B.1		🟨	🟨			🟨	🟩	🟩	🟨
		Radiative Balance	I.B.2							🟩	🟨	🟩
		Vertical Motion	I.B.3			🟨			🟨	🟨	🟩	
	Clouds and hazes	Cloud Chemistry	I.C.1		🟩	🟩						🟨
		Greenhouse Constituents	I.C.2		🟨	🟩		🟩				
		Lightning	I.C.3			🟨	🟨					
		Biologically relevant chemistry	I.C.4			🟨						
Surface and Interior	Geodynamics	Stratigraphy/deformation	II.A.1									
		Outgassing	II.A.2	🟨								
		Interior	II.A.3						🟩			
		Active volcanism and tectonism	II.A.4			🟨			🟩			🟨
		Absolute rock ages	II.A.5									
	Differentiation	Local surface composition	II.B.1									
		Large scale compositional 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 tesserae	III.A.2									🟨
	Interaction of interior-surface and atmosphere over time	Evidence of hydrous minerals & sediments	III.A.3									🟨
		Atmospheric sources & sinks	III.B.1									
		Rock weathering investigations	III.B.2									🟨
		Altitude profiles of reactive species	III.B.3									🟨
		Sulfur outgassing from the surface	III.B.4									🟨

2. Venus Bridge Orbiter and Surface System (V-BOSS, GRC)

V-BOSS exploits investments in high-temperature electronics to deliver a small lander to the surface of Venus capable of surviving for a full diurnal cycle (117 days), supported by an orbiter that performs complementary science and serves as a telecom relay. Orbital imaging and bolometers on the lander define the upward and downward infrared radiant flux, respectively, providing closure on a key measurement of the energy balance of Venus's atmosphere. Monitoring of atmospheric temperature, pressure, and wind velocity at the surface will provide insight into coupling of the surface and the massive, super-rotating atmosphere. Orbital multiband infrared imaging of the surface will produce the first global composition map of Venus, perhaps revealing granitic rocks that indicate a complex history of the crust or H_2O-bearing minerals that point to a wet past. Other science investigations are detailed in the V-BOSS report.

V-BOSS would launch in 2025 on a lunar trajectory and use two passive lunar flybys and a powered Earth flyby to inject to Venus. The combined orbiter and lander require an ESPA Grande for rideshare accommodation. The lunar transfer can be accomplished as a secondary payload on a lunar mission (expected to become more frequent under new US policy) or as an upper-stage restart from GTO. The orbiter and lander separate 30 days from Venus, the orbiter inserts on a highly elliptical orbit using chemical propulsion, and the lander touches down at mid-southern latitudes at night.

GRC's Long-Lived In Situ Solar System Explorer (LLISSE) program is developing high-temperature mechanisms and SiC electronic circuits for sensors, data handling, communications, and power management to TRL 6 by 2019-2021. However, there is no imminent low-power solution for data storage. Therefore the V-BOSS lander must live-stream data to the orbiter. Because the first-generation lander is battery powered, data acquisition is limited to 2 minutes every 12 hours. This is sufficient for the long-term monitoring goals and also emphasizes the need for a coordinated and dedicated orbiter to support lander telecom.

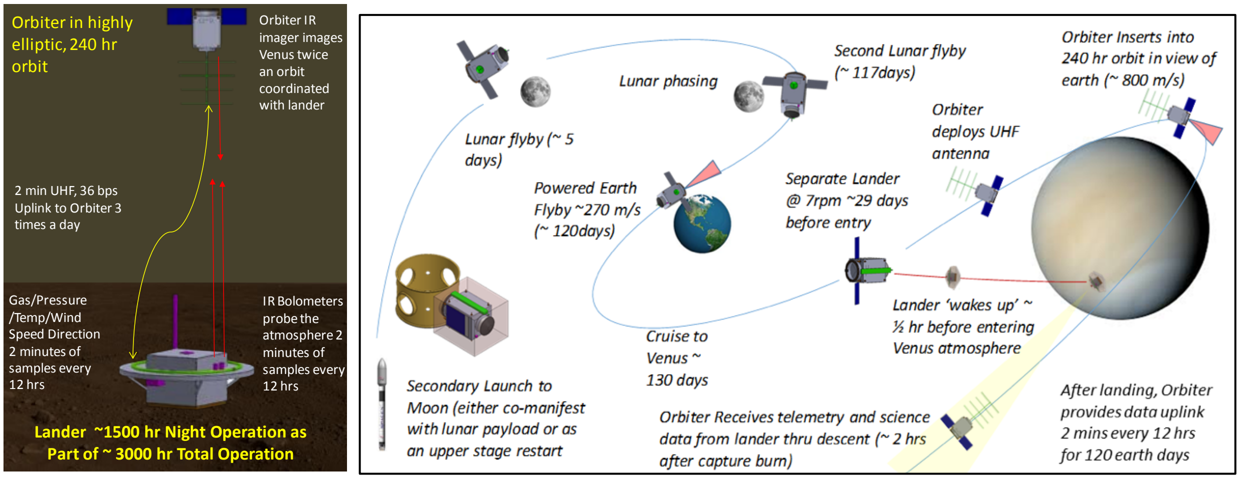


Figure 1. V-BOSS joint orbiter and long-lived lander mission.

3. Venus Bridge In Situ and Orbital Concepts (JPL).

The JPL team elected to perform introductory architecture studies (CML 2) of a broader range of smallsat orbiters and in situ missions. Four new concepts (probe, balloon, submillimeter orbiter, and radio science orbiter with cubesats) paralleled analysis of an atmospheric skimmer and infrared orbiter that received PSDS3 funding (CML 4). The ultraviolet orbiter is analogous to GSFC's CuVE PSDS3; although GSFC personnel participated in the JPL study, the Venus Bridge concept is distinct. Finally, the particles and fields orbiter was derived independently by UC Berkeley based on its MISEN PSDS3 for Mars. **Table 3** defines the acronyms used for these missions in the remainder of this report and describes their high-level science goals and measurements.

The atmospheric skimmer conclusively addresses two of the highest-priority VEXAG investigations of atmospheric evolution. The probe samples the atmosphere at higher altitude than in previous missions and aims to determine the nature of the ultraviolet absorber that strongly influences the planet's atmospheric energy balance. The ultraviolet orbiter (UVO) has similar objectives using broadband, high-resolution spectra. The particles and fields orbiter (PFO) is analogous to MAVEN, studying atmospheric escape. The balloon characterizes clouds and winds and features a new kind of investigation, infrasound measurement of seismicity. The infrared orbiter (IRO) has complementary objectives and also involves a new technique of measuring the airglow of Venus quakes. The submillimeter orbiter (SMO) is essentially the VESPER mission—twice a Discovery finalist—with miniaturized instrumentation for sounding of the upper atmosphere. The radio science orbiter with cubesats (RSOC) probes the atmosphere down to tens of km altitude using mutual radio occultations.

Table 3. JPL Mission Architecture Studies for Venus Bridge

Mission Concept	Instruments	Mission Concept Description	Science Contacts	Related PSDS 3 Concept
Atmospheric Element				
VB-Skim	High resolution mass spectrometer mass range	Measure the relative abundances of Ne, O isotopes, bulk Xe, Kr, and other noble gases to determine if Venus and Earth formed from the same mix of solar nebular ingredients, and to determine if large,cold comets played a substantial role in delivering volatiles to Venus.	C. Sotin (JPL)	Cupid's Arrow
VB-Probe	Simple MS Nephelometer and USO	Measure wind velocity in the altitude range 45 to 70 km at one location on the planet and characterize the aerosol layers including an investigation of the unknown UV absorber.	D. Atkinson (JPL)	SNAP for Venus and Outer Planets
VB- Balloon	Nephelometer and infrasound sensor	Track the balloon through at least three circumnavigations of Venus, characterizing the particulate content of the clouds and measuringconvective activity, turbulence and the infrasound activity.	K. Baines (JPL)	NA
Orbiter Concept				
VB-PFO Particles and Fields Orbiter	Ion mass analyzer, electron spectrometer magnetometer & boom	Characterize the processes that determine atmospheric escape on Venus by measuring neutral and ionized species and magnetic fields under a variety of solar activity conditions	R. Lillis (UCB) G. Collinson (GSFC)	MISEN for Mars
VB-UVO Ultraviolet Orbiter	UV Imager and spectrometer	Characterize Venus' unknown UV absorber(s), to understand the planet's radiative and thermal balance, atmospheric dynamics, and chemistry of its upper clouds	V. Cottini (U Md) N> Gorius	CUVE
VB-IRO Infrared Orbiter	Two channel Infrared imager (1.27 and 4.3um)	Measure atmospheric perturbations in airglow to characterize seismicity & seismic wave propagation to determine crustal thickness. Characterize gravity waves in the upper atmosphere to measure wind velocity	A. Komjathy B. Sutin and A. Didion (JPL)	VAMOS
VB-SMO Submillimeter Orbiter	Miniature Submillimeter spectrometer at XX GHz	Investigate the chemistry and dynamics of the middle atmosphere of our sister planet- from the base of the global cloud cover to the lower thermosphere with the goal of understanding what controls the superrotation	G. Chin (GSFC) and B. Drouin (JPL)	VESPER (Discovery)
VB-RSOC Radioscience Orbiter and CubeSats	X band transmit and receive systems on SmallSat and CubeSats	Use radiooccultations in smallsat cubesat crosslinks a to generate atmospheric temperature and pressure profiles down to approximately 35 km altitude as a finction of latitude longitude and time of day	J. Lazio (JPL) S. Asmar (JPL)	NA

Because two of the three in situ elements (skimmer and balloon) are substantially larger than the probe (which is comparable to the V-BOSS entry vehicle), accommodation of physically linked orbiter and atmospheric vehicles was challenging. Therefore JPL elected to treat all of the deliveries to Venus independently. The in situ elements consequently have attitude control and propulsion capabilities. Escape trajectories from GTO were derived, using two lunar flybys and a powered close approach of Earth. Both chemical and SEP propulsion were carried throughout the studies as appropriate but direct lunar injection is preferred for the latter because excessive time is spent circling out through the radiation belts from GTO. The SEP spacecraft fit on the standard ESPA but the in situ vehicles with their solid-rocket motors and the chemical-propulsion orbiters require ESPA Grande. Ride-alongs with Lucy and Psyche were found to be energetically favorable and allow deletion of some propulsion elements, although the current SIMPLEx Draft AO requires proposal submittal by 7/1/18 for consideration.

Three Venus orbits were studied for science applications: 6-hour elliptical (PFO, UVO), 24-hr circular (IRO), and 2-hr circular (SMO, RSOC). The short-period, low-altitude orbits require aerobraking that was not analyzed and could have a significant impact on mission cost. However, the 6-hour orbit is considered a viable alternative for SMO and presumably for RSOC as well. **Table 4** summarizes launch masses for generic flight elements. Chemical orbital insertion was constrained to be visible from Earth. SEP arrival is not a critical event and spiral-down is gradual. Note the 2023 to 2025 Venus arrivals using GTO-lunar transfers.

Table 4. Comparison of launch masses to Venus for chemical propulsion, SEP, and atmospheric elements with dry mass allocations of 75, 50, and 100 kg, respectively.

	Launch (wet) mass (kg) by orbit type				**Flight time (yr) by orbit type**				**Earliest Science Return**
	N/A	**6 hr ell**	**24 hr cir**	**2 hr cir[a]**	**N/A**	**6 hr ell**	**24 hr cir**	**2 hr cir[a]**	
Chemical orbiter									
from GTO		205	230	205		>0.7	>0.7	>1.2	Oct '23
from Lucy		220	250	220		2.0	2.0	2.5	Oct '23
from Psyche		170	190	170		4.8	4.8	5.3	May '27
SEP Orbiter									
from GTO		135	135	125		>2.6	>2.1	>2.6	Mar '25
from Lucy		80	80	70		3.5	3.0	3.5	Oct '24
from Psyche		80	80	70		5.6	4.1	5.6	Mar '28
Atmo. element									
from GTO	185				>1.0				Feb '24
from Lucy	100				3.6				May '25
from Psyche	125				4.4				Jan '27

[a] requires aerobraking

The probe and balloon both use the new HEEET TPS (assumed development complete). Vehicles with HEEET can enter the atmosphere at much shallower angles than previously attempted, which is enabling for the probe in that it can sample higher altitudes than before. The skimmer can use older PICA TPS because it does not dissipate all of its kinetic energy in the atmosphere.

The orbital and in situ missions can have complementary science (although none exploit simultaneous observations like V-BOSS). For example, UVO and the probe both investigate the ultraviolet absorber, IRO and the balloon seek Venus quakes, and the skimmer and PFO assess atmospheric composition and loss.

Telecom relay is considered vital for the balloon and offering major advantages to the probe. Direct-to-Earth communications are sufficient for the skimmer.

4. Cost

Along with differences in the technical studies of the two NASA centers came differences in costing philosophy. GRC adopted a traditional approach that assumed all V-BOSS flight elements are contracted to a major aerospace firm including 10% fee. In order to meet the cost cap, however, technology developments to TRL 6 (other than those associated with LLISSE), the radio for Earth communication (GFE under PSDS3), launch vehicle and accommodation, fuel, and operation were not included. These exclusions exist elsewhere as "non-PI" costs in PSDS3, Discovery, and New Frontiers. GRC used Monte Carlo simulation to derive a most likely cost of \$161M, which leads to a final estimate of \$201M (FY18) by including 25% reserves on Phases A-D. Without the above exclusions, the final cost to NASA could be higher by 15% or more. Even so, the Class D mission has no fault tolerance.

JPL used a combination of grassroots and parametric scaling to derive point cost estimates for the 8 missions ranging from \$92–\$116M (FY18) including ~30% reserves on Phases A-D. With each mission in the vicinity of \$100M, a two-mission Venus Bridge program would appear to be tractable and has greater flexibility in mission selection. However, it should be noted that costing was aggressive, assuming unproven university or smallsat providers under JPL supervision and incorporating minimal fault tolerance for the Class D missions. Additional instrument development also was not considered.

5. Findings and Conclusions

The studies performed by GRC and JPL are complementary and illuminate the range of Venus science investigations and technology demonstrations that could be executed with a few smallsats. The GRC concept jointly launches an orbiter and a small lander that perform simultaneous measurements. A dedicated telecom relay is required by the lander. This configuration allowed V-BOSS to hew closely to the Focus Group direction to study linked orbital and in situ elements and provide maximum synergistic science. The JPL in situ elements were not readily accommodated with an orbiter and so each element was framed as a separate mission. Science synergies still exist, but the separation simplifies the mission set and furthermore can amplify programmatic flexibility and diversity. Both reports emphasize flexibility in accommodating alternative science investigations. High-temperature electronics, miniaturized instruments, new architectures, and on-board data processing are enabling technologies for Venus smallsat missions.

To meet the desired cap, GRC excluded several important components in their costing and JPL's approach to cost control was outsourcing to entities without established records in interplanetary flight. Including operations and additional development and mission assurance even for Class D, the total cost to NASA for the mission packages described here is likely to exceed the desired $200M point. However, **the Venus Bridge studies confirm that the answer to "what can you do for $200M" is "probably a couple of smallsats, with significant risk."** Maturation of these concepts through Step 1 proposals and vetting through Science and TMC panels would of course better identify flaws and select the most viable missions for further study. Because the best leverage could be obtained from PSDS3 by studying multiple smallsats, the Focus Group did not consider a single mission with a $200M cap.

VEXAG has uniformly endorsed all opportunities to renew US Venus exploration, including Discovery, New Frontiers, Flagship, and international participation. These opportunities could now include Venus Bridge, which would help transfer legacy experience in Venus and galvanize a new generation of Venus scientists. VEXAG thanks NASA for the opportunity to consider low-cost missions as part of a balanced program of Venus exploration.

Appendix 1. Venus Bridge Focus Group Participants.

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