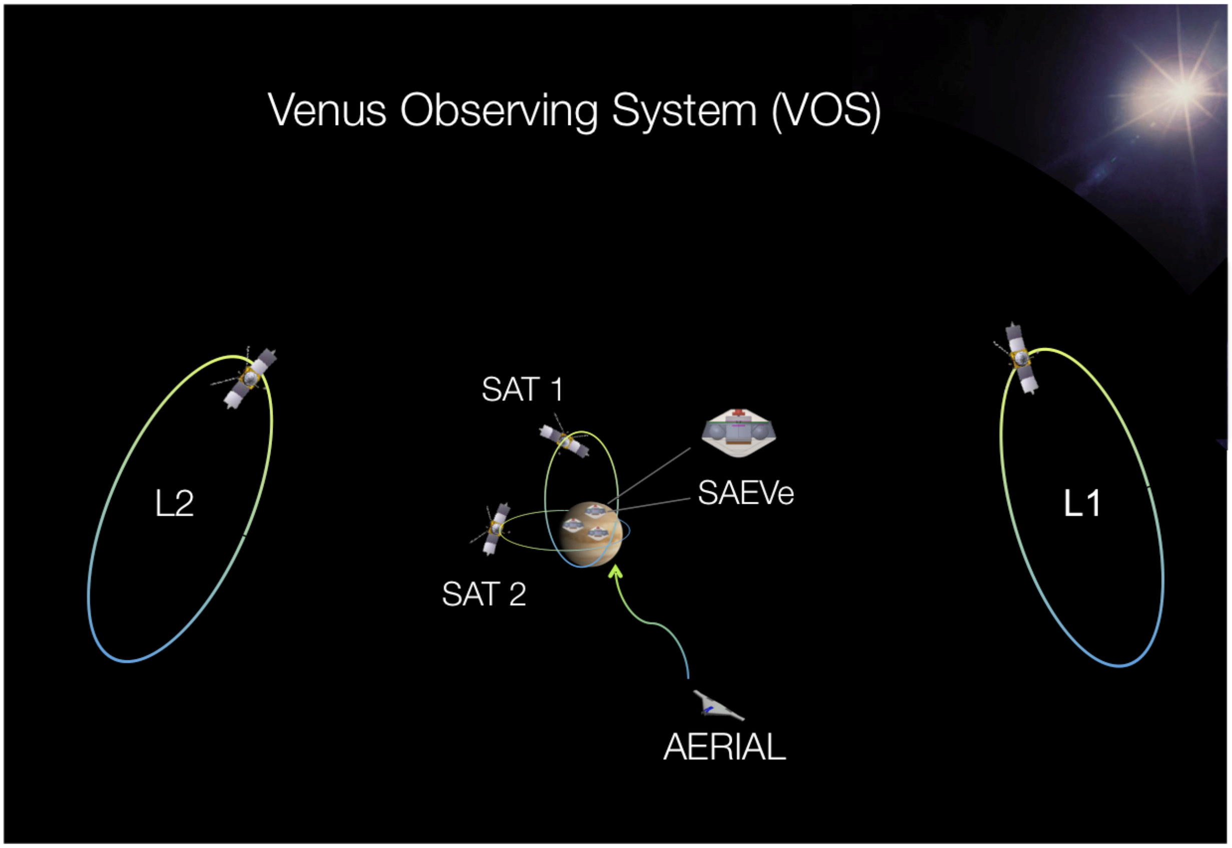
Venus Observing System (VOS): Monitoring Climate, Surface, Atmospheric Escape and Search for Bio-signatures



Not to scale. L1 and L2 are about 1 million km from Venus. All Spacecraft images and orbits are for illustrative purpose only

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1. **Introduction.** After numerous survey and monitoring missions to Venus with fly-by spacecraft, orbiters, entry probes/landers and balloons since Mariner 2 flew past Venus in 1962, many questions remain unanswered. Recent missions raise intriguing questions about variations in albedo on decadal timescales. Although the past missions have revealed a lot of information about the planet's plasma environment, atmosphere, surface and a little about the interior, they have not provided the comprehensive, systematic or synoptic observations of the planet that the major atmospheric questions require. For Earth, a constellation of polar and geosynchronous spacecraft, and networks of air and surface observations provide crucial information to monitor weather and climate. While Venus does not require such a comprehensive network, continuous observations of the cloud cover are necessary and Lagrange Point Orbiters (LPOs) along the Sun-Venus line offer this capability (Limaye and Kovalenko, 2019). We describe here the Venus Observing System (VOS), a concept proposed for NASA's Planetary Mission Concept Studies competition that can address the deficiencies of the past and currently proposed missions to Venus. The modular design of VOS includes four small orbiters carrying identical instruments, a small number of Seismic and Atmospheric Venus Explorer (SAEVe) units (Kremic et al., 2017) deployed over the planet, and one or more aerial platforms. Of the small orbiters, two are deployed at L1 and L2 points, located about one million km away from Venus along the vector to the Sun on either side of the planet. The other two are inserted into short period (4-8 hours), eccentric polar and equatorial orbits.

VOS science goals are to (i) Determine the detailed energy balance of Venus' atmosphere over one solar cycle, (ii) Determine the loss rate of water from Venus over its history, (iii) Search for bio-signatures in the clouds of Venus, while identifying the 'unknown absorber(s)', (iv) Monitor Venus' surface meteorology and seismic activity continuously for 4 months, and (v) serve as a relay to Earth for *in situ* missions placed anywhere on Venus for 11 years. These goals can be achieved by meeting the following science measurement objectives.

a. Continuous monitoring of reflected solar radiation by multispectral imaging and spectrometers
b. Continuous day and night monitoring of the emitted thermal infrared radiation (8-12 μm)
c. Dense coverage of radio occultation profiles from mutual events between Venus orbiters and L1, L2 Lagrange point orbiters, over almost all latitudes and local times
d. Monitoring the night side cloud infrared opacity (1.0 -3.0 μm) using spectral imaging
e. Mapping the surface emissivity in near-IR window wavelengths to constrain surface mineralogy
f. Measuring escaping ions from Venus orbiters and solar wind from L1 (upstream) and plasma tail from L2 (downstream)
g. Determine the composition, morphology and physical and chemical properties of Venus cloud aerosols
h. Identify and quantify unidentified absorbers in Venus' clouds and atmosphere
i. Search for organics in the Venus atmosphere and determine whether or not they are biogenic
j. Determine if Venus is seismically active over a 4-month duration on the surface
k. Monitor the pressure, temperature, and winds at landed sites for 4 months
l. Obtain the composition of the lower scale height of Venus' atmosphere
m. Obtain descent and landed image(s) of the surface from each lander location
n. Improve position determinations of floating/flying platforms in the atmosphere and relay their data
o. Measure cosmic ray flux in the clouds and high energy particles in the vicinity of Venus

2. Venus Observing System Architecture

The modular (deployed in segments), scalable (adding more small satellites or in-situ platforms), and affordable architecture that can realize the science objectives includes:

- Two small spacecraft in orbit around L1 and L2 Lagrange points (about one million km from Venus) to observe Venus continuously with ~ 10 km resolution multispectral imaging and UV-IR spectroscopy
- Two small spacecraft in short period orbits (4-8 hours) around Venus – one in polar orbit and the other in an equatorial orbit.
- An instrumented flying/gliding/floating platform to sample the lower cloud layer on Venus (48-52 km) for habitability (water, phosphates, redox energy sources), bio-signatures (compartmentalization, biopolymers), cloud particle properties, and environmental conditions.
- Three to five long-lived surface stations distributed around the planet for obtaining atmospheric measurements during descent and monitoring surface conditions after landing. High temperature sensors, command and data handling electronics, and telecom allow these landers to survive as long as their high temperature batteries last (about four months).

Lagrange Point Orbiters (LPOs) are being considered for the Venera-D mission being studied jointly by Roscosmos/IKI and NASA (Zasova et al., 2019) and the science value of LPOs for monitoring Venus has been described by Limaye and Kovalenko (2019). Their deployment at L1 and L2 has been described by Kovalenko et al. (2019). These and other VOS elements are described below along with each of the measurements to be considered.

2.1 Small Lagrange Point Orbiters around L1 and L2 Lagrange points.

The L1 and L2 Lagrange points along the Sun-Venus line provide excellent vantage points to continuously monitor the day (L1) and night (L2) hemispheres. Equipped with a multispectral imaging system, spectrometer (UV-NIR), radio science and solar wind instruments, one orbiter each will be placed in orbit around the L1 and L2 Lagrange points (~113-day period) to monitor the reflectance and emitted radiation from the day and night hemispheres. NIR opacity of the cloud cover will be monitored at 2.3 µm. Incoming solar wind will be measured from the L1 orbiter and the Venus plasma tail conditions from the L2 orbiter. Both of the Lagrange orbiters will provide daily mutual occultation events with the Venus orbiters except for about 7-10 days every 113 days (orbital period of L1 and L2 orbiters). Both will also be capable of relaying data from in-situ platforms on Venus (aerial platform and SAEVe landers).

2.2 Two small Short Period Venus orbiters.

Two small orbiters carrying the same instrument suite as the Lagrange point orbiters will be placed in short period orbits around Venus. One will be in a near polar orbit and the other in a near equatorial orbit. These spacecraft will supplement the imaging coverage over different phase angles and somewhat higher resolution. This will enable a better understanding of the phase angle dependence of cloud motion observations that has affected Venus Express and Akatsuki results. These two orbiters will: (i) characterize the atmospheric escape from Venus in conjunction with the incoming solar wind measurements from the L1 orbiter and the distant tail of Venus' plasma wake from the L2 orbiter (previously the Venus ion tail has been detected even from Earth's L1 point (Grünwaldt et al., 1997)), (ii) enable mutual radio occultations, and (iii) supplement the cloud motion measurements from L1 and L2 orbiters with nadir observations which will view Venus at different phase angles.

2.3 Aerial Platform(s).

The aim of the aerial platform is to sample a limited vertical portion of the Venus cloud layer, which extends from 47 km to 70 km altitude at low latitudes, but up to only about 67 km at polar latitudes. The science goals for the aerial platform are: (a) search for substances that are responsible for absorption of solar radiation (0.2 – 1.0 µm) and which may account for some of the opacity at near infrared wavelengths (1 – 3 µm), (b) characterize the bounds of habitability and potential bio-signatures by measuring cloud particle physical, chemical and optical properties, and (c) monitor surface activity (volcanism) through 1 µm imaging and infrasonic detection of quakes. The desired measurements include; (i) visible and near infrared (1-5 µm) spectral radiance, (ii) Extinction measurements over 1-5 m path length between 0.2 -1.0 µm on the night side using a flash lamp, (iii) chemical sensors for measuring biomarkers, trace species, and *p*H, (iv) inertial sensors, environmental sensors (T,p), (v) cosmic ray and high energy particle detectors, (vi) infrasonic/acoustic signatures of any quakes, (vii) surface imaging in 1 µm spectral windows, and (viii) electrical activity.

2.4 Long Life Surface Stations - (SAEVe). The science implemented by SAEVe (Kremic et al., 2018) is focused on seismology and temporal meteorology, long standing gaps in our data on Venus and measurements enabled only by long duration operations. Multiple SAEVes can be considered for deployment on the surface to provide the first long term measurements from the surface of Venus from different locations. The data are relayed by long period orbiters around Lagrange points or even around Venus in carefully chosen orbits. At the present and near future state of technology there is no memory storage possible at Venus surface conditions, hence all data need to be transmitted and collected by capable communication relay orbiters.

2.5 VOS Instruments - All platforms. The four orbiters carry identical instruments except that the Venus orbiting cameras will have different optical specifications due to different range to Venus compared to LPOs with only the focal lengths/optical elements differing. The aerial platform payload will be constrained by mass and TRL, and only instruments currently under development (TRL>4) are considered for the VOS concept (Table 1).

Table 1. Potential VOS Instruments by platform.

LPO and Venus ORBITERS	AERIAL PLATFORM*	SAEVe
Integrated Camera Suite UV-NIR, SWIR and LIR cameras	Venus Organics Analyzer	Chemical sensors (including *p*H, methane, SO_2, COS, H_2S)
Ion mass spec., Electron analyzer, Magnetometer	Cloud Particle Microscope	Meteorological Sensors (T,p,w)
Radio Science	Cosmic Ray Sensor	Seismometer
UV-NIR Mapping spectrometer	UV-NIR spectrometer	Descent and Surface Imager
	High Energy Particle Detector	Solar Radiation
	Raman LIDAR	
	1 µm camera for surface imaging	
	Microphone/Infrasound sensor	
	Chemical sensors (including *p*H, methane, SO_2, COS, H_2S)	

**The payload to be prioritized based on mass constraints. The notional list includes instruments currently available or under development and may be distributed among multiple units due to mass constraints.*

3.2 Monitoring Radiative Energy Balance/Climate of Venus over a Solar Cycle. The global cloud cover of Venus holds many puzzles and one, recently coming to the fore, is whether the albedo of Venus is changing over time This recent finding tells us that surprisingly, current Venus cloud layer climate may experience rapid decadal variations, but the mechanism is unknown. Venus Express VMC and Akatsuki UVI cameras, and HST spectrometer observations suggest that the albedo is varying over time and may be related to the solar cycle (Lee et al., 2019). Recent Venus Express and Akatsuki images reveal that the 365 nm albedo of Venus is changing and hence, the cloud layer heating rate should also be changing due to variations in the abundance of unidentified UV absorbers in the cloud layer. This is where the bulk of the solar absorption takes place and where variation in absorber concentrations are responsible for the albedo changes. Such changes in the solar heating rate may be responsible for the changes in the strength of the cloud level atmospheric circulation as inferred from the measurements of cloud motions (Khatuntsev et al., 2014; Horinouchi et al., 2018). The 365 nm albedo has also been recently linked with topography (Bertaux et al., 2016; Jessup et al., 2020) but no such link was found from the more extensive Akatsuki observations (Horinouchi et al., 2019). The quantification and separation of these temporal and spatial signals require systematic observations that VOS can obtain, and similar to how the Deep Space Climate Observatory (DSCOVR) monitors Earth's climate from the L1 Lagrange point (Marshak et al., 2018).

3.2.1 Monitoring Albedo. For monitoring the climate/radiative balance of Venus, measurements of the albedo (and influx of solar radiation) and emitted radiation are necessary. The incident solar radiation can be inferred from the solar radiation output measurements being made routinely from spacecraft near Earth (Coddington et al., 2016) and extrapolated to Venus, but can also be monitored continuously from the L1 orbiter. VOS will enable monitoring the geometric albedo globally by continuous imaging and whole disk spectroscopy from the L1 Lagrange point orbiter, supplemented by the polar and equatorial orbiters.

3.2.2 *Monitoring Emitted Radiation from Venus*. Monitoring the emitted thermal radiation from Venus as measured by continuous imaging at 8-12 μm from L1 and L2 orbiters will cover all local times and enable continuous assessment of the radiative balance of Venus over a solar cycle. The near-polar orbiter will provide additional high latitude coverage.

3.2.3 Thermal Structure (40-80 km). The possibility of climate variation in the cloud layer over a solar cycle can be assessed by monitoring the thermal structure in the 40-80 km altitude range from the dense coverage offered by the mutual radio occultation events between the two short period Venus orbiters and the two Lagrange orbiters (113 day period). There are dozens of occultation events between the four orbiters each day except for some short gaps during each L1/L2 orbital period. The eccentricity and the orbital periods of the two Venus orbiters can be optimized to address competing science goals.

3.2.4 Cloud Layer atmospheric circulation. VOS will provide continuous imaging from the Lagrange Point orbiters and will yield complete daily local time coverage of cloud motions, far better than any Venus orbiters. These measurements will significantly improve the global (horizontal and vertical) coverage of the cloud motion measurements and detect long term changes reported previously (Khatuntsev et al., 2013; Kouyama et al., 2013) and now from Akatsuki data (Horinouchi et al., 2018). Further, the vastly improved thermal profile coverage from mutual occultation events will yield a much better mean thermal structure in the cloud layer and yield much better estimates of the cyclostrophically balanced zonal flow.

3.3 Mapping near-IR surface emissivity. Maps of the near-IR Venus surface emissivity at one wavelength (1.02 μm) were made for the first time using the VIRTIS instrument on Venus Express (Helbert et al., 2008; Mueller et al., 2008). Emission from the surface can be seen through windows in Venus' spectrum, although VEX's orbit allowed only the southern hemisphere of Venus to be mapped. Nevertheless, numerous geologic features, including large shield volcanoes (Smrekar et al., 2010) correlate with surface emissivity differences. VOS will map the nightside thermal emissivity from the L2 spacecraft in 5 wavelengths, producing 5-point near-IR spectra over the entire globe. With increasingly available laboratory spectra at Venus surface conditions, these measurements will place strong constraints on Venus' surface mineralogy and how it may change over time due to reactions with the atmosphere. VOS will also be able to definitively determine whether granitic continent-like crust exists on Venus, which could only have been emplaced when there was abundant water at the surface (Hashimoto et al., 2008).

3.4 Search for Biogenic signatures. The possibility of life in the niche of Venus' clouds has been sporadically considered for more than half a century and has recently received more attention due to advances in studying life in extreme environments. Since the physical properties of any microorganisms are likely to be similar to the known cloud particle properties in the mid and upper cloud layers (e.g. Mode 1 and Mode 2 particles), a means of discrimination is required. To make these measurements, aerial platforms capable of sampling the habitable region which may extend from about 48 km to 62 km above the mean surface are required. Potential measurements include; (i) spectral properties, (ii) physical properties, and (iii) chemical properties. The spectral properties of single particles can be measured in the lab but are not currently practical from an aerial platform. Ambient cloud layer spectra can be obtained on the day side, while spectra can be obtained on the nightside using a white light lamp. The physical properties of sampled aerosols can be measured from an imaging microscope and a nephelometer. The chemical properties can be obtained from an organics analyzer (Mathies et al., 2017) and a time-resolved standoff fluorescence-Raman sensor (Farsund et al., 2012; Misra et al., 2016).

3.5 Cloud aerosol properties. Knowing the ambient cloud layer properties is essential to understand the cloud particle characteristics and possible biogenic signatures. These can be obtained from a nephelometer, miniature MEMS chemical sensor suite for specific gases (SO_2, H_2S, CH_4, COS, HF, HCl, others) and a *p*H sensor. Additionally, a spectrometer (UV-NIR) is needed to measure the absorption properties on the day and night sides (using a white light lamp).

3.6 Impact of cosmic ray and high energy particles impact on microorganisms. The peak ionization level due to cosmic rays is estimated to occur at about 63 km (Dartnell, 2011; Dartnell et al., 2015), somewhat above where the peak abundance of microorganisms may be present on Venus (48-52 km). As conjectured, the atmospheric circulation may bring any microorganisms to higher levels (Limaye et al., 2018) and subject them to a higher dosage of radiation, although a high radiation environment does not exclude extremophile microorganism survival (Levin-Zaidman et al., 2003). Cosmic ray flux has never been measured inn Venus atmosphere and the aerial platform offers an attractive opportunity to learn about its impact on the Venus cloud layer.

3.7 Atmospheric Escape and Solar wind interaction. Reliable measurements of the atmospheric escape from Venus over time are needed to estimate the quantity of surface water in the past. Only Venus Express and Pioneer Venus have done experiments to estimate rates of water loss during different phases of the solar cycle and these estimates vary by three orders of magnitude Ion escape at low energy range (0 – 0.5 KeV) is significant and has yet to be measured during high solar activity conditions. It is also important to have spacecraft in suitable orbits; VOS will provide a near polar and a near equatorial orbiter around Venus with incoming solar wind measured near L1, and the far Venus plasma tail measured from the L2 orbiter. The orbit inclination is important for sampling the escaping ion flux. The Pioneer Venus orbit (polar) was more suitable than the Venus Express orbit (low latitude periapsis).

3.8 Geology and Surface Properties. VOS enables the monitoring of the night side through 1 µm atmospheric windows from the L2 Lagrange point. This will include looking for surface changes or thermal anomalies (Shalygin et al., 2015; Knicely and Herrick, 2019) that could indicate active volcanism (Basilevsky et al., 2012). VOS will deploy several Seismic and Atmospheric Exploration of Venus (SAEVe) recently developed at NASA/GRC (Kremic et al., 2018). The SAEVe units will also make measurements of the composition of the Venus deep atmosphere, in the lower-most scale height that is in contact with the surface. This has never before been done, but is of paramount importance for understanding how the surface and atmosphere interact chemically with each other. Direct in situ measurements using high temperature sensors and electronics enable these measurements at the 10's of ppbv levels for most atmospheric gases.

Summary. The VOS concept being modular in design can be implemented in stages and by multiple agencies through international collaboration and coordination. The key element that should be deployed first are the two Lagrange orbiters that can provide communications relay capability for any subsequent Venus atmospheric or surface platforms. The two Venus orbiters provide phase angle coverage of the planet for measurements that need it. With appropriate eccentricities, inclinations and periods, they can provide far more dense occultation coverage to provide routine thermal structure data on the atmosphere. The aerial platforms are key to searching for biogenic signatures and cloud aerosol properties. Dropsondes can also be deployed from the aerial platforms to supplement deep atmosphere coverage. VOS Lagrange Point Orbiters will provide complete relay coverage of in situ platforms at Venus for at least a solar cycle. SAEVe units provide a seismic network and can be supplemented by follow on missions. It is anticipated that the ISRO mission will improve upon the surface mapping provided by Magellan and many of the VEXAG goals for the atmosphere will be returned from Discovery or New Frontiers missions, otherwise they can be integrated into the VOS concept.

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