Exploration of Venus' Atmosphere by Low-Cost Distributed Sensing Architecture

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Abstract: All high-priority Venus atmosphere science is enabled or enhanced by in situ exploration elements. We describe a distributed sensing platform that allows for observation of multiple interacting regional and global phenomena over wide spatial and temporal scales and which can provide correlated, ground-truth data for remote sensing assets and modeling efforts.

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1 Executive Summary

Venus' atmosphere hosts a multitude of dynamic processes which are visible at both global and regional scales, which operate on at timescales of hours to decades, and which are present throughout the atmospheric column from surface to exosphere. This paper describes a mission concept for enhancing and transforming Venus atmospheric science through widely distributed data gathering via swarm probes. Open questions associated with mechanisms driving Venus atmospheric processes requires that specific studies be undertaken regarding the coupling between regions where the relative rate of dynamical/chemical/ and/or thermal structure is variable (see Brecht et al. whitepaper for detailed discussion of observations needed to support theoretical modeling efforts[1]). This requires coincident observation of the fundamental atmospheric physical properties (temperature, pressure, wind, composition, etc.) over a broad range of altitudes, local solar times and latitudes as well as detailed and coincident observation of external forcings such as incoming solar radiation, solar pressure and solar wind.

We advocate for recognition of a distributed sensing aerial platform as a unique and necessary component in Venus atmospheric exploration that is key to linking remote sensing and in situ data to dynamic, comprehensive models of the planet's multiscale phenomena. We encourage investment in specific technology and infrastructure that enables this mode of exploration at Venus and other planetary environments.

Synchronized, multi-platform observations naturally add complexity to the architecture of Venus missions, but this is well justified given the coincident and connected observations that are needed to adequately constrain and simulate the physical mechanisms that maintain Venus' fundamental/quintessential atmospheric processes. Underscoring this is the fact that the Venus Exploration Analysis Group (VEXAG) Goals, Objectives, and Investigations for Venus Exploration (GOI) guidance document identifies 11 of 23 Investigations as benefiting from, or requiring, an in situ, atmospheric component[2].

The combination of exceptionally low cost and low mass with very low risk enables the Lofted Environmental Atmospheric Venus Sensors (LEAVES) to obtain key in situ, atmospheric to either augment and enhance a mission (i.e., by adding an atmospheric sensing element to an orbital mapper, or by gathering distributed, in situ, "ground truth" data to complement simultaneous remote observations), or as a standalone mission taking advantage of a Venus-targeted or flyby opportunity.

LEAVES is designed to fill a niche between short-duration dropsondes and long-duration mobile aerial platforms, with a cost equivalent to, or significantly below, a SIMPLEX or technology demonstration opportunity. The following salient points are described more thoroughly in the text that follows:

- Per-unit mass of 120 g
- 9-hour, unguided, freefall descent with science operations between 100 km and 35 km
- Designed to deploy directly from orbit without aeroshell
- All components are currently available, with TRL 4-6
- Efficient packaging means that 100 units can be stowed and incrementally deployed
- Low power operation requires orbital asset to provide data relay and geopositioning

2 Introduction

The forces that drive Venus' atmospheric dynamical phenomena at the regional and global scales remain shrouded in questions. These questions exist in large part due to limitations of remote observing techniques which are restricted to specific atmospheric depths, at certain Venus local times, relative to the wavelength of observation and the viewing geometry of the observation. There is no wavelength that allows simultaneous global observation of Venus' day and nightside wind properties over a vertical depth of more than 10 to 15 km at a time VEXAG identifies as one of the three Goals for Venus exploration to, "*Understand atmospheric dynamics and composition on Venus*"[2]. In situ probes are needed to address the eight essential and important investigations associated with this goal, and would serve as an important supplement to remote observations. Conventional approaches to atmospheric sensing via dropsondes and balloons, or proposed long-duration missions involving mobile aerial platforms, primarily involve monolithic architectures. ***As such, these relatively massive conventional architectures are not designed to make simultaneous observations of multiple interacting phenomena at regional or global scales.***

The Lofted Environmental Atmospheric Venus Sensors (LEAVES) concept will deploy widely distributed sensors, repeatedly, in a manner that increases the latitude, local time, and altitude coverage over what may be obtained via limb/occultation or nadir measurements with a distribution that allows strongly coincident global monitoring, as required for the advancement of numerical modeling studies[1]. Optimized LEAVES design trades converge on a solution that could be considered a pico- or femto-satellite (i.e. those with a mass < 1 kg), allowing for a mission that can deploy dozens or hundreds at low cost. These lightweight probes will be operational between 100 and 30 km, with long dwell times in Venus' poorly explored tropospheric region (~ 55 and 30 km)[3]. LEAVES glider mobility design is ideal for characterizing the densest and most poorly understood regions of Venus' atmosphere.

3 Lofted Environmental Atmospheric Venus Sensors (LEAVES)

The initial Lofted Environmental Atmospheric Venus Sensors (LEAVES) mission design development was completed via the NASA Innovative Advanced Concepts (NIAC) program. The LEAVES mission platform concept includes mature, readily-available components and is capable of hosting a simple but effective sensor suite that can enable novel and valuable science in the clouds of Venus. With a projected surface area of 1 m² and mass of only 120 g, each LEAVES unit has a high aerodynamic drag which allows for a slow descent from 100 km to 35 km lasting approximately 9 hours, with a lateral drift of around 2000 km. An additional advantage of this architecture is that each unit is capable of independent aerocapture and direct re-entry. That is, no aeroshell is required in order to deploy LEAVES from an orbiting platform, whether configured as a single sonde or as a swarm (10s to 100s) of units.

A concurrent engineering study [4] performed to optimize the LEAVES structure for mass and aerial lifetime resulted in a platform shaped like an inverted, 3-sided pyramid with flexible Mylar® panels, below which is suspended the science payload: 6-axis inertial measurement unit, multi-gas chemical sensor, temperature and pressure transducer, low-power radio, and batteries (Fig. 1). An advantage of this structure is that it functions as a cube-corner, radar retroreflector that allows for geolocating of the operating sensors (and hence, data) via active scanning by an X-band orbital radar instrument in ranging mode. All sensors and electronics necessary for

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science operations are integrated onto this platform in a physical arrangement that promotes self-stabilization while deployed in the atmosphere. Atmospheric data are simultaneously collected by dozens or hundreds of single-architecture mini-probes (LEAVES) that are passively aerodynamically suspended by taking advantage of the high winds and high density of Venus' atmosphere.

Figure 1. Single LEAVES unit fully deployed as an inverted pyramid radar retroreflector

LEAVES is made possible by micro-scale, solid-state sensors designed for measurement of crucial species on a descending sonde/probe or lander and engineered to survive unprotected even at the surface of Venus. Mass spectrometry and gas chromatography are exceptional techniques for characterizing unknown constituents in an atmosphere, but in many cases they lack the ppm and sub-ppm level of sensitivity necessary to quantify many minor species, and tend to only function over a limited range of altitudes. Target-specific MEMS chemical sensors (and other nano-scale sensing technologies) allow for precise, quantitative detection of known species to sub-ppm levels, for a fraction of the cost, mass, and power of even the smallest mass spectrometer. Quantitative measurements of trace reactive gases (CO, NO, OCS, SO_x, H₂, O₂, H₂O, HF, and HCl) are enabled by an array of single-species sensors, each with an accuracy of better than 10 ppm with an acquisition time of <5 s [5, 6]. These sensors provide the sensing capabilities for specific target species that is comparable or better than conventional instruments, but in a much smaller, reduced power sensor package which requires no chemical, thermal, or pressure mitigation.

Ambient condition sensors include temperature, pressure, and light sensors, which are all commercially available, off-the-shelf, low-mass, and low-power. While some other heritage components have been developed for deployment in the hazardous conditions present at Venus, few of them have been miniaturized to achieve the mass necessary for consideration.

Data acquired by the LEAVES units are communicated via low-power transmission utilizing conventional radio modulation. An RF link budget analysis of communications capabilities concludes that a dipole antenna, acting as a supporting wire in the structure shown in Figure 1, coupled to a commercial modulator (i.e., Frequency-Shift Keying or Code Division Multiple

Access) in transmit-only mode, can transfer on the order of 10 bps to an orbital relay station at 80,000 km or less. Higher data rates via smaller separation distance, higher gain, more power, or compression would allow extension of the data package to a larger suite of sensors.

3.1 Concept of Operations and Mission Profile

LEAVES is perfectly suited for inclusion in a Venus-targeted orbital mission as a secondary payload. The following ConOps assumes that LEAVES is carried aboard a polar (or near-polar) orbiter that utilizes an elliptical aerobraking and science campaign.

1. Launch and cruise (duration 5 months): 100 flat-packed units can be stored in a dispenser during cruise phase with no requirement for power, thermal control, or communication.
2. Arrival and aerobraking (duration 2 months): An elliptical aerobraking orbit with periapsis of 150 km and apoapsis of 10,000 km is assumed. LEAVES cohorts are released near periapse, during successive orbits, in cohorts of 10 units at a time. LEAVES units decay in altitude due to atmospheric drag over days to weeks as orbital platform completes aerobraking campaign.
3. Orbit raising and preliminary science operations (duration 8 months): Periapsis is raised to 300 km with apoapsis at 6000 km. Stochastic forces on individual LEAVES units (i.e., solar pressure, atmospheric interactions, deployment location) cause them to disperse laterally and in re-entry times. Communications and tracking of LEAVES units is established by the orbiter as LEAVES units initiate operations at 100 km altitude. LEAVES units perform science operations for approximately 9 hours until they reach an altitude of 30 km and experience thermal failure. The orbiter performs continuous science operations to allow for correlation of remote and in situ data.
4. Orbit circularization (optional): All LEAVES units deployed during aerobraking are assumed to have ceased operation. Any further deployment (i.e. above 200 km) is likely prohibited by insufficient atmospheric density to allow for capture and re-entry of LEAVES units. Deployment of a cohort of LEAVES at this stage will require the inclusion of a de-orbit propulsive unit. Alternatively, the LEAVES stowage and deployment module may be detached during aerobraking and used with a remote trigger to continue deployment during Steps 3 and 4.

3.2 Application to Venus Atmosphere Science

LEAVES primarily and directly addresses 7 of the 8 identified Investigations included in the VEXAG Goal to “Understand atmospheric composition and dynamics on Venus” (shown in the traceability matrix below), and can contribute to a further 2 Investigations regarding geologic history, habitability, and planetary evolution[2]. We note that this VEXAG document specifically addresses the need for simultaneous in situ and remote measurements that LEAVES is intended to address (“... *degeneracies between spatial and temporal variations would remain—as are present in the meteorological data from the VeGa balloons—in the absence of simultaneous measurements from orbiters and aerial platforms*”)[2]. Broadly, the LEAVES science payload can be divided into three, baselined, subsystems that address the Investigations listed in Figure 2: *temperature and pressure, motion, and composition*.

Mapping the thermal and pressure gradients of the mesosphere and troposphere, at a range of altitudes, latitudes, and at different local solar times, is necessary to determine the drivers for dynamic phenomena manifested as local, regional, or global circulation structures and instabilities[7]. For example, the depth to which polar vortices and “cold collars” perturb the

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global thermal gradient is challenging to determine from remote observations but would be straightforward for LEAVES. Moreover, when combined with radiometric flux measurements (a possible LEAVES payload component) and compositional data (for opacity measurement and modeling) the temperature sensor provides a spatially-resolved indicated of heat deposited through radiative transfer. Linked global traces of gas abundances and temperature will permit self-consistent studies of Venus' general circulation relative to the balance of chemical and radiative processes active in the atmosphere per altitude and local solar time, enabling higher fidelity modeling and a deeper understanding of global circulation behaviors.

GOAL	OBJECTIVE	INVESTIGATION	MEASUREMENT	INSTRUMENT / COMPONENT
2. Understand atmospheric composition and dynamics on Venus	A. What processes drive the global atmospheric dynamics of Venus?	Characterize the dynamics of the lower atmosphere (below about 75km) of Venus, including: retrograde zonal super-rotation, meridional circulation, radiative balances, mountain waves, and transfer of	Regional updraft / downdraft	6-axis IMU, radio tracking, barometer
			Turbulence	6-axis IMU
			Meridional and zonal motion	Radio tracking
			Radiometric flux	UV-NIR flux radiometer
		Determine the role of mesoscale dynamics in redistributing energy and momentum throughout the atmosphere of Venus.	Lightning intensity and frequency	RF receiver
			Thermal gradient	Temperature/pressure transducer
	B. What processes determine the baseline and variations in Venus atmospheric composition and global and local radiative balance?	Characterize atmospheric radiative balance and how radiative transport drives atmospheric dynamics on Venus.	Multispectral radiometry	Up/down radiometer
		Characterize the nature of the physical, chemical, and possible biological interactions among the constituents of the Venus atmosphere.	Location and time-resolved chemical species quantification	Target-specific MEMS chemical species sensors
		Determine the physical characteristics and chemical compositions of aerosols in Venus atmosphere as they vary with elevation, including discrimination of aerosol types/components.	Particle nephelometry / morphometry	Near-field imager, nanophotonic particle sensor
		Characterize the unknown shortwavelength absorber in the upper atmosphere of Venus and its	Location and time-resolved chemical species quantification	Target-specific MEMS chemical species sensors
		Determine the products of volcanic outgassing on Venus and their effects on atmospheric composition	Location and time-resolved chemical species quantification	Target-specific MEMS chemical species sensors

Figure 2. LEAVES traceability matrix for VEXAG Goal B, Objectives A and B, and associated Investigations.

Spatial tracking of each LEAVES unit, provided through a combination of onboard accelerometers and gyroscopes with remote radio tracking and triangulation, provides direct measurements of small-scale turbulence, orogenic vertical transport, and regional circulation. Depending on the deployment latitude, drift of any LEAVES unit between latitudes yields direct measurements meridional circulation, which may also have significant vertical components[7], and drift in local solar time indicates zonal circulation. These data would provide independent verification of cloud feature-based velocity tracking at depths inaccessible to optical tracking methods[8].

Venus' bulk atmospheric composition is generally known, with trace gas distributions based partly on models where previous in situ and remote observations are incomplete[9]. However, the spatial and temporal variation in these gases, and implied rates of interconversion between some species (particularly sulfur-bearing compounds) is poorly constrained[10, 11]. In addition, the physical behavior of Venus' bulk atmosphere below 45 km may create novel, but not yet observed, mixing structures [12, 13]. LEAVES' greatest strength lies in the ability to provide quantification and characterization of targeted gas species, with precision of at least 1 ppm, lateral resolution of better than 10 km, and vertical resolution of better than 1 km. These fundamental measurements are essential for accurately interpreting the potentiality and impact of volcanic outgassing activity and for identifying how surface-atmosphere chemical processes influence gas distributions in the lower atmosphere. Compositional data are also necessary to help constrain the composition, formation precursors, and dissipation products of atmospheric

aerosols and to help elucidate the nature of the unknown UV absorber[3, 14, 15]. The chemical species sensors when combined with an optional radiometer could address the critical question of the depth and extent to which photochemistry is responsible for chemical disequilibrium observed due to the excess of SO₂ at Venus' cloud tops [3, 10, 16, 17]. The release of LEAVES sensors globally, i.e. near simultaneously over a range of pole to pole latitudes and the subsequent near-simultaneous global sampling of SO_x, temperature, and other trace species (OCS, HCl, etc.) relative to the horizontal drift removes all ambiguity about the role of horizontal transport in maintaining the species distributions. This would revolutionize our understanding of how Venus' sulfur cycle proceeds. By providing a level of detail on the species distributions dependence and relationship to temperature and transport not obtainable by any other method, LEAVES would improve our ability to predict and/or identify likely chemical sources of the yet to be identified extra sulfur-reservoir.

Finally, recent studies of the climate history of Venus strongly suggest that the planet may have retained liquid water oceans for billions of years[18]. If indeed Venus was a habitable niche for life in its history, it has been further suggested that bacterial or microbial life may have evolved and even survived to present day in Venus' clouds[3]. Microscopic optical sensors are ideal for the LEAVES platform and could significantly enhance the search for signs of life in planetary atmospheres.

4 Summary and Recommendations

The LEAVES mission concept enables unprecedented synergism between remote observations and in situ sensing of Venus' atmosphere. Through the strategic orbital deployment and distribution of dozens to hundreds of passive drifting sensor units, fundamental data can be acquired regarding the physical processes and composition of the atmosphere over a wide range of altitudes, geographic locations, and solar conditions. This "swarm" approach takes advantage of low mass, cost, and risk to obtain valuable data that would otherwise be inaccessible or impractical for a traditional monolithic platform. The resulting data would directly address knowledge gaps identified in the current *VEXAG Goals, Objectives, and Investigations for Venus Exploration*, with specific benefit for ongoing efforts to develop comprehensive models of atmospheric phenomena.

4.1 Development and Investment Needs

LEAVES is enabled by the continued miniaturization of sensors and electronics. Specific technological approaches are required for usage in hazardous and extreme environments. Further development of the heat-tolerant components would allow LEAVES to probe the full depth of the atmosphere to the surface. **We advocate for continued investment by NASA in high-temperature, low mass, low power, technologies, including digital electronics, communications, sensors, power generation, and power storage.**

By definition, pico- and femto-scale exploration platforms such as LEAVES are highly mass and power constrained. This means that swarm architectures made up of multiples of these small probes require support of a host platform to provide critical infrastructure services. First, low power probes have very limited range and bandwidth for data upload. In most cases a swarm network will require a communications relay that is capable of receiving multiple data uplinks simultaneously, caching these data, performing initial data integration, reduction, and compression, and relaying the data to terrestrial ground stations. It is possible that this service

could be provided by long-duration aerial or surface stations, but it is more reasonable to expect that this capability would best fit with an orbital platform. Second, distributed data are most useful when they are correlated with location and time. In environments such as Venus, there are no pre-existing positional references, and direct-to-Earth communications for long baseline interferometry is prohibitive due to mass and power requirements. So a local (to Venus) spatial and temporal reference must be used. Temporal resolution can be easily achieved by time-stamping by the relay station. But geolocating of small probes, in situations where there is no GPS or equivalent and no direct-to-Earth communications are possible, remains a technical barrier for all exploration destinations, including the Moon. These infrastructure components are critically needed for enabling communications with assets throughout the solar system, with funding to support these resources allocated separately from the PI-led science mission component. **Therefore, we advocate and strongly recommend that NASA provides investment into future exploration platforms that include a long-lived component (i.e., capable of surviving and operating much longer than the requirements driving the scientific instrumentation payload) consisting of a communications relay and positional reference beacon(s) that can be used by subsequent missions.**

LEAVES' value as an exploration platform is driven by its exceptionally compact and low power components, and its capability to deploy from orbit. In order to achieve a high level of confidence in successful use at Venus, and to extend this exploration paradigm to other atmospheric targets (i.e., Earth, Mars, Jupiter, Saturn, Titan, Uranus, and Neptune) **we advocate for NASA to solicit and support robust studies that optimize shape, areal mass density, and orbital deployment conditions for each target, including comprehensive aerodynamic modeling, simulation, and empirical validations.** The result of these exercises would be a catalog of standardized platforms for all bodies in the solar system with effective atmospheres, which would allow straightforward and cost-effective integration and infusion of new micro-scale technologies to planetary exploration.

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