A LOW-MASS ATMOSPHERIC SENSOR PLATFORM CONCEPT FOR DISTRIBUTED EXPLORATION AT VENUS.

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Introduction: The evolution of Venus is directly related to how past or present volcanism brings volatiles to the surface and how those volatiles are transported and distributed throughout the atmosphere. Understanding those physical transport processes and the chemical reactions that occur as the atmosphere responds to those changes requires distributed, in situ mapping of reactive species and ambient conditions across the planet and throughout the vertical atmospheric column. The Venus Exploration Analysis Group (VEXAG) identifies "*an in-situ study of global atmospheric circulation*" as a high priority for understanding the operation of the planet's atmosphere[1]. We endeavor to address four measurement priorities: "*small-scale waves and turbulence*," "*magnitude and direction of the vertical motion*," "*turbulence/ convection as a function of local time*," and "*simultaneous meteorological properties including pressure and temperature, and abundances of trace gaseous species and aerosols*"[1].

Traditionally, atmospheric exploration of Venus has been conducted via remote sensing from orbital or ground-based stations, from descending probes, from landing probes during a descent phase, or by balloon. Recent mission concepts and proposals generally follow these same paradigms (albeit with significantly enhanced instrument capabilities), with the exception of controlled-flight aircraft and aerostats [e.g. 2-6]. However, the continued miniaturization of sensors and supporting electronics, especially those suited for harsh environments [e.g. 7-10] has resulted in the opportunity to develop another mission architecture altogether… one that replaces a monolithic platform with a highly parallelized, distributed "swarm" of inexpensive, low-mass, low-power sensors. Venus provides an ideal target candidate for this type of architecture, having a dense atmosphere that causes lofted objects to reach a relatively slow terminal velocity and thereby maximizing useful residence times.

Concept: The LEAVES (Lofted Environmental and Atmospheric VEnus Sensors) concept is an ultra-lightweight, passively-lofted, inexpensive atmospheric sensor package that is robust enough for the harsh Venus environment, cheap enough to deploy in a swarm configuration, and sensitive enough to yield valuable new information on planetary atmospheres. LEAVES uniquely enables atmospheric sensing through combining sensors, electronics, and communications on a lightweight physical structure that acts as a passive, stabilized lifting body when in the presence of turbulent winds, such as those found in the upper and middle atmosphere of Venus. This "slow descent" paradigm replaces portions of investigations traditionally performed by single sondes, ballute probes, balloons, and aircraft. The benefits of this architecture include scalability, straightforward integration as a secondary payload, and reduced cost of obtaining high-priority science data. LEAVES components, such as harsh environment chemical species sensors and communications electronics appropriate for Venus are now commercially available, and materials suitable for operation in Venus' middle atmosphere have been extensively tested and are readily available.

LEAVES fills an exploration platform gap between dropsondes and aerostat/aerobot balloons. In the former case, isolated vertical profiles of the atmosphere are obtained in a very short amount of time. In the latter case, isolated horizontal (with some limited vertical) atmospheric profiles are obtained over an extended period of time. In both of these traditional cases, a comprehensive global "snapshot" of atmospheric conditions remains elusive due to sparse lateral and vertical coverage. Via deployment of a network of inexpensive, independent atmospheric sensors (each of which has a high residence time due to a low-mass and high surface-area support platform) LEAVES provides a way of obtaining comparatively dense coverage in both lateral and vertical extents with a temporal resolution between that of dropsondes and balloons.

Platform: A single LEAVES unit is comprised of a thin, ultralight, leaf-shaped platform that is flexible enough to stow in a collapsed, folded configuration prior to atmospheric entry. All sensors and electronics necessary for 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 of identical copies that are passively aerodynamically suspended and distributed by taking advantage of the high winds and high density of Venus' atmosphere. A preliminary design for each mini-probe is a 0.5 m^2 Mylar® "leaf," upon which is mounted a patch antenna, 6-axis inertial measurement unit, multi-gas chemical sensor, temperature and pressure transducer, low-power radio, battery, and solar irradiance and azimuthal sensor (Fig. 1). Each of the LEAVES units weighs under 100 g and consumes <1 W of power at peak operation.

Preliminary aerodynamic analyses performed by the COMPASS team at the NASA Glenn Research Center, using a standard reference Venus altitude-density profile[11], indicates that a single LEAVES unit with the above configuration will remain lofted for a minimum of 111 hrs, enough time to complete a full global cycle in the superrotating troposphere. This does not include the effect of winds or updrafts that could significantly extend the lofted lifetime. Figure 1 shows a conceptualization of a single, fully-deployed LEAVES unit.

A unique aspect of LEAVES is the in situ data collection of the chemical composition of the atmosphere, enabled by a suite of novel solid-state sensors designed for measurement of crucial species (e.g. on a descending sonde/probe or lander), and operation in relevant Venus environments[7-10]. These sensors provide the sensing capabilities of higher-mass, legacy science instruments but in a much smaller, reduced power sensor package which requires no chemical, thermal, or pressure mitigation. Species identified by the most recent Decadal Survey[12] for Venus exploration are targeted by an array of single-gas sensors (CO, NO, OCS, SOx, H2, O2, H2O, HF, and HCl), each capable of quantitatively measuring the respective species with an accuracy of better than 10 ppm with an acquisition time of <5 s[9].

Data from the LEAVES units are communicated via low-power commercial cellular technology. Preliminary estimates of communications capabilities suggest that a patch antenna embedded in the Mylar® substrate, coupled to a commercial code division multiple access (CDMA) modulator in transmit-only mode, can transfer on the order of 10 bps to an orbital relay station at a range of 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 include all 9 chemical species as well as inertial measurement unit (IMU) status.

Notional mission profile: LEAVES is perfectly suited for inclusion in a Venus in situ mission as a secondary payload. During atmospheric descent, multiple (up to several dozen) LEAVES units would be packaged within a primary descender structure (or within an independent deployment unit protected by the same aeroshell). Upon reaching a target altitude near the cloud tops of ~75 km, the LEAVES units are ejected incrementally, so that the full payload of units are deployed along a vertical profile covering approximately 75 – 45 km of altitude. At the time of deployment, each unit expands from its stowed configuration to form a "leaf" (or alternatively, a ballute or streamer) which increases the drag and lofted lifetime of the sensor package. Each unit immediately begins sampling the atmosphere and transmitting low-bandwidth data to an orbiting communications platform. Over the next ~ 100 hours, the altitude of each unit slowly decays, resulting in many data profiles covering wide vertical and horizontal (and to a lesser degree, temporal) ranges throughout the Venus mid-atmospheric column. The resulting data are then transmitted by the orbiter to terrestrial receiving stations where they are ultimately assembled into a three dimensional "snapshot" of the planet's atmosphere. It is also reasonable to expect that some LEAVES units may remain suspended in the atmosphere long enough to observe one or more transitions through the entire cycle of a solar day, thereby adding a fourth dimension to the profile data and providing important information regarding solar forcing of the planet's environment.

Summary: The LEAVES concept is specifically enabled by a new generation of miniaturized electronics and sensors that will be increasingly integrated into planetary missions of all scales and at all targets. This implies that some science targets that are cost-prohibitive for heritage architectures may be effectively explored by fleets of expendable, miniature probes, or in other cases, by using similar low-mass/cost/power sensor platforms in extended-duration configurations.

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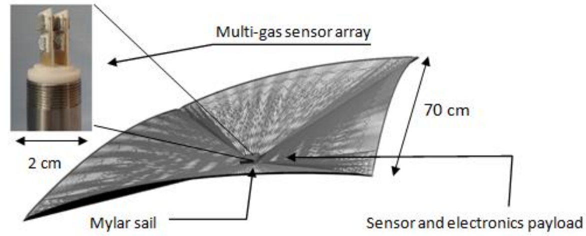

Figure 1. LEAVES concept unit, fully deployed. (Gas sensor array from [9]).