The dense atmosphere of Venus and the high temperatures in the lower atmosphere and surface have presented impediments to the deployment of exploration techniques that work on airless bodies and planets with thin atmospheres such as Mars. However, they also create opportunities for the use of aerial platforms to explore Venus in many different ways. This paper reviews the brief experience with deploying aerial platforms at Venus, the various mission concepts that have been proposed over the last three decades and a vision for their application through 2050.

**VEGA BALLOON MISSION**

It is more than 30 years since the first and only aerial platforms were deployed at Venus, or indeed at any planet, by the Soviet Union in 1985. Two VEGA aerostats implemented as 3.5m superpressure balloons were successfully deployed at Venus and were each tracked from Earth as planned for about two earth days as they drifted halfway around the planet in the super-rotating atmospheric flow at an altitude of about 55 km. Although the total payloads suspended beneath each aerostat was only 6.9 kg, including sensors, batteries and communications equipment, VEGA remains an important proof of concept paving the way for more ambitious missions.

**MISSION CONCEPTS**

There has been no aerial platform mission to Venus since VEGA and currently none are under development. However, in this period there have been several proposals in both the US and Europe to fly more capable aerostats at Venus. There have also been some important technology developments and the option space for the use of aerial platforms at Venus has been extensively explored.

**VEGA-Type aerostats with larger payloads:** One direction of research has been to develop an aerostat with a much larger payload capability than VEGA. JPL has been developing superpressure balloons tolerant of both the sulfuric acid environment on Venus and capable of accommodating the diurnal stresses induced on the balloon. A 5.5-m balloon with a payload capability of 45 kg is now at TRL 5 [1] and a 7.0-m balloon with a payload of 110 kg is now under development. Demonstrations have also been conducted of aerial inflation of superpressure balloons.

Several proposals have been made to apply this technology to a NASA or ESA mission. The VALOR Venus Aerostatic-Lift Observatories for in-situ Research proposal was typical of these which focused on the atmosphere [2]. The European Venus Explorer (EVE) conceived at about the same time, also focused primarily on the atmosphere. Other more ambitious concepts involved the deployment of sondes from the aerostat. In this case, the aerostat serves as both a platform for precise deployment of the sondes and also as a communications relay. The proximity of the balloon to the short lived sondes enables greater data return than would have been possible for sondes communicating with an orbiting or flyby spacecraft.

The 2011 Planetary Science Decadal Survey recommended a Venus Climate Mission (VCM) as a small Flagship mission, comprising an aerostat, deep probe, and two sondes. The objectives for the aerostat align with previous atmospheric goals. The deep probe would be released during initial descent and provide atmospheric and chemical data into the deep atmosphere, whereas the sondes could be released any time. Recent work suggests valuable geoscience studies can be performed from the aerostat itself. Infrasound signatures of earthquakes can be detected in the atmosphere [3] and natural-source electromagnetic sounding can probe the upper mantle [4]. Together, these techniques can constrain the geodynamics of Venus without ever touching the surface.

**Venus Geoscience Aerobot:** More ambitious concepts for the use of aerostats at Venus have also been formulated. The Venus Geoscience Aerobot (VEGAS) concept [5] has a buoyant platform capable of making repeated short visits to the surface of Venus, and extracting power from the thermal gradient in the atmosphere in the process of conducting these maneuvers. VEGAS would exploit the properties of water ammonia mixtures for buoyancy and altitude control.

**Aerostats and Sample Return:** Venus Surface Sample Return (VSSR) has long been considered to be enabled by balloon loft of the ascent rocket [6]. An intermediate mission concept – Venus In Situ Explorer (VISE) advocated by the 2003 PSDS [7] was to perform sample analysis in a buoyant station at the element balloon-float altitude. A number of concepts for implementing VSSR and VISE have been considered including an innovative dual balloon concept. One spin off of this effort was a concept for a near surface balloon system called the Venus Mobile Explorer (VME) first identified in the NASA Solar System Roadmap of 2006 [8].

**Altitude Control:** In 2011, motivated by enduring questions about the nature of the mysterious time variable ultraviolet haze in the Venus upper atmosphere, up-
per atmosphere, JPL began an investigation of approaches to altitude cycling in the 55 to 70 km range. Initially concepts using either ambient gas ballast (AGB) or Lift Gas Compression (LGC) were explored by the group at Smith College [9]. Subsequently, a concept for involving mechanical compressions by changing the volume of the envelope was developed by Red Line Aerospace using their Ultra High Pressure Vessel (UHPV) technology [10] offering potential simplifications in fabrication and deployment of the aerostat.

**Aerial Platforms with horizontal control:** Aerostats at a float altitude of 55 km will circumnavigate the planet in about five earth days as a result of the superrotating flow and are expected to gradually drift towards the nearest pole. The rate is believed to be small a few meters per second but quite uncertain. Concepts for controlling this motion have been studied in recent years.

A solar powered Venus aircraft can fly high in the clouds where there is sufficient energy. However, according to Landis [11] in order to stay aloft it must “station keep” on the sun side of the planet by flying in the opposite direction to the flow.

The Venus Atmospheric Maneuverable Platform (VAMP) concept developed by Northrop-Grumman [12] is a semi-buoyant, maneuverable, solar powered air vehicle conceived for flight in the Venus’ atmosphere on both the night and dayside.

**FUTURE ROLE OF AERIAL EXPLORATION**

Aerial platform technology must play a vital role in the future exploration of Venus. We envisage a phased approach beginning with proven technologies that operate in the upper reaches of the Venus atmosphere where temperatures are near Earth surface ambient. In subsequent decades, aerial platforms would penetrate deeper in the atmosphere in step with advances in the technology for operating in those environments. Opportunities should be taken to demonstrate these technologies in advance of a major commitment of science payloads.

**Near Term (2016 to 2025):** the focus should be on formulating missions such as Venus Climate Mission, endorsed by the 2011 Planetary Science Decadal Survey and Venera D, a mission under study by a joint NASA-IKI SDT which includes an aerial platform option. These platforms would be based on mature technologies for light gas superpressure aerostats that operate near 55 km altitude. In addition, to the atmospheric science these platforms can also address geophysical objectives through the use of infrasound generated by Venus quakes, electromagnetic sounding using Schumann resonances, and searching for remnant magnetism.

This should also be a period for intensive technology investment in more capable systems that can make excursions in altitude both to 65 or 70 km near the top of the cloud layer and downward to 40 km near the base of the cloud layer. Other objectives would include systems capable of control in latitude including heavier than air and hybrid technologies. There should be a focus on systems capable of miniaturization enabling low cost missions with rapid turnaround.

**Mid-Term 2025 to 2035:** In this time frame, it should be possible to deploy aerial platforms with altitude control in the range of 40 km to 70 km. For the lower altitude range, these can use high temperature electronics technologies that are maturing today. Given the new science that will be enabled by the ability to repetitively profile in altitude, scientifically productive missions should be possible with modest payloads. The science would include investigations of a broad habitable zone within the cloud layers.

Technology work in this time frame should focus on systems for the lower 40 km of the atmosphere including the near surface environment. Success in this phase will hinge on contemporaneous progress in high temperature electronics. This phase could include tech demos of mobile systems with limited scientific measurement capabilities in the near surface environment.

**Long Term 2035-2050:** Aerial mobile exploration would be extended to the surface with sophisticated in situ measurement capabilities. The technology would now also be ready to implement VISE the mission that the Decadal Survey originally conceived in 2003 – an aerial platform that would raise surface samples to 55 km for prolonged analysis under benign conditions.

Technology work should focus on the aerial platform requirements for surfacer sample return Several architectural concepts have been identified and the focus would be on the enabling technologies for the mission.

**References:**