
Introduction: Although it is Earth’s closest neighbor, we know very little about the compositional profile of Venus’s dense atmosphere, the elemental composition and geochemistry of Venus’ surface materials, and the nature of the planet’s internal structure and overall geological evolution [1,2]. The limitations of previous measurements of Venus’ atmosphere and surface emphasize the tremendous opportunities for leaps in scientific understanding that would be achieved with a coordinated scientific exploration plan for Venus, including investment in technologies that will enable unprecedented in situ measurements of its surface, atmosphere, and interior. Our desire is to understand why Earth and Venus are so very different, even though they are nearly the same size, are located in the same region in the inner solar system, and presumably formed from identical primordial materials. The differences between Earth and Venus must therefore provide clues about the evolution of terrestrial planets in general and will place constraints on the potential habitability of such planets in this or other planetary systems. M-dwarf rocky planets are modeled to be Venus-like, so better characterizing this planet will enable the development of approaches to understanding M-dwarf planets’ habitability potential, a problem of interest within the astrobiology and exoplanetary science communities in the era enabled by such upcoming missions as JWST, TESS, and WFIRST. In addition, the possibility that Venus is a keystone example of a terrestrial planet that harbored an “ocean” which was subsequently lost as recently as 0.75 to 1 Ga [3] offers potential for understanding so-called “lost ocean worlds”.

Here we provide a brief description of our integrated vision for the exploration of Venus through ~2050, with emphasis on the 2035-2050 “vision horizon”. Our plan follows the NASA Mars Exploration Program’s Seek/In Situ/Sample paradigm [4] and is initiated by a deep atmosphere compositional probe such as the Discovery Step 2 finalist known as DAVINCI [5]. We will describe pathways for the scientific exploration of Venus that build upon DAVINCI in situ analytical chemistry results and lead to science-driven mission measurements for the 2035-2050 time frame with associated enabling technologies and critical modelling capabilities. Since the harsh Venus environment presents severe engineering challenges, we will consider mission implementations that do not require Venus surface sample return as a culmination of the next 30+ years of scientific exploration, i.e. in situ investigations integrated with synergistic orbital observations that vastly extend current capabilities, as well as new physical models.

Concepts Currently Under Development: Work on Venus exploration concepts has been ongoing since the early 1980s, including, for example, surface geophysical network missions, long-lived middle-atmosphere balloons, mobile surface explorers, integrated flagship missions with orbiters, powered airborne platforms, landers, as well as ruggedized landers. Such concepts have been described in VEXAG reports over the past 10 years, and were critical test cases for technology roadmap analyses that VEXAG sponsored over the past ~ 5 years [2]. Some important examples include:

- Venus geophysical/geochemical networks
- Mobile Venus surface/near-surface explorers (bellows-based or others)
- Tether-based Venus exploration approaches
- Ultra-high resolution orbital reconnaissance of Venus (similar to MRO at Mars but with SAR)
- In situ analytical chemistry beyond current New Frontiers goals (i.e., beyond VISE [1])
- “Grace does Venus” concepts for shallow interior studies via multiple-orbiters or gravity gradiometers
- Long-lived balloon-borne concepts
- RPS-powered long-lived landed laboratories
- Tessera-accessible analytical laboratories [6]
- Venus upper atmosphere and orbital Cubesats

These examples offer either vantage point or measurement advantages over the state of current capabilities, many of which have been proposed to recent open competitions at NASA and ESA (e.g., Discovery, New Frontiers, ESA M-class etc.).

Stretch Scientific Goals at Venus: Assuming an initial “gateway” mission that addresses the atmospheric composition and evolution goals described in the past two NRC Decadal Surveys [1,5], what must we “visioneer” as a Venus scientific exploration capability by circa 2050? This raises some critical questions about scientific strategy in the current absence of new information about the surface and deep atmosphere composition.

Past habitability via relic mineralogical and geochemical records: The evolution and decline of the Venussian critical zone is recorded in its stratigraphic record. Former environmental dynamics are also addressable in the rock record in part, requiring a benchmark against contemporary measurements of environmental dynamics, e.g., magnetic variation, radiation environment, wind speed and direction, etc.
The stratigraphically resolved assemblages will provide documentation of diagenesis, particularly aqueous alteration, which is key to understanding the presence and timing of subaqueous paleoenvironments. This goal could make use of mobile surface exploration with Mars (i.e., MSL/Curiosity) quality measurement systems, as well as orbital reconnaissance with sub-meter resolution. Key advances would require long-lived high temperature operations, mobility involving short “hops” or flights, and ultra-wide bandwidth orbital radar sensors beyond the current state of the art in planetary sciences.

**In situ geochronology of plains vs tessera:** Venus’ thick atmosphere prevents the accumulation of a significant cratering record for relative age-dating of the major surface units, such as the tessera (uplands) which are hypothesized to be remnant continents formed from nascent plate tectonics, or the plains which are suspected to be more recently resurfaced. **In situ** geochronology measurements to determine absolute dates of formation would provide critical information on the surface history of Venus as well as inform terrestrial planet formation and evolution. This goal would require landed measurements of the quality currently being demonstrated on Mars via MSL’s SAM suite (with APXS) with sufficient time for sampling, context analysis, and measurements ideally at more than one locality.

Other key goals involving the character of the shallow interior of Venus, its lower atmosphere dynamics (and role of super-critical CO2), and how the planet may have “lost” a global ocean would ideally require a strategic program of orbital, airborne, and surface based observations in a coordinated architecture, as was developed for Mars, together with enhanced laboratory and modelling capabilities.

**Missions to Address These Scientific Questions:** These (and other) scientific goals will require the development of new mission concepts that stretch our current technical capabilities and will only become possible with technology and engineering demonstration flight experiments. Defining these science capability and measurement goals and their engineering requirements now will help us formulate the technology development over the next decades that will make such missions possible, either in the framework of competed missions (Discovery, New Frontiers, Cubesats) or via occasional strategically-directed missions (“Flagships” similar to MSL).

Studying the past habitability potential of Venus via its rock record will require a mission that operates on Venus with an approach similar to the MSL/Curiosity Rover but with a different style of mobility. A study of the geochronology of the spatially-dominant basaltic plains versus the complex-ridged terrain uplands (tessera) will require a surface mission capability that permits reaching multiple sample locations in the plains and/or tessera with **in situ** geochronology instrumentation of the scale of complexity of current GCMS/elemental analyzers (i.e. MSL/SAM and its descendent geochronology optimized pyrolysis mass spectrometers). Studies of the shallow Venus interior and dynamics may be advanced by longer-lived, landed 3-axis seismometers, as well as via multi-frequency ground penetrating radar measurements. A multi-orbiter approach similar in operation to the ongoing GRACE Earth Science mission [7] would offer an incredible increase in the understanding of the shallow interior of Venus and the record of late heavy bombardment – executing such a mission with advanced gravity gradiometers and high-frequency radar altimeters would require attention to spacecraft orbit maintenance at very low altitudes and with high-precision radial orbit determination.

Ultimately, we can imagine science-guided missions in 2035 to 2050 time-frame that are catalyzed by the next mission to Venus, whatever that will be. Together with JAXA’s Akatsuki, the near-term flight mission observations of Venus will promote technology and engineering investments in architectures that connect Venus’ unique history to the evolution of the entire solar system and beyond. Such near-term missions would set in motion a direction with specific hypotheses and measurement and vantage point requirements that would culminate in the missions required for the 2035-2050 era. Ultimately, an innovative implementation for Venus surface-based sample return must be considered, just as it is for Mars and the Moon. Assessing the habitability and biological potential of Venus will be an essential element of any strategy for the ~ 2050 timeframe, but it will depend on our next few steps in the robotic scientific exploration of Venus and key investments.

**REFERENCES:**


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