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Venus should be an Earth-like planet due to its similar size and adjacent position in the solar system, but its dense atmosphere, high surface temperature, lack of water, and unique geology indicate it developed very differently. Venus is effectively a controlled experiment in the atmospheric and geological evolution of terrestrial planets. With the recent explosion of findings on extrasolar planets, Venus figures prominently in assessing the likelihood that Earth-sized means Earth-like elsewhere in the galaxy.

The Venus Exploration Analysis Group (VEXAG) has formulated a series of reports that describe the scientific goals [1], technology plan [2], and exploration roadmap [3] that will advance knowledge of Venus in the coming decades. Here we review how these documents frame Venus exploration and we extrapolate to 2050. We also draw on other recent work describing new measurement techniques and instrument development.

Science. VEXAG's current science planning [1] centers on three unprioritized goals: (I) Understand atmospheric formation, evolution, and climate history, (II) Determine the evolution of the surface and interior, and (III) Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present. Subsidiary, prioritized objectives and investigations pose specific questions, including: What controls the superrotation and the greenhouse? How do clouds influence energy balance and climate? Is the cloud zone habitable? How does Venus release heat from its interior and how is this related to resurfacing and outgassing through time? How chemically evolved is the crust? The technology and roadmap documents, described below, present capabilities that could substantially resolve these questions.

Technology. The dense atmosphere and high surface temperature of Venus affect both orbital remote sensing and spacecraft entry and in situ operations. In particular, >40 years after the first lander deployed to Venus, these vehicles can survive for no more than a few hours. Technologies required for the next few decades of Venus exploration [2] are, in priority order, (1) new thermal protection systems (TPS) for atmospheric entry, (2) high-temperature subsystems and components for long-duration (months) surface operations, (3) aerial platforms for similar long-duration operations in the atmosphere, (4) in situ instruments for landed missions, (5) deep space optical communications, (6) advanced power and cooling technology for long-duration surface operations, (7) advanced descent and landing. Related technology requirements include aerocapture, deployable heat shields, pinpoint landing and hazard avoidance, surface or near-surface mobility platforms, directed movement of all platforms, sample-return technology (including ascent vehicle), thermal control, and data storage.

Roadmap. The roadmap combines science and technology into specific mission recommendations. Near, mid-, and far-term time frames were assumed to represent 2014-2019, 2020-2024, and 2025 and beyond, respectively [3].

Near-term missions are improved orbital remote sensing (radar imaging, infrared emissivity, gravity, topography), sustained aerial platform, deep probe, short-duration lander, multiple probes/dropsondes, and flyby opportunities. The last was studied by the Venus Gravity Assist Science Opportunity (VeGASO) report [4], which describes how the Bepi-Colombo, Solar Probe Plus, and Solar Orbiter missions (initially) could provide useful measurements during Venus fly-bys. ESA's completed Venus Express and JAXA's ongoing Akatsuki will serve as cornerstones for atmospheric science.

All of the remaining missions, or mixtures thereof, have been studied or proposed for flight. VERITAS and DAVINCI, currently in Phase A, address the orbital and deep-probe missions, respectively. ESA's EnVision (under review) would similarly make improved orbital measurements, whereas the EVE balloon (proposed earlier) satisfies the aerial platform and dropsondes. The Venus Climate Mission (VCM, ref. 5) studied by the 2011 Planetary Science Decadal Survey (PSDS), would deploy a balloon, a deep probe, and dropsondes. The 2009 Venus Design Reference Mission (VDRM: ref. 6) included an orbiter, two balloons, and two landers. This high-end flagship concept could itself have addressed all of the near-term mission requirements.

Mid-term missions are multiple deep probes, short-duration tessera lander, and a long-lived geophysical lander. The tessera lander was studied [7] as part of the 2011 PSDS. Recent progress on high-temperature electronics has brought forth new concepts for long-lived (months or more) geophysical landers [e.g., 8], but there is still no appropriate data storage. Live-streaming would then require extensive orbital assets for continuous data capture. The Russian Venera-D mission [9] in principle includes an element with 24-hr survival, but this is insufficient for geophysical monitoring and is conceptually in the short-term framework. Ongoing science definition [10] may reorient the mission.

Far-term missions are surface (or near-surface) platform with regional mobility, long-lived seismic network, and sample return. The Venus Mobile Explorer flagship (VME, ref. 11) studied by the 2011 PSDS may have been ahead of its time, but derivatives of the metallic bellows float technology could enable regional traverses to search for evidence of an ancient ocean on Venus. Rovers could exploit innovative mechanical designs and wind-powered propulsion [12].

A seismic network is a necessary extension of a pathfinding long-lived lander in order to move from crude estimates of seismicity to imaging of the interior and mapping quake mechanisms and locations.

Finally, surface sample return represents NASA's desired (temporary) end state for exploration of all solar-system bodies. For Venus, this has long been considered to be enabled by balloon loft of the ascent rocket [13]. An intermediate mission concept (VISE) advocated by the 2003 PSDS [14] was to perform sample analysis in a buoyant station at the clement balloon-float altitude. Continuing advances in and miniaturization of mineralogical and chemical instrumentation (e.g., age dating) imply improving cost-effectiveness of in situ analysis. On the other hand, cloud sample return motivated by a search for extant life could be an important stepping stone to surface sample return

Revised Roadmap to 2050. As currently framed, the science objectives for Venus will require multiple missions to achieve. With a horizon to 2050, however, we do not know what the next questions will be, i.e., what are the "unknown unknowns." With regard to technology, substantial progress is being made on 1, 2, 4, and 5; but much more needs to be done for our strategy for 2035-2050 to be fully unconstrained by and exploitive of the Venus environment.

Given the lack of any Venus missions before 2020, the likelihood of a few Venus missions at most before 2030, and the time to implement technology, we conservatively stretch the roadmap time frames to 2030, 2040, and 2050, respectively. The revised roadmap would then implement orbiter, probe/sonde, and short-term lander in the 2020s, aerial platforms and pathfinding long-lived landers in the 2030s, and (near) surface mobility, geophysical network, and sample return in the 2040s.

New Visions for 2050. New elements can be added to the VEXAG roadmap using ongoing developments in geophysics, small satellites, aerial platforms, and temporal monitoring.

Due to strong mechanical coupling between the atmosphere and ground, seismic waves are launched into the atmosphere, where they may be detected by infrasound on a balloon or infrared or ultraviolet signatures from orbit [15]. This could effectively shift the far-term seismic network into the mid-term with aerial platforms or near-term with orbiters.

NASA wishes to enhance science return by manifesting cubesats or smallsats as secondary payloads on every planetary launch. Many Venus orbital remote-sensing observations could be carried out in small, single-instrument spacecraft, particularly in constellations. A communications relay infrastructure is another obvious application.

Aerial platforms will be essential to regional-to-global study of the Venus atmosphere and surface. VDRM and VCM planned to use balloons, essentially upscaled versions of the 1986 VEGA mission. While the basic science objectives can be achieved this way, horizontal control such as provided by the VAMP concept [16], would provide control in latitude and allow specific targets to be investigated. Vertical mobility would enable sampling of different levels of the atmosphere.

Finally, as the basic mechanisms of the atmosphere, surface, and interior are understood, 4D (space + time) monitoring will become important. This will involve updated reflights of earlier missions, possibly in constellations, to look for tectonic, volcanic, or mass-wasting surface change and continuous atmospheric study.

Conclusion. The VEXAG science objectives, technology plan, and roadmap are a robust outline for Venus exploration for the next several decades. Science responses to new mission findings will occur no earlier than the mid-2020s, with any changes to the mission set implemented in the 2030s. As we move toward 2050, new capabilities in global monitoring, beyond the existing roadmap, can be added. Significant and sustained technology investments throughout the next decades are necessary to realize this vision. The road to our closest neighbor is clear, but remains long.

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