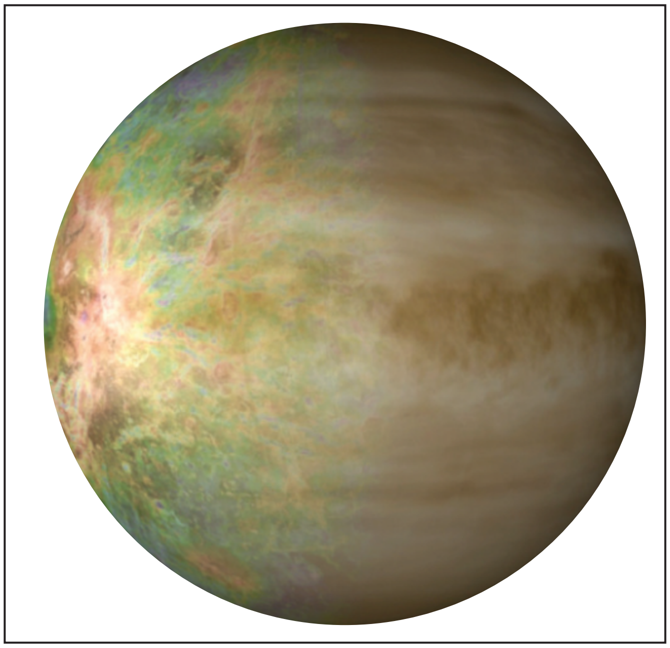
Venus: Constraining Crustal Evolution from Orbit Via High-Resolution Geophysical and Geological Reconnaissance



Prepared by:

James B. Garvin (NASA's Goddard Space Flight Center,
301-286-5154, James.B.Garvin@nasa.gov)
Lori S. Glaze (NASA's Goddard Space Flight Center)
Sushil Atreya (University of Michigan)
Bruce Campbell (Smithsonian Center for Earth and Planetary Studies)
Don Campbell (Cornell University)
Peter Ford (Massachusetts Institute of Technology)
Walter Kiefer (Lunar and Planetary Institute)
Frank Lemoine (NASA's Goddard Space Flight Center)
Greg Neumann (NASA's Goddard Space Flight Center)
Roger Phillips (Southwest Research Institute)
Keith Raney (Johns Hopkins University/Applied Physics Laboratory)

Endorsed by:

Steve Baloga (Proxemy Research)
Bruce Banerdt (Jet Propulsion Laboratory)
A. T. Basilevsky (Brown University/Vernadsky Institute)
George Burba (Vernadsky Institute)
David Crisp (Jet Propulsion Laboratory)
Larry Crumpler (New Mexico Museum of Natural History and Science)
Linda T. Elkins-Tanon (Massachusetts Institute of Technology)
Herb Frey (NASA's Goddard Space Flight Center)
Marty Gilmore (Wesleyan University)
Richard Grieve (Geological Survey of Canada)
David Grinspoon (Denver Museum of Nature and Science)
Eric Grosfils (Pomona College)
Vicki Hansen (University of Minnesota Duluth)
Steven Hauck (Case Western Reserve University)
Jim Head (Brown University)
Robert Herrick (University of Alaska Fairbanks)
Noel Hinners (Retired)
Noam Izenberg (JHU/Applied Physics Laboratory)
Catherine Johnson (University of California San Diego)
Donna Jurdy (Northwestern University)
Ozgur Karatekin (Royal Observatory of Belgium)
Sanjay Limaye (University of Wisconsin Madison)
Ralph Lorenz (JHU/Applied Physics Laboratory)
Pat McGovern (Lunar and Planetary Institute)
Daniel Nunes (Jet Propulsion Laboratory)
David Sandwell (University of California San Diego)
Jerry Schubert (University of California Los Angeles)
David Senske (Jet Propulsion Laboratory)
Buck Sharpton (University of Alaska Fairbanks)
Brian Shiro (National Oceanographic and Atmospheric Administration)
Sue Smrekar (Jet Propulsion Laboratory)
Mauro Spagnuolo (UBA CONICET)
TommyThompson (Jet Propulsion Laboratory)
Allan Treiman (Lunar and Planetary Institute)

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Venus remains the least well understood of the terrestrial (silicate) planets. Major gaps in understanding include how planetary-scale crustal resurfacing operated, the formation and evolution of highlands including tessera, and whether evidence of past environments is preserved at the surface. Constraining the global thermal and magmatic evolution of Venus remains a priority if the planet is to be placed into its appropriate context with Mars, Earth, Mercury, and the Moon.

EXECUTIVE SUMMARY AND CONTEXT

Venus remains mysterious largely due to the impossibility of high-resolution optical imaging or laser altimetry. The dense occluded CO_2 atmosphere of Venus can be penetrated only by longer wave techniques, such as radar. Geodetic-precision global topography could resolve key issues associated with crustal volcanic resurfacing, the origin and evolution of complex ridged terrain *(tessera)*, and whether ancient impact basins are preserved within the crustal column. Improvements in topography that approach a factor of 100 better than currently available data from *Magellan* will enable local to regional-scale studies of flexure, impact crater modification, volcanism, and sedimentary processes (if any). In addition, high resolution polarimetric SAR imaging of targeted regions and landforms can be employed to quantitatively investigate key aspects of the crustal resurfacing cycle, as well as an array of fundamental geologic issues tied to the relative chronology of the planet and how processes have operated in space and time. Finally, selection of critical Venus landing sites will necessarily depend on geologic and geophysical factors that require higher resolution imaging and topography than presently available, if they are to be optimized for scientific impact. Such data can only be acquired from an appropriately instrumented low-altitude Venus geophysical/geological orbiter.

A Venus Geophysical/Geological Orbiter (VGGO) in a low-altitude circular orbit equipped with a geodetic-precision radar altimeter and a high resolution polarimetric SAR (nominally at C-band or S-band), could extend current understanding of Venus in a fashion similar to that which was achieved for Mars via the *Mars Global Surveyor* Mars Orbiter Laser Altimeter (MOLA) and Mars Orbiter Camera (MOC) investigations [Smith et al. 2001; Malin and Edgett, 2000]. High frequency and bandwidth radar altimetry, enhanced by means of delay-Doppler processing methods [Ford et al., 1991; Raney 1998], can provide along-track topographic sampling at horizontal scales as fine as 50 m (~1 km across track) with ~1 m ranging precision. When such radar altimeters are operated in a circular, inclined orbit, global gridded topography can be obtained at kilometer scales with absolute vertical accuracies of 1–10 m. High-resolution S-band hybrid polarity SAR imaging [Raney, 2007] with resolution as fine as ~10 m will enable investigations of local to regional scale processes not possible with currently available *Magellan* SAR imaging (at horizontal resolutions of 100–150 m).

Introduction and Background

The compelling measurements provided by NASA's *Pioneer Venus* and *Magellan* missions to Venus, as well as Soviet *Venera* and *Vega* missions, have motivated a suite of key questions about the planet that should be addressed within the next decade if Venus is to be placed in its proper scientific context with respect to Mars, Earth, and Mercury (Figure 1). In spite of *Magellan's* global mapping of topography, emissivity, and landforms, a myriad of unresolved questions remain that require higher resolution sampling [Venus II, 1997; Crisp et al., 2002; Luhman and Atreya, 2007; NOSSE 2008; VEXAG 2009]. Key gaps in understanding the thermal and magmatic evolution of Venus require planetary-scale datasets with horizontal and vertical resolution that rival currently available datasets for Mars (i.e., from MGS and *Mars Reconnaissance Orbiter* [MRO]), the Moon (i.e., from JAXA's *Kaguya* and now NASA's *LRO*), and soon for Mercury (i.e., *MESSENGER*). In order to provide the necessary surface altimetric and image resolution, active microwave methods (radar) are required because of the high opacity and dense Venus atmosphere.

As has been demonstrated for Mars and the Moon, geodetic-quality topography gridded at km-scales is an essential boundary condition from which to develop or constrain physical models of crustal processes. With a typical vertical precision of ~80 m and along-track resolution of 8–10 km, the *Magellan* radar altimeter instrument was not able to provide sufficient sampling to produce kilometer (or better) spatial resolution topography

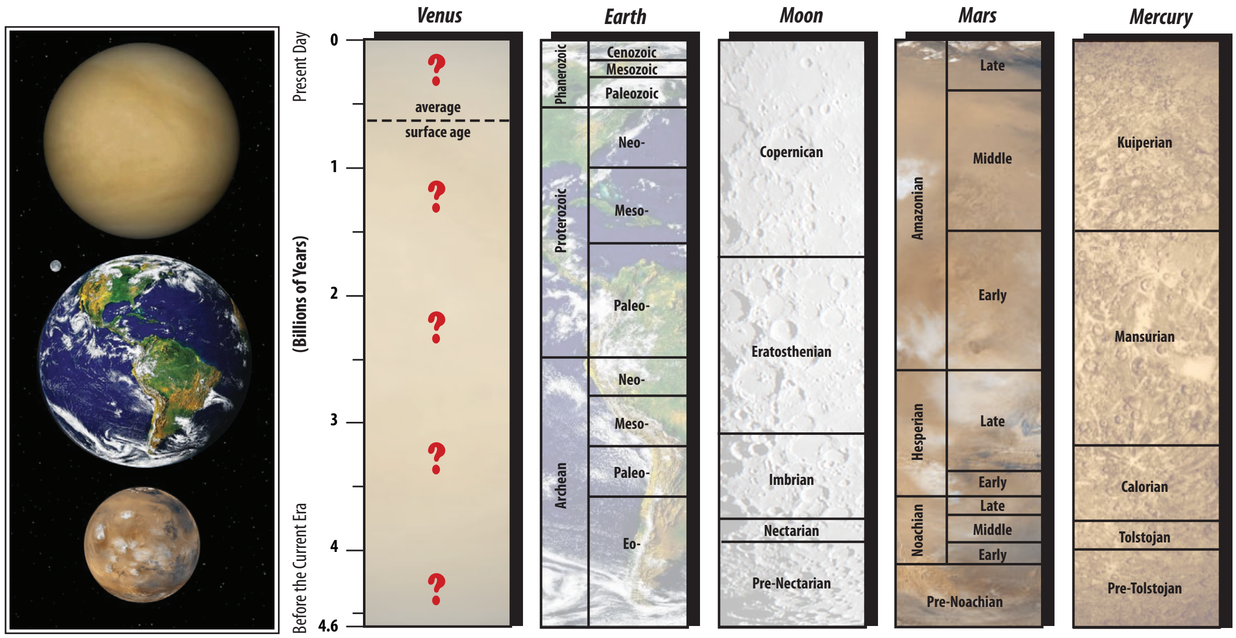

Figure 1: The unknown relative chronology of Venus severely limits current understanding of the crustal evolution of the terrestrial planets. A Venus geophysical orbiter (VGGO) can resolve some of the unknowns and place Venus in context with the other terrestrial planets.

on a planetary scale at 1–10 m vertical precision. Likewise, *Magellan*'s S-band SAR imaging sampled the planet at horizontal resolutions of typically ~150 m, thereby providing essential regional context for geologic features, but inadequate for untangling the spatial and temporal relationships associated with dominant crustal processes.

The *Mars Global Surveyor* [MGS] mission illustrates this "resolution gap" most effectively. Prior to MGS, the best available planetary-scale imaging resolution for Mars was ~100–200 m, and topographic sampling was no finer than about 60 km with vertical uncertainties of 100's of meters or more. With the MGS MOLA laser altimeter, a global digital elevation model (DEM) for Mars was developed with ~1–2 km grid cells at 1–10 m absolute vertical accuracy (relative to the center of mass of the planet) [Smith et al., 2001]. Similarly, the MGS MOC visible wavelength imaging experiment covered a few percent of the surface area of Mars at an average spatial resolution of 3–4 m/pixel, revealing details of processes that were undetectable at 100 m resolution, such as hillside gullies. There is no doubt that data from these two instruments completely revolutionized our understanding of Mars and yet their enormous impact was impossible to predict *a priori*. Improvements in topography and imaging equivalent to those from MGS at Venus will assuredly discover unique aspects of the planet's crustal evolution that are presently unknown and perhaps unimagined, just as they have done for Mars.

This white paper describes a small, representative set of questions about Venus for which global-scale geophysical and geological "reconnaissance" is required via high resolution geodetic-quality radar altimetry and polarimetric SAR imaging. It is intended to document current gaps in understanding that can be resolved from the vantage point of a low-altitude orbiter that requires a circular, inclined orbit to facilitate geodetic precision altimetry. Additional measurements possible from such an orbiting spacecraft mission include near IR surface albedo and temperature observations by means of instruments that can exploit well-established surface IR windows (i.e., at 1.02, 1.10 and 1.18 μm). Surface near-IR mapping of temperature and albedo may be able to constrain some aspects of regional composition on the basis of recent results from the ESA *Venus Express* mission [Mueller et al., 2008]. As an example, if large expanses of felsic material can be confirmed on Venus, it would suggest the presence of liquid water at some point in the past [Campbell and Taylor, 1983].

Major Issues in Crustal Evolution of Venus

In spite of major strides achieved by *Magellan* [Venus II, 1997; Crisp et al., 2002], the most basic details of the thermal and magmatic evolution of Venus remain unresolved and poorly constrained, when compared with our growing understanding of the Earth, Moon, Mars, and Mercury (e.g., basic chronology as illustrated in Figure 1). This gap in knowledge limits current understanding of the origin and evolution of the terrestrial planets and should be attacked in the upcoming decade via a geophysical/geological microwave orbiter at Venus. An increase in radar image resolution (SAR) and 3-D spatial topographic resolution (geodetic altimetry) would be fully equivalent to the contributions of the Mars Orbiter Camera (MOC) and Mars Orbiter Laser Altimeter (MOLA) on the *Mars Global Surveyor* (MGS) mission.

The fundamental question remains: What is the thermal evolution of Venus and why has it been so seemingly different than its planetary "twin," the Earth, whose geodynamical engine is expressed at the surface through plate tectonics? [1] This question is key to understanding how terrestrial planets evolve in general because the two planets are so similar in size, mass, and presumably heat sources. The question could be answered by understanding the volcanic, tectonic, and flexural stratigraphy of Venus—in both the relative and absolute sense. Magellan gave us a tantalizing glimpse into these matters, but ironically raised more questions than it answered.

[1] *We did not invent this overarching question. It has been posed for decades as a (or the) fundamental question for Venus. If we can't address this question in the next decade, then Venus will remain an enigma (see Figure 1).*

The outcome of the thermal/geodynamical history of Venus is expressed in its volcanic (and tectonic) resurfacing history, for this is directly related to the planetary heat engine, which is likely driven by mantle convection. Volcanism on Earth is dominated by the creation of new oceanic crust at mid-ocean ridges and the steady drumbeat of lithospheric recycling at subduction zones. By contrast, steady plate tectonic processes on Venus may have been replaced by a quasi-stability of the lithosphere, which on time scales of about half a billion years founders into the mantle beneath, recycling large quantities of heat and releasing vast quantities of lava to bury the present surface and remove all traces of impact craters (the Catastrophic Resurfacing Hypothesis [CR]). At the other extreme, Venus has been operating with a stable lithosphere, removing interior heat by conduction and by volcanism, which is steady over sufficiently-long time scales. The difference between these scenarios may be pinned to the role of water, or lack thereof, in controlling the strength of the lithosphere. Tied up in the contentious debate over resurfacing is its spatial and temporal heterogeneity. The homogenous, or "directional," view is that specific geological units were emplaced globally in a well-ordered sequence, while the opposing view, "non-directional," has it that processes were heterogeneous in both space and time over the observable geological record.

A relative chronology for Venus can be developed by addressing crustal resurfacing on multiple fronts. Untangling the crustal resurfacing history is fundamental to understanding why the thermal evolution of Venus has been so different from Earth, and placing constraints on the resurfacing time scale requires scientific investigations not possible with *Magellan* data. Geodetic quality radar altimetry (analogous to MGS' MOLA) can characterize subtle changes in elevation with far greater horizontal resolution and vertical accuracy, providing a new basis for detailed modeling of crustal thermal environments and searching for subtle signatures of ancient impact basins likely to have been buried beneath a veneer of volcanic deposits (Figure 2). At fine scales, high resolution and sensitivity imaging radar can reveal the hidden complexity of volcanic deposits linked to resurfacing and erosion. These observations can

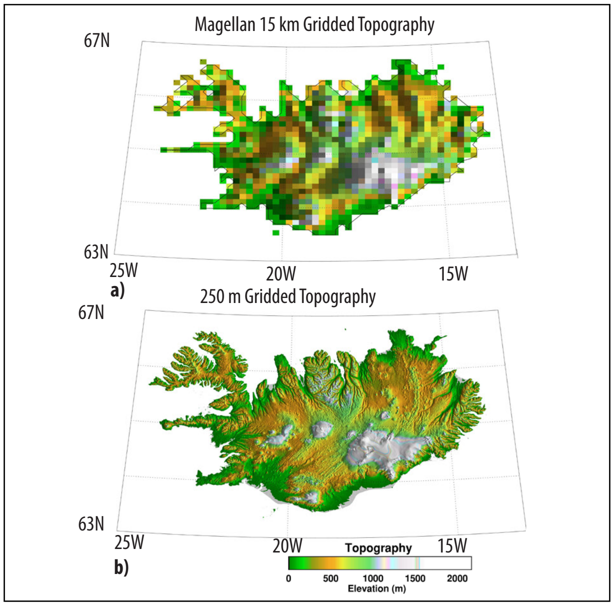

Figure 2: (a) Simulation of Iceland at *Magellan* resolution; (b) high resolution topography of Iceland illustrating geological processes that can be detected via a VGGO radar altimeter.

provide new boundary conditions upon which revised models of Venus' crustal resurfacing can be developed. Several specific examples are provided here.

Impact Craters: The heart of the resurfacing issue is the time scale over which lava flows obliterated the previous surface. A complex stratigraphic history could have taken place in "the blink of an eye" (geologically speaking), or could have extended over hundreds of millions of years. Pegging the stratigraphic history to a geologic time scale is necessary to establish the resurfacing rate and thus an understanding of how the venusian heat engine has operated. *Magellan* data have not been able to resolve this question. Short of absolute age dating from returned samples (not expected for at least the next two decades), impact crater geomorphology offers the best opportunity for achieving this objective.

The apparent lack of tectonic and volcanic modification of craters was a major underpinning of the CR hypothesis when it was proposed. Craters themselves provide their own geomorphic index of age in terms of the evolution of exterior radar-dark halo deposits that erode with time due to aeolian or other processes. Dark halos tend to be absent in regions with very high spatial crater densities (greater than planetary mean age) and in areas of very low spatial crater densities (less than planetary mean age), which also appear to be regions that are volcanically and tectonically active [e.g., the Beta-Atlas-Themis ("BAT") region]. Thus it seems that exogenic processes (e.g., aeolian) remove halos given enough time unless endogenic processes (volcanism, tectonism) act first. High spatial resolution polarimetric SAR images and geodetic topography of craters are powerful ways to discriminate between geologically active and inactive regions on Venus, in order to understand precisely how dark haloes are removed. SAR images and altimetry can provide definitive answers at scales not possible with *Magellan* about the mechanisms of crater modification, including the degree of ejecta embayment, crater floor infilling, and rim breaching. High spatial resolution polarimetric SAR images can also be used to search for a potential population of small "splotches"—patches of fine-grained material produced when a bolide too small to reach the surface explodes in the atmosphere. Such splotches may be useful for improving crater statistics and consequently for establishing a relative surface chronology [Phillips and Izenberg, 1995].

The possibility of identifying buried impact craters with subtle surface expressions not detectable by *Magellan* on Venus would completely rewrite the current resurfacing history paradigm and opens up the possibility of discovering the relative ages of buried surfaces on Venus. The MOLA geodetic gridded topography revealed the presence of quasi-circular depressions (QCDs) across Mars [Frey, 2006], believed to represent older impact features now buried by sediments or lava. If they exist on Venus, shallowly buried impact basins at scales of 100's of km to more than 1000 km (in diameter) may remain detectable over billions of years, as on the Moon and Mars. The presence of large QCDs associated with the major Venusian plains regions would suggest that ancient (late heavy bombardment) crust exists beneath perhaps only a few km of volcanic fill, while the absence of such features would suggest a very deep infilling or complete removal of such ancient basins.

Tesserae: About 20% of the Venus surface is characterized as highlands, many of which are highly deformed, isostatically compensated "crustal plateaus". Structural deformation patterns of criss-crossing linear features, known as *tessera*, are typical of crustal plateaus. At the *tessera*/plains boundary, two hypotheses can be tested. The first hypothesis suggests that *tessera* emplacement and associated deformation occurred early in the history of Venus. This model suggests that the *tessera*/plains contact should be sharp and at a nearly constant elevation. In comparison, if activity associated with *tessera* formation continued into more recent geologic time, plains material would slope up to the contact.

Within areas mapped as *tesserae,* both graben and ribbon terrain [Gilmore et al., 1998, Hansen et al., 2000] have been mapped from *Magellan* SAR imaging data. The dominant wavelengths of these structures can provide insight into the mechanical properties of the upper crust and lithosphere [Hansen, 2006; Ghent and Tibuleac, 2002]. In some cases these features have been observed just at the limit of the resolution of the *Magellan* SAR data. High spatial resolution SAR images can clearly delineate dominant scales of deformation and age relations between different episodes of deformation (Figure 3).

Lobate Plains Lava Flows: It has been suggested that the *lobateness* of lava flow fronts fades with time due to weathering processes and that this establishes a geomorphic index for the age of volcanic emplacement. The age classification of volcanic units on the basis of *lobateness* of flow fronts seems to be consistent with global crater densities

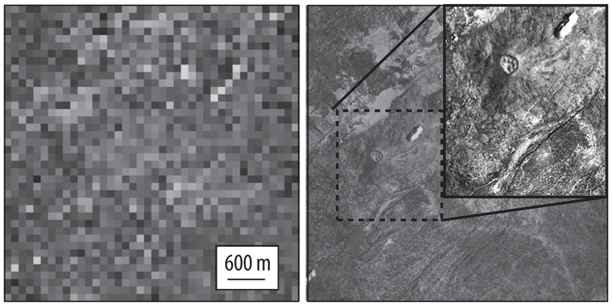

Figure 3: SAR image of the mid-Atlantic ocean ridge in Iceland as seen at *Magellan* SAR resolution and at 5 m horizontal resolution.

on these units. With high resolution SAR imaging (~10 m scale) and geodetic altimetry data, this relationship can be tested against detailed stratigraphic superposition results and with more detailed information from craters.

Crustal Structure: An appropriately-designed and instrumented geophysical orbiter can supply additional information on crustal structure. Such a mission could establish the "flexural stratigraphy" of Venus, essentially mapping the elastic thickness, a surrogate for heat flow, at many places on the planet. Various kinds of mass loads, including volcanoes and those associated with faulting, flexurally deform the lithosphere. Because of its coarseness, both horizontally and vertically, the *Magellan* radar altimeter was only able to support reliable elastic thickness (and thus heat flow) estimates from flexural topographic signals in about a dozen places. A next-generation geodetic-quality radar altimeter will increase the number of estimates by at least an order of magnitude as well as significantly reduce uncertainties associated with altimetric measurements to better than several meters. Further, the flexural results will be integrated with the geologic stratigraphy established by such an orbiter (via high resolution SAR), and thus the spatial and temporal evolution of heat flow can be constructed. Improved gravity data would also help address key questions related to crustal structure. Major improvements beyond *Magellan* can also be achieved by a spacecraft in a low orbit with precision tracking.

Example Mission Concept for VGGO

There are several potential missions that could provide the required planetary-scale topographic and radar imaging data to resolve the scientific questions outlined above. One concept for a Venus geophysical/geological orbiter would take advantage of developments in Earth orbital radar remote sensing, as demonstrated by the Canadian Space Agency's RADARSAT-2 polarimetric SAR orbiter, as well as advanced, high-frequency oceanographic and ice radar altimeters such as those presently operating on ESA's ENVISAT and NASA's OSTM missions. Compact hybrid polarity S-band SAR imaging systems presently in lunar orbit [Chin et al., 2007] demonstrate the value of high-sensitivity Stokes parameter imaging of planetary surfaces, as have Earth-based studies using the Arecibo-Green Bank and Goldstone systems over the past 15 years [Carter et al., 2004].

In order to achieve the necessary global topographic sampling and targeted high resolution and sensitivity SAR imaging, an optimized Venus geophysical/geological orbiter (VGGO) will require a circular orbit with an inclination that maximizes areal coverage and altimeter groundtrack cross-overs.

There are at least four viable methods for achieving the required sampling. In the simplest case, a single-beam, nadir-oriented delay-Doppler radar altimeter (DDRA) can be utilized to slowly build up coverage over time, and within two Venus rotations (i.e., each rotation is 243 Earth days), sufficient data to produce a global km-scale topographic grid could be achieved. One possible embellishment to this approach would be to employ a multi-beam radar altimeter to increase coverage per orbit and produce improved sampling density and altimeter cross-overs, thereby enhancing the absolute vertical accuracy of the measurements. A third possibility would employ an orbital repeat-pass interferometric SAR (InSAR) at either S- or L-band to produce high spatial resolution topography on a region-by-region basis, as Earth orbiting SAR missions (ENVISAT, RADARSAT-2) achieve for targeted areas, although InSAR at Venus presents substantial technical challenges. With any InSAR approach an independent source of absolute calibration (i.e., ground control points) is required if center-of-mass referenced topography is to be derived. The ultimate approach would involve a simultaneous, dual-antenna InSAR instrument in circular, low-altitude Venus orbit, producing regional coverage at horizontal scales as fine as 30–50 m; however, such methodologies would produce data at rates of 500 Megabits per second or more, and would require high data-rate transmission to Earth and massive on-board storage. The 2009 Venus Flagship mission study [Bullock et al., 2009] recommended the dual-antenna InSAR method for regional topographic sampling on the basis of its exquisite spatial resolution, but recognized it was suitable only for Flagship-class missions.

As a pre-Flagship mission alternative, an existence proof mission concept (VGGO) that would employ a low-altitude (< 400 km) circular, inclined orbit and a high-frequency delay-Doppler radar altimeter is outlined that would offer a cost-effective option for acquisition of global-scale geodetic topography in the upcoming decade.

A state-of-the-art DDRA altimeter operated at high frequency with a suitable antenna (i.e., at least ~3 m in diameter) could provide 50–200 m along track sampling (~1 km across track) at ~1–2 m vertical precision for most Venus surfaces by means of along-track delay-Doppler processing [Ford et al., 1991; Raney 1998] at data-rates that are typical of current operational planetary missions. In order to achieve an ultimate vertical accuracy (relative the center of mass of Venus) of 1–10 m, precision radial orbit determination will be required, as has been demonstrated by MGS through the use of two-way X-band tracking using the Deep Space Network (DSN) and an on-board ultra-stable oscillator (USO). Any geodetic topographic mapping will require the combined use of two-way tracking at X band via the DSN together with altimetric cross-over analysis, as was pioneered by the MGS MOLA investigation for Mars [Smith et al., 2001; Neumann et al., 2001]. The combination of a low-altitude, inclined circular orbit with precision two-way tracking and altimeter cross-overs will enable a global geodetic topographic grid to be established for Venus from a suitably-equipped orbiter spacecraft in approximately one Earth year.

In addition to nadir-oriented delay-Doppler radar altimetry, targeted high resolution and sensitivity S- or C-band radar imaging at resolutions as fine as ~10 m can be achieved by means of state-of-the-art high-bandwidth, hybrid polarity SAR instruments [Raney 2007]. Earth-orbiting instruments such as those operating on the Canadian Space Agency's RADARSAT-2 are pioneering such measurements today at ~10 m scales, and more compact implementations are possible by means of large-area reflector antenna systems. Globally-targeted high-resolution hybrid-polarity SAR instruments in a low-altitude circular Venus orbit would be able to achieve 10 km x 10 km image frames at 45 degree incidence with sensitivities far better than *Magellan* (i.e., Noise-Equivalent Sigma Zero or NEqσ_0 of -29 to -30 dB). In a nominal three-cycle (i.e., 3 Venus revolutions or 729 Earth days) Venus geophysical/geological orbiter mission, several percent of the surface area of the planet could be imaged by such a high-bandwidth SAR, depending on DSN telecommunication rates and selected orbiter spacecraft telecommunications systems. For such targeted SAR images, on-board processing (other than minimal compression) is not recommended, since SAR image formation increases the data volume per frame, usually by a large factor.

Summary

A dedicated Venus geophysical/geological orbiter (VGGO) with a suitable geodetic-quality delay-Doppler radar altimeter and high-resolution hybrid-polarimetric SAR holds the promise of revolutionizing our understanding of the preserved geology of Venus, just as the *Mars Global Surveyor* MOLA and MOC investigations achieved for Mars. Through this type of mission and its quantitative observations, strong constraints on the thermal/geodynamical history of Venus will be established. To achieve this goal will require the integration of geodetically controlled precision topography and hybrid-polarity high-resolution SAR for a broad range of surface features, including impact craters, volcanic lava flows, and *tessera*.

Current technologies for achieving km-scale topographic measurements via geodetic-quality radar altimeters are routine in the Earth sciences, and can be adapted to Venus. The potential for high frequency delay-Doppler radar altimetry with along-track sampling as fine as ~50 m is within reach, on the basis of existing airborne and spaceborne instruments. By implementing a Venus geophysical/geological orbiter in a low-altitude, circular orbit, altimetric cross-over analysis can be used to produce vertical accuracies of 1–10 m, more than an order of magnitude improvement over *Magellan*. Likewise, high-bandwidth SAR instruments can now produce ~10 m resolution polarimetric radar imaging of the Earth at high sensitivity, and these technologies can be applied from a low-altitude circular orbiting spacecraft at Venus. In addition, km-scale mapping of surface albedo variations are possible using existing-technology IR spectrometers that would provide complementary compositional constraints. Within the upcoming decade, a Venus geophysical/geological orbiter mission could set the stage for a follow-on Flagship mission, an example of which is described in the NASA Venus Flagship Mission Study [Bullock, et al., 2009].

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