VERITAS – a Discovery-class Venus surface geology and geophysics mission

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***Abstract*— Our understanding of solar system evolution is limited by a great unanswered question: How Earthlike is Venus? We know that these "twin" planets formed with similar bulk composition and size. Yet the evolutionary path Venus followed has diverged from Earth's, in losing its surface water and becoming hotter than Mercury. What led to this? The answer has profound implications for how terrestrial planets become habitable and the potential for life in the universe.**

Prior Venus missions discovered that its surface (like Earth's) is covered with diverse geologic features formed mostly in the last billion years. It probably remains geologically active today. Recent results from ESA's Venus Express mission indicate current volcanic activity in at least one location. Water, though not stable on the surface, is likely still shaping interior dynamics, driving volcanic outgassing, and influencing surface and atmospheric chemistries. However, without moving tectonic plates, how similar is Venus to Earth? Does it represent a transitional state between the tectonically inactive terrestrial planets and Earth? Is Venus still geologically active today? Does it retain the chemical signature of past water near the surface? VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) mission will answer these questions. The mission goals, which flow directly from the Planetary Science Decadal Survey, the SMD Science Plan, and VEXAG goals, are: 1) understand Venus' geologic evolution, 2) determine what geologic processes are currently operating, and 3) find evidence for past or present water. The mission design also enables a unique opportunity to send a microsat probe into the atmosphere, carrying a compact mass spectrometer to sample the noble gases and their isotopes just below the homopause – high payoff additional science for only incremental cost.

The primary mission goals of VERITAS, accomplished by seven objectives, require just two instruments and a gravity science investigation over a 2-year orbital mission. VEM (Venus Emissivity Mapper) maps surface emissivity using six spectral bands in five atmospheric windows that see through the clouds. VISAR (Venus Interferometric Synthetic Aperture Radar) generates a long-awaited DEM (digital elevation model) at 250 m horizontal postings with 5 m height accuracy.

NASA's Discovery program is cost-constrained, so a viable Discovery mission has to fit within the available funding. The approach adopted by the VERITAS team is to use a heritage spacecraft adapted for the environment at Venus, and to follow the old adage – keep it simple. The mission has only two instruments, and VISAR for example has only one mode of operation. The VEM instrument is a simple pushbroom imager with no moving parts. Gravity science is carried out using the spacecraft's fixed-antenna telecom system. No new technologies are used. Onboard processing of the radar data using a COTS space-qualified processor reduces data volume to levels commensurate with downlink rates for other NASA planetary orbiters, so no heroics are required to get the data back. Mission operations are simple and repeatable. Finally VERITAS is implemented by an experienced team, that is well-qualified for their assigned responsibilities, and have worked together on many previous, successful planetary missions.

TABLE OF CONTENTS

1. INTRODUCTION 1
2. SCIENCE RATIONALE 2
3. CONCEPT OF OPERATIONS 3
4. SCIENCE IMPLEMENTATION 4
5. MISSION ENHANCEMENTS 8
6. RELEVANT EXPERIENCE 9
7. CONCLUSIONS 9
ACKNOWLEDGEMENTS 10
REFERENCES 10
BIOGRAPHY 10

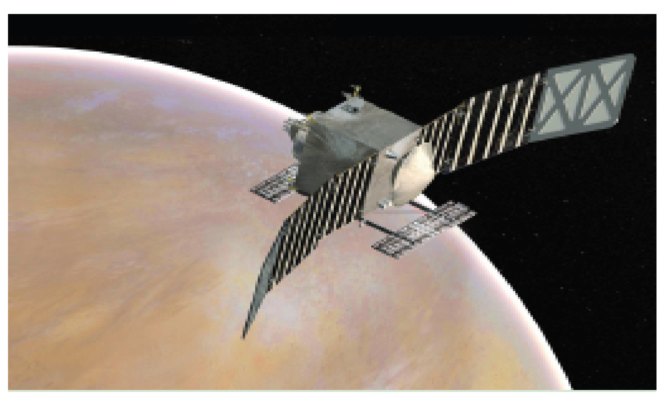

Figure 1. VERITAS in orbit at Venus

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1. INTRODUCTION

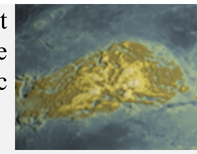
The Venus Emissivity, Radio Science, Insar, Topography, And Spectroscopy (VERITAS) mission, illustrated in Figure 1, was proposed to NASA's 2014 Discovery opportunity [1] and is one of five missions selected for Phase A Concept Study in October 2015 [2]. NASA's Discovery Program was initiated in 1992 and has flown a series of very successful, lower-cost, highly focused, scientific space missions to explore our Solar System. The Discovery 2014 opportunity solicited missions that could launch no later than end of calendar year 2021. The downselect to the final candidate(s) selected for flight will follow the completion of the Concept Study phase, in mid-2015. If VERITAS is selected to go forward, it will be the first Discovery mission to target Venus, and NASA's first Venus mission in more than 25 years.

Table 1. By revealing Venus' geologic history, determining how active it is today, and searching for the fingerprints of past and present water, VERITAS will answer the fundamental question: How Earthlike is Venus? This is essential in predicting whether Earth-sized planets in habitable zones are more likely to resemble Earth, or Venus.

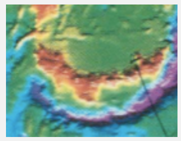
Australia

Earth's continents, formed when basalt melted in the presence of water, hold the record of several billion years of tectonic evolution.

Did Venus' large plateaus (known as tesserae) form the same way?

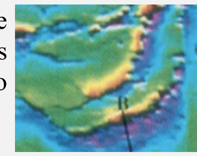


Ovda Regio



Earth's defining geologic feature, plate tectonics, may contribute to its habitability. Subduction is necessary to initiate plate tectonics.

Does subduction occur on Venus?



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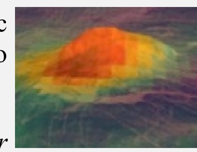
Hawaii

Volcanism shapes atmospheric composition and provides a window into interior processes.

Is Venus volcanically active? Is water still outgassing? Does this imply the presence of significant subsurface water?



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2. SCIENCE RATIONALE

A deep understanding of solar system evolution is limited by a great unanswered question: How Earthlike is Venus? We know that these "twin" planets formed with similar bulk composition and size. Yet Venus followed a divergent evolutionary path, losing its surface water and becoming hotter than Mercury. How did this happen? The answer has profound implications for how terrestrial planets become habitable and the potential for life in the universe.

Activity inside the smaller terrestrial planets – Mercury, Mars, and the Moon – slowed to a trickle as they cooled billions of years ago. Earth, of course, is still tectonically active, driven by interior heat. Prior Venus missions discovered that its surface (like Earth's) is covered with diverse geologic features formed mostly in the last billion years. It probably remains geologically active today. Water, though not stable on the surface, is likely still shaping interior dynamics, driving volcanic outgassing, and influencing surface and atmospheric chemistries. However, without moving tectonic plates, how similar *is* Venus to Earth (Table 1)? Does it represent a transitional state between the tectonically inactive terrestrial planets and Earth? Is Venus still geologically active today? Does it retain the chemical signature of past water near the surface?

VERITAS (Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy) will answer these questions. Our goals, which flow directly from the National Acadmey's Planetary Science Decadal Survey, the NASA Science Mission Directorate (SMD) Science Plan, and the Venus Exploration Advisory Group (VEXAG) goals are: 1) understand Venus' geologic evolution, 2) determine what geologic processes are currently operating, and 3) find evidence for past or present water.

These goals, accomplished by seven objectives (Table 3), require just two instruments and a gravity science investigation over a 2-year orbital mission. VEM (Venus Emissivity Mapper) maps surface emissivity using six spectral bands in five atmospheric windows that see through the clouds. VISAR (Venus Interferometric Synthetic Aperture Radar) generates a long-awaited DEM (digital elevation model) at 250 m horizontal postings by 5 m height accuracy (Table 2), maps the planet at 30 m and 15 m

Table 2. VERITAS's advances in measurement resolution and accuracy enable answers to fundamental questions about Venus' geologic evolution and present state.

Parameter	Magellan or Venus Express	VERITAS
SAR resolution	115–280 m	15m, 30 m
Altimetry resolution	Vertical:10–100 m Along-track: 8–15 km Cross-track: 12–27 km	5 m 0.25 km 0.25 km
Infrared surface imaging	1 (usable) channel, SNR ~10 *	6 channels, SNR 1000
Gravity field	avg. deg. 70 (~270 km)	avg. deg. 130 (~145 km)

resolution, and pinpoints active deformation zones using repeat-pass interferometry. The spacecraft Ka-band telecom subsystem maps Venus' gravity field with 2–3× improved resolution, enabling the first global estimates of elastic thickness. Emissivity SNR and spectral coverage improve over Venus Express [3] by 100× and 6×, respectively; and the global radar datasets have at least 10× greater resolution than Magellan [4]. Together, these rich datasets enable VERITAS to answer fundamental science questions, provide an invaluable resource for a new generation of Earth, planetary, and exoplanet scientists, and reveal the truth about how Earthlike Venus really is.

Table 3. VERITAS Goals and Objectives trace directly to NASA's Planetary Science Goals

NASA PLANETARY SCIENCE GOALS	VERITAS GOALS AND OBJECTIVES	
Explore and observe the objects in the solar system to understand how they formed and evolve	Constrain Venus' geologic evolution	• Origin of tesserae • Buried features • Resurfacing • Tectonic deformation
Advance the understanding of how the chemical and physical processes in our solar system operate, interact, and evolve	Determine what geological processes are currently operating	• Volcanism • Weathering • Faulting
Explore and find locations where life could have existed	Find evidence for past or present water	• Mineralogical evidence of past water • Volcanic outgassing

3. Concept of Operations

VERITAS is a Venus orbital investigation with a science payload that includes a radar – VISAR; and a multispectral imager – VEM, contributed by DLR. Gravity science measurements are obtained through two-way tracking of dual-frequency telecom signals from VERITAS to Earth.

Figure 2 shows the trajectory design, which uses a "low performance" launch vehicle, as defined in the Discovery AO, with a Type IV transfer to Venus. Science observations begin almost immediately after Venus orbit insertion (VOI), followed a few months later by the start of aerobraking (Fig. 3) to reduce altitude and circularize the orbit. During aerobraking, the 52 sq. m. area of the solar arrays generates sufficient drag to reduce the orbital energy, as the spacecraft is carefully controlled to pass through the upper portions of Venus' atmosphere. The final science orbit is optimized for DEM acquisition using the VISAR radar instrument and VEM surface-composition data acquisition.

Table 4. The VERITAS science mission profile is divided into two phases.

Characteristic	Value
Science Phase I (Mission Days 829-909)	
Orbit	Elliptical, periapsis ~North pole
Duration	118 d total: 81 d after arrival; 37 d during conjunction
Science Phase II (Mission Days 1224-1953)	
Orbit	Circular, 88.5° inclination, altitude 175–250 km
Duration	729 Earth days (3 Venus cycles)

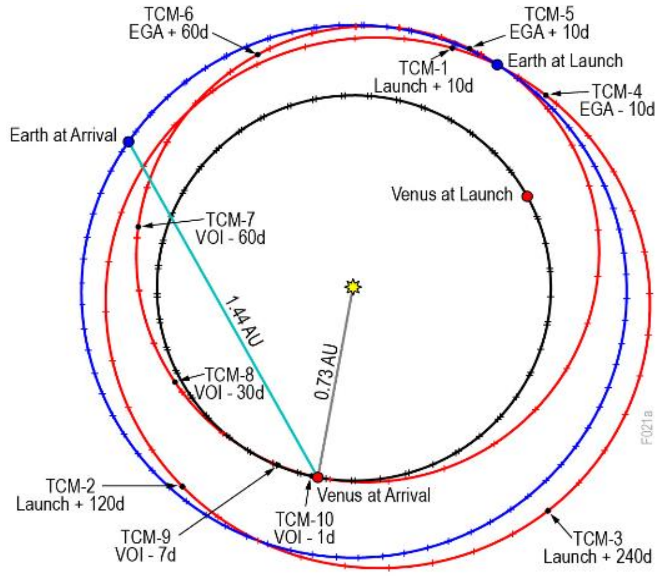

Figure 2: Earth-Earth-Venus Type IV trajectory for the 2021 launch opportunity.

The launch period starts in late 2021 to begin a 27-month Earth-Earth-Venus trajectory (Figure 2), arriving in Feb 2024. An important benefit of the mission design is a backup launch opportunity with identical post-VOI timeline, and no impact on science operations. Following Venus Orbit Insertion (VOI), a period reduction maneuver (PRM) establishes the initial science orbit, and Science Phase I begins (Table 4 and Figure 4). During this period, VEM observations are made from a similar orbit to that of Venus Express, allowing early comparisons, and mapping of features seen by that mission with higher SNR and in greater spectral detail. After conjunction, aerobraking (Figure 3) establishes the low altitude, near-polar science orbit for Science Phase II, which covers three 243.3 day ground-track repeat cycles. Total mission duration is 64 months (including 1 month of post-launch checkout) and requires 1480 m/s of ΔV.

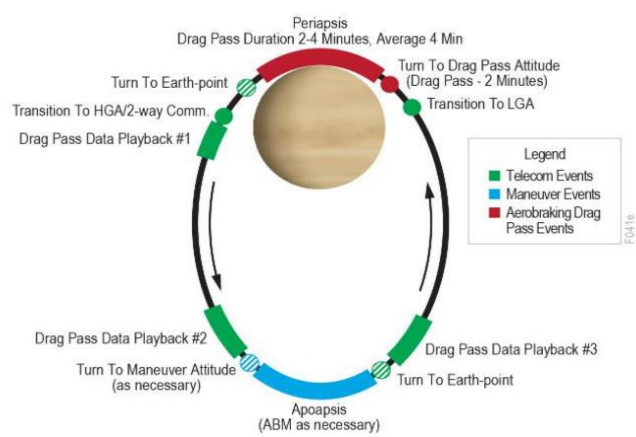

Figure 3: Aerobraking operations span 257 days and provide the equivalent of 2.4 km/s of Delta-V

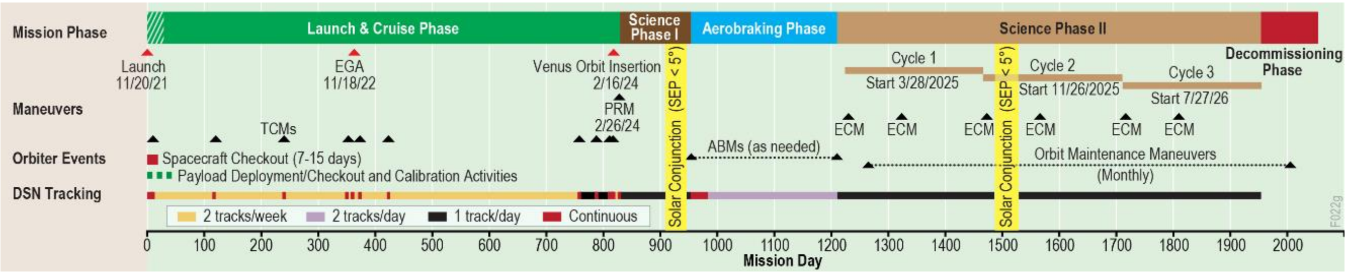

Figure 4. Mission timeline for a late 2021 launch, showing activities during Cruise and Early Orbit Operations, the elliptical orbit of Science Phase I, Aerobraking, and the Science Phase II orbit

During aerobraking, the per-orbit maximum allowable heat rate is a function of the orbit period and geometry relative to the sun. The reference design of the aerobraking campaign, shown in Figure 5, includes 112% margin against this limit. Aerobraking maneuvers are designed to maintain the margined limit for at least two days in the event one is missed due to an autonomous “pop-up” maneuver, triggered by higher-than-expected heating on a given pass.

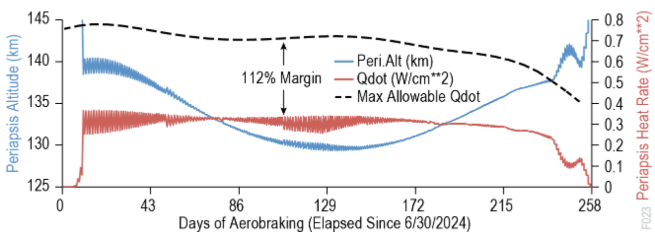

Figure 5. The aerobraking campaign takes VERITAS down to its Science Phase II orbit, with 112% margin on heating rates for the spacecraft against the atmospheric variability observed by ESA’s Venus Express [3].

The 88.5 deg inclination Science Phase II Phase orbit is designed to meet the VISAR Signal-to-Noise (SNR) and coverage requirements while minimizing the ΔV cost to maintain the orbit. VISAR requires at least a 500-meter overlap between adjacent ground-swaths, which places a floor of 176.3 km on the orbit altitude. VISAR SNR considerations place a ceiling of 255 km on the orbit. Due to Venus’ extraordinarily slow rotation (243-day sidereal period), the ground-track at the Equator moves <10 km per orbit. This means that, from this orbit, it takes one full 243-day cycle for the 14-km swath VISAR instrument to ‘see’ the entire planetary surface, assuming it could acquire data on each orbit track.

VEM data acquisitions are more constrained – the instrument operates only on night-time passes, and when nadir-pointed. VERITAS’ approach to management of the spacecraft thermal budget by keeping one face always pointed to cold sky means that periodically the entire spacecraft is rotated through 180 degrees, flipping the fixed-geometry VEM instrument from its nominal nadir position to a skywards direction. This constraint means that VEM observations are only possible roughly half of the time during Science Phase II – still more than sufficient to meet the science requirements.

During Science Phase II, which is the most data-intensive phase of the mission, each day is divided up into 16 hours for VEM and VISAR data acquisition, then 8 hours for data downlink back to Earth, and gravity science measurements. This strategy stems from the inclusion of the heritage high gain antenna for telecom, which is fixed-mounted on the top deck of the spacecraft. During nominal data acquisition the spacecraft is aligned so that VISAR is pointed off-nadir by 30 degrees, and VEM is nadir-pointed; during downlink periods the high gain antenna is pointed Earthwards by steering the entire spacecraft to point in that direction.

4. SCIENCE IMPLEMENTATION

To meet the science requirements, VERITAS’ suite of measurements include high-resolution topography, imaging, gravity field, and the first-ever surface composition and deformation maps for Venus.

Venus Interferometric Synthetic Aperture Radar (VISAR)

VISAR generates a global high-resolution DEM, SAR images with up to 15 m resolution, and surface deformation measurements with 2 mm precision (Table 5). It has only one operational mode, allowing simple operations with on/off commands. The DEM is generated using Single-pass InSAR with two antennas separated by a fixed (rigid) baseline (Figure 6) of length 3.1 m. The optimal observing geometry points the antenna perpendicular to the platform’s flight track, with an off-nadir angle of ~30°.

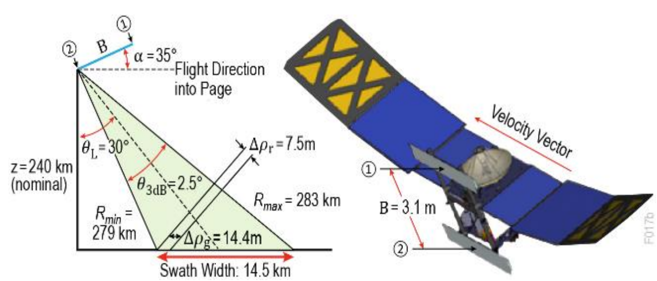

Figure 6. VISAR flight configuration and observing geometry are optimized for InSAR DEM acquisition with baseline separation B = 3.1 m.

VISAR’s 14-km swath guarantees significant overlap between adjacent orbit tracks, simplifying mosaicking. The antennas are placed at opposite ends of a compact, rigid support structure firmly attached to the spacecraft. For a 14 km swath width, each VISAR antenna needs an angular across-track field of view (FOV) of 2.5°, achieved with an antenna height of 0.6 m. SAR imagery with 15 m spatial resolution (cross-track) is easily achieved with a 20 MHz bandwidth. The antenna length of 3.9 m is chosen to minimize SAR aliasing effects.

The VISAR Block Diagram (Figure 7) shows the division of subsystem responsibilities between JPL and ASI, which contributes the RF electronics subsystem (RFES). The digital electronics subsystem (DES) controls system timing. A chirp generator generates radar pulses that are routed to the RFES. One of two redundant 300-W output TWTAs, amplifies pulses for transmission. RF pulses are directed towards the planetary surface through one of two waveguide antennas. Both antennas collect return echoes and route them into two RF front-end receivers in the RFES and then a frequency downconverter. The DES digitizes signals from each receiver and passes the output first to the onboard processor (OBP), then to the solid-state recorder (SSR). Calibration loops (using re-routed radar pulses) are used to calibrate the radar transmit and receive paths. The OBP generates fully focused SAR images and interferograms for storage by the SSR (Figure 8). All OBP software algorithms have been successfully implemented on other platforms (e.g., for UAVSAR, SMAP, SWOT). During the mission, we have the option of uploading improvement/correction software to the OBP, providing additional risk mitigation and science margin.

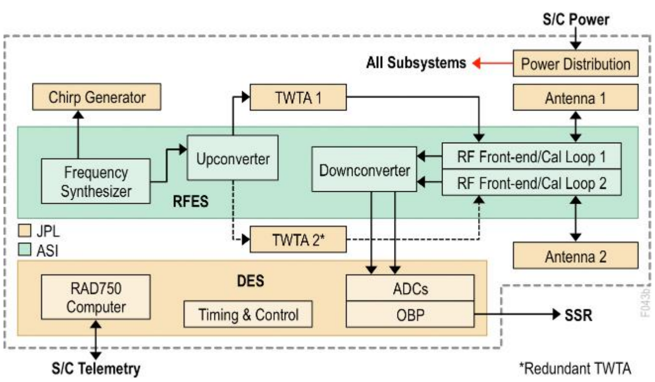

Figure 7. VISAR Block Diagram

Venus orbital investigations are constrained by available downlink capacity and "reasonable loading of the DSN" for Discovery. VISAR's OBP reduces data volume by coherently combining measurements from the two SAR antennas to generate interference patterns, known as interferograms. Significant data compression (from 10× to 1000×) occurs only after a "look-averaging" step, wherein spatial resolution and spatial sampling are reduced (Figure 8). With knowledge of the spacecraft ephemeris, VISAR interferograms are converted on the ground to a surface DEM, as was performed in 2000 with SRTM data for most of Earth's surface [5]. The same VISAR measurements are "square-law detected" through onboard processing to generate high-resolution, intensity-only SAR images of radar surface reflectivity at 30 m and 15 m spatial resolution. DEM and SAR image products follow the same processing flow, with differing degrees of look-averaging and/or square-law-detection. On repeat orbits, some data is collected for repeat-pass interferometry - those data are returned 'raw' – i.e. with no processing applied on-board.

Ground-based processing includes mosaicking to produce a global DEM and SAR images (calibrated using a radiometric correction). Repeat-pass Interferometry (RPI) data from acquisitions over the same area (separated by a 243 day cycle) are processed for precise surface deformation and correlation measurements. Raw RPI data also provide full-resolution interferograms for higher-resolution DEM analysis and OBP algorithm verification.

Table 5. VISAR data products easily meet requirements

Performance Capabilities	Value	Reqt.
Height Accuracy (m)	4.4	10
Best Image Resolution (m)	15	20
DEM Coverage (%)	148%	100%
30-m Image Coverage (%)	144%	100%
15-m Image Coverage (surface area fraction)	0.23	0.15
Repeat-Pass I/F Deformation Error (cm)	0.2	2.0
Repeat-Pass I/F Coverage (%)	0.16	0.1

The noise-equivalent sigma-zero (σ^o) is set at -16.2 dB, allowing VISAR to image the tiny fraction of features expected to have lower σ^o values than those observed by Magellan (σ^o = -15 dB). Overall radiometric performance is comparable to Magellan but with much better spatial resolution. A single polarization (HH) suffices at the selected wavelength/incidence angle because backscatter is dominated by wavelength-scale roughness effects rather than dielectric effects.

The VISAR radiometric calibration approach emphasizes end-to-end prelaunch instrument characterization including TWTA power output, antenna gain and phase pattern, baseline stability over temperature, pulse shape, receiver gain, A/D convertor characteristics, and calibration loop characterization. During flight operations, the calibration loop monitors TWTA output, and RFES and DES characteristics using sample pulses routed through the receivers and DES. For relative radiometric calibration of image products to better than ±2.0 dB, overlaps between successive orbit passes are compared. Magellan backscatter from very rough surfaces on Venus serves as a reference for absolute radiometric calibration to within ± 1.0 dB. Ephemeris data and tie points are applied between orbital pairs to improve the ephemeris for geometric location accuracy.

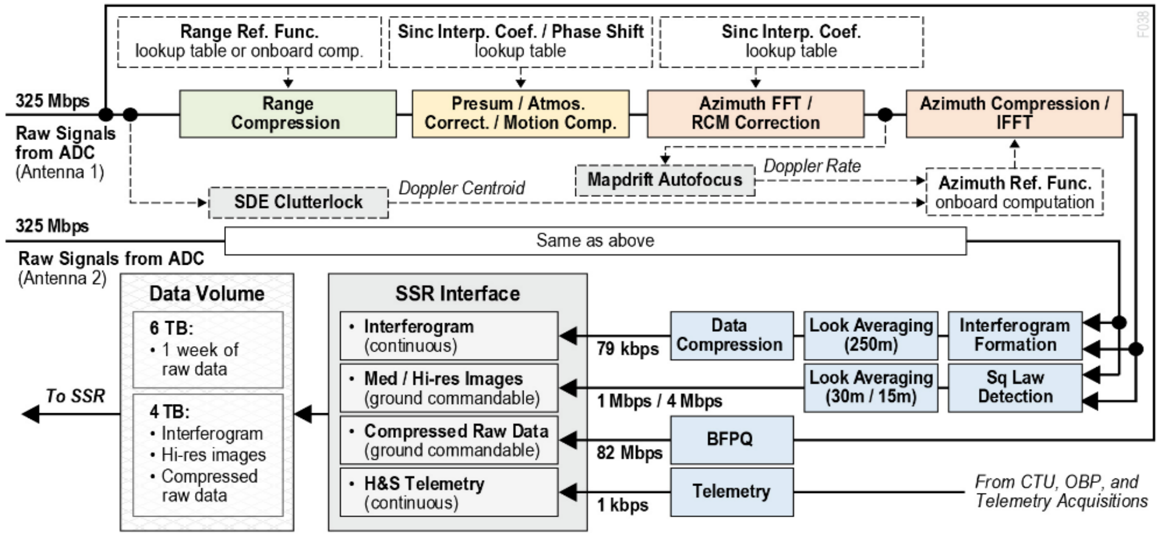

Figure 8. VISAR's output data volume is reduced by 10-1000× through onboard processing, providing downlink margin. Proven processing algorithms are executed in a flight-qualified, COTS processor.

Venus Emissivity Mapper (VEM)

DLR's VEM instrument leverages a proven measurement technique pioneered by VIRTIS on Venus Express ([6], [7]). It similarly uses narrow-band atmospheric windows to study Venus' surface composition, but with greatly improved sensitivity and spectral and spatial coverage (Table 2). VEM's design draws strongly on DLR's BepiColombo MERTIS instrument. It also incorporates lessons learned from VIRTIS: band-center and width-scatter are ~5× more stable; a baffle decreases scattered light and improves sensitivity; and a filter array (rather than a grating) provides wavelength stability and maximizes signal to the focal plane array.

Spatial resolution for VEM is limited by scattering in the Venusian atmosphere and the requirement is established at 100 km for the surface imaging bands. SNR requirements for VEM are band-dependent and range from 4-500. Expected performance, based on VIRTIS measurements of the minimum expected surface and atmospheric radiances (Figure 9) easily exceeds these requirements. VEM observes 88% of the surface, compared to the 70% requirement, and provides many repeat observation opportunities because of its relatively wide swath when compared with the 10 km orbit ground track separation. For example, with its 30° field of view (FOV), VEM can observe an active volcanic event up to 10 times on adjacent orbits within a time span of ~15 hours, satisfying a requirement for repeat coverage for short-lived thermal signatures.

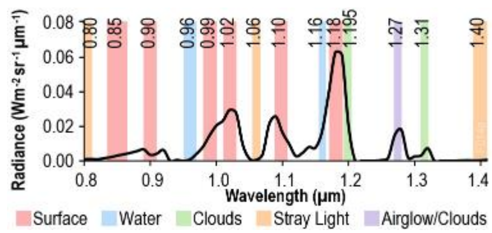

Figure 9. Night-side radiances in required spectral bands define the minimum expected signal for VEM.

The block diagram for VEM is shown in Figure 10. A baffle protects the instrument from stray light. Telecentric optics image the scene onto the filter array. A four-lens objective relays this image onto the detector. The 30° optical FOV yields a swath width of 113 km at an altitude of 215 km, providing a thorough sampling of surface emissivity and orbit-orbit repeat coverage. VEM oversamples at 10 km per pixel to account for local atmospheric water vapor variations and cloud removal.

VEM uses a multilayered dielectric-coating ultra-narrow-band filter array to split the light into 14 bands. The filter array is located at an intermediary focus of the optical path. Each band is imaged onto one of the focal plane array (FPA)'s 17 500-pixel rows. Surface mineralogy bands are spatially interleaved between cloud bands to provide before and after calibration.

The FPA is a space-qualified 256×500 HgCdTe detector array operating at <200 K to provide high SNR. It is cooled with a space-qualified Ricor K508 cooler with a mean time-to-failure of >10,000 hours. The same cooler operated successfully for 7 years on the Venus Express SOIR instrument.

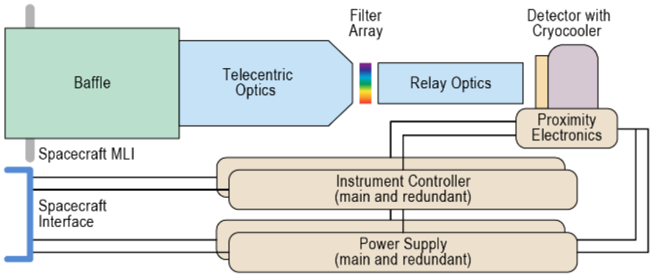

Figure 10. The VEM design uses standard optical components with redundant instrument controller and power supply.

VEM performance is summarized in Table 6.

Table 6. VEM capabilities easily meet requirements

Key parameter	Capability	Requirement
Swath width	128 km	50km
Ground resolution	50 km	100 km
Cloud-top resolution	10 km	100 km
Spectral bands	14	2
Spectral range (microns)	0.85 – 1.7	1.02-1.19
Spectral bandwidth (per band)	10 nm	40nm
SNR at 1.02 µm	600	4

Gravity Science

Two coherent radio links (X- and Ka-band) provide communication between the Deep Space Network (DSN) and the spacecraft Telecom Subsystem via the high-gain antenna. Two-way Ka-band Doppler data quality is approximately 0.015 mm/s at 10 s integration time leading to a 145 km spatial resolution capability (vs. a 200 km requirement), and an accuracy of 3 mgal at degree and order 130 (vs. a 7 mgal at 95 degree and order requirement).

VERITAS' high-resolution, globally uniform gravity field provides up to 3× improvement over Magellan (Figure 11). VERITAS results are cross-calibrated with best-resolution Magellan coverage using areas of overlap.

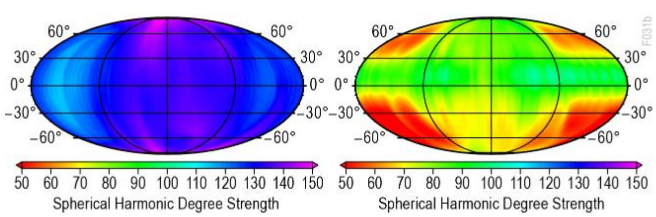

Figure 11. VERITAS's globally consistent gravity field (left) fills in Magellan holes (red, right) with up to 3× improved resolution.

Data Handling

Science data are downlinked each day during one 8-hour pass with a 34-m DSN antenna. Figure 11 shows the resulting available data volume for science for each day over the course of the mission. Data stored in the SSR is matched to the downlink volume for any given day. The cumulative data volume over the entire mission is ~58Tb (~20X larger than Magellan in total).

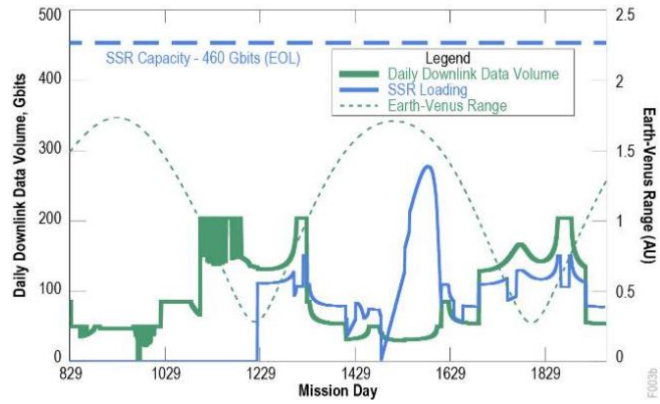

Figure 12. Daily downlink data volume capability exceeds requirements which range from 32.5 (min) to 135.5 (max) Gb/day; and SSR loading is always < 460 Gb End-of-Life (EOL) capacity.

Science team members are responsible for preflight characterization and inflight radiometric and geometric calibration of each data product. They also generate higher-level products for science analysis. As the mission timeline advances, steady progress is made towards achieving VERITAS' science objectives through the generation of the higher-level data products to meet the measurement requirements (Figure 14). All raw and calibrated data are archived in the PDS, within six months of acquisition.

Higher-level science data products are analyzed to address mission Science Objectives (Figure 13).

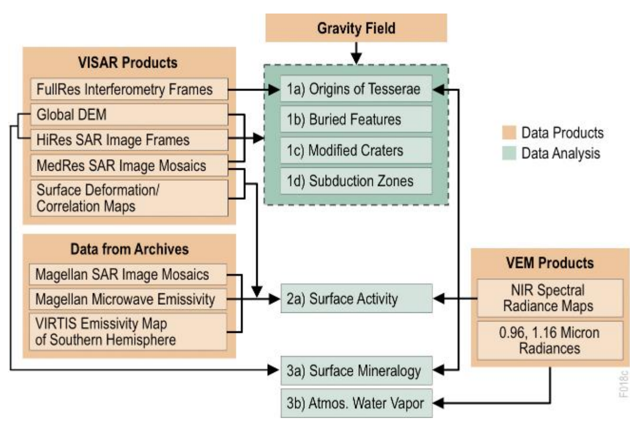

Figure 13: High-level data products flow into data analysis led by Science Team members to address each of VERITAS' Science Objectives 1a) through 3b)

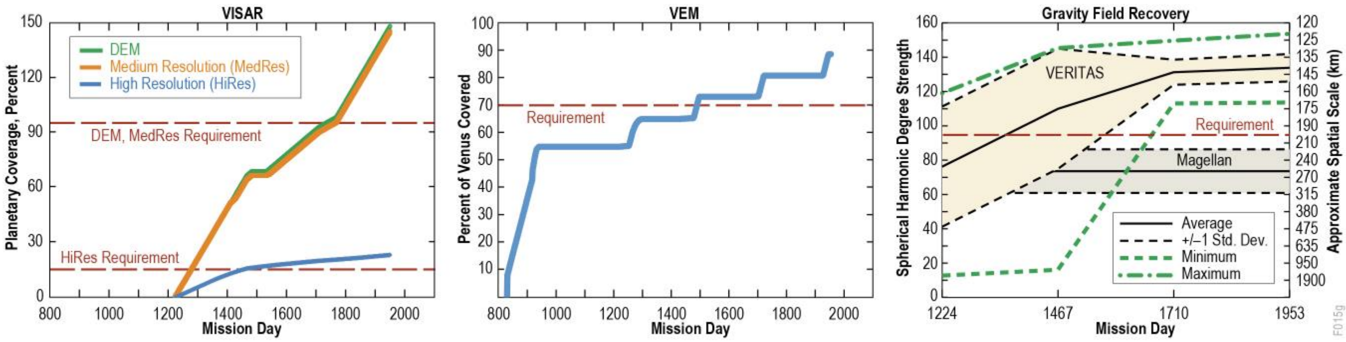

Figure 14. Early completion of high priority VISAR, VEM, and Gravity Science data products provides science margin that can be traded as the mission timeline progresses.

5. Mission Enhancements

Participating Scientist Program

A Participating Scientist Program is a low-cost way to enhance the value of VERITAS' science to NASA and broaden science community engagement. It allows scientists to take advantage of some of the exciting bonus science opportunities the mission offers, for example:

- Atmospheric science using aerobraking data;
- Atmospheric science using VEM NIR bands (only used for improving surface retrievals in the Baseline mission);
- Seismology using VEM data to search for gravity waves in the atmosphere, due to possible seismic events;
- Further deformation studies of areas prioritized by the broader science community;
- Exoplanet characterization and modeling based on emergent VERITAS results.

A participating scientist program also allows scientists who may be formulating a follow-on mission, such as a probe or lander, to engage early in their planning cycle to identify potential landing sites and plan targeted observations to characterize them.

Extended Mission

VERITAS can be extended (subject to the guidelines in the NASA SMD Mission Extension Paradigm) up to four additional 243 day cycles to provide:

- Follow up on Baseline mission discoveries;
- Potential landing site characterization for future probes/landers;
- More uniform gravity field measurement resolution;
- HiRes imaging in additional areas of interest;
- Continuing RPI observations at old and new targets.

The length of the proposed extended mission will depend on how much fuel is available at the end of prime mission.

Technology Demonstration (TDO)

The "Cupid's Arrow" nanosat TDO, carried as an optional additional payload to Venus, enables high payoff science at a fractional additional cost. Released after Venus orbit insertion, the nanosat uses a new, ultra-compact Quadrupole Ion Trap Mass Spectrometer (QITMS) with unrivaled sensitivity to determine atmospheric noble gas abundances and isotope ratios.

VERITAS carries Cupid's Arrow to Venus' orbit (Figure 15) and deploys it on an Aerobraking Pass. The nanosat requires a relatively small nudge of 1.25 m/s of ΔV in the along-track direction to send it on its path, dipping below the homopause. 7.5 hrs after release, the spin-stabilized nanosat (Figure 16) flies the QITMS through the

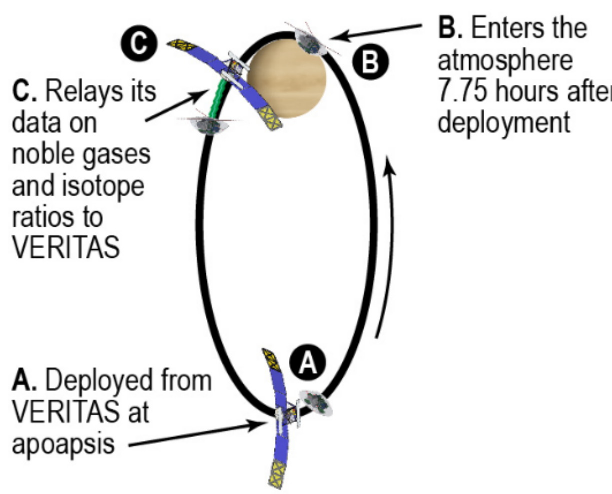

Figure 15. The trajectory for Cupid's Arrow is designed to sample the noble gases in Venus' atmosphere at a 120 km altitude.

atmosphere, threading its way to dip briefly below a 120 km altitude and providing 30 watt-hours for the noble gas measurements. The compact mass spectrometer then pops open a cap and ingests a sample for analysis, completing its investigation and calibration after 20 minutes. The nanosat then exits the atmosphere and relays 16 Mb of data to VERITAS from a range of ~1000 km. The environmental conditions are 9.6 km/sec, density 500 kg/km^3, heating rate 18 W/cm^2, max G of 0.014, and a dynamic pressure 9.9 Pa. Heating rates are higher than for the VERITAS spacecraft, yet still modest and far lower than direct-entry probes.

Cupid's Arrow leverages mature, flight-qualified Avionics and other subsystems developed for recent JPL planetary CubeSats including MarCO (in development) and INSPIRE (completed). Communication with VERITAS is via an omnidirectional, low-gain UHF-band antenna.

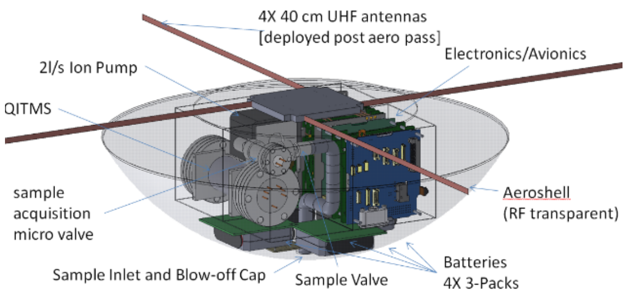

Figure 16. Cupid's Arrow flight system configuration.

Technology Infusion

Included as part of the VERITAS payload is a demonstration of the Deep Space Optical Communications (DSOC) instrument, which transmits data to a ground terminal on Earth using optical wavelengths (Figure 17). The optical terminal on VERITAS will demonstrate the feasibility and functionality of direct-to-Earth optical communications links from the deep-space environment, retiring key risks and clearing the way for widespread infusion of this technology into future missions.

Moreover, assuming the DSOC demonstration is successful and put into operational use, it could actually provide for a significant increase in the daily data volume returned by VERITAS. With just one 8-hour communications pass, at a single NASA ground station located at Table Mountain in California, optical comm permits more than a 10-fold enhancement in peak daily data volume (~2500 gigabits/day versus 205 gigabits/day). This would allow VERITAS to return more high-resolution SAR image data, or study surface deformation using Repeat-pass I/F over much larger areas (100X).

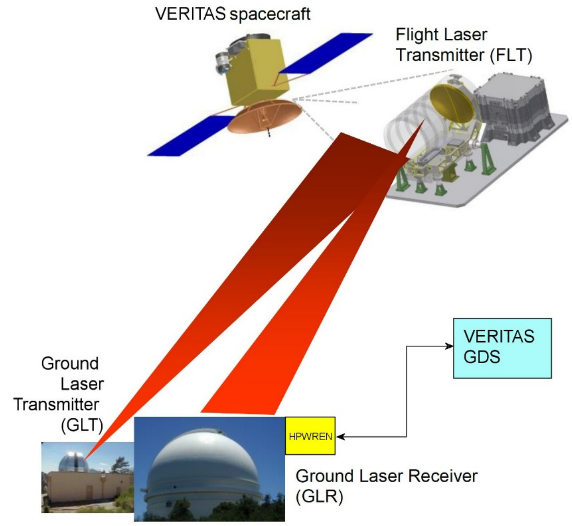

Figure 17. DSOC communication with ground stations provides significantly higher data rate for the equivalent mass and power of a state-of-the-art telecom system.

6. RELEVANT EXPERIENCE

VERITAS leverages long-standing successful partnerships. JPL and Lockheed Martin have teamed successfully many times over the past 20 years. Together, they draw on many successful mission collaborations on deep-space missions, including aerobraking at Venus and Mars. Environmental differences between a Mars and a Venus orbiter are factored into the mission and spacecraft design to adapt LM's MAVEN bus for VERITAS.

JPL and ASI together have decades of experience in radar science and engineering, and JPL has demonstrated many times the ability to lead the development and operations of payloads conceived as multinational efforts, including joint efforts with ASI and DLR. DLR has delivered and operated several imagers on other planetary missions.

7. CONCLUSIONS

In this paper we have described a conservative approach to achieving breakthrough science at our sister planet within a Discovery-class budget. VERITAS' two instruments and gravity science investigation yield global, high-resolution altimetry and imaging, and the first maps of deformation and global surface composition. Applying these state-of-the-art measurements to Venus, VERITAS can reveal its' geologic history, determine how active it is today, and search for the fingerprints of past and present water. This answers a fundamental question: How Earthlike is Venus? This information is essential to predicting whether Earth-sized planets in habitable zones are more likely to resemble Earth or Venus.

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REFERENCES

[1] Discovery 2014 Announcement of Opportunity , NASA Solicitation: NNH14ZDA014O, Nov 2014.

[2] NASA Discovery program press release, Oct 2015.

[3] Venus Express home page: http://sci.esa.int/venus-express/

[4] Johnson, W.T.K. (1991). Magellan Imaging Radar Mission to Venus, Proc. IEEE, 79(6), June, 777–790.

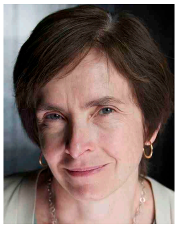
[5] Rabus, B., Eineder, M., Roth, A., Bamler, R. (2003). The Shuttle Radar Topography Mission (SRTM): A new class of digital elevation models acquired by spaceborne radar. ISPRS Journal of Photogrammetry & Remote Sensing, 57(4), 241–262.

[6] Helbert, J., et al. (2008). Surface brightness variations seen by VIRTIS on Venus Express and implications for the evolution of the Lada Terra region, Venus. GRL, 35.

[7] Mueller, N. (2012). The surface of Venus observed by VIRTIS on Venus Express at one micrometer wavelength, Doctoral thesis, University of Münster, Germany.

BIOGRAPHY

Dr. Anthony Freeman (IEEE Fellow, 2000) received a B.Sc. (Hons.) degree in Mathematics and a Ph. D. in Astrophysics, both from the University of Manchester (formerly UMIST). His technical interests include the architecture of innovative space missions and novel radar observing systems and techniques. He is currently the manager of the Innovation Foundry at NASA's Jet Propulsion Laboratory (JPL). The Innovation Foundry is an incubator for ideas, and helps between 100 and 150 of JPL's formulation teams mature their concepts every year. These ideas span all of JPL's future space missions for NASA in Planetary Science, Astrophysics, Earth Science and Human Space Flight, and some work outside the NASA envelope. He is the informal chair of JPL's "cubesat kitchen cabinet" which has helped realize at least 19 nanosat projects, pushing towards a future where interplanetary cubesats are common. In his previous position he was the program manager of the Earth System Science Formulation office, which led the formulation of new ideas for Earth Science missions at JPL, including the SMAP, SWOT, NISAR, GRACE Follow-on missions, and Earth Venture investigations proposed to NASA. Dr. Freeman served as the Capture Lead for VERITAS in Step I.



Dr. Sue Smrekar is a geophysicist with a specialty in the tectonics and geodynamics of Venus and Mars. She is especially interested in what causes planets to evolve to different convective states. A focus is on how did Venus and Earth evolve differently, as well as the lessons for understanding exoplanet evolution. She got her undergraduate degree in Geophysics/Applied Math at Brown University, and her PhD in Geophysics at Southern Methodist University. She did her postdoc at MIT before coming to JPL in 1992. Since then she has balanced research with project responsibilities, including Project Scientist for Deep Space 2, pre-project scientist for MSL, and Deputy Project Scientist for MRO. She is currently the Deputy Principal Investigator/Project Scientist for the InSight mission to Mars, which launches in March 2016. She has also been involved in heat flow instrument development, including the instrument on InSight. She is the Principal Investigator for VERITAS.

Peter Xaypraseuth is currently serving as the Lead Flight System Engineer on the NASA-ISRO SAR (NISAR) Mission and is responsible for overseeing the design of the Engineering Payload and the interfaces to the ISRO spacecraft.

Peter received a B.S. in Aerospace Engineering from California State Polytechnic University, Pomona in 2000. He has been with JPL for more than 17 years, with most of that time spent on the Mars Reconnaissance Orbiter mission, where he had various systems engineering roles throughout Development and into Operations. He has also worked on the Dawn mission as a Systems Engineer responsible for developing contingency plans and also the GRAIL mission where he served as the lead Mission Engineer. He served as the Lead Systems Engineer for VERITAS during the initial proposal effort.