MAPPING VENUS FROM ORBIT: OPPORTUNITIES AND CHALLENGES OF NEAR INFRARED EMISSIVITY MAPPING.

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Introduction: Several competing Venus mission proposals currently include spectrometers in their payload focused on the 1 µm region. These build upon the proof-of-concept by the VIRTIS instrument on Venus Express (VEX) [1-7], which was an imaging spectrometer focused on atmospheric science. VIRTIS showed that mapping of surface emissivity variability is possible from orbit. Building on this the Venus Emissivity Mapper (VEM) instrument is an instrument specifically developed for global mapping of the surface composition in all available spectral windows. Incorporating the lessons learned from VIRTIS, VEM is currently part of the proposed NASA VERITAS as well as the ESA EnVision missions. The proposed DAVINCI+ mission architecture also includes an orbital element with a multi-band imaging system intended to measure surface emissivity of few selected regions [8].

Multi-band rock type mapping: The biggest question raised by the VIRTIS observations of the surface variability was how much information is really contained in the limited number of spectral windows. A dedicated effort to set up a new Venus high temperature spectroscopy laboratory allows this question to finally be addressed [9-11].

Recent laboratory data show that while absolute emissivity would be beneficial, relative emissivity measurements are sufficient if enough of the windows are observed with high precision. Applying the updated analysis of atmospheric error for VEM parameters [12] and VERITAS' global coverage with multi-look operations and high precision global topography [13], VEM capability for relative emissivity precision is better than 1% for most surface bands [11].

The VEM concept of obtaining six surface bands allows spectral slopes between bands and band ratios to be calculated. There are 15 possible combinations of each, adding 30 different values that can be leveraged for mapping. This also allows rock types to be identified with a high level of confidence beyond the basic distinction of mafic vs granitic rock types.

VIRTIS-style hyperspectral instruments: There can be no doubt that the VIRTIS mapper produced many groundbreaking insights into relative emissivity of volcanoes and flows on Venus [1-7]. The goal of the instrument (a flight spare of the VIRTIS instrument on the ESA Rosetta mission) was to study the atmosphere of Venus. Still it proved the concept of mapping the surface from orbit. However, the processing and interpretation of VIRTIS measurements were challenging and most results are based relative variation in the most easily accessible band at 1.02 µm.

VIRTIS data were initially processed to correct for instrumental straylight from the dayside of Venus and to improve wavelength registration [14]. These corrected data were then inverted to emissivity at 1.02, 1.10, and 1.18 µm using lookup tables created by an atmospheric radiative transfer model. Emissivity was observed to vary significantly from region to region, indicating some lateral variability of atmospheric parameters, most likely near-surface atmospheric temperature. Because the trends are consistent over hundreds to thousands of km, it is possible to correct for them heuristically. However, high noise in 1.10 and 1.18 µm maps derived from VIRTIS data results in large uncertainties of spectral shape [14].

Several issues limited what could be achieved with VIRTIS. First of all, Magellan topography was used to define the surface pressure and temperature boundary conditions for the radiative transfer model. Radar altimetry data from the Magellan mission [15] had to be referenced to the VIRTIS spectral footprint. All uncertainties in the Magellan derived topography directly impact the derived emissivity maps. For VIRTIS, the wavelength assignment of the bands shifted due to slight thermal deformation of the optical system. In addition, the spectral shape and slope of the instrumental straylight was variable and had to be modeled to match the data [14].

Surface emissivity derivation requires a correction for the variable opacity of the atmosphere. The opacity of the cloud layer can be probed via thermal emission of the deep atmosphere observable in atmospheric windows, e.g. at 1.31, 1,51, 1.74 and 2.3 µm wavelength. This cannot account for all parameters of cloud microphysics and other atmospheric variables so that some uncertainty remains [16]. The effect of this unknown atmospheric variability can be significantly reduced by averaging [2, 14] or fitting many observations simultaneously with a common emissivity [16], but some error contributions are not random. In particular the large uncertainty of deep atmosphere CO_2

continuum absorption required that an arbitrary average emissivity for the entire Venus surface be assumed.

A recent reanalysis of the VIRTS data [14] highlights some of the resulting limitations. The fact that different regions require different atmospheric corrections shows that our model of the lower atmosphere [16] is incomplete, though additional infrared data would provide an opportunity to enhance our knowledge in that regard. Small emissivity variations estimated from VIRTIS data provide evidence of surface composition variation, interpreted as differences in weathering [5, 6]. The most recent VIRTIS analysis [14] shows only few significant variations of spectral shape because the 1.10 and 1.18 µm window uncertainties are large owing to the higher sensitivity to errors in the straylight and atmospheric corrections resulting from the higher atmospheric opacity. While there are indications that the radar altimetry of the tessera terrain is not fully reliable [2], there are examples like Alpha that has been shown to have a real lower emissivity signature [17].

VEM-style 14-Band Spectrometers: Incorporating all the valuable lessons learned from VIRTIS and Venus Express allows the design of an instrument concept and design that will finally facilitate obtaining a global map of the rock types of the surface of Venus. VEM's design draws heavily on DLR expertise in multi- and hyperspectral instrumentation, including the BepiColombo MERTIS instrument (launched and commissioned in 2018, with successful operations during the 2020 Venus flyby).

The Venus Emissivity Mapper [12, 18, 19] is the first flight instrument designed with a focus on mapping the surface of Venus using all atmospheric windows around 1 µm. It provides much improved instrumental straylight suppression, spectral calibration stability and signal to noise ratio over the VIRTIS-style instrument [14,16], and can systematically map the planet, especially when coupled with a high-resolution radar mapper to improve topographic resolution.

Using a multi-spectral imager concept with narrow-band filters instead of a hyperspectral design allows only the bands required to map the surface to be targeted. Band filters allow bandwidth to be optimized and maximize the Signal-to-Noise ratio for each window while providing a high wavelength accuracy. VEM would observe all five surface windows using six narrow surface band filters, ranging from 0.86 to 1.18 µm. The 1.02 µm window is wide enough to be covered with two slightly offset band filters. Coverage of the bands at 0.80 and 0.91 µm not observed by VIRTIS would provide much better constraints on surface spectral signatures. The newly available laboratory data [9-11] allow to further optimize bandwidth and bandcenter for each surface band.

As shown by VIRTIS, the main challenge in obtaining surface emissivity values is to correct for atmospheric contributions. VEM addresses this with eight additional bands providing simultaneous measurements of atmospheric water vapor abundance as well as cloud microphysics and dynamics, permitting accurate correction of atmospheric interference. Three cloud bands at 1.195, 1.310, and 1.510 µm allow correction for variability in the cloud opacity. VEM's cloud bands are close to the surface bands, providing near-optimal correction. Two bands measure near-surface water abundance improving the atmospheric correction and provide insights into potential outgassing of the surface. Finally, three background bands allow compensation for residual stray light.

VEM combines all this information in an updated version of the extensively tested pipeline developed to process VIRTIS data [2], combined with a radiative transfer model (RTM) [14,16].

Conclusions: Dedicated instruments targeted at mapping the surface of Venus in the 1 µm region will provide us new insights into the evolution, past and current state of Venus. While these observations are challenging we have now all the elements necessary to close one of the biggest knowledge gaps left for terrestrial planets. We can finally obtain a global map of surface rock types for Venus, but this requires multi-band imaging covering all available surface bands and accurate surface topography.

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