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Venus surface data extraction from VIRTIS/Venus Express measurements: Estimation of a quantitative approach

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[1] Nightside emission measurements of the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) on the Venus Express spacecraft were used to estimate the potential for surface data extraction. A selection of orbits over the northern hemisphere was performed for footprints that cover different scales of surface elevation variations. A correction method was used to remove stray light from the measured spectra that is due to direct sunlight striking the instrument. A preliminary radiative transfer calculation technique was applied to simulate Venus nightside radiation. The basic features of the measured spectra are well reproduced. Present limitations of the algorithm are discussed. The variability of the emission window radiances with respect to cloud opacity and surface elevation is modeled and discussed in direct comparison with the measurements. It is demonstrated that a multispectral analysis in the surface and deep atmosphere window ranges (1.0–2.3 μm) and the use of radiance ratios are well suited to decloud the data and to extract surface information from the VIRTIS measurements. This method allows a mapping of surface topography and the retrieval of the surface temperature. A preliminary topography retrieval at Beta Regio was performed and compared with Magellan radar data. Differences are possibly due to emissivity variations on the surface.


1. Introduction

[2] Most of Venus’s surface consists of gently rolling plains with little relief. There are several depressions and two large highlands, Ishtar Terra in the northern hemisphere and Aphrodite Terra along the equator. The Magellan radar images indicated a violent volcanic activity in the planet’s past [Saunders et al., 1992; Solomon et al., 1992]. Extended lava plains, dotted with isolated shield volcanoes and volcanic constructs dominate the geology. The deformations on Venus are not a result of Earth like plate tectonic. They are probably related to the dynamic forces within the planet’s mantle [Basilevsky and Head, 1988, 2002].

[3] Little is known about the surface material. Most of it appears to consist of basalt, but the primary material is poorly classified. The volcanic landforms are consistent with low-viscosity eruptions, which are characteristic of mafic materials like basalt [Head et al., 1992]. However, Magellanic data suggest that some high-viscosity lava formed pancake domes and festoons [McKenzie et al., 1992; Taylor, 2006], which could be related to the presence of more felsic materials like rhyolite.

[4] Recent estimates have demonstrated that there may be significant spatial variations in the surface emissivity as large as 20%, which correspond to the difference between granitic and basaltic rocks [Hashimoto and Sugita, 2003]. The chemical and mechanical erosion of the primary material is controlled by reactions of the surface with the hot and dense atmosphere. The study of the chemical composition and the physical properties of the lower atmosphere and surface of Venus are crucial for the understanding of the surface evolution and the climate of the planet.

[5] Although Venus Express primarily focuses on atmospheric science, it also supplies valuable information about the surface. VIRTIS, the Visible and Infrared Thermal Imaging Spectrometer [Drossart et al., 2007; Piccioni et al., 2007], is one of the important experiments dedicated to atmospheric and surface data extraction. VIRTIS is the first instrument operating in an orbit around Venus with the capability to systematically investigate the nightside emission of the planet in the near-infrared atmospheric windows. It performs the first detailed global exploration of the depths of the thick Venusian atmosphere. It provides for the first time clues to the emissivity of surface materials and it may provide direct evidence of active volcanism if present [Baines et al., 2006]. The feasibility of such studies was demonstrated first by Galileo/NIMS [Carlson et al., 1991].
and Cassini/VIMS [Baines et al., 2000] during the Venus flybys.

VIRTIS measurements of the thermal emission from the Venus nightside reveal a high variability of near-infrared spectra over the planet. This is mainly a consequence of spatial variations of cloud opacity and surface elevation, but differences are also due to changes in atmospheric temperature and absorber contents as well as variations of the surface emissivity. While the maximum information on surface and deep atmosphere-surface interaction is obtained from the spectral windows located between 1.00 and 1.35 μm, the windows at 1.74 and 2.3 μm provide information about atmospheric temperature and composition below the main cloud deck.

We focus our work on the extraction of surface data from VIRTIS measurements. The present approach is based on a data selection from orbits over the northern hemisphere where the footprints cover a broad range of surface elevation variations including deep valleys like Guinevere Planitia (50°N, 290°E) and high mountain regions like Ishtar Terra (70°N, 340°E) and Beta Regio (30°N, 280°E). A quantitative evaluation of the measurements requires detailed radiative transfer simulations that include appropriate spectral line databases, deep atmosphere continuum absorption features, and multiple scattering effects due to the dense cloud deck. The main intention of part I of the paper, however, is a feasibility study and an estimation of a quantitative approach to extracting surface information instead of elaborated quantitative retrievals.

2. Data Selection

The data were selected from VIRTIS-M-IR measurements over the northern hemisphere of Venus. According to Figure 1, each narrow stripe extends roughly from the equator to the North Pole. It is part of the measurements obtained during one Venus Express (VEX) orbit. One stripe consists of a series of exposures during one VEX orbit. Each exposure yields a frame of 64 spatial pixels times 432 spectral pixels. The 64 pixel wide swath corresponds to a width of roughly two degrees of longitude in the surface footprint, while the latitude remains approximately constant for any pixel in the frame. Thus, the coverage of the pixel footprints of the selected data resembles a latitudinal cross section of spectra at a fixed longitude. Because of the highly elliptical shape of the orbits, a pixel footprint on the surface is of the order of approximately 4 km in longitudinal and 1 km in latitudinal direction at 20°N, but only 0.4 km times 0.1 km at 83°N.

The required stripes were found by searching for pushbroom observations with small observation angles close to nadir. This ensures a minimal atmospheric influence on the measured signatures. In this way, the viewing geometry is approximately constant within one stripe, except for a framewise progression of the latitude of the
to elevation rises up to 5600 m at Beta Regio. It goes down to 5000 m and lowlands down to 10 km of view, although there is dark night on the planet’s surface. An examination of the most extreme examples (orbits 137 and 139) shows that the spectral characteristic changes abruptly at the terminator. The difference in radiation measured immediately before and after the eclipse is a good indicator of the amount of stray light. The correction algorithm averages the difference over all pixels of the corresponding frames to ensure a good statistical relevance. Approximately 1 min elapses between the two measurements. This corresponds to a footprint distance of just 125 km. Using the difference between the two measurements seems to be justified, because it will rarely be possible to identify real surface features at the measured wavelengths.

To simplify matters, the stripes are named for the corresponding orbit number. As a result, gaps will occur between the groups. Including the topographical variation with latitude is fairly small. These orbits cover lowlands from 10°S to 80°N and 237°E to 265°E. Stronger topographical variations with latitude occur in groups 2 and 3, respectively. Group 2 comprises orbits 110, 113, and 116. The footprints range from 5°S to 83°N and 270°E to 288°E. The surface elevation rises up to 5600 m at Beta Regio. It goes down to −1.6 km at Guinevere Planitia and it is fairly uniform in the north. Group 3 contains orbits with similar topographical variations with latitude as in group 2, but these orbits, with the numbers 146 to 154, span high mountains in high latitudes (Ishtar Terra region at an elevation of up to 6000 m) and lowlands down to −1.5 km elsewhere. They range from 10°S to 83°N and 332°E to 345°E.

Some of the selected spectra show a strong increase of radiance with decreasing wavelength in the 1–2.5 μm range; that is, the lower envelope in that spectral range is lifted as it is illustrated by the dashed line in Figure 2. A scrutiny of the viewing geometry reveals that this effect is due to direct sunlight close to, but outside the VIRTIS field of view, although there is dark night on the planet’s surface. An examination of the most extreme examples (orbits 137 and 139) shows that the spectral characteristic changes significantly over a small footprint distance and time interval. The change is correlated with the exposure point, as similar occurrences along other orbits confirm. When the Sun angle (i.e., the angle between observation direction and the instrument-to-Sun vector) decreases, the stray light initially increases, but it disappears abruptly at the point where the Sun becomes eclipsed by Venus itself from the VIRTIS point of view. This stray light effect must not be confounded with upper atmosphere scattering close to the terminator [Meadows and Crisp, 1996] and with indirect light from the illuminated crescent of Venus scattered into the VIRTIS field of view [Müller et al., 2008], respectively. It is not a surface or atmospheric feature, but is due to direct sunlight striking the VIRTIS instrument.

The orbits 137 and 139 with long (3.3 s) and short (0.36 s) exposure times, respectively, can be used to remove the stray light effect to a large extent, because it is most pronounced here and vanishes quickly upon entering eclipse.

The main NIR window positions are 1, 1.02 μm (9765 cm⁻¹); 2, 1.10 μm (9105 cm⁻¹); 3, 1.18 μm (8465 cm⁻¹); 4, 1.28 μm (7843 cm⁻¹); 5, 1.31 μm (7657 cm⁻¹); 6, 1.74 μm (5770 cm⁻¹); 7, 2.30 μm (4357 cm⁻¹).

**Figure 2.** Initial and stray light-corrected nightside spectrum of VIRTIS (orbit 149, 9°S). The main NIR window positions are 1, 1.02 μm (9765 cm⁻¹); 2, 1.10 μm (9105 cm⁻¹); 3, 1.18 μm (8465 cm⁻¹); 4, 1.28 μm (7843 cm⁻¹); 5, 1.31 μm (7657 cm⁻¹); 6, 1.74 μm (5770 cm⁻¹); 7, 2.30 μm (4357 cm⁻¹).
every orbit are confined to less than two degrees in longitude. The orbits are divided into bins of one degree in latitude. The mean over all pixels of each bin is then written as a function of latitude. This procedure is applied to the radiance values as well as to the corresponding Magellanic elevations.

[15] Figure 3 presents a set of four VIRTIS-M spectra in the wavelength range from 1.0 to 2.6 \( \mu m \) taken along orbit 151 (group 3) at different latitudes over the northern hemisphere. This orbit crossed the equatorial lowlands as well as high mountain regions at Ishtar Terra. Figure 3 shows that VIRTIS measurements of the thermal emission from the Venus nightside reveal a high variability of near-infrared spectra over the planet. The main reasons for the observed differences are spatial variations of cloud optical depth and surface elevation, but their influence can be very clearly distinguished in dependence on wavelength as will be shown below. Window signatures at 2.3 and 1.7 \( \mu m \) are sometimes very small and may even disappear. This is due to an extreme cloud thickness in these cases. Radiation changes may be also due to changes in atmospheric temperature profile and absorber contents and also due to variations in the surface emissivity, but their influence is usually much smaller.

3. Preliminary Radiative Transfer Simulations

[16] A radiative transfer model is used to simulate VIRTIS-M spectra. It allows for absorption, emission, and multiple scattering by atmospheric gaseous and particulate constituents in planetary atmospheres. The algorithm was described in detail by Haus and Titov [2000], who applied it to the atmosphere of Mars. Although Earth, Mars, and Venus differ substantially with respect to their total atmospheric thermal regime and composition, the basic method of radiative transfer simulation is the same. It can be applied to quantitative analyses even in the field of environmental and air pollution research [Haus et al., 1994, 1998]. The atmosphere of Venus above the dense cloud deck is rather similar to the conditions in the Earth’s stratosphere and mesosphere with respect to its thermal regime. Therefore, only minor modifications are required in the radiative transfer algorithm to simulate VIRTIS dayside measurements. The extreme temperature and pressure regime in the deep atmosphere of Venus, however, makes high demands on new theoretical and methodical work including hot gaseous absorption bands, far spectral line wings and pressure-induced absorption. Much effort has been devoted to explaining the effects of spectral line shape under high temperature and pressure conditions [e.g., Burch et al., 1969; Tonkov et al., 1996; Filippov and Tonkov, 1998; Ma et al., 1999; Tvorogov and Rodimova, 1995; Afanasenko and Rodin, 2005], but up to now, the related works do not offer a self-sufficient model that is suitable for practical calculations over the full spectral range that is of interest for surface and deep atmosphere studies. This is the reason why currently most simulation algorithms make use of empirically determined continuum opacities to fit the observations.

[17] Unless satisfactory models or laboratory measurements are available, the measured VIRTIS radiation spectra are used to determine the relative magnitude of continuum absorption as well as cloud absorption and scattering features from the signatures themselves. Therefore, the radiative transfer simulation that has been applied throughout this work is a preliminary one, but it will be further developed in near future. The main intention of this paper is to provide a feasibility study and an estimation of a quantitative approach to extracting surface information from VIRTIS data instead of elaborated quantitative retrievals. Nevertheless, the simulation results obtained so far look very promising as is shown below.

[18] Look up tables of quasi-monochromatic absorption cross sections \( k(\nu, \rho, T) \) of gaseous constituents in the atmosphere of Venus are calculated on the basis of a line-by-line procedure, where \( \nu \) is the wave number [\( \text{cm}^{-1} \)], \( \rho \) the atmospheric pressure [\( \text{mbar} \)], and \( T \) the temperature [K] covering the altitude range 0–140 km. Cross sections of \( \text{SO}_2 \), HF, HCl, and OCS are evaluated based on the HITRAN 2004 catalog [Rothman et al., 2005] where a Voigt profile with a line cut of 125 cm\(^{-1} \) is used. \( \text{H}_2\text{O} \) and \( \text{CO} \) cross-section calculations (line cut 125 cm\(^{-1} \)) use the HITEMP 1995 catalog [Rothman et al., 1995]. Since this
older database only contains H2O lines of the main isotope 161, the minor isotopic species were added from HITRAN04. The HDO abundance is considered to be 150 times the telluric one [deBergh et al., 1991]. The even higher abundance in the upper atmosphere [Bertaux et al., 2007] is not considered at present. HITRAN04 and HITTEMP95 were found to be inadequate for simulating near-infrared emissions from Venus nightside with respect to the main constituent, carbon dioxide. Carbon dioxide opacities were finally calculated by using line parameters from the high-temperature carbon dioxide spectroscopic databank (CDSD) compiled by Tashkun et al. [2003]. Figure 4 compares the results of a pure CO2 radiative transfer simulation in the spectral range 1.0–1.45 μm when the three different databases are used. The high number of additional week spectral lines that are contained in the CDSD database yields many additional absorption features under the high temperature and pressure conditions in the deep Venusian atmosphere. Significant changes in comparison with HITRAN04 and HITTEMP95 also occur at longer wavelengths.

[19] The diamond line in Figure 4 marks the strong influence of water vapor on the 1.10 and 1.18 μm windows and the intermediate range. It is evident that the striking 1.10 μm window feature only appears when H2O is considered in the simulation. A constant volume mixing ratio of 25 ppm from 0 to 46 km altitude was applied throughout this paper, is 26.9 at 1 μm. It is well established that the upper cloud particles (mainly H2SO4) consist of a water solution of sulphuric acid (75% H2SO4 by weight). The composition of the cloud absorption, scattering and extinction are calculated on the basis of a particle number density model that essentially corresponds to that described by Moroz [2002b].

[20] Empirical continuum absorption coefficients have been used so far in window ranges where it is needed. The continuum cross section k_c is currently determined from a Venus “reference spectrum” (compare Figure 5) when the clouds are included in the simulation procedure. The bottom line (inverted triangle) in Figure 4 shows the influence of continuum absorption on a pure gas simulation in the 1.0–1.45 μm range. With the continuum included, the simulated relative peak values and profiles of the window signatures are much closer to the observed ones.

[21] Mie scattering theory is applied to derive the microphysical parameters of the H2SO4 clouds, where a four modal log normal size distribution is used (modes 1, 2, 2', and 3 according to Pollack et al. [1993]). Optical depths of cloud absorption, scattering and extinction are calculated on the basis of a particle number density model that essentially corresponds to that described by Moroz [2002b]. The total cloud opacity of a so-called standard model, which is applied throughout this paper, is 26.9 at 1 μm. Unity total optical depth occurs near the upper limit of the main cloud deck at an altitude of 70 km. There are many open questions with respect to the chemical composition and the particle size distribution of the clouds [Moroz, 2002b; Taylor, 2006]. It is well established that the upper cloud particles (mainly mode 2 and mode 2’) consist of a water solution of sulphuric acid (75% H2SO4 by weight). The composition of the
smaller mode 1 droplets is unknown. The large mode 3 particles are probably highly variable in composition and spatial and temporal distribution.

[22] Rayleigh scattering optical depths are considered according to Hansen and Travis [1974]. The total Rayleigh optical depth at 1 μm is 1.54; that is, it is not negligible within the short-wavelength windows. Radiation multiple scattering in the dense cloudy atmosphere is considered by a successive order procedure where the source functions are calculated in a two-stream approximation of the angular-dependent radiation field [Arnold et al., 2000; Haus and Titov, 2000].

[23] The synthetic quasi-monochromatic intensity spectra at the model top level of the atmosphere (140 km) that are generated by the radiative transfer code are convolved with the VIRTIS spectral response function. A constant spectral resolution of 10 nm and a Gaussian instrumental response function have been used so far. In the wave number frame, 10 nm correspond to 100 cm⁻¹ at 10000 cm⁻¹ (1 μm), 25 cm⁻¹ at 5000 cm⁻¹ (2 μm), and 4 cm⁻¹ at 2000 cm⁻¹ (5 μm), respectively.

[24] Figure 5 compares a synthetic spectrum with the VIRTIS measurement performed at 30°N on orbit 90. The surface elevation according to Magellan topography is ~1.04 km there. This spectrum was selected as the “reference spectrum” to investigate the combined effects of cloud scattering and gas continuum absorption. The spectral range from 1 to 2.6 μm shown in Figure 5 covers the atmospheric windows located at 1.02, 1.10, 1.18, 1.28, 1.31, 1.74, and 2.3 μm. The simulation was performed for the Venus standard atmosphere [Seiff et al., 1985]. An update of these VIRA data by VIRA-2 [Moroz and Zasova, 1997] was not required for the investigations intended here, since the temperature and pressure profiles below 50 km remained unchanged. The calculations indicate that temperature changes within and above the clouds do not influence the surface and deep atmosphere signals.

[25] The preliminary quantitative simulation approach yields a more or less good fit to the observed spectrum, although there are some discrepancies (mainly at 1.7 and 2.3 μm). They are probably due to an inappropriate choice of spectral line profiles, line cut and continuum parameters. Additionally, the lower atmospheric temperature profile may be slightly different from the VIRA standard profile. Small changes can result in significant window flank shifts as corresponding calculations have shown. This will be investigated in more detail in near future.

4. Results

[26] Figure 6 illustrates the simulated radiances at the top level of the Venus atmosphere for cloud optical depths (opacities) that differ from the standard model by a factor of 0.7, 1.0, 1.4, 2.0, and 2.5, respectively. The surface
elevation is constant at a value of –1.04 km. Each window is sensitive to changes in the cloud opacity, but the contrasts increase toward longer wavelengths. Cloud contrast is most apparent within the 2.3 μm window. The aerosol single scattering albedo below 1.5 μm is very close to unity; that is, conservative scattering is the dominating cloud feature. In other words, the clouds do not contribute to thermal emission, but act as a strong attenuator of radiation that originates from below the cloud deck and emerges into space. Little spectral dependence of upwelling radiation is added by the clouds below 1.5 μm. This is the reason why it should be possible to use multispectral radiation measurements of the Venus surface and lower atmosphere in the 1.0–1.35 μm window complex to eliminate cloud interferences.

As expected, there is a dependence of radiation on cloud opacity in the windows 1–5 that leads to constant radiance ratios. There is an increasing contribution of cloud absorption with increasing wavelength. Thus, the linear dependence is lost and the radiances at 1.7 and 2.3 μm decrease much faster with growing cloud opacity. As a

Figure 6. Simulated nightside radiances spectra in dependence on cloud opacity factor. Radiances decrease with increasing factor. Factor 1 corresponds to a total cloud optical depth of 26.9 at 1 μm. The surface elevation is –1.0 km.

Figure 7. Simulated averaged window radiances as a function of cloud opacity factor. The integers in the box refer to the band number introduced in Figure 2. The surface elevation is –1.0 km.
consequence, a cloud correction algorithm, which makes use of radiance ratios, tends to fail for longer wavelengths.

Figure 8 compares measured and simulated averaged window radiance ratios as a function of the wavelength-averaged radiance that was measured at 2.3 \( \mu m \). The radiance at 2.3 \( \mu m \) is most sensitive to changes in cloud optical depth as is clearly visible in Figures 6 and 7, and also in Figure 3. It is insensitive to changes in surface elevation (compare Figures 9 and 10). Cloud opacity is not a free parameter in the measurements as it is in the simulations. It cannot be measured directly by the VIRTIS instrument. But the observed strong variability at the left-hand flank of the 2.3 \( \mu m \) window is a good indicator of cloud thickness on the Venus nightside. Thus, a scatterplot of measured radiance ratios against the measured 2.3 \( \mu m \) radiance, which decreases with increasing cloud opacity, has the same physical background as a plot of simulated ratios against the cloud opacity. This is convincingly demonstrated in Figure 8. The scatterplot is restricted to measurements from the 19 orbits shown in Figure 1, and the surface elevation according to Magellan topography is constrained to the interval \([-1500 \, m, -500 \, m]\). The restriction to a narrow elevation interval is necessary to omit strong radiation changes due to topographical changes (compare Figure 9). It is assumed that the quantitative differences between measurement plot and simulation result, which are visible in the case of 6/1 and 7/1 ratios, are due to present inaccuracies in the spectral line profiles and continuum coefficients at these wavelengths.

Figure 9. Simulated nightside radiance spectra in dependence on surface elevation for the standard cloud model (opacity factor 1.0). Radiances decrease with increasing elevation in the surface windows. The 1.74 and 2.3 \( \mu m \) windows are unaffected.
Another important conclusion can be derived from Figure 8. All the measurement points are distributed up to a maximum 2.3 μm radiance value of about 0.065 W/(m² sr μm). This value corresponds to a cloud opacity factor of 0.95 (compare Figure 7) and seems to indicate that the assumed standard cloud optical depth of 26.9 (opacity factor 1.0) is rather the lower limit of what is present in the real Venusian atmosphere. Since continuum parameters were derived based on this standard model, a possible conclusion is that not only higher cloud opacities, but also lower continuum values are closer to reality than those adopted in the present "standard case model." This will be addressed in future investigation.

The possibility to eliminate cloud signals from the VIRTIS measurements below 1.5 μm by the use of radiance ratios is of decisive importance for our future work that will mainly focus on Venus surface data extraction and the study of surface and lower atmosphere interactions.

Figures 9 and 10 illustrate the change of simulated radiances with surface elevation and wavelength. The cloud opacity was held constant in the simulations. The windows at 1.02, 1.10, and 1.18 μm exhibit a clear dependence of transmitted radiation on topographical features and, thus, on surface thermal emission. The radiance decreases considerably with increasing elevation, since high-elevation surfaces are substantially cooler and emit less thermal radiation. An elevation change of 12 km results in a surface temperature change of almost 100 K. The window at 1.28 μm still shows a minor influence of surface temperature, while it is mainly determined by features of the lower atmosphere (15–30 km). The surface elevation (temperature) does not observably influence the 1.31, 1.74, and 2.3 μm windows radiances, respectively. A simulation was performed, where the surface contribution was excluded assuming a surface emissivity value of zero. Thus, a quantitative estimate of the surface thermal emission contribution to emission within the Venus atmospheric windows was obtained. In the windows 1 (1.02 μm), 2 (1.10 μm), 3 (1.18 μm), and 4 (1.28 μm), the surface contributes 97 (95) %, 59 (60) %, 27 (40) %, and 1.3 (<2) % to the total emission. The values in parentheses are the corresponding results of Meadows and Crisp [1996].

Figure 11 compares measured and simulated averaged window radiance ratios as a function of surface elevation. Since the radiance at 1.02 μm is most sensitive against elevation changes, the ratios are not constant and, thus, a valuable measure of surface topography and surface temperature, respectively. The scatterplot contains all measurement data bins from the 19 orbits shown in Figure 1. As Figure 11 shows, these orbits pass predominantly over lowlands with an elevation between −1 km and 0 km. Another maximum occurs between 2 and 4 km (Beta Regio, Ishtar Terra). There is again a very good qualitative correlation between measurements and simulation.

Figure 10. Simulated averaged window radiances as a function of surface elevation. The integers in the box refer to the band numbers introduced in Figure 2. The cloud opacity factor is 1.0.

Figure 11. Comparison of measured (scatter points) and simulated (lines) averaged window radiance ratios as a function of surface elevation. The scatterplot of measured ratios includes all bins from the 19 orbits of groups 1–3 (compare Figure 1). The integers in the box refer to the band numbers introduced in Figure 2. Values included in parentheses denote the corresponding nominal wavelengths. The cloud opacity factor in the simulation is 1.0.
Figures 12a–12f yield additional evidence of the important finding, that emission window radiance ratios can be used to separate atmospheric and surface properties in the measured Venus spectra. It shows the radiances at 1.10, 1.18, and 2.30 μm and the radiance ratio 1.18/1.02 in comparison with surface elevation according to Magellan topography as a function of latitude for orbits (a–b) 90, (c–d) 113, and (e–f) 150. The ratios are based on measured radiances, which have been displayed and discussed before by Arnold et al. [2007].

[34] Figures 12a–12f yield additional evidence of the important finding, that emission window radiance ratios can be used to separate atmospheric and surface properties in the measured Venus spectra. It shows the radiances at 1.10, 1.18, and 2.30 μm and the radiance ratio 1.18/1.02 in comparison with surface elevation according to Magellan topography as a function of latitude for three selected orbits. Orbit 90 (Figures 12a and 12b) at 250°E is representative for group 1 measurements over predominantly low elevation areas in the northern hemisphere of Venus. Orbit 113 (Figures 12c and 12d) touched the center of Beta Regio and the deep depressions of Guinevere Planitia at 283°E, while orbit 150 (Figures 12e and 12f) passed over the highlands of Ishtar Terra at 339°E. Higher elevations should result in lower radiances of the windows 1 (1.02 μm) and 3 (1.18 μm), and vice versa. This is the case at Beta Regio, Guinevere Planitia, and Ishtar Terra in comparison to the surrounding terrains. But it is rather hard or even impossible to verify this behavior for smaller topographical variations. The window 1 and 3 measurements on orbit 90 (Figure 12a), for example, indicate higher radiances at 35°N, but this has nothing to do with an elevation decrease. The high window 7 (2.3 μm) radiance value at this location proves that much lower cloud opacity is the cause. The same holds true on this orbit at 60°N. The ratio 1.18/1.02 (Figure 12b), on the other hand, follows the elevation profile in most details. The elevation subsidiary summit at Ishtar Terra on orbit 150 at 65°N (Figure 12e) is not reflected in decreasing window 1.
and 3 radiances, since it is masked by a local cloud decrease (enhanced window 7 radiance). The ratio 1.18/1.02 (Figure 12f) shows this feature very well.

[35] The high correlation between the ratios of radiances measured in the surface windows between 1.0 and 1.35 μm and the planetary topography can be used to extract surface data of Venus. Figure 13 demonstrates this capability for some parts of orbits in the vicinity of Beta Regio including the orbits of groups 1 and 2. Figure 13a shows the topographical “target state” as it is defined by the Magellan data, which were smoothed over the swaths with respect to the 100 km resolution limit to be comparable with the VIRTIS data. Figure 13b is the “actual state” of the topography retrieval from VIRTIS data, which is obtained from a linear regression of the r3/r1 (1.18/1.02) scatterplot shown in Figure 11. The ratio r3/r1 as a function of the Magellan elevation h reads r3/r1(h) = (3.08 ± 0.01) + (0.319 ± 0.008) · h/km, with an error of twice the standard deviation. The ratio for each radiance measurement on a pixel basis is mapped to the elevation according to the linear fit of measurement data shown in Figure 11 (1.18/1.02 versus Magellan elevation) and depicted in the same color coding as the Magellan elevation. The black edging is used to stress the footprints.

[36] In general, the VIRTIS and Magellan topographies are largely in agreement with each other, but differences occur in certain small areas. These areas will be of special interest for future data analyses. The examination of differences at comparable elevations and surface temperatures may give hints either to local variations of the deep atmospheric temperature profiles and composition or to different surface materials.

[37] As discussed above, the window 1 at 1.02 μm contributes more than 95% to the total emission of the Venus nightside. Thus, any relative change in the surface emissivity corresponds to approximately the same relative radiance change. It should be possible to detect a difference of a few percent. According to Hashimoto and Sugita [2003], there may be spatial variations in the surface emissivity of Venus as large as 20%, which correspond to the difference between granitic (rhyolitic) and basaltic rocks due to a different iron oxide content in the rocks.

5. Conclusions

[38] The VIRTIS-M nightside IR data form a valuable basis for systematic and continuous surface and deep atmosphere studies of Venus. The observed high variability
of measured signatures is mainly due to spatial variations of cloud optical depth and surface elevation. The conservative character of cloud scattering below 1.5 μm, where the clouds do not contribute to thermal emission, makes it possible to use multispectral radiation measurements of the Venus surface and lower atmosphere emission in the 1.0–1.35 μm window complex to separate cloud interference and surface influences.

[39] The radiance in the left-hand flank of the 2.3 μm window does not depend on surface features and minor constituent distribution changes in the lower atmosphere. It is, therefore, a good indicator of cloud thickness on the Venus nightside and can be used for quantitative estimates. From the comparison of measured and simulated averaged radiances ratios as a function of 2.3 μm averaged radiance and, hence, of cloud opacity, it can be concluded that a cloud optical depth in the order of 27 is a lower limit with respect to the VIRTIS data that have been investigated so far.

[40] Measurements as well as radiative transfer simulations have proven a high correlation between the radiances ratios in the emission windows between 1.0 and 1.35 μm and the surface elevation. This allows a mapping of surface topography and the retrieval of surface temperature. On the basis of measured radiances at 1.18 and 1.02 μm and their ratios, the surface topography in selected regions around Beta Regio has been retrieved and compared with the Magellan data. The way the results largely agree proves that the ratio method to decloud the VIRTIS data is well suited to extract surface information. Differences have been observed in certain small areas. To the first order, the radiances ratios are a function of surface temperature. Small deviations from this first-order dependence are possibly due to surface materials that exhibit different emissivity characteristics. Müller et al. [2008] and G. L. Hashimoto et al. (Galileo near-infrared mapping spectrometer data suggests felsic highland crust on Venus, submitted to Journal of Geophysical Research, 2008) deal with observed emissivity variations.

[41] The preliminary radiative transfer simulations have demonstrated the capability of the algorithm to investigate the surface of Venus. Future studies will focus on a separation of atmospheric and surface radiances contributions in the measured VIRTIS signals and a possible separation of surface temperature and emissivity by a comparative investigation of different surface windows and their radiances ratios. Since the orbit repetition increases during the mission operation, it will be possible to distinguish between static and dynamic local variations and to gather more detailed information about the surface of Venus on a global scale.

[42] These objectives can only be achieved by further progress in the radiative transfer simulations to eliminate the masking of the Venus nightside windows by far wing and pressure-induced absorptions of the deep atmosphere constituents. A great deal of theoretical and numerical effort will be required, including taking appropriate spectral line databases and line profiles into account, as well as revised models of cloud composition.

References


Meadows, V. S., and D. Crisp (1996), Ground-based near-infrared observations of the Venus nightside: The thermal structure and water abundance