INDICATION OF A NEAR SURFACE CLOUD LAYER ON VENUS FROM REANALYSIS OF VENERA 13/14 SPECTROPHOTOMETER DATA

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ABSTRACT

Radiance measurements by an entry probe during its descent through the atmosphere allow to retrieve a vertical profile of the optical properties. The retrieval problem is in principle similar for the Venera probes, the last of which landed on Venus in 1982, and the Huygens probe, which will land on Titan in January 2005. However, for the optically very thick atmosphere of Venus, an approximation of the angular dependence of the radiance allows an analytical retrieval of the optical properties, while this is not possible for the optically less thick atmosphere of Titan. Therefore the Titan Inverse Radiation Model (Tirm) has been developed, which numerically computes the radiative transfer and estimates optical properties by assimilating measurements from the Descent Imager/Spectral Radiometer of the Huygens probe. Both methods — the analytical approximation and a modified version of Tirm— are used to estimate the extinction profile throughout Venus' atmosphere from Venera spectrophotometer measurements. We find a pronounced layer of increased extinction at an altitude of 1–2 km above the surface indicated by the data of Venera 13 as well as by the data of Venera 14. This can be interpreted as a cloud deck. It may be related to surface areas of high radar reflectivity and low radio emissivity which can be noticed at higher elevations in the Magellan Venus orbiter data. The material forming the cloud deck and accumulating onto the highlands of Venus could be small solid particles of PbS (galena) or Bi_2S_3 (bismuthite).

Key words: Venus; Venera; Titan; Huygens.

1. INTRODUCTION

If the optical properties throughout a planetary atmosphere and the boundary conditions — i.e., solar insolation at the top and surface albedo at the bottom — are known, the radiance inside the atmosphere can be modeled by radiative transfer computations (see e.g. Yanovitskij 1997). When analyzing radiance measurements from a descent probe, we have to solve the inverse problem to retrieve the optical properties of the atmosphere, cf. Fig. 1.

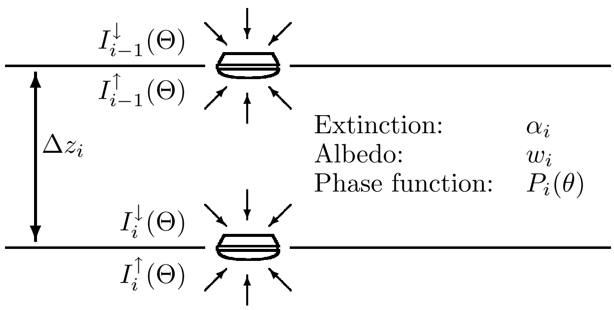

Figure 1. Retrieving the optical properties — volume extinction coefficient α_i, single scattering albedo w_i, and scattering phase function $P_i(\theta)$ — in an atmospheric layer i between two successive radiance measurements I_{i-1} and I_i taken during the descent.

In January 2005, the Huygens probe will descent through the atmosphere of Saturn's moon Titan and its Descent Imager/Spectral Radiometer (DISR) will take images and spectral measurements at various directions and wavelengths (Tomasko et al. 1997a). Titan is unique in the solar system as it is the only moon with a considerable atmosphere (Taylor & Coustenis 1998). At the surface, the pressure is 1.5 times that of Earth's atmosphere. Photolysis of the atmospheric constituents nitrogen and methane in the stratosphere leads to a complex organic chemistry. By aggregation aerosols are produced which form the orange haze layer observed by the Voyager probes (Rages et al. 1983; West et al. 1983). At visible wavelengths, the optical thickness of Titan's atmosphere is about three (McKay et al. 2001). The sun is still visible at the surface, but the total illumination is dominated by diffuse radiance concentrated in a pronounced solar aureole.

To retrieve the scattering phase function of the aerosols forming the haze layer, the Titan Inverse Radiation Model (Tirm) has been developed (Grieger

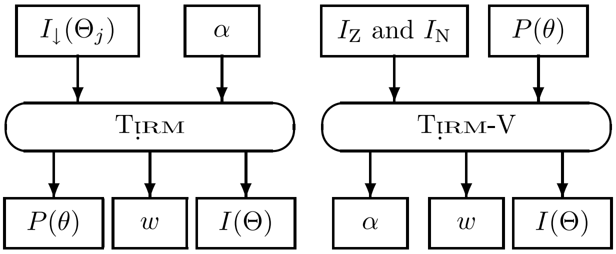

Figure 2. Illustration of the Titan Inverse Radiation Model (TIRM) and the Venera adapted version (TIRM-V). For details on input and output quantities see text.

et al. 2003a), cf. Fig. 2. It takes as input the intensity $I_\downarrow(\Theta_j)$ of the downward radiance measured by the Solar Aureole Imager (SA), a subinstrument of the DISR, at two wavelength, 500 and 935 nm. The viewing directions Θ_j at which the SA provides intensity measurements comprise two vertical stripes of 6×50 pixels each, with a field of view of 6° width in azimuth and extending from 25° to 75° in zenith angle. One such stripe is orientated towards the sun (but slightly off the sun to avoid the direct solar beam) and the other in the direction opposite to the sun (Tomasko et al. 1997a).

The volume extinction coefficient α also needed as input can be estimated from measurements by another DISR subinstrument, the Upward Looking Visible Spectrometer (ULVS). The estimation of α depends on the angular distribution of downward radiance. This is not known a priori, but as the complete radiance field $I(\Theta)$ is an output of TIRM, a consistent solution can be found by iteration (Grieger et al. 2003b). By assimilating DISR measurments in this way, TIRM estimates the vertical profiles of scattering phase function $P(\theta)$ and single scattering albedo w.

Similar to Huygens/DISR, the spectrophotometers on board of the Venera Venus entry probes took radiance measurements at different directions and wavelengths during the descent through the atmosphere (Moshkin et al. 1983). The original intension of the work presented herein was to use Venera spectrophotometer data as a test bed providing a consistency check for the application of a modified version of TIRM. However, there are some considerable differences between Titan and Huygens/DISR data on one hand and Venus and Venera spectrophotometer data on the other hand.

One difference is the angular resolution of measurements. While the SA of the DISR will provide images of the solar aureole that allow to retrieve the phase function of the scattering particles, only measurements in two directions, zenith and nadir, where available from Venera 13 and 14 spectrophotometers. The Venera radiance measurements are described in section 2.

Another difference lies in the optical thickness of the atmospheres of Titan and Venus. At the two wavelengths where the SA takes images, 500 and 935 nm, the direct solar beam penetrates the atmosphere down to the surface (Tomasko et al. 1997b) and the diffuse radiance is concentrated in a pronounced solar aureole. On the contrary, Venera 13 and 14 started their measurements at an altitude of about 60 km (Moroz 1983), where they were already entering the main cloud layer. At the onset of observations, the sun may have been visible, but soon the optical depth became very large (Moroz et al. 1980; Moroz 1981). The direct solar beam was obscured and the angular dependence of the radiance approached a quite simple pattern independent of azimuth. As a consequence, it is possible to analytically retrieve optical properties assuming the limit case of radiance measurements infinitely deep in an optically very thick atmosphere (Ekonomov et al. 1983). The results of this analytical inversion are presented in section 3.

Table 1. Properties of the Venera landing sites.

	Venera 13	Venera 14
Latitude	−7°30’	−13°15’
Longitude	305°00’	310°10’
Altitude	100 ± 200 m	−600 ± 200 m
Temperature	738 K	743 K
Pressure	89.5 atm	93.5 atm

The extinction profiles obtained in this way exhibit an intriguing layer of increased extinction close to the surface. At first, this appears spurious, because the analytical approximation rested on the assumption that maesurements are taken deep in the atmosphere, far away from the upper and the lower boundary. This assumption does not neccessarily hold close to the surface, which represents the lower boundary of the atmosphere. To verify the analytical results, the extinction profile according to Venera 14 measurements is also estimated with an adapted version of TIRM as described in section 4. This more comprehensive approach takes the surface into account and robustly reproduces the extinction feature.

Such a pronounced layer of increased extinction close to the surface of Venus has not been reported before. Possible constituents of a low cloud deck and its relation to surface areas of high radar reflectivity and low radio emissivity are discussed in section 5.

2. VENERA SPECTROPHOTOMETER DATA

On March 1 and March 5, 1982, Venera 13 and 14, respectively, reached the surface of Venus as the last, most developed probes of the Venera lander series, see Fig. 3. Locations and elevations of the landing sites are listed in Tab. 1 (cf. Moroz 1983). The landing locations are mapped onto the surface topography from Magellan radar measurements[1] in Fig. 4.

[1]The Magellan orbiter data is available from the NASA Planetary Data System, e.g. at http://pds-

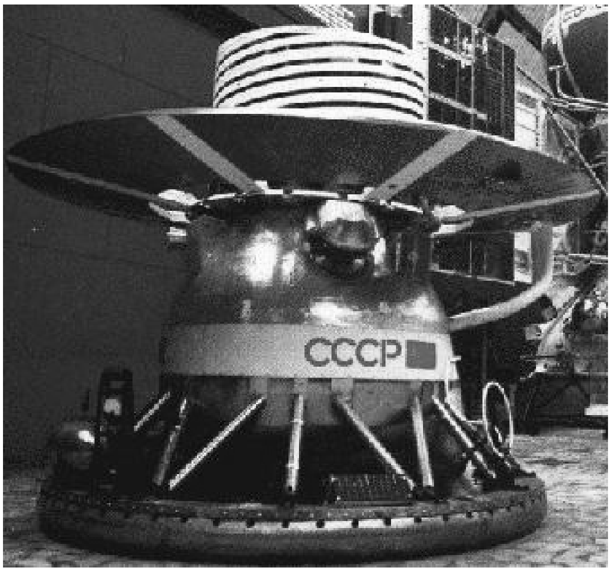

Figure 3. The Venera 13 lander. The spiral structure at the top is the antenna. The plate below it is sufficient to reasonably limit the descent speed in the dense Venusian atmosphere. No parachute was used in the last phase of the descent.

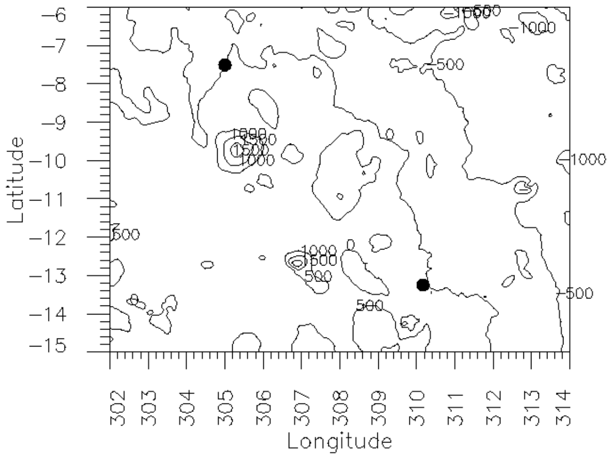

Figure 4. Venera 13 (upper left dot) and Venera 14 (lower right dot) landing sites mapped onto the Magellan topography. Both landing sites are close to the zero elevation isoline. The exact elevations are −33.1 and +47.5 m, respectively.

There is a disagreement between the landing altitudes as originally estimated and between the elevations given by the Magellan topography. However, the uncertainties of the estimated landing locations as well as the uncertainites of the estimated landing altitudes are probably quite large.

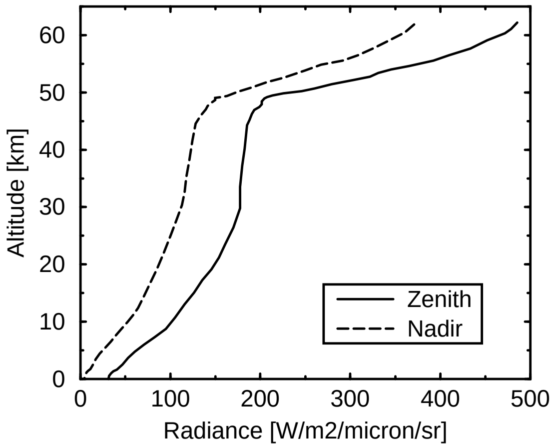

Figure 5. Verera 13 spectrophotometer radiance measurements at 700–710 nm.

During the descent of the probes through the atmosphere, the spectrophotometer measured the radiance inside the atmosphere over a wavelength range of 480–1140 nm in six different directions (Moshkin et al. 1983; Moroz 1983). The field of view of each measurement had a width of about 20°. About 3000 spectra were obtained by Venera 13 and 14. Unfortunately, new attempts to read the original data from magnetic tapes were unsuccessful, and only graphic materials are still available. The inaccessibility of the prime material is regrettable, but, fortunately, the graphic data are sufficiently representative. Graphs were digitized to form a secondary database of satisfactory accuracy (Ignatiev et al. 1997). However, from the original data for six viewing directions, only the data for two of them, i.e. one close to zenith and one close to nadir, had been digitized so far and were available for this study. The radiance measurements for one particular wavelength are shown in Figs. 5 and 6. The difference between Venera 13 and Venera 14 data in the absolute intenity values lies withing the estimated systematic error of ±40 % (Moshkin et al. 1983).

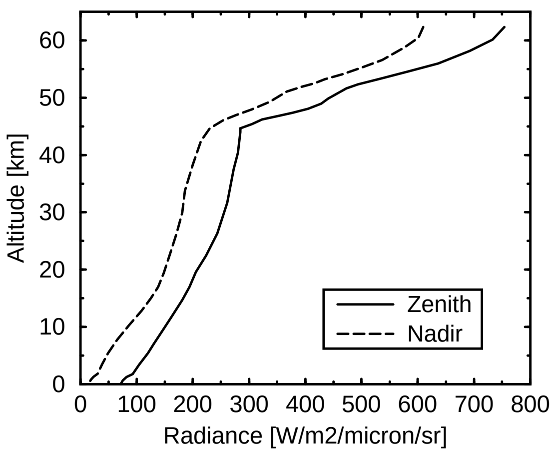

Figure 6. Verera 14 spectrophotometer radiance measurements at 700–710 nm.

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3. APPROXIMATIVE ANALYTICAL INVERSION

Deep in an optically thick atmosphere like Venus', the angular dependence of the radiance intensity approaches a simple pattern. The intensity I becomes independent of the azimuth of the viewing direction and the dependence on the zenith angle θ can be approximated by

$$I(\theta) = I_{\rm Z}\,(1 - b + b\,\cos\theta), \qquad (1)$$

with $I_{\rm Z}$ being the zenith radiance intensity and b being some constant (see Ekonomov et al. 1983, and references therein). In this case, volume extinction coefficient α, single scattering albedo w and phase function asymmetry factor g are approximately related to zenith and nadir radiances, $I_{\rm Z}$ and $I_{\rm N}$, respectively, through

$$\alpha\,(1-g) = \frac{1}{I_{\rm Z} - I_{\rm N}} \cdot \frac{\rm d}{{\rm d}z}(I_{\rm Z} + I_{\rm N}), \qquad (2)$$

$$\alpha\,(1-w) = \frac{1}{3\,(I_{\rm Z} - I_{\rm N})} \cdot \frac{\rm d}{{\rm d}z}(I_{\rm Z} - I_{\rm N}). \qquad (3)$$

These are two equations for the three unknown parameters α, w, and g, thus an additional assumption has to be made. Similar to previous work (Ekonomov et al. 1983; Moshkin et al. 1983), we assume the phase function asymmetry factor to be $g = 0.7$. Alternatively, one could think of prescribing the single scattering albedo w and calculating the extinction α from Eq. (3), but as w is very close to unity in Venus atmosphere, the result for α would depend very sensitively on w. Thus fixing g and using Eq. (2) to calculate α yields much more robust results.

Of course the phase function asymmetry factor g is not constant throughout the atmosphere. It varies with the number density and size distribution of aerosol particles. Thus we can not directly retrieve the extinction α, but rather the product $\alpha\,(1-g)$. To put some intuitive numbers at the graphs shown below, we assume $g = 0.7$.

Given a fixed phase function asymmetry factor, Venera descent probe spectrophotometer measurements of zenith and nadir radiance intensities can be used to estimate the volume extinction coefficient and the single scattering albedo through Eqs. (2, 3) from about 60 km altitude down to the surface. However, it is important to note that the resultant extinctions are uncertain within a factor $1-g$.

For the estimation of extinction coeffients according to Eq. (2), $I_{\rm Z}$ and $I_{\rm N}$ have to be sampled to the same altitude points. This type of analysis had basically been performed before, but only using a very limited number of altitude points (Ekonomov et al. 1983; Moshkin et al. 1983). Herein, we supersample the measurements with a constant vertical resolution of 100 m to make full use of the vertical resolution of the data that varies between about a hundred meters and a few kilometers. Note that this does not address the original sampling rate of the primary data during the descent, but rather the secondary database recovered from graphic materials, cf. section 2.

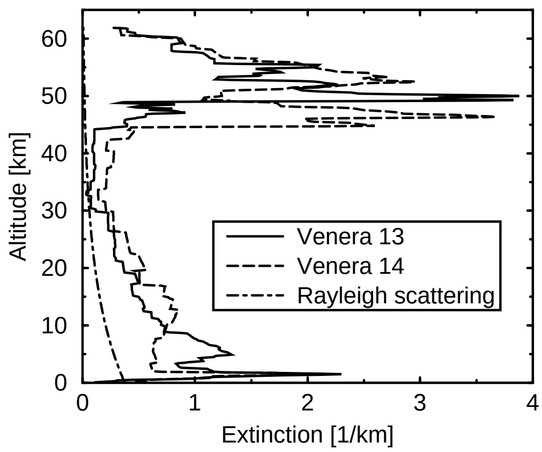

Figure 7. Extinction profiles over the complete altitude range as retrieved from Verera 13 and 14 spectrophotometer data at 700–710 nm assuming a phase function asymmetry factor $g = 0.7$. Absolute values are uncertain within a factor $1-g$.

The respective analysis of Venera 13 and 14 spectrophotometer data yields the extinction in dependence on the altitude with a higher vertical resolution than reported before. The results are presented in Fig. 7. The main cloud deck between 45 and 60 km altitude is clearly visible in the results from Venera 13 as well as Venera 14. For the later, the double stucture is more pronounced.

In Fig. 8, we present a zoom-in of the low altitude range. A pronounced peak of increased extinction 1–2 km above the surface of Venus can be noticed. The feature shows up similarly in the measurements of both Venera probes.

In fact, an annomaly in the extinction profile at 1–2 km altitude shows up over the complete wavelength range of available measurements. For Venera 14, this comprises 480–1140 nm, while for Venera 13 only data for wavelengths longer than 700 nm have been digitized appropriately so far, cf. section 2. Fig. 9 shows the optical depth between 1 and 2 km altitude above the surface as a function of wavelength. For wavelengths longer than 900 nm, negativ optical depths show up. This is due to the fact that the thermal emission from the atmosphere becomes significant at longer wavelengths, and its contribution to the measurements was neglected in the analytical approximation used for the retrieval. However, between 700 and 900 nm, the spectra from Venera 13 and Venera 14 agree quite well.

These analytical results obtained based on Eq. (2) may be questioned close to the bottom of the atmosphere. There the surface becomes visible (Moroz 2002), and the assumption that the dependence

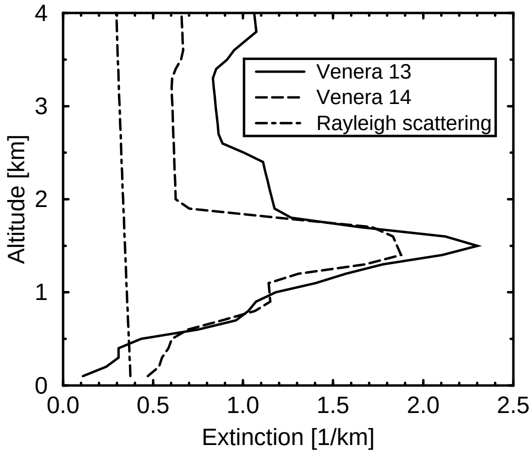

Figure 8. Like Fig. 7, but a zoom-in of the low altitude range.

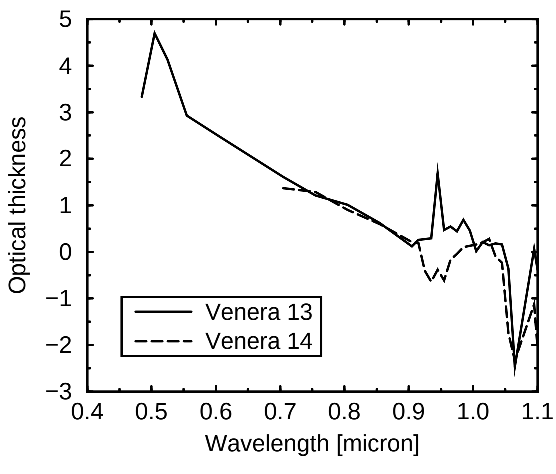

Figure 9. Retrieved optical thickness between 1 and 2 km altitude. Similar to the extinction, the absolute values are uncertian within a factor of $1 - g$, cf. Fig. 7. Negative values are spurious, for details see text.

of the radiance intensity on the zenith angle of the viewing direction can be approximated by a the cosine profile as given by Eq. (1) does not hold any more for downward looking directions. Therefore the inverse estimation of optical properties based on this assumption as supposition has to be viewed with caution at this stage.

4. RETRIEVAL OF OPTICAL PROPERTIES WITH TIRM

To check wether the extinction peak found with the analytical approximation (section 3) could be an artefact due to the neglection of the near surface, we alternatively estimate the extinction profile with a slightly modified version of the Titan Inverse Radiation Model (TIRM, Grieger et al. 2003a,b).

The original version of TIRM has been developed to retrieve the optical properties of the atmosphere of Titan from measurements by the Descent Imager/Spectral Radiometer (DISR) on board the Huygens probe, cf. section 1. The DISR will make similar observations as the Venera spectrophotometers — albeit at higher spatial and spectral resolution — during its descent through Titan's atmosphere. However, TIRM has to be adapted to the more restricted data situation for Venus. The appropriately modified Venera version TIRM-V is illustrated in Fig. 2. Besides zenith and nadir radiance intensity measurements, $I_{\rm Z}$ and $I_{\rm N}$, the scattering phase function $P(\theta)$ has to be provided. It is assumed to be a Henyey–Greenstein function with an asymmetry factor $g = 0.7$. This asymmetry factor was also assumed in section 3. The output of TIRM-V comprises vertical profiles of volume extinction coefficient α, single scattering albedo w, and the complete radiance intensity field $I(\Theta)$ in dependence on viewing direction Θ.

Within TIRM-V, the atmosphere is assumed to be plane-parallel and to consist of 620 evenly spaced layers, with constant optical properties throughout each layer. The altidude range considered is 0–62 km. Given an illumination from above and a surface albedo at the bottom of the model atmosphere, the radiance is iteratively propagated downward and upward until the algorithm converges to a consistent solution. The details of the radiative transfer computations are described by Grieger et al. (2003a).

For the Titan application, the model atmosphere reaches up to 450 km and thus represents the complete altitude range that contributes to scattering processes. As usual in planetary radiative transfer computations, TIRM is illuminated from above by a point light source. For the Venus version TIRM-V, the illumination of the model atmosphere is different. The Venera probes started their measurments already deep in the atmosphere and provided only data from about 62 km altitude down to the surface. The model atmophere of TIRM-V covers just this altitude range and thus only represents the lower part

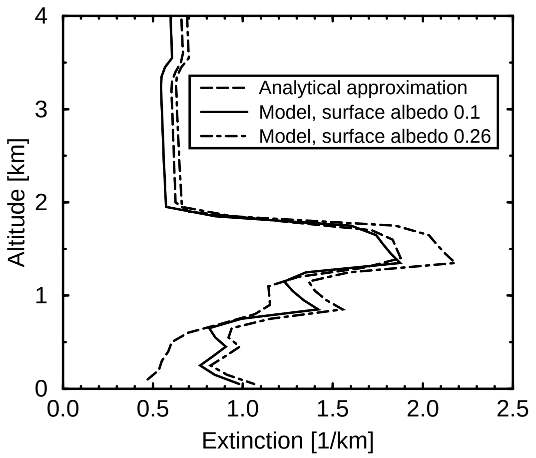

Figure 10. Extinction profiles retrieved from Verera 14 spectrophotometer data at 700-710 nm. by two methods, analytical (cf. section 3) and with a numerical radiative transfer model (cf. section 4).

of the real atmosphere, with another optically thick part on top of it. Therefore, we here only illuminate the top of the model atmosphere with diffuse downward radiation according to Eq. (1). The parameters of this cosine profile are chosen to match the first zenith and nadir measurements taken by the Venera spectrophotometers at about 62 km altitude.

While iterating downward and upward through the model atmosphere, the extinction coefficient and single scattering albedo in each layer is continuously adjusted to reproduce the observed zenith and nadir radiance intensities. As the scattering phase function is prescribed, there are two parameters in each model layer which are adjusted to match two observations at each layer boundary. Hence, a unique solution is found that almost exactly matches the radiance measurements.

Radiative transfer computations have been performed with assimilation of Venera 14 zenith and nadir spectrophotometer measurements at 700–710 nm for various assumed surface albedos. The resultant extinction profiles for two different albedos are compared to the analytical approximation in Fig. 10. The albedo of 0.1 represents the value usually assumed for Venus' surface (Moroz 1983, 2002), while with 0.26 the best fit to the nadir looking measurements close to the surface was obtained.

The extinction profiles estimated with Tirm-V differ only marginally from the analytical approximation. In particular, there is only a weak dependence on the assumed surface albedo, and the Tirm-V results clearly show the same pronounced layer of increased extinction 1–2 km above the surface. This supports the indication of a near surface cloud layer, at least it rules out that the findings of section 3 are an artefact of the neglection of the surface.

A by-product of a Tirm-V computation is the complete radiance intensity $I(\Theta)$ for every viewing direction Θ (cf. Fig. 2), i.e., the spatial pattern of sky brightness. As Venera 13 spectrophotometer measurements are available over the complete optical wavelength range, the sky radiance can be computed for any arbitrary wavelength, e.g., for the three colors red, green, and blue. Merging these three radiance intensity patterns yields real color images of the Venusian sky as seen from different altitudes[2].

5. DISCUSSION

We have used zenith and nadir radiance intensity measurements to retrieve the extinction profile throughout Venus' atmosphere. The analytical approximation (section 3) as well as numerical Tirm-V computations that consider different surface albedos (section 4) both give similar results: A layer with high extinction shows up at 1–2 km altitude. It is present at all wavelengths between 480 and 1140 nm and shows up in the data of both, Venera 13 as well as Venera 14.

An important question is wether this extinction peak observed at the same relative altitude above the surface by both Venera probes is also located at the same absolute altitude. The altitudes of the Venera 13 and 14 landing sites were estimated to differ about 700 m, cf. Tab. 1, but mapped on the Magellan topography, they appear quite similar, see Fig. 4. However, the uncertainties do not allow to rule out one of these possibilities. If we discard the altitude estimations and assume the landing locations to be exact, the extinction peak occurs at constant absolute altitude. This is what a cloud deck would look like. But if the altitude estimations are correct, the absolute altitude of the extinction peak also differs about 700 m between the two Venera landing locations.

It should be mentioned that there is some scepticism about the validity of the Venera spectrophotometer data close to the surface, especially for the downward looking directions (Moshkin et al. 1983; Moroz 2002). However, the fact that the extinction feature shows up in a very similar way for both Venera probes and that it is present over the complete wavelength range makes it difficult to explain it as an artefact due to an intrument failure. Therefore, it may be worthwhile to look for processes that could create such a near surface cloud deck as indicated by the observations.

Venus has been extensively mapped by radar, initially from Earth, and later in great detail from Venus orbit by the Magellan spacecraft. Ever since the 1970s scientists have puzzled over the peculiar high radar albedo of parts of the planet. Whereas the Venusian lowlands generally have a rather low radar

[2]Color images can not be reproduced within this volume. However, a presentation comprising such simulated color images of the Venusian sky is available online at http://www.space-vision.biz/veneratalk.html.

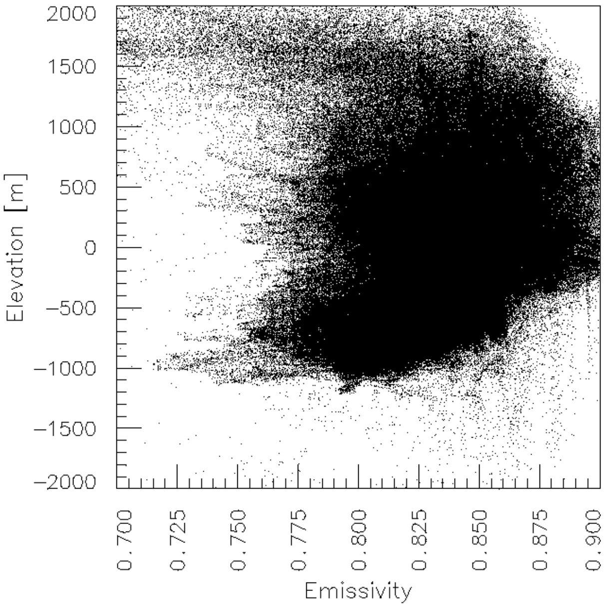

Figure 11. A scatter plot of radio emissivity versus elevation from the Magellan data tile extending from 285° to 330° in longitude and from −41° to 0° in latitude.

albedo that is compatible with e.g., dry basaltic rock, the highlands above altitudes of 2.5–4.8 km (Klose et al. 1997) usually show radar albedos as large as 0.5 or even larger (Pettengill et al. 1992b). Such albedos are comparable with that of snow in the visible, hence the name "radar snow".

The same mountainous areas exhibiting high radar albedo do also display low radiothermal emissivity, as found by Pioneer Venus and confirmed by Magellan (Ford & Pettengill 1983; Pettengill et al. 1992a). Although the Magellan reflectivity data have a far superior spatial resolution, studies of the anomalous areas have tended to focus on the emissivity data, because they are less strongly affected by surface roughness (Wood 1997). The effects of surface roughness can not be subtracted from the reflectivity data with confidence.

It is tempting to presume that there is some relation between the clouds that we may have observed between 1 and 2 km altitude and this so-called radar snow that caps the mountains of Venus. Although the radar snow usaually occurs at slightly higher altitudes, there is also some indication of it just at the altitude of the extinction feature in the Venera data. In Fig. 11, a scatter plot showing the radio emissivity versus surface elevation for the 45° × 41° Magellan data tile comprising the Venera landing sites is shown. It indicates preferentially low radar emissivities at elevations of 1500–1800 m.

Various models have been proposed to explain the radar snow, not all of them allow for any obvious relation with the deck of low clouds that we suspect. E.g., a large cover factor of decimeter sized voids in surface rocks can invoke a high radar albedo (Pettengill & Ford 1993), or a low-loss soil layer (Tryka & Muhleman 1992).

However, Magellan bistatic radar observations of the Maxwell Montes highlands (Pettengill et al. 1996) are best explained by models in which the highlands are covered by a semi-conducting layer (Brackett et al. 1995). Various studies have analyzed chemical compounds that could make up such a layer. Pyrite (FeS), and other compounds of iron, have properties that are compatible with the radar observations (Pettengill et al. 1982; Ford & Pettengill 1983), but Fegley (1997) states that any pyrite on the surface of Venus should rapidly decompose into iron-oxides and sulfur vapor. I.e., the atmospheric abundance of sulfur is too low and the atmosphere is too oxidizing for pyrite to be stable.

Other scientists suggested that the radar snow is some sort of volatile semi-metallic compound that is cold-trapped on the coolest locations of the surface, i.e., the highlands. E.g., Pettengill et al. (1996) suggested that the metallic frost might be elemental tellurium. This element would also make an interesting candidate for cloud formation. If the compound can form frosts above a given altitude, it can probably condense into clouds at slightly lower altitudes. However, Schaefer & Fegley (2003) make a strong point that elemental tellurium can not exist near the surface since the element will be trapped in compounds with sulfur.

Schaefer & Fegley (2003) explore the volatile metal chemistry on Venus from the lowest elevations (−2.6 km in Diana Chasma) to the bottom of the global main cloud layer at about 50 km altitude using chemical equilibrium calculations that include S, Pb, Bi, Te, Sb and 20 other elements. They considered about 660 compounds of the trace metals and find a few particularly interesting candidates for metallic snow: PbS (galena) and Bi_2S_3 (bismuthite). Given the proper abundances for lead or bismuth, these could accumulate in the highlands. Moreover, the compounds have the proper dielectric constants to form radar snow. Mixed compounds of bismuth and lead with sulfur may also be good candidates, but at the moment their properties are not known well enough to judge. For Earth-like abundances of bismuth and lead, Schaefer & Fegley (2003) predict that bismuthite is stable above an altitude of 1.6 km, and that galena is stable everywhere on Venus' surface. If these abundances are smaller by a factor of about 2 for bismuth, and of about 10 for lead, then both galena and bismuthite can form and survive at altitudes above 2–3 km. Schaefer & Fegley (2003) make a point that it is reasonable for Venus to have a lower content of Bi and Pb than Earth.

If either bismuthite or galena forms from trace amounts of Pb or Bi in the atmosphere, and if the compound is indeed stable on the surface of Venus in the highlands but not in the lowlands, and if it forms the radar snow, then one would expect some sort of transition region between the lower and the higher altitudes. I.e., a layer in the atmosphere where particles of this compound form and drift around until they snow out onto the highlands or until they descent into the lower atmosphere and disintegrate; i.e., a cloud layer near the altitude where the Venera probes may have observed clouds. It seems very worthwhile to model such cloud formation and to check whether such clouds, and in particular their predicted optical depth as a function of wavelength, are compatible with the Venera observations.

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