A correlated-\(k\) model of radiative transfer in the near-infrared windows of Venus

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Abstract

We present a correlated-\(k\)-based model for generating synthetic spectra in the near-infrared window regions, from 1.0 to 2.5\(\mu\)m, emitted from the deep atmosphere of Venus on the nightside. This approach is applicable for use with any near-infrared instrument, ground-based and space-borne, for analysis of the thermal emissions in this spectral range. We also approach this work with the view of using the model, in conjunction with a retrieval algorithm, to retrieve minor species from the Venus Express/VIRTIS instrument. An existing radiative-transfer model was adapted for Venusian conditions to deal with the prevailing high pressures and temperatures and other conditions. A comprehensive four-modal cloud structure model based on Pollack et al. [Near-infrared light from Venus’ nightside: a spectroscopic analysis. Icarus 1993;103:1–42], using refractive indices for a 75% H\(_2\)SO\(_4\)25% H\(_2\)O mixture from Palmer and Williams [Optical constants of sulfuric acid; application to the clouds of Venus? Appl Opt 1975;14(1):208–19], was also implemented. We then utilized a Mie scattering algorithm to account for the multiple scattering effect between cloud and haze layers that occur in the Venusian atmosphere. The correlated-\(k\)-model is shown to produce good agreement with ground-based spectra of Venus in the near infrared, and to match the output from a line-by-line radiative-transfer model to better than 10%.

Keywords: Planetary atmospheres; Venus; Near-infrared windows; Correlated-\(k\); Retrievals

1. Introduction

1.1. The near-infrared windows

The discovery in 1983 of what is now referred to as the “near-infrared windows” (NIR windows) on Venus was the result of fortuitous observation. Observers, using the Anglo-Australian Telescope (AAT), were conducting an infrared survey of the night sky, when they measured anomalously high fluxes from the nightside of Venus [1]. They had stumbled upon wavelengths in the electromagnetic spectrum where thermal radiation from the deep atmosphere is able to escape into space. These spectral “windows” are physically possible in the Venusian atmosphere because of the following three conditions: (1) cloud particles scatter...
rather than absorb incident light, (2) emissions emanate between strong CO₂ and H₂O absorption lines, and (3) the wings of the Venusian CO₂ lineshape are less absorbing than those of other lineshapes. These effects combine together to enable radiation emitted from the surface and troposphere to escape to space. These emissions are only seen on the nightside because they are much weaker than the solar flux on the dayside. The images at these NIR windows show very large contrasts, much greater than those seen at visible or UV wavelengths, mainly due to the variation of the vertically integrated amount of cloud. Here was a new way to study the lower atmosphere without the need to send expensive descent spacecraft through the atmosphere to take in-situ measurements.

The nature of these NIR windows was revealed through radiative-transfer modelling by Kamp et al. [2] using the data from Allen and Crawford [1], which, successful for the most part, replicated the spectral location and shape of the NIR windows. Since then, many ground-based and some space-based observations have been carried out. The main two NIR windows discovered by Allen and Crawford [1] are located at 1.73 and 2.3 μm. Following the success of numerical modelling [2], numerous ground-based observations occurred, which capitalized on this breakthrough. The most notable was that made by Bezard et al. [3], who measured the 1.7 and 2.3 μm windows at very high spectral resolution from data taken at the Canada France Hawaii Telescope (CFHT). At 2.30 μm, numerous absorption features are prominent and positively identified as CO₂, CO, SO₂, OCS, H₂O, HDO and HF. HCl was seen in the 1.74 μm window as well [4], using the same data taken from Ref. [3] at 2.3 μm, and measured an H₂O mixing ratio of 34 ppm and an HDO ratio of 1.3 ppm.

A few years prior, Crisp et al. [5] used images at these wavelengths to track cloud features, estimating a rotation period of 6.5 days. Further “windows” were discovered by Crisp et al. [6] at wavelengths of 1.01, 1.10, 1.18, 1.27 and 1.31 μm, with an O₂ airglow at 1.27 μm.

Further spectroscopic measurements were made by Crisp et al. [6] and Meadows and Crisp [7], retrieving mixing ratios for H₂O of 40 ± 20 and 30 ± 10 ppm, respectively, with no vertical variations seen by either authors at the heights probed. Pollack et al. [8] also provided further constraints for lower atmospheric abundances for CO, 23 ± 5 ppm at 36 km, OCS, 4.4 ± 1.0 ppm at 33 km, and SO₂, 180 ± 70 ppm, respectively. Meadows and Crisp [7] imaged the nightside disc in the surface windows, regions where the emissions originate from the surface, at 1.0, 1.10 and 1.18 μm, as well as measuring H₂O mixing ratios at these heights. Two fly-bys of Venus in 1990 and 1999, by the Galileo/NIMS [9,10] and Cassini/VIMS [11] spacecraft, respectively, gave us the only tantalising views of the NIR windows from space, unimpaired by terrestrial limitations. Unfortunately, due to the nature of observing at one instance in time, only limited information concerning the circulation of the atmosphere was gleaned. In spite of this, variations of CO in latitude could still be seen [12], as could cloud morphology and particle variations [13]. A summary of past observations using the NIR windows can be found in Refs. [14,15].

1.2. Venus Express/VIRTIS

Venus Express was launched in November of 2005 by the European Space Agency (ESA) and entered Venusian orbit in April 2006 [16]. It is a derivative of the successful Mars Express spacecraft, which entered the orbit of Mars in December 2003. On board are seven remote sensing and in-situ instruments designed primarily to observe the atmosphere of Venus. One of these instruments is the visible and infrared thermal imaging spectrometer (VIRTIS), originally designed for ESA’s Rosetta mission. The versatility and operational wavelength ranges of VIRTIS means it is well suited for the science goals around Venus and constitutes a major part of the scientific payload on the Venus Express mission. VIRTIS is divided into two sub-systems: VIRTIS-M, an imaging spectrometer at medium spectral resolution, and VIRTIS-H, a higher-resolution spectrometer, but with no imaging capacity.

VIRTIS-M is the mapping spectrometer part of VIRTIS [17,18] and scans Venus in four dimensions; two spatial dimensions: one spectral and one temporal. The two spatial dimensions occupy a 256 × 256 pixel array, with 432 spectral domains for the third dimension. VIRTIS-M has a scan mirror and views in both the visible and infrared channels. Thus, VIRTIS-M is further subdivided into VIRTIS-M VIS, which covers the spectral range from 0.25 to 1.0 μm, and VIRTIS-M IR, which covers 0.95–5.0 μm. The spectral resolving power (λ/Δλ)
for the VIRTIS-M channels is between 100 and 200. The data product from VIRTIS-M comes in the form of a spectral cube.

The other half of VIRTIS is the VIRTIS-H channel: a high-resolution echelle rating spectrometer for spectrometry. VIRTIS-H uses a cross-dispersing prism and a flat diffraction echelle grating to lay several high-resolution orders across a single focal plane array. The echelle grating separates orders from 7 to 16 into a two-dimensional array, with 1.85–2.31, 2.00–2.51, 2.18–2.78, 2.40–3.00, 2.67–3.34, 3.00–3.76, 3.43–4.29 and 4.00–5.00 μm corresponding to the eight different spectral orders. For a particular spectral order, the spectral resolution varies with wavelength. The echelle grating spectrometer has a spectral resolving power between 1000 and 2000, depending on the order.

2. The model

The radiative-transfer model is based on the model of Refs. [2,19] and has been used extensively in conjunction with a retrieval model to retrieve cloud properties and gaseous abundances from numerous datasets [20–25]. We now detail the work done in modifying the existing radiative-transfer model in order to produce synthetic spectra for the nightside NIR windows, as would be viewed from an instrument like the VIRTIS instrument on Venus Express.

Prevailing conditions in the deep atmosphere of Venus, such as the high pressures and temperatures, dictate special requirements of a radiative-transfer model, which were not present at the outset of this work. Parameters such as lineshapes, line-widths, cutoffs and absorption coefficients were all tailored for use with terrestrial spectra from the gas giants and were invalid for the task at hand. In addition to this, the retrieval algorithm used later in this work utilises a correlated-\(k\) (CK) approach. This required the creation of pretabulated look-up tables for the absorption coefficients. At the beginning of this work, it was not known whether the CK approach was sufficiently accurate to reproduce the complex NIR windows. We show that, with the required parameterisations, it is indeed possible to do so. As a result, we are able to run multiple-scattering calculations, which would take the traditional line-by-line method a much longer period to complete. This is important since the radiation from the NIR is arriving from deep in the lower atmosphere, where the infrared photons will have scattered off cloud particles multiple times.

2.1. Spectral data

Our model uses parameters from the HITRAN2K and HITEMP spectral databases. HITRAN is the high-resolution transmission spectral database, which contains physical parameters of gases required for radiative-transfer calculations of atmospheres. It contains parameters including line intensity, air and self-broadening half-widths and absorption cross-sections for 38 different gases, including their isotopes. Recent editions of HITRAN are from 1996 [26] and 2000 [27] (known as HITRAN2K). The latest edition of HITRAN, HITRAN2004 [28], has additional parameters to HITRAN2K, but are not relevant to this work. HITRAN2K is thus the spectral database used for all the gases, except CO\(_2\). In addition to CO\(_2\), our model contains seven other gases; H\(_2\)O, SO\(_2\), CO, OCS, H\(_2\)S, HCl and HF. These gases have been chosen because they provide the majority of the total absorption and emission in the infrared part of the spectrum.

The spectral data for CO\(_2\) have been taken from HITEMP, rather than HITRAN2K. Whilst HITRAN2K does contain lines from hot bands, it is most likely that they do not contain enough of these hot bands that are necessary to create accurate synthetic spectra. Indeed, this has been previously modelled by Pollack et al. [8]. Hot bands also include overtones, combinations and differences. These transitions are usually of low intensity and are therefore termed weak lines. These weak lines become very important when attempting to model the NIR window regions of Venus, where the atmosphere is very hot and optically thick and the emissions from the lower atmosphere are escaping from regions between strong CO\(_2\) band heads. HITEMP is a molecular spectroscopic database, containing line-by-line parameters for four different gases at high temperatures [29,30]. The HITEMP database is an additional spectral database that complements the HITRAN database. References and quick summaries for HITEMP can be found in Refs. [8,12,31]. The parameters have been calculated to 1000 K and are designed to include weak rotational lines and bands up to this temperature.
2.2. Atmospheric profiles

The atmospheric vertical profile is given as a function of height and/or pressure and includes the temperature at that height/pressure, as well as the volume-mixing ratio of the individual gases. The profiles extend up from 0 (surface) to 100 km. We initially used the temperature profiles of Refs. [32,33] which were used by Kamp et al. [2] and Collard et al. [12]. The a priori volume-mixing ratios of Ref. [34] were used when setting up and validating the model, which were derived from a mixture of Venera, Mariner 5, 10 and Pioneer Venus Orbiter data.

The vertical profiles of the compositions are taken directly from the existing database. The HDO/H2O ratio has been set at 0.03 in accordance with observations. This has been done by multiplying the line strengths for terrestrial H2O by 0.97 and HDO by 130. The only region where we are sensitive to the D/H ratio is in spectral interval of 2.34–2.43 μm, where HDO bands are present in the HITRAN2K database. No HDO spectral line information exists for the lower wavelength window regions.

2.3. Collisional broadening and lineshape

In our model of the Venusian atmosphere, the CO2–CO2 self-broadening half-widths have been taken directly from the HITEMP database, while the CO2–H2O foreign-broadened half-widths have been taken from Ref. [35]. In the absence of any CO2 foreign-broadening data for the trace gases, all the remaining trace gases have been air-broadened using the air-broadened half-widths supplied by HITRAN2K.

In the Venusian atmosphere, both the effects of pressure Lorentzian broadening and temperature broadening are important. In practice, both lineshapes are convolved to calculate the observed absorption by using the Voigt lineshape, parameterized in our model according to Ref. [36]. Due to the very high pressures that prevail on Venus, the lineshape for CO2 is better described by a sub-Lorentzian line profile [37]. This effect, called collisional line mixing or line coupling, has been well documented and described [7,38]. Unlike the Lorentz lineshape theory, where the colliding atoms are modelled as hard elastic spheres, collisional line mixing is caused by the rotational inelastic collisions between atoms, causing a transfer of energy between rotational bands, the result being that line intensities are transferred onto each other and the lines are coupled.

The Venusian infrared emission windows are located between strong CO2 band heads. If it were not for sub-Lorentzian absorption, much less radiation would escape through them. The sub-Lorentzian nature of the lineshape caused by collisional line mixing results in the apparent narrowing of the lineshape and is usually accounted for by applying a multiplicative z correction factor in the lineshape formulation.

In the region away from the line centre where \((v-v_0) \gg \chi_0\), the equation for the absorption for Lorentzian broadening and wings of Voigt broadening lines reduces to

\[
k(v) = \frac{S \chi_0}{\pi (v-v_0)^2}.
\]

A variety of different correction factors used by different authors have been tested. Below are their formulations

Ref. [4]:
\[
\chi = 1, \quad |v-v_0| < (\ln \chi_0/C),
\]
\[
\chi = \chi_0 \exp(-C|v-v_0|) \quad |v-v_0| \gg (\ln \chi_0/C),
\]
where C and \(\chi_0\) are constants with values of 0.028(cm\(^{-1}\))\(^{-1}\) and 3.16, respectively.

Ref. [1]:
\[
\chi = 1, \quad |v-v_0| < 3 \text{ cm}^{-1},
\]
\[
\chi = 1.35 \exp(-|\delta v|/10), \quad 3 \text{ cm}^{-1} \leq |v-v_0| \geq 10 \text{ cm}^{-1},
\]
\[
\chi = 0.614 \exp(-|\delta v|/47), \quad 10 \text{ cm}^{-1} \leq |v-v_0| \geq 120 \text{ cm}^{-1},
\]
\[ \chi = 0, \quad 120 \text{ cm}^{-1} \leq |v - v_0|. \]

Ref. [40]:
\[ \chi = 1, \quad |v - v_0| < 3 \text{ cm}^{-1}, \]
\[ \chi = 1.084 \exp(-0.027|\delta v|), \quad 3 \text{ cm}^{-1} \leq |v - v_0| \geq 150 \text{ cm}^{-1}, \]
\[ \chi = 0.208 \exp(-0.016|\delta v|), \quad 150 \text{ cm}^{-1} \leq |v - v_0| \geq 300 \text{ cm}^{-1}, \]
\[ \chi = 0.025 \exp(-0.009|\delta v|), \quad 300 \text{ cm}^{-1} \leq |v - v_0|. \]

Close to the line centre, the sub-Lorentzian lineshape takes the form of the pressure-broadened lineshape, where \( \chi \) equals unity. Away from the line centre, the \( \chi \) factor takes on an exponential decay, making the absorption due to that line fall away much quicker than the standard Lorentz shape. In our Venus model, we have opted for the correction factor by Tonkov et al. [39] because the authors set out explicitly to determine the values for the \( \chi \) correction factor in view of improving the radiative modelling of Venus. The \( \chi \) values laid out by Tonkov et al. [39] extend to 300 cm\(^{-1}\) from the line centre. However, in our calculations, the absorption coefficient is truncated at 120 cm\(^{-1}\) from the line centre. Beyond this value, no contributions by other bands are calculated. This cut-off value has been deduced from extensive experimentation. After 120 cm\(^{-1}\), there is little effect on the observed spectra.

We should also note finally that the \( \chi \) correction factor is also temperature dependent. Implemented by Kamp et al. [2] and Meadows and Crisp [7], the effect of this temperature dependency, however, is small and is not considered to improve the situation, as noted in Refs. [3,12].

2.4. \( \text{CO}_2 \) continuum absorption

Collision-induced absorption (CIA), sometimes referred to as pressure-induced or continuum absorption, results from the interaction, and deformation, of two non-polar molecules (in our case \( \text{CO}_2 \)) colliding under pressure and mainly affects the far wings of strong bands. A temporary dipole is induced by the quadrupole and higher moments as molecular symmetry is broken. This allows for normally forbidden transitions to take place. The probability of collisions between atoms dictates the line strengths of the bands and hence is a function of the square of the local number density of that gas. This interaction is very brief, making the lines broad. The combined effect of many such broad absorption lines gives rise to the “continuum” absorption.

On Venus, this additional source of opacity is significant because of the long path lengths of \( \text{CO}_2 \) that exist in the atmosphere. In addition, the partial pressure of \( \text{CO}_2 \) reached at the surface nears 100 atm, further exacerbating the effects by this continuum absorption. Because the NIR windows originate from the deep atmosphere, where both of these effects are strong, the effects of the continuum must be taken into account when modelling the NIR windows.

Laboratory measurements: A number of different experiments have been conducted to determine the contribution due to collision-induced absorption, which is in the form of \( a \), where \( a \) (in cm\(^{-1}\)/amagat\(^2\)) is a constant to be determined, and is the local number density of \( \text{CO}_2 \) (in amagats). All experiments have centred in the 2.2–2.5 \( \mu \text{m} \) region. Moore [40] and Moskalenko et al. [41] measured similar values for \( a \) of \( 2.0 \times 10^{-8} \text{ cm}^{-1}/\text{amagat}^2 \) whilst BrodBek et al. [42] give a value of \( 1.6 \times 10^{-7} \text{ cm}^{-1}/\text{amagat}^2 \), somewhat higher than the other measurements. Recently, Tonkov et al. [39] measured a value of \( 4.0 \times 10^{-8} \text{ cm}^{-1}/\text{amagat}^2 \). All laboratory measurements have been taken at room temperature and no measurements exist in the 1.73 and 1.18 \( \mu \text{m} \) regions. In general, when applied to synthetic spectra, the measurements do not give a good match with the observations of Venus, probably because the temperature dependence has not been measured and is difficult to estimate theoretically.

Model estimates of the continuum: Because of difficulties in measuring the continuum in the laboratory and a lack of understanding as to the micro-physical processes that are occurring in the Venusian environment, it has been commonplace to model \( a \) as a free variable to be fitted with observations. \( a \) takes different values in different spectral windows, but is assumed to be wavenumber independent within the window itself.
In the 2.3 μm emission window, the value of α required to replicate the correct shape of the spectral features ranges from a low value of $2.5 \times 10^{-8}$ cm$^{-1}$/amagat$^2$ derived by Pollack et al. [8], through a moderate estimate of $4 \times 10^{-8}$ cm$^{-1}$/amagat$^2$ deduced by de Bergh et al. [43] to an upper estimate of $7 \times 10^{-8}$ cm$^{-1}$/amagat$^2$ used by Bezard et al. [3]. The range of values can be attributed to the differences in the cloud models used by the authors, since increasing CIA has a similar effect as increasing the opacity of a high grey cloud layer. The effect of changing α can be seen in Fig. 1. As we increase the CIA values, the magnitude of the radiances decreases, as this adds more opacity in the height where the radiation is emitted.

In the 1.73 μm window, similar considerations apply, necessitating estimates of the continuum in order to accurately reproduce the observed spectra. Values for α range between $5.0 \times 10^{-9}$ and $8.0 \times 10^{-9}$ cm$^{-1}$/amagat$^2$ [3,8,43]. The 1.18 μm window is more of a problem since it is not flanked by strong CO$_2$ bands as are the other two windows, resulting in an absence of distinct spectral features in the emission [44]. The result is a difficulty in estimating the continuum because the opacity caused by clouds is similar to that of the continuum, but a match with observations can be made by altering the water profile in the model and the value for the CO$_2$ continuum. Values for α range between zero (no continuum) [43] and $3.0 \times 10^{-9}$ cm$^{-1}$/amagat$^2$ [44], corresponding to high and low concentrations of water vapour in the deep atmosphere, respectively.

2.5. Correlated-κ tables

Because of the long computational time required by line-by-line calculations, an alternative method is preferable in solving the radiative transfer equations. A method called the CK distribution uses pre-tabulated absorption coefficients called the $κ$-distributions as the source of information on the opacity of the gases in the

![CO2 CIA Values at 2.3 micron Window](image)

Fig. 1. Effect of different CO$_2$ CIA values on spectra at 2.3 μm, for a given cloud model. Increasing the CIA values not only decreases the total outgoing radiances, but also dampens the spectral features.
atmosphere. By doing so, the absorption coefficients are regrouped and ranked in a specific spectral interval according to their strengths. This yields a much smoother integration of the absorption coefficients, which in turn makes the calculation much quicker than the classical line-by-line method. The CK-distribution method is based on the work of Lacis and Oinas [45] and is also described in depth in Refs. [46,47].

We computed CK tables for all gases in wavelength space at a spectral resolution of 1 nm (0.001 μm) corresponding to the spectral resolution of VIRTIS-H, in the spectral intervals of 0.95–1.35 μm (covering the surface), 1.69–1.79 μm (covering the 1.74 μm emission window) and 2.15–2.55 μm (covering the 2.3 μm emission window). The k-tables covering all gases, CO₂, H₂O, CO, SO₂, HCl, HF, H₂S and OCS, have been pretabulated. The k-distribution was calculated on a grid of 20 pressure points, equally spaced in log space, and 20 temperatures points, equally spaced in linear space. The pressure points ranged from e⁻¹⁷ to e⁵ bar, corresponding to 4 × 10⁻⁸ bar (height 120 km) and 148 bar (since e⁴ would have been insufficient for the surface pressure), respectively. The temperature values range from 150 K (found at an altitude of 120 km) to the maximum expected surface temperature of 760 K. Further sets of k-tables were computed at VIRTIS-M’s spectral resolution of 0.01 μm, for the same species and at the same pressure and temperature settings given above. For use with other IR instruments, a re-calculation of the k-tables at the spectral resolution of the instrument would be the only thing required.

2.6. Clouds

Upwelling radiation from the deep atmosphere is greatly attenuated by interaction with clouds and is highly variable. Data from past missions show there is a massive cloud layer extending from a height of approximately 48 up to over 65 km. The cloud layer is flanked above and below by haze layers and the particle composition is principally a mixture of sulphuric acid (H₂SO₄) and water [48]. It is understood there are at least four sizes, or modes, of particles prevalent in the atmosphere [49]. Mode 1 is the smallest of the particulates, with an average radius of 0.3 μm, found mostly in the upper cloud deck, while some are still found in the middle and lower cloud layers. Mode 2 is also present in the upper cloud layer and it is this particle mode that is responsible for the majority of the optical opacity with a size of 1 μm radius. Slightly larger than mode 2, the mode 2’ class prevails in the lower and middle cloud layers. Finally, mode 3, the largest of the particles, with a radius of 3.5 μm, co-exists with mode 2’ in the lower and middle cloud decks.

The cloud and haze in the Venusian atmosphere is modelled as a mixture of 75% H₂SO₄ and 25% water (H₂O) for all cloud modes. This mixture was used by Pollack et al. [8] and Marcq et al. [50] in their model of the NIR windows, and is justified in Refs. [51–54]. The refractive indices of this mixture are given in Ref. [55]. Values for n and k, the real and imaginary parts of the refractive indices, respectively, are obtained in the visible and infrared wavelengths using transmission and reflection measurements of H₂SO₄ solutions of varying concentrations at a temperature of 300 K. These values are read into the model as a look-up table when calculating the single scattering albedo, extinction cross-section and the phase function at the associated wavelengths. In calculating the aforementioned single scattering albedo and the extinction cross-section, it is necessary to define the size distribution of the H₂SO₄ particles.

Initial tests used a cloud model comprised of four modes according to Ref. [8], with their associated extinction cross-section and single scattering albedo. They each have their own fractional scale heights (that is its distribution as a function of height), as well as their respective cloud top heights and cloud bottom heights. Since the number of unknown variables mentioned above are large, the problem is completely under-constrained. Thus, it is possible to fit the measured spectra to within error with a multitude of different cloud models. This also assumes the cloud layer consists entirely of a mixture of H₂SO₄ (75%) and H₂O (25%). However, descent probe data indicate there are more acidic mixtures of H₂SO₄ and H₂O, up to little or no H₂O component in the mixtures, but we have only used the above concentration of the H₂SO₄/H₂O mixture in our model.

The effect of increases in the optical depth of the intervening cloud layer is largely to act as a grey absorber. This has been widely investigated [3,7,8]. Over a narrow spectral interval, such as that of an individual NIR emission window, the effects of the various cloud modes and their properties on the emitted radiances are nearly wavelength independent, since the scattering albedo of H₂SO₄ particles in this spectral region and intervals are almost constant [51]. Therefore, when comparing the forward model results with observations, it
is satisfactory to note only the spectral positions of the peaks and the shape of the emission windows and not their absolute intensities. However, over a larger spectral range, between 1.72 and 2.50 µm for instance, the attenuation of radiation by the mode particles will become non-grey. This property has been used extensively to investigate the spatial distributions of cloud particles in the Venus atmosphere, most notably by Carlson et al. [13]. Therefore, we include the full four-modal cloud model since it not only is more complete and rigorous, but also provides the fundamental basis for future investigations concerning cloud distribution and variability from the Venus Express/VIRTIS dataset.

Whilst the wavelength-independent effect of the cloud layer on spectra has been well investigated and documented, the effect of scattering in the atmosphere, both from the cloud layer and from gaseous opacity, on the weighting function merits further discussion. Fig. 3 shows the change in the weighting function at 2.30 µm. We see that the “pure” weighting function from gaseous opacity places the maximum of the weighting function at approximately 14 km. Once we include the CO₂ CIA opacity of $3.5 \times 10^{-8} \text{cm}^{-1} / \text{amagat}^2$, the standard in our model, this weighting function increases in height by another 10 km to peak at 25 km. We then include the effects of scattering from the cloud layer, prescribed by the [8] profiles, and the gaseous opacity. The scattering atmosphere is calculated at 10 discrete zenith angles (5 upwards and 5 downwards). The effect of this scattering does not change the height of the weighting function, as one would expect if the cloud layer is much higher than the peak of the weighting function. However, the inclusion of multiple-scattering calculations on thermal emissions will be important when viewing from high emission angles, as well as combined multiple emission window studies.

![Graph](image-url)

**Fig. 2.** (Top) The forward model spectrum, using the LBL (red) and CK (blue) methods, for the 1.0 µm emission windows centred on 1.10, 1.18, 1.27 and 1.31 µm. This spectrum is run at 5 cm⁻¹ resolution. The weighting functions for these micro-windows can be seen in Fig. 4 in the left panel. (Bottom) The same spectral region taken from Pollack et al. [8].

![Graph](image-url)

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3. Results

We now present our current best estimates on the emissions seen with observations from 1.05 to 2.5 μm. Telescopic observations at 1.73 and 2.3 μm provided by Bezard et al. [3] formed the basis for comparison. The data were taken on 30 June 1991 using the CFHT on Mauna Kea, Hawaii. An apodised resolution of 0.14 cm\(^{-1}\) was achieved, with a field of view of 5 arcseconds diameter. The Venus diameter is 29 arcseconds and the location was 15°S latitude. The reference spectra from 1.10–1.31 μm have been taken from Ref. [56].

In the wavelength range of 1.05–1.4 μm, a number of micro-windows can be seen in Fig. 2. They occupy narrow wavelength ranges and are centred at 1.10, 1.18, 1.27 and 1.31 μm. The value of the absorption coefficient \(\sigma\) due to CO\(_2\) collision-induced absorption used here is \(1.5 \times 10^{-9}\) cm\(^{-1}\)/amagat\(^2\) [8] for all windows. This figure shows the synthetic spectra produced from the line-by-line calculation and the CK calculation, as well as the measured spectra and the residuals between the different model calculations. Both forward models agree to good approximation with each other. The residuals between the LBL and CK method at these window regions are much less than 10%, with a maximum difference in radiances of \(2 \times 10^{-5}\) W/cm\(^2\)/sr/μm at the 1.18 μm window (Fig. 2).

The weighting functions for these micro-windows are shown in Fig. 4. These show the radiation in this region to originate from the surface and the very low atmosphere, confirming what has already been established in prior literature [6]. At 1.01, 1.10 and 1.18 μm, the radiation originates mostly from the surface, whilst the 1.27 and 1.31 μm regions probe between 10 and 30 km and surface to 25 km, respectively.

The 1.74 μm emission originates from between 15 and 30 km in the atmosphere (Figs. 4 and 7). As can be seen from Fig. 5, the model match is in reasonable agreement with observations. This calculation (top of Fig. 5) is at a resolution of 0.15 cm\(^{-1}\), which should be comparable with the resolution of the observations taken by Bezard et al. [3] in 1991 with the CFHT. The current value for the absorption coefficient for CO\(_2\) in this window is set at \(6.0 \times 10^{-9}\) cm\(^{-1}\)/amagat\(^2\), a value used by de Berah et al. [43]. The residuals are again very small, with less than 10% difference between the LBL and CK synthetic spectra. The maximum intensity difference is \(1 \times 10^{-4}\) W/cm\(^2\)/sr/μm at 1.74 μm.

The 2.3 μm window region is important because it provides information of concentrations in trace gases that cannot be probed in the other spectral regions. Variations in concentrations of SO\(_2\), OCS, CO and HF are all
Fig. 4. (Left) Weighting functions for the 1.0–1.31 μm emissions, (centre) the weighting functions for the 1.73 μm emission window and (right) the weighting functions for the 2.3 μm emission windows are plotted here. The horizontal lines at 45 and 70 km indicate the bottom and top of the cloud decks, while the dotted weighting functions indicate the weights for the edges of the emission windows, where minimal emissions escape to space.
uniquely sampled in this 25–40 km height range. The importance of this region cannot be overstated, as this is also the sole region to probe in the height range just below the base of the overlying cloud deck at 45 km. From 2.20 to 2.32 μm, the shape of the peaks is the product of flanking CO₂ bands, shortwards of 2.20 μm. The emissions fall off beyond 2.50 μm, due to wings of the strong CO₂ band at 2.6 μm. As mentioned in previous sections, there is a need for the parameterization of the collision-induced absorption due to CO₂, and this is no different in this window. The value of the absorption coefficient used here for these calculations is set at $3.5 \times 10^{-8} \text{ cm}^2 \text{ molecule}^{-1} \text{ amagat}^2$ as used by Bezard et al. [3]. Fig. 6 shows our simulated spectra for this region using the LBL and CK method (top), plotted above real, high-resolution spectra (middle) and the residuals of the models (bottom). The weighting functions for this spectral region are given in Fig. 4 (right panel). Again, the differences between the two methods are small, with 2.5% difference at the CO₂ bands between 2.2 and 2.3 μm, and maximum of 10% difference for the remaining region.

3.1. Sensitivities

3.1.1. Minor species

We now define a Jacobian, which can also be known as the functional derivative or the sensitivity kernel, to be the rate of change of radiance with the rate of change of a variable, given by $\frac{dy}{dx},_{\text{far}}$, where $y$ is the
measured radiance, $x$ the given state vector and $x_a$ is the a priori state vector. The state vector contains the variables we are retrieving, which for these cases are the vertical profiles of gas abundances. Figs. 7 and 8 show the Jacobians for these emission windows.

There are few spectral lines from trace gases in the spectral region between 1.10 and 1.31 $\mu$m. Tests have shown, however, that a degree of sensitivity to H$_2$O can be achieved [8]. This is evident from Fig. 7. The greatest signal comes from the 1.18 $\mu$m window. This window provides the best chance of retrieving H$_2$O from the very lowest altitudes, from the surface to a height of 10 bar pressure. A certain sensitivity to water can also be gleaned from the 1.10 $\mu$m window.

We can see the sensitivity of the 1.74 $\mu$m window to H$_2$O and HCl from Fig. 7. Whilst this is the only region in the NIR where HCl can be probed, it is understood that HCl is homogeneous in the lower atmosphere and is not expected to vary significantly [57,58]. It also provides information on the concentration of H$_2$O, and although all of the NIR windows probe H$_2$O, this window is not sensitive to multiple species like the 2.3 $\mu$m window. This makes determination of the amount of H$_2$O prevalent in this height range an easier proposition. This window also provides us a better opportunity to constrain the water gradient as a function of height, as the weighting functions, i.e., in a region between those probed by the 1.18 and 2.3 $\mu$m windows.

From Fig. 8, we see the functional derivatives for CO, H$_2$O, OCS, HF and SO$_2$ at the 2.30 $\mu$m window. It is clear from these plots that the spectral signatures overlap. To examine their effects on the spectra, we have
performed a number of sensitivity studies. Fig. 9 shows the results of a simple test of the sensitivity of the 2.3 \( \mu \)m window to changes in concentrations of the two most active gases in this region. In the top plot, changes in the concentrations of CO and H\(_2\)O result in the change of the shape of the \textit{a priori} spectrum. The \textit{a priori} concentrations of CO and H\(_2\)O are derived from Refs. [34,59], which stand at 20 and 100 ppm, respectively, from the surface to a height of 35 km. These values are used to derive the nominal case calculation. The CO concentration is then doubled to 40 ppm, and H\(_2\)O concentrations are set to 200 ppm. The bottom plot shows the percentage change in radiance due to the changes in concentrations. The CO sensitivity is within the spectral range of 2.30–2.43 \( \mu \)m, as noted in Refs.[3,8]. The H\(_2\)O sensitivity also lies in the same spectral region. The impact on the spectrum by changes in OCS and SO\(_2\) concentrations can also be seen in the same figure.

3.1.2. Temperature

A more subtle impact on the 2.3 \( \mu \)m radiances than cloud modal variability is the effect of changes in the temperature structure as a function of latitude. We know that as one approaches the poles, the stratospheric temperature structure changes, as revealed by the Pioneer Venus Orbiter (PVO) in particular [32,60,61], and is
different from the mid-latitude and equatorial temperature profiles. From data taken by PVO and Seiff et al. [60], were able to reconstruct the temperature structure from 30 to 100 km at various latitudes. The left panel of Fig. 10 shows these model temperatures at latitudes 30°, 45°, 60°, 75° and 80°. Even at 35 km, there is a few Kelvin difference between the temperature at latitudes 30° and those at higher latitudes. These temperature profiles have been used to create synthetic spectra, shown in the top right panel. As one increases in altitude, between 40 and 60 km, the temperature cools, which causes a decrease in the CO₂ opacity at these heights. Since we are probing at 35 km, below the heights where this temperature change is taking place, it results in an apparent increase in radiances from 2.18 to 2.40 μm. A shift of 20 K at the 40 km region would change the output intensity by 20% in this spectral region. This effect would be overcompensated by the retrieved cloud opacity imposed on the spectra. However, from 2.40 to 2.45 μm, the weighting function shifts upwards, causing the decrease in the temperature structure to reduce the outgoing radiances. The ratio of polar spectra to that of the 30° spectrum is shown in the bottom right panel. It indicates that the most sensitive regions to a change in temperature structure are in the wings of the 2.3 μm window. This would primarily affect the retrieval of SO₂ values, and, to some degree, the OCS values. In the future, up-to-date temperature profiles, particularly for the Polar Regions, should be used when fitting spectra from these latitudes.

Fig. 8. The Jacobians, plotted against pressure level and wavelength, for the 2.30 μm window, showing its sensitivity to a change in temperature, CO, H₂O, HF, OCS and SO₂. These results are plotted using VIRTIS-H spectral resolution of 1 nm. These plots include the effects of CIA.
4. Conclusion

The central aim of this work was to show, using specific parametrizations tailored for Venusian conditions, that the correlated-$k$ (CK) approach to modelling synthetic spectra is capable of generating accurate spectra from the nightside troposphere. This was also done with a view to retrieving minor species from the Venus Express spacecraft using the VIRTIS instrument.

A generic radiative-transfer model, currently used to study Jupiter, Saturn and Titan, with data from the Galileo and Cassini spacecrafts was adapted for the study of the Venus atmosphere by Venus Express/VIRTIS. Spectral lines from the HITEMP database were used for CO$_2$ absorption, whilst HITRAN2K formed the basis for the remaining gaseous species. Spectral parameterisations used to accurately model the high pressures and temperatures from the deep nightside troposphere include sub-Lorentzian lineshape according to Ref. [39], CO$_2$–CO$_2$ self-broadening half-widths from the HITEMP database and CO$_2$–H$_2$O self-broadening half-widths were taken from Ref. [35]. The $k$-distribution was tabulated under these conditions, at VIRTIS-M and VIRTIS-H spectral resolutions of 10 and 1 nm, respectively, for use in the CK distribution model. The model can easily be adapted for use with other instruments by changing the resolution of the aforementioned $k$-tables. CO$_2$ collision-induced absorption correction factors were applied, following the formulation in Ref. [3]. A comprehensive, four-modal cloud structure by Grinspoon et al. [62], using look-up tables with refractive indices for a 75% H$_2$SO$_4$25% H$_2$O mixture from Ref. [55], was also implemented. The forward model accurately modelled all the nightside near-infrared windows at 1.10, 1.18, 1.27, 1.31, 1.73 and...
2.3 μm, with differences between the line-by-line and CK model synthetic radiances of approximately 5%. This enables us to use this model, in conjunction with a retrieval model, to interpret and analyse the large amounts of Venus Express/VIRTIS data, which, otherwise, would take significantly longer. Investigations into the effects of changes in the temperature profile also suggest that the wings of the 2.3 μm window are sensitive to a change in temperature above a 38 km altitude.

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References


