

Search for spatial variations of the H₂O abundance in the lower atmosphere of Venus from NIMS–*Galileo*

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Abstract. The spectroscopic data of the Near-Infrared Mapping Spectrometer (NIMS), recorded during the *Galileo* flyby of Venus, are analysed to retrieve the water vapour abundance variations in the lower atmosphere of Venus at night. The 1.18 μm spectral window, which probes altitude levels below 20 km, is used for this purpose. Constraints on the CO₂ continuum and far-wing opacity from existing ground-based high-resolution observations are included in the modelling of the NIMS spectra. The NIMS measurements can be fitted with a water vapour mixing ratio of 30 ± 15 ppm, in agreement with analyses of ground-based nightside observations. The water vapour abundance shows no horizontal variations exceeding 20% over a wide latitude range (40°S, 50°N) on the nightside of Venus. Within the same selection of NIMS spectra, a large enhancement in the O₂ fluorescence emission at 1.27 μm is observed at a latitude of 40°S, over a spatial area about 100 km wide.

Introduction

The determination of the H₂O abundance in the atmosphere of Venus, both above and below the clouds, has led to many controversial results over the past decades. As reviewed by Von Zahn *et al.* (1983), considerable variability in the H₂O abundance above the clouds has been reported from airborne high-resolution spectrometric measurements, with mixing ratios ranging from 0 to 30 ppm. This variability was interpreted by Barker (1975) as due to the possible presence of local wet spots on the

planet. An analysis of the *Pioneer* Venus infrared radiometer data (Schofield *et al.*, 1982), also probing the cloud tops, confirmed the presence of a wet region in the mid-afternoon sector, probably generated by the action of solar radiation on the hydrated sulphuric acid droplets, while the H₂O abundance on the dark side was below the detection limit (6 ppm).

The abundance of water vapour below the clouds is more difficult to investigate by remote-sensing techniques, because, at most thermal wavelengths, radiation originates from the cloud region or above. *In situ* measurements obtained from the *Venera* 11/12 and *Pioneer* Venus (PV) spacecraft led to conflicting results, with water mixing ratios ranging from 20 to 5000 ppm (Von Zahn *et al.*, 1983; Fegley and Treiman, 1992). They also suggested a marked decrease in the H₂O abundance from the 40 km level (i.e. just below the clouds) down to the surface. Little information is presently known about possible spatial variations of H₂O in the lower atmosphere. Such an analysis is clearly important to constrain radiative equilibrium and thermochemical models of Venus's atmosphere.

Allen and Crawford (1984) discovered that thermal emission, coming from the lower atmosphere of Venus, was detectable from the nightside of Venus at specific near-infrared wavelengths, located between the strong CO₂ and water vapour absorption bands. These atmospheric windows (centred at 1.10, 1.18, 1.27, 1.74 and 2.3 μm) can thus be used to retrieve information about the atmospheric composition below the clouds (Kamp *et al.*, 1988; Kamp and Taylor, 1990). Near-infrared ground-based spectroscopy of the nightside at high resolution (up to 40,000) (Bézard *et al.*, 1990, 1993; de Bergh *et al.*, 1991, 1993) and at lower resolution ($R = 450$ –1800; Crisp *et al.*, 1991a; Pollack *et al.*, 1993) have provided information about the mixing ratios of several minor constituents of the lower atmosphere (H₂O, CO, OCS, SO₂, HF, HCl).

Imaging Venus's night side in narrow-band filters within the 2.3 μm window, Crisp *et al.* (1991b) concluded that no H₂O horizontal variations in excess of 10% existed in the 30–45 km region at the time of their observations. We note however that, analysing 2.3 μm spectra recorded over a "cold" and a "hot" region, Bell *et al.* (1991) concluded that the water concentration below 55 km in the "hot" region (thus having reduced cloudiness) was enhanced by a factor of ~ 5 relative to the "cold" spot. They suggested that this water enrichment could be linked to local evaporation of H₂SO₄ particles. Further spatially resolved measurements are clearly needed to confirm the existence of such large horizontal variations of water at these levels.

The *Galileo* flyby of Venus in February 1990 provided another opportunity to investigate the composition of the deep atmosphere of Venus, with the advantage of high spatial resolution (≈ 25 km), using the Near-Infrared Mapping Spectrometer (NIMS). The observation of the dark side of Venus with the *Galileo*–NIMS experiment has been described in Carlson *et al.* (1991) where the preliminary results of the Venus encounter have been detailed. In particular, mean abundances of H₂O at two different depths were derived from the analysis of the 1.7 and 2.3 μm spectral windows.

The present paper is devoted to a study of the water abundance on the nightside and a search for its possible spatial variations from the analysis of the NIMS spectra, using the 1.18 μm window. The next section describes the NIMS observations and data selection. Then, the atmospheric model and the radiative transfer calculations are described. Results are presented in the following section. Our conclusions are summarized in the last section.

NIMS observations and data selection

A complete description of the NIMS instrument can be found in Carlson *et al.* (1992). NIMS is an imaging spectrometer which covers the 0.7–5.2 μm spectral range with a spectral resolution of 0.013 μm below 1 μm and 0.026 μm above. The pixel size is 0.5 mrad, which corresponds to a spatial resolution of 25–50 km on the Venus disc. The set of Venus observations recorded by NIMS is described in Carlson *et al.* (1991). Two different types of observations were performed: multispectral partial disc images recorded at 17 different wavelengths (VPDIN-1 and VPDIN-2, where VPDIN stands for Venus Partial Disk Imaging Nightside), and complete spectra at maximum spectral resolution, recorded at specified locations, over small rectangular areas of 20 consecutive pixels (VJBARS, for "Venus Jail Bars").

The VJBARS sequence was used for the spectroscopic analysis of H₂O. The distribution of the VJBARS spectra over the Venus disc is shown in Fig. 1. This global sequence includes 24 subsets whose characteristics are listed in Table 1.

The 1.18 μm window has been selected for the H₂O analysis because, like the 1.10 μm window, it is strongly affected by H₂O opacity: in addition, radiative transfer calculations show that, in this window, thermal emission mostly originates from the 5–20 km altitude range, therefore allowing a measurement of the H₂O mole fraction

likely to be representative of the bulk atmospheric water vapour content of Venus's atmosphere. In comparison, the 1.7 μm window sounds the atmosphere in the 20 km region, while at 2.3 μm , the 30–40 km altitude range is probed. The 1.10 μm region could not be used because of the very low signal-to-noise ratio of the NIMS data at this wavelength.

In order to increase the signal-to-noise ratio of the NIMS data at 1.18 μm , a spatial average over the 20 spectra of each VJBARS set has been performed. In individual spectra, the instrument noise is lower than 1 DN (data number), and the digitalization noise is the main limitation. Nevertheless, the natural variability of the spectra within each area (mainly due to cloud opacity) is found to be larger than 0.5 DN, ensuring a reduction of noise by averaging.

As a second step, a continuum had to be subtracted from each spectrum. The magnitude of the continuum can be estimated from Fig. 2, which shows a typical averaged VJBARS spectrum, before and after continuum subtraction. Radiative transfer calculations show that thermal emission from Venus is essentially zero (even at the low spectral resolution of NIMS) in certain spectral regions located between the transparency windows, due to the strong atmospheric absorption by H₂O and CO₂. However, the observed raw spectra show a residual flux at these wavelengths, e.g. near 1.05, 1.23 and from 1.35 to 1.65 μm . This continuum originates (1) from a small amount of scattered light from the dayside of Venus, and (2) from a residual instrumental background. It was removed by constraining the Venus thermal flux to be zero at 1.04 and 1.23 μm , and by interpolating linearly the continuum between these two wavelengths. The effect of the correction is shown in Fig. 2.

A third correction had to be applied with regard to the wavelength scale. An independent spectral calibration has been made by comparing the NIMS data to the ground-based spectra in Crisp *et al.* (1991a), Bézard *et al.* (1990) and de Bergh *et al.* (1993) downgraded to a 0.026 μm resolution. This comparison clearly showed that a uniform wavelength shift of +0.006 μm compared with the original calibration had to be applied to the NIMS data. This slight correction, not taken into account in previous calculations (Carlson *et al.*, 1991), has been included in the present study.

The 1.18 μm window is bounded by H₂O absorption at short wavelengths, and CO₂ absorption on the long-wavelength side. The transparency at the peak of the window is high enough to let some radiation from the surface escape the Venus atmosphere. Maps at 1.18 μm obtained with NIMS (Carlson *et al.*, 1991) show a correlation between brightness and cloud opacity, as observed at 1.7 and 2.3 μm . The contrasts are nevertheless lower than at 2.3 μm , as shown in the correlation diagram of Fig. 3, which plots the flux at 1.18 μm vs the flux at 2.3 μm , and also in Table 1 by comparing the radiance variations in the three windows. The lower contrast at 1.18 μm is due to the lower absorption of H₂SO₄ droplets at such short wavelengths. Cloud particles then behave as pure scatterers, so that the attenuation from the cloud system roughly scales as $1/\tau$. There is also a correlation of the 1.18 μm flux with the altitude of the surface (Carlson *et*

AREAL COVERAGE 24 - 26 km RESOLUTION

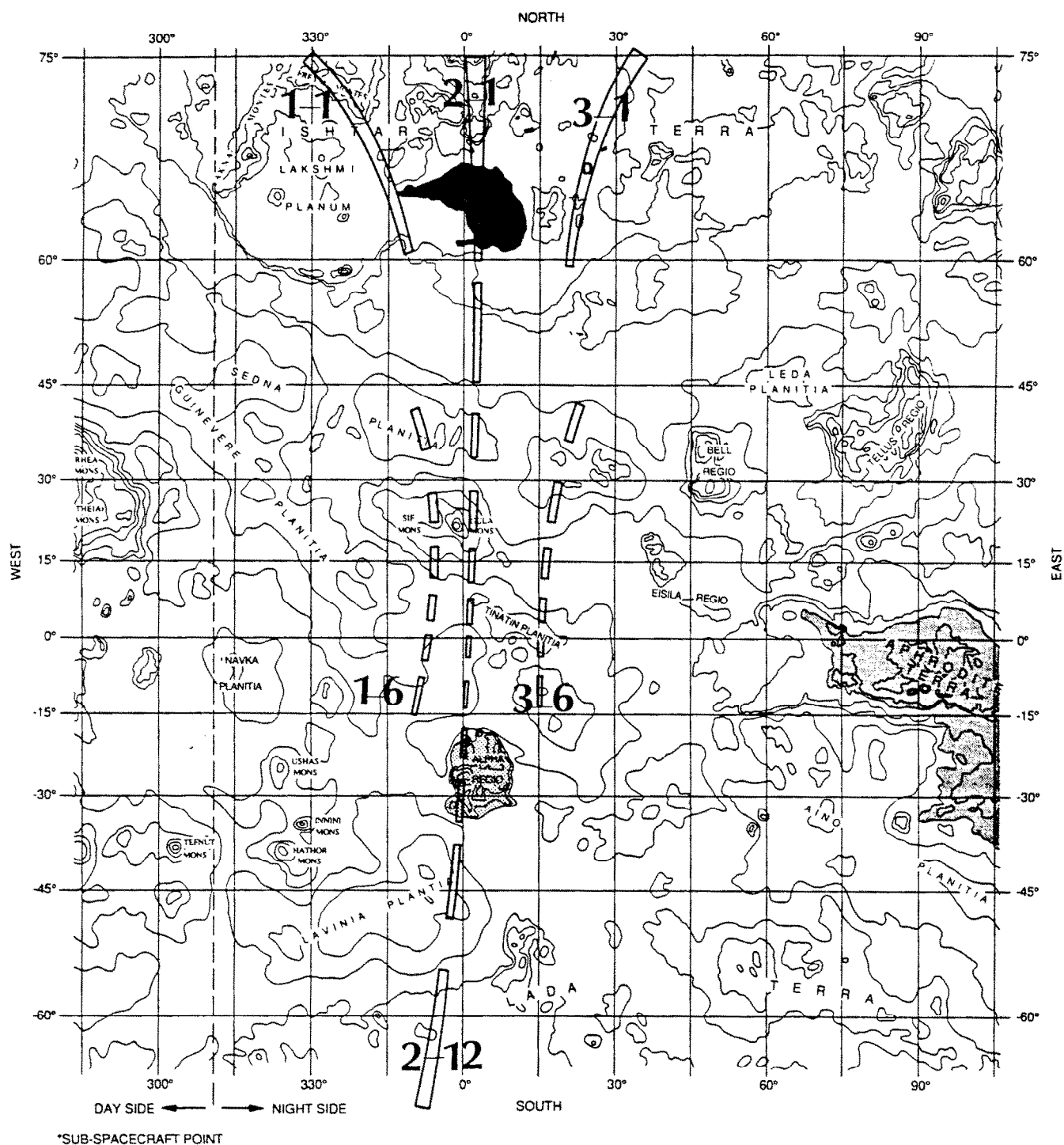
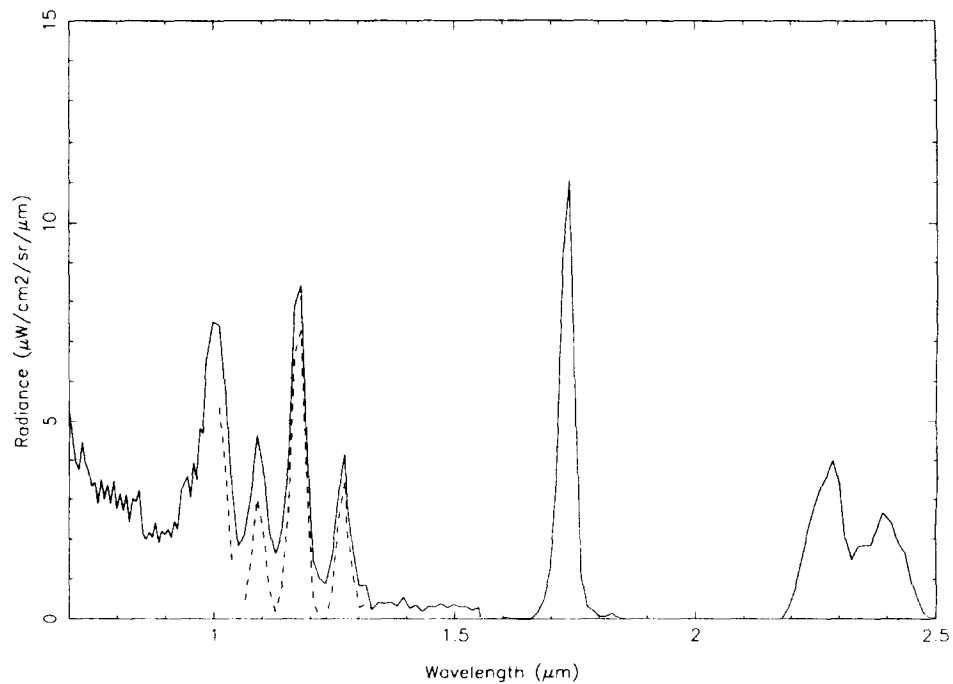


Fig. 1. Distribution of the VJBARS spectra over the Venus disc as a function of latitude and longitude. The 2-01 VJBARS set is located over Maxwell Montes. Each VJBAR corresponds to 20 individual spectra, distributed spatially along the long dimension of the footprint, which have been coadded spatially to retrieve the spectra listed in Table 1. The identification of the spectra used in Table 1 is in the form $X-Y$, with X = column number (1, 2 or 3) and Y = line number ($1 \leq Y \leq 6$ for $X = 1, 3$; $1 \leq Y \leq 12$ for $X = 2$)

Table 1. List of selected spectra

Identification	Latitude (degrees)	Longitude (degrees)	Emission angle (degrees)	Altitude (km)	Radiance at 1.18 μm	Radiance at 1.7 μm	Radiance at 2.3 μm
1-01	34.8	348.7	31.3	-1.02	7.96	15.77	7.02
1-02	24.6	350.7	21.6	0.79	7.17	15.62	7.12
1-03	14.4	351.7	13.1	0.44	6.67	8.96	1.36
1-04	5.8	352.5	9.5	-0.14	7.28	11.06	3.99
1-05	-3.4	352.8	12.9	0.44	7.89	17.00	8.94
1-06	-12.5	353.3	20.2	0.03	7.51	15.02	7.37
2-01	64.2	354.0	58.9	10.83	5.15	13.75	5.63
2-02	47.4	357.7	42.0	0.44	7.17	17.58	9.56
2-03	35.2	358.6	29.9	-0.78	7.73	14.75	6.32
2-04	25.3	359.3	20.0	0.50	6.69	13.40	5.60
2-05	16.2	359.8	11.0	0.62	7.08	11.76	4.44
2-06	7.2	0.2	2.2	-0.32	7.08	11.46	4.68
2-07	-1.0	0.3	6.2	0.27	7.30	14.74	6.88
2-08	-9.6	0.7	14.6	-0.38	7.43	13.98	6.18
2-09	-19.3	1.1	24.2	2.13	7.38	18.48	11.60
2-10	-29.5	1.5	34.3	1.55	6.21	15.86	—
2-11	-41.3	2.0	46.0	0.68	5.98	13.68	7.38
2-12	-59.2	3.1	63.9	-3.58	4.76	8.43	3.78
3-01	40.9	18.0	39.7	-0.03	7.03	13.88	6.59
3-02	29.0	16.3	28.7	0.15	7.96	17.96	9.30
3-03	18.7	15.0	20.2	0.38	7.98	18.58	9.72
3-04	9.7	14.6	15.2	0.68	6.69	12.04	4.56
3-05	0.7	14.7	14.8	-0.78	7.77	16.05	8.22
3-06	-8.7	15.1	19.6	0.33	7.53	17.36	10.24

**Fig. 2.** Example of NIMS VJBARS spectrum, summed over the 20 pixels. Solid line: raw data; dashed line: corrected spectrum, after subtraction of a residual continuum due to scattered light from the dayside and instrumental background

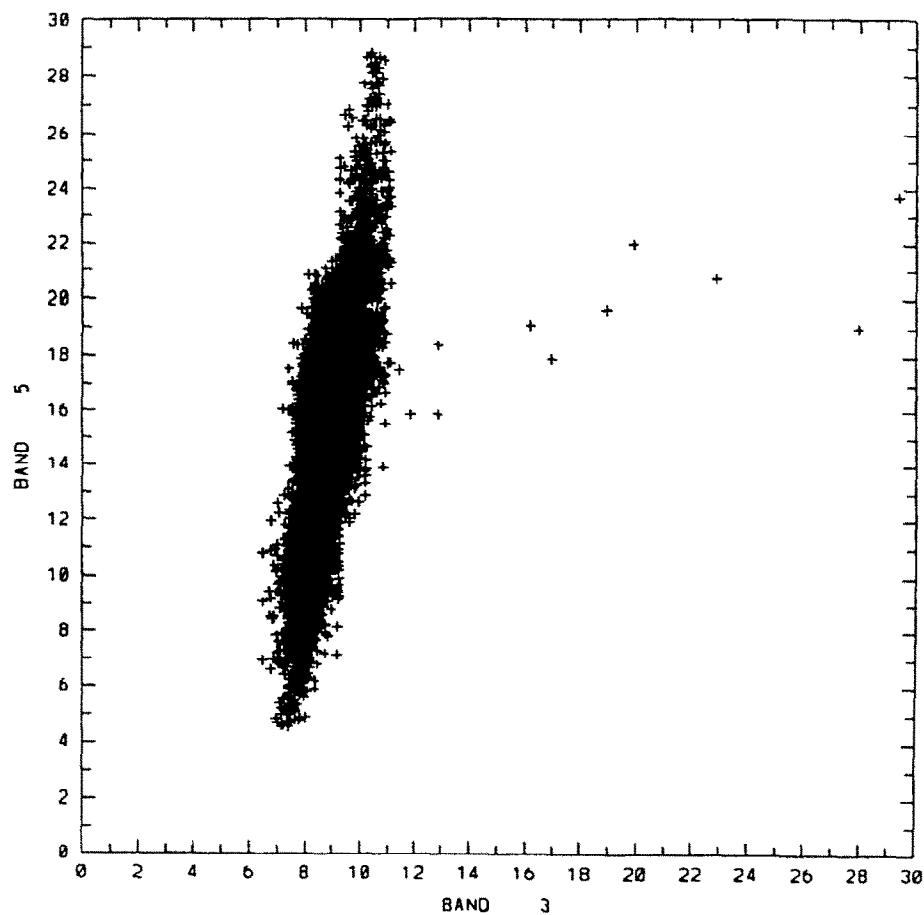


Fig. 3. Correlation diagram of the NIMS radiances at 1.18 and 2.3 μm . The data are taken from the VPDIN-1 image, in detectors 3 (1.18 μm) and 5 (2.3 μm). The unit along each axis is in DN (Data Number), corresponding to an uncalibrated radiance for bands 3 and 5. The contrasts are significantly weaker in Band 3 (1.18 μm) as a result of lower absorption by H₂SO₄ cloud droplets

al., 1991). The contrast is particularly marked in the region of Maxwell Montes which rises to an altitude of ~ 10 km.

Atmospheric model

To analyse the NIMS spectra in the 1.18 μm window, synthetic spectra have been generated by means of a line-by-line radiative transfer program which includes scattering by cloud particles. Molecular opacity from H₂O and CO₂ is taken into account. For CO₂, we used a new high-temperature database derived from detailed quantum mechanical calculations (Wattson and Rothman, 1992; Pollack *et al.*, 1993). We assumed a sub-Lorentzian lineshape, with an exponential dependence of the χ -factor, for the CO₂ lines beyond 3 cm^{-1} of line core. We used simplified cloud models derived from *Pioneer* orbiter and descent probe measurements (Crisp, 1986). The radiative transfer model also includes an additional continuum opacity as discussed below.

We first compared our calculations with high-resolution (0.4 cm^{-1}) spectra recorded by one of us (BB), C. de Bergh, D. Crisp, J. P. Maillard and T. Owen, at the Canada–France–Hawaii telescope on Mauna Kea on 1 July 1991 (Fig. 4). The observations, along with a preliminary

analysis, are presented in de Bergh *et al.* (1993). This comparison allows us to discriminate between the various sources of opacity and thus better constrain the atmospheric model. The high-frequency side of the window is dominated by absorption from the $\nu_1 + \nu_2 + \nu_3$ band of water vapour centred near 8810 cm^{-1} (1.135 μm). Many individual H₂O lines are visible in the window longward of 8440 cm^{-1} . Absorption in the low-frequency side is due to far-wing absorption from a CO₂ band near 8300 cm^{-1} (1.205 μm). It is also possible that an additional source of “continuum” opacity, probably due to extreme far wings of strong CO₂ bands and/or collision-induced CO₂ opacity, is present. Such a “continuum” opacity is clearly needed to reproduce the observed spectra in the 2.3 and 1.7 μm windows. In these windows, its strength can be determined by fitting the amplitude of permitted CO₂ lines detected in high-resolution spectra (Bézard *et al.*, 1990; Pollack *et al.*, 1993). This is not the case in the 1.18 μm window, where no individual band of CO₂ produces any marked feature. The low-frequency side of the window cannot be used reliably for this purpose because of our ignorance of the far-wing lineshape for the relevant CO₂ band (especially at high temperature). Only an upper limit of $\sim 3.5 \times 10^{-9} \text{ cm}^{-1} \text{ amagat}^{-2}$ can be set from flux considerations.

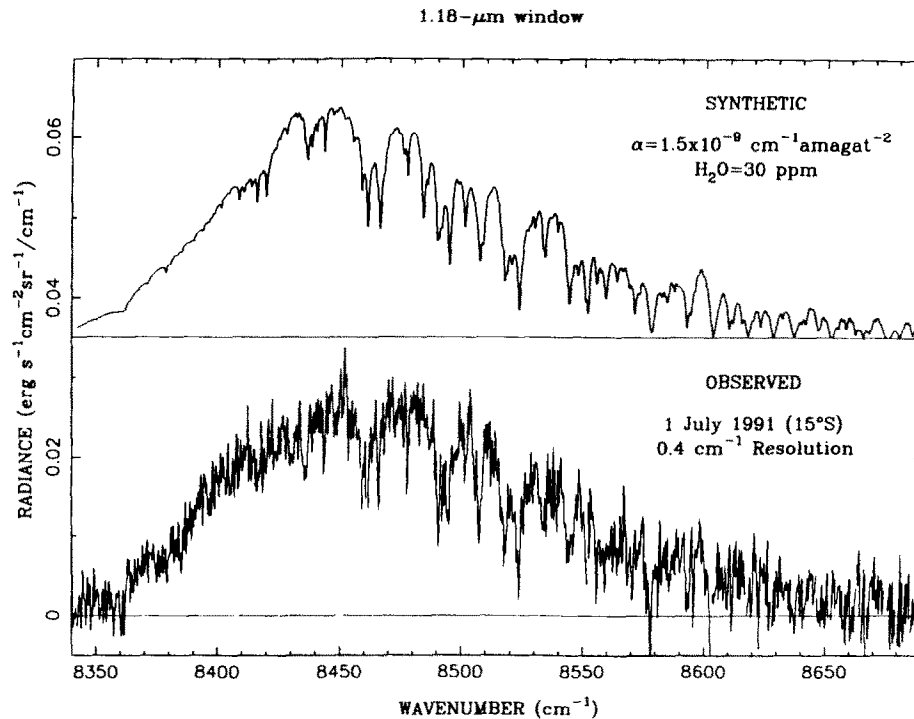


Fig. 4. Lower panel: spectrum of the nightside of Venus recorded at a resolution of 0.4 cm^{-1} at the Canada–France–Hawaii Telescope on 1 July 1991 U.T. The 5 arcsec circular aperture was centred at 15°S latitude. The low-frequency side of the window ($\sigma < 8430 \text{ cm}^{-1}$) is dominated by the far wing of a CO_2 band head at 8309 cm^{-1} . Absorption features longward of 8440 cm^{-1} are due to water vapour. Upper panel: synthetic spectrum calculated with a constant water vapour mixing ratio of 30 ppm below the clouds. A continuum opacity parameterized with a constant binary coefficient equal to $\alpha = 1.5 \times 10^{-9} \text{ cm}^{-1} \text{ amagat}^{-2}$ has been added. The integrated cloud opacity has been adjusted to match the observed flux level. An exponential χ -factor has been assumed for the far-wing lineshape of the CO_2 lines

Our nominal atmospheric model includes a continuum absorption coefficient α equal to $1.5 \times 10^{-9} \text{ cm}^{-1} \text{ amagat}^{-2}$. In this model, the bulk of the thermal emission originates from the 5–20 km altitude range. The integrated cloud optical depth was chosen to match the observed flux at the peak of the window, and the CO_2 far-wing lineshape has been adjusted to best reproduce the low-frequency side of the window (Fig. 4). The χ -factor we adopted for this nominal case is:

$$\begin{aligned} \chi &= 1 & \text{for } \Delta\sigma \leq 3, \\ \chi &= 1.35 \exp(-\Delta\sigma/10) & \text{for } 3 < \Delta\sigma \leq 10, \\ \chi &= 0.526 \exp(-\Delta\sigma/175) & \text{for } \Delta\sigma > 10, \end{aligned}$$

where $\Delta\sigma$ is the distance from the line centre, expressed in cm^{-1} .

An H₂O mixing ratio (assumed to be constant below the cloud deck) of about 30 ppm then allows us to reproduce the observed water vapour absorption features. We stress however that the actual deep abundance of water vapour is still uncertain by $\sim 50\%$ (i.e. $\pm 15 \text{ ppm}$) due to the uncertainty in the “continuum” opacity (de Bergh *et al.*, 1993).

In a second step, we computed synthetic spectra for various abundances of water vapour to search for possible spatial variations in the NIMS data set (Fig. 5). As cloud particles are located well above the line forming region, cloud opacity acts as a grey filter on the $1.18 \mu\text{m}$ spectrum.

On the other hand, water opacity drastically affects the extension of the window to short wavelengths (Fig. 6).

For each NIMS spectrum, we determined the best fitting H₂O mixing ratio. This was done by maximizing the correlation coefficient between observed and synthetic spectra over the six data points from 1.147 to $1.212 \mu\text{m}$. This procedure is equivalent to minimizing the χ^2 for two parameters, the H₂O mixing ratio and the cloud optical depth, since a variation in the latter acts as a multiplicative constant.

Results

H₂O retrieval

The inferred H₂O mixing ratios are given in Table 2. Four spectra have not been considered in our analysis; two of them (1-03 and 2-10) because of instrumental problems (partial obscuration by the booms) and those characterized by an emission angle larger than 50° (2-01 and 2-12) (for which our two-stream radiative transfer model may not be accurate enough).

As detailed above, the absolute value of the H₂O mixing ratio in the retrievals depends on the assumptions made for the CO_2 “continuum”. The uncertainty in the absolute value of H₂O ($\pm 15 \text{ ppm}$) is therefore much larger than

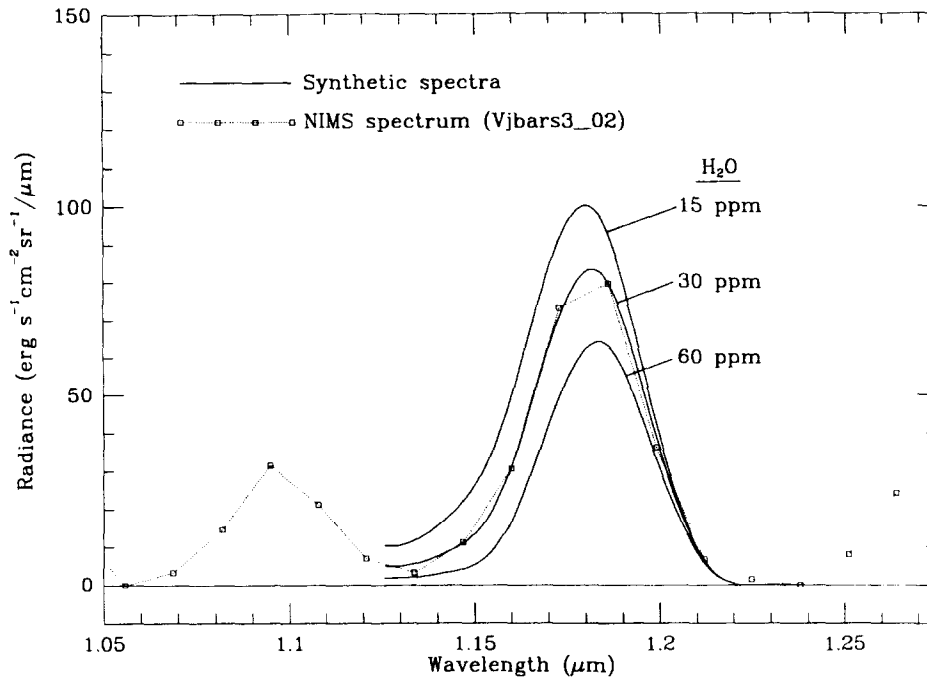


Fig. 5. Synthetic spectra calculated at the NIMS resolution ($0.026 \mu\text{m}$) for H₂O mixing ratios of 15, 30 and 60 ppm (solid lines). A NIMS spectrum is shown for comparison (dotted line). The cloud optical depth has been adjusted to yield the best agreement of the 30 ppm model with the observed spectrum in a least-square sense

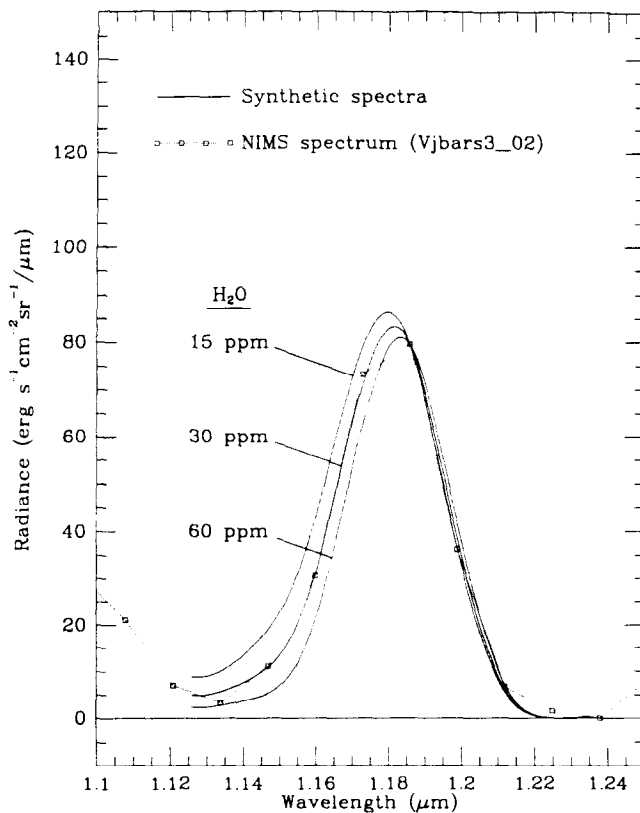


Fig. 6. Same as Fig. 5 except that the three synthetic spectra have been renormalized to match the NIMS flux at $1.186 \mu\text{m}$. This multiplication by a constant factor is equivalent to changing the cloud optical depth. The width of the $1.18 \mu\text{m}$ window, and more precisely its extension towards short wavelengths, is very sensitive to the amount of water vapour

that attached to the *relative* variations of H₂O ($\approx \pm 1$ ppm), since the CO₂ continuum itself is not expected to vary spatially.

The error bar given in the third column of Table 2 corresponds to the uncertainty in the relative variations of H₂O, and was derived by increasing χ^2 by 1 from its minimum value. It thus corresponds to the formal error (1 SD) on the water abundance due to random noise only. In particular, it does not include any possible systematic error, such as improper correction of the scattered light in the NIMS data or incorrect atmospheric modelling. For each spectrum, the minimum χ^2 is still significantly larger than would be expected from random noise only. This means that errors other than noise are present either in the data or in the model. Part of the discrepancy comes from the inability of the model to fit the CO₂-dominated side of the window perfectly, as can be seen in Fig. 4. However, we note that, unlike the absolute amount of water, the inferred horizontal variations do not depend on the assumed atmospheric model.

The mean value of the derived H₂O mixing ratio is 27 ppm, with a mean standard deviation of 2 ppm. The standard deviation of the sample amounts to 8% of the mean and is only twice higher than that due to noise. It then appears that the variability of water in this NIMS sequence is extremely limited. There is, however, one spectrum (3-01) which significantly departs from the mean water vapour abundance. The mixing ratio there is $18 \pm 4\%$ lower than the average and might reflect a small but real deficiency in water. The main conclusion of this study is nevertheless that, in the NIMS sequence investigated here, the spatial variations of water are limited and do not exceed 20%.

Table 2. Analysis of the 1.18 μm window in the *Galileo*-NIMS spectra (VJBARS sequence)

Spectrum identification	H ₂ O mixing ratio (ppm)	Error bar* (ppm)
1-01	30.2	1.1
1-02	26.8	0.9
1-04	27.6	1.0
1-05	27.5	1.0
1-06	30.1	1.0
2-02	30.1	1.1
2-03	25.9	1.4
2-04	27.9	1.1
2-05	26.7	1.4
2-06	27.7	1.3
2-07	28.8	0.9
2-08	27.5	1.0
2-09	27.3	1.1
2-11	24.9	1.1
3-01	22.3	1.0
3-02	28.2	1.3
3-03	25.1	1.0
3-04	28.7	1.6
3-05	29.5	1.1
3-06	24.5	0.9

* 1-SD formal error due to noise only.

Weighted mean of the mixing ratio: 27.3 ppm.

Standard deviation of the sample: 2.1 ppm

O₂ emission

O₂ airglow contributes to the flux emitted in the 1.27 μm window (Allen *et al.*, 1992). This emission originates from the ~ 90 km region, as O atoms transported from the day-side recombine to produce molecular oxygen in the $^1\Delta$ vibration state. Subsequent relaxation of O₂ to the ground state produces the observed fluorescence at 1.27 μm . We have searched for spatial variations of the 1.27 μm flux using the same set of spectra (VJBARS). The brightness in this window is fairly uniform, and its small variation correlates with that in the other atmospheric windows, except for one small area, where the 1.27 μm emission is enhanced by a factor of 2. The excess emission is safely attributed to O₂, because the same enhancement would also be observed at 1.18 μm if it was due to a lower cloud opacity. Furthermore, as shown in Fig. 7, the spectrum in this particular area does not strongly differ from the surroundings in the 1.7 and 2.3 μm windows, implying a fairly uniform cloud coverage.

Since the spectra in the VJBARS sequence are scanned along a meridian, the latitudinal extent of the emission can be retrieved, at the NIMS spatial resolution which is about 40 km for the scan considered. The emitting area, defined as having an emission at 1.27 μm of more than 50% of the average value is found at the following location:

Latitude = 39.3°S;

Longitude = 2.23°;

Extension $\approx 1.1^\circ$ in latitude (about 100 km);

Excess radiance: $2.88 \mu\text{W cm}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$, at an emission

angle of 46° , corresponding to an excess flux of $0.585 \mu\text{W cm}^{-2}$ in the window, assuming a 4π sr isotropic emission and dividing by a factor of 1.45 to correct for reflection from underlying clouds. The intensity of this local emission thus corresponds to ≈ 4 MR (megarayleighs). The correction factor is expressed as:

$$1 + A \frac{\Omega \cos^2 \theta}{\pi},$$

where A is the albedo of the clouds (assumed to be Lambertian), θ is the emission angle pertaining to the observations, and Ω is the solid angle of the emitting area seen from the cloud tops along the line of sight. Assuming that the cloud tops are located 25 km below the emitting area, Ω is equal to 1.04π for the geometry of the relevant NIMS observations ($\theta = 46^\circ$). A cloud albedo $A = 0.90$ was adopted.

The observed local O₂ airglow emission is 2 times higher than originally observed by Connes *et al.* (1979), and recently by Allen *et al.* (1992). We compare here the intensities uncorrected for reflection from underlying clouds, because of the differences in the adopted correction factors. It is comparable with the maximum strength of the emission observed at the CFHT (with a 5 arcsec aperture) at 15°S on 1 July 1991 U.T. (Crisp *et al.*, 1991b). The region of enhanced brightness in the NIMS spectra is located near 40°S latitude and is thus further from the antisolar point than observed by Allen *et al.* (1992). In the frame of their interpretation of the O₂ emission, involving downwelling of the upper layers of the atmosphere on the nightside, the NIMS observations imply that small-scale structures in the global day/night circulation are important in the production of this phenomenon.

Conclusions

The present analysis provides information about the water vapour abundance of Venus on the nightside, and on the spatial variations of the O₂ emission.

Strong O₂ emission is observed at 1.27 μm in a small area, about 100 km wide, at a latitude of 40°S, southward of the nearly equatorial emissions reported by Allen *et al.* (1992). Within the emitting area, a flux of about 4 MR is found, within a factor of 3 of previous ground-based observations.

The mean value of the H₂O mixing ratio derived by our analysis (30 ± 15 ppm) is compatible with previous estimates obtained from near-infrared spectroscopic observations of the nightside. From the 2.3 and 1.7 μm windows, which probe atmospheric regions near 35 and 20 km respectively, H₂O mixing ratios of 25 and 50 ppm were retrieved from the NIMS experiment, with a factor of 2 uncertainty (Carlson *et al.*, 1991). Using high-resolution ground-based spectra, Bézard *et al.* (1991) and de Bergh *et al.* (1993) derived, from the three spectral windows at 1.18, 1.74 and 2.3 μm , a uniform H₂O mixing ratio of 30 ± 15 ppm below the clouds. Pollack *et al.* (1993) independently reached the same conclusion from an analysis of 1.10, 1.74 and 2.3 μm ground-based spectra at moderate spectral resolution. We find no confirmation of the large H₂O values measured by the gas chromatographs and

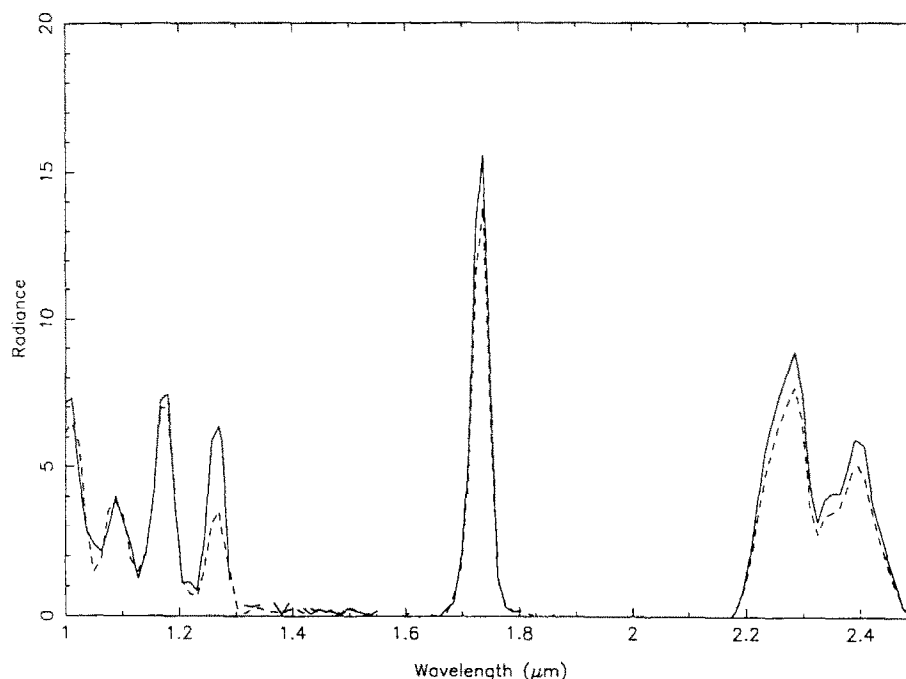


Fig. 7. Two NIMS spectra recorded inside (solid line) and outside the region of maximum O₂ emission at 1.27 μ m. Both spectra have similar fluxes at 1.18, 1.7 and 2.3 μ m, implying similar cloud parameters, whereas the 1.27 μ m flux is much higher for the position (39.3° S, 2.23°) in latitude and longitude

mass spectrometers aboard *Pioneer* Venus and *Venera* 11/12 (see Von Zahn *et al.*, 1983, and references therein), nor of the strong depletion towards the surface suggested by the spectrophotometric *Venera* data (Moroz *et al.*, 1980; Young *et al.*, 1984) and the PV mass spectrometer measurements (Hunten *et al.*, 1989; Donahue and Hodges, 1992). Nevertheless, the 50% error in the H₂O abundance, mainly due to the largely unknown CO₂ continuum opacity precludes definite conclusions about a possible moderate decrease of the water abundance near the surface. The lack of any marked vertical gradient in the H₂O profile seems to rule out the presence of any significant atmospheric sink near the surface, such as carbonic acid gas (H₂CO₃). Its formation at deep atmospheric levels from the association of H₂O and CO₂ molecules was postulated by Lewis and Grinspoon (1990) to interpret the near-surface depletion of water suggested by earlier analyses. The present work combined with high-resolution ground-based studies likely implies that H₂CO₃ is not as stable as predicted by Lewis and Grinspoon from an estimation of the relevant thermochemical data.

The main result of the present analysis is that the column abundance of H₂O derived from our NIMS sample does not vary by more than 20% over a large latitudinal range (40°S, 50°N). If the sample is limited to mid-latitudes ($\pm 30^\circ$), the variations are smaller than 10%. In addition, there is no correlation between the H₂O abundance and the cloud opacity. As an example, for spectra 1-04 and 2-09, whose fluxes at 2.3 μ m differ by a factor of 3 because of cloud opacity, the derived H₂O mixing ratios are 27.6 and 27.3 ppm respectively. Finally, there is no apparent variation of H₂O with topography, as the retrieved H₂O mixing ratio for spectrum 2-09, which corresponds to the highest surface elevation in the sample

(Alpha Regio, at 2.1 km), is equal to the mean value (27 ppm). We note however that the CO₂ continuum opacity probably prevents us from probing altitude levels as deep as 2 km. Further analysis will be possible in the region of Maxwell Montes where some spectra have been recorded. The high emission angles, the large variability of spectra within the relevant NIMS VJBARS set (2-01), and the pointing uncertainties have not allowed us to analyse these spectra so far.

In conclusion, the present study shows no evidence for wet or dry areas in the lower atmosphere of Venus at night. As mentioned above, the presence of such spots has been suggested above the cloud decks in the mid-afternoon, as a possible result of the solar radiation. Since we probe much deeper in Venus's atmosphere, our result is obviously not inconsistent with this statement, nor with the low upper limit derived above the clouds over the entire nightside from the *Pioneer* Venus infrared radiometer data (Schofield *et al.*, 1982).

The lack of large variations in the deep H₂O abundance has important consequences for the physics of Venus's atmosphere. First, it implies that the determination of the H₂O abundance obtained from ground-based spectroscopy of the nightside and in the present analysis both correspond to the global water content of Venus's atmosphere. The observed low abundance of water vapour establishes that Venus is much dryer than suggested by the initial interpretations of the *in situ* measurements of the *Venera* and *Pioneer* Venus probes. The ~ 30 ppm H₂O mixing ratio observed in the low atmosphere rules out the presence of any hydrated silicates on the surface of Venus, which has been a moot question for decades. Recent thermochemical calculations by Fegley and Treiman (1992) show that no pure hydrated silicates are stable

anywhere on the Venusian surface under water concentrations lower than 100 ppm. The results of the present study also have important implications for radiative equilibrium modelling of the atmosphere, as H₂O is a major absorber at infrared wavelengths. Finally, the inferred water vapour abundance provides a constraint for future thermochemical models of Venus.

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