Measurements of the mean, solar-fixed temperature and cloud structure of the middle atmosphere of Venus

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SUMMARY

Data from the orbiter infrared radiometer (OIR) of the Pioneer Venus mission have allowed the global structure of the middle atmosphere of Venus to be studied in detail for the first time. Between 4 December 1978 and 14 February 1979 this instrument made over 300,000 soundings in ten spectral channels, covering most of the northern and some of the southern hemisphere in the altitude range 65–100 km (100–0.01 mb). Preliminary analyses indicate that mean atmospheric structure in this region is strongly dependent on latitude and local time of day, although day-to-day variations are seen. This paper presents the mean temperature field and cloud top structure retrieved from the data of five OIR channels averaged in a solar-fixed coordinate system. The retrieval scheme and the derivation of the weighting functions that characterize the vertical response of each channel are also described.

The middle atmosphere can be divided into two distinct regions separated by a low-latitude temperature minimum of less than 170 K at 95 km in the retrieved zonal-mean temperature field. Below 95 km, day-night temperature contrasts are small but above 70 km pole–equator contrasts are positive reaching a maximum of 20–25 K at 85 km. Fourier analysis shows that within 45° of the equator the longitudinal variation of temperature is dominated by wavenumber-2 tidal structure with a phase that moves eastwards with increasing altitude. Above 95 km, the pole–equator temperature gradient is reversed, day–night contrasts become appreciable and wavenumber-1 longitudinal structure dominates. At equatorial latitudes mean cloud optical depth at 11.5 μm is unity at 100 mb (66–5 km), and the cloud top has a scale height of 0.85 times the atmospheric value. The cloud top falls slowly with increasing latitude and has a wavenumber-1 longitudinal dependence of ±20 mb (±1 km), with the highest cloud found just before the evening terminator. Retrievals are insensitive to cloud structure in the polar regions, but it is clear that the cool collar that surrounds the warm polar region is not a high-cloud feature. It is in fact a deep temperature inversion in which temperatures can be more than 30 K less than equatorial values at the same level.

1. INTRODUCTION

The remote sounding measurements of the orbiter infrared radiometer (OIR) on the Pioneer Venus orbiter have allowed the structure and variability of the middle atmosphere of the planet to be studied for the first time on a global scale. Following orbit insertion on 4 December 1978 the OIR returned data for 72 days, almost one third of the Venusian year, making about 300,000 soundings with ten spectral channels. The results of a preliminary analysis of this data set have been presented (Taylor et al. 1979a, b, 1980), and the aims of the OIR experiment together with the design and properties of the instrument have also been described (Houghton and Taylor 1975; Taylor et al. 1979c; Deld fever et al. 1980). Conceptually, the instrument is based on techniques which are now used routinely for temperature sounding of the earth’s atmosphere (Houghton et al. 1982).

It is clear from the preliminary analyses cited above that the mean thermal structure of the middle atmosphere is strongly dependent on latitude and local time of day at most levels. Day-to-day variations are also seen. The aim of this paper is to establish the mean, time-independent temperature structure of this region of the atmosphere in a solar-fixed coordinate system, in order to reveal zonal-mean structure and average diurnal variations. We shall also describe for the first time the detailed algorithms developed for temperature sounding on Venus and present an error analysis. Table 1 summarizes the basic optical properties of the five OIR channels assigned to remote temperature sounding. As OIR channels are sensitive to atmospheric and aerosol opacity a two-parameter absorbing cloud model is also derived from the data, both to investigate the mean optical properties of the Venusian cloud tops at infrared wavelengths and to improve the retrieval of temperature profiles near the clouds.
TABLE 1. OIR TEMPERATURE-SOUNDING CHANNELS—OPTICAL PROPERTIES

<table>
<thead>
<tr>
<th>Channel*</th>
<th>Field of view**</th>
<th>Effective wavelength†</th>
<th>Spectral resolution‡‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(degrees)</td>
<td>(cm⁻¹)</td>
<td>(µm)</td>
</tr>
<tr>
<td>1</td>
<td>5.0</td>
<td>667.0</td>
<td>15.0</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
<td>679.4</td>
<td>14.7</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>727.2</td>
<td>13.8</td>
</tr>
<tr>
<td>4</td>
<td>1.25</td>
<td>764.4</td>
<td>13.1</td>
</tr>
<tr>
<td>5</td>
<td>1.25</td>
<td>872.0</td>
<td>11.5</td>
</tr>
</tbody>
</table>

* Channel numbers used in text.
** All channel fields of view are co-aligned.
† The effective wavelength is that of an equivalent monochromatic channel.
‡‡ Channel 1 employs the gas-correlation chopping technique using a pressure modulator radiometer; its spectral resolution is defined by the width of spectral lines in the pressure modulator cell. At room temperatures this is limited to approximately 1.5 × 10⁻² cm⁻¹ by Doppler broadening. The channel-1 resolution in the table corresponds to the highest PMC pressure setting for which pressure broadening is dominant. The spectral resolution of the other channels is the halfwidth of the roughly triangular spectral response defined by a grating spectrometer.

2. HORIZONTAL AND VERTICAL COVERAGE

The spin-stabilized Pioneer Venus orbiter moves in a highly eccentric 24-hour orbit in a plane inclined at about 105° to the ecliptic and fixed in inertial space. Its altitude is maintained in the range 150–200 km at periapsis, which occurs at approximately 18°N 208°E in celestial coordinates, and rises to 66 900 km at apoapsis (Colin 1980). The orbiter spin axis is aligned with the celestial south polar axis and is inclined at 45° to the field-of-view axis of the OIR instrument, so that the coverage obtained is limited chiefly to the northern hemisphere of Venus. A representative set of orbit parameters and the corresponding idealized coverage pattern are given in Fig. 1.

Beneath the orbiter the solid body of the planet rotates in a retrograde sense with a period of 243 days. Consequently the coverage pattern of Fig. 1 moves eastwards by 1.48° per orbit in a planet-fixed coordinate system. Similarly it moves westwards (later in the Venrian day) by 1.60° (6.41 Venrian minutes) per orbit in a planet-centred, solar-fixed coordinate system. The latter drift corresponds to a net rotation of 115.4° during the 72 days for which OIR data were obtained, giving almost complete coverage of all local times of day in the northern hemisphere. In the southern hemisphere coverage is progressively reduced and is lost entirely between 35 and 45°S. For this reason, the temperature and cloud structure retrievals discussed in this paper are limited mainly to the northern hemisphere.

The intensity of radiative flux incident on a radiometer viewing a semi-infinite, horizontally stratified atmosphere from space can be expressed as an integral of the form

\[ I = \int_0^\infty J(y)K(y) \, dy \tag{1} \]

where \( y \) is a suitable vertical scale, \( J(y) \) is the source function for emission at level \( y \), and \( K(y) \) is a weight or weighting function. Under conditions of local thermodynamic equilibrium (LTE) \( J(y) \) is the Planck function corresponding to the temperature at level \( y \) and the effective wavelength of the radiometer, and \( K(y) \) is the first derivative of the transmission function from \( y \) to space in the spectral region defined by the radiometer (Houghton et al. 1982). If a logarithmic pressure scale is chosen for \( y \), \( K(y) \) is only weakly dependent on atmospheric temperature structure, but is strongly influenced by viewing geometry and the spectral characteristics of the radiometer. The measurement of \( I \) and a knowledge of \( K(y) \) in Eq. (1) form the basis for the retrieval of \( J(y) \) and hence the temperature profile.
Normalized weighting functions for the five OIR radiometer channels described in Table 1 are shown in Fig. 2. These functions apply to a nadir view of a model atmosphere with the temperature and cloud structure indicated in the figure; their derivation, verification, and properties are discussed in section 4.

It is clear from Fig. 2 that the limits on vertical coverage are set by the cloud tops at approximately 100 mb (65 km) and by the channel-1 weighting function at about 0.01 mb (105 km). Within this range the width of the functions impose a vertical resolution of 5–10 km on retrievals, although some improvement can be gained by making use of their variation with zenith angle (section 4).

3. COORDINATE SYSTEMS AND ASSUMPTIONS

In order to retrieve mean atmospheric temperature and cloud structure, calibrated radiances for each channel, corresponding to the entire 72-day data set, are averaged in a series of latitude, longitude and zenith angle ‘bins’. Latitude and longitude are specified in a planet-centred, solar-fixed coordinate system in which the equator lies in the orbital plane of Venus and the north polar axis is parallel to the orbit polar axis. Zero longitude occurs at local noon and the sub-solar point lies on the equator. The relation between these coordinates and local time of day is illustrated in Fig. 3.

Bins of 10° in latitude and 30° in longitude, extending from 10°S to 90°N, were chosen to optimize horizontal resolution whilst limiting errors in equivalent temperature arising from measurement noise and short-term fluctuations in atmospheric structure. Within each latitude-longitude bin data were assigned to nine zenith angle bins with mean values of μ ranging from 0.95 to 0.15. μ is the cosine of the angle subtended by the
Figure 2. Normalized weighting functions for the five OIR temperature sounding channels plotted as a function of pressure and altitude for a vertical view of a representative model atmosphere (solid lines). The model profile employed in the calculations (dashed line) is identical to the first-guess equatorial profile used in retrievals. Cloud is described by a homogeneous model with unit optical depth at the 100 mb level (dotted line). The channel-1 weighting function is calculated for the high PMR pressure setting and a typical line-of-sight velocity of 40 km s\(^{-1}\). The channel numbers correspond to those of Table 1.

Figure 3. The Venus-centred, solar-fixed, coordinate system. Solar latitudes (degrees north) and longitudes (degrees east) are shown and are related to the following: SS = sub-solar point, MT = morning terminator, AS = anti-solar point, ET = evening terminator, and NP = north pole. The northern hemisphere radiance binning scheme is also indicated.
Figure 4. Mean limb-darkening curves for OIR channels 1 to 5, constructed from data averaged in the latitude-longitude bin centred at $15^\circ$N, $225^\circ$E in the solar-fixed coordinates of Fig. 3. The solid lines represent the variation of mean equivalent temperature with cos(zenith angle) and the error bars indicate the standard error in this mean. The typical scatter in temperature removed by averaging is illustrated by the dotted lines which give the standard deviation of individual soundings from the mean. Instrument noise rather than atmospheric variability is responsible for the large scatter in the channel-1 curve.

instrument field-of-view axis to the local vertical at a 6102 km-radius reference sphere based on the centre of mass of Venus. Typical limb-darkening curves for the OIR temperature sounding channels, derived from data averaged in the bin $10-20^\circ$N, $210-240^\circ$E, are shown in Fig. 4. Standard errors in mean temperatures and standard deviations from the mean are also shown. The latter parameter quantifies the range of temporal and spatial variability removed by averaging.

If it is assumed that cloud and temperature structure are horizontally uniform within a given latitude-longitude bin and undergo no long-term changes, the averaged data in each of the zenith angle bins of Fig. 4 can be treated as an individual measurement or channel in the retrieval scheme. This allows information on the dependence of emitted intensity on local zenith angle to contribute to retrieved profiles, extending vertical coverage and improving vertical resolution. This assumption is not necessary if the soundings falling within a given bin have a distribution of zenith angles that is independent of latitude, longitude and time. In practice this distribution is determined by coverage geometry and orbit-to-orbit variations in data-taking patterns and is not random. However,
the assumption is valid at all latitudes and levels except near the cloud tops northwards of 60° where strong horizontal and temporal variations in atmospheric structure are found.

The vertical scale \( y \) in Eq. (1), used throughout this paper, is a logarithmic pressure scale defined by \( y = \ln(p_0/p) \), where \( p \) is the atmospheric pressure in bars and \( p_0 = 1.0 \) bar. The one-bar reference level is set at 6102 km from the centre of mass of Venus at all latitudes and longitudes (Sieff et al. 1980), and corresponds to an altitude of 52 km. Fifty levels ranging from \( y = 0 \) to \( 49/3 \) (about \( 1.0 \times 10^{-7} \) bar, \( 125 \) km) are considered in the retrieval scheme, and altitude is derived as a secondary parameter from the retrieved temperature profile using the hydrostatic equation.

4. Weighting functions

Instrument weighting functions for channels 2 to 5, corresponding to the 49 layers between the levels defined above, are calculated by differencing transmissions to space along the instrument’s field-of-view axis (section 2):

\[
K(L) = TR(L + 1) - TR(L).
\]  

(2)

The transmission functions themselves contain gaseous and aerosol components and for a grey, non-scattering cloud can be described by the expression

\[
TR(L) = TR(U_g, P_g, T_g)\exp(-U_c(CPO, HC))
\]  

(3)

where \( U_g \) is the amount of gaseous absorber in the path, \( P_g \) and \( T_g \) are the mass-weighted pressure and temperature of an equivalent, homogeneous, Curtis–Godson path, and \( U_c(CPO, HC) \) is the aerosol optical depth along the path.

For a given atmospheric model cloud optical depth depends on \( CPO \) and \( HC \). \( CPO \) is the pressure level corresponding to unit cloud optical depth for nadir viewing at 11.5 \( \mu \)m (channel 5) and \( HC \) is the ratio of aerosol density scale height to atmospheric scale height. The spectral variation of cloud extinction coefficient is represented by a single factor \( K(5/4) \), the ratio of extinction coefficients at the wavelengths defined by channels 5 and 4. Channels 1 to 3 are not significantly affected by cloud opacity and, together with channel 4, occupy a spectral region where extinction coefficients for sulphuric acid clouds are not strongly dependent on wavelength. The factor \( K(5/4) \) is set to 1.7 based on Mie-theory calculations for 1-0 \( \mu \)m-radius sulphuric acid droplets (Aumann and Orton 1979, Fig. 3). These give values of 1.55 and 1.75 for 73-4 and 84-5\% concentrations of sulphuric acid by weight, based on the refractive index data of Sill et al. (1977), and 2.25 for a 75% solution based on the data of Palmer and Williams (1975). Tests show that retrieved values of \( CPO \) and \( HC \) are sensitive to changes in \( K(5/4) \), and that they vary roughly as \( K(5/4)^{1/2} \) and \( K(5/4)^{1/4} \), respectively. Retrieved temperatures at constant pressure levels near the cloud tops fall by about 1 K for a 10% increase in \( K(5/4) \), but cloud top temperatures remain virtually constant.

In the retrieval scheme \( U_g, P_g, T_g \) and \( U_c(CPO, HC) \) can be evaluated rapidly from the hydrostatic equation given cloud and atmospheric models and viewing geometry. It is assumed for this purpose that the atmosphere has a constant carbon dioxide volume mixing ratio of 0.965 below the \( 1.0 \times 10^{-7} \) bar level, the remaining constituent being nitrogen (Oyama et al. 1980). However, the gaseous transmission function requires lengthy calculation and is therefore derived from empirical models. Details of these models are given in appendix A. Transmission and therefore weighting functions for channels 2 to 5 depend strongly on \( U_g, P_g \) and \( U_c(CPO, HC) \), but weakly on \( T_g \). Consequently they vary chiefly with zenith angle.

Channel-1 transmission functions, defined by the spectral response of a pressure modulator radiometer or PMR (Taylor et al. 1972; Curtis et al. 1974), depend not only on \( U_g, P_g \) and \( T_g \) but also on the component of spacecraft velocity directed along the line of sight and on the PMR pressure setting. In this work only the highest of the three available pressure settings is considered, because of its greater signal-to-noise ratio and
more well-defined weighting function, and the effect of cloud opacity is neglected. The introduction of a fourth variable makes the approach adopted for the calculation of transmission functions for channels 2 to 5 slow and cumbersome. Therefore as channel-1 weighting functions are even more weakly dependent on $T_g$ than those of channels 2 to 5, they are interpolated directly from a pre-calculated table of functions derived for a single, representative model atmosphere (Dickinson 1972, 1976). Details of the necessary transmission calculations, the look-up table and the interpolation scheme are given in appendix B.

Transmission calculations for channels 2 to 5 have been verified using the flight instrument by comparison with measurements of transmission through the 1008 m carbon dioxide path provided by an 8 m, 126 traversal, White cell facility at the Jet Propulsion Laboratory, which was fabricated for this purpose. This cell is unsuitable for channel-1 transmission measurements, and the validity of channel-1 calculations has been tested against experiment using the flight PMRs and a 10 m White cell at Oxford University. Agreement to 0.015 in transmission is achieved for channel 1 for a representative range of path pressures, and the extension of these results to the 10 km paths typical of nadir viewing in the Venusian atmosphere can be justified by the selective spectral response of the PMR, which is concentrated near the centres of strong atmospheric lines (Schofield 1980).

5. The Retrieval Scheme

Each of the latitude-longitude bins described in section 3 contains averaged radiances for five spectral channels in up to nine zenith angle bins, giving a possible 45 quasi-independent channels subject to the assumptions of section 3. A particular channel is characterized by a mean radiance, a standard error in radiance, and a weighting function. Standard error is derived from the statistics of individual measurements averaged within a bin and the weighting function is calculated following section 4, given cloud and atmospheric models and viewing geometry. Equivalent temperatures and associated errors can be derived from radiances given the effective wavelength of the channel considered (Table 1). Channel-1 soundings with line-of-sight velocities below 20 km s$^{-1}$ have significant response to emission from above 1.0 x 10$^{-7}$ bar and are rejected before averaging.

The temperature profile and two-parameter cloud model which give the best fit to the radiance measurements for a given latitude-longitude bin are retrieved using first-guess models and the following iterative and relaxation technique. Initially cloud is represented by a uniformly-mixed model (i.e. $HC = 1.0$) with unit optical depth at 11.5μm occurring at the 100mb level, whereas the first-guess temperature profile is derived from a tabulation in pressure and latitude developed to reproduce the gross features revealed by OIR data and by the Pioneer Venus entry probe and occultation experiments (Sieff et al. 1980; Kliore and Patel 1980). The tabulated temperature profiles are shown in Fig. 8.

The optimum cloud model and temperature profile are found by a two-dimensional iteration in $CPO$ and $HC$ to minimize the weighted residual:

$$RESID(CPO, HC) = \sum_i ABS[R_m(i) - R_c(i)]WT(i)^2/\sum_i WT(i)^2$$

where the summations extend from $i = 1$ to 45. $CPO$ and $HC$ are the cloud parameters defined in section 4. $R_m(i)$ is the measured radiance for channel $i$, $WT(i)$ is the associated inverse standard error, and $R_c(i)$ is the radiance calculated from Eq. (1) given the optimum retrieved temperature profile for the cloud model considered and the corresponding weighting function for channel 1. It is assumed in this calculation that emission from levels above 1.0 x 10$^{-7}$ bar, in the upper tails of the higher weighting functions, is zero.

In Fig. 5(a) the residual of Eq. (4) is contoured as a function of $CPO$ and $HC$ for the data of Fig. 4, and the final cloud model obtained after iteration is indicated. Convergence is good at all latitudes and longitudes, as is clear from the figure, except above 60°N for
Figure 5(a). The weighted-mean residual of Eq. (4) contoured as a function of cloud scale height and unit optical depth pressure level, for retrievals performed on the averaged data shown in Fig. 4. The units of the residual are $hW \text{ cm}^{-2} \text{ sr}^{-1}/\text{ cm}^{-1}$. The final cloud parameters selected by the iterative retrieval scheme are indicated.

Figure 5(b). As Fig. 5(a), but for the averaged data corresponding to 65°N, 225°E in solar-fixed coordinates. Unlike Fig. 5(a), however, the data are consistent with a range of cloud parameters.
the reasons discussed in section 3. The variation of the residual with CPO and HC in a northerly bin is shown in Fig. 5(b).

For a given cloud model the optimum retrieved temperature profile is derived using a modified, non-linear relaxation method, similar to those of Chahine (1970) and Smith (1970), to minimize the residual of Eq. (4). At each step in the relaxation process the temperature profile at a given level is multiplied by a perturbing or relaxation factor which is a weighted combination of correction factors derived for individual channels, i.e.

\[ T_{n+1}(L) = T_n(L)F_{1,n}(L) \]  \hspace{1cm} (5a)

where

\[ F_{1,n}(L) = \sum F_{2,n}(i)WT(i)K(i, L)/\sum WT(i)K(i, L) \]  \hspace{1cm} (5b)

and

\[ F_{2,n}(L) = B^{-1}\{\lambda(i), R_m(i)\}/B^{-1}\{\lambda(i), R_c, n(i)\}. \]  \hspace{1cm} (5c)

In (5c) \(B^{-1}\) signifies the inverse Planck function, \(\lambda(i)\) is the effective wavelength of channel \(i\), \(R_m(i)\) is the measured radiance for this channel, and \(R_c, n(i)\) is the radiance calculated for the temperature profile \(T_n(L)\). \(F_{2,n}(i)\) is therefore the ratio of desired and retrieved equivalent temperatures for channel \(i\). In (5b) \(WT(i)\) is the inverse standard error in radiance for channel \(i\), \(K(i, L)\) is the weighting function for channel \(i\) at level \(L\). The factor \(F_{1,n}(L)\) is thus the weighted mean of the factors \(F_{2,n}(i)\) and is dominated by the most accurate measurement with its weighting function peak closest to \(L\).

Above \(L = 39\) \((y = 38/3, 0.003\) mb), about one scale height above the channel-1 weighting function peak, \(F_{1,n}(L)\) is held constant at its value at \(L = 39\). This ensures that in the absence of any other information the gradient of the retrieved profile above this level is identical to that of the first-guess model, which is isothermal. Below the peak of the deepest weighting function \(F_{1,n}(L)\) is scaled linearly to unity at level 1, so that the retrieved profile is constrained progressively by the first-guess profile with decreasing altitude until it is identical at the 1 bar level.

If the weighting functions corresponding to each measurement were delta functions, relaxation would proceed until the value of \(F_{2,n}(i)\) in Eq. (5c) approached unity for all channels and the residual of Eq. (4) approached zero. However, the overlap of real weighting functions coupled with measurement noise ensure that in practice the residual tends asymptotically to a small value for a given cloud model. Numerical investigations show that 15 relaxations from the first-guess temperature profile are sufficient to approach this value. As relaxation progresses, weighting functions for channels 2 to 5 are recalculated to allow for temperature profile changes and corresponding variations in geometry. It is found that such recalculations are unnecessary after each relaxation step and to save time they are performed before the first, sixth and eleventh steps. At the same time, and after the final relaxation step, the retrieved profile above 115 km is made consistent with those derived from orbiter drag measurements (Keating et al. 1980). These are characterized by the temperature at 115 km and an exospheric temperature. The former temperature is derived from the retrieved profile and the latter is interpolated from the Fourier series in local solar time given by Keating et al.

Figure 6(a) shows the perturbation of the temperature profile from the first-guess profile for the 1st, 5th, 10th and 15th steps in the relaxation scheme, using the data of Fig. 4. The corresponding values of the relaxation factor \(F_{1,n}(L)\) are shown in Fig. 6(b). The convergence of the residual is illustrated in Fig. 6(c) and it is clear that the asymptotic value has been approached closely by the 15th iteration.

6. RESULTS – ERRORS AND LIMITATIONS

The temperature profile and cloud model errors resulting from a relaxation scheme
Figure 6(a). The perturbation of the retrieved temperature profile from the first-guess profile (dashed line) for the 1st, 5th, 10th and 15th steps in the relaxation procedure of Eq. (5). The data used are those of Fig. 4 and the final retrieved cloud model parameters are adopted. Cloud unit optical depth is indicated by the dotted line.

Figure 6(b). The relaxation factor $F_{1,n}(L)$ given by Eqs. (5a, b) corresponding to the temperature perturbations of Fig. 6(a). The dashed line corresponds to a hypothetical exact solution for which $F_{1,n}(L)$ is unity at all levels.
are difficult to calculate analytically and must be evaluated by testing the solution numerically. The following sources of error can be identified.

1. Errors in measured radiance.
2. Residual errors in radiance after relaxation.
3. The limits on vertical resolution and coverage imposed by weighting functions.
4. The influence of first-guess atmospheric models.

Figure 7(a) shows the temperature profile retrieved from the data of Fig. 4 together with an error estimate which considers sources 1 to 3 above. Limb-darkening curves derived from the retrieved profile and cloud model are compared with the raw data in Fig. 7(b). It can be seen from this figure that agreement is good and that residuals are comparable with measurement errors, especially for the more accurate measurements.

The error bars in Fig. 7(a) are defined by the expression

\[ TERR(L) = \left( ET_1(L)^2 + ET_2(L)^2 \right)^{1/2} \]  

(6a)

where

\[ ET_i(L)^2 = 1.0/\sum K(i, L)/ER_1(L)^2 \]  

(6b)
Figure 7(a). The retrieved temperature profile and cloud height for the data of Fig. 4. The retrieved profile is represented by a continuous line, the first-guess profile by a dashed line, and the pressure level corresponding to unit cloud optical depth by a dotted line. The error bars shown are those of Eqs. (6a, b, c).

Figure 7(b). Limb-darkening curves generated from the raw data of Fig. 4 (solid lines) and from the retrieved profile and cloud model of Fig. 7(a) (dashed lines), for OIR channels 1 to 5. The error bars on the former curves indicate standard errors in mean measured temperature.
and

\[ ET_2(L)^2 = 1.0/\sum K(i, L)/ER_2(L)^2. \]  

(6c)

\( TERR(L) \) is the net temperature error at level \( L \), \( ET_1(L) \) and \( ET_2(L) \) are contributions due to measurement and residual errors respectively, \( K(i, L) \) is the weighting function for channel \( i \) at level \( L \), and \( ER_1(i) \) and \( ER_2(i) \) are respectively measured and residual radiances for channel \( i \). \( TERR(L) \) is small near weighting function peaks when measured and residual radiances are small. Above \( \gamma = 12 \) and below the clouds weighting functions tend to zero and \( TERR(L) \) becomes large. Physically \( TERR(L) \) is the maximum temperature perturbation at a single level \( L \) that is consistent with combined measurement and residual errors in radiances. Single perturbations from the retrieved profile with a greater vertical extent must be correspondingly smaller. The variation of \( TERR(L) \) with altitude in Fig. 7(a) clearly indicates the region where measurement information is available.

The nature of the relaxation scheme of Eqs. (5a, b, c) makes the shape of the retrieved profile dependent on the first-guess profile and the shape of the weighting functions. The former effect is dominant at the upper and lower limits of coverage whereas the latter is more important in the centre. If first-guess profiles are chosen to ensure that perturbations during relaxation are not too large, the latter effect is minimized. However, features that are much narrower than weighting functions, for example narrow cloud top temperature inversions, cannot be retrieved unless they are represented in the initial profile. This is not a disadvantage when it is noted that such small-scale, variable features will probably be smeared out in the averaged data used in retrievals.

Errors arising from the first-guess profile and cloud model are more difficult to deal with. The structure of the cloud ceiling may well be more complex than the two-parameter model fitted to the data by the retrieval program. However, narrow cloud layers, like temperature features, will be smeared out in the averaged data, and the two-parameter model provides a good general description of the cloud tops.

The effect of changing the first-guess temperature profile can be investigated by retrieving cloud and temperature profiles for the same data using several different guesses which lie within the limits imposed by current knowledge of the atmosphere. The family of profiles developed to represent the latitude variation of the first-guess profile is ideal here. Figure 8 displays the nine retrieved profiles corresponding to the data of Fig. 4 and these profiles. The first-guess profiles are shown for comparison, shifted by 75 K to avoid confusion, and retrieved cloud unit optical depths are also indicated. Differences are only appreciable near the limits of vertical coverage and are comparable with the error bars of Fig. 7(a). The retrieved profiles with pronounced temperature and cloud height deviations from the mean correspond to first-guess profiles with deep cloud top temperature inversions, which are not found at low latitudes, and have relatively large residuals.

7. Retrieved Temperature Structure — Zonal-Mean Field

The zonal-mean temperature field derived from profiles retrieved for all the latitude-longitude bins of section 3 is shown in Fig. 9, together with the latitude variation of the zonal-mean value of \( CPO \). Its chief features can be summarized in the following way.

At equatorial latitudes temperatures fall monotonically from the cloud tops to a minimum below 170 K at 95 km and rise again to more than 180 K above 100 km. This minimum becomes less marked and moves to higher levels with increasing latitude. At 105 km the pole is 15–20 K cooler than the equator but between 70 and 95 km the pole is warmer than the equator, often by as much as 25 K. Polewards of 50°N an inversion centred near 65 km begins to develop. This is most intense near the cloud tops in the polar collar region from 60–80°N, where temperatures are up to 30 K less than those at the same pressure level in equatorial latitudes. However, near the pole itself cloud top temperatures approach low-latitude values. Beneath the clouds the first-guess model is
largely unperturbed by OIR data so that the temperature structure has the approximate latitude variation inferred from the probe and occultation results (section 5).

Zonal-mean equatorial cloud structure can be represented by the two-parameter model of section 3 with $CPO = 100\,\text{mb (66.5 km)}$ and $HC = 0.85 \pm 0.05$. $CPO$ appears to increase with latitude in both hemispheres reaching a maximum of 105 mb (66.0 km) at 45°N. $HC$, the ratio of cloud to atmospheric scale heights, is independent of latitude to 55°N. At latitudes polewards of 55°N experimental limb-darkening curves become physically unrealistic near the cloud tops for the reasons discussed in section 3, and retrieved values of $CPO$ and $HC$ are unreliable (see Fig. 5(b)), showing considerable variation round latitude circles. However, it is clear that Fig. 5(b) is consistent with values of $CPO$ near or greater than 100 mb in the collar region and with $HC$ being independent of
latitude. At the pole itself the very small lapse rate makes the retrieval scheme insensitive to $HC$ and to values of $CPO$ in the range 25 to 150 mb.

At the equator the lapse rate derived from the zonal-mean temperature field is approximately $3.5 \text{K km}^{-1}$ near the cloud tops and lies in the range $3$ to $4 \text{K km}^{-1}$ from 65 to 85 km. Cloud top lapse rates fall slowly with increasing latitude to $3 \text{K km}^{-1}$ at $45^\circ\text{N}$ and rapidly become negative in the polar collar before returning to small positive values near the pole.

8. RETRIEVED TEMPERATURE STRUCTURE – LONGITUDINAL VARIATIONS

Plots of the variation of retrieved temperature profiles round latitude circles show a great deal of interesting solar-fixed structure which is revealed entirely by OIR data.
Figure 10(a). The retrieved mean longitudinal temperature field and cloud structure in the latitude range 0–30°N. Temperature is contoured as a function of pressure and solar longitude and the cloud level is represented by the dotted line. The altitude scale is approximate and corresponds to the mean for all the retrieved profiles. The relation between solar longitude and local time of day is given in Fig. 3.

Figure 10(b). The departure of the temperature field of Fig. 10(a) from its zonal-mean value in the range 0–30°N.
because the first-guess model used in retrievals is independent of longitude. Figure 10(a) shows the mean retrieved temperature field from 0–30°N plotted as a function of pressure and longitude, and also indicates the longitudinal dependence of mean cloud height in the same region. Figure 10(b) displays the deviation of the field of Fig. 10(a) from the zonal mean temperature profile from 0–30°N.

It can be seen that above 100 km (4 × 10⁻³ bar) wavenumber-1 structure is dominant with temperatures just before noon exceeding mean nighttime values by 15–20 K. However, a small, warm region, which is most intense at southern equatorial latitudes but persists to relatively high latitudes, is observed just before midnight at this level. Below 100 km temperature contrasts are smaller and wavenumber-2 structure is dominant at all levels above the cloud tops. Longitudinal variations decay below the clouds as the perturbing effects of OIR data on the first-guess profile tend to zero.

The most remarkable feature revealed by Figs. 10(a, b) is the gradual eastward (upwind) tilt of solar-fixed wavenumber-2 structure with increasing altitude at a mean rate of 25° per scale height (62 km⁻¹). At the cloud tops temperature maxima are found just before local noon and midnight, and move eastwards by more than 180° in longitude by the 100 km level. Above 105 km and below the clouds there is little information in the OIR data and the retrieval scheme forces this tilt to zero (section 5).

Mean equatorial cloud structure from 0–30°N shows distinct wavenumber-1 characteristics, with cloud height (CPO) ranging from 85 mb (67–2 km) near the evening terminator to 120 mb (65–3 km) close to the morning terminator. Cloud scale height (HC) varies by ±0.1 about its mean value of 0.85, but these changes are not correlated with cloud height. Cloud top temperature, that is the temperature at pressure level CPO, has a predominantly wavenumber-2 structure with a peak-to-peak amplitude of approximately 6 K about a mean of 246.5 K, and with minima occurring just before the morning and evening terminators.

The dependence of wavenumbers 1 and 2 temperature structures on latitude and altitude is illustrated more quantitatively in Figs. 11(a, b) and 12(a, b). These figures plot the amplitudes and phases of wavenumbers 1 and 2 structures respectively, derived from the relevant Fourier sine and cosine coefficients, which are calculated by representing the variation of temperature with latitude at each altitude and pressure level by Fourier sine and cosine series.

Figure 11(a) shows that wavenumber-1 amplitudes are appreciable only near the cloud tops and above 100 km. The intense features below the mean cloud ceiling near the pole are artefacts of the retrieval scheme produced by variations in retrieved cloud parameters at this level, particularly HC (section 7), and it is also felt that the feature at 65°N above 100 km is exaggerated by the retrieved profile for a single bin which contains noisy and anomalously low channel-1 radiances. However, there is clear wavenumber-1 structure at the latter location. Subject to the above comments, wavenumber-1 amplitudes fall rapidly from 2–3 K near the cloud tops to about 1 K between 70 and 100 km. Above 100 km amplitudes are greatest just north of the equator and fall steadily to low values near the pole. It can be seen from Fig. 11(b) that where amplitudes are appreciable wavenumber-1 phases vary little with latitude. Maxima occur near noon at high altitudes and near sunset at the cloud ceiling.

It is clear from Fig. 12(a) that wavenumber-2 amplitudes are considerable at all levels above the cloud tops except near the pole. Again amplitudes are unreliable below the clouds in the polar regions. From 10°S to 60°N amplitudes rise from about 2 K at the cloud tops to 4–5 K at 80 km and fall again to 2–3 K at higher levels, except near the equator where amplitudes exceed 5 K above 100 km because of the pre-midnight hot spot. The eastward drift of wavenumber-2 phase with increasing altitude is very clear in Fig. 12(b). However, below 85 km phase varies little with latitude. Above this level there is a steady eastward drift with increasing latitude.

Strong, variable wavenumbers 1 and 2 features in radiance data for individual orbits are seen in the polar regions near the cloud tops. However, it appears from Figs. 11 and
Figure 11(a). The amplitude of wavenumber-1 longitudinal temperature structure, derived from retrieved profiles and contoured as a function of pressure and latitude. Zonal-mean cloud levels are represented by the dotted line and the approximate altitude scale is the mean of those derived for all the retrieved profiles.

B. PHASE - WAVENUMBER 1

Figure 11(b). The phase of wavenumber-1 longitudinal temperature structure in solar coordinates, corresponding to the amplitudes of Fig. 11(a).
Figure 12(a). The amplitude of wavenumber-2 longitudinal temperature structure, derived from the same data as Fig. 11(a).

Figure 12(b). The phase of wavenumber-2 longitudinal temperature structure in solar coordinates, corresponding to the amplitudes of Fig. 12(a).
12 that there are also mean solar-fixed wavenumbers 1 and 2 features in this region, although retrievals are unreliable near the cloud tops for the reasons discussed in section 3. From 70–80°N wavenumber-1 amplitudes are greater than at the equator, although 30–60° out of phase, and wavenumber-2 amplitudes are greater than and approximately 180° out of phase with those at the equator.

9. DISCUSSION, CONCLUSIONS, AND FURTHER WORK

The aim of this paper is to present the final results on the climatological mean temperature structure of the Venusian atmosphere from the cloud tops to the 105 km level, based on the most recent data from the Pioneer Venus mission, without attempting to explain the dynamical causes of the features described. However, a few general comments can be made.

It is clear that the low-latitude temperature minimum at 95 km separates regions of markedly different zonal and meridional temperature structure, and it may occupy the transition region between the zonal circulation regime observed near the cloud tops and the day-to-night regime predicted in the mesosphere and thermosphere by the models of Dickinson and Ridley (1975, 1977). This is supported by the fact that zonal winds derived from a two-dimensional, axisymmetric, diagnostic circulation model tend to low values above 85 km, given the zonal-mean temperature field of Fig. 9 (Elson 1978, 1982).

Well above the clouds the main features of the zonal temperature field shown in Fig. 9 have previously been inferred from relatively cursory analyses of preliminary data and have been described together with their dynamical consequences (Taylor et al. 1980; Elson 1979). Although different in detail the field presented here is consistent with these results. The existence of the cloud top temperature inversion in the collar region is supported by OIR, occultation and probe data, but the physical processes that cause it are not well understood. In the thermal images produced by the OIR, the collar contains wavenumber-1 structure and forms a cold boundary between the more axially symmetric lower latitudes and the complex polar region where wavenumber-2 dipole structure with a rotation period of about 2.9 days is observed. Finally the gradual increase in cloud top pressure level with latitude suggested by Fig. 9 is consistent with Pioneer Venus photopolarimeter results (Kawabata et al. 1980).

The longitudinal wavenumber-2 structure of Fig. 10(a) observed over a broad range of equatorial latitudes must be a solar tide and may be upward propagating. It is interesting to note that the low-latitude temperature field contains wavenumbers 1 and 2 components of comparable magnitude at the cloud tops (Figs. 10(a, b)), as does the solar heating function. However, only the wavenumber-2 component persists, and indeed intensifies, with increasing altitude. If the tide does propagate upwards with a relatively constant phase tilt, the location of its temperature maxima may explain the shifting of the sub-solar maximum observed above 100 km towards the morning side of noon and the existence of the pre-midnight equatorial temperature maximum at the same level. However, the latter feature may also mark the descending arm of a sub-solar to anti-solar circulation regime at high levels. It coincides roughly with a region of enhanced nitric oxide night airglow seen at the same latitudes just after local midnight (Stewart et al. 1980).

In Fig. 10(a) the wavenumber-1 structure of the cloud ceiling may be a marker for zonal wind streamlines. If this is so, the mean vertical wind component has a roughly wavenumber-1 dependence on longitude, with uplift occurring on the dayside and descent on the nightside. For a horizontal wind component corresponding to the rotation period of 5.4 days seen in OIR data (Apt and Leung 1982), given the peak-to-peak variation of 1.9 km in cloud height, maximum vertical velocities of 1.3 cm s⁻¹ occur near noon and midnight. Alternatively solar radiation may act during the day to increase the optical thickness of the clouds which then tend to disperse during the night.

The three-dimensional temperature field and the cloud structure derived in this paper
together with data from the OIR far-infrared channel at 45 μm have been used to study the global distribution of water vapour in the Venustian atmosphere (Schofield et al. 1982). The results gained have also been combined with atmospheric and cloud opacity models to re-address the Venustian thermal balance problem (Schofield and Taylor 1982).

**APPENDIX A**

**TRANSMISSION CALCULATIONS — CHANNELS 2 TO 5**

In the retrieval scheme the gaseous transmission through an atmospheric path in any of the spectral intervals defined by channels 2 to 5 is calculated from the empirical expression

\[ TR(U_g, P_g, T_g) = \exp[-\exp(A(T_g) + B(T_g)\ln(P_g) + C(T_g)\ln(U_g))] \]  

(A1)

where \( U_g \) is the amount of gas in the path, \( P_g \) is its mass-weighted pressure, and \( T_g \) is its mass-weighted temperature. \( A(T_g) \), \( B(T_g) \) and \( C(T_g) \) are unique functions of temperature for each instrument channel and are represented by fourth-order polynomials.

The above expression was fitted to full overlapping-line transmission calculations for each channel, based on the latest available AFGL parameter compilation for carbon dioxide (Rothman 1981). The Voigt profile was used, and the sub-Lorentz shape of the far wings of CO₂ lines was represented crudely by ignoring the wings of lines lying more than 15 cm⁻¹ outside the spectral band-pass defined by a given channel.

For each channel, transmission calculations were performed for 250 combinations of path temperature, length, and pressure, covering the range encountered by the OIR instrument in the middle atmosphere of Venus. Ten path pressures of the form \( (\exp(-N)) \) bar, where \( N = 0 \) to 9, were considered at each of five path lengths of the form \( (5 \times 10^5 \exp(N)) \) cm, where \( N = 0 \) to 4, and these 50 calculations were repeated for path temperatures of 160, 200, 240, 280, and 320 K.

The expression above was fitted to the transmission data for a given channel in the following way. At each path temperature \( A(T_g) \), \( B(T_g) \) and \( C(T_g) \) were chosen iteratively to minimize the standard deviation between model and calculated transmissions. The values of \( A \), \( B \) and \( C \) derived for each channel and temperature are given in Table A1, together

<table>
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<tr>
<th>Channel</th>
<th>Path temp. (K)</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
<th>Standard deviation</th>
<th>Maximum deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>160</td>
<td>1.101979</td>
<td>0.566841</td>
<td>0.568355</td>
<td>0.30233E-02</td>
<td>0.11813E-01</td>
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<td>0.899536</td>
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<td>0.548596</td>
<td>0.36632E-02</td>
<td>0.12463E-01</td>
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<td>0.725808</td>
<td>0.516102</td>
<td>0.528844</td>
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<td>0.13676E-01</td>
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<tr>
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<td>0.509313</td>
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<td>0.14494E-01</td>
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<tr>
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<td>320</td>
<td>0.508600</td>
<td>0.461011</td>
<td>0.488670</td>
<td>0.49608E-02</td>
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<td>320</td>
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<tr>
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<td>0.10544E-01</td>
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<tr>
<td>5</td>
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<td>0.77505E-02</td>
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<tr>
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<td>0.614192</td>
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<td>0.23057E-01</td>
</tr>
</tbody>
</table>
with the standard and maximum deviations associated with each fit. From the five values of $A$, $B$ and $C$ corresponding to the above temperatures fourth-order polynomials were derived to represent the variation of each parameter with temperature. The calculation of one of these parameters from the polynomial coefficients at a particular temperature can be illustrated by the equation

$$A(T_g) = A(6) \sum_{N=1}^{5} A(N) TX^{(N-1)} + A(7)$$  \hspace{1cm} (A2)

where $TX = (T_g - 240.0)/80.0$ is temperature normalized to the range $-1$ to $+1$. Both temperature and the parameters $A$, $B$ and $C$ are normalized to this range before the polynomial fitting is performed and the sixth and seventh coefficients are required to scale the parameters to their original values.

To calculate transmission for a given channel and path $T_g(K)$, $P_g$(bar) and $U_g$(bar cm at $T_g$) must be known. $A(T_g)$, $B(T_g)$ and $C(T_g)$ can then be derived from Eq. (A2) and transmission can be calculated from Eq. (A1).

**APPENDIX B**

**CHANNEL-1 WEIGHTING FUNCTIONS**

Channel-1 weighting functions for the high-pressure modulator cell (PMC) pressure setting are derived from a look-up table based on 115 pre-calculated weighting functions corresponding to a single model atmosphere and covering the range of zenith angles and line-of-sight velocities encountered during the Pioneer Venus mission. These functions are calculated by differentiating cubic-spline fits to the corresponding transmission functions.

Channel-1 transmission functions were calculated from spectral data derived from the band and rotational constants of Drayson and Young (1967). Although less exhaustive than the AFGL data discussed in appendix A, these are quite adequate because of the concentration of channel-1 spectral response near strong lines. The full calculation of channel-1 transmission functions is far more complex and time-consuming than the broadband calculations used for channels 2 to 5, but can be simplified considerably by the non-overlapping line and histogram approximations. These approximations neglect line overlap and allow lines to be grouped into histograms of 20 to 30 'lines'. Resulting errors in transmission are small, but are most significant when atmospheric path pressures are high and when the temperatures of atmospheric and PMC paths differ greatly. From comparisons with full transmission calculations the following empirical expression was developed to correct for these approximations

$$T2(y) = T1(y) \exp[-\exp\{-1.183 - 0.1965 \ln(P_g U_g)\} - 9.3 \times 10^{-6}(DT)^2 \ln\{T1(y)\}]$$ \hspace{1cm} (B1)

where $T2(y)$ and $T1(y)$ are the corrected and uncorrected transmission functions, respectively, $y$ is the logarithmic pressure scale defined in section 3, $DT$ is the temperature difference between atmospheric and PMC paths, $P_g$ is the mass-weighted pressure of gas in the path (bars), and $U_g$ is the amount (grammes). The corrected transmissions are accurate to better than 2% for path temperatures in the range 160–320 K and all relevant zenith angles and line-of-sight velocities (Schofield 1980).

Transmission calculations were performed at 60 levels ranging from $y = 0$ to 29.5 in steps of 0.5, for 115 combinations of 5 zenith angles and 23 line-of-sight velocities. Zenith angles of 0, 48, 63, 72, and 89.9° at the 6104 km level were chosen to give roughly equal increments in the logarithm of absorber amount above a given pressure level, and line-of-sight velocities of 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.3, 1.6, 1.9, 2.1, 2.4, 2.7, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 7.0, 8.0, 9.0 and 10.0 km s$^{-1}$ were selected to allow for the increased dependence of transmission on this parameter at low velocities.

In the retrieval program the look-up table used to calculate weighting functions
consists of a table of coefficients derived by fitting a fourth-order polynomial to the variation with zenith angle of the weighting function derived from the above transmission functions at each level and line-of-sight velocity. Given a zenith angle and a line-of-sight velocity, weighting functions are derived from this table in the following way. At a particular level, weighting functions corresponding to the desired zenith angle are derived rapidly from the polynomial coefficients for the three tabulated line-of-sight velocities closest to the required value. The function at this velocity is then calculated from a quadratic fit to these points. This procedure is repeated at each level to build up a complete weighting function. In order to allow channel-1 weighting functions to be assigned to the averaged data used in retrievals, a mean line-of-sight velocity is calculated for each of the zenith angle, latitude–longitude bins defined in section 3.

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