

Retrieval of Tropospheric CO Profiles Using Correlation Radiometer: I. Retrieval Experiments for a Clear Atmosphere

Wu Beiyong (吴北婴)

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029

John Gille

National Center for Atmospheric Research, P.O. Box 3000, Boulder CO 80307, U.S.A.

(Received January 4, 1999; revised February 8, 1999)

ABSTRACT

This paper discusses the retrieval scheme associated with the gas correlated radiometer—MOPITT which will be on board of EOS-AM1 to measure the global vertical profiles of carbon monoxide. The vertical resolution and retrieval errors caused by errors in the temperature profiles and in the surface temperature have been assessed. The main results are:

a. Assuming the noise equivalent radiance (NER) of $1.8 \times 10^5 \text{ W m}^{-2} \text{ sr}^{-1}$, the surface temperature can be deduced from the wide band signals with uncertainty less than 1 K, and the atmospheric term of the modulated signal can be deduced with errors almost equal to the NER which does not significantly increase errors in the retrieved CO profiles.

b. With typical uncertainty in temperature profiles, errors in the retrieved profiles at latitudes lower than 70° are generally less than 20% with the first guess of 100 ppbv. (If a better first guess was used, the errors may decrease).

c. By incorporating the total column CO amount derived from the reflected solar radiation in $2.3 \mu\text{m}$ spectral region into the retrieval, the accuracy of the retrieved CO profile below 6 km may be greatly improved.

d. In the retrieval experiment with 10 CO profiles representing the typical CO profiles, the r.m.s. relative / absolute errors of the retrieved CO profiles are about 10% / 15–20 ppbv.

Key words: CO retrieval, Correlation radiometer, MOPITT

1. Introduction

Measurement of CO profiles in the troposphere is of primary importance for improving our understanding of the global system. This opinion has been put forward in the report of the World Meteorological Organization (1985): "Definition of trends and distribution for tropospheric CO is essential." (World Meteorological Organization, 1985). This is because Carbon monoxide (CO) plays a very important role in the chemistry of the troposphere and lower stratosphere through its influence over hydroxyl radical (OH) and ozone concentration. Because of its short atmospheric residence time (2–3 months) and nonuniform geographical distribution, it is necessary to monitor the temporal-spatial change of CO around the globe. For this purpose, a gas correlation radiometer—Measurements of Pollution in the Troposphere (MOPITT) was proposed by Drummond at University of Toronto and selected for EOS-AM1 platform. The operation of this instrument is based on the correlation spectroscopy technique which has been used successfully for radiometers on board Nimbus 4,5,6 and 7 (Abel et al., 1970; Curlic et al., 1974; Ellis et

al., 1973; Drummond et al., 1980). Technical improvements include the combination of two modes of modulation: pressure modulation radiometer (PMR) and length modulation radiometer (LMR). The former has been used in several applications while the latter is a new design suitable for the detection of lower troposphere where the atmospheric pressure is higher.

As an initial study of the retrieval schemes for MOPITT project, this paper describes the retrieval scheme using the gas correlation signals in two spectral regions: the CO fundamental band around 2140 cm^{-1} ($4.7 \text{ }\mu\text{m}$) and the first overtone around 4260 cm^{-1} ($2.4 \text{ }\mu\text{m}$), the achievable accuracy and other related problems. CO profiles measured by Seiler and Fishman (1981) are used in a line-by-line code to simulate the upward propagating atmospheric radiation and the signals measured by the PMRs or LMRs. A non-linear iteration scheme is proposed to retrieve CO profiles from these signals. The total column CO amount derived from the $2.3 \text{ }\mu\text{m}$ reflected solar radiation is used to improve the retrieval accuracy in the near-surface layer. The effects of the absorption by other gases such as methane, ozone, water vapor and nitrous oxide on the measurement as well as the retrieval in the presence of solid clouds will be discussed in a separate paper. Discussing the basic retrieval scheme and corresponding limits and accuracy, this study will lay a basis for further operational retrieval algorithms.

2. Basic equations

The principle behind correlation spectroscopy is that of spectral selection of radiation emitted or absorbed by a gas using a cell containing a sample of the same gas as the filter. Using two cells containing different amounts of the gas concerned, the differential transmittance of the two cells will be zero in the whole spectral interval except at the center or near the wing region of the absorption lines of this gas. This is equivalent to a filter which can selectively pass the radiation modulated by certain gas, but eliminate the interference by other gases. The modulation of gas in the cell can be achieved by many methods. For tropospheric detection, Drummond at the university of Toronto proposed to use combinatively LMRs and PMRs. Technically, LMR can be modulated to higher cell pressure. It is more suitable for the detection of lower troposphere. Due to a first approximation, it is the product of the mass of gas and the half width of absorption line that affects the transmittance of the cell, PMRs may be equivalent to LMRs in the discussion of retrieval scheme. The radiative transfer equations in a plane-parallel atmosphere for a two state correlation radiometer (PMR or LMR) are:

$$S_{w0} = \frac{1}{2} G_w \int_{\Delta\nu} \tau_{iw} [I_\nu - \int_0^{p_s} q(p)(I_\nu - B_\nu) \frac{k_\nu(p)}{g} \tau_\nu(p) dp] d\nu, \quad (1)$$

$$S_{m0} = G_w G_m \int_{\Delta\nu} \tau_{im} [I_\nu - \int_0^{p_s} q(p)(I_\nu - B_\nu) \frac{k_\nu(p)}{g} \tau_\nu(p) dp] d\nu, \quad (2)$$

where S_{w0} is the wide band radiance ($\text{W m}^{-2} \text{ sr}^{-1}$), S_{m0} is the side band radiance ($\text{W m}^{-2} \text{ sr}^{-1}$) or modulated signal, G_w and G_m are the electronic gains of the wide band and side band channels, respectively, p_s is the pressure at the ground surface, p is the atmospheric pressure, I_ν is the surface emission which is a function of the surface temperature, B_ν is the Planck function as a function of atmospheric temperature (pressure), $\tau_\nu(p)$ is the atmospheric transmittance, $k_\nu(p)$ is the CO absorption coefficient, $q(p)$ is the CO mixing

ratio, g is the acceleration of the gravity, $\tau_{iw} = \tau_i[\tau_i + \tau_h]$ and $\tau_{im} = \tau_i[\tau_i - \tau_h]$ are the transmittances of the instrument, τ_f is the overall optical filter transmittance, τ_i and τ_h are the monochromatic gas transmittances of the cell for the two states, respectively.

S_{m0} and S_{w0} are the measured signals. Both of them have contributions from the surface and atmosphere, but most of the wide band signal S_{w0} comes from the surface emission because the atmospheric transmission in the 4.6 μm spectral region is close to unity except near the spectral line center while S_{m0} mainly comes from the atmosphere. In the retrieval, the surface term I_v is deduced from the wideband signal S_{w0} and then introduced in the calculation of the surface term of the modulated signal S_{mg} . The following equations are thus constructed:

Eq. (2) may be written as:

$$S_{mg} - S_{m0} = G_w G_m \int_0^{p_s} q(p) dp \int_{\Delta v} (I_v - B_v) \frac{k_v(p)}{g} \tau_v(p) \tau_{im} dv = \int_0^{p_s} q(p) R_m(p) dp, \quad (3)$$

$$S_{mg} = G_w G_m \int_{\Delta v} I_v \tau_{im} dv, \quad (4)$$

where a quasi-weighting function is defined as follows:

$$R_m = G_w G_m \int_{\Delta v} (I_v - B_v) \frac{k_v(p)}{g} \tau_v(p) \tau_{im} dv. \quad (5)$$

As mentioned above, S_{mg} can be derived if the surface term I_v is known. The left hand side of Eq. (3) is thus known. Eq. (3) is a Fredholm integral equation of the first kind. The retrieval of the CO profile based on Eq. (3) is a non-linear problem because the atmospheric transmittance $\tau_v(p)$ is a function of atmospheric compositions including CO. R_m is not the classical weighting function in temperature retrieval because it depends on CO mixing ratio also. Therefore, the relative contribution of each level to the received signal is determined by both R_m and $q(p)$. To retrieve CO profile from the signals, auxiliary information on the temperature profile is needed. The sensitivity of the retrieval to errors in temperature measurement should be assessed. In order to calculate the surface emission the surface temperature should also be known. Besides, there are some inherent problems, e.g., the measurement is not sensitive to CO change in the near surface layer and isothermal layer, etc. (Zeng, 1974).

3. Retrieval experiment

In analyzing the signals and designing the retrieval scheme, the line-by-line code (GENLIN) developed by Drummond was used. In this code the atmosphere path is expressed in terms of N layers each containing only a single gas. In the following calculation, the atmospheric path is divided into 30 layers. Typical temperature profiles for low, mid and high latitudes and CO profile measurements are used to define the atmospheres considered. The spectral region covered is from 2140 to 2192 cm^{-1} (4.56–4.67 μm) which is further divided into several subranges with a width of 2 cm^{-1} . The spectral step for calculation is 0.005 cm^{-1} in each subrange.

3.1 The vertical resolution and channel selection

To analyze the spatial resolution of this non-linear retrieval problem, the weighting

function for the variation of the modulated signal is calculated. The variation of the modulated signal with respect to $q(p)$ is

$$\delta S_m = \delta S_{mR} - \delta S_{m0} = \int_0^{p_s} K_v^*(p) \frac{\delta q(p)}{q(p)} dp, \quad (6)$$

where the weighting function for δS_m is

$$K_v^*(p) = [- (I_v - B_{v_s}) \tau_v(p_s) k_v(p) \frac{q(p)}{g} + k_v(p) \frac{q(p)}{g} \int_{p_s}^p \frac{\partial B_v(p)}{\partial p} \tau_v(p) dp] G_w G_m \tau_{im}, \quad (7)$$

where $\tau_v(p_s)$ is the vertical transmittance of the whole atmosphere, B_{v_s} is the Planck function at the surface temperature. The characteristics of the weighting functions for the initial set of channels are listed in Table 1. A constant CO mixing ratio of 100 ppbv and temperature profile at 40°N are used in this calculation for a 10 mm cell pressure modulated radiometer (PMR).

The weighting functions for several sets of channels were compared. As the equivalent width of an absorption line is a function of the product of the half width α of the absorption line and the mass of the gas, the shape and value of the weighting functions are determined by the product of the pressure in the cell and the mass of absorbing gas in the cell. There are about 4 distinct channels among all tested sets. The 10 mm PMR channel with different pressure differences is one of the representative sets for all the combinations. Therefore, the 10 mm PMR channel with different pressure differences is one of the representative sets for all the combinations. Therefore, the 10 mm PMR channels with various pressure differences are selected in the following retrieval experiments.

Even with the variation of PMR and LMR, the peaks of the weighting functions can not be separated very much in altitude (other technical developments, such as double passing the LMRs, may improve this in future). The widths are also similar, and there is clearly a large amount of overlap of the weighting function. However each channel still contributes to the total information available. It is clear that the vertical resolution of this technique is limited. Although the peaks of weighting functions for the four channels shown in Table 1 are at about the same altitude, their half widths and shapes are not identical. That means that they are not totally correlated. There is still new information brought about by each channel. Because of all the weighting function peak in the range from 6 to 10 km, the channels are not sensitive to CO changes in the near-surface layer. Complementary information should be used in this layer. In this study, the reflected solar radiation at 2.3 μm is used to increase the retrieval accuracy in the near-surface layer.

Table 1. The Halfwidth, Peak Value and Peak Position of the Weighting Function

Channel	Halfwidth (km)	Peak value ($\text{W m}^{-2} \text{sr}^{-1}$)	Peak position (km)
200–400 hPa	11.29	-5.79E-30	6.75
100–200 hPa	11.01	-7.18E-30	6.75
50–100 hPa	10.34	-6.25E-30	8.25
25–50 hPa	9.15	-3.96E-30	9.75

3.2 The retrieval scheme using signals in the 4.6 μm spectral region

For this non-linear problem, Chahine method (Twomey, 1977) was adopted for its relative simplicity and accuracy. By this method, the CO mixing ratio at pressure p_j is obtained by the following iteration:

$$q^{(k)}(p_j) = \frac{S_{mg} - S_{m0}}{S_{mg}^{(k-1)} - S_{m0}^{(k-1)}} q^{(k-1)}(p_j), \quad (8)$$

where j is the index of height, k is the number of iterations. The surface term of the modulated signal S_{mg} is derived from the wide band measurement. The wide band signal S_{m0} consists of almost entirely the surface emission because the atmospheric transmission in the 4.6 μm spectral region is close to unity except near the spectral line center. The first term of the Eq. (2) (S_{mg}) can thus be obtained from the total wide band signal. Two kinds of retrieval experiments were carried out. One is for a known surface temperature. The other uses the surface temperature deduced from the wide band signal. The r.m.s. errors in the retrieved CO profiles and the residual in the signals are calculated.

3.2.1 Retrieval with a known surface temperature

Table 2. The r.m.s. Error in the Retrieved Profile and the Residual (Chahine Method, first guess: 100 ppbv. Measurement error = $1.8 \times 10^{-5} \text{ W m}^{-2} \text{ sr}^{-1}$, for CO profile: 58°N, 42°N and 53°S). S_0 is the measured signal, $q^{(0)}$ is the first guess of CO profile, $q^{(k-1)}$ is the CO profile for $(k-1)$ th iteration

Case	Profile (ppbv)				Signal ($\text{W m}^{-2} \text{ sr}^{-1}$)	
	With respect to $q^{(k)}(p)$		With respect to $q^{(0)}$		With respect to S_0	
	r.m.s. ab	r.m.s.rela	r.m.s. ab	r.m.s.rela	r.m.s.ab	r.m.s.rela
58°N	1.82e-9	0.0163	1.11e-8	0.122	1.15e-5	0.0098
42°N	8.46e-10	0.0094	2.45e-8	0.137	1.58e-5	0.0133
53°S	1.44e-9	0.0230	6.99e-9	0.138	1.68e-5	0.0218

Retrieval experiments were conducted with a known surface temperature. Three CO profiles were used in this test. They are: profiles measured in 53°S, 42°N and 58°N by Seiler and Fishman (Seiler and Fishman, 1981). The temperature profile of June in 40°N was used in this calculation. The r.m.s. errors of the results are shown in Table 2. The definitions of the absolute and relative r.m.s. errors are:

$$r.m.s.ab = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - x_i^0)^2},$$

$$r.m.s.rela = \sqrt{\frac{1}{N} \sum_{i=1}^N \left(\frac{x_i - x_i^0}{x_i^0}\right)^2},$$

where N is the number of levels, x_i and x_i^0 are the retrieved and the true CO mixing ratio, respectively for the case of CO profile (ppbv); N is the number of channels, and x_i and x_i^0 are the derived signal and true signal ($\text{W m}^{-2} \text{ sr}^{-1}$) for the case of measured signal.

3.2.2 Retrieval results with surface temperature derived from the wide band signals

As discussed above, the surface term in the modulated signals may be derived from the wide band signal. This is more realistic because both signals can be obtained simultaneously in practice. The regression relation between S_{w0} and S_{mg} and the regression relation between S_{w0} and T_g (the surface temperature) may be calculated with a first guess of the CO profile. Then, retrieval can go on as described in the following paragraph using S_{mg} and T_g derived from those regression relations. After the true values of the integrated ($S_{m00} = S_{mg0} - S_{m00}$), surface (S_{mg0}) and total (S_{m00}) terms of the modulated signal and the total term (S_{w00}) of wide band signal are calculated using the assumed true temperature, CO profiles and the surface temperature, the iterations are carried out at following steps:

a. Calculating a set of S_{w0} and S_{mg} corresponding to the surface temperatures in the normal climate range with a first guess of CO profile $q^{(k-1)}$, $k=1,2,\dots$ is the number of iteration.

b. Finding the regression relation between the wide band signal S_{w0} and the surface term of the modulated signal S_{mg} and the regression relation between S_{w0} and the surface temperature T_g .

c. Finding the estimated values of the surface term of the modulated signal (S_{mg1}) and the ground temperature (T_{g1}) from the above calculated regression relations using the simulated measurement value $S'_{w00} = S_{w00} + \Delta S$ where ΔS is the measurement error which is assumed to distribute randomly with the normal distribution of standard deviation ΔS over all the channels.

d. Finding the difference between the measured modulated signal S'_{m00} and the estimated surface term S_{mg1} : $S_{md1} = S'_{m00} - S_{mg1}$.

e. Calculating the weighting function using the first guess CO profile, temperature profile and the estimated T_{g1} .

f. Retrieving a new CO profile from the S_{md1} .

g. Repeat steps a–g using the retrieved CO profile as a new guess.

The same 3 CO profiles as in Table 2 were selected in this experiment. The r.m.s. errors are shown in Table 3.

Table 3. The r.m.s. Error in the Retrieved Profile and the Residual with the ground temperature T_g being derived. ΔT_g is the difference of the retrieved and true surface temperature. ΔS_{md} is the difference of the derived and true integrated term of the modulated signal. Other symbols are the same as Table 2.

Case	ΔT_g (K)	ΔS_{md} (max)	Profile (ppbv)				Signal ($W m^{-2} sr^{-1}$)	
			With respect to $q^{(k)}(p)$		With respect to $q^{(0)}$		With respect to S_0	
			ab	rela	ab	rela	ab	rela
58°N	0.56	1.62e-5	4.44e-9	0.044	1.28e-8	0.125	1.46e-5	0.014
42°N	0.49	1.95e-5	3.19e-9	0.023	2.99e-8	0.171	1.59e-5	0.015
53°S	0.69	1.92e-5	8.83e-10	0.012	6.96e-9	0.132	1.37e-5	0.020

Table 3 indicates that the uncertainty in the estimated surface temperature is less than 0.7 K and the uncertainty in the resulting S_{md} is less than $2.0 \times 10^{-5} W m^{-2} sr^{-1}$. Compared with errors shown in Table 2, errors shown in Table 3 are not significantly larger. This experiment verifies the feasibility of the above proposed retrieval scheme.

3.2.3 Retrieval with errors in the temperature profile

Table 4. The r.m.s. Error in the Retrieved Profile and the Residual (Same as Table 3 except for Using Temperature Profile: 10°N with 1 K Errors)

Case	$\Delta T_g (K)$	$\Delta S_{nd} (max)$	Profile				Signal	
			With respect to $q^{(k)}(p)$		With respect to $q^{(0)}$		With respect to S_0	
			ab	rela	ab	rela	ab	rela
58°N	0.45	1.60e-5	3.25e-9	0.0287	1.18e-8	0.126	6.44e-6	0.0072
42°N	0.43	1.60e-5	4.63e-9	0.0394	3.79e-8	0.211	9.53e-6	0.0116
53°S	0.63	2.23e-5	2.77e-9	0.0397	6.74e-9	0.136	1.77e-5	0.0273

Table 5. The r.m.s. Error in the Retrieved Profile and the Residual (Same as Table 3 except for Using Temperature Profile: 40°N with 1 K Errors)

Case	$\Delta T_g (K)$	$\Delta S_{nd} (max)$	Profile				Signal	
			With respect to $q^{(k)}(p)$		With respect to $q^{(0)}$		With respect to S_0	
			ab	rela	ab	rela	ab	rela
58°N	0.54	1.75e-5	2.60e-9	0.0232	1.17e-8	0.124	5.99e-6	0.0054
42°N	0.45	2.02e-5	3.67e-9	0.0257	2.68e-8	0.171	1.53e-5	0.0152
53°S	0.68	1.89e-5	9.69e-10	0.0136	6.46e-9	0.133	1.36e-5	0.0196

Table 6. The r.m.s. Error in the Retrieved Profile and the Residual (Same as Table 3 except for Using Temperature Profile: 70°N with 1 K Errors)

Case	$\Delta T_g (K)$	$\Delta S_{nd} (max)$	Profile				Signal	
			With respect to $q^{(k)}(p)$		With respect to $q^{(0)}$		With respect to S_0	
			ab	rela	ab	rela	ab	rela
58°N	0.65	1.43e-5	1.96e-9	0.0178	1.19e-8	0.125	5.88e-6	0.0041
42°N	0.56	2.89e-5	3.26e-9	0.0211	2.44e-8	0.166	1.75e-5	0.0136
53°S	0.75	1.82e-5	8.39e-10	0.0112	6.99e-9	0.145	1.59e-5	0.0170

Table 7. The r.m.s. Error in the Retrieved Profile and the Residual (Same as Table 3 except for Using Temperature Profile: 10°N with Typical Winter Errors)

Case	$\Delta T_g (K)$	$\Delta S_{nd} (max)$	Profile				Signal	
			With respect to $q^{(k)}(p)$		With respect to $q^{(0)}$		With respect to S_0	
			ab	rela	ab	rela	ab	rela
64°N	0.45	1.56e-5	4.68e-9	0.0399	2.55e-8	0.188	1.74e-5	0.0162
58°N	0.53	1.79e-5	2.04e-9	0.0204	1.43e-8	0.133	9.53e-6	0.0102
42°N	0.51	1.76e-5	4.05e-9	0.0405	4.62e-8	0.240	1.10e-5	0.0135
53°S	0.68	2.40e-5	3.17e-9	0.0510	9.21e-9	0.154	1.39e-5	0.0205

Table 8. The r.m.s. Error in the Retrieved Profile and the Residual (Same as Table 3 Except for Using Temperature Profile: 75°N with Typical Winter Errors)

Case	ΔT_g (K)	ΔS_{mid} (max)	Profile				Signal	
			With respect to $q^{(k)}(p)$		With respect to q^{601}		With respect to S_0	
			ab	rela	ab	rela	ab	rela
58°N	0.78	4.03e-3	1.22e-9	0.0130	1.67e-8	0.352	3.84e-5	0.0210
42°N	0.71	5.05e-3	1.52e-9	0.0154	2.17e-8	0.358	4.09e-5	0.0233
53°S	0.82	2.93e-3	1.24e-9	0.0196	1.28e-8	0.361	1.77e-5	0.0153

In practice, temperature is measured with errors. In order to assess the induced errors in the retrieval, three temperature profiles with errors randomly distributed over the altitude range with the normal distribution of standard deviation 1 K were used. They are the temperature profiles for 10°N, 40°N, and 70°N, respectively. The r.m.s. errors of the results are shown in Tables 4, 5 and 6. Tests were also carried out (Tables 7 and 8) using temperature profiles for 10°N and 75°N with typical temperature errors in winter which are usually larger.

Comparing Tables 4, 5 and 6 with Table 3, it can be found that errors in the temperature profiles slightly increase the retrieval errors. Besides, the latitudinal variation of the temperature profile can also slightly affect the retrieval results. As the errors in the temperature profile are larger in winter, they present the worst situation in the temperature profile. It can be found that retrieval errors increase very much for the case with the temperature profile of 75°N because the Planck function is more sensitive to errors in the temperature at lower temperature.

3.3 Scheme using the additional reflected solar radiation in 2.3 μm spectral region

As shown in Table 1, the sensitivity of the retrieval is limited in the near-surface layer. In order to improve the retrieval accuracy at levels near the surface, the additional information on the reflected solar radiation in 2.3 μm spectral region is used to derive the total columnar CO amount. The following scheme was designed to utilize this information. When the total columnar CO amount is known and the columnar CO amount above 6 km (Q_{up}) is calculated from the retrieved CO profile, the CO amount below 6 km (dQ) can be obtained. It is found by numerical simulations that dQ is highly correlated with the CO mixing ratio at levels below 6 km. Figs. 1(a)–1(e) show the correlations between dQ and q_8 , $q_{1.5}$, $q_{3.0}$, $q_{4.5}$ and $q_{6.0}$ (the true CO mixing ratio at surface, 1.5 km, 3.0 km, 4.5 km and 6.0 km level, respectively) with the global mean CO profile as the first guess. It can be seen that the values of CO mixing ratio below 4.5 km level are highly correlated, but the CO value above 6 km is not well correlated with the CO value below.

The relation between dQ and CO mixing ratio changes slightly with the first guess (Fig. 2). This is not surprising because dQ depends on the retrieved profiles which rely heavily on the first guess.

The regression relations between $dQ = Q_{\text{true}} - Q_{\text{up}}$ and CO mixing ratio at several lower levels can be calculated beforehand based on certain first guess of the CO profile. In the retrieval experiment, when the total columnar CO amount (Q_{true}) is known, dQ can be calculated by integrating the retrieved CO profile over the height range from 6 km up. The retrieved CO values at each of those levels may be corrected based on the found regression relations.

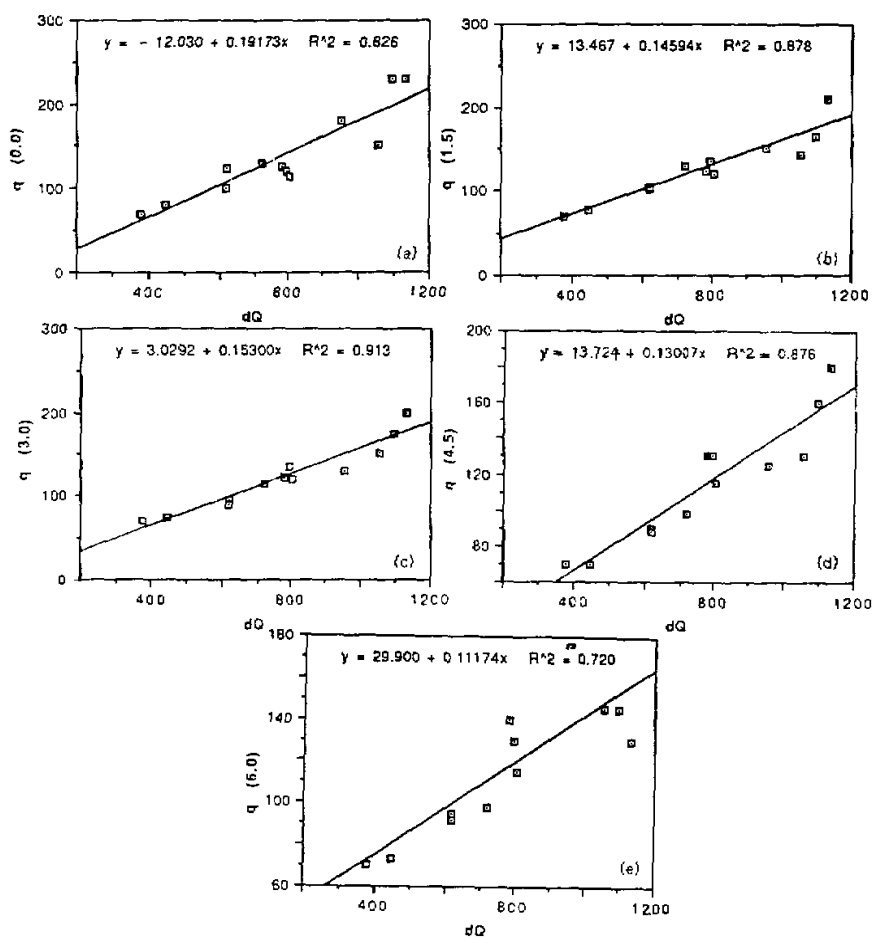


Fig. 1 (a). Correlation between dQ and q_0 ; (b) Correlation between dQ and $q_{1.5}$; (c) Correlation between dQ and $q_{3.0}$; (d) Correlation between dQ and $q_{4.5}$; (e) Correlation between dQ and $q_{6.0}$.

3.4 Retrieval results

The accuracy of the retrieval depends on the first guess. To improve the retrieval accuracy, the first guess should be made to be close to the real CO profile. Therefore, instead of the constant CO profile used in Section 2, a global mean CO profile was calculated by averaging over a set of 24 typical CO profiles measured by Seiler and Fishman (1981). As the concentration and shape of CO profiles change with latitude, the average was weighted according to the area covering the corresponding latitudes.

Following the retrieval steps described in Section 2, two types of experiments were conducted. In type (a), only signals in the $4.6 \mu\text{m}$ spectral region were used with the global mean CO profile as the first guess. In type (b), besides using the global mean as the first guess, the total columnar CO amount was used through the linear regression relations to

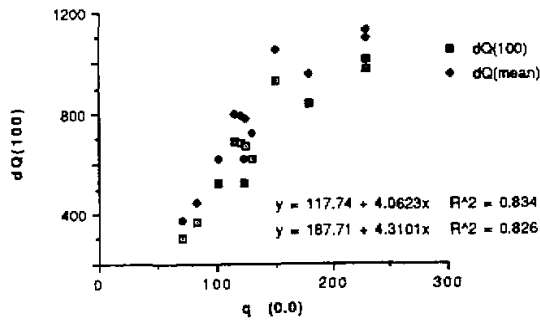


Fig. 2. The relation between dQ and CO mixing ratio with different first guess.

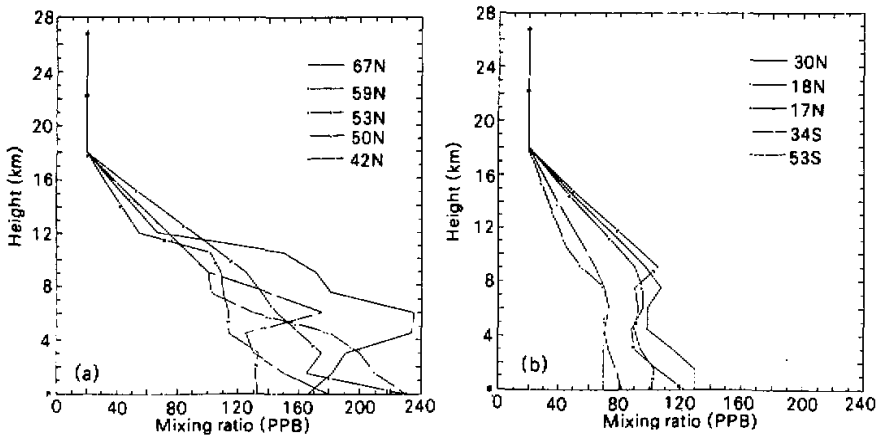


Fig. 3a and 3b. 10 CO profiles used in the retrieval experiment.

correct the CO values at level below 4.5 km in the final retrieved profile when the residual met the criterion. 10 typical CO profiles (Fig. 3a and Fig. 3b) were used in this experiment. The errors in measurements were assumed to be $1.8 \times 10^{-5} \text{ W m}^{-2} \text{ sr}^{-1}$. The average absolute and relative errors in the 10 retrieved profiles as a function of height are shown in Fig. 4 and Fig. 5. The standard deviation of the 10 profiles is also shown for comparison. By using the global mean CO profile as the first guess, the retrieval errors are less than that shown in Table 2 through Table 4. Clearly the retrieved profiles are substantially more accurate than the average of the 10 profiles. In the upper troposphere, the retrieval errors are generally less than 10%, i.e. 15–20 ppbv. Errors increase rapidly in the layer below 2 km and reach 30% at the surface. By using the regression relation to correct CO values below 6 km, the retrieval accuracy improves further. Therefore, it is very important to obtain the CO columnar amount from the additional $2.3 \mu\text{m}$ reflected solar radiation detection.

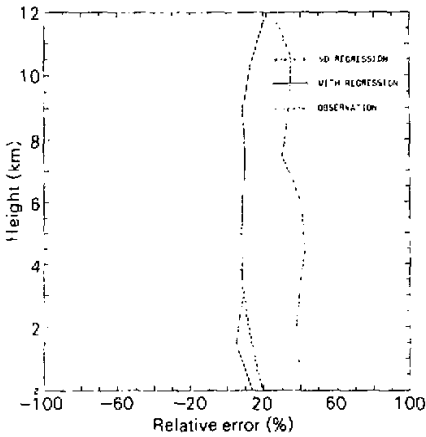


Fig. 4. Average absolute errors of the retrieval.

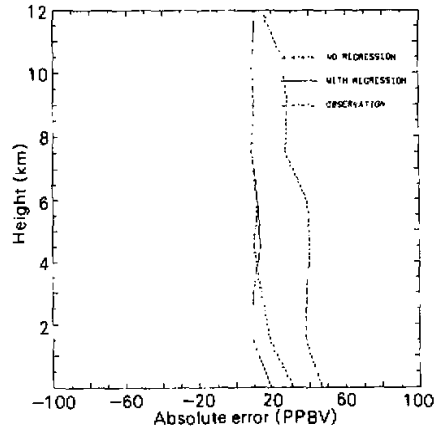


Fig. 5. Average relative errors of the retrieval.

4. Summary

In this paper, the scheme of retrieving CO profiles has been discussed. The retrieval errors induced by errors in the temperature profiles and in the surface temperature have been assessed. The following conclusions may be drawn from the above study:

a. Assuming the noise equivalent radiance (NER) of $1.8 \times 10^{-5} \text{ W m}^{-2} \text{ sr}^{-1}$, the surface temperature can be deduced from the wide band signals with uncertainty less than 1 K, and the atmospheric term of the modulated signal can be deduced with errors almost equal to the NER which does not significantly increase errors in the retrieved CO profiles.

b. Errors in the temperature profile may increase errors in the retrieved CO profile. With typical uncertainty in temperature profiles, errors in the retrieved profiles at latitude lower than 70° are generally less than 20% with the first guess of 100 ppbv. (If a better first guess was used, the errors may decrease). An extreme case was calculated with temperature profile at 75°N plus typical winter errors. In this case the error was about 35%, much greater than other cases.

c. By incorporating the total column CO amount derived from the reflected solar radiation in $2.3 \mu\text{m}$ spectral region into the retrieval, the accuracy of the CO profile below 6 km may be greatly improved.

d. In the retrieval experiment with 10 CO profiles representing the typical CO profiles, the r.m.s. error of the retrieved CO profiles is about 10% or 15–20 ppbv.

We wish to thank Prof. J. Drummond at University of Toronto for providing the line-by-line code and many useful discussions, Dr. Paul Bailey and Cheryl Craig of the National Center for Atmospheric Research for consulting on computational problems, Dr. J. McConnell of the York University for providing the model CO profile and Dr. Bob Chatfield and Dr. Guy Brasseur of the National Center for Atmospheric Research for useful information on CO observations.

REFERENCES

- Abel, P. G. et al., 1970: Remote sensing of atmospheric temperature from satellites II. The selective Chopper Radiometer for Nimbus D. *Proc. Roy. Soc. Lond.*, **A320**, 35-55.
- Curlie, P. D. et al., 1974: Remote sensing of atmospheric temperature from satellites V, The Pressure Modulator Radiometer for Nimbus F. *Proc. Roy. Soc. Lond.*, **A377**, 135-150.
- Drummond, J. R. et al., 1980: The stratospheric and Mesospheric Sounder on Nimbus 7. *Phil. Trans. Roy. Soc. Lond. A* **296**, 219-241.
- Drummond, J. R., 1992: "The use of EOS for studies of atmospheric physics". J. C. Gille and G. Visconti ed., North-Holland (Amsterdam, Oxford, New York, Tokyo).
- Ellis, et al., 1973: Remote sensing of atmospheric temperature from satellites IV. The selective Chopper Radiometer for Nimbus 5. *Proc. Roy. Soc. Lond. A* **334**, 149-170.
- Seiler, W., and J. Fishman, 1981: The distribution of Carbon monoxide and ozone in the free troposphere. *J. G. R.*, **86**, **C8**, 7255-7265.
- Twomey, S. 1977: *Introduction to the mathematics of inversion in remote sensing and indirect measurements*, Elsevier Scientific Publishing Company.
- WMO, 1985: Atmospheric Ozone, WMO Global Ozone Research and Monitoring Project, Report No. 16, Vol. II, P478 and P 490. NASA, FAA, NOAA, UNEP, WMO, CEC, BMFT.
- Zeng, Q., 1974: *Principles of Atmospheric Infrared Sounding (in Chinese)*, Science Press, pp 174.