# REMOTE SENSING OF TERRESTRIAL MESOSPHERIC TEMPERATURES BY MODULATION SPECTROSCOPY METHOD WITH BREAKDOWN OF LTE TAKEN INTO ACCOUNT

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*The effect of local thermodynamic equilibrium (LTE) breakdown on the accuracy of thermal sensing of the Earth's mesosphere using modulation spectroscopy techniques is considered; the physical phenomena responsible for such breakdown are studied. Computer simulations demonstrate that the numerical procedure, suggested to take account of LTE breakdown, are quite effective; the expected accuracies are estimated.*

## INTRODUCTION

Lately, modulation techniques along with the method of radiation spectral filtration have found wide application to remote sensing of the Earth from space. In Ref. 1 a measurement system was described built around a set of $CO_2$ -filled cells, the pressure within which was varied periodically.

According to authors of Ref. 1 this system makes it possible to retrieve information on the atmospheric thermal regime at 40 to 90-km altitudes from measurements of the radiation outflow from nadir in the 15-μm $CO_2$ band. However, correct description of the transfer of 15 μm $CO_2$ radiation in the earth's atmosphere is known to be impossible above 70 km without taking account of breakdown of local thermodynamic equilibrium (LTE).[2]

The present paper pursues the tasks of 1) assessing LTE breakdown and its effect upon the temperature retrievals by the above-described observational technique; 2) analyzing the physical sources of this effect.

## MATHEMATICAL FORMULATION OF THE PROBLEM

We start from the following expression for the Intensity of radiation reaching the detector at a frequency ν in the 15-μm band

$$I_\nu = \exp[-\tau_\nu(P_c, T_c)] \int_0^{z_{max}} S(z) \frac{\partial}{\partial z}\left[ \exp\left\{ \int_z^{z_{max}} \sigma_\nu(z')dz' \right\}\right] dz + S(T_c)\,[1 - \exp(-\tau_\nu(P_c, T_c))]. \quad (1)$$

The first term here describes radiation which has left the atmosphere and been attenuated in an $CO_2$-containing cell (the latter has an optical depth $\tau_\nu$ at pressure $P_c$ and temperature $T_c$); the second term describes radiation from the cell itself; the source function is denoted as $S$, and the volume absorption coefficient of monochromatic radiation is $\sigma_\nu$. We ignore the radiation contribution to $I_\nu$ from the underlying surface in the expression (1) since a spectral input filter is present, with its transmission window covering the center of the 15-μm band. Besides, the parameters of the cells actually used limit the sensitivity of the measured signal to atmospheric characteristics within the 40–90 km range of altitudes.[1]

This last circumstance allows us to employ the isolated-line approximation to describe atmospheric radiation transfer. Within this approximation it is quite simple to account for the input from the whole set of spectral lines in the transmission window of the above-mentioned spectral filter.

If the cell pressure is modulated, its value is changed periodically

$$P_c = P_{c0} + \Delta P_c \cdot \sin\omega t, \quad (2)$$

so that instead of radiation intensity we record the depth of its modulation

$$I_{m,\nu} = I_\nu(P_{max}) - I_\nu(P_{min}). \quad (3)$$

Integrating (3), with Eq. (1) taken into account, over frequency domain within the contour of each separate spectral line and summing all the lines from above, we obtain the desired value of the measured signal

$$I_m(P_{c0}) = \int_0^{z_{max}} S(z)\, R_{LTE}(P_{c0}, z)\, dz, \quad (4)$$

where

$$R_{LTE}(P_{c0}) = \frac{\partial}{\partial z}\left\{ \sum_l \int_0^{\infty} d\nu\, e^{-\int_z^{z_{max}} \sigma_{\nu,l}(z')dz'}\right.$$

 

$$\times \left[ e^{-\tau_{\nu}(T_c,\ P_{max})} - e^{-\tau_{\nu}(T_c,\ P_{min})} \right] \Bigg\} d\nu \qquad (5)$$

is the weighting function. The latter is valid only for the modulation method of thermal sensing under LTE conditions,[1] and is written in the isolated-line approximation (the index $l$ used to number the lines). To simplify our expressions we omitted the term in $R_{LTE}$ due to cell radiation, since its intensity is always known (provided cell parameters do not change with time). Also, instead of considering all the vibrational transitions, which form the 15-μm $CO_2$ band, and calculating their sum, we will consider the one fundamental transition of the $CO_2$ principal isotope. The latter simplification is not fundamental in character and is justified by the dominating contribution of the above-stated transition to the total 15-μm band intensity.

Furthermore, following Ref. 3 we can write

$$S(z) = \int_0^{z_{max}} G(z,\ z')[1 - \ (z')]B(z')dz', \qquad (6)$$

where $B(z)$ is the LTE source function (the Planck function); $\Lambda(z)$ is the probability of quantum survival during Raman scattering; $G$ is the Green function, satisfying the equation

$$G(z,z'') = \frac{(z)}{2} \int_0^{z_{max}} K(z,z')\ G(z',z'')dz' + \delta(z - z''); \qquad (7)$$

its kernel is described in Ref. 2.

Substituting (6) into (4), we obtain

$$I_m(P_{c0}) = \int_0^{z_{max}} R(P_{c0},\ z')B(z')dz', \qquad (8)$$

where

$$R(P_{c0},\ z') = \int_0^{z_{max}} R_{LTE}(P_{c0},\ z'')G(z'',\ z') \times$$

$$\times [1 - \ (z')]dz'', \qquad (9)$$

is the new weighting function of the temperature determination equation, accounting for deviations from LTE.

As can be seen, ignoring such deviations means replacing $S(z)$ in (4) by $B(z)$, and keeping $R_{LTE}(P_{c0}, z)$ for the weighting function. On the other hand, the relationships (8) and (9) describe a method to account for LTE breakdown during temperature retrievals.

## ANALYSIS OF NUMERICAL RESULTS

A detailed description of the technique for the numerical solution of Eqs. (4) and (8) can be found in Ref. 4. It is based on representing the desired atmospheric pressure profile as a segment of a Chebyshev polynomial series with unknown coefficients. The more terms in such a series, the heigher approximation accuracy is for the actual atmospheric temperature distributions. However the rms error of retrieval is also increasing simultaneously. Indeed, following Ref. 1, when choosing, the parameters of the modulation cells, we cam only obtain a few weighting functions, the maxima of which are positioned at various levels within the altitude range we are interested in. Therefore, that maximum number $N$ of the terms of the polynomial series was found, which would still provide for stable retrieval of the temperature profile. This criterion is satisfied by $N = 4$.

Figure 1 presents the weighting functions $R_{LTE}$ and $R$ for two values of $P_{c0}$ which, in the case of LTE, reach maxima at 60 and 90 km. It can be seen that in the first case (60 km) LTE breakdown become noticeable only at $z \geq 80$ km. In the second case (90 km) the maximum shifts downward. The new displaced position of the weighting function coincides with the maximum of the Green function $G(z, z')$ for $z > 80$ km and thus results from processes of multiple photon scattering followed by frequency redistribution.

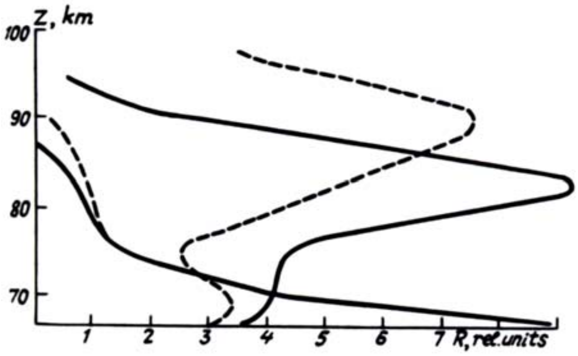


*FIG. 1. Variation of weighting functions to account for LTE breakdown. Solid line refers to case when LTE breakdown is taken into account; dashed line refers to the LTE approximation.*

A similar multiple scattering effect can be found by analyzing the weighting functions from the initial equation; it is used for determining the temperature from tangential path measurements.[3] The only difference that slant paths make is that the weighting function maxima in the perigee region, clearly evident for LTE, becomes less pronounced in the presence of LTE breakdown, without vanishing altogether, however.

The horizontal sections of the curves in Fig. 2 reflect the particular circumstance that during sensing of the atmosphere along tangential paths the photons emitted by the atmosphere from below the perigee do not enter the detector. This statement is only true in case of LTE. It becomes easy to determine the sensing perigee altitude from the intersection point of the weighting function in the LTE approximation with the 0$z$ axis.

Now we consider in more detail the physical nature of the variables in the relationships (6) and (7). Let a quantum be emitted at a certain level $z'$ in the atmosphere. Assuming complete redistribution of photons between different frequencies and emission lines, this quantum, with a probability of $\frac{(\lambda)z}{2}K(z, z')$, will be scattered at a level $z$.[5]

The function $K(z, z')$ is related to $\tilde{K}(\tau(z), \tau(z'))$, used in Ref. 2, in the following manner:

$$K(z, z') = \tilde{K}(\tau, \tau')\cdot\sigma_{\nu}(\tau') \quad (10)$$

so that at large optical distances between $z$ and $z'$ ($z$ is the upper, and $z'$ is the lower atmospheric levels) it behaves as $[/\tau - \tau'/]^{-z}$ (Ref. 6), increasing with higher $z'$. However, the value of the volume absorption coefficient $\sigma_{\nu}(z')$ behaves differently. Its altitude dependence is determined, for a constant $CO_2$ mixing ratio, by the atmospheric density, which decreases exponentially with the altitude $z'$. Therefore, the variable $K(z, z')$ is essentially a product of two monotonic functions, one of which increases for higher $z'$, for a constant $z$, while the other decreases.

This means that the variable $K(z, z')$ has to have a maximum at $z' \neq z$. In other words, there must exist a certain local altitude range in the relatively dense atmosphere, which strongly affects formation of the source function in the upper thin atmospheric layers. Recalling that the Green function is represented as a series in terms of functions divisible by $K(z, z')$ (Ref. 5), one understands the origin of the maximum of $G(z, z')$ and, hence, of $R(P_{c0}, z')$ in terms of the argument $z'$.

A numerical experiment was performed to reconstruct $T(z)$ for the found value of $N$ and the constructed weighting functions $R_{LTE}$, $R$. The number of $CO_2$ cells and their parameters corresponded to those given in Ref. 1, and the desired temperature distribution — to the CIRA-72 atmospheric model. The value of $T_0$ = 200 K (the isothermal atmosphere) was employed for the initial approximation.

The experimental results are presented in Fig. 3. The problem (8) was solved in three iterations. For the conditions described the achieved accuracy of $T(z)$ retrieval up to 100 km is no worse than 4 K. Meanwhile, ignoring deviations from the LTE causes errors in excess of 10 K even at 90 km. Above 100 km the reconstructed profile is only similar to the actual one. This occurs because of a weak influence of the atmosphere above that level upon the signal (see Fig. 1).

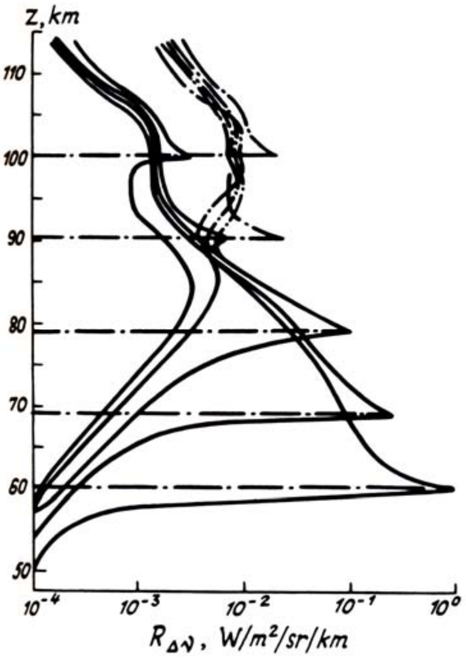


*FIG. 2. Weighting functions for the equation of thermal sensing along tangential paths as a function of the sensing perigee.[3] Dash-dot lines refer to LTE approximation (the sensing perigee is given by the intersection point of the weighting function with the 0z- axis), solid line refers to case when deviations from the LTE are taken into account identical sighting parameters).*

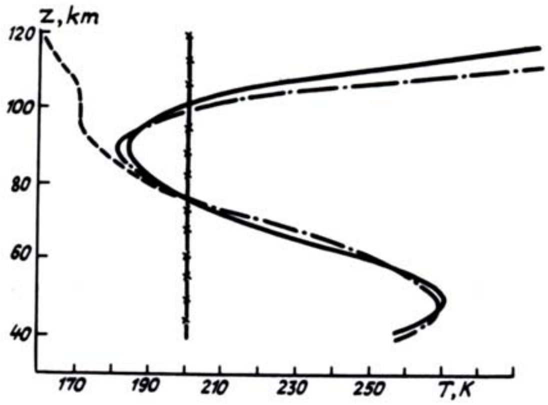


*FIG. 3. Results of numerical experiment of temperature reconstruction: solid line is the "true" profile; -x-x- is the initial approximation ($T_0$ = 200 K); dash-dot is the reconstructed profile Cthree iterations); dashed line is the profile reconstructed ignoring LTE breakdown.*

The above assessment of the technique accuracy is highly arbitrary. Thus, if one tried to reconstruct a wavy profile, such a technique would only yield a smoothed curve, and the error would be close to the initial wave amplitude.

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