A Feasibility Study for Active Remote Sensing of Atmospheric Carbon Monoxide Based on Differential Absorption of Infrared Radiation Along Vertical Paths

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***Abstract*—In this paper, we describe a differential method for estimating mean concentrations of atmospheric molecular components along a quasivertical rectilinear Earth–air path utilizing a transmitter-receiver pair operating at infrared. The choice of a differential method is due to the need to limit calibration problems without utilizing more complex and costly systems such as DIAL, whose capabilities are definitely oversized for this kind of measurement. For this objective, a preliminary selection of the optimal wavenumbers for each molecular species of interest is needed. This is the main issue discussed in this paper, after which the analysis focuses on the effects of the uncertainties on atmospheric parameters that need to be estimated to provide the final mean concentration estimates. The feasibility study is carried out on carbon monoxide, considered as test species of interest in the reported simulations of atmospheric propagation, based on standard atmospheric models. Technological requirements are finally discussed.**

***Index Terms*—Active remote sensing, carbon monoxide, infrared radiation, spectral attenuation measurements.**

I. Introduction

ATMOSPHERE-related quantities and parameters are typically obtained by spaceborne and airborne passive instruments like infrared/microwave radiometers and interferometric intrumentations [1] The increasing use of satellites pushes the research toward the realization of systems, based both on spaceborne/airborne and ground instrumentation, designed to exploit attenuation measurements at the infrared [2], [3]. However, these systems suffer from an intrinsic lack of accuracy mainly caused by uncertainties about the emissivity function (temperature profile, source emissivity, etc.). Radiometers suffer also from a basic spatial resolution problem (related to their standard field of view) that does not allow for local scale measurements over areas of particular interest (for instance over urban areas or natural gas emission zones).

In this paper, we analyze an active infrared measurement system, not necessarily alternative to passive systems, since it may provide complementary information for estimating the total amount of atmospheric components along a quasivertical Earth-air/space measurement path. The system offers a better opportunity for monitoring phenomena that develop themselves in limited areas, thanks to a spatial resolution (defined by the transmitter-receiver link) higher than that provided by passive instruments.

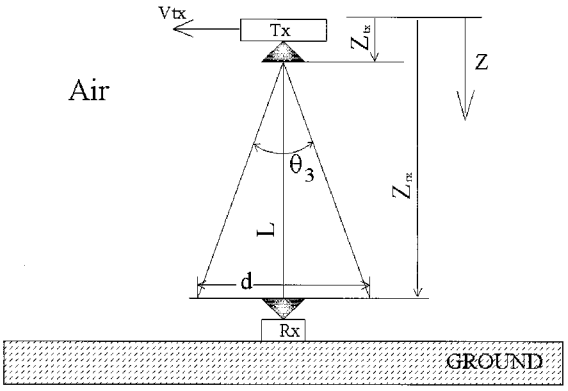

Fig. 1. Simple scheme of an atmospheric transmitter-receiver pair.

Though the system analysis presented in the paper has a general theoretical validity and holds for any monitored molecular species, we focus on the case of carbon monoxide for two reasons. First, this is to provide the reader with a clear example useful for understanding the approach used, and second, because CO is an atmospheric component of paramount interest in the remote sensing of the atmosphere. Applications of this technique are foreseeable in the remote sensing of atmospheric pollutants by airborne/spaceborne sensors, in particular over areas of interest such as volcanic areas, plants, and densely inhabited urban zones.

The paper is structured as follows. In Section II, the basic principles of infrared propagation in the atmosphere are reviewed. This section introduces the differential attenuation method discussed in Section III, exploited for estimating the amount of molecular components by means of power measurements from which link attenuations are obtained. In Section IV, we discuss more in depth the power/system requirements posed by the proposed application, in different operative modes. Finally, Sections V and VI deal with the CO case, exploiting a standard atmospheric model and a spectroscopic data compilation.

II. Attenuation of Infrared Radiation in the Atmosphere

Let us consider a transmitter–receiver pair, as sketched in Fig. 1, z_t and z_r, being the transmitter and receiver positions, respectively. The spectral radiance received in z_t can be expressed

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using the formal solution of the one-dimensional (1-D) radiative transfer [4]

$$J(z_r,\nu) = J(z_t,\nu)e^{-\tau(z_t,z_r,\nu)} + \int_{z_t}^{z_r} S(z,\nu)e^{-\tau(z,z_r,\nu)}\,dz \tag{1}$$

where

- ν wavenumber in cm^{-1};
- $J(z_t,\nu)$ spectral radiance incident upon z_t;
- $S(z,\nu)$ accounts for the spectral emission contributions between z and $z+dz$ along the integration path;
- $\tau(z_1,z_2,\nu)$ so-called optical depth corresponding to a path length (z_2-z_1), and it is defined by the relation

$$\tau(z_1,z_2,\nu) = \int_{z_1}^{z_2} k(z,\nu)\,dz \tag{2}$$

where $k(z,\nu)$ (dimension $[L^{-1}]$) is the extinction coefficient of the propagation medium. It accounts for the power losses between z and $z+dz$.

For the limiting case, where the first term of (1) is much greater than the second one (namely, when the transmitted spectral radiance is much greater than the emission contributions $S(z,\nu)$) and considering the emission from a point source, we obtain the Beer-Lambert law in terms of the spectral irradiance $I(z,\nu)$

$$I(z_r,\nu) = I(z_t,\nu)e^{-\tau(z_t,z_r,\nu)}. \tag{3}$$

The natural logarithm of the total attenuation $A(\nu)$, defined as the ratio between transmitted and received irradiance, is the optical depth. Thus

$$A(\nu) = e^{\tau(z_t,z_r,\nu)}. \tag{4}$$

The attenuation coefficient $k(z,\nu)$ depends on several different contributions that can be decomposed in Rayleigh, Mie, and molecular absorption, respectively, denoted as k_R, k_M, and k_G [5]. k_G accounts for all the absorbing molecular species along the integration path. Thus, $k(z,\nu)$ can be expressed as the sum of all separate contributions

$$k(z,\nu) = k_R(z,\nu) + k_M(z,\nu) + \sum_{i=1}^{N} k_{Gi}(z,\nu). \tag{5}$$

$k_{Gi}(z,\nu)$ is related to the absorption of the ith molecular species between z and $z+dz$ at the wave number ν. This is generally given as the product between the concentration of the ith molecular species $N_i(z)$ and its absorption cross section $\sigma_i(z,\nu)$. Such a section is then given as the sum of all absorption lines of the ith molecular species

$$\sigma_i(z,\nu) = \sum_{l} \sigma_{il}(z,\nu). \tag{6}$$

In the infrared range, the absorption lines σ_{il} are due to the vibro-rotational transitions, and their shape depends on atmospheric conditions, namely, pressure P and temperature T, so the dependence of σ_i on z implies dependence on $T(z)$ and $P(z)$. The optical depth of (2) can finally be decomposed as

$$\tau(\nu) = \tau_M(\nu) + \tau_R(\nu) + \sum_{i-1}^{N} \int_{z_t}^{z_r} N_i(z)\sigma_i(z,\nu)\,dz \tag{7}$$

where τ_R and τ_M are the optical depths related to k_R and k_M, respectively.

III. Differential Absorption Method

Let us define $\tau_0(\nu)$ as the optical depth due to a molecular species of which we want to measure the mean concentration over the integration path. The power $P(\nu)$ collected using a receiver located in z_r is obtained by combining (3) and (7), yielding

$$P(\nu) = CI_t(\nu)\exp\{-[\tau_M(\nu)+\tau_R(\nu)+\tau_G(\nu)+\tau_0(\nu)]\} \tag{8}$$

where $\tau_G(\nu)$ is related to the attenuation of all remainder molecular species, $I_t(\nu) = I(z_t,\nu)$, and C takes into account for the overall system losses (i.e., propagation attenuation, receiver characteristics).

Considering the transmission at two frequencies ν_1 and ν_2, the power received at both frequencies is

$$\begin{aligned} P(\nu_1) = {} & C_1 I_t(\nu_1)\exp\{-[\tau_M(\nu_1) + \tau_R(\nu_1) \\ & + \tau_G(\nu_1) + \tau_0(\nu_1)]\} \end{aligned} \tag{9}$$

$$\begin{aligned} P(\nu_2) = {} & C_2 I_t(\nu_2)\exp\{-[\tau_M(\nu_2) + \tau_R(\nu_2) \\ & + \tau_G(\nu_2) + \tau_0(\nu_2)]\}. \end{aligned} \tag{10}$$

The ratio between these two received powers is then given by

$$\begin{aligned} \ln\left[\frac{P(\nu_2)}{P(\nu_1)}\right] = {} & \ln\left[\frac{C_2 I_t(\nu_2)}{C_1 I_t(\nu_1)}\right] + [\tau_M(\nu_1) - \tau_M(\nu_2) \\ & + \tau_R(\nu_1) - \tau_R(\nu_2) + \tau_G(\nu_1) - \tau_G(\nu_2) \\ & + \tau_0(\nu_1) - \tau_0(\nu_2)]. \end{aligned} \tag{11}$$

If ν_1 and ν_2 are such that

1) $C_2 I_t(\nu_2) \cong C_1 I_t(\nu_1)$;
2) $\tau_R(\nu_1) \cong (\tau_R(\nu_2)$ and $\tau_M(\nu_1) \cong \tau_M(\nu)2)$ (Rayleigh and Mie scattering effects are approximately the same at ν_1 and ν_2);
3) $\tau_0(\nu_1) \gg \tau_0(\nu_2)$ (the species of interest absorbs significantly more at ν_1 than at ν_2);
4) $\tau_0(\nu_1) \gg \tau_G(\nu_1)$ and $\tau_0(\nu_1) \gg \tau_G(\nu_2)$ (the species of interest absorbs significantly more than all others at ν_1 and ν_2)

the latter equation can be approximated, yielding

$$\ln\left[\frac{P(\nu_2)}{P(\nu_1)}\right] \cong \tau_0(\nu_1). \tag{12}$$

Using (2) for $\tau_0(\nu_1)$ and expressing the attenuation coefficient as the product between the concentration and the cross section, we obtain

$$\ln\left[\frac{P(\nu_2)}{P(\nu_1)}\right] \cong \int_{z_t}^{z_r} N_0(z)\sigma_0(\nu_1,z)\,dz. \tag{13}$$

As mentioned above, the absorption cross section depends on temperature and pressure. As a consequence, when atmospheric propagation paths are not horizontal, the shape of σ_0 depends on the altitude. Thus, it cannot be extracted from the integral.

Let us define an equivalent cross section $\sigma_{eq}(\nu)$ such that

$$N_{mref}\sigma_{eq}(\nu)L = \tau_{0ref}(\nu) \tag{14}$$

where $L = (z_r - z_t)$, $\tau_{oref}(\nu)$ is the optical depth referring to a predefined reference atmospheric model, and N_{mref} is the mean concentration over the integration path for the same reference model, namely, $N_{mref} = (1/L)\ \int_{z_t}^{z_r}\ N_{0ref}(z)\ dz$.

Indicating with N_m the mean concentration over the integration path, if ν_1 is such that

$$N_m\sigma_{eq}(\nu_1)L = \int_{z_t}^{z_r} N_0(z)\sigma_0(\nu_1, z)\ dz \tag{15}$$

holds for any possible plausible atmospheric condition (in terms of temperature and pressure profiles) or at any possible plausible concentration profile $N_0(z)$, we may rewrite (13) as

$$\ln\left[\frac{P(\nu_2)}{P(\nu_1)}\right] \cong N_m L\sigma_{eq}(\nu_1). \tag{16}$$

In this way, one can obtain the mean concentration of a molecular species over a rectilinear path of length L through two power measurements carried out at two different wavelengths that satisfy the conditions 1–4 above. Of such conditions, the first two are mainly related to the transmitter's and receiver's characteristics (emitted power, optical efficiency, etc.). Concerning the remaining two conditions, the most severe is certainly the last one, since it requires a detailed analysis of spectroscopic characteristics of the species of interest.

IV. Link Design

In this section, referring to Fig. 1, we address the problem of designing the infrared transmitter-receiver system parameters based on their relative distance and velocity. Referring to a cylindrical coordinate system with the z-axis perpendicular to ground and the origin in the transmitter, the irradiance at the receiver (at distance L from transmitter) is

$$I_r(L,\rho) = \frac{P_0}{4\pi L^2}G(L,\rho)\frac{1}{A} \quad [\text{W/cm}^2] \tag{17}$$

where

P_o transmission power (Watt);
A total path attenuation;
$G(z,\rho)$ gain pattern.

In the case of a Gaussian beam

$$G(z,\rho) = \frac{8}{\theta_3^2}e^{-2\rho^2/(z\theta_3)^2} \tag{18}$$

where θ_3 is the half power beamwidth. Assuming that the transmitter flies along a line parallel to the Earth with velocity V_t, the available illumination time (accounting for the half power beam only) t_{av} is

$$t_{av} = \frac{2L}{V_t}tg\left(\frac{\theta_3}{2}\right) \approx \frac{L\theta_3}{V_t}. \tag{19}$$

During t_{av}, attenuation measurements at the attenuated and reference wavenumbers ν_1 and ν_2 must be made. We shall assume that during t_{av}, two identical pulse signals of equal duration are transmitted at the two wavelengths. However, it must be recalled that the minimum integration time τ_d of the infrared receiver is assigned depending on SNR requirements. In fact, in practice, $\tau_d = 1/2\Delta f$, where Δf is the receiver's noise bandwidth. Therefore, two cases can occur in general: 1) t_{av} fits the minimum signal to noise ratio requirements at the receiver ($t_{av} > 2\tau_d$, since two wavelength measurements are needed), and 2) $t_{av} < 2\tau_d$.

In the case of infrared receivers, the minimum received power can be written as a function of the detectivity D^* [4]

$$(P_{rx})_{\min} = \frac{SNR_{\min}}{D^*}(A_d\Delta f)^{1/2} \tag{20}$$

where A_d is the detector area (in cm^2) and $\text{SNR}_{\min}$ is the minimum acceptable SNR. The minimum received power is obtained by (17) assuming maximum attenuation $A_{\max}$. Therefore, combining (17) and (20) we get

$$\frac{SNR_{\min}}{D^*}(A_d\Delta f)^{1/2} = \frac{P_0}{4\pi L^2}\ \frac{8}{\theta_3^2}\ \frac{1}{A_{\max}}A_d \tag{21}$$

from which

$$\frac{P_0A_d^{1/2}}{\theta_3^2} = \frac{SNR_{\min}}{D^*}(\Delta f)^{1/2}\frac{4\pi L^2}{8}A_{\max}. \tag{22}$$

Typical receiver system parameters' values taken as reference in this kind of infrared remote sensing applications are $D^* = 10^{11}$ Hz$^{1/2}$/W , $\text{SNR}_{\min} = 2$ and $\Delta f = 1$ Hz [13]. Notice that imposing $\Delta f = 1$ Hz implies that a minimum value for τ_d is imposed. Substituting such values in (22), one gets

$$\frac{P_0A_d^{1/2}}{\theta_3^2} = \frac{\pi L^2}{10^{11}}A_{\max}. \tag{23}$$

The left term of (23) encompasses all system parameters that can be adjusted in the link design. For this reason, such terms will be estimated in the different operating cases discussed in the following.

As a final remark, notice that the transmitter and receiver roles can be exchanged without modifying the results, assuming a reciprocal propagation medium.

A. Spaceborne Case

For the spaceborne case, realistic parameters are $L = 220$ km, $V_t = 7.5$ km/s (Shuttle). Having assigned a specific value to Δf, (19) gives a minimum value for θ_3: $(\theta_3)_{\min} = 35 * 10^{-3}$ rad. Thus, (23) becomes

$$P_0A_d^{1/2} = 18.62 \cdot A_{\max}[w \cdot cm]. \tag{24}$$

B. Airborne Case

For the airborne case, we consider $L = 10$ km, and $V_t = 800$ km/h. Using the same value for the noise bandwidth $(\theta_3)_{\min} = 22 * 10^{-3}$ rad and (23) gives

$$P_0A_d^{1/2} = 0.015 \cdot A_{\max}[w \cdot cm]. \tag{25}$$

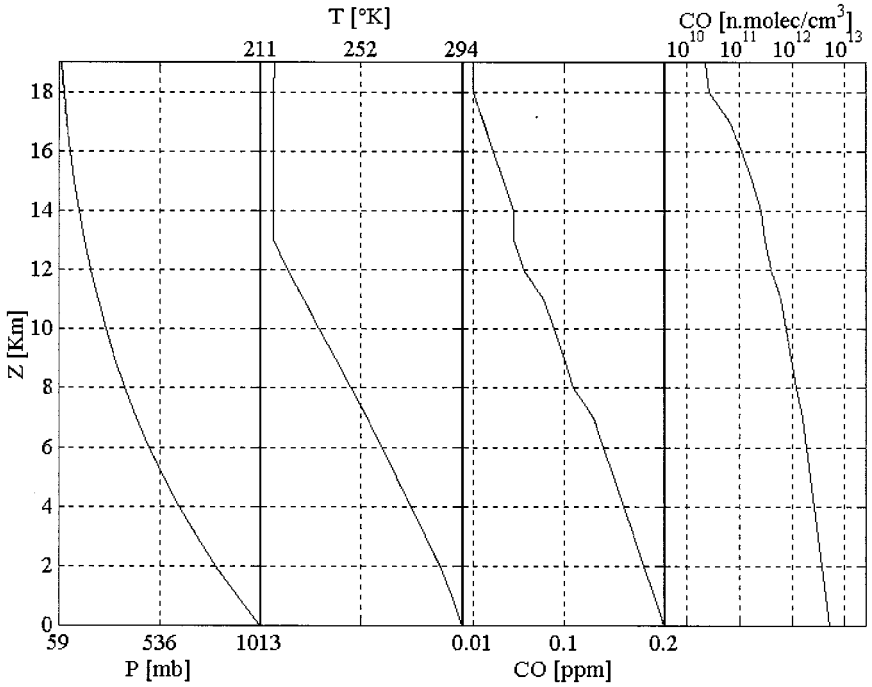

Fig. 2. Vertical profiles of temperature and pressure (standard summer atmosphere) and of CO concentration from ground to 20 km.

C. Aerostat Case

In the aerostat case we choose L = 10 km. In this case we assume that $V_t = 0$, in order to have no limitation about the detection time, the minimum for θ_3 depends exclusively by the transmitter's pointing system. We chose $(\theta_3)_{\min} = 2*10^{-3}$ rad (value obtainable by several off-axis paraboloids)

$$P_0 A_d^{1/2} = 1.26 \cdot 10^{-4} A_{\max}[w \cdot cm]. \tag{26}$$

As a final remark to the link design, it must be pointed out that scattering and Mie effects, increasing the propagation loss, cause in general a degradation of the SNR at the receiver. Unfortunately, any estimate of such additional attenuation would be extremely unreliable, since scattering and Mie effects are strongly dependent on regional characteristics of aerosols [6]. For this reason, they were not considered throughout this work. On the other hand, recent accurate studies on atmospheric transmission modeling allow to conclude that a signal degradation not exceeding 5% is expected caused by aerosols in the spectral region of interest (around 4.7 μm, as indicated in the following sections) [7].

V. Attenuation Measurements in the Spectral Absorption Interval of Carbon Monoxide

The use of (16) to estimate the vertical amount of CO in the atmosphere through the differential attenuation method requires the preliminary determination of the two wavenumbers, ν_1 and ν_2. The procedure adopted is based on spectroscopic data provided by the HITRAN96 database [8] and on standard models of atmosphere (molecular composition [9] profiles and temperature/pressure vertical profiles [10]). We computed the optical depth $\tau_0 + \tau_G$ considering two spectral ranges. The first, around 2169 cm^{-1}, is characterized by the R6 CO absorption line [11], and the second, around 2500 cm^{-1}, is characterized by low molecular absorption. The vertical profiles of CO concentration, temperature and pressure are shown in Fig. 2.

Fig. 3 shows the attenuation $A(\nu)$ around 2169 cm^{-1} over a vertical path considering the atmospheric layers from ground to 20 km altitude. To calculate the molecular cross sections, we accounted for all the absorption lines of the most abundant isotopes (those labeled as 1 in the HITRAN compilation [12]) in the range (2158,2190) cm^{-1}. In this spectral range, the main absorbing molecules are H_2O, N_2O, and CO_2. In order to compute their concentration values, we considered a standard atmospheric composition. Observe that when ν_1 is comprised in the range (2169.1,2169.3) cm^{-1}, the total attenuation $A(\nu_1)$ is only due to CO, so we have $\tau_0(\nu_1) \gg \tau_G(\nu_1)$.

The spectral attenuation around 2500 cm^{-1} is shown in Fig. 4 considering the same integration path. All the absorption lines contained in the (2483,2510) cm^{-1} range were accounted for. The main absorbing molecules in such spectral range are N_2O, CH_4, H_2O, and N_2, while absorption due to CO is negligible. Furthermore, total molecular attenuation is much lower than that around 2169 cm^{-1} (about three orders of magnitude). Therefore, choosing $\nu_2 = 2501$ cm^{-1} conditions 3 and 4 listed in Section III are met, namely, $\tau_0(\nu_1) \gg \tau_0(\nu_2)$, $\tau_0(\nu_1) \gg \tau_G(\nu_1)$, and $\tau_0(\nu_1) \gg \tau_G(\nu_2)$.

In order to determine the wavenumber that minimizes the error in the approximation of (13)–(16), we analyzed the optical depth variations in the (2169,2169.5) cm^{-1} range using 200 simulated profiles of CO concentration. Fig. 5(a) reports the reference CO profile used in simulations. We generated 200 different CO profiles independently and randomly. For each profile and from ground to 10 km altitude, the CO concentration was set free to vary uniformly within two orders of magnitude around the reference value. In this way, we obtained CO profiles having

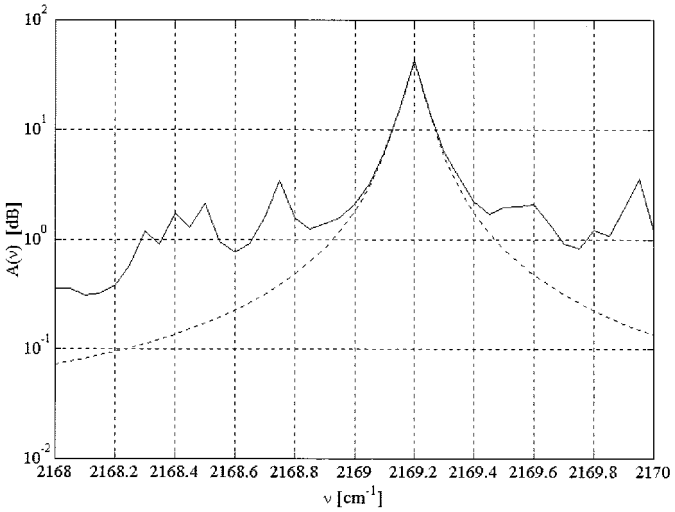

Fig. 3. Spectral attenuation around the R6 [11] absorbing CO line. Continuous line: total attenuation (mainly contributed by CO, CO_2, N_2O, and H_2O); dashed line: attenuation contributions due to CO only.

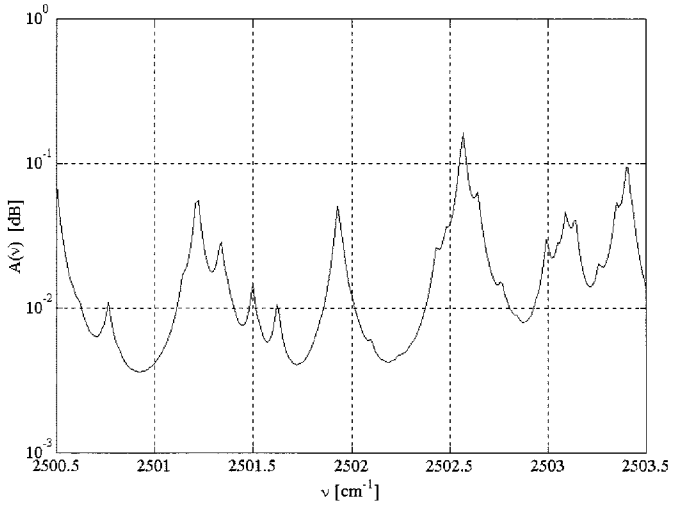

Fig. 4. Spectral attenuation around 2500 cm^{-1}. Main contributors are H_2O, N_2O, CH_4, and N_2.

mean values, over a 20 km path length, ranging between about $8.28 \cdot 10^{11}$ and $6.48 \cdot 10^{12}$ molec./cm^3.

Let us define the sensitivity absolute error $es(\nu)$ as:

$$es(\nu) = \left| \frac{\tilde{\tau}_0(\nu) - \tau_0(\nu)}{\tau_0(\nu)} \right| \tag{27}$$

where $\tau_0(\nu)$ is the "true" optical depth, and $\tilde{\tau}_0(\nu)$ is the optical depth approximated using $\sigma_{eq}(\nu)$. $\tilde{\tau}_0(\nu)$ is thus given by

$$\tilde{\tau}_0(\nu) = N_{om}\sigma_{eq}(\nu)L \tag{28}$$

where N_{0m} is the mean concentration over the integration path of length L, relevant to a CO simulated concentration profile. The reference atmospheric model used to compute the equivalent cross section $\sigma_{eq}(\nu)$ is that shown in Fig. 2. In Fig. 5(b) are plotted the variation bars (max and min values) of the spectral attenuation for the complete set of the 200 CO profiles. Finally, Fig. 5(c) shows the minimum and maximum values of $es(\nu)$ for the same profiles. Notice that at 2169.15 cm^{-1} and 2169.24 cm^{-1} $es(\nu)$ is smallest, assuming values around 5%. Moreover, at these two wavenumbers, the attenuation $A(\nu)$ is extremely variable (some tens of dB).

VI. Effects of Variations of Temperature and Pressure

The accuracy with which the mean concentration along the integration path can be estimated depends also on the vertical profiles of temperature and pressure and on their short term variations. In this section, we examine the effects of the uncertainty of such profiles on the mean concentration estimates. The approach used for this purpose is the same described in Section V for the variations of concentration. The error functional exploited is still that of (27), where τ_o is the "true" optical depth computed by modifying the temperature and pressure profiles, while $\tilde{\tau}_o$ is that computed using (28) (we recall that σ_{eq} is *always* computed by means of the standard profiles).

For each profile and from ground to 20 km altitude, temperature and pressure were set free to vary uniformly in an interval respectively equal to 5% of their reference value. Fig. 6 and Fig. 7 refer, respectively, to temperature and pressure (the profiles and their variation ranges are plotted in the upper left figure). They show that the effects of this kind of uncertainty are definitely negligible with respect to the effects of the uncertainty on the concentration profiles. In fact, in the temperature case and in the wavenumber region of interest, we get errors less than 0.5%, with the minimum errors occurring at the wavenumbers selected though the aforementioned method. In the pressure case, the error pattern is practically the same: the error is more than double, however at the selected wavenumbers we still get the minimum errors.

As mentioned in Section IV, the quantification of scattering and Mie effects would be is extremely unreliable. It is, however, envisaged that the dependence on wavenumber of both τ_R and τ_M is such that the relative spectral distance, using $\nu_1 =$ 2169.15 (or 2169.4) and $\nu_2 = 2501$, is not sufficient to invalidate condition 2.

VII. Conclusions

The proposed active method for estimating the total amount of atmospheric components is an alternative to passive infrared systems, bringing major advantages in those cases where high resolution and spatially localized monitoring is needed (volcanic areas, industrial plants, urban areas etc.). As far as technological requirements are concerned, as shown in the CO case, the power measurements that must be performed according to the proposed method require a spectral resolution better than 0.1 cm^{-1}. This asks for infrared laser sources such as semiconductor diode lasers, largely employed for the measurement of molecular concentrations of atmospheric components along horizontal ground paths [13]. The main limitations are obviously encountered for the transmission power in the Earth-satellite case, for which peak powers of about 1 kW are needed to meet the minimum requirements discussed in case A of Section IV. Instead, power levels achievable by semiconductor transmission diodes [14] are sufficient to meet the requirements posed by cases B and C, assuming a reference

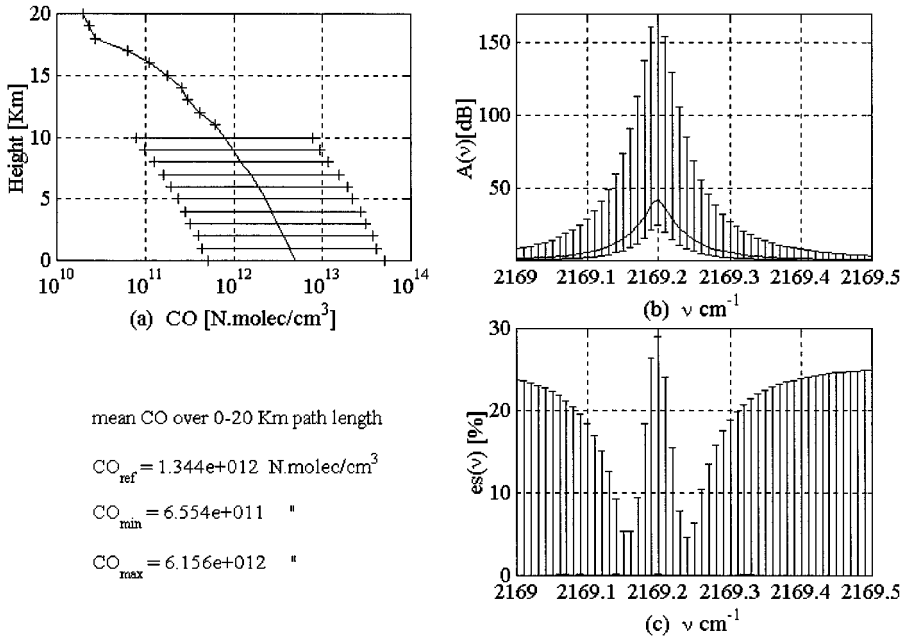

Fig. 5. (a) Reference CO vertical profile (continuous line) and variation ranges for the random generation of 200 profiles. (b) Spectral attenuation due to CO around 2169.2 cm^{-1} and variation bars (min and max) obtained considering all of the 200 CO profiles. (c) Variation bars (min and max) of the absolute sensitivity error $es(\nu)$.

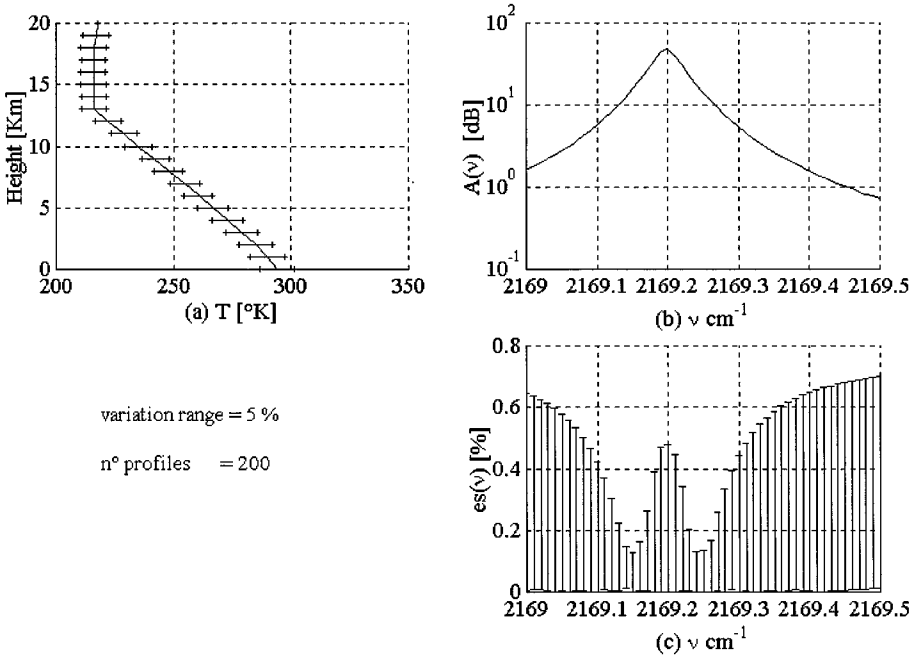

Fig. 6. (a) Reference temperature vertical profile (continuous line) and variation ranges for the random generation of 200 profiles. (b) Spectral attenuation due to CO around 2169.2 cm^{-1} (pertinent to the CO reference profile). (c) Variation bars (min and max) of the absolute sensitivity error $es(\nu)$.

value of the order of 100 cm^2 for the equivalent area of the receiving optics and 20 dB maximum total attenuation.

The differential method for received power measurements, chosen so as to permit that spectral contributions that are "flat" in the frequency range within the two selected frequencies cancel each other on average, is sensitive only to time variations of the received power difference. Therefore, through a differential power stabilization system at the transmitter, measurements are directly exploitable without requiring *ad hoc* calibration. However, a residual calibration error is possible caused by spatial inhomogeneities across the propagation beam (generated by turbulence effects in the atmosphere).

A foreseeable development of this matter concerns the reconstruction of two-dimensional (2-D) vertical concentration fields of atmospheric components by means of a tomographic network constituted by several quasivertical paths, built up by a single mobile transmitter and a baseline of receivers at ground. A tomographic approach to the reconstruction of 2-D horizontal fields of pollutants in limited areas was presented in [15]. Such an approach could be used for solving the cited vertical 2-D

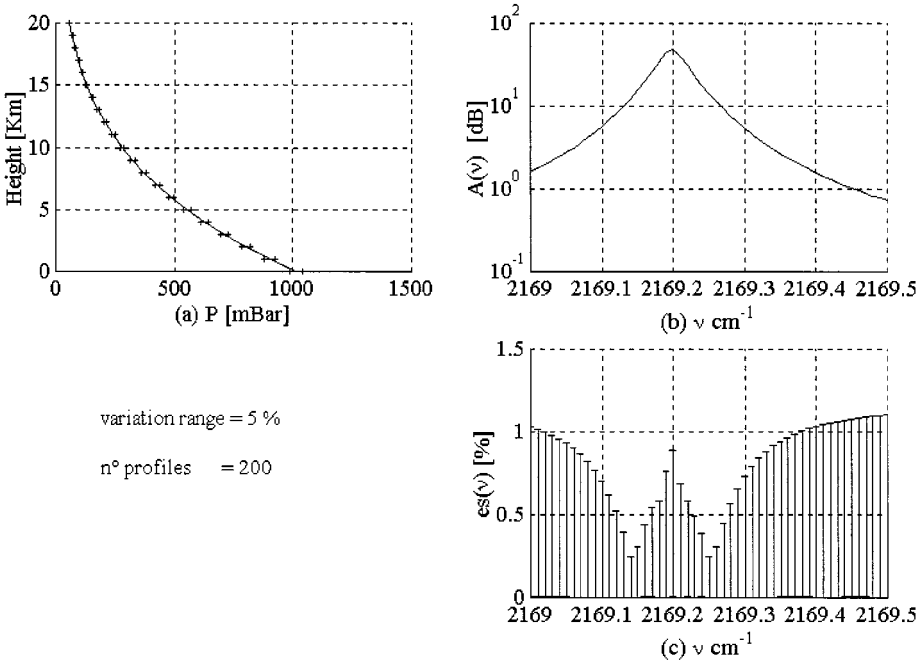

Fig. 7. Same as Fig. 6, referring to the pressure profile.

inversion problem. However, a specific redefinition of the algorithm reported there is required due to the intrinsic lack of vertical resolution of the mentioned 2-D vertical tomographic network.

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