

Initial Field Measurements of Atmospheric Absorption at 9–11 μm Wavelengths

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ABSTRACT

A field adapted spectrophone system employing a tuneable CO_2 laser source (over wavelengths 9.2–10.8 μm) was used to measure atmospheric gaseous and particulate absorption at an isolated desert location in the southwestern United States. Measurements were made both for ambient conditions (when aerosol particulate absorption was found to be negligible compared to that of gases) and for dusty conditions resulting from vehicular traffic. For ambient conditions the gaseous absorption coefficient was found to vary with time from expected levels upward by as much as a factor of 3. Sources which could be correlated with increased absorption are discussed. For dusty conditions the spectrophone data were compared with estimates of the absorption coefficient calculated on the basis of measured particle size distributions together with estimates of particle complex indices of refraction. Temporal variation of the absorption coefficient correlated quite closely for the two methods while the calculated values were generally higher. Sampling and calculational uncertainties are suggested as likely to be responsible for this discrepancy.

1. Introduction

Measurement of the absorption due to atmospheric gaseous and particulate matter at infrared wavelengths is a subject of current interest because of the relevance of communications, atmospheric sensing and radiative transfer problems. To date, estimates of atmospheric absorption generally have been derived from measurements/estimates of the concentration of significant contributors at the wavelengths of interest. These concentration data are then converted to absorption coefficients at specific wavelengths. For gaseous absorption this may involve an insufficient data base of absorption coefficients, primarily for trace gases. In the case of particles, assumptions involving both shapes and complex indices of refraction must generally be made (Jennings *et al.*, 1978).

This paper reports on relatively direct *in situ* field measurements of both gaseous and particulate absorption made using a CO_2 laser spectrophone system. The spectrophone technique obviates many of the problems associated with currently used much less direct approaches for obtaining atmospheric absorption. The measurements were made in spring 1978 at a remote desert site in the White Sands Missile Range, NM. Although both gaseous and particulate absorption are discussed, the focus is on absorption by soil-derived dust generated by vehicular traffic.

2. Background

In a previous paper (Bruce and Pinnick, 1977) a spectrophone for *in situ* measurements of atmospheric gaseous and/or particulate absorption was described. Environmental chamber measurements on known atmospheric aerosols (quartz and calcite dust) were made with this system which allows continuous flow-through sampling and a high degree of isolation from acoustic noise. Measurements for known atmospheric gaseous absorbers (methane: Bruce *et al.*, 1976; ammonia: Brewer and Bruce, 1978; water vapor: White *et al.*, 1978) have also been reported using similar spectrophones. In general, the gaseous absorption measurements were in good agreement with those obtained using long-path transmission cells with beam-folding optics (White Cells). In the case of aerosols, the measurements were compared to Mie theory predictions of absorption (for spherical homogeneous particles) based on measured particle size distributions and knowledge of particle complex refractive indices (which had previously been measured). Though the particles were quite irregular in shape, the measured and calculated results compared reasonably well (generally within a factor 2) for the substances measured.¹

¹ Spectrophone measurements of absorption by diesel exhaust smoke have recently been reported (Roessler and Faxvog, 1979).

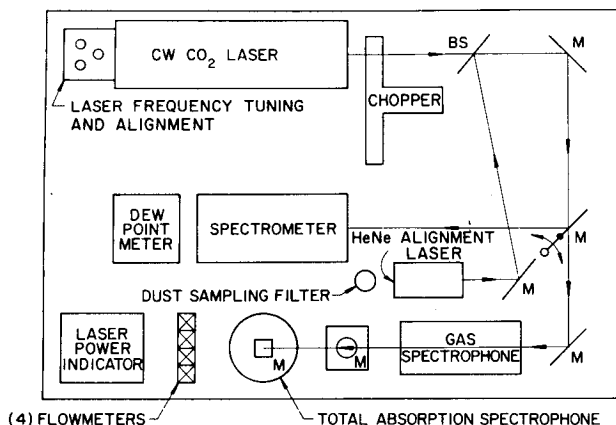


FIG. 1. Schematic (top view) of the portable optical table showing optical paths for both the CO₂ and the He-Ne alignment lasers, spectrometer for laser line identification, gas and total absorption spectrophones, power meter and two of the auxiliary systems used, i.e. (EG&G) dew-point hygrometer and dust sampling filter using 0.2 μm Nuclepore filter elements. Flowmeters are for the spectrophones and the auxiliary measurements. BS and M refer to adjacent beam splitters or mirrors.

However, when atmospheric gases and dust are encountered in the field as in this paper, the presence of unknown trace gases and particles of undefined composition complicates any comparison of spectrophone measured absorption as compared with that predicted. For gases, comparison presumes distinctive (and well-known) spectral patterns at the probe laser wavelengths to permit identification of the species. The particulate comparison is more complex. In this case both elements of the comparison are based on measurements which may involve sampling errors which are hard to define, e.g., they are a function of wind speed and direction. Spectrophone operational parameters (chopping rates and power densities) must be chosen to ensure adequate response to the particles. Principal criteria for these choices were that the period of optical beam modulation exceed the thermal cooling time for the largest contributing absorbing particles and that probe beam power densities be low enough that optical properties not be significantly altered for contributing sizes of particles of a given complex index and thermal diffusivity. Since a light scattering counter was used to measure particle size and concentration, its response and size resolution for particles characteristic of soil-derived dust must be defined. Finally, dust composition must be determined. An additional complication arises from the fact that the dust composition may be a strong function of size (Lindberg and Gillespie, 1977) and that refractive index information for the various dust constituents (which are required for Mie calculations of absorption) have been reported only for a few specific minerals.

3. Measurement system

The ensemble of instrumentation consists of a spectrophone system for gaseous and particulate absorption measurements and correlative measurement instrumentation including a light-scattering aerosol counter, a filter sampler and a dew point hygrometer.

A schematic representation of the spectrophone system is shown in Fig. 1 where the laser beam path is traced through the alternate routes of spectrometer and spectrophones. Briefly, the differential resonant spectrophone system consists of two measurement elements. One samples both gaseous and particulate atmospheric contents through an unfiltered intake; a second, whose intake is filtered to remove particles, samples only the gaseous component. The gain-equalized difference signal from the two elements is due to the particles while switching the total absorption leg of the difference signal to electrical ground gives only the molecular absorption.

Both spectrophones are cylindrically symmetric with the coaxial laser probe beam. The gas spectrophone has cell end windows while the beam and atmospheric constituents enter the "total" (gas and particle) absorption spectrophone through the open upper end as illustrated in Fig. 2. Acoustic wave filters and a microphone designed to promote laminar flow occupy the central region followed by a tube with relatively high acoustical inertance terminating in a calorimeter. This tube is a low-pass filter that minimizes flow noise from the pump connection (where it is not yet laminar) and any signal due to the interaction of the laser beam with the calorimeter. The CO₂ laser used for these measurements is a modified commercial unit (GTE Sylvania model 948) tuneable from approximately 9.15 to 10.8 μm in about 80 lines. Signal processing for the spectrophone system is indicated in the block diagram of Fig. 3. Pulsed laser sources could be sub-

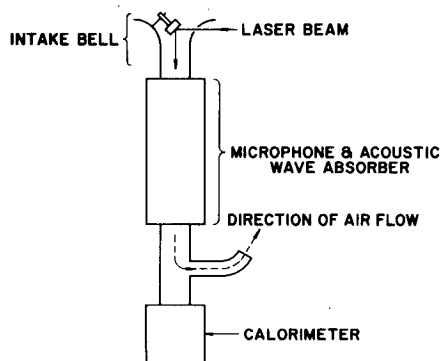


FIG. 2. Schematic diagram (side view) of the total (gas and particle) absorption spectrophone.

stituted for the cw source and signal processing as described previously (Bruce *et al.*, 1976).

Considerable attention was given to the calibration of the light-scattering counter (a Knollenberg model CSASP-100) used for measurement of aerosol size distributions and concentrations. The principle of operation of this instrument and determination of its response to spherical and nonspherical particles of various compositions are described in earlier papers (Pinnick and Auvermann, 1979; Pinnick and Rosen, 1979). Briefly, the instrument works on the principle that as aerosol flows through an illuminated volume, light scattered by a single particle into a given (near forward scattering) solid angle is measured and used to determine particle size by electronically classifying response pulses according to their magnitude. In order to define the instruments' size resolution for measurement of soil-derived aerosols, we have made laboratory measurements of its response to uniform irregular particles with refractive indices characteristic of those of soil dust constituents. The results, which are shown compared to theoretical response calculations for spheres of equal cross section in Fig. 4, show that the instrumental size resolution is defined by an envelope enclosing the theoretical response curves. This envelope (shown by the dashed curves in Fig. 4) indicates what uncertainty in particle size results from a certain response (or pulse height) measurement, taking into account the fact that the particles are irregular and have different compositions (and refractive indexes). This envelope has been extended slightly for application to soil dust con-

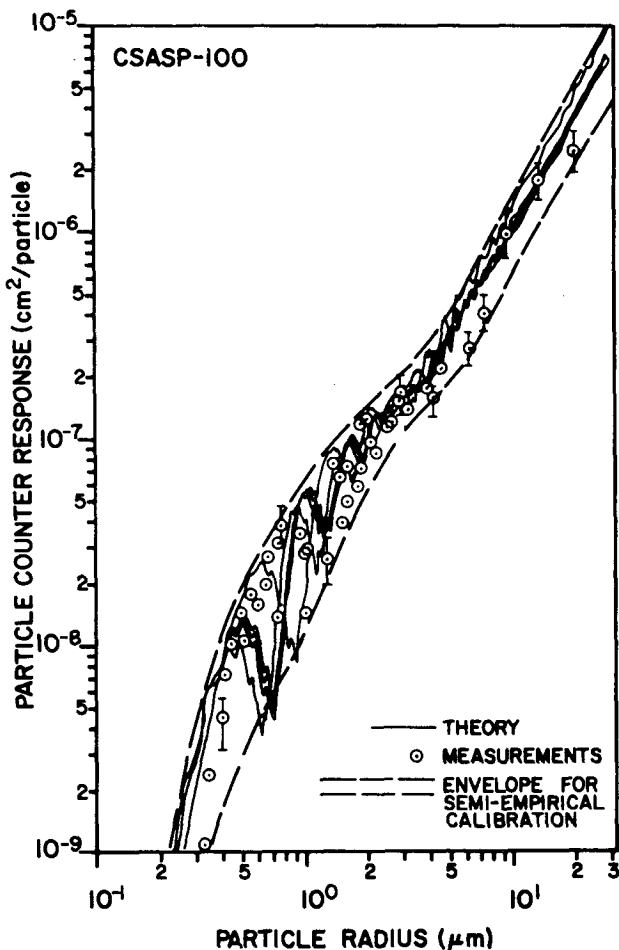


FIG. 4. Knollenberg CSASP response: measured (circles) for nonspherical particles of doublet-shaped polystyrene (refractive index $m = 1.592 - 0i$), cubical sodium chloride ($m = 1.54 - 0i$), ellipsoidal potassium chlorate ($m = 1.409 - 0i$), and slightly nonspherical pollens and spores [puff balls, lycopodium powder, paper mulberry, ragweed, sweet vernal and pecan] (with $m = 1.53 - 0i$); and calculated using Mie theory (smooth solid curves) for spheres of equal cross section and refractive index. The envelope indicated by the smooth dashed curves defines an estimate of range of uncertainty in particle size that results for a particular response measurement for particles of unknown shape and refractive index.

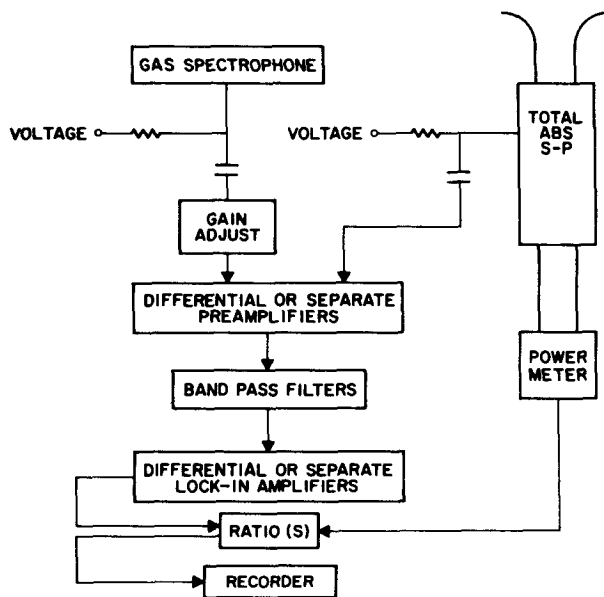


FIG. 3. Signal processing for the cw laser resonant differential spectrophone system.

stituents in an attempt to take into account their slightly wider range of refractive indexes and more irregular shapes. A curve drawn through the center of the envelope is then taken as the calibration for the instrument (to connect instrument response to particle size) and the envelope itself is used to define the particle sizing errors.

Air flows into both spectrophone and particle counter through intake bells which attempt to give relatively smooth flow through their measurement region and approximately isokinetic sampling when wind speeds are small.

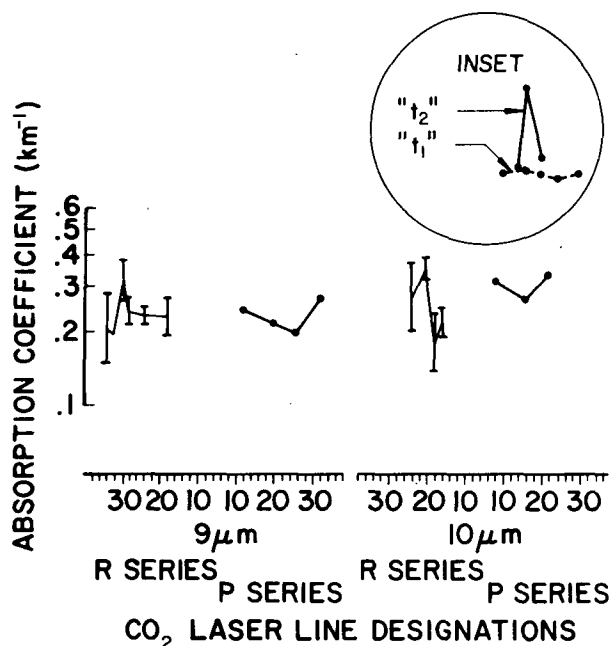


FIG. 5. Atmospheric absorption coefficient data illustrating levels (points) and variations (vertical bar) for a 3 h midday period (4 April 1978). Insert is a relative absorption (semilog) plot for 10 μm P series CO_2 laser wavelength segment at two times whose significance is identified in the text. Straight lines connect measurement values for ease of identification.

4. Measurements and analysis

The CO_2 laser spectrophone system utilized for measurement of gaseous and particulate absorption can generally adequately define the spectral dependence of the particulate absorption in the 9–11 μm region, even though there are gaps between the four laser bands within this region. Molecular constituents cannot be completely characterized using the laser source since atmospheric gaseous absorption lines are much more numerous than the laser probe lines and effectively much narrower than the laser line spacing. However, the fixed patterns of the constituent gases generally do have strong, spectrally distinct contrasts for the absorbing constituents. This may permit identification of absorbing gaseous concentrations by deconvolution of the spectra using self-consistency.²

The measurements were performed partly to survey absorption by ambient atmospheric gases at the desert site. For purposes of gaseous analysis, measurements were made for 60–80 easily obtained laser lines with an estimated probable single-measurement accuracy of 15%. However, significant changes in the absorption can occur in less time than is required for a complete manual spectral scan (~ 2 h).

² Samuel, C., C. W. Bruce and R. J. Brewer, 1978: Spectrophone analysis of gas samples obtained at field site. U.S. Army ERADCOM Tech. Rep. ASL-TR-0009, 45 pp.

Such changes have the effect of altering the observed spectral pattern and the result is that deconvolution of the results may not give accurate concentrations by self-consistency of the spectra. Use of selected sets of laser probe lines is much more satisfactory since the measurement period can be made smaller than that for atmospheric changes. The technique used for choosing a minimum number of spectral lines is discussed by Samuel *et al.* Water vapor and carbon dioxide produce most of the ambient level atmospheric absorption in the 9–11 μm atmospheric transmission spectra window. Absorption by atmospheric CO_2 measured with a $\text{C}^{12}\text{O}_2^{16}$ laser probe is an exception to the assumption of distinctive spectra. Here the band profile of the absorption coefficient peaks varies relatively slowly with wavelength. Examples of distinctive trace gas spectra are those of ozone which appeared at levels as high as 0.030 ppm based on coefficients by Patty *et al.* (1974) and ammonia, which appeared at levels as high as 0.023 ppm based on coefficients by Brewer and Bruce (1978).

For ambient atmospheric conditions the spectrophone-measured net absorption coefficients ranged from the expected ambient values to several times that value. The magnitude and temporal variation in the absorption coefficients during one 3 h midday period for a number of CO_2 laser lines is shown in Fig. 5. These variations, as was mentioned, were larger than expected as was the average level of the absorption. The major contribution was expected to stem from carbon dioxide at roughly 0.07 km^{-1} and water vapor at about 0.04 km^{-1} for the relative humidity encountered (about 3 torr). In previous samples of desert air analyzed in the laboratory, the 9–11 μm gaseous absorption coefficients were also often found to be high by approximately twice the expected value (Samuel *et al.*, 1978).² In that case, possible contamination of the stainless sample system was suspected; but here, the flowing sample changed in a matter of seconds, making this cause highly unlikely. Of course, the presence of personnel may have contributed to the high absorption. This potential problem will be avoided in the future by the development of an automated laser tuning system.

To point out the caution needed in interpreting the source of absorption in spectrophone measurements, several observations regarding interaction between personnel in the locale and the measurements might be of interest.

At one point the absorption signal rose off scale (roughly $3\times$ previous value) and persisted over several spectral lines. Then it was noticed that a meteorological observer ~ 15 m upwind was carrying a lighted cigarette. After the cigarette was extinguished the absorption returned to previous levels.

On another occasion a particle counter was being

cleaned with Freon 22 and acetone about 40 m downwind, (wind speed $\sim 7 \text{ m s}^{-1}$). The absorption coefficient increased when the cleaning began and decreased when the cleaning stopped. That the increase in absorption was due to these cleaning agents was obvious from the already familiar spectral dependence of these laboratory solvents. The increase (labeled t_2) relative to a more typical result (labeled t_1) is shown in the inset in Fig. 5 where a segment of the CO_2 laser $10 \mu\text{m P}$ series is repeated for the two conditions.

A strong smell of creosote from a balloon enclosure persisted during some periods of high absorption so an off-line spectrophone spectral analysis was performed in the laboratory on a sample taken in the enclosure. The results showed that creosote could not have been the source of the increase in absorption.

During measurements of atmospheric absorption under ambient conditions, the particulate absorption coefficient at $10 \mu\text{m}$ was found to be generally less than 10% of the net gaseous absorption. Only occasional passage of vehicular traffic on the unpaved desert roads and one dust devil produced absorption coefficients $> 10^{-1} \text{ km}^{-1}$.

Next, dust generated by vehicular traffic over the desert terrain was investigated. To correlate the spectrophone-measured absorption coefficient with an independent dust measurement the (previously mentioned) Knollenberg probe was placed $\sim 1 \text{ m}$ from the spectrophone probe. The dust created by repeated circulation of a military truck vigorously driven over nearby desert terrain was then continuously measured with the spectrophone at a fixed CO_2 laser frequency, while the counter accumulated data for consecutive 5 s intervals. The time resolution for the spectrophone was limited to about 1 s by the signal bandwidth used and again the estimated probable error is 15% for particle radii $< 10 \mu\text{m}$ (excepting the elusive sampling errors).

Comparison of spectrophone measurements of absorption coefficient with calculations based on the Knollenberg data was then attempted. This goes well beyond correlation of absorption coefficient with particle densities and requires some knowledge of the dust particles composition (or refractive index). Therefore, following the tests, vehicular dust which settled onto the ground were taken to the laboratory where both spectral analysis and chemical content could be analyzed.

The spectral analysis was accomplished by dispersing the sample dust in an environmental chamber and scanning the spectral region of concern using spectrophone systems similar to those used in the field. The reliability of these results do depend to some degree on the assumption that the size distribution of redispersed dust sample is the same as it was in the field (Jennings *et al.*, 1978).

TABLE 1. Results of soil analysis with complex indices.

Mineral	Identification wavelength (μm)	Fractional composition (%)	Complex index at $9.21 \mu\text{m}$ (n_r, n_i)
Gypsum	2.82	26	2.0, 0.30
Calcite	6.94	14	1.7, 2.0
Montmorillonite	9.80	35	0.86, 5.4
Quartz	12.82	25	1.0, 5.4

The chemical analysis was attempted using two methods, x-ray diffractometry and IR-spectrophotometric analysis. The x-ray analysis revealed a strong quartz component but little else since not all of the dust consisted of crystalline material. The spectrophotometric analysis was much more informative because of the distinct IR spectral absorption patterns of the minerals involved (Hoidale and Blanco, 1969). In this analysis the sample transmission spectra between wavelengths $2.5\text{--}40 \mu\text{m}$ were measured with a Perkin Elmer model 521 infrared grating spectrophotometer. The spectral transmission "fingerprints" of the substance under test were compared with those of known pure reference samples to assess the fractional composition of the unknown dust sample (Duyckaerts, 1959). In this spectrometric estimate of mineral composition the following assumptions were made: (i) the sample and reference particulate size spectra are identical functions of those distributions; (ii) the absorption resonance peaks were assumed to be unique to a particular mineral; and (iii) sample and reference minerals were assumed to be in the same chemical state. Under these assumptions the fractional mineral composition of the dust sample was then calculated by converting the transmission spectra to absorption coefficients and scaling the absorption resonance peaks linearly with mineral mass concentration. The results of this analysis are shown in Table 1. It is noteworthy that the minerals identified (quartz, montmorillonite, calcite and gypsum) were also found in naturally occurring aerosol samples collected within 4 km of where this test was conducted, although the proportions of each mineral were markedly different (Hoidale and Blanco, 1969).

Using the fractional composition values of Table 1 and the complex refractive indices of the constituents, the contributions to the total absorption coefficient of each component can be calculated using Lorenz-Mie theory. Assumptions made in this process are those of particle sphericity, homogeneity, and similar size distributions for each constituent. In addition, for the birefringent quartz and calcite particles, the absorption was calculated by considering two populations of particles, one having refractive index of the ordinary ray and one the extraordinary ray, and adding the absorption coeffi-

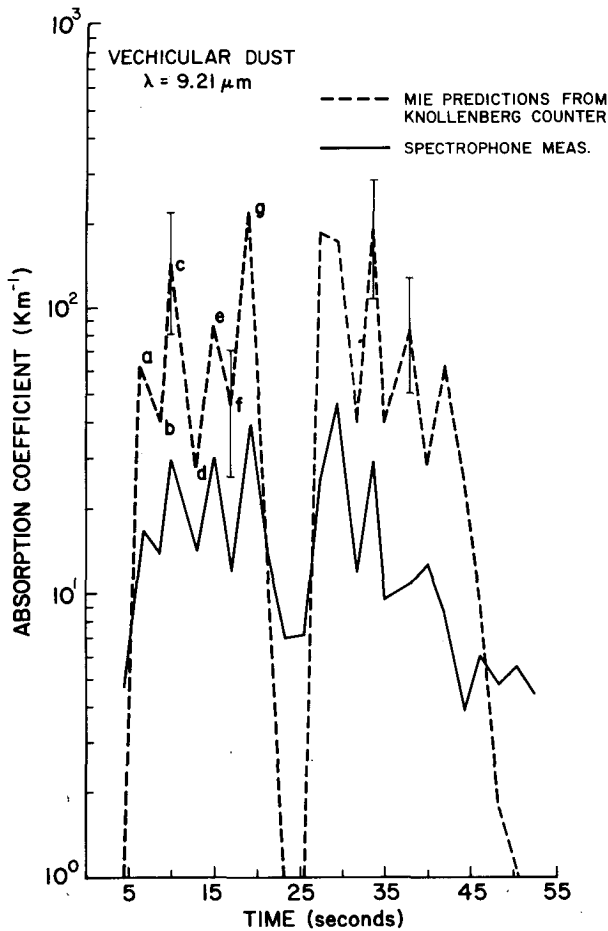


FIG. 6. Absorption coefficient of vehicle dust at the $9.21 \mu\text{m}$ R(34) CO_2 laser line as a function of time during the test: measured using *in situ* spectrophone (solid line); and calculated from particle size distribution measurements made with a Knollenberg light-scattering aerosol counter (dashed line). The "error" bars superimposed on the Knollenberg-based predictions indicate only the error caused by uncertainty in particle size determination. Other sources of error in the predictions (see text) and differences in the spectrophone and Knollenberg probe sampling efficiencies are expected to cause the remaining discrepancy between measured and predicted absorption.

cients for these fractional populations on a $\frac{2}{3}$ - $\frac{1}{3}$ basis.

Even a rough estimate of the effect of these assumptions on the calculated absorption coefficients would be very difficult at this time. Furthermore, it should be noted that the complex indices for these constituents are not well known, and montmorillonite, for example, does not have a fixed composition. Quartz is probably the best defined with respect to index and the others may be accurate within perhaps a factor of 2.

An example of the spectrophone-measured dust absorption coefficients compared to those predicted from the Knollenberg counter dust size distribution measurements together with the spectro-

photometric analysis of the dust composition appears in Fig. 6. Knollenberg data were taken continuously during this 2 min period, although the instrument particle count rate exceeded the maximum reliable rate (determined in the laboratory to be $\sim 1000 \text{ s}^{-1}$ under these conditions) for several 5 s accumulation intervals. (The predictions of absorption for this suspect data generally fall above the 100 km^{-1} level in Fig. 6). In any case, the predicted absorption for all of the Knollenberg data displays similar temporal variation as the spectrophone measured absorption, although the values are higher by a factor 3-5. The "error" bars shown for the Knollenberg-based predictions indicate only possible error caused by uncertainty in particle size determination made from the counter measurements: no estimate of errors accompanying the assumption of spherical particles, of the approximate treatment for birefringent particles, and of the assumption of similar size distribution for each dust mineral constituent was attempted.

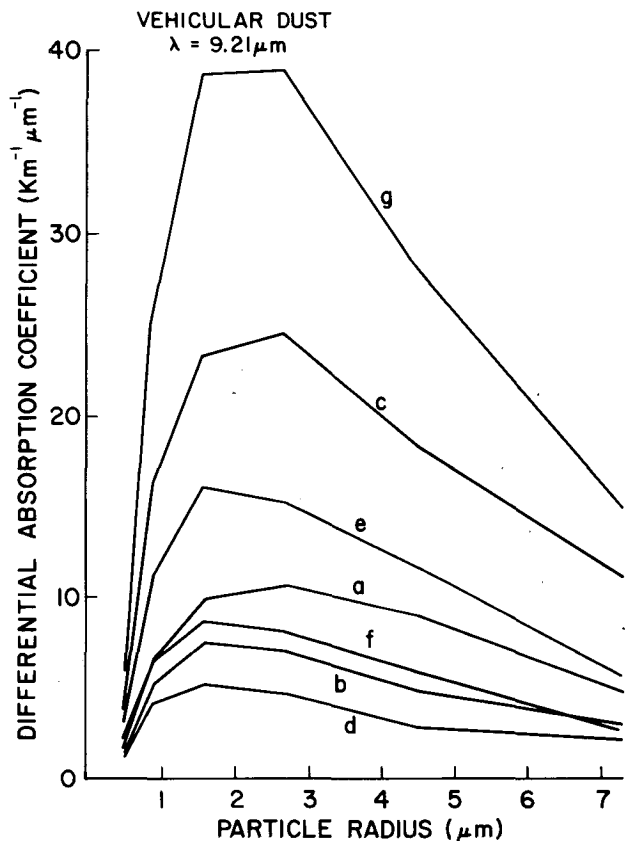


FIG. 7. Differential absorption coefficients of vehicular dust showing that 1-5 μm (equivalent) radius particles dominate absorption at the $9.21 \mu\text{m}$ CO_2 laser line. These coefficients are calculated from the Knollenberg size distribution measurements made at times a-g (in Fig. 6) together with estimates of the vehicular dust refractive indexes (see text for additional details of this calculation).

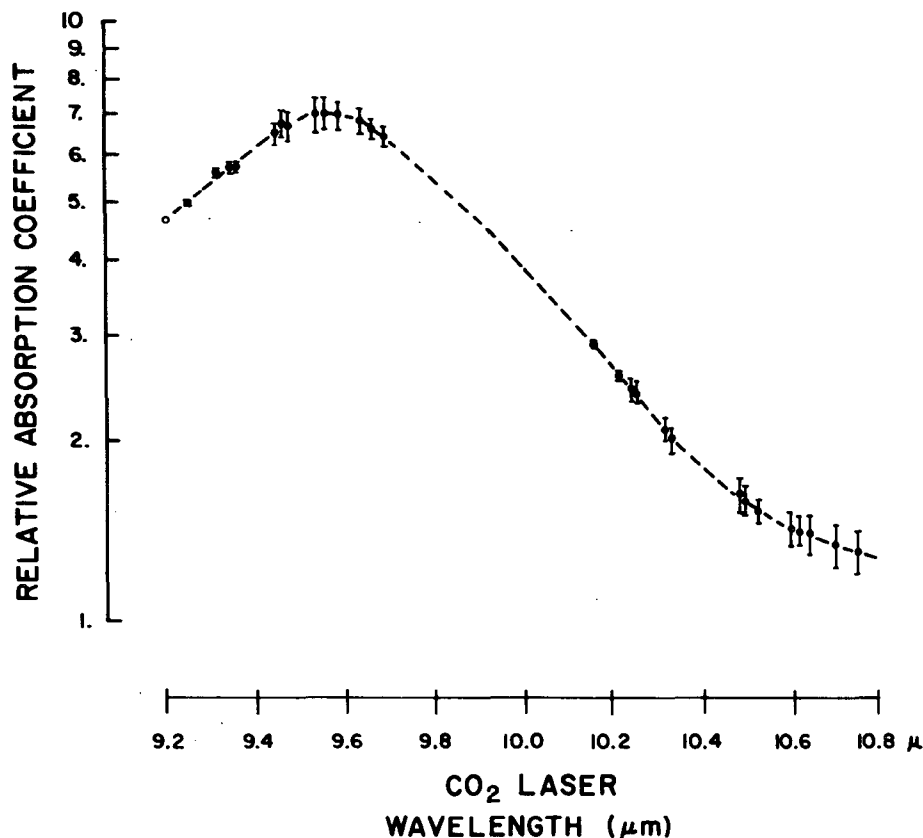


FIG. 8. Spectrophone absorption measurements of the spectral dependence of samples of vehicle dust.

Thus, in view of the multitude of rather critical assumptions made in predicting absorption from the Knollenberg size distribution data, and considering the fact that the aerosol sampling losses may be significant and different for the spectrophone and Knollenberg sensors, agreement of the measured and predicted absorption in Fig. 6 is considered respectable.

In order to determine how much absorption (at the 9.21 μm wavelength) is contributed by particles of various sizes, the differential absorption coefficients were calculated from the Knollenberg size distribution measurements. The results for 35 s of data (corresponding to times denoted a-g in Fig. 6) are presented in Fig. 7. They suggest that the absorption is dominated by particles with radii in the 1-5 μm range irrespective of dust loading.

Finally, spectrophone measurements of the spectral dependence of the absorption for the vehicular dust redispersed in a laboratory environmental chamber is shown in Fig. 8. Because of the uncertainties mentioned earlier for the complex indices of the dust constituents, no attempt was made to calculate a result for comparison. However, the spectral profiles for quartz and calcite dusts meas-

ured using spectrophones (for similar size distributions) and transmission spectra for montmorillonite and gypsum measured using the spectrophotometer techniques suggest that the strong absorption feature in the 9 μm region in Fig. 8 is due partly to quartz, but that its broad character and its extension past 9.6 μm is probably due to the presence of clay minerals such as montmorillonite.

5. Summary

Measurements of both gaseous and aerosol atmospheric absorption made with a differential CO₂ laser spectrophone system have been reported. The spectrophone allows *in situ* measurements to be made on a real-time basis at frequencies of electro-optical systems, and obviates some uncertainties present in other methods.

In the case of atmospheric gases, it is quickly learned from the use of this system how easily absorption may be significantly increased due to local and often innocuous appearing sources. Numerous trace gas pollutants at the 1 ppm level have absorption coefficients comparable to the ambient absorption and distinctive spectral patterns for the 9.2-

10.8 μm emission line spectrum of a $\text{C}^{12}\text{O}_2^{16}$ laser. This suggests that the spectrophone device may be well suited for air pollution studies.

Measurements of absorption by atmospheric particulates is more difficult than for gases. While the interaction between the spectrophone laser beam and the particles, and the acoustical sensing are reasonably well understood, accurate sampling of all sizes of particles under windy conditions is difficult. (However, sampling particles with any other currently available technique faces similar difficulties.) One aspect of the importance of the particulate component is that of its extreme variability. Quiescent and low-wind conditions generally produce absorption coefficients that are negligible compared with the gaseous component at wavelengths $\sim 10 \mu\text{m}$, while high winds and/or anthropogenic disturbances can raise the particulate absorption by orders of magnitude to well above the gaseous component.

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REFERENCES

- Brewer, R. J., and C. W. Bruce, 1978: Photoacoustic spectroscopy of NH_3 at the 9 μm and 10 μm $^{12}\text{C}^{16}\text{O}_2$ laser wavelengths. *J. Appl. Opt.*, **17**, 3746–3749.
- C. W. Bruce, and R. G. Pinnick, 1977: *In situ* measurements of aerosol absorption with a resonant cw laser spectrophone. *J. Appl. Opt.*, **16**, 1762–1765.
- , B. Z. Sojka, B. G. Hurd, Wendel R. Watkins, Kenneth O. White and Z. Derzko, 1976: Application of pulsed-source spectrophone to absorption by methane at DF laser wavelengths. *Appl. Opt. Lett.*, **15**, 2970–2972.
- Duyckaerts, G., 1959: The infra-red analysis of solid substances. *Analyst*, **84**, 201–214.
- Hoidale, G. B., and A. J. Blanco, 1969: Infrared absorption spectra of atmospheric dust over an interior desert basin. *Pure Appl. Geophys.*, **74**, 151–164.
- Jennings, S. G., R. G. Pinnick and H. J. Auvermann, 1978: Effects of particulate complex refractive index and particle size distribution variations on atmospheric extinction and absorption for visible through middle-IR wavelengths. *Appl. Opt.*, **17**, 3922–3928.
- Lindberg, J. D., and J. B. Gillespie, 1977: Relationship between particle size and imaginary refractive index in atmospheric dust. *Appl. Opt.*, **16**, 2628–2630.
- Patty, R. R., G. M. Russwurm, W. A. McClenny and D. R. Morgan, 1974: CO_2 laser absorption coefficients for determining ambient levels of O_3 , NH_3 and C_2H_4 . *Appl. Opt.*, **13**, 2850–2854.
- Pinnick, R. G., and H. J. Auvermann, 1979: Response characteristics of Knollenberg light-scattering aerosol counters. *J. Aerosol Sci.*, **10**, 55–74.
- , and J. M. Rosen, 1979: Response of Knollenberg light-scattering counters to non-spherical doublet polystyrene latex aerosols. *J. Aerosol Sci.*, **10**, 533–538.
- Roessler, D. M., and F. R. Faxvog, 1979: Opto acoustic measurement of optical absorption in acetylene smoke. *J. Opt. Soc. Amer.*, **69**, 1699–1704.
- White, K. O., W. R. Watkins, C. W. Bruce, R. E. Meredith and F. G. Smith, 1978: Water vapor continuum absorption in the 3.5–4.0 μm region. *Appl. Opt.*, **17**, 2711–2720.