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EXPERIMENTALLY DETERMINED RELATIONSHIP BETWEEN
EXTINCTION AND LIQUID WATER CONTENT (U)

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INTRODUCTION

To develop effective electro-optical weapon systems, it is necessary to have a clear understanding of the importance of and correlations between various atmospheric parameters in the wavelength regions of interest. A careful measurement program is essential to the development of this understanding and it provides the basis for accurate simulation of electro-optical system performance.

Measurement systems should be chosen to give as direct results as possible. This choice minimizes assumptions which effect the validity of the results. It also reduces the data analysis needed for the interpretation of results, thereby making results available in real time.

This paper reports the results of environmental chamber measurements of extinction coefficients at CO₂ laser wavelengths and of liquid water content (LWC) of a variety of droplet size distributions. The liquid water content measurements were made with two

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→ recently developed systems which are described, in detail, in Bruce et al. [1]. The results are in general agreement with calculated results of Pinnick et al. [2], based on measured fog droplet size distributions and give further verification to Chylek's [3] prediction of a unique linear relation between extinction at approximately $11\mu\text{m}$ and liquid water content of fogs for all size distributions with maximum particle radii less than or approximately equal to $14\mu\text{m}$.

EXPERIMENTAL APPROACH

The measurements of this paper were made in an environmental chamber having a volume of approximately 1 cubic meter. Water droplets were generated within the chamber, and minimum stirring was used to ensure uniform spatial distribution of the particles.

Figure 1 is a diagram of the optical system used in the measurements. The (half power) diameter of the laser beam is approximately 1 cm in the measurement region. Early measurements made with a larger diameter ($\times 3$) beam did not significantly improve the steadiness of the output signal. The laser path through the chamber is in the vertical direction. Warm dry air in the form of a thin sheet is blown across the (exterior) mirrors at the top and

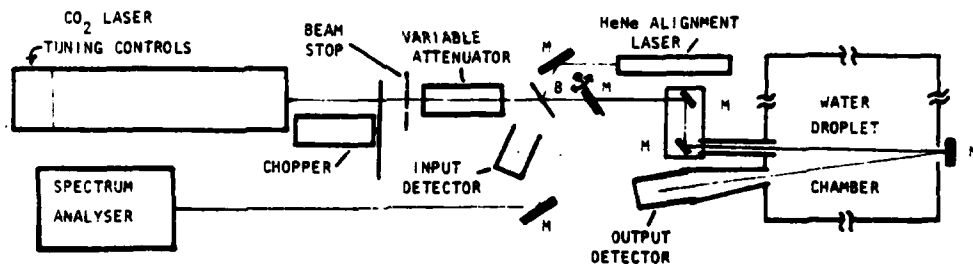


Figure 1. Optical system. M-represent mirrors, B-represents beam splitter. One mirror is rotatable to permit laser line identification. The CO₂ laser incorporates automatic line scanning and stabilization. An optical beam chopper is retained so that an aerosol spectrophone (measures absorption coefficient) and alternate detectors for other lasers may be used. An adjustable aperture for the CO₂ laser beam, window flush for the in- and out-put mirrors, liquid water content measurement systems and particle counter are omitted in this diagram.

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bottom of the chamber to prevent accumulation of water droplets on their surfaces. A sample of the input beam is monitored by a reference power meter. Both calculations and parametric measurements have been used to determine the attenuation necessary to prevent significant heating and evaporation of the water droplets. A mirror is rotated into the beam path to direct the beam to a spectrum analyzer during tuning of the laser.

Sampling throats for the liquid water content measuring systems are located approximately in the lower center of the chamber. Sampling is at a rate of 10 to 15 liters per min. The sampling throat of a commercial light scattering counter extends through one side of the chamber to a point close to the extinction path and the liquid water content sampling throats. This instrument is used to monitor the droplet size distributions and, through these, the contributions of different size particles to the extinction coefficient (differential extinction coefficient).

PRELIMINARY EXPERIMENTS

Although the measurement systems used in this study are relatively direct, several extensive preliminary investigations were conducted to ensure the existence of appropriate experimental operating conditions.

The first of these involved the commercial instrument used to monitor the particle size distributions--Particle Measuring Systems (PMS) classical scattering aerosol spectrometer. This instrument is sensitive to water droplets with radii from 0.23 μ m to 16 μ m.

This instrument counts particles of different sizes by doing pulse height analysis of laser light (0.63 μ m) scattered by single particles into a particular solid angle. Determination of particle size is indirect because the scattering depends on particle refractive index and on the geometry of the optical system.

The instrument used in this study was checked to be sure that particles were counted in the correct size range channels. This was done by using single-size nearly transparent beads for channels counting particles with radii up to about 4 μ m and with calibrated bead mixtures for channels counting particles with radii between 4 μ m and 16 μ m. No measurement was made of particle counting efficiency. The results from the studies with mixed bead sizes indicate that counting efficiency was relatively constant for all channels since the curves obtained with calibrated bead mixtures had approximately the correct shapes for the size mixtures used.

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Care must be exercised to limit the density of aerosol sampled by the counter since counting is based on the assumption of single scattering by individual particles and distortion of results may occur at high count rates. A variety of dilution techniques were tried in which droplet-free air was mixed with the droplet sample stream from the chamber in the inlet throat of the PMS counter. Care was taken to minimize disturbance of the flow character. The results obtained indicate that use of these techniques extended the number density range of the instrument by a factor of about 3, but that further dilution of these water droplet distributions caused definite distortion of the differential extinction curves. The differential extinction curves were used only in a relative sense, i.e., the shape of the curve and the particle radius, r_p , at which peak extinction occurred were used as characteristic parameters of the chamber droplet distributions, since an absolute calibration was not available to relate a measured size distribution to actual extinction coefficient and liquid water content.

The second of these preliminary studies was an investigation of the conditions for generation of droplet size distributions and differential extinction profiles within the ranges found in naturally occurring light to heavy fogs. The differential extinction profiles show the contribution to extinction of particles with radii in relatively small size ranges. Peak extinction for fogs normally occurs in the particle radius range of $2\mu\text{m}$ to $10\mu\text{m}$. No attempt was made to specifically tailor size distributions to be representative or any particular type of fog but rather to provide a span of fog droplet sizes.

Commercially available "cool mist vaporizers" were used to generate droplet distributions which had monomodal differential extinction curves. The radius of peak extinction, r_p , could be varied from about $8\mu\text{m}$ to $16\mu\text{m}$ by using a variety of throttling and impaction techniques. A stable mode of operation with peak extinction at particle radii of $10\mu\text{m} \pm 1\mu\text{m}$ was finally used. Condensation droplet distributions were produced by introducing cold gaseous nitrogen into the saturated vapor of the chamber. These distributions are characterized by relatively narrow, monomodal differential extinction curves with peak extinction for droplet radii of $4\mu\text{m} \pm 1\mu\text{m}$. Both types of droplet distributions were generated with densities ranging from about 0.01 to 4.0 gm/m^3 . The shape and peak position of the differential extinction curves were not particularly sensitive to variation of the droplet number density. Typical differential extinction curves are shown in figure 2.

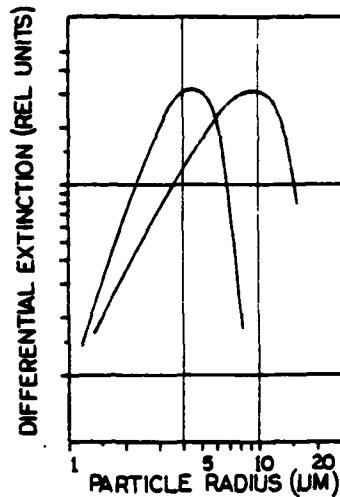


Figure 2. Typical differential extinction curves for condensation droplet (left peak) and mechanically generated (right peak) size distributions.

A study of the spatial uniformity of the droplet distributions was made by varying the location of the droplet generators and using several stirring mechanisms. Most of the mixing results from the circulation caused by the droplet generators. A small fan with specially tailored blades provides the small additional circulation (in the form of a donut within the chamber) required to obtain spatially uniform distributions.

The last of the preliminary studies involved characterization of two new sensing systems which give real-time measurements of liquid water content. These instruments and their characterization will be reported in detail elsewhere [1]. Only a summary will be given here.

One system involves a mass accumulation technique in which droplets are collected on a three-dimensional filter consisting of layers of flannel on a screen base. If the accumulated mass is measured and divided by the sampling time and the volume flow rate through the filter, an absolute measurement of LWC is obtained in units of mass density. The three-dimensional filter is critical to successful measurements since water droplets would clog a two-dimensional filter and lead to inaccurate sampling. Sampling times between 15 s and 4 min were used for both light and heavy mass density droplet distributions and have yielded reproducible results.

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Caution is necessary in this measurement to apply a time-dependent correction factor which results from quite rapid initial absorption of water by the dry filter fibers. This effect actually represents equilibration of the flannel to the relative humidity of the chamber. Since this effect is rapid and reproducible, the necessary correction is straightforward. Mass collection was studied to determine an adequate number of layers of flannel.

For the environmental chamber measurements, filters are preweighed in sealed containers, inserted into a sampling throat with O-rings seals, and are replaced in their original container for post sampling weighing. They are then dried with a stream of ambient air for later use. A similar but real-time system incorporated into a top loading electronic balance is also used.

The second LWC measurement system uses a differential sampling technique and phase-sensitive detection. The system has two sampling throats. One throat is vertical and unobstructed and the flow through it contains both vapor and water droplets; the other throat contains a series of flannel filters with offset openings which create free-flow conditions through a tortuous path so that the resulting sample contains only vapor. A rotating half disc alternately selects samples from the two throats and permits them to flow through a heated woven wire grid which evaporates the droplets. The wire diameter was chosen to be much larger than the water droplets to provide a good capture efficiency. Evaporation of water from the grid causes cooling and a change in the grid resistance; This results in an approximately linear change in the voltage applied across the grid by a constant current power supply. A reference signal for a lock-in amplifier is obtained from the throat selecting half disc and the synchronous voltage change across the grid is measured. The resulting signal has been shown to be proportional to the total mass density measured with the filter system in a series of measurements over a wide range of environmental chamber conditions. Single and multiple layer grids have been used and no significant difference in results was found.

EXPERIMENTAL PROCEDURES

The extinction coefficient measurements in this study were made with the laser tuned to the $10\mu\text{m}$ R-16 CO_2 transition line at a wavelength of $10.27\mu\text{m}$. The laser beam power was monitored continuously--both prior to the input mirror for the fog chamber (sampled by a beamsplitter) and after it left the chamber. The length of the path within the chamber was 1.79 m.

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Optical alignment and laser line stability were periodically checked and no problems were encountered. The power meters and the differential LWC system were stabilized and baselines were established.

The droplet generators were then turned on and the chamber was brought to a droplet equilibrium condition which was characterized by constant values for both laser output power and LWC. After recording these values, the droplet generators were turned off and the chamber was again allowed to reach an equilibrium with only vapor present. This establishes a procedure for the measurement of changes in transmission of laser power due to droplets only.

The droplet generators were again turned on and, after equilibrium conditions were reached, a set of three filter measurements of liquid water content was made. PMS counter measurements were then made and the droplet generators were turned off. After a settling time to return to vapor-only conditions, the same measurement process was repeated with a different power supplied (by use of a Variac) to the droplet generators. Variac settings between 60 and 100 percent were used to provide a variety of droplet number densities. Size distributions and the shape and position ($r_p = 10\mu\text{m} \pm 1\mu\text{m}$) of the differential extinction coefficient curves remained almost constant for all similar sets of experiments.

Different droplet size distributions were obtained by following the above procedure for establishing vapor saturation as well as equilibrium droplet conditions and then introducing cold nitrogen gas into the center of the chamber. After an initial mixing period of about 1 min, chamber conditions became essentially uniform. Following this, both the laser output power and differential LWC signals decayed (over a period of 6 to 10 min) back to those representative of ambient temperature conditions.

For some of these condensation droplet measurements, the droplet generators were turned off before the cold nitrogen was introduced. Under these conditions, the position of r_p for the differential extinction coefficient curves was at about $4\mu\text{m} \pm 1\mu\text{m}$.

When the droplet generators continued operation, the position of r_p either occurred at an intermediate position or the size distribution was bimodal with a variety of shapes and the two-peak extinction positions within the range of $4\mu\text{m}$ to $10\mu\text{m}$.

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Since chamber conditions varied with time for these condensation experiments, the LWC filter measurements were made only under the original equilibrium conditions to establish a calibration value for the differential LWC measurement.

The PMS counter measurements also required a special procedure. Since the counter significantly depleted the chamber's contents, size distributions were measured on alternate measurement sets for repeated conditions. There was an equilibration period when the counter was first turned on. The data for this period (about 3 s) were discarded. Then, several valid 2 s sampling sets of data were obtained.

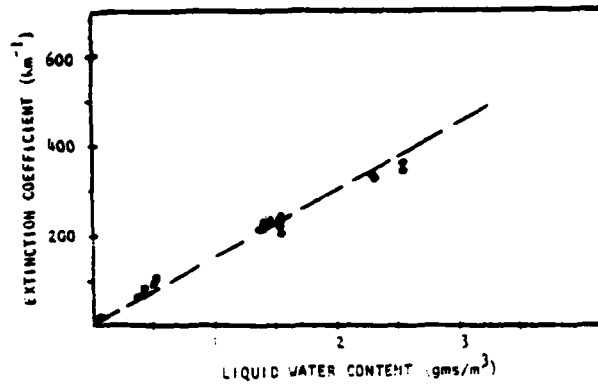
RESULTS

The measured relationship between the extinction coefficient at $10.27\mu\text{m}$ and the liquid water content of environmental chamber droplet distributions are shown in figures 3a through 3c.

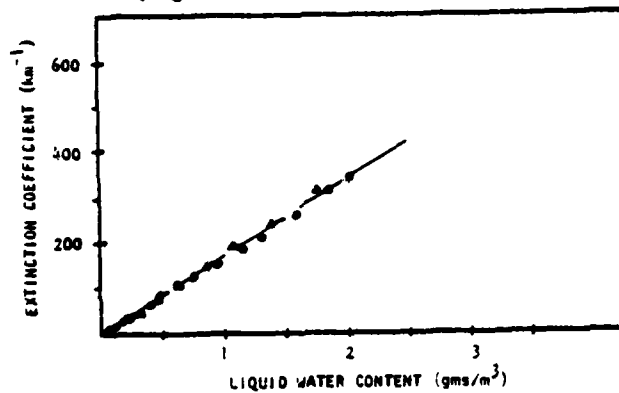
Each of the size distributions clearly show a linear relation between the measured quantities. The ratio between them shows some variation as a function of the droplet distribution generation mechanism: the slope for mechanically generated distribution (figure 3a) is $152\text{ km}^{-1}/(\text{gm}/\text{m}^3)$, for condensation droplet distributions (figure 3b) $168\text{ km}^{-1}/(\text{gm}/\text{m}^3)$, and for the combination of distributions (figure 3c) is $158\text{ km}^{-1}/(\text{gm}/\text{m}^3)$, although it could presumably vary anywhere between the other two values.

However, the data for all of the distributions may be combined to yield a linear relation with a slope of $159\text{ km}^{-1}/(\text{gm}/\text{m}^3)$ with an estimated combined experimental error of $12\text{ km}^{-1}/(\text{gm}/\text{m}^3)$ or 8 percent.

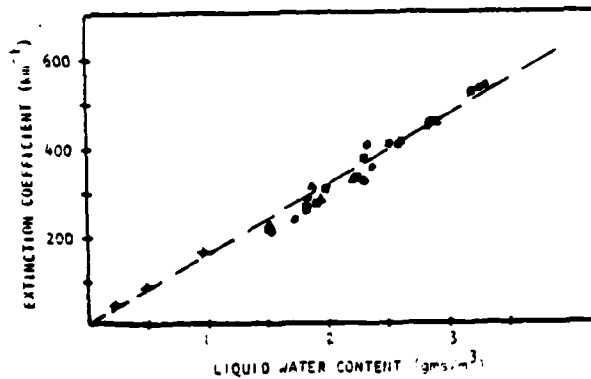
The PMS counter measurements of the size distributions were used in a Mie scattering program calculation of extinction coefficient (using a previously measured value for the complex index of refraction for water at this wavelength by Hale et al. [4] and liquid water content. This data is assumed to give relative results only, because the absolute calibration of the instrument is not known, but the ratio of the calculated quantities of $166 \pm 12\text{ km}^{-1}/(\text{gm}/\text{m}^3)$ is in reasonable agreement with that of the measured slopes. The calculated extinction and liquid water content values themselves were close to the measured values for one counter used but were very different for another, supposedly similar unit.



(a) Mechanically generated droplet size distributions.



(b) Condensation droplet size distributions.



(c) Droplet distributions generated by combinations of the mechanical and condensation techniques.

Figure 3. Extinction coefficients as functions of liquid water content for mechanically generated, condensation, and combination droplet size distributions.

CONCLUSIONS

Measurements have been made of the extinction coefficient at $10.27\mu\text{m}$ and independently, of the liquid water content of a large number of environmental chamber droplet size distributions with radii spanning those of a variety of fogs. A linear relation has been found which is approximately independent of the size distribution. The measured ratio of extinction coefficient to liquid water content is $159\text{ km}^{-1}/(\text{gm}/\text{m}^3)$.

These results are in good agreement with the linear relation predicted by Chylek [3] and calculated by Pinnick et al. [2] at $11\mu\text{m}$ based on PMS counter size distribution measurements of fogs and hazes.

These results involve complex measurements that are very sensitive to the environment. Nevertheless, they do support the thesis that liquid water content can be used at $10\mu\text{m}$ wavelengths as a measure of extinction--a most important quantity in the application of military systems (e.g., to European environments).

Systems for the measurement of liquid water content under field conditions are being developed from those used in this study. They will be used in European and other field environments beginning in 1980.

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