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FINAL REPORT **NASA CR-**175158

for NASA Grant NAG5-58

entitled

"A Laboratory Investigation of the Reflective Properties of Simulated, Optically Thick Clouds"

Principal Investigator: Thomas B. McKee

Co-Investigator: Stephen K. Cox

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Grant Period 05/15/80 - 09/30/82

(NASA-CR-175158) A LABORATORY INVESTIGATION OF THE REFLECTIVE PROPERTIES OF SIMULATED, OPTICALLY THICK CLOUDS Final Report, 15 May 1980 - 30 Sep. 1982 (Colorado State Univ.) 64 p HC A04/MF A01 CSCL 20P G3/74
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This report presents an overview of the progress made toward the specific scientific goals of the Cloud Field Optical Simulator project. A somewhat more detailed account may be found in the appendix which contains the first semi-annual report, the annual report submitted in mid 1982, and a paper entitled "Design and verification of a cloud field optical simulator," which has been submitted for publication in the Journal of Applied Meteorology.

The activity during the first six months of the contract period was concentrated mainly on the physical design and construction of the CFOS laboratory. The device which resulted consists of the following components: a radiation source comprised of an array of five incandescent lamps; a cloud target field 2 meters in diameter mounted in a vertical plane which can be rotated about its vertical diameter; an array of fifteen high quality silicon photodiodes capable of viewing the target field from variable observation coordinates; and a data collection/display station which uses an Apple II computer as the primary data logger. A diagram of the CFOS is presented in Figure 1 of the attached paper.

The next phase of the research included development of calibration procedures, improvement in the spatial uniformity of the source, and experiments with various materials for simulating optically thick clouds. A two step calibration procedure was used to establish the relative sensitivities of the detectors. In the first step the approximate sensitivities were measured using a small source which could be coupled to the collimator tubes of the individual diodes. The relative sensitivities were further adjusted using large sheets of target material which was nearly isotropic over the zenith angle regime of interest. It was found that the array of source lamps could be aimed at the target cloud field such that the incident irradiance varied by less than ±3% over the target cloud field.

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Radiances reflected from large sheets of various materials were measured in the CFOS and compared to reflected radiances which were calculated using a Monte Carlo radiative transfer model. The materials tested included surgical cotton, rayon fibers, and several types of styrofoam. None of the materials were exact analogues to the scattering process in water clouds as modeled by the Monte Carlo model. However, cotton and decorative billet styrofoam were found to approximate the natural process and also were the most practical with which to work. The region of worst agreement between simulated and modeled reflected radiances was found in the forward scattering direction at large zenith angles where simulated values were always less than the corresponding modeled values. The design features of CFOS and some of the initial measurements of simulated reflected radiances for a 0° solar zenith were presented at the Fourth Conference on Atmospheric Radiation in Toronto in June 1981.

The research conducted after the Toronto meeting is summarized in the attached annual report (see Appendix). Various efforts were made to improve the measurement process and the interpretation of the results as they pertain to real clouds. These improvements included installation of optical filters to limit the measurement to the visible portion of the spectrum and the adoption of an algorithm for establishing the optical depth of the simulated clouds.

After the optical filters were installed, the simulation materials were re-examined and the results were again compared to modeled results. No improvement was found in the overall simulated radiance patterns. However, it was deemed desirable to retain the filtering so that features in the measured radiance patterns could be visually appreciated.

The algorithm for determining optical depth utilizes the theoretical prediction of a nearly linear relationship between the ratio of cloud reflectance to cloud transmittance and the optical depth. This relationship was demonstrated for various theoretical cases and it was further demonstrated that a similar relationship exists between the area mass density (g/cm^2) of surgical cotton and the reflectance to transmittance ratio of the sample.

Work during the final phase of the contract period was concentrated on simulation of radiances reflected by finite clouds. Radiances reflected by a field of regularly spaced finite cubic, styrofoam-simulated clouds were measured. By accounting for the solid angle subtended by the clouds within the detector's field of view it was possible to solve for the radiance pattern reflected by a single cubic cloud. The results indicate that the dramatic transition to increased backscatter and diminished forward scatter predicted by theory as the solar zenith angle increases is simulated well. These latest measurements indicate that the impact of realistic cloud geometries on reflected radiances can be realized using the CFOS. The manuscript entitled 'Design and verification of a cloud field optical simulator' by Davis, Cox and McKee has been submitted to Journal of Applied Meteorology. The manuscript is presently being revised and should be returned for final review in the very near future.

The completed project has demonstrated that critical radiation properties of finite clouds can be simulated in the laboratory. CFOS is now ready for use in application.

D1

N84 20337

Semi-Annual Report

for

NASA Grant NAG5-58

entitled

A Laboratory Investigation of the Reflective Properties of Simulated Optically Thick Clouds

Principal Investigator: Thomas B. McKee

Co-Investigator: Stephen K. Cox

Department of Atmospheric Science
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Grant period: 05/15/80 - 05/15/82

The first six months have been spent in designing and constructing the Cloud Field Optical Simulator (CFOS). The CFOS is now nearly complete. A set of photographs are attached as figures to illustrate actual appearance of CFOS as it is ready for operation.

Figure 1 shows a schematic diagram of CFOS as originally proposed.

Figure 2 shows the 2 meter diameter cloud field mounted on the cloud field grid support which is located inside a large (4 meter) black enclosure with a circular front aperture and drapes. The data logging system is also visible on the left.

Figure 3 shows a close-up of the data logging system. The system now includes tape drives (upper left), clock and paper tape (lower left), controls for the rotation of the cloud field and detector ring (lower center), output display of all 15 detector (middle center), and power controls (right).

Figure 4 shows the light source which is an array of 5 sealed beam theater lights. The incident light beam has less than 5% variation across the 2 meter cloud field.

Figure 5 shows the cloud ring with the drapes partially closed as it is normally used for large solar zenith angles.

Figure 6 shows the entire cloud field and assembly. The cloud field support can be rotated about the vertical axis by the drive at the top, and rotated about a horizontal axis by rolling on the small wheels driven from the bottom. The detector ring (small solid ring from top to bottom, 4 meter diameter, with 15 detectors) can be rotated about a vertical axis through 360°.

The time schedule proposed originally is shown in Table 1. We are on schedule at the present time. Hardware acquisition and development is nearly finished. Material selection is completed as we are using Rayon fibers 3 μm to 5 μm in diameter. Verification and testing will be started in February 1981.

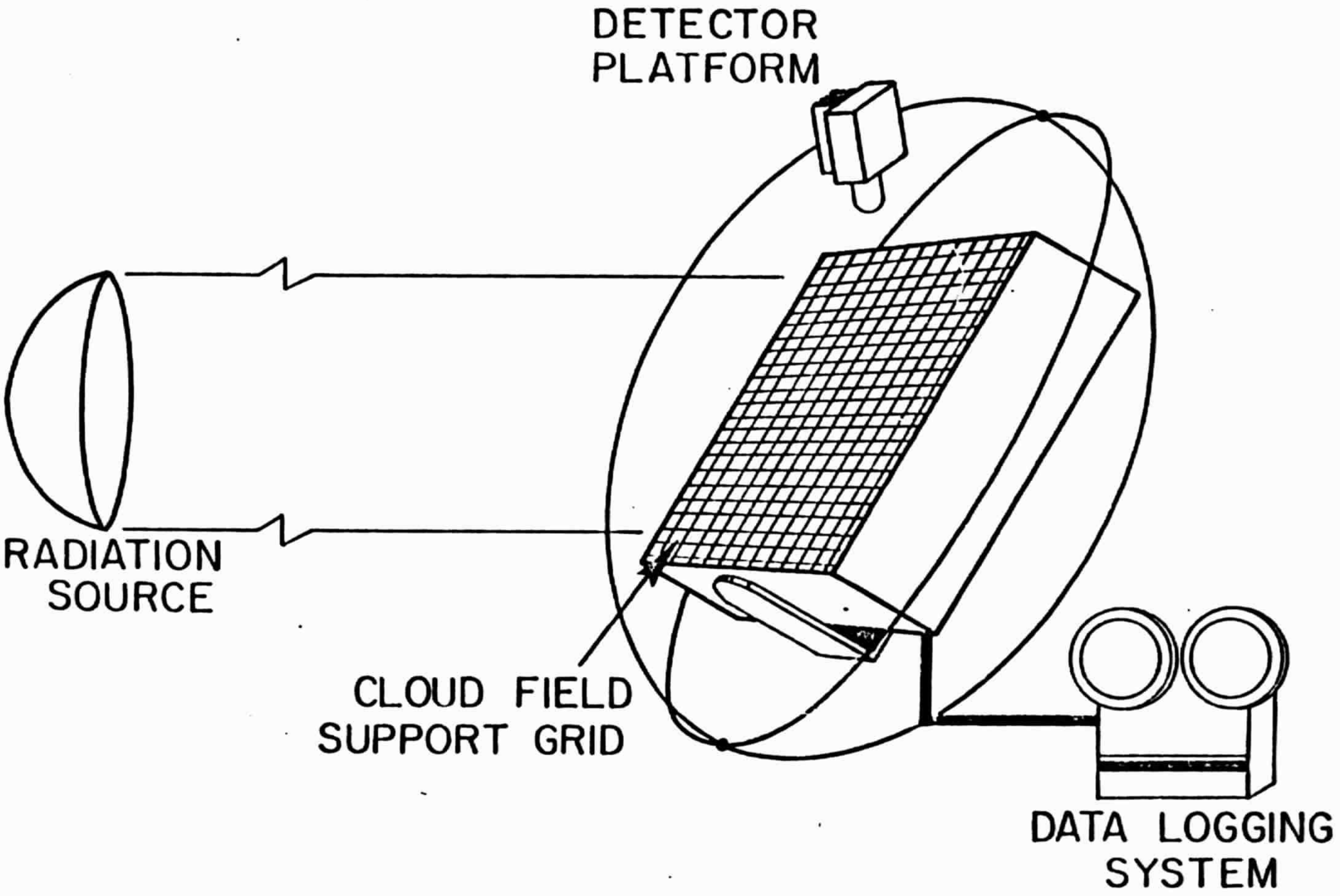

FIGURE 1.

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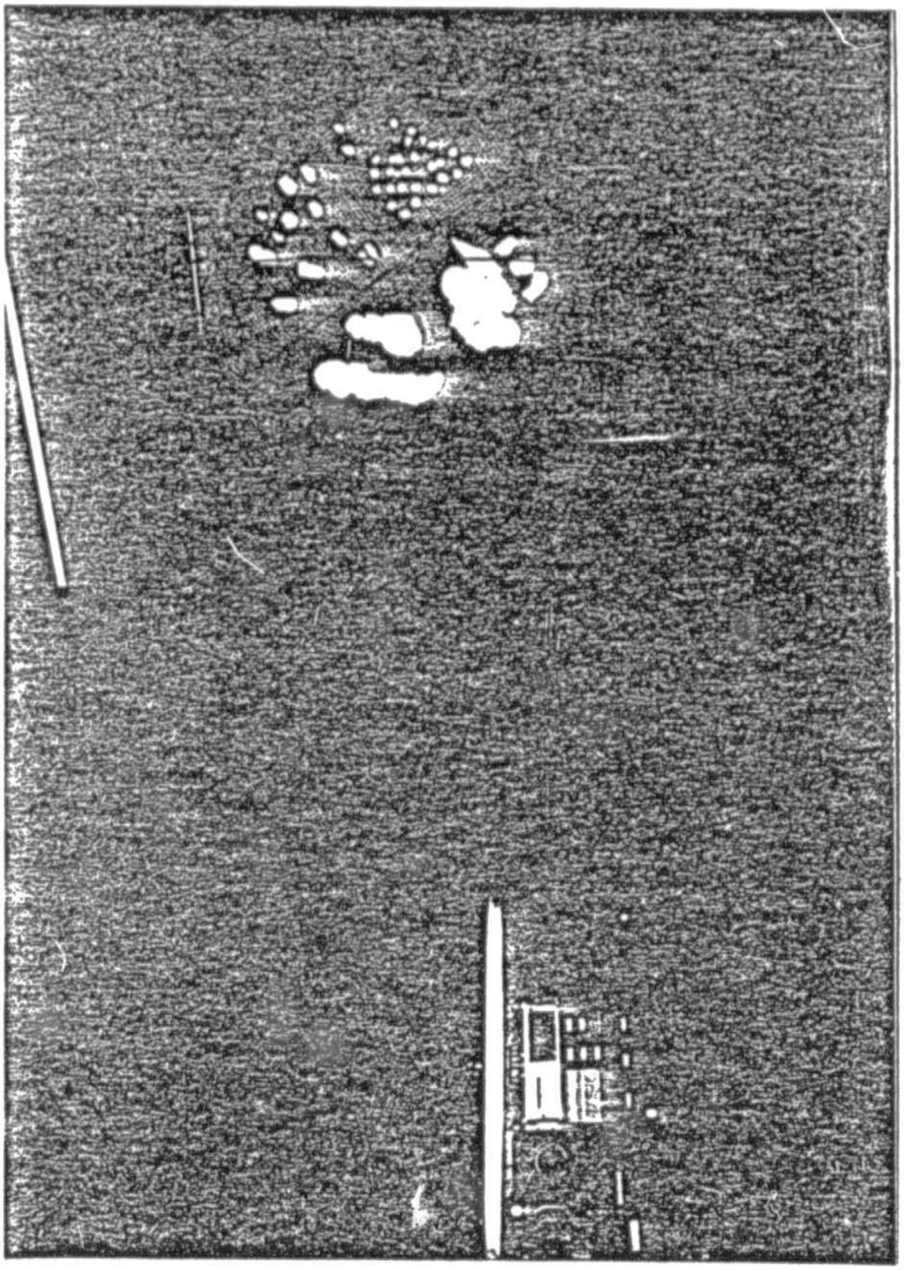

FIGURE 2.

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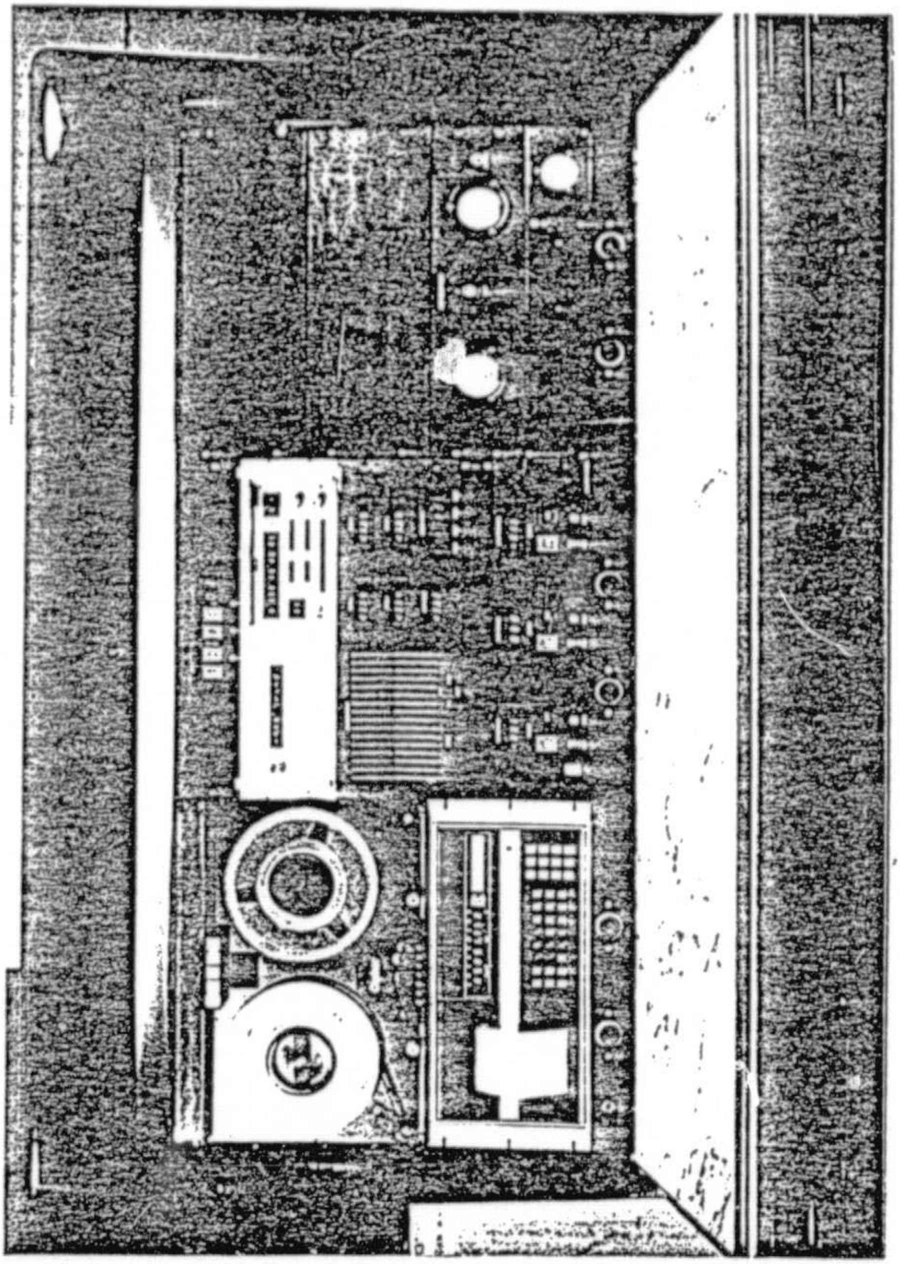

FIGURE 3.

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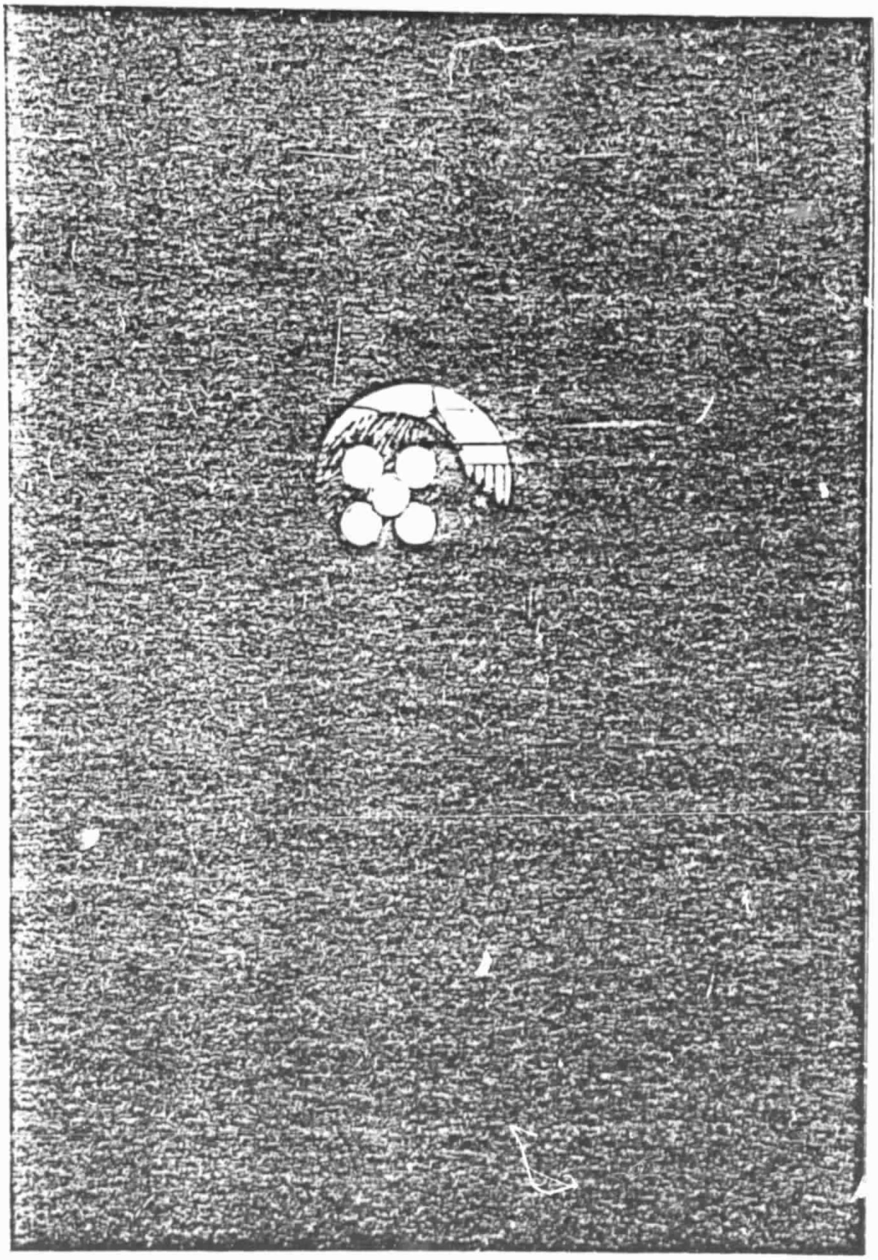

FIGURE 4.

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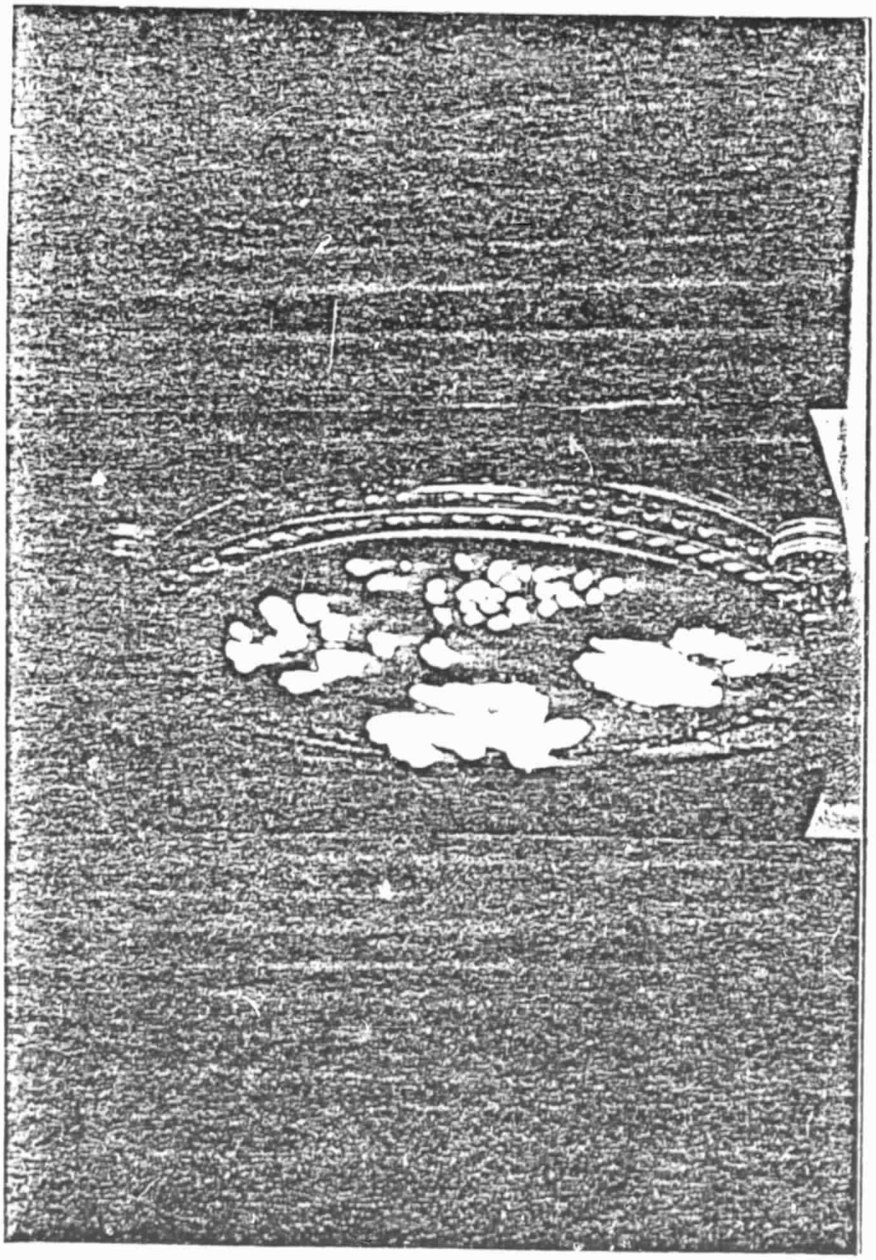

FIGURE 5.

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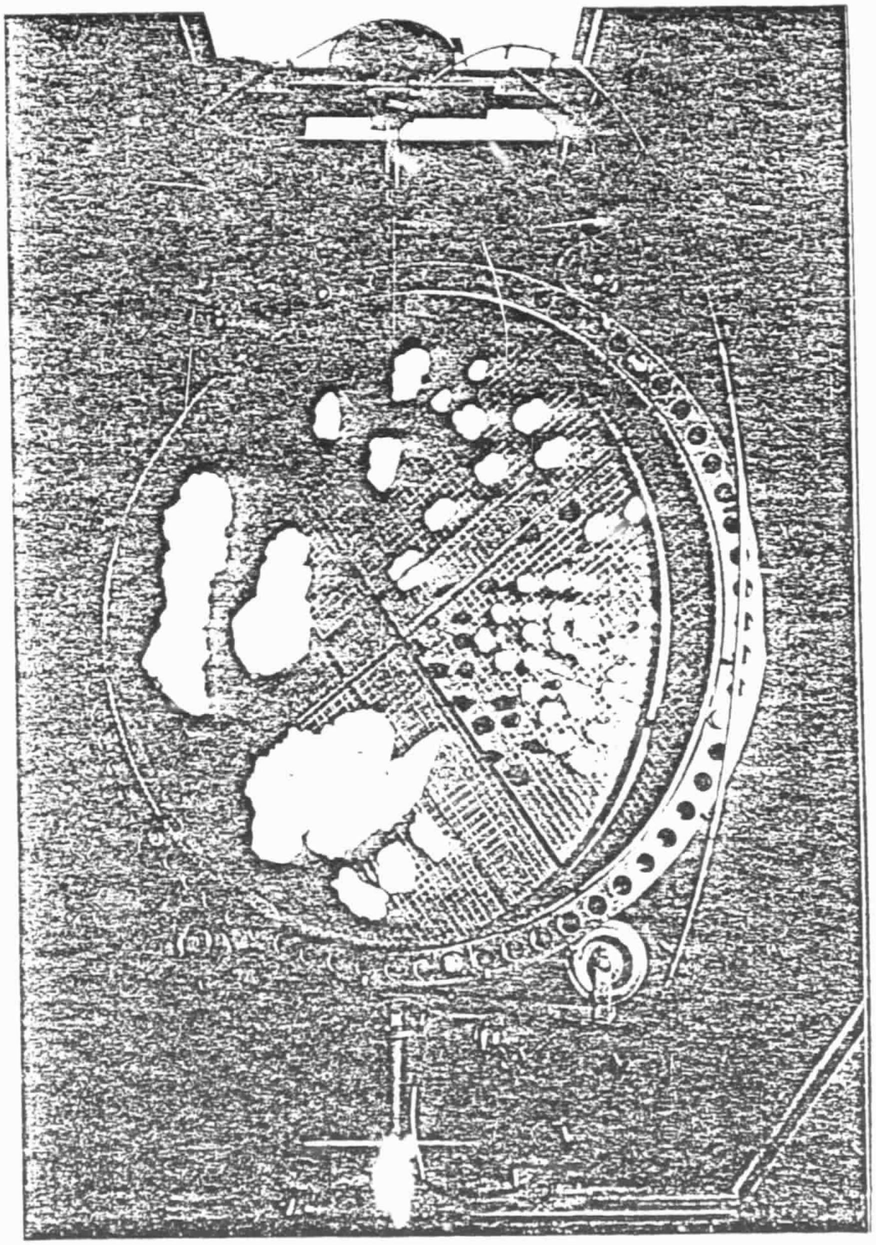

FIGURE 6.

TABLE 1. Time Plan

	0	6 mo	12 mo	18 mo	24 mo
Hardware acquisition and development	XXXX	X X X X			
Verification and testing		X X X X	X X X X		
Materials selection	XXXX				
Image qualification		X X	X X X		
Cloud field bidirectional reflectance properties			X X X X	X X X	
Cloud field transmittance properties			X X	X X X X	

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N84 20338

Annual Report
for
NASA Grant NAG5-58
entitled

"A Laboratory Investigation of the Reflective Properties of Simulated, Optically Thick Clouds"

Principal Investigator: Thomas B. McKee
Co-Investigator: Stephen K. Cox

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado 80523

Grant period: 05/15/80 - 05/15/82

This report summarizes the progress toward the specific research goals of the cloud field simulation project which has been made since June 1981. Accomplishments prior to this date were reported in our first semi-annual progress report in February 1981 and at the Fourth Conference on Atmospheric Radiation, Toronto.[1]

During the reporting period stated above, progress toward the research goals of CFOS (the Cloud Field Optical Simulator) may be noted in the following areas: (1) improvement in the shape of the desired (visible) spectral response of the measurement, (2) selection of two usable materials for cloud simulation, (3) a means of assigning a "visible" optical depth to the simulated clouds and (4) confirmation that the apparatus is capable of detecting basic finite cloud characteristics. A brief description of the accomplishments in each of these areas follows.

(1) Improved Spectral Bandpass

In order to insure that the measurements were limited to the visible portion of the spectrum an optical filter was placed in front of each detector. Figure 1 shows the relative responses of the system with and without the filter. Although insertion of the filter resulted in a relatively poorer S/N ratio it ensures that the measurements will not include spectrally dependent effects which are visually unobservable.

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[1] McKee, T. B., J. M. Davis, and S. K. Cox, 1981: Design and verification of a cloud field optical simulator. Preprints Fourth Conference Atmospheric Radiation, Toronto, Amer. Meteor. Soc., pg. 227.

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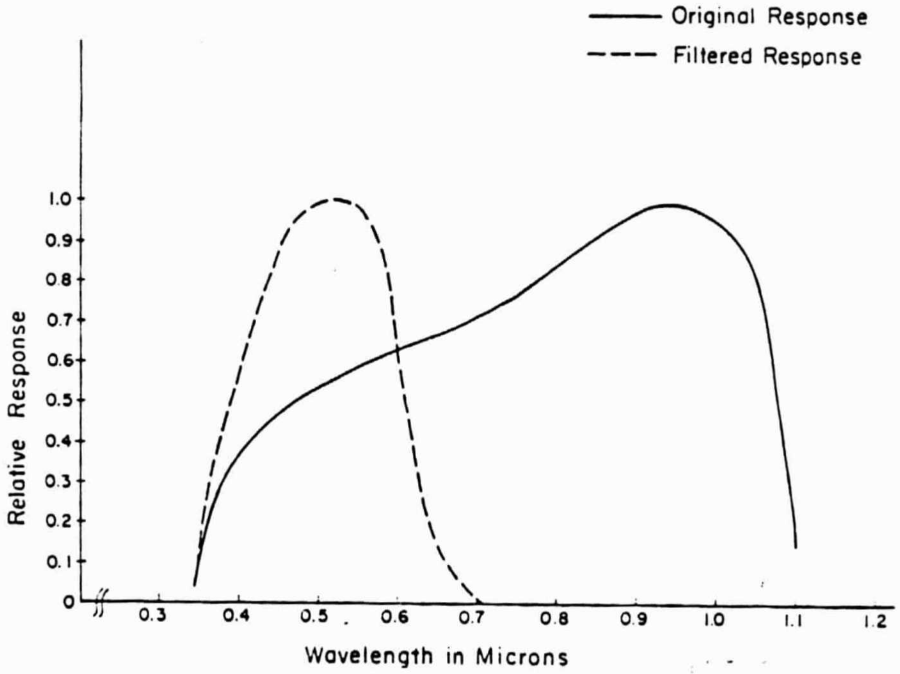

Figure 1. Relative spectral response of the original and filtered CFOS photodiode.

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2. Selection of Suitable Materials for Cloud Simulation

Several materials have been examined in a search for one which adequately simulates the visible reflective properties of optically thick clouds. The criteria which were used to rate the materials were first, the behavior of the radiances reflected into the principal plane by a horizontally semi-infinite cloud, and second, the visual appearance of the clouds simulated from the material. Based on these criteria, two materials were found to be superior to all others tested; they are surgical quality sterilized cotton and decorative billet styrofoam which is marketed by Dow Chemical. Figures 2 and 3 compare measured principal plane reflected radiances of the two materials with theoretical curves for semi-infinite clouds from Monte Carlo radiative transfer calculations. The model was run for two solar zenith angles $\mu_o = 1.0$ and $\mu_o = 0.5$ using the C.1 droplet distribution at a wavelength of 0.7 μm. All radiances have been normalized by the dividing by reflected radiance at the zenith. The materials are almost equivalent in satisfying the first criteria. However, the styrofoam is slightly better in the backscatter direction. The assignment of an equivalent optical depth to the simulation materials is discussed in the next section.

Both materials do well in simulating the visual appearance of clouds. If we add a third criterion, namely the practicality of working with the materials, the styrofoam becomes preferable for a number of reasons. First, the styrofoam material is rigid and will maintain a constant ratio of geometric to optical depth, and the shape of the simulated clouds will not distort due to gravity with rotation of the

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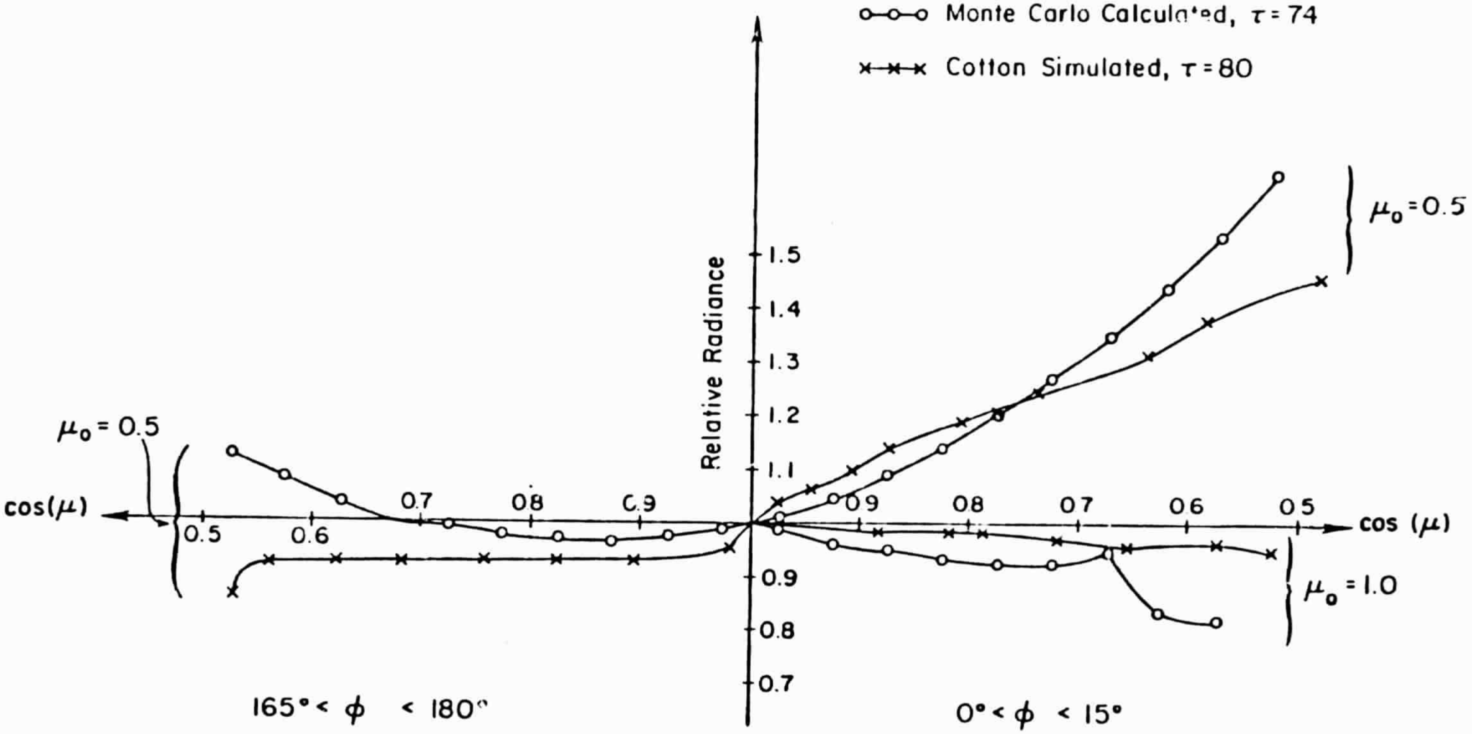

Figure 2. A comparison between the calculated and simulated reflected radiances from semi-infinite clouds for solar zenith angles of 0° and 60° using cotton as the cloud simulation material.

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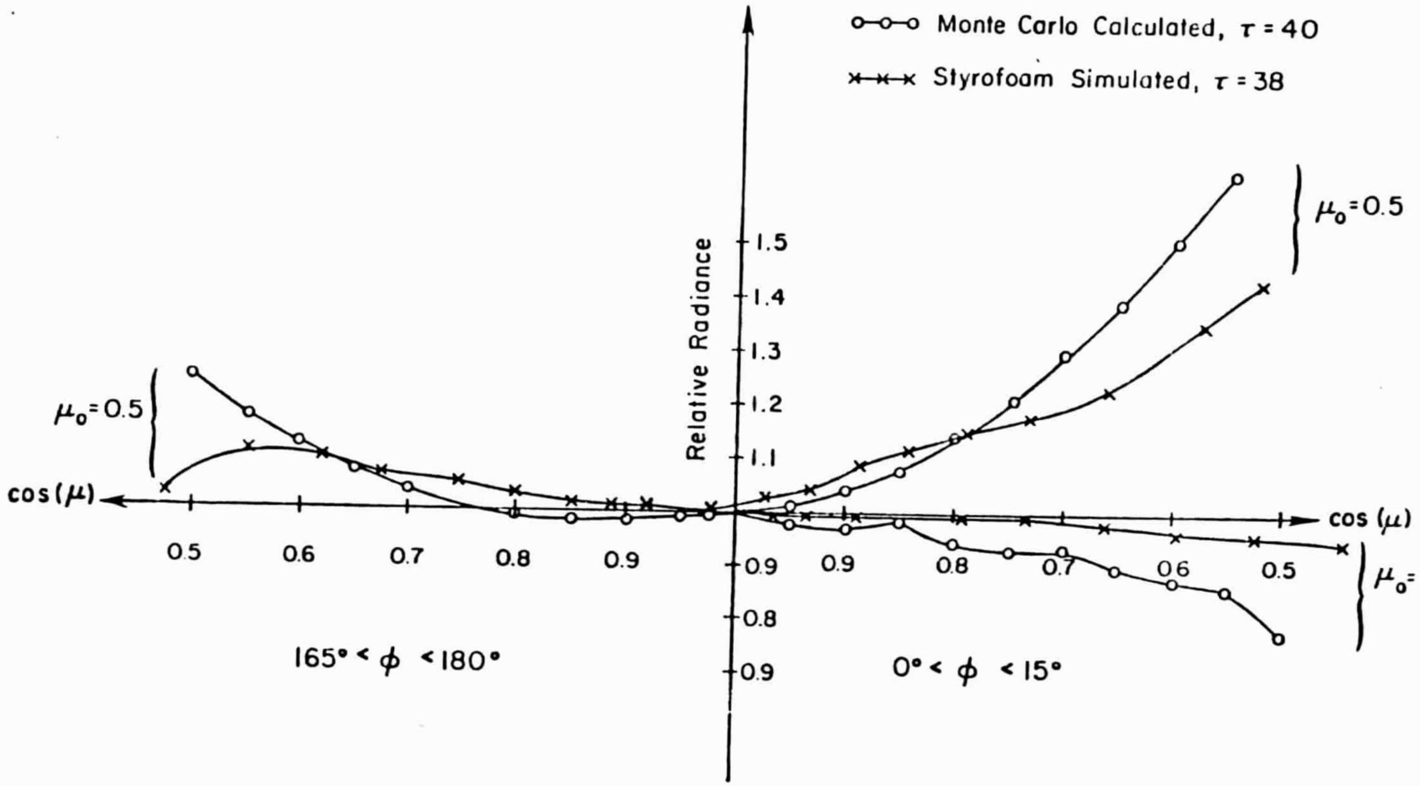

Figure 3. A comparison between the calculated and simulated reflected radiances from semi-infinite clouds for solar zenith angles of 0° and 60° using styrofoam as the simulation material.

CFOS apparatus about the simulation zenith. Second, simulated styrofoam clouds are easily exchanged from one cloud scene to another or moved about within a cloud scene. Finally the styrofoam simulated clouds are easily made into regular shapes, i.e. cubes, cylinders, inverted paraboloids etc. for comparison with theoretical results for finite clouds.

3. A Method of Assigning a Visible Optical Depth to the Simulated Clouds

In order to relate the reflective properties of simulated clouds to real water clouds it is necessary to have an accurate estimate of the optical depth of the simulated clouds. One means of doing so is based on the bulk radiative properties of a 'semi-infinite' sheet of the cloud material at 0° zenith. Specifically theory predicts that the ratio of spectral reflectance R_λ to spectral transmittances T_λ of a semi infinite cloud over a non reflecting surface is nearly a linear function of optical depth, see for example Coakley and Chy'lek (1975) and Stephens (1978). Figure 4 shows a plot of the ratio of R/T generated from the parameterization of Stephens (1978) for water clouds in the visible portion of the spectrum. Also shown is the same ratio from a simple Eddington-model which employed the Henyey-Greenstein approximation for various cases and also a few results of the R/T ratio from Monte Carlo calculations. The linear dependance between R/T and τ the visible optical depth is apparent.

An equivalent visible optical depth (τ_e) may be assigned to the CFOS cloud simulation material by measurement of the ratio of R/T for a sheet of the material with a large ratio of

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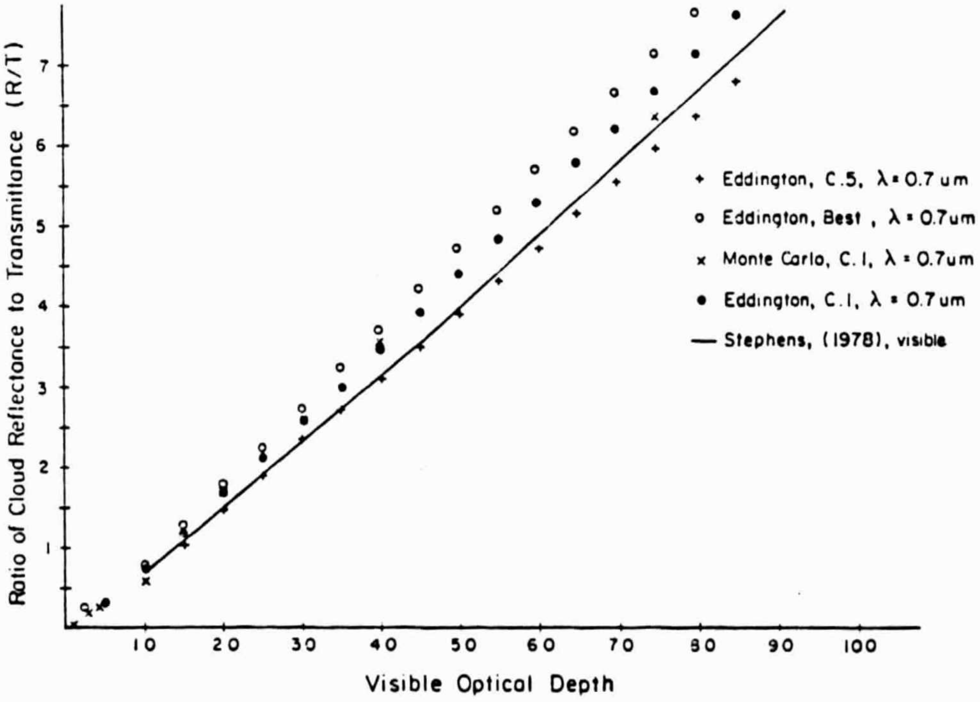

Figure 4. A plot of the ratio of reflectance to transmittance derived from various calculations as a function of optical depth.

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horizontal to vertical dimension. Once τ_e is established for a large slab of styrofoam several clouds may be 'sculptured' from the slab while maintaining in each the vertical dimension of the original slab. The procedure requires an additional step in the case of cotton since the vertical structure of the original 'slab' (surgical cotton is available in 12" by 60" sheets) can not be maintained while forming clouds of a realistic shape. However, it was found that the mass of the material in a vertical column of unit cross section is also related to the ratio of the R/T in a nearly linear manner; see figure 5. Thus, for a cloud simulated from surgical cotton an approximate visible optical depth may be assigned by weighing the cloud and measuring the cross sectional area to determine the area mass density then using the R/T line as a transfer function to τ_e. The additional measurement is yet another limitation to the suitability of using cotton as the cloud simulation material.

4. Retrieval of Basic Finite Cloud Features

The most recent accomplishment with the CFOS concerns the ability to measure the reflected radiances of finite clouds. Figures 6 and 7 are comparisons between radiances reflected into the principal plane by finite clouds as measured on CFOS and the same quantities predicted by the theoretical Monte Carlo model as described in McKee and Cox (1974). The radiances in each case have been normalized by the radiance measured or calculated at the zenith. The CFOS profiles have been retrieved from measurements over a field of simulated (styrofoam) cubic clouds cut from a slab of material whose R/T ratio corresponds to an equivalent optical

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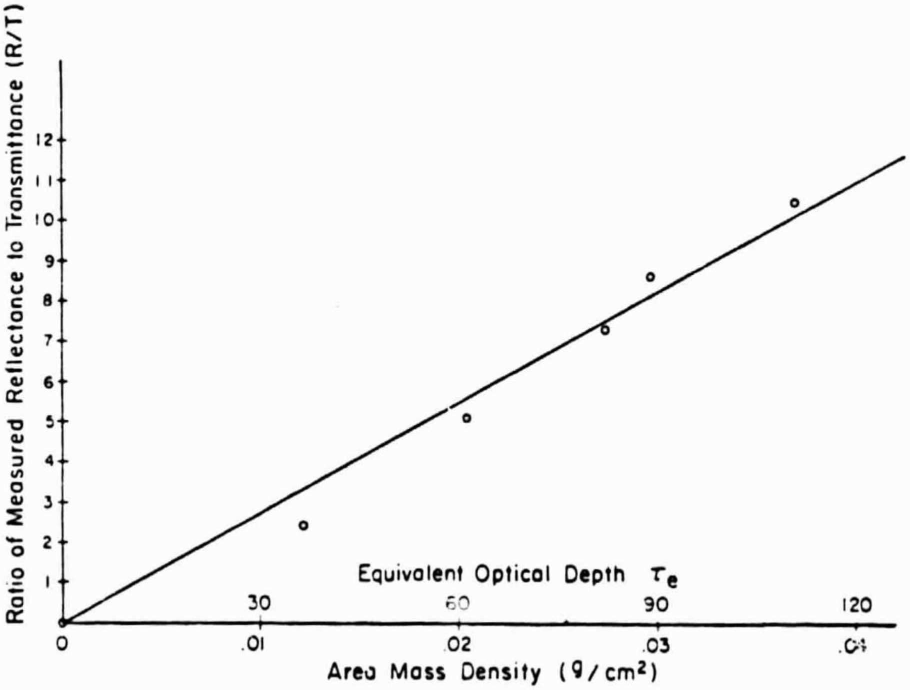

Figure 5. A plot of the ratio of reflectance to transmittances measured by CFOS for a 'semi-infinite' cotton simulated cloud plotted as a function of area mass density and equivalent visible optical depth (T_e).

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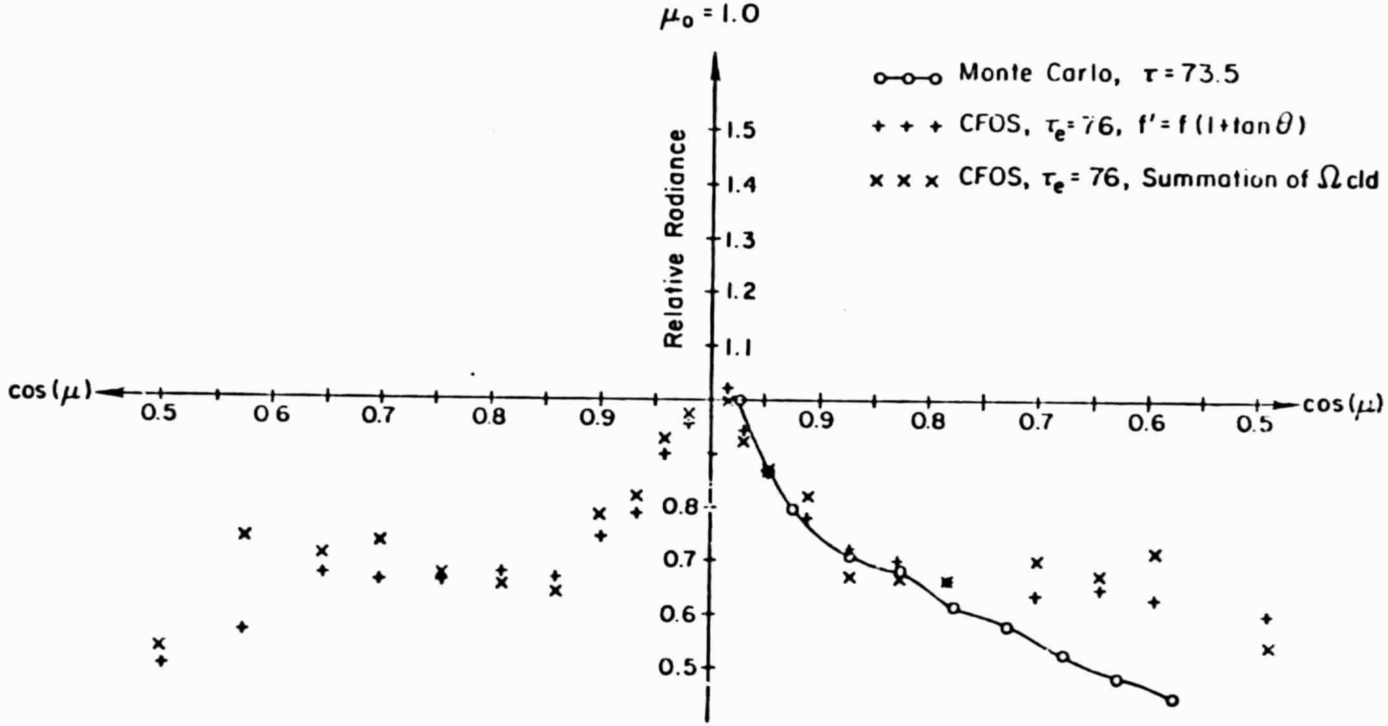

Figure 6. A comparison between calculated and simulated reflected radiances from finite cubic clouds for a solar zenith angle of 0° using styrofoam for the simulation material.

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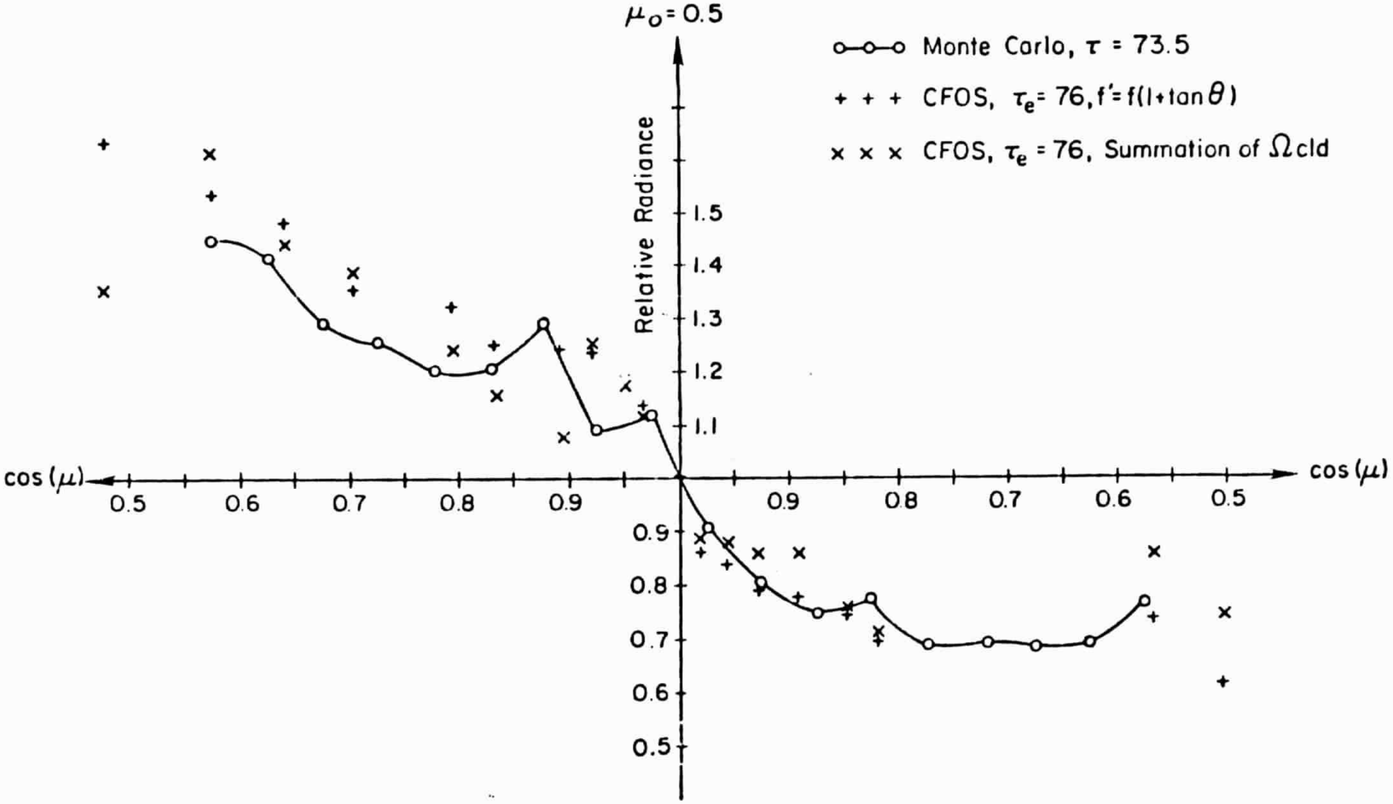

Figure 7. A comparison between calculated and simulated reflected radiances from finite cubic clouds for a solar zenith angle of 60° using styrofoam for the simulation material.

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depth $\tau_e = 76$. The clouds were evenly spaced on a horizontal grid such that the true fraction cloud cover (f) was 0.04. Figures 6 and 7 each show two measured profile retrievals. One assumes that as the nadir angle (θ) increases, the solid angle of cloud field relative to the underlying surface increases as $(1 + \tan\theta)$ resulting in a modified fractional cloud cover $f' = f\,(1 + \tan\theta)$; see Davis, Cox, and McKee (1979). The second treatment utilizes the exact geometry of the cloud field and the CFOS detectors, counts the clouds in the field of view and calculates the total solid angle subtended by the clouds and their shadows. The radiance measurement (N) is given as

$$N = N_{cld}\,\Omega_{cld} + N_{clr}\,\Omega_{clr} + 0\,\Omega_{sdw}$$

In the above formula the subscripts cld, clr and sdw stand for cloud, clear and shadow, respectively, and Ω represents solid angle. It is assumed that there is no radiance contribution from the shadow regions. The N_{clr} measurements were made over the surface on which the clouds were mounted. The albedo of the surface was 0.02. The second treatment results in a 'noisier' curve because the cloud is either considered completely within or exterior to the field of view. Nevertheless, smoothed versions of the curves are in good agreement. The apparent disagreement between measured and calculated radiances at large nadir in the 0° solar zenith angle case is believed to be due primarily to the basic scattering properties of the material. Similar disagreement is seen in the radiance comparisons for infinite clouds at 0° zenith.

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It should be noted that retrieval of the finite cloud reflected radiances, as described above, represents a rigorous test of the CFOS concept. The low surface albedo combined with the extremely small fractional cloud cover result in reflected radiances at the lowest bound of the domain for which CFOS was originally intended. Larger clouds, smaller cloud spacing and more realistic simulated surfaces will all tend to increase the radiance signal. In addition, the above experiment represents the retrieval radiances reflected from only part of the scene. Measurement of total scene radiances are of a more stable nature. Thus, it appears that the CFOS concept is indeed a valid means of exploring the effects of realistic cloud geometries on the radiances reflected by optically thick clouds and cloud fields.

D3

N84 20339

DESIGN AND VERIFICATION OF A CLOUD FIELD OPTICAL SIMULATOR

by

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Department of Atmospheric Science
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Fort Collins, CO

October, 1982

Abstract

A concept and an apparatus designed to investigate the reflected and transmitted distributions of light from optically thick clouds is presented. The Cloud Field Optical Simulator (CFOS) is a laboratory device which utilizes an array of incandescent lamps as a source, simulated clouds made from cotton or styrofoam as targets, and an array of silicon photodiodes as detectors. The device allows virtually any source-target-detector geometry to be examined. Similitude between real clouds and their CFOS cotton or styrofoam counterparts is established by relying on a linear relationship between optical depth and the ratio of reflected to transmitted light for a semi-infinite layer. Comparisons of principal plane radiances observed by the CFOS with Monte Carlo computations for a water cloud at 0.7 μm show excellent agreement. Initial applications of the CFOS are discussed.

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1.0. Introduction

During the past two decades the atmospheric science community has witnessed and participated in an expanding effort to quantify the interaction of solar radiation with clouds. Studies of this process have been motivated by the recognition of the significant role of clouds in modulating the net shortwave component of the earth's radiation budget. Investigations have been stimulated by the relatively recent capability of sampling the reflected shortwave component using earth orbiting satellites. Imagery from meteorological satellites has revolutionized the way in which weather systems are observed and tracked, namely by monitoring the distribution and movement of the attendant cloud fields.

Although the basic tasks of measuring the reflected component of the radiation budget and monitoring the earth's weather systems may be accomplished directly from measurements or images, insight into the processes affecting the radiation budget or the appearance of a weather disturbance requires an understanding of the relationship between the summative properties of the measurement or image and its components. For example, a change in the orientation of a cloud formation which is characteristic of a region may significantly change the shape of the diurnal variation of the albedo. Although wide field of view measurements would detect the change, an explanation of its cause would require radiance

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measurements coupled with a knowledge of the bidirectional reflectance pattern for such a cloud formation. As a second example, suppose it is postulated that a specific severe weather phenomenon is usually associated with a particular type of cloud structure such as the appearance of a well developed cloud turret. The turret may appear darker or brighter than the surrounding cloud types depending on the sun-turret-background-observer geometry. Understanding this relationship may prove invaluable in verifying the presence of the turret and thus the correlation between the two events.

Investigation of the relationship between the summative and component features of a cloud scene may be undertaken in at least three different ways. First, the transfer of solar radiation through clouds of a realistic shape may be modeled by seeking a solution of the appropriate radiative transfer equation. Examples of such efforts for clouds of a quasi-realistic shape may be found in Busygin et al. (1973), McKee and Cox (1974, 1976), Aida (1977), Davies (1978), McKee and Klehr (1978), Reynolds et al. (1978), Davis et al. (1979 a,b), Welch et al. (1980), and Welch and Zdunkowski (1981). Although all of the above efforts examine the interaction of solar radiation with clouds of finite extent, only relatively simple shapes have been employed such as cubes, cylinders, inverted paraboloids and spheres. Also, of the above, only Davies (1978) has employed a method of solution other

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than the Monte Carlo method. However, the analytic solution has thus far been sought only for clouds of cuboidal shape. The transfer of solar radiation through cloud fields has been considered by Busygin et al. (1973, 1977), Avaste and Vaymikko (1974), Glazov and Titov (1976, 1979), Aida (1977), Titov (1979, 1980), and Welch and Zdunkowski (1981 I, II). The emphasis of these works has been on the flux densities of the reflected, absorbed, or, especially the transmitted component of solar radiation, and little effort has been made to relate these quantities to what is measured by narrow or medium field of view satellite sensors or to what is seen in a satellite image. This state of affairs is due to the lack of a universally applicable analytic method and the large amount of processing time required to execute Monte Carlo simulations.

A second way to obtain the desired relationships is through direct observation. Several studies have been carried out to associate measurements of solar radiances reflected by a cloudy atmosphere to the corresponding reflected flux densities. See for example, Arking (1965), Bartman (1968), Brennan and Bandeen (1970), Ruff et al. (1968), Salomonson (1968), Stowe et al. (1980), and Davis and Cox (1982). Others have concentrated on measurements of localized radiance patterns from individual clouds or cloud decks; see McKee et al. (1982), Griggs and Marggraf (1967). The measurements over cloudy scenes have been

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carried out from satellite, aircraft and balloon platforms and lack the specific information on cloud shape, size and location necessary to provide an understanding of the radiance to irradiance relationship. The localized radiance measurements provide precise information as to cloud type but sampling from many angular positions is difficult to achieve in a time frame during which the cloud parameters remain essentially constant; i.e. they lack simultaneity. Finally, either type of observational program is extremely costly.

This paper describes an approach which falls into a third category for obtaining the relational information; laboratory simulation. This approach has been relatively untried; see Margolis et al. (1972) and Kuenning et al. (1978), and yet is an extremely practical concept. Aside from the initial expenditure for the laboratory device, the required measurements may be obtained with relatively little cost. In addition, the approach described below utilizes scattering from simulated clouds which are static. Thus, any number of measurements may be made from various sensor positions resulting in a 'simultaneous' description of the radiance pattern. Cloud sizes, shapes and spacings are easily changed and the effects on the resulting radiance patterns may be immediately observed. Images of cloud features may be obtained using, for example, a vidicon camera from various observing geometries providing an interpretational tool of great

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value when correlated with 'cloud truth'. The laboratory approach has probably been overlooked because of a lack of confidence that the exact scattering properties of clouds could be faithfully reproduced. However, many of the recent theoretical investigations of finite clouds listed above have revealed that cloud shape is more important than cloud microphysical properties in determining the scattering properties of optically thick clouds. This realization, combined with the advantages of a laboratory approach given above, provided the motivation for development of the Cloud Field Optical Simulator (CFOS) described below. This article describes the design features of the CFOS and provides initial results as verification that it can indeed provide valuable insight into the relationships between the composite properties of realistic cloud scenes and the radiative streams from which such scenes are realized.

2.0 Description of the CFOS apparatus

The CFOS apparatus is designed to measure the simulated reflection of shortwave radiation by optically thick clouds. The CFOS basically consists of a light source, a target cloud field, an array of radiation detectors and a data display/collection system. Figure 1 shows a schematic of the CFOS which is housed in a 10 x 10 m^2 dark room at the Department of Atmospheric Science at Colorado State University. Each of the components which comprise the CFOS have been selected or designed to

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simulate as closely as possible the actual interaction of visible solar radiation with real clouds and to perform measurements on the simulation analogous to the real world case. Each aspect of the CFOS is described below along with the rationale used in selecting various options in the component design.

2.1 The Source

In simulating the interaction between the visible solar irradiance and clouds it is desirable to duplicate as closely as possible three characteristics of the natural source. First, the source should possess, to the extent possible, a visible spectrum of a 5700 K black body radiator. Second, the beam irradiance should be uniform across the area of the cloud field, and third, the beam should be parallel. Because the cost of constructing a solar simulator approaching the above description would have been prohibitive, efforts were focused on achieving the latter two characteristics for the following reasons. First, theoretically the spectral distribution of the incident radiation is important only in relation to the microphysical properties of the cloud; i.e. scattering properties at a wavelength λ are determined only as a function of the ratio λ/r, where r is the radius of the droplet. Since simulated clouds used in the CFOS are not composed of droplets (much less the specific droplet distributions measured in real clouds) and in view of the considerations given above, achieving the proper spectral

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response was given a lower priority and emphasis was given to designing a source which fulfilled the remaining criteria. Maintaining the proper spatial characteristics of the beam, as specified in the second and third criteria listed above, assures that the effects of cloud geometry are accurately taken into account. Doing so, even at the expense of achieving less than optimum spectral characteristics, is consistent with recent findings concerning the importance of cloud geometry as discussed in the introduction. To these ends it was found that an array of low voltage display lamps provided illumination with the best spatial uniformity over the target cloud field. The low voltage design of the lamps allows small filament assemblies to be precisely placed at the focal points of accurately molded reflectors. The result is a smooth illumination curve which decreases slowly (7% in the first 4°) as a function of the angle from the beam axis of each lamp. Use of an array of overlapping beams, each aimed at a different section of the cloud field, results in an irradiance uniform to within ±3% of the mean value in the plane of the cloud field. The source was placed behind a circular aperture 0.5 m in diameter to shield the cloud field from stray light and to constrain the beam to within 3° of its axis, thus assuring nearly parallel light. The beam is reflected by a large plane mirror in order to allow enough distance (20 m) for the nearly parallel beam to diverge to a cross section

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sufficient to illuminate the entire target area (≈3 m^2). Although the source output is reasonably constant in time it is monitored by a wide field of view detector near the cloud field so that the effects due to even small variations may be accounted for in the analysis.

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2.2 The cloud field assembly

The target cloud field assembly consists of the simulated clouds and the hardware necessary to support and orient the clouds with respect to the incoming radiation and the detectors. The assembly is contained in a separate 4mx4mx4m black box in the laboratory room. The types of materials used to construct the simulated clouds are discussed in sections 3.0 - 3.3. As shown in Figure 1, the target cloud field is mounted in a circular area approximately two meters in diameter. The incoming radiation enters through a large aperture in one face of the box. The target cloud field is oriented in a vertical plane and has two rotational degrees of freedom. The first of these allows rotation about the vertical axis of the cloud field and simulates changing solar zenith angle. The second rotation is about an horizontal axis through the center of and perpendicular to the plane of cloud field which allows simulation of a change in solar azimuth angle. Each of these rotations is driven by a separate motor and may be controlled at the data display station. The rotations are monitored to the nearest degree through the use of optical encoders and associated logic circuitry. Any sun-cloud geometry of interest may be easily simulated in the CFOS as a result of this design.

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2.3 Sensor array

In order to examine the relationship between the summative and component properties of radiation reflected from the simulated clouds it is necessary to sample the radiation field from a number of angular viewing coordinates. The placement of the CFOS sensors with respect to the cloud field may be seen in Figure 1. Fifteen sensors are mounted on a semi-circular ring whose ends are attached to the cloud field apparatus at points above and below the cloud field on its vertical diameter which serves as an axis of rotation for the ring. The sensors are spaced at increments of 10° of arc along the ring beginning at the center of the ring and proceeding toward its ends. This sensor configuration permits a density of angular sampling of the reflected radiation which is more than adequate to establish the relationships between the desired quantities.

Each sensor consists of a high quality silicon photodiode with a built in high gain operational amplifier circuit. The diodes are mounted in small cylindrical enclosures each of which contains a spectral filter and two circular diaphrams. The diaphrams limit the field of view of each photodiode to 7.5° half angle. The relative spectral responses of the detectors with and without the optical filters are shown in Figure 2. The filtered spectral response corresponds closely to that of the human eye. Thus, features visually observed should be evident also in the measurements. The field of view of the detectors is such that the center detector resolves a circular area 0.5 m in diameter when viewing the cloud field at the nadir. By using the relationships between the optical and geometric properties of simulated and real clouds (see sections 3.0 - 3.3) it is possible to associate the CFOS sensor configuration with that of a real world sensor 100 Km above the earth's surface with a nadir ground resolution of 25 Km.

2.4 Data display/collection station

As pointed out in the introduction, one of the advantages of a laboratory investigation of the radiative properties of clouds lies in the ability to observe an unchanging cloud field from a variety of angular coordinates. This feature is fully appreciated by observing the changes in the various detector voltages as the 'sun-cloud-sensor' geometry changes. The output of each sensor including the source monitor may be read from digital voltmeters at the data display/collection station. An array of light emitting diode bar graph displays indicates the voltage outputs of all 15 diodes simultaneously giving an instantaneous sample of the radiance patterns. The simulated solar zenith and azimuth angles and the angle of rotation of the detector ring are controlled from and monitored at the display station.

In order to examine the structure of the radiance patterns and to detect changes in the field or image as

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the clouds' geometric properties are changed it is necessary to assemble all measurements into a single representation of the reflected radiance pattern. This is accomplished in two stages by the CFOS. First the data are recorded using an Apple II microcomputer as a smart data collection device. Various parameters such as sampling rates and the numbers of measurements included in average readings may be programmed into the data collection process. Second, the data from the floppy diskette in the Apple II are transferred to an Apple III microcomputer where they are processed. The processing is relatively simple; measurements are rotated into a nadir-relative azimuth angle coordinate system, voltages are divided by relative sensitivities, effects caused by variations in the source are removed, the reflected radiances are integrated over the lower hemisphere to obtain a flux density, and various graphical displays are generated. The total time of the processing of the data is about 15 minutes. Thus, experiments may be repeated for slight perturbations in the cloud field geometry and changes in the radiance field may be appreciated within a short time. Also, data and displays from the radiance patterns may be saved on diskette files for later viewing and comparison.

The CFOS apparatus described above is unique in concept and design and should provide insight into the composition of wide field of view satellite measurements

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and images. It offers an interactive setting in which cloudy scenes may be created, observed visually and whose relative radiance fields may be measured quantitatively. The next section describes the verification of the CFOS and in doing so furthers the appreciation of the similitude between the CFOS and the real world.

3.0 Verification of the CFOS concept

The previous sections have described an elaborate device designed to measure the simulated radiative properties of clouds of a realistic shape. In the sections which follow the properties of the simulated clouds and the relationship of their scattering properties to those of simulated water clouds are discussed. The verification of the CFOS is based not on analogies between the microphysical properties of real and simulated clouds, but rather on comparisons of observable radiative properties.

3.1 Selection of suitable materials for cloud simulation

The validity of measurements obtained from the CFOS depends, almost entirely, on the measurable radiative properties of the simulated clouds. Several materials were examined in a search for one which adequately simulates the visible reflective properties of optically thick clouds. The criteria which were examined in the selection process were first, the behavior of the radiances reflected into the principal plane by a horizontally semi-infinite cloud, and second, the visual appearance of the simulated clouds and

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cloud fields. Based on these criteria, two materials emerged as superior to all others tested; they are surgical quality sterilized cotton and decorative billet styrofoam which is marketed by Dow Chemical.

Figures 3 and 4 show comparisons between the radiances reflected into the principal plane by cotton and styrofoam simulated clouds compared with theoretical curves derived from a Monte Carlo radiative transfer calculation. The model was run for a C.1 droplet distribution with no absorption for a wavelength of 0.7 μm and for solar zenith angles with cosines of $\mu_o = 1.0$ and $\mu_o = 0.5$. The radiances have been normalized to the value at the zenith and are displayed as a function of the cosine of the zenith angle into which they are reflected. Scattering into the forward direction ($0° \leq \phi \leq 15°$) where ϕ is measured relative to the principal plane is depicted in the right halves of the figures and backscatter ($165° \leq \phi \leq 180°$) is indicated in the left halves. The materials are almost equivalent in satisfying the first criteria. The styrofoam simulated clouds display a slightly more realistic behavior in the backscatter direction.

Both materials do well in simulating the visual appearance of real clouds. Figure 5 shows photographs of styrofoam simulated clouds of a realistic shape. If we add a third criteria, the ease of working with the materials, the styrofoam is preferable for the following reasons.

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First, the styrofoam is rigid and will maintain a constant ratio of geometric to optical depth, and the shape of simulated clouds will be retained regardless of orientation. Second, the simulated styrofoam clouds are easily placed and maneuvered in a cloud field and may be categorized and stored for use in other cloud scenes. Finally styrofoam clouds are easily made into regular shapes i.e. cubes cylinders, spheres etc. so that their radiation properties may be compared with theory.

3.2 The optical depth of simulated clouds

In order to relate the reflective properties of simulated clouds to real water clouds it is necessary to have an accurate estimate of the optical depth of the simulated clouds. One means of doing so is based on the bulk radiative properties of a 'horizontally-infinite' sheet of the cloud material at 0° zenith. Specifically theory predicts that the ratio of the spectral reflectance R_λ to the spectral transmittance T_λ of a semi infinite cloud over a non reflecting surface is nearly a linear function of optical depth, see for example Coakley and Chylek (1975) and Stephens (1978). Figure 6 shows a plot of the ratio of R/T generated from the parameterization of Stephens (1978) for water clouds in the visible portion of the spectrum. Also shown is the ratio (R_λ/T_λ) calculated using an Eddington model for various microphysical distributions and also a few results of the R_λ/T_λ ratio from Monte Carlo calculations. The linear dependence between

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R/T and τ, the visible optical depth, is apparent.

An equivalent visible optical depth (τ_e) may be assigned to the CFOS cloud material by measurement of the ratio of R/T for a sheet of the material with a large ratio of horizontal to vertical dimension. Once τ_e is established for a large slab of styrofoam several clouds may be 'sculptured' from the slab while maintaining in each the vertical dimension of the original slab. The procedure requires an additional step in the case of cotton since the vertical structure of the original 'slab' (surgical cotton is available in 12" by 60" sheets) can not be maintained while forming clouds of a realistic shape. However, it was found that the mass of the material in a vertical column of unit cross section is also related to the ratio of the R/T in a nearly linear manner; see figure 7. Thus, for a cloud simulated from surgical cotton an approximate visible optical depth may be assigned by weighing the cloud and measuring its cross sectional area to determine the area mass density, then using the R/T line as a transfer function to obtain τ_e.

3.3 Retrieval of basic finite cloud features

A crucial test of the CFOS is the ability to measure the reflected radiances of finite clouds. Figures 8 and 9 show comparisons between radiances reflected into the principal plane by finite clouds as measured on the CFOS and the same quantities predicted by the theoretical Monte Carlo model described in McKee and Cox (1976). The radiances in

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each case have been normalized by the radiance measured or calculated at the zenith. The CFOS profiles have been retrieved from measurements over a field of simulated (styrofoam) cubic clouds cut from a slab of material whose R/T ratio corresponded to an equivalent optical depth $\tau_e = 76$. The clouds were evenly spaced on a horizontal grid such that the true fractional cloud cover (f) was 0.04. Figures 8 and 9 show two measured profile retrievals. One assumes that as the zenith angle (θ) increases, the solid angle of the observed cloud field relative to the underlying surface increases as $(1 + \tan\theta)$ resulting in a modified fractional cloud cover $f' = f\,(1 + \tan\theta)$; see Davis, Cox, and McKee (1979). The second treatment utilized the exact geometry of the cloud field and the CFOS detectors, counted the clouds in the field of view and calculated the total solid angle subtended by the clouds and their shadows. In this interpretation the radiance measurement (N) is given as

$$N = N_{cld} \bullet \Omega_{cld} + N_{clr} \bullet \Omega_{clr} + 0 \circ \Omega_{sdw}.$$

In the above formula the subscripts cld, clr and sdw stand for cloud, clear and shadow, respectively, and Ω represents the fractional solid angle subtended by each target component. It was assumed that there was no radiance contribution from the shadow regions. The clr measurements were made ofthe surface on which the clouds were mounted in the absence of the clouds. The albedo of

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the surface was 0.02. The second treatment resulted in a 'noisier' curve because a single cloud was either considered completely within or exterior to the field of view. Nevertheless, smoothed versions of the curves are in good agreement. The apparent disagreement between measured and calculated radiances at large zenith in the 0° solar zenith angle case is believed to be due primarily to the basic scattering properties of the material. Similar disagreement is seen in the radiance comparisons for infinite clouds at 0° zenith.

It should be noted that the retrieval of the finite cloud reflected radiances described above represents a rigorous test of the CFOS concept. The low surface albedo (0.02) combined with the extremely small fractional cloud cover (0.04) resulted in reflected radiances at the lowest bound of the domain for which the CFOS was designed. Larger clouds, smaller cloud spacing and more realistic simulated surfaces will all tend to increase the radiance signal. In addition, the above experiment represents the retrieval radiances reflected from only part of the scene. Measurements of total scene radiances are of a more stable nature. Thus, the CFOS concept is indeed a valid means of exploring the effects of realistic cloud geometries on the radiances reflected by optically thick clouds and cloud fields.

4.0 Suggested areas of investigation using the CFOS

As mentioned in the introduction there are important aspects of the interaction between clouds and solar radiation which are not well understood. Investigation of the radiative transfer in clouds of a realistic shape has been limited in scope due to the expense of dedicated field experiments and the difficulty in solving the radiative transfer equation for complex geometries. Discussed below are a few specific topics which merit investigation, which have not been extensively studied due to the reasons given above and for which the CFOS is an ideal means of obtaining the necessary information.

First, it was noted in the introduction that there have been several attempts to compile bidirectional reflectance models for various types of clouds. Obtaining the data necessary for such models requries considerable effort. The models generated to date have been specified as a function of simple cloud type and solar zenith angle regime. However, these models may not be applicable in areas where the cloudiness changes appreciably according to a diurnal cycle. In such cases simple cloud typing is probably inadequate and one should probably work with descriptors of cloud distributions such as given by Plank (1969). Cloud distributions based on cloud size and the number of clouds may be obtained from imagery but obtaining the angular variation in the reflected radiance fields is considerably more difficult. Changes in the reflected radiance fields with diurnal variations in cloud statistics could be easily measured using the CFOS. Various realizations of known

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cloud distributions could be constructed and changes in the reflected radiance fields assessed. At the very least, such an investigation would provide an indication of the range of variation in bidirectional reflectance models attributable to diurnally changing cloud distributions.

Second, a related problem concerns the radiance fields of broken cloud cover over medium to high albedo surfaces. For the case of large fractional cloud cover, low cloud base height and large surface albedo, cloud-cloud and cloud-surface interactions become important in influencing the reflected radiance fields. However, the implications of such complex interactions have not been sufficiently investigated. The CFOS apparatus may provide critical values of the cloud parameters and surface albedo for which such interactions have a significant impact on reflected radiances.

A third area of investigation concerns a situation faced by modelers of radiative transfer who, as previously stated, are searching for analytic solutions to the radiative transfer equation under ever more realistic situations. The degree of the geometric detail of modeled clouds which will result in observable changes in the reflected radiances is not presently known. Considerable effort may be invested in obtaining methods of solution to complex equations only to find imperceptible influences in observable quantities. A knowledge of this point of diminishing returns would be valuable. The CFOS could provide such knowledge. By measuring the radiances reflected from simulated clouds of increasing geometrical structure while maintaining the basic cloud shape, the point at which no changes in reflected radiances are detected, (if such a point exists), could be found. This investigation cloud serve as an independent indication of the geometric complexity required in models. This discussion applies to studies of individual clouds and cloud fields.

In addition to the three research oriented applications discussed above, CFOS has great potential in imagery interpretation. Specific cloud features may be readily observed from virtually unlimited observer and illumination orientations. This application is very promising for instructional purposes as well as post-mortem satellite imagery interpretation and analysis.

The above are only a few of many potential applications of the CFOS. Those which have been mentioned involve the investigation of the reflected radiance field. However, it should be noted that the CFOS may also be utilized to examine the transmitted radiance field which plays a significant role in determining surface energy budgets and is important in solar energy studies. Also, the examples cited were based on the present configuration of the CFOS. Refinements in the apparatus would not only add to the confidence of present efforts but undoubtedly extend the practicality of the CFOS to the investigation of other heretofore unexplored aspects of the interaction between solar radiation and clouds.

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5.0 Summary

A concept and an apparatus designed to investigate the reflected and transmitted distributions of light from optically thick clouds has been presented. The laboratory apparatus, CFOS, utilizes incandescent lights as a source, simulated clouds made from cotton or styrofoam as targets and silicon photodiodes as detectors. Virtually any source-target-detector geometries may be examined with CFOS.

Similitude between real clouds and their CFOS cotton or styrofoam counterparts is established by relying on a linear relationship between optical depth and the ratio of reflected to transmitted light for semi-infinite layer. Comparisons of principal plane reflected radiances observed by CFOS with Monte Carlo computations for a water cloud at 0.7 μm show excellent agreement.

Primary initial applications of CFOS include studies of bidirectional reflectance patterns from cloud fields, of cloud to cloud and ground to cloud interactions over high albedo surfaces and in satellite imagery interpretation and analysis.

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Figure 2. The relative spectral responses of the detectors used in the CFOS with and without optical filters.

Figure 3. A comparison of the relative radiances reflected into the principal plane by cotton simulated clouds (measured by the CFOS) to those calculated using a Monte Carlo model for water clouds. Comparisons are shown for solar zenith angles of 60° and 0°. (Only one of the symmetric branches is shown in the 0° case).

Figure 4. A comparison of the relative radiances reflected into the principal plane by styrofoam simulated clouds (measured by the CFOS) to those calculated using a Monte Carlo model for water clouds. Comparisons are shown for solar zenith angles of 60° and 0°. Only one of the symmetric branches is shown in the 0° case.

Figure 5. Photographs of a styrofoam simulated cloud system. The second photograph is an enlargement of the first showing the detail of the area between the simulated cumulonimbus clouds.

Figure 6. The ratio of reflectance to transmittance for

horizontally infinite clouds plotted as a function of optical depth in the visible region of the spectrum for a solar zenith angle of 0°. Values of the ratio from the Eddington and Monte Carlo models are valid at 0.7 μm, values from Stephens (1978) are representative in the visible ($\lambda \lesssim 0.75$ μm).

Figure 7. The ratio of reflectance to transmittance for cotton simulated 'horizontally infinite' clouds plotted as a function of the area mass density of the material which is used as a transfer function to obtain the equivalent optical depth of simulated clouds.

Figure 8. A comparison between calculated and simulated radiances reflected from finite cubic clouds into the principal plane for a solar zenith angle of 0° using styrofoam as the cloud simulation material.

Figure 9. A comparison between calculated and simulated radiances reflected from finite cubic clouds into the principal plane for a solar zenith angle of 60° using styrofoam as cloud simulation material.

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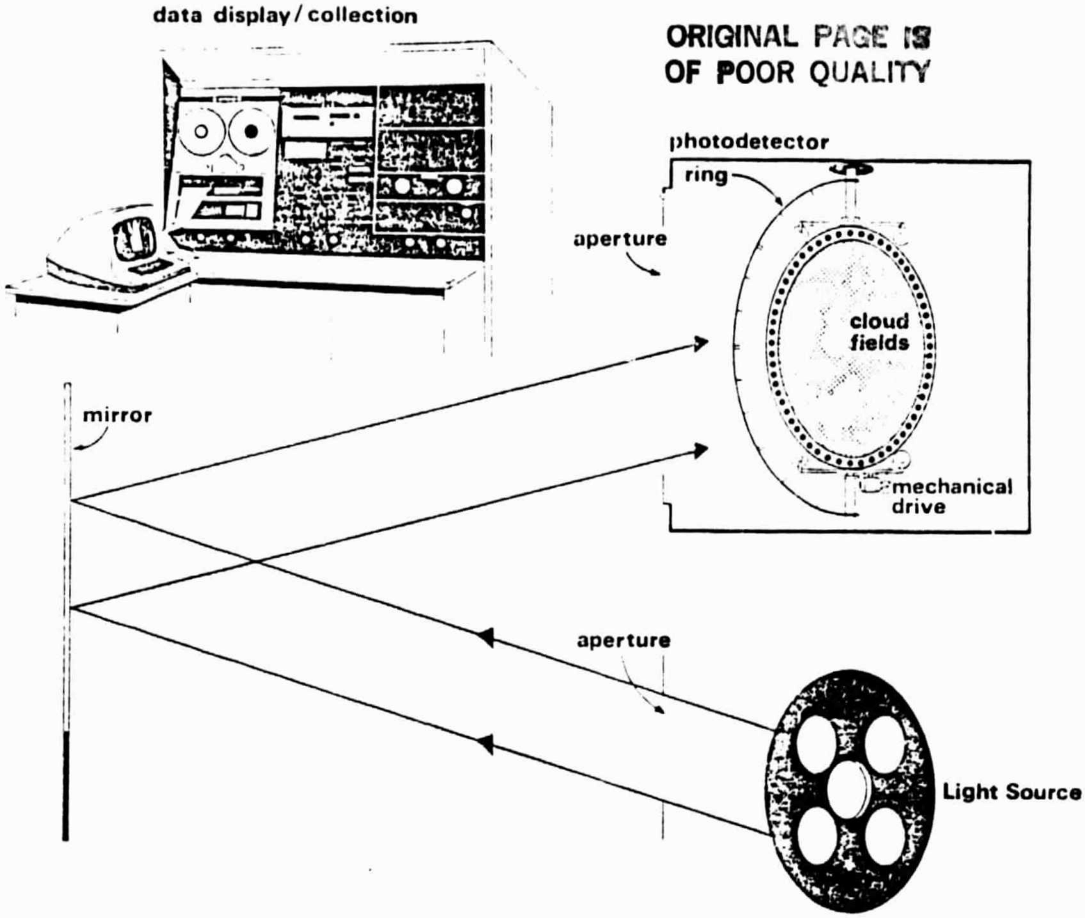

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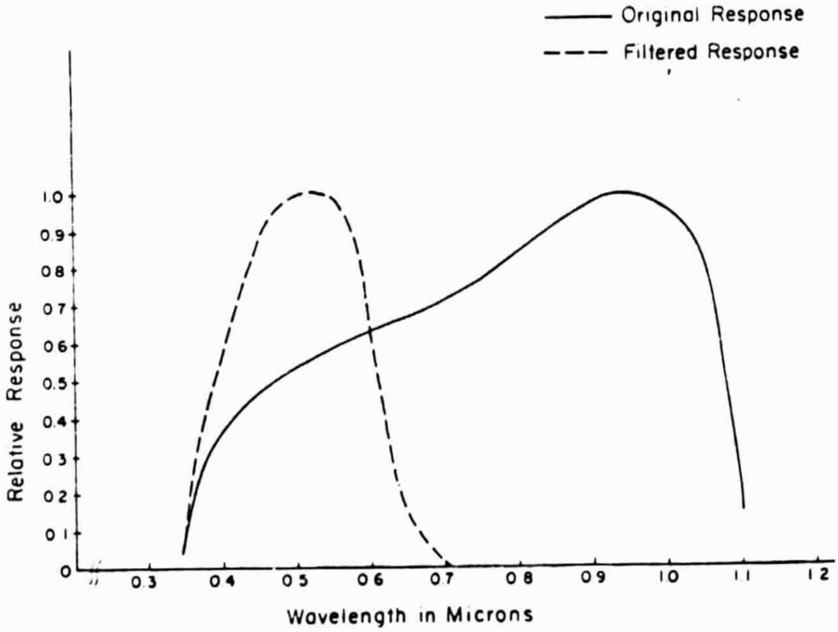

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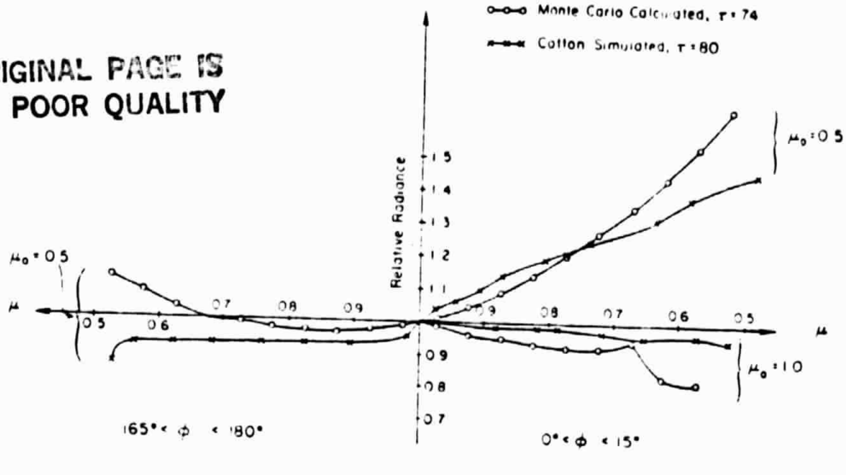

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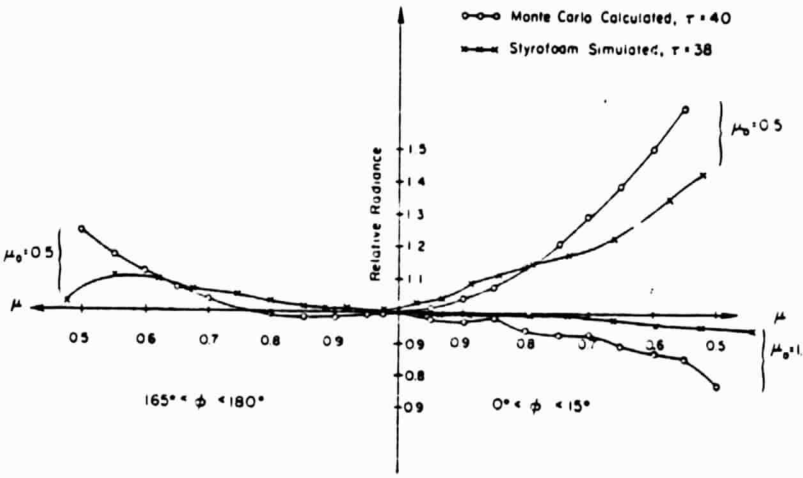

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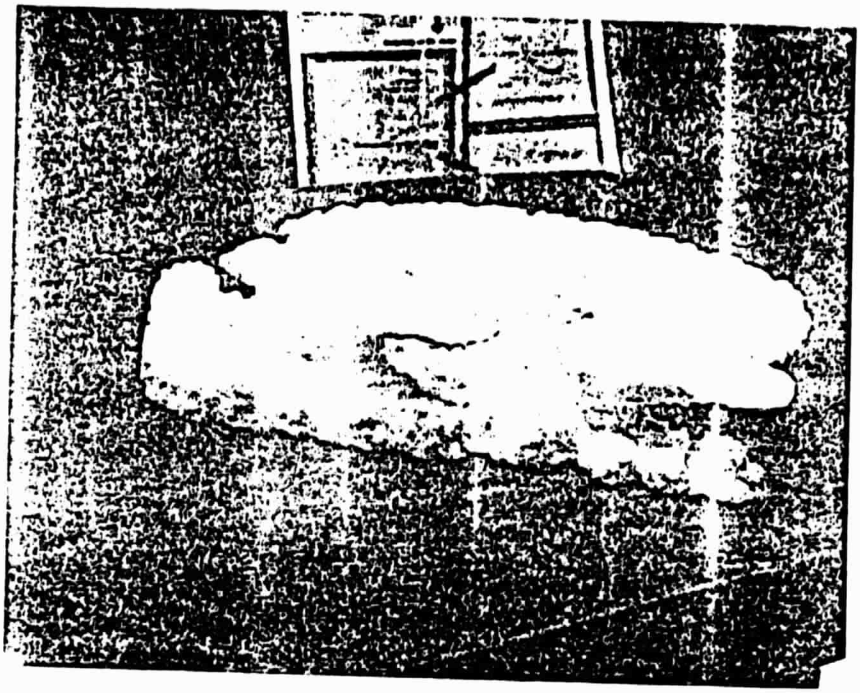

Figures 5

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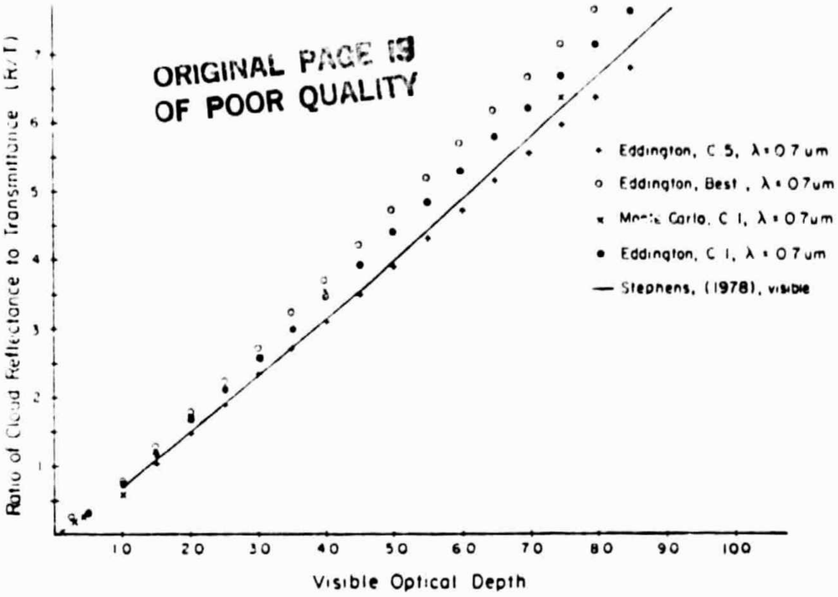

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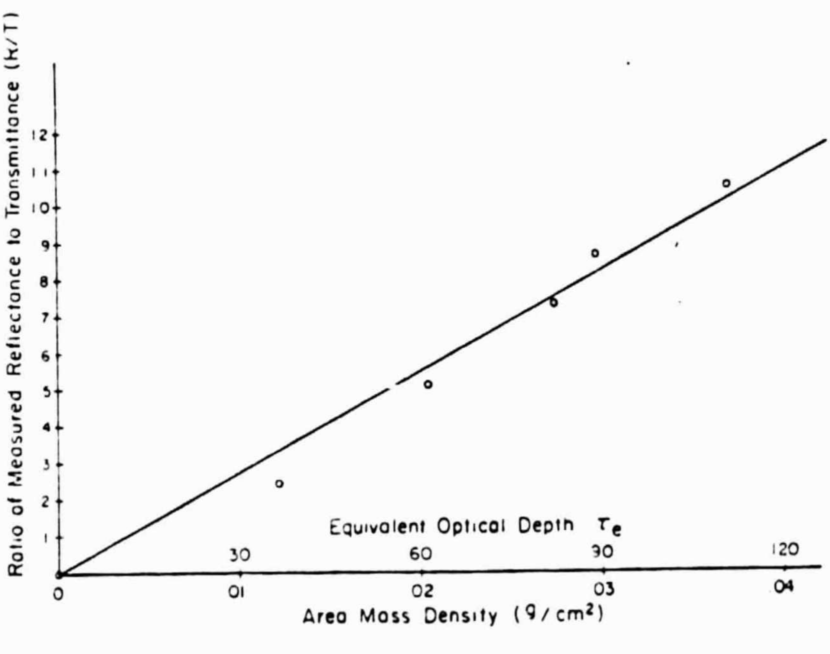

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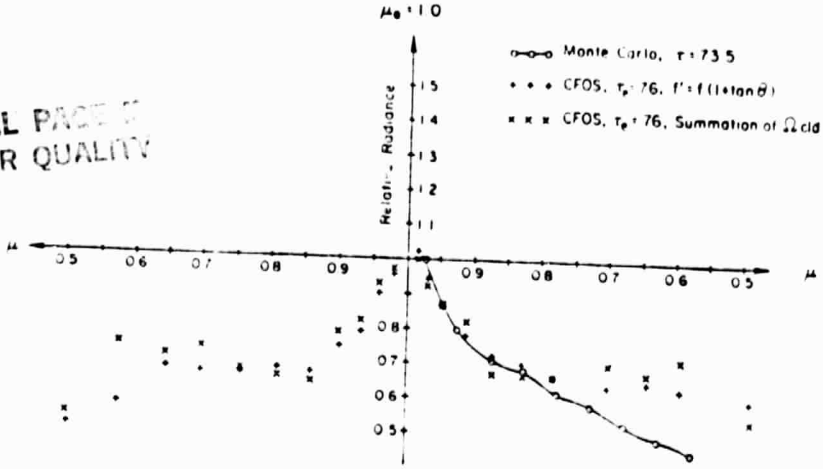

Figure 8

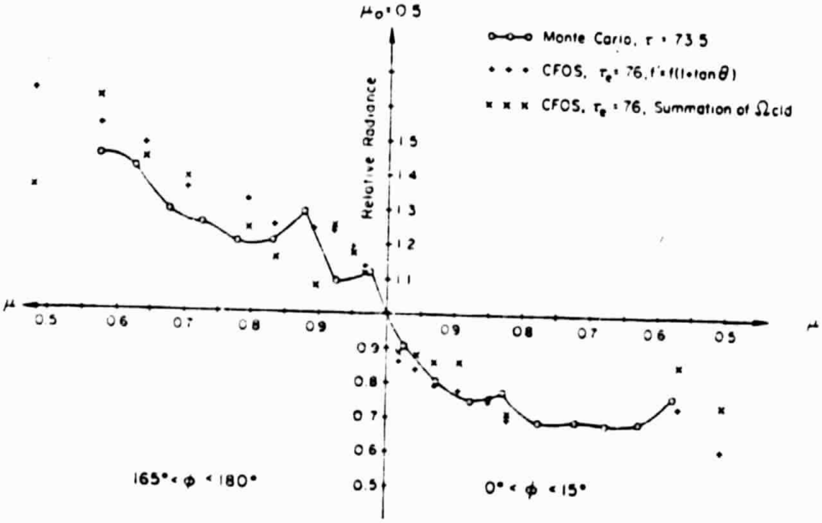

Figure 9