The Polarimeter and the Multispectral Radiometer as Remote

Probes of Aerosols

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Introduction

The puzzling features of skylight polarization engaged the attention of scientists for many generations until Chandrasekhar's solution to the equation of radiative transfer provided a quantitative explanation. Careful experiments conducted at UCLA by the late Professor Zdenek Sekera and his students established that the observed polarization data were at variance with the results of Chandrasekhar and this deviation was correctly attributed to the presence of turbidity in the atmosphere. This led Professor Sekera to suggest that the measurement of skylight polarization could be a means to study turbidity in the atmosphere.

The data accumulated during the 1950's and '60's substantiated Professor Sekera's Conjecture that particulates in the atmosphere indeed polarize the radiation in a distinctive manner, but unfortunately no quantitative statements were made.

Perhaps the first real effort in this direction was that of Dr. C. R. N. Rao, a student and associate of Professor Sekera, at UCLA, who interpreted polarization measurements made from a high flying balloon to obtain the turbidity of the atmosphere. Here aerosols were, however, assumed to be non-polarizing scatterers, an unphysical assumption that was made to simplify the numerical calculation. Since the ground reflection had similar properties the effects due to turbidity and that due to the ground were very similar. That is to say, if a certain value of turbidity and ground reflection would give rise to a fit of the data it would be possible to change the two parameters to obtain another fit.

In addition to this ambiguity, it is stated in their paper that some sets of data were fit by one haze type while others used a different haze type. The source of this confusion was explained in Kuriyan and Sekera 1974, Kuriyan et al. 1976a. It is observed that the various haze types give rise to the same phase matrix and hence as far as radiative properties are concerned, the haze types are equivalent to one another. This also implies that the best that can be achieved is a determination of the equivalent optical parameters and this ambiguity in the determined parameters is an intrinsic weakness of the method. However, the calculated radiative fluxes (or radiation field in any direction) is without any ambiguity and hence the claim that such methods are useful in meteorological investigations where the radiation field and fluxes are to be determined and not the exact size of the particulates.

Once this was understood it was easy to accomplish the late Professor Sekera's goal, to "invert" optical measurements to derive atmospheric parameters. The method adopted was to compile a catalogue of radiation fields for all physically occurring values of the aerosol parameters and then match measurements against this catalogue to infer the parameters. Elimination in the redundancy of the haze types enabled the compilation of the complete catalogue with the least entries and a recipe was devised to search the catalogue to obtain the requisite fit. This is described in Kuriyan (1974), Kuriyan et al. (1974a) where 3 sets of data were fit to derive the particulate characteristics.

Objectives of this Contract

Even though the feasibility of the polarimeter as a probe of atmospheric aerosols was established in the above papers (Kuriyan 1974; Kuriyan et al. 1974a) there remained the need for systematic observation under varying meteorological conditions to remove any lingering doubts on the viability of the method. The principal objective of this contract was addressed to this point. This required the compilation of a catalogue, measurements of polarization from the ground over a period of time at a suitable location, correlation of the existent meteorological parameters with the inferred aerosol parameters.

There was also the need to establish the consistency of the method and the usual method is to have some 'ground truth' measurements. A question that required an answer was the specification of a ground truth measurement consistent with the goals of the experiment.

The extension of this technique to the monitoring of upwelling radiation by space borne polarimeters was required. In this mode of operation the ground becomes an important source of radiation and in some sense the effect of the ground must be accounted. In the ground based experiment the measurement was relatively simple while the space borne mode will necessitate the specification of the measurement geometry. This implies that a study must be undertaken to arrive at the optimum configuration of measurement. In this contract we were expected to provide some preliminary analysis of these two important questions.

The only other passive method of remote probing of atmospheric particulates is the extinction radiometer. It seemed desirable and, therefore, it was proposed to be part of this contract, to conduct an in depth study of this method and compare it against the polarimeter to see if one could complement/supplement the other.

Tasks that were completed during this contract

1. Establishing the viability of the polarimeter as a ground based remote probe of atmospheric particulets:

   (i) The first task was to compile a catalogue for various representative values of the aerosol parameters. The cost of the computer program was quite considerable and so it was proposed that the programs be executed at NASA Langley. Unfortunately this task has only begun and it is too early to state when this will be completed. To establish the viability we needed a catalogue for at least one wavelength and we were able to complete it at UCLA (for $\lambda = 0.7\ \mu m$) from borrowed funds. This was used to interpret the measured data.

   In view of the success of our method we feel that this catalogue will be of use to others. It seemed desirable to present the results of the catalogue in a graphical form so that other users may follow our recipe (without incurring the large computer expense) and infer atmospheric particle characteristics from polarization measurements. This compilation can be made available for distribution if a small amount of additional funds are released.

(ii) The second stage of the task was to measure the radiation field under varying atmospheric conditions and this was accomplished by my student Mr. R. C. Willson (who was employed part time at J.P.L.) using the TRW NASA polarimeter. Large amounts of data were gathered at various locations near L.A. and the atmospheric parameters inferred using our recipe. Mr. Willson made a careful study of the prevailing meteorological conditions so as to arrive at a correlation between meteorological factors and particulate characteristics. He was able to show, for instance, that the refractive index of the atmospheric aerosol particles approached that of water (~ 1.36) when coastal winds brought the marine aerosols over the observing stations while the dry desert winds resulted in the raising of the refractive index to that of silicates (~1.5). These form part of Mr. Willson's thesis (produced under the supervision of the Principal Investigator of this contract) the abstract of which is reproduced in the Appendix I. Mr. Willson was not supported at anytime by this contract but the catalogue provided by this grant was used by Mr. Willson.

(iii) An unusual opportunity for proving the use of the polarimeter presented itself when Professor Suomi suggested that this be included as a last minute entry to the GATE project. Mr. Willson was able to obtain funds from J.P.L. to go on board the S. C. Oceanographer and make these measurements. Unfortunately we did not anticipate the correct amount of time or funds needed to complete this project. But the experiment had an international import and hence it seemed wise to complete it in as short a time as possible. We are glad to report that our analyzed data was submitted for publication on the 10th of June 1975 and it seems that we are about 6 months to 1 year ahead of any other experiments on this project. (Kuriyan et al. 1975). Since the submission of the report for publication we have been informed that satellite photographs have confirmed our observation of the occurrence of an extraordinarily turbid atmosphere on one day during phase I of the GATE project.

II. Ground truth -- consistency checks on the method.

Our theoretical analysis leads to the conclusion that the equivalent aerosol parameters that we infer lead to unambiguous statements on the radiation field. Therefore, the 'ground truth' in these experiments ought not to be in situ measurements of aerosol sizes but measurements of the radiation field or fluxes.

The consistency checks we proposed were as follows

(i) Make measurements of radiation field for one zenith angle of observation and one sun position (along a cone defined by the angle of observation) and derive the optical parameters. Use the derived parameters in the radiative transfer equation to calculate the radiation field in all other directions. Make a measurement of the radiation field at other angles and compare it to the calculated field.

(ii) From the derived parameters calculate the radiation field at other wavelengths. Compare this calculation against measurements at other wavelengths.

Thus the multiple angle multi wavelength measurements are nontrivial consistency checks on the method.

III. Satellite Borne Polarimeter

In this mode of operation, the upwelling radiation is monitored by the polarimeter. It is necessary to subtract the effect of the ground because it can often mask the effects of aerosols. The careful and elaborate study that we have undertaken leads us to the following recipe. (See Appendix II).

In the long wavelength region aerosol scattering is dominated by the ground effect and hence it is possible to consider the measurement of the radiation field at about 0.8 μm to be entirely that of the ground. If we assume that the polarization characteristics of the ground do not change with wavelength (in the visible region) then we can use the measured characteristic as the ground source for another wavelength say 0.45 μm. At this wavelength the aerosol (and Rayleigh) scattering dominates the ground effect (which is still non-negligible). Thus the technique adopted is to use the long wavelength measurement as a calibration of the ground and the short wavelength to study the combined effect of ground, aerosol and molecular scattering.

The problem is, therefore, reduced to that of studying the aerosol effects. For this purpose we can arrive at a recipe similar to that used in the ground based mode. This aspect of the research (to arrive at a recipe) remains to be completed. To include realistic ground effects it is necessary to modify the existing program. This has been partially accomplished but the running of the program will require more funds. So also the catalogue at short wavelengths will be completed at NASA Langely Computer in the near future with the assistance of Dr. A. Deepak.

On the matter of optimum configuration it is necessary to analyse the various cases individually. At this time we have completed one realistic case. The measurements are assumed to be made in the sun plane and the ground assumed to be a non reflecting surface. (This will hold over the oceans except at the specular angle). It is possible, in this case, to arrive at a recipe to infer the atmospheric parameters.

These details are presented in Appendix III.

IV. The other passive instrument for remotely probing for aerosols is the extinction radiometer. Conventionally the extinction optical thickness is determined and thus the turbidity of the atmosphere deduced. Our investigation has led us to believe that there is much more information in such data. We have shown that high precision multispectral extinction measurements (at least 4 wavelengths) can be used to infer the aerosol parameters. In this mode of operation the direct intensity of radiation is measured and hence is complementary to polarimeter measurements. The results of this analysis are presented in Kuriyan 1974b.

The instrument that is required is a high precision radiometer capable of measuring optical depth to an accuracy of at least 3 significant figures. Unfortunately we do not have access to such a device and hence our analysis has remained in the theoretical domain. We have deduced our results on the basis of simulated measurements (from numerical results). Serious work is underway to sharpen our analysis (to tolerate larger errors in measurement) using very powerful techniques involving the theory of solution of Fredholm Equations and it is expected that in a few months a definitive answer can be obtained.

We consider this an extremely valuable contribution to the contract since the results will point the direction of the next satellite extinction experiments. Our studies show that the polarimeter and the radiometer are complementary devices and any information obtained from one will greatly facilitate the analysis of the other. For instance in the GATE project eventhough the radiometer was not very precise, the value of the optical thickness derived enabled us to obtain fits of polarimeter data very quickly as they eliminated one variable from the problem.

V. The status of polarimeter and radiometer as remote probes of aerosols is discussed in Kuriyan 1975 which will be published in <u>Optical Engineering</u>. The question of remote versus in situ method is also given some consideration.

VI. The TRW-UCLA helicopter experiment gathered data of upwelling radiation using the TRW and GE polarimeter. While 2 sets of data gathered by the TRW polarimeter was fit to obtain the atmospheric optical parameters none of the GE data were reduced--principally due to lack of funds in that contract. We have now reduced the GE data and plotted them as graphs. These are given in Appendix IV. In order to obtain the optical parameters it is necessary to compile the catalogue at these wavelengths and use one of our techniques. At present we do not have the relevant catalogues and hence the analysis is incomplete.

Future Work

Polarimeter as a ground based remote instrument is an operational device. At present the analysis is performed by looking up graphical solutions and perhaps this can be automated, to scan electronically and obtain fits.

For the upwelling mode some more work remains. The other modes of configuration must be analysed. The ground reflection must be introduced in a realistic fashion and the algorithm that we prescribed checked. Ultimately, of course, the weakness in this phase is the lack of data and hence it is urged that some more data be acquired. The compilation of the catalogue must also proceed.

Radiometer

We do not have an instrument sufficiently precise to check our theoretical analysis. This method can become a real-time aerosol monitoring device since the analysis is done by a computer. With the improvements in analysis that is being carried out at this time at UCLA we anticipate considerable sharpening of the tolerance for errors in the measurement.

Other Activities

During the period of this contract one student Mr. R. C. Willson a part time employee at J.P.L. completed his Ph.D. at UCLA under the supervision of the Principal Investigator J. G. Kuriyan.

In addition to this Mr. D.H. Phillips completed his master's degree in Meteorology and Mr. D. Broutman completed his Bachelor's degree in Meteorology. Both Mr. Phillips and Mr. Broutman were funded by this contract. Partial support (through the Work Study program) was provided for undergraduate students Mr. Y. S. Kim (who completed the 0.7 μm graphical catalogue), Mr. P. Teensma (who assisted Mr. Kim) and Mr. Zvi Shippony (who is working on the inversion of radiometric data), a Ph.D. student in Applied Mathematics at UCLA.

The Principal Investigator J. G. Kuriyan was invited to address the discussion meeting of the Royal Meteorological Society in Jan. 1975 where the polarimeter as a probe of aerosols was discussed. The Principal Investigator took this occasion to visit Professors H. C. van de Hulst, K. Bullrich, J. W. Hovenier to apprise of them of the progress in this area of research.

Professor K. Y. Kondratyev extended an invitation to the P.I. to attend the GATE Radiation program subcommittee meetings at Leningrad in June 1975. During this meeting it was decided that a concerted effort be expended to organize an international Global radiation experiment. It was conforting to note that our results on the Dakar experiment was well ahead of the GATE schedule and that satellite photographic confirmation of our results were available.

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APPENDIX I.

ABSTRACT OF THE DISSERTATION

Determination of Effective Radiative Transfer Models

for Atmospheric Aerosol Hazes from Ground Based Measurements

of the Scattering and Extinction of Solar Radiation by the Atmosphere.

Correlation of Models with Meteorological Conditions.

by

Richard Clayton Willson

Doctor of Philosophy in Meteorology

University of California, Los Angeles, 1974

Professor Jacob G. Kuriyan, Chairman

Ground based measurements of the scattering of solar radiation by the turbid earth's atmosphere have been made using two independent observational techniques. The scattered intensity (I) and degree of polarization (P) have been observed with a polarimeter in almucantar scans for various zenith angles. The extinction of the direct solar beam as a function of wavelength by the aerosol laden atmosphere has been observed with a Multispectral Extinction Radiometer viewing the central 20 percent of the solar disk. These observations have been compared with the observables predicted by radiative transfer computations for a turbid, vertically inhomogeneous, absorbing, multiply scattering model atmosphere (with ground reflectance). Aerosol models in terms of a Deirmendjian Haze-H type size distribution, index of refraction and optical

thickness are retrieved. In general since more than one type of aerosol overlays an observation site the models are a composite description of the atmospheric turbidity.

There is a nonuniqueness in the method since many different aerosol models can produce the same radiative effects. The usefullness of this investigation rests on the fact that the method allows the determination of the effective optical parameters of aerosols in one of the equivalent representations. An application of the results of this technique is the computation, without ambiguity, of the net fluxes for turbid atmospheres.

Observations have been made under a wide range of meteorological conditions in the southern California region and in the south Atlantic Ocean area during the GARP Atlantic Tropical Experiment. These have been successfully analyzed to yield effective radiative transfer models of the atmospheric aerosol content overlying each observation site. The aerosol models have been correlated with meteorological conditions for pre-GATE observations. (The models derived from the GATE will be correlated with GATE meteorological data when it becomes available in late 1975). The pre-GATE correlations for southern California measurements show strong relationships between movements of different types of air mass across our field of view and aerosol models. Marine air produces aerosol models with water-like refractive indices (1.34). Santa Ana conditions which bring dry desert air to southern California yield aerosol models with silicate-type refractive indices (1.54). Mixed meteorological conditions in which neither of these air movements dominates yield intermediate refractive indices. The presence of large amounts of anthropogenic aerosol (smog) produces high model refractive indices using this technique.

APPENDIX II.

<u>One possible method of accounting for ground reflection</u>

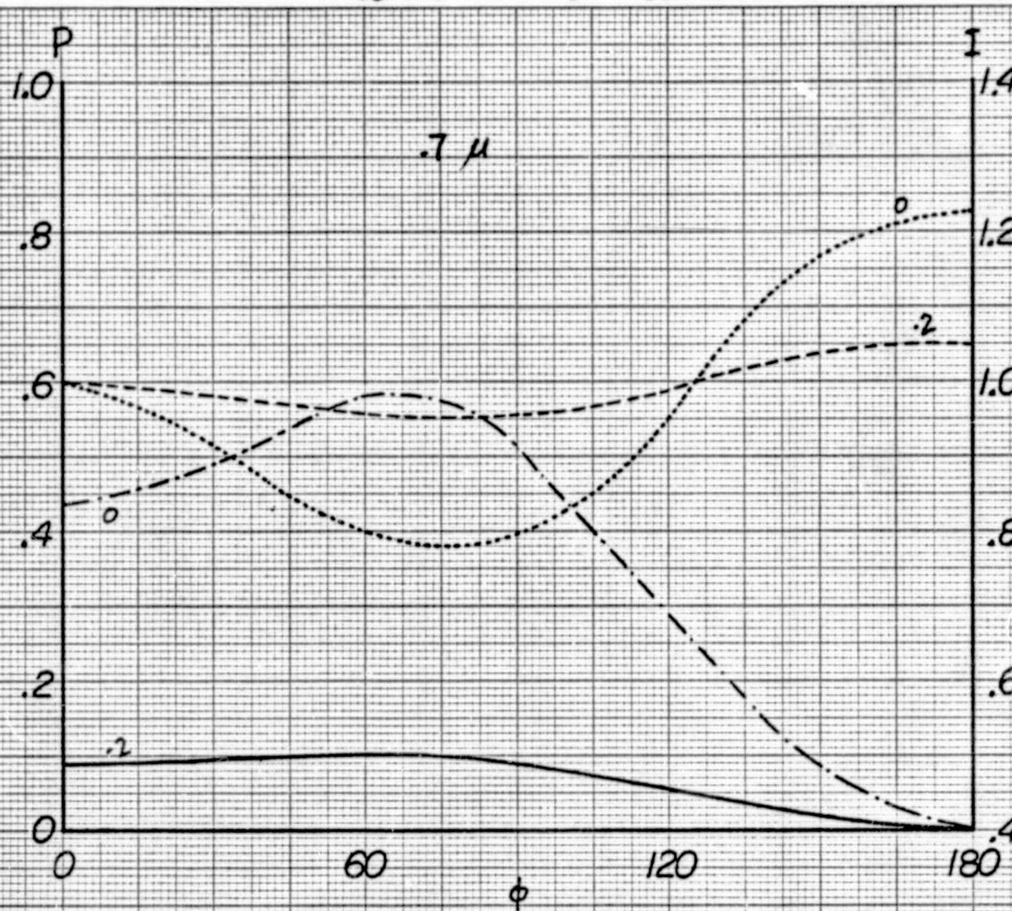
Note in fig. (a) at $\lambda = 0.7$ μm when the ground reflection is ignored ($A = 0$) the polarization (P) and the intensity (I) curves have great deal of variation with φ. But when a ground reflection of 20% ($A = 0.2$) is introduced the radiation is almost unpolarized and isotropic. Here the ground is a Lambert reflector and, therefore, produces unpolarized isotropic radiation and we see that a 20% reflecting ground dominates the aerosol effects.

In fig. (b) at $\lambda = 0.45$ μm on the other hand even $A = 0.2$ (which is large for this region of the spectrum) diminishes but does not eliminate the aerosol features.

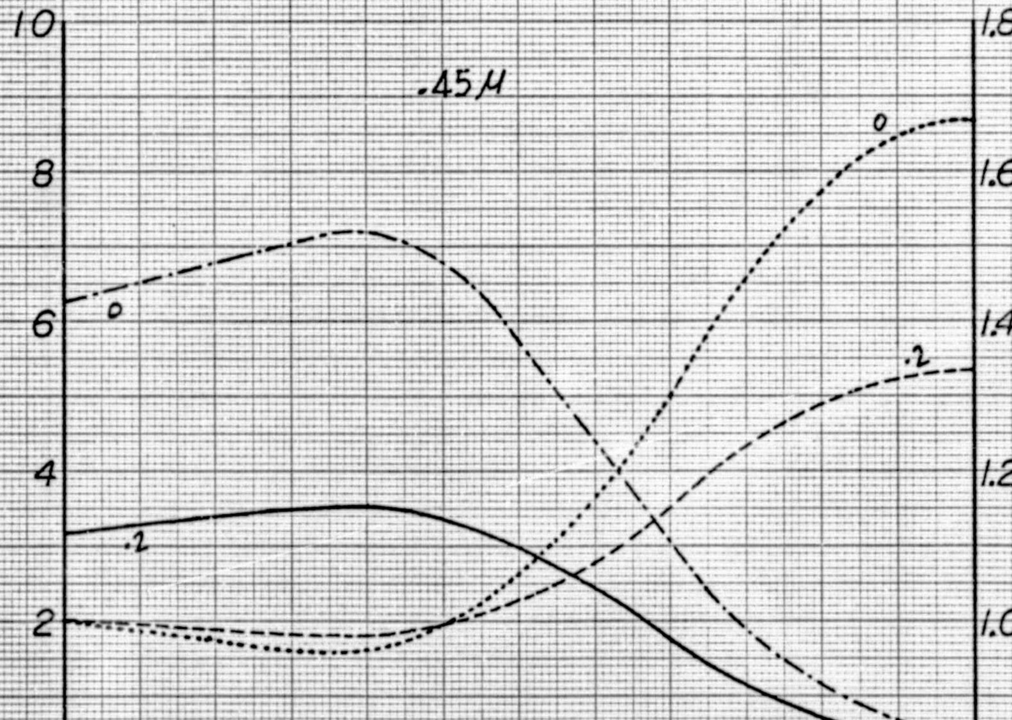
This leads us to suggest that the long wavelength region be used as a measure of the ground reflection characteristics and these features used in the program for $\lambda = 0.45$ μm so as to eliminate the ground effect from the short wavelength region.

Once the effect of the ground is isolated and eliminated then we can arrive at prescriptions for obtaining the various aerosol parameters. While this has not been done, principally because the 0.45 μm catalogue is not available, there is no reason to believe it will not work. In fact, in the next section we provide one such presciption (for the case of no ground reflection).

$\theta_0 = 50°$ $\theta = 50°$



(a)



(b)

APPENDIX III.

Sun Plane Analysis for Zero Ground Reflection

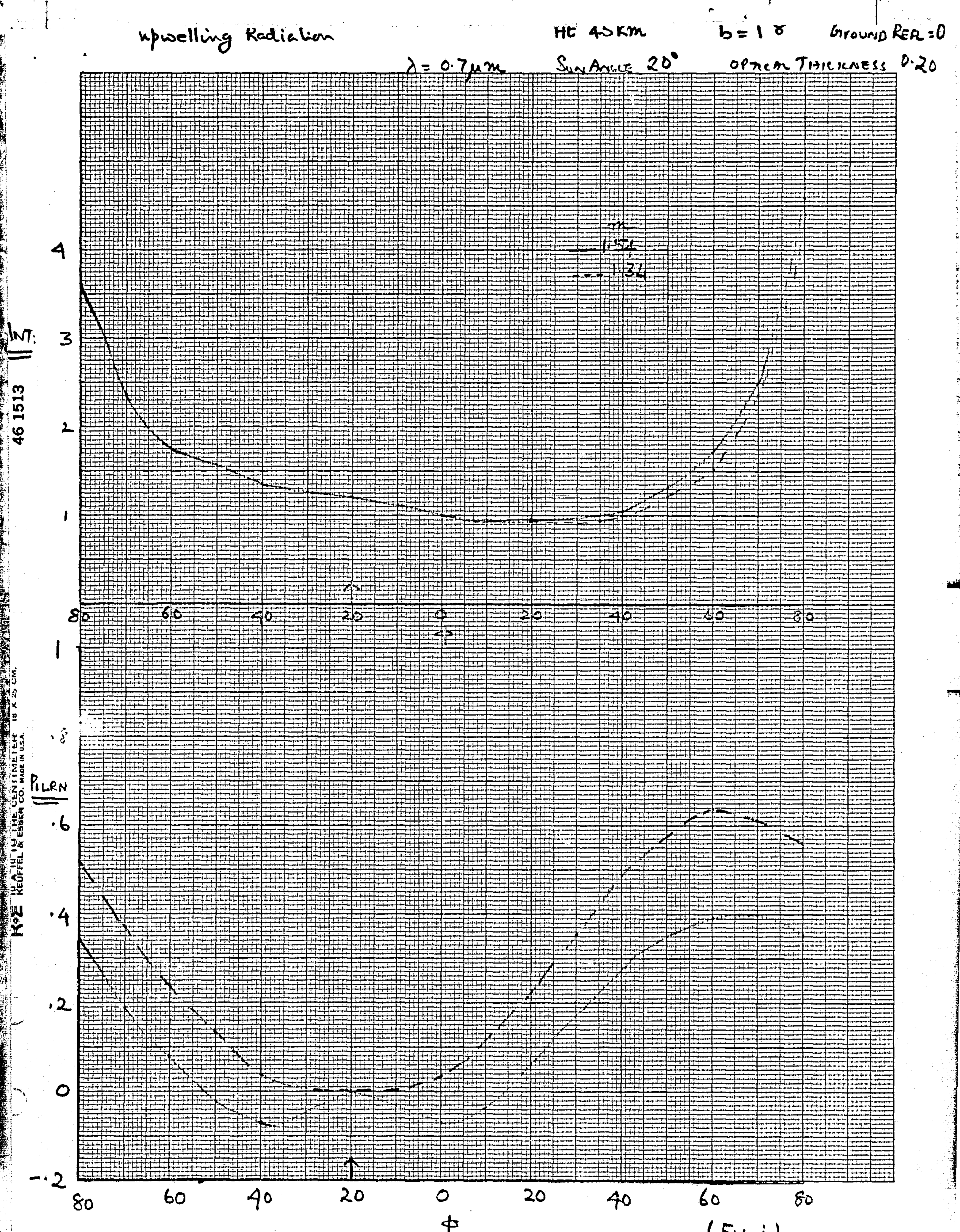
This is a possible configuration over (cloudless) ocean.

The recipe is as follows.

(1) 0.7 μm the I curves (for varying m) (fig. i) overlap in the region near Antisolar point. Therefore this region of the curve must be fit by varying b and τ alone. It seems as if the fit can be achieved either decreasing b or increasing τ. But this is not true since in the region $\varphi = 0$ to 80° there is a cross-over for the τ (fig. ii) curves. That is if τ increased the curve on $\varphi = 0$ to 180° will rise (fig. ii) while b is decreased the curve in the same region will fall (fig. iii). So it is possible to isolate (and remove) the dependence of m by examining the I curve.

(2) Then an examination of the P curve will help fix the value of m.

Even though only one set of graphs (for one solar angle) is provided with this report the analysis has been performed for other solar angles as well. A preliminary analysis for $\lambda = 0.575$ μm confirms our conclusion.

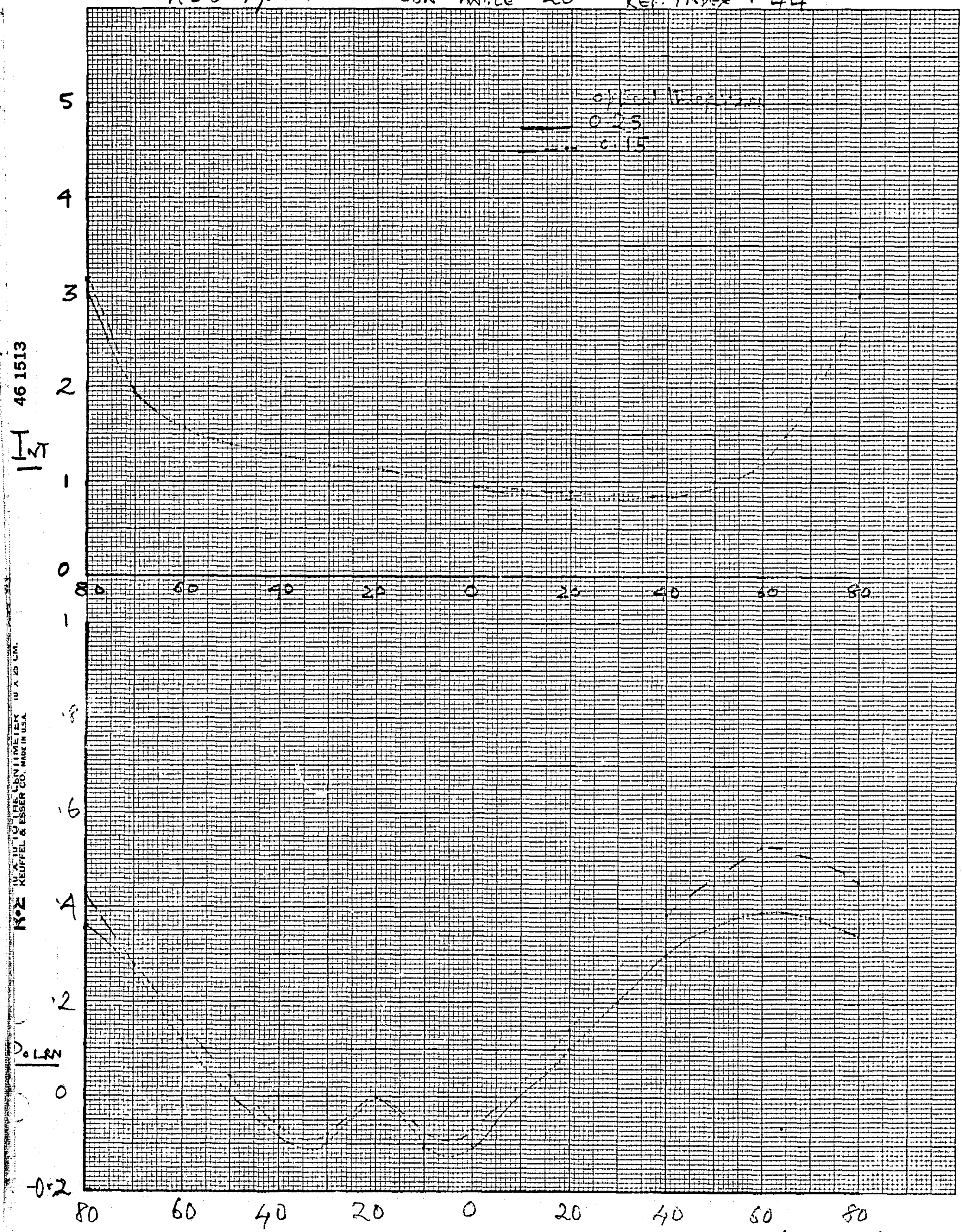


upwelling Radiation
Ht 45KM
b = 1 8
GROUND REF. = 0
λ = 0.7μm
SUN ANGLE 20°
OPTICAL THICKNESS 0.20
m
1.54
1.34
INT.
PLRN
φ

(FIG i)

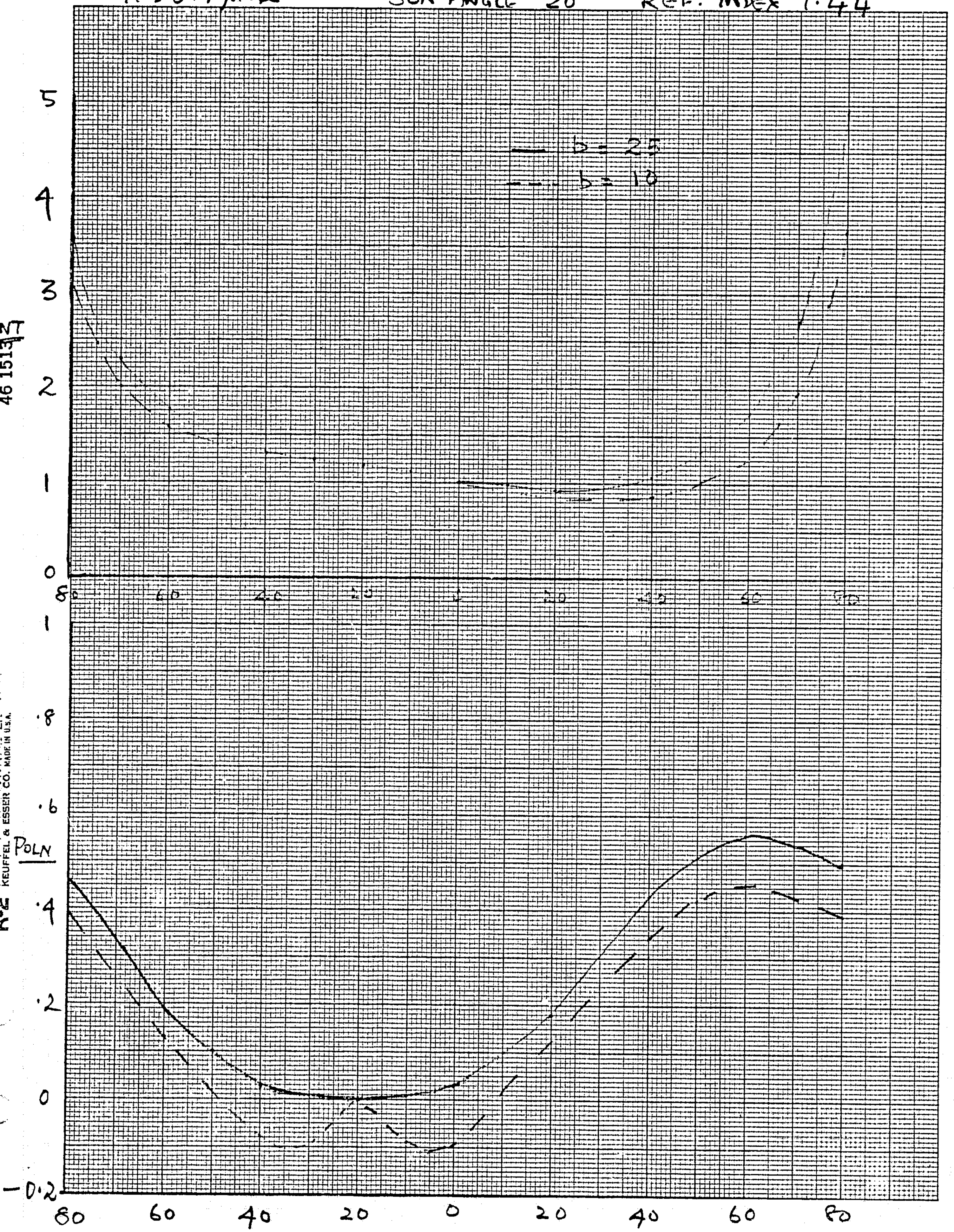
upwelling radiation HE = 45 Km b = 10 Ground = 0

λ = 0.7 μm Sun Angle 20° Ref. Index 1.44



(Fig ii)

upwelling radiation   HT = 45km.   OPTICAL THICKNESS = 0.20
GROUND REFLECTION = 0
$\lambda = 0.7\,\mu m$ SUN ANGLE 20°   REF. INDEX 1.44



(Fig iii)

Remote measurement of aerosol particle

characteristics and their significance to meteorology

by

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Abstract

The radiation field measurements using a polarimeter and a multispectral radiometer can be used to infer the equivalent optical parameters of aerosol particles. The importance of this experiment lies in the fact that radiative effects of particulates can be calculated without ambiguity if these effective parameters are known. In addition to providing illustrative examples of the derivation of atmospheric parameters from radiation measurements, a critical discussion of the implications underlying these model calculations are given so that the physical significance and the usefulness of these experiments can be better appreciated.

Introduction

The specter of a change in climate due to the industrial activities of man[1] and the consequent deleterious effect of a changed environment on man has encouraged the investigation of the effect of pollutants on the heat budget of the atmosphere. In order to estimate the climatic impact of pollutants it is necessary to know their global distribution as well as the nature of their interaction with solar radiation.

The experimental methods of determining the concentration and distribution of gaseous pollutants are readily available as are the theoretical programs for computing the radiative effects of such absorbers in the atmosphere. Particulates, on the other hand, scatter and absorb radiation and to investigate them is a slightly more difficult task.[2] This paper shall concern itself with this problem, to summarize the theoretical and experimental achievements to date and to evaluate the merits of remote measurements vis à vis in-situ methods. Examples will be provided only to illustrate the method used to interpret the data so as to appreciate the usefulness of such experiments. Unfortunately, not much effort has been expended in the development of instruments that will exploit the information derived from these recent theoretical studies. It is hoped that a clarification of the assumptions underlying the theoretical model, the method used to interpret the data and the usefulness of the derived parameters will encourage the development of sophisticated instruments that can better serve the research workers in this field.

Yamamoto and Tanaka, Eiden and Eschelbach, Bullrich et al., Kondratyev, Herman, Dave and Braslau as well as studies conducted at UCLA suggest that aerosol particles can reduce or increase the global albedo depending on their optical parameters.[3] Heating or cooling of 1°C/day seems possible and this means that ignoring the aerosol effects in the interaction of solar visible radiation with the earth and its atmosphere can lead to corresponding errors in the estimate of the heat budget. Grassl[4] points out that the radiative cooling in the infrared due to aerosols can be as much as 0.1°C/day. In order to compute the total radiative effect of aerosols, model calculations must be performed to include both the visible and the infrared regions and reasonable values of the index of refraction assumed for the various spectral regions. Since the infrared emissions of aerosols will be absorbed by the molecular constituents of the air, it seems reasonable, on heuristic grounds, to predict that the infrared cooling will not completely off set the change due to the visible radiation interacting with aerosol particles. At present the numerical models of the general circulation of the atmosphere ignore aerosol effects and it would be interesting to see if such changes due to aerosols can have any effect on the general circulation.

General description of the model

The optical characteristics of the particulates such as refractive index, m, and size distribution, n(r), determine their scattering properties. It is the custom to assume that these particles are spherical and that they have a uniform refractive index. Then it is possible to use the results of Mie theory to calculate their interaction with the radiation field.

As a justification for this assumption it is suggested that the aerosol particles acquire, in the atmosphere, a water coating and become near-spherical in shape. Such heuristic arguments are physically plausible and when they are used as substitutes for proof they detract from the value of the experiment. It is important to recognize the rigorous implications of such model calculations in order to appreciate the significance of the derived results. Strictly speaking the incoherent scattering of an assembly of particles, irregular though they may be, is being simulated by a collection of spherical scatterers of uniform refractive index. Shifrin[5] shows the equivalence of a collection of ellipsoids to that of spheres. It may be impossible to simulate, using spheres, the scattering property of one irregular object or a symmetrical array of non spherical objects such as needles or hexagonal cylinders. But, by and large, such unusual circumstances do not prevail, at least as far as the atmospheric particulates are concerned, and it is this expectation that leads us to the consideration of these simple equivalent systems. It will be shown later that the parameters of the model are observable in that they can be determined from experiment and non trivial experimental checks on the consistency of the method will determine the validity of the equivalent parameterization. If experiments indicate that the picture of aerosol particles as an assembly of spheres is too simplistic to accommodate the observed scattered radiation field then considerable theoretical work will have to be performed to adequately handle scattering of irregular objects of arbitrary distribution. The presently available experimental data suggests that the simple model adopted here is quite sufficient.

Such a model for aerosol particles can be used to compute the scattered radiation field in any one of the methods described in the literature[6]. The aerosol optical depth, calculated from Mie theory, will lead to the direct solar radiation, if the Beer-Lambert law is adopted.

We shall consider two devices that operate in the visible region of the solar spectrum, the polarimeter[7], that measures the scattered radiation field and a multispectral radiometer[8] (MSR) that measures the direct solar radiation.

Polarimeter as a remote probe of atmospheric particulates

A prototype rotating polarizer type polarimeter designed and constructed by TRW, Inc. for NASA Langley Research Center has been used in developmental work at UCLA.[6] Light is collected by a 20 cm fl f 3.5 lens and brought to a focus on a 0.5°, circular, view limiting aperture. A first relay lens collimates the light for passage through the rotating Glan-Thompson prism linear polarizer. A second focusses the emergent light on a silicon PiN photodiode detector and op amp combination. One of four narrow band ($.01\ \mu$) filters can be positioned in front of the detector at a time. The four center wavelengths are $\lambda = .448\ \mu$, $.575\ \mu$, $.701\ \mu$ and $.822\ \mu$. The basic features of this instrument are shown in diagrammatic form in fig. 1. The field-of-view is defined by the size of the entrance aperture and focal length of the telescope. Typically, 0.5° and 0.2° fields-of-view are employed for low and high intensity scattering, respectively. The incident flux passing through the aperture is collimated by a relay lens and transmitted through the rotating Glan-Thompson Prism. The prism is a near-perfect linear polarizer with high transmittance throughout the near-ultraviolet-visible-near infrared wavelength range. The action of the rotating prism "analyzer" introduces an AC component into the light transmitted by it that is proportional to the polarized component in the incident skylight. The "analyzed" light is brought to a focus on the four detectors by the second relay lens, after passing through beam splitters and narrow band filters.

The amplifying electronics are all solid state. At present, signal conditioning electronics produce two d.c. voltages, one proportional to the intensity of scattered skylight, and a second proportional to the degree of polarization. The detector signal, under conditions in which measurements of partially polarized light are made, is a combination d.c. and a.c. signal as in fig. 2. The intensity (I) and degree of polarization (P) are:

$$I \propto 2\,V_{d.c.}$$

$$P = (\sqrt{2}\,V_{a.c.})/V_{d.c.}$$

where $V_{d.c.}$ and $V_{a.c.}$ are the effective d.c. and rms a.c. measured voltages. The amplification of the d.c. component is not critical since all measurements are normalized with respect to the solar vertical plane. At present, the TRW polarimeter uses an analog multiplier to produce a d.c. signal equal to the degree of polarization. The two signals are displayed on digital panel meters and recorded manually. The polarimeter is mounted on an alt-azimuth tracker. The tracker has angular readout scales in both azimuth and elevation, facilitating the precise determination of polarimeter orientation.

A single set of measurements is comprised of 17 pairs of AC and DC signal voltages at a given zenith angle of observation separated by intervals of 22.5° in azimuth. The first and last measurements are made in the solar vertical plane and all other measurements are referenced in azimuth to this plane.

In addition, the solar zenith angle and time of measurement are recorded. Sets of data are usually taken at observation zenith angles of 30°, 40°, 50° and 60°.

The process of data reduction begins with the computation of the solar zenith angles during the observations, using the times of the measurements, the values of solar declination, ephermeris transit and their diurnal variations. Any differences between observed and calculated solar zenith angles due to instrument misalignment can be used to correct the observation zenith angles as well. After correcting the data for instrument offset and drift, the degree of polarization and total, normalized intensity is computed, using equations given above.

An improved polarimeter is being developed by Mr. R. C. Willson that is compact, light weight and has more photometric precision than the present instrument. Four parallel channels, each with its own lens, filter and detector will have 0.5° fields of view and share a single rotating polarizer. Log detection electronics will be used to scale six decades of response to a 0-10 v.d.c. range. The detectors will be PiN photodiodes in the reversed bias, constant current mode. The effective d.c. of the signals and d.c. signals proportional to the r.m.s. a.c. of the signals will be preamplified, A-D converted and recorded on cassette tape, along with time code, wavelength and angular position data.

The polarimeter will be mounted on the solar tracker described in the next section. Scans will be made at azimuth reading from 0° to 360° relative to the solar vertical plane and at zenith angles 0 to 90°.

The data is compared against a catalogue of radiation field calculated for various representative aerosol parameters. The programme[9] developed by J. V. Dave using the iterative scheme was used and the computations carried out on an IBM 360-91. The processed data output contains in addition to the degree of polarization and normalized intensity, the azimuth angle of each measurement relative to the solar vertical plane, the solar zenith angle and the scattering angle.

The size distribution of the aerosol particles was assumed to be of the form $a\,r^2 e^{-br}$ where a is related to the concentration and is allowed to vary with height while b is related to the modal radius $r_c = \frac{2}{b}$ and is indicative of the average size of the particles. We have shown elsewhere that the choice of other size distributions such as $A\,r\,e^{-B/r}$ can lead to similar results. This implies that the size distribution is only one member of an equivalent class of distributions all of which lead to the same radiation field. Thus if the goal is to calculate the radiative effects of aerosol particles, the determination of the parameters of any one equivalent distribution is necessary and sufficient.

The ground reflects the radiation and adds to the scattered field. It is the convention to assume[10] the ground to be a Lambert reflector. That is, the reflected radiation from the ground is isotropic and unpolarized. In the mode of operation of the polarimeter, looking up at the sky at small scattering angles, the ground reflection contributes little to the total radiation field and this assumption is not very critical. In fitting the data it was assumed that at

$\lambda = 0.7$ μm the ground had an albedo of 0.2, a value that was fixed for subsequent measurements.

For the compilation of the catalogue the vertical profile was assumed to be that given by Elterman.[11] Preliminary studies indicate that in a ground based mode the polarimeter probes the entire atmosphere and leads to average parameters for the whole region and is, therefore, insensitive to changes of vertical profiles. Further the original catalogue included only real indices of refraction. They have since been augmented to include complex indices of refraction.

In fig. 3 is one example of the fit obtained from the catalogue and the data gathered. The parameters obtained by the fit are $b = 25 \pm 2$, $m = 1.54 \pm 0.02$ and $\tau = .25 \pm .03$. There are numerous other examples of this type and they will constitute the Ph.D. dissertation of Mr. R. C. Willson.

A consistency check on this formalism would be to conduct the same experiment at a) different wavelength; b) different angle of observation and verify if the parameters obtained are the same. Mr. Willson's observations indicate that this consistency does exist and, therefore, the concept of equivalent parameters is a viable technique. The extensive and systematic observations conducted by Mr. Willson indicates a strong correlation of these equivalent parameters with meteorological conditions such as a decrease of the refractive index when coastal winds bring marine aerosols over the L.A. basin and an increase when the desert (Santa Ana) winds blow the dry aerosol particles over the observation area.

In an aircraft or satellite version of this experiment the polarimeter would look at a region near the sun through the earth's limb. In this mode of operation the analysis is identical to what has been carried out in this section. This is not to be confused with the usual proposal for a satellite polarimeter experiment where the upwelling diffuse radiation field is monitored, where the ground effect is very important and a scheme must be devised to subtract it from the radiation field. Such an algorithm was developed and used to fit two sets of data gathered as part of the UCLA-TRW helicopter experiment. Clearly this is a statistically insufficient amount of data to warrant any serious conclusion except to express a general air of optimism. More data will have to be acquired before the study of upwelling radiation can match the detailed investigation that we have conducted of the downwelling radiation.

Multispectral radiometer as a remote probe of atmospheric particulates

In a recent paper[8] it was shown that the precise measurement of extinction optical depth at many wavelengths can be used to infer the equivalent optical parameters of the atmospheric aerosols including the complex index of refraction. The assumptions in this theory are the same as before, i.e. spherical scatterers, uniform refractive index and a size distribution given by $n(r) = ar^2 e^{-br}$.

The method is based on the observation that the ratio of optical depths at λ_1 and λ_i is a known function of b and m, calculable from Mie theory. This function is calculated for the range of physically realizable values of b and m, and stored in a computer. Any measurement of the ratio of optical depths at λ_1 and λ_i can then be compared against the calculated values to arrive at the allowed values of (b,m) that correspond to the measurement. This is repeated so that λ_i takes other values and the corresponding (b,m) determined. Since b is a geometrical number independent of wavelength, and m is assumed to be independent of wavelength, the pair of values (b,m) common to all the ratios (λ_1, λ_i) will be the optical parameters that we seek.

Numerical simulations indicate that if the optical depths are known to three significant figures the errors are $\Delta b = 1\%$, $\Delta n = 0.04$, $\Delta k = 0.02$ where $m \equiv n-ik$. The errors are larger when the optical depth is known less accurately. There must be a minimum of at least three ratios (or four wavelengths) and the farther apart these are, the better is their resolution. However, they cannot be too far apart or else the assumption of a uniform refractive index over the region of measurement may not be valid.

Since ratios of optical depths are considered,the height dependent term a(h) cancels out and, therefore, the results are independent of vertical profile. In satellite occulatation experiments this will eliminate the tedious and difficult considerations due to the sphericity of the medium.

The present instrument, designed by Mr. R. C. Willson and made by the UCLA Department of Meteorology, is a prototype device built for use in the GARP Atlantic Tropical Experiment and is basically a 10 channel filter photometer. It has a 17 cm f 3.5 achromatic lens that focusses the solar image on a PiN silicon photodiode. The 0.025 cm diameter diode defines a circular field of view of 0.086°, covering the central region of the sun. Ten narrow band optical filters 0.01 μm with central wavelengths ranging from 0.4 μm to 0.7 μm can be positioned in front of the detector, one at a time. The detector is used with an FET op amp, in the constant current mode, producing very low drift with temperature and linear output over more than 7 decades of light intensity. Twelve linear gain stages are provided in 1-2-5 steps. The signal is displayed on a digital panel meter and at present data is recorded manually. Power for the circuitry is supplied by an AC-DC converter located in a separate box.

The instrument is manually pointed at the sun, aimed by centering the solar image generated by a hole aperture on a target. A single series of measurements consists of an initial detector zero reading, a signal voltage reading with each of the 10 filters in place, and a final zero reading. The measurement repeatability with the present instrument is $\pm 0.5\%$.

The next instrument proposed by Mr. R. C. Willson is a grating spectrometer where a transmission grating mounted in front of a small catadioptric-telescope will form an image of the solar spectrum on an array of Si PiN photodiodes in the telescope image plane. The grating will be tilted relative to the telescope axis to effect a spectral scan. Detector electronics will be FET constant current mode to achieve the advantages of linearity and low drift. The detector itself will be temperature controlled, yielding measurement repeatability of ±0.1% or better. Use of multiple detector arrays minimizes the range of movement required for the grating to effect a scan of wavelength. Grating movement will be effected by use of a piezoelectric device. Its angular position will be measured by an angular position transducer, calibrated in wavelength in the laboratory by comparison to known standard spectra.

Wavelength scans can be made very rapidly, at least 10 per second, and a large quantity of solar extinction data can be generated in a short time. The detector output will be coded digitally and recorded on magnetic cassette tape, along with the code for the wavelength of the observations.

The MSR will be mounted on a servo-controlled, alt-azimuth solar tracker. The tracker will use a solid state, four-quadrant detector located at the undiffracted central image at the telescope focal plane to generate error signals for the tracking electronics. Tracking accuracy will be $\pm 0.05^{\circ}$. Elevation and azimuth drives will be by geared stepping motors.

The solar tracker-MSR instrument will be mounted on a servo-controlled stable platform. The azimuth plane of the tracker will be maintained in a horizontal position to within $\pm 0.05^{\circ}$. True north will be detected and a signal generated giving the solar vertical plane-to-true-north azimuth angle at all times within $\pm 0.1^{\circ}$.

The solar tracker will operate in two modes. The first is oriented to the sun. The second is an all-sky scan at any pre-selected sites of azimuth and zenith angles. The solar tracking mode is for the MSR measurements. The second mode is for polarimeter measurements. Both modes, their operation times and alt-azimuth scans will be sequenced automatically by internal electronics. The data, along with position, wavelength and time coder, will be formatted for direct play back into computer systems. (Schematic drawings of the present and second generation MSR are shown in figures 4 and 5 respectively).

Since the theoretical analysis requires high precision measurements, a careful analysis of the sources of errors are in order. The optical depths are calculated by the use of the Beer-Lambert law $V = V_o \exp(-\tau \sec \theta)$ where V is the voltage measured, V_o the extraterrestrial voltage, θ the zenith angle of the sun and τ the total optical thickness defined as $\tau \equiv \tau_R + \tau_A$ where R and A stand for Rayleigh and aerosol respectively. At certain wavelengths it may be necessary to include the absorption effects due to other atmospheric constituents such as water vapor or ozone. By measuring V at two positions of the sun sufficiently close together in time so that the optical thickness is unchanged it is possible to solve for V_o. By repeating this measurement an average value of V_o can be obtained. The immediate problem that arises is, of course, the accuracy with which V_o can be determined and to estimate the temporal change in V_o. Closely related to this question is the accuracy of the Beer-Lambert law. For instance, if the optical thicknesses are large, the multiply scattered radiation field can contribute significantly to the beam in the solar direction and thus invalidate the discussion. On the GARP-Atlantic Tropical Experiment the MSR was on board a ship and due to the lack of a stable platform the rocking of the boat posed a severe pointing problem. The errors in the measurement result in the large error bars on the determined parameters. These problems are all under investigation.

Multispectral extinction measurements were obtained by Knestrick et al.[12] for a horizontal path over the Chesapeake Bay with the use of an artificial laboratory source. Since the value of V_o is accessible to laboratory measurements there is a possibility that the errors here are substantially less than our case. It is possible to obtain solutions for 10 sets of data (out of 36) with relatively small errors. For illustrative purposes let us pick data set corresponding to October 30. Our analysis yields a value of $b = 27.5$, $m = 1.33 - i\,0.05$. In Table I the optical depths calculated with these parameters are compared against the measured values. Perhaps the deviation in the calculated optical depth at 0.78 μ is due to the neglect of water vapor absorption. To derive the parameters only four wavelengths are needed, so this predicts the other four optical depths and hence has an internal consistency check. Comparison of the other sets of data will be the content of a forthcoming paper by J. G. Kuriyan, D. H. Phillips and D. Broutman.

The work of Hanel and Bullrich[13] suggests that if the power law distribution $n(r) = \frac{1}{\gamma^{\nu+1}}$ is used then it would be difficult to infer the refractive index. This is due to the fact that the power law distribution is ill behaved for small values of r and the calculation of optical depth becomes very sensitive to the limits of integration. So if the power law distribution is used then cut-offs in the integration will be required and depending on the value of the cut-off parameter the results will vary. The gamma distribution that is chosen in our work $n(r) = ar^2e^{-br}$, on the other hand, is well behaved for small and large values of r.

Table 1

Date: October 30

λ	Measured Optical Depth	Calculated Optical Depths
.40	.25	.25
.43	.22	.22
.46	.197	.197
.47	.184	.178
.56	.138	.136
.67	.096	.091
.78	.091	.109
1.04	.042	.041

Table I

From our theory optical depths at the first 4 wavelengths yield the equivalent parameters $b = 27.5$, $m = 1.33 - 0.05\,i$ and this is used to calculate the other optical depths in this table.

Summary and conclusions

Atmospheric particulates were assumed to be effectively replaced by spherical scatterers with a uniform refractive index and distributed in size according as the function $n(r) = ar^2 e^{-br}$. It is then possible to use Mie theory and the multiple scattering codes to calculate the scattered radiation field as well as the direct beam that reaches the earth in terms of the effective optical parameters of aerosol particles. Ground based measurements of the radiation field using a polarimeter or multispectral extinction using a radiometer can yield the aerosol optical parameters. While the radiation field does not seem to have sufficient information to determine the size distribution uniquely, the calculated radiative fluxes do not have any ambiguity. Hence the statement that the determination of the equivalent aerosol parameters is important to probe the radiative effect of particulates.

Implicit in this model is the hypothesis that an assembly of spherical scatterers can simulate the radiation field due to the atmospheric particulates. Calculational expediency rules in favor of these simple models but since the parameters of the model are observable it is possible to devise consistency checks. In the case of the polarimeter it is possible to derive the optical parameters from a measurement of the intensity and polarization at one wavelength for a fixed zenith angle of observation and azimuth ranging from 0 to 180°. The derived parameters can be used to <u>calculate</u> the radiation field (using the radiative transfer equation) at other wavelengths and for different angles of observation. So multiple wavelength and viewing angle measurements will provide a check on the model. Of course, the assumption of horizontal homogeneity is essential if the multiple viewing angles are to yield consistent results Often, in the L.A. basin, for instance, due to the swiftly changing meteorological conditions the horizontal homogeneity may not be a good assumption. In such cases there is a need to introduce at least two different aerosol types to fit the data obtained from a scan in azimuth. In the case of the MSR only four wavelength measurements are required to derive the aerosol parameters. These can be used to calculate the optical depth at other wavelengths. So a measurement at more than 4 wavelengths will automatically lead to a consistency check. In view of the lack of precision of the presently available MSR this will remain a theoretical observation. It is desirable to compare results from the MSR against those from the polarimeter. The numerical simulation as well as the illustrative example given above should, of course, eliminate any reservations regarding the viability of the MSR.

To extend the above measurements to a spacecraft application the polarimeter and the MSR would be in an occulting mode and the radiation field measured for a scattering angle of about 40°. In the case of the spaceborne MSR it will be possible to directly measure V_o and hence eliminate a very serious source of error that exists in the ground based experiment. Further, for the MSR, the vertical profile can be arbitrary, since it cancels out of the ratio of optical depths and thus severe problems relating to the sphericity of the atmosphere can be obviated by the adoption of our formalism. A combined instrument of a polarimeter and

MSR would yield valuable complementary information of crucial importance to meteorological studies related to atmospheric particulates.

In situ methods, in principle at least, will provide the actual parameters of aerosols, provided the sampling and analysis does not affect the particles that are being studied and if a sufficiently representative sample can be obtained. Let us for the moment grant the fact that the collection and analysis of the samples are performed with extreme precision. The investigations of Hanel[14] in Bullrich's group at Mainz suggests that when the relative humidity exceeds 85% the size of the aerosol particle is critically dependent on the exact value of the relative humidity. These conditions exist in inversion layers and model calculations indicate that aerosol particles trapped in inversion layers can account for most of the total optical depth of the atmosphere. Thus in order to arrive at the aerosol parameters using in situ methods, extensive sampling must be performed in these layers and the relative humidity measured with great precision (better than 0.1% for relative humidity in excess of 90%). If this is possible then the lab analysis of the aerosol sizes can be extrapolated to obtain the actual size in the atmosphere. Needless to say these are severe limitations on the experiment. It would be essential to use the parameters derived from in situ methods in the radiative transfer equation so as to calculate the radiation field and compare it against the measured radiation field. In the absence of this consistency check the utility or relevance of the in situ methods to meteorological calculations is not conclusively established. On the other hand if the cloud nucleation abilities of aerosols are being investigated the in situ parameters are indeed superior to those derived from remote methods.

In conclusion the theoretical models for the calculation of the radiative effects of aerosol particles require the inference of parameters such as optical depth, the complex index of refraction and the equivalent size distribution. Two instruments, the polarimeter and the multispectral radiometer are offered as candidate experiments for local monitoring via ground stations or global monitoring via spacecraft occultation experiments. Measurements of optical depth at one wavelength or turbidity factor, as has been the custom, are insufficient to provide useful information for meteorological calculations and new experiments and instruments must be devised to take advantage of the theoretical developments in this field.

Acknowledgements

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Fig. 1 Schematic diagram of the TRW-UCLA polarimeter RL-Relay lens; GT-Glan-Thompson prism; BS, OF-Dichroic beam splitters; F1-4-narrow band pass filters, D1-4 detectors; A1-4 Amplifiers.

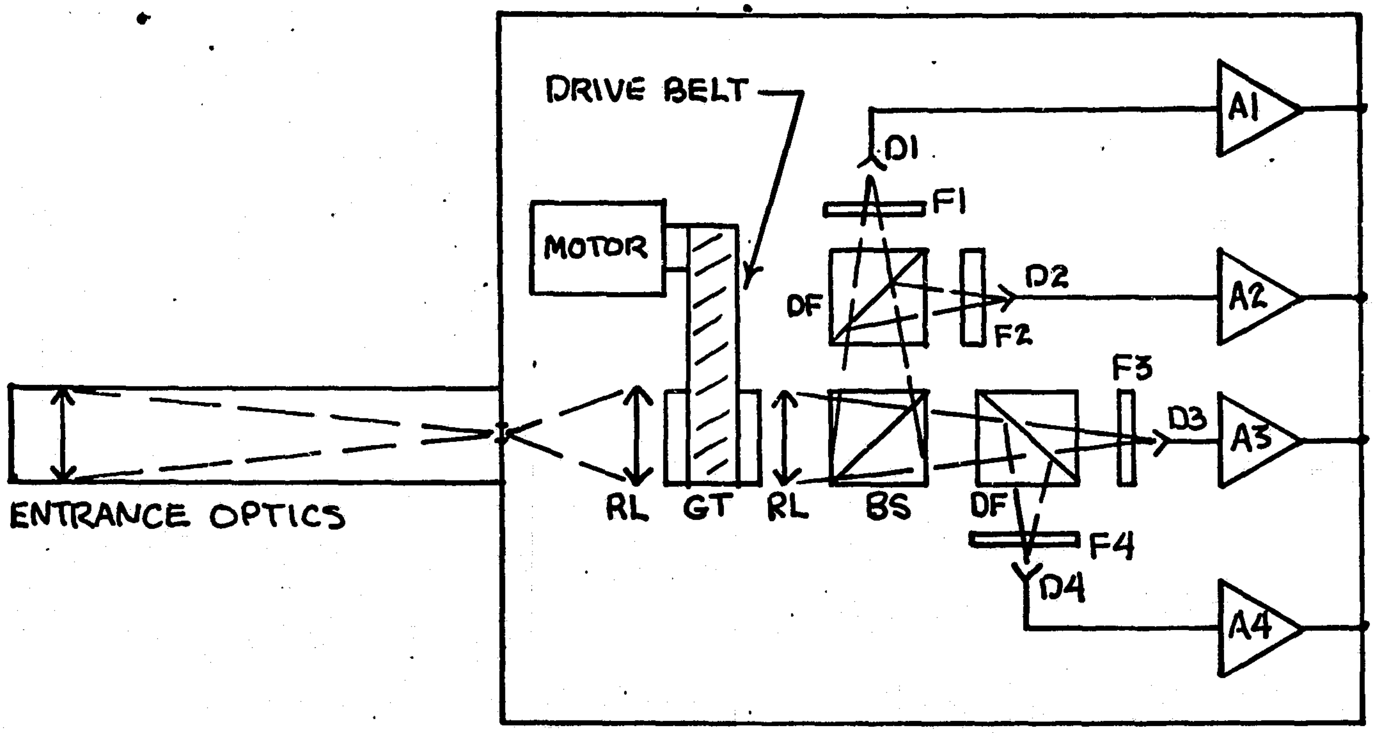
Fig. 2 The output signal from the polarimeter has a d.c. component $V_{d.c.}$ proportional to the total scattered intensity and an a.c. component $2\sqrt{2}\,V_{a.c.}$ proportional to the degree of polarization.

Fig. 3 Data gathered on 8/12/73 fit by $b = 25$, $m = 1.54$, $\tau = 0.25$ and $A = 0.2$ for a wavelength 0.7 μm.

Fig. 4 Schematic diagram for Willson's UCLA-Multispectral radiometer (1) iris diaphragm, (2) achromatic lens, 17 cm focal length f 3.5, (3) filter wheel, (4) PiN si photodiode detector, (5) FET op amp, (6) 12 position gain switch 1-2-5 steps, (7) output signal, (8) rotating polarizer to add polarimeter to MSR, (9) motor for polarimeter.

Fig. 5 Schematic diagram of Willson's high precision MSR, (1) Iris diaphragm, (2) transmission diffraction grating, (3) piezoelectric scanner, (4) angular position sensor, (5) catadioptric telescope,

(6) detector array with quadrant detector and Si PiN photodiodes, (7) detector preamplifiers, (8) quadrant amplifiers, (9) angular position sensor electronics.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MOTOR
D1
F1
DF
D2
F2
F3
D3
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A2
A3
A4
ENTRANCE OPTICS
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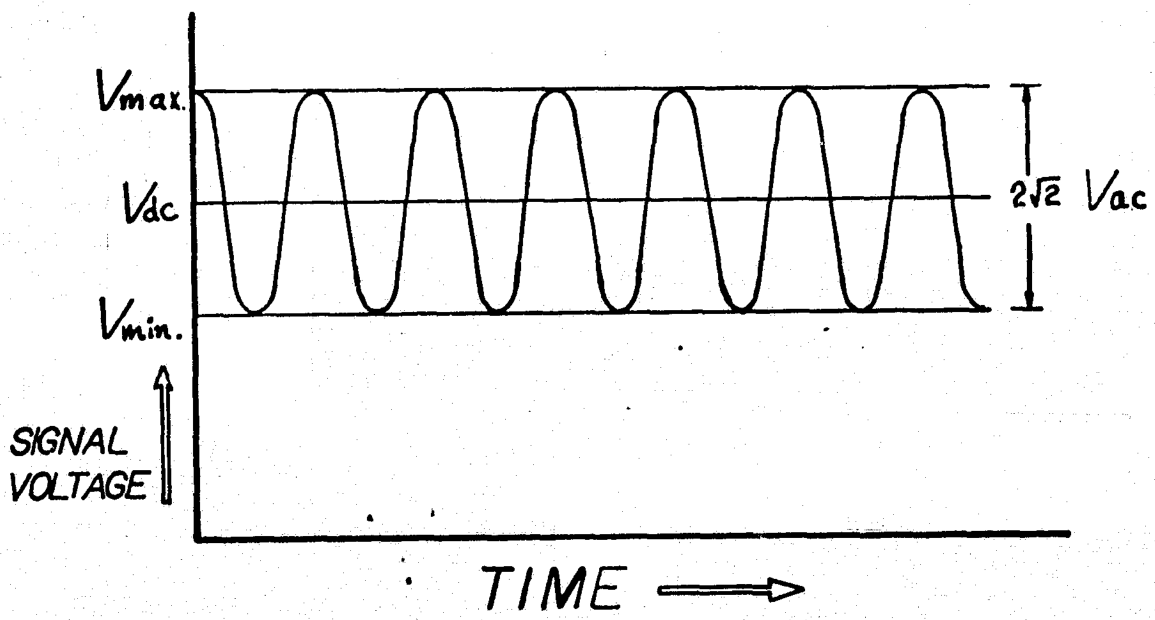
GT
RL
BS
DF
F4
D4

Fig. 1


Vmax.
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VOLTAGE
TIME

Fig. 2

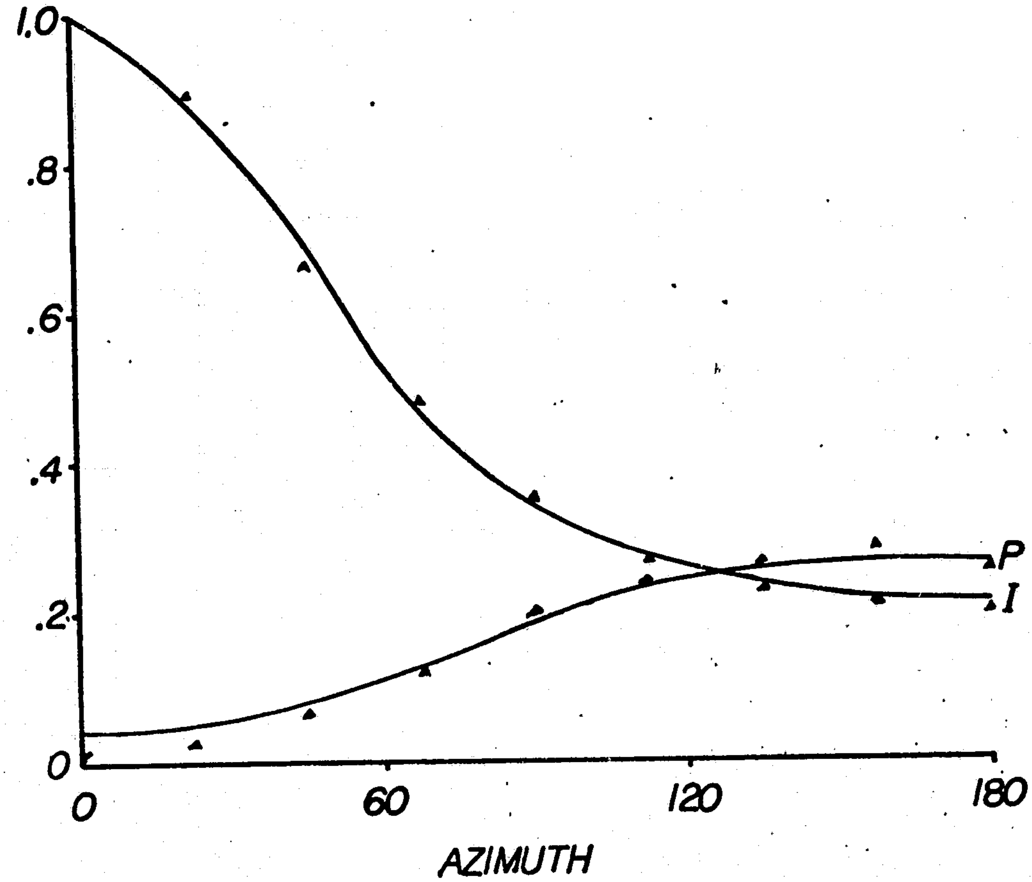

Fig. 3

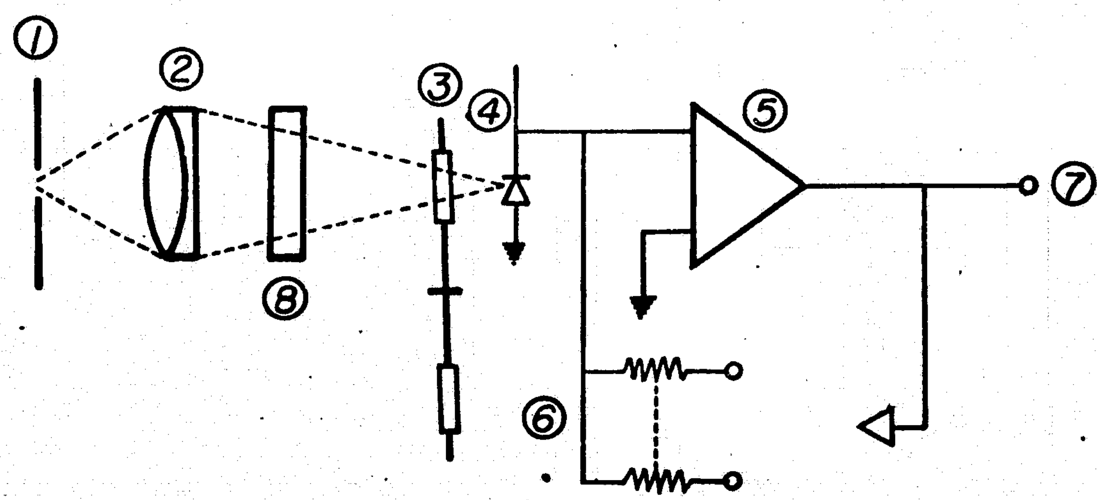

Fig. 4

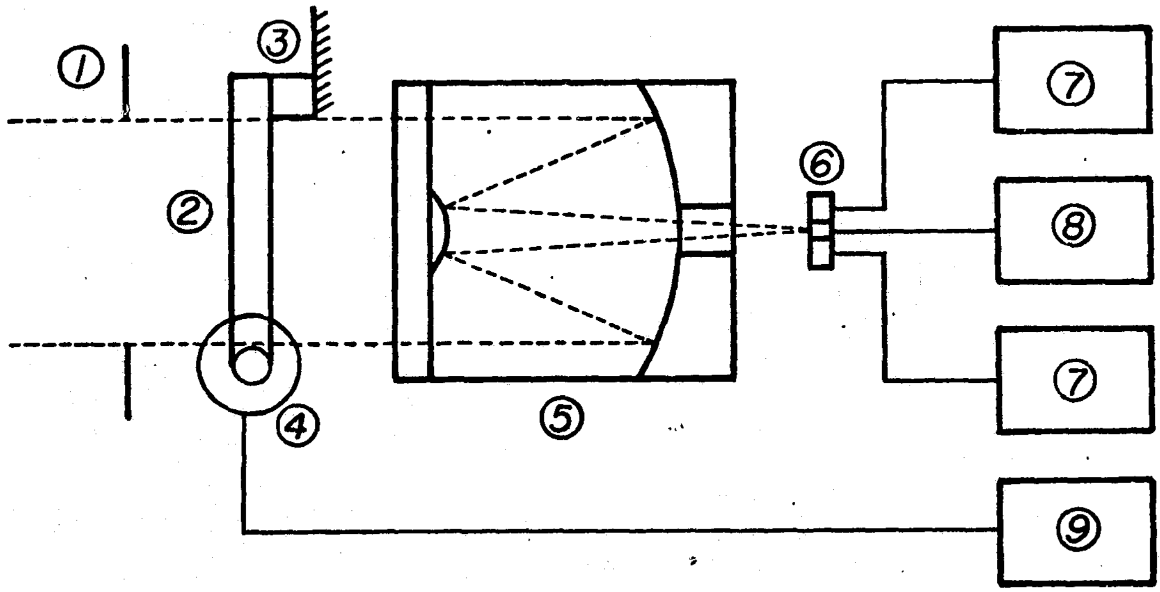

Fig. 5

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Aerosol optical parameters and the radiative fluxes during phase I of the GATE project[†]

by

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1. Introduction

Terrestrial weather and climate are a consequence of the complicated interactions and feedback mechanisms that exist between the solar radiation field and the atmosphere. It has been recognized that to piece together the mystery of climatic phenomena, simultaneous observations of all the atmospheric parameters are required and the Global Atmospheric Research Project (GARP) is an international experimental effort designed to achieve this scientific objective. The GARP Atlantic Tropical Experiment (GATE) was the most recent experiment held off the coast of Dakar, Senegal. This paper will describe a radiation experiment conducted on board the S. S. Oceanographer during phase I of this project between June 28 and July 13, 1974.

The differential heating due to solar radiation is the source of energy for atmospheric motions and hence a knowledge of the heating rates at various levels is of paramount importance. Since flux divergences can be related to heating rates the traditional experimental determination consists of the simultaneous measurements of fluxes at two different levels so as to calculate the flux divergence. The difference of the fluxes is a small quantity compared to the fluxes and, therefore, the requirements of precision and simultaneity of the flux measurements, and the identity of the instruments at the two levels impose severe restrictions on the experimental arrangement. Small errors in the flux measurement can lead to very large errors in the calculated flux divergences.

If the optical parameters of the atmospheric constituents are known then it is possible to use the theory of radiative transfer in turbid atmospheres and calculate the radiative fluxes in the atmosphere. In these theoretical calculations, irrespective of the actual state of affairs, atmospheric aerosols are abstractly represented as spherical scatterers with a uniform refractive index and their distribution in sizes described by a function n(r). The justification for this assumption rests entirely on the supposition that scattered radiation fields that occur in nature can be reconstructed using this model. Extensive observations conducted by Willson at UCLA (1975) suggests that this is indeed the case and, hence, a determination of the optical parameters of the model is an alternate, and consistent, method of calculating the radiative fluxes in the atmosphere. To digress for a moment, it is possible to conjure up situations where the scattering patterns cannot be represented in terms of our simple model and then new complications such as multimodal distributions of aerosol types, size distributions that vary with height, etc. must be introduced. Undoubtedly there is some mathematical value to such models but in the absence of experimental justification their physical content is minimal.

A prescription for interpreting ground based polarimeter measurements of the radiation field to obtain the bulk optical parameters of aerosol particles has been suggested in the literature and the experiments that have been performed at UCLA (Kuriyan 1974; Kuriyan et al. 1974a; Willson 1975) have confirmed its validity. A complementary scheme (Kuriyan et al. 1974b) of interpreting multispectral extinction measurements has remained in the theoretical domain principally due to the lack of availability of high precision radiometers.

For the GATE project, one of us (R.C.W.), used a polarimeter and a multispectral radiometer to measure the radiation field at various wavelengths. This paper will deal with the analysis of the data gathered during phase I of the project. The optical parameters that are derived are used to calculate the fluxes at the top and bottom of the atmosphere. If the vertical profile of aerosols is known or assumed then the fluxes at any intermediate level of the atmosphere can also be deduced.

The paper is arranged as follows: section 2 provides a brief explanation of the scheme used to interpret the data as well as the assumptions of the model. The experiment is described in section 3 while the derived results are given in section 4. The paper concludes with section 5 with a discussion of the implications of these results to climatic studies.

2. Explanation of the method and assumptions of the model

Chandrasekhar (1950) obtained the radiation field in a multiply scattering plane parallel molecular atmosphere and Sekera (1951, 1956, 1957), Bullrich (1964) and Rozenberg (1968) considered the effect of aerosols on skylight polarization. Van de Hulst, Herman, Dave, Hansen, Grant and Hunt, Tanaka, Twomey, Collins and Wells, Plass and Kattawar and many others have solved the general transfer problem in a turbid atmosphere. The review articles of Hunt (1971), Irvine and Lenoble (1974), Lenoble (1974), Yamamoto and Tanaka (1974) and Hansen and Travis (1975) provide an exhaustive list of references on this topic.

In most of these treatments the atmospheric aerosols are assumed to be horizontally stratified spherical Mie scatterers with a uniform refractive index. Concentrations of aerosols vary with height but other properties such as size distribution and refractive index are held constant for the column of the atmosphere. A notable exception to this is Herman's (1974) treatment of stratospheric aerosol distributions. However, in the absence of systematic investigations on the effect of such vertical variations in aerosol properties, and since the measured radiation fields can be accommodated without such variations, it seems a little premature to incorporate this additional degree of freedom in the theory.

The observations of skylight polarization by the late Professor Sekera and his students under conditions of varying turbidity led to his suggestion (Sekera 1967) that the polarimeter could probe the bulk properties of aerosol particles. Balloon borne polarimeter measurements were interpreted by Rao et al. (1973) while Coffeen (1969) and Hansen and Hovenier (1974) derived the optical properties of the haze over the cloud deck on Venus from ground based polarimeter observations of Venus. To obtain the aerosol characteristics we shall adopt the method described in Kuriyan (1974) and Kuriyan et al. (1974a) which consists of matching measurements against catalogues of radiation fields that have been compiled for the entire range of physically realizable values of the aerosol parameters. The compilation of such catalogues required an exhaustive sensitivity analysis of the various parameters as well as a judicious choice of size distribution that eliminated redundant parameters without sacrificing the generality of the description.

In our analysis we use Deirmendjian's (1969) haze H type function $n(r) = ar^2e^{-br}$ to represent the size distribution of aerosols. The parameters a and b can be varied to generate the phase matrix elements corresponding to haze L and M type (Kuriyan 1974, Kuriyan et al. 1974a). This observation was the basis for the claim that the conventional parameterization of aerosols are redundant. As pointed out elsewhere (Kuriyan 1975) these problems of non-uniqueness are generic to, and therefore, an intrinsic limitation of remote techniques. Needless to say, the choice of other size distributions such as the power law distribution will not obviate this problem. The preliminary results of our numerical studies indicates that the ground based measurements are insensitive to variations in vertical profile suggesting that this mode of operation probes the entire atmosphere. For reasons of convenience, therefore, we have adopted Elterman's (1968) aerosol profile. The index of refraction of the particulates was allowed to be complex but the poor quality of the data did not permit the determination of the small imaginary part.

3. The experiment.

The polarimeter was mounted on an alt-azimuth tracker that had angular read out scales in both azimuth and elevation and this enabled the precise orientation of the polarimeter. For each set of measurements the polarimeter scans the sky along a cone with the local vertical as its axis and the observation zenith angle as its vertex angle. The azimuth angle is measured with respect to the solar vertical plane. The measurements were made at two wavelengths 0.7 μm and 0.575 μm and at various zenith angles of observations. Cloud scattering causes a great deal of polarization and, therefore, it was essential that the field of view of the polarimeter be free of clouds. This was rare during phase I of the GATE project and limited the amount of data that could be gathered.

Lambert-Beer's law $I = I_o e^{-\tau/\mu}$ can be used to derive the extinction optical depth τ provided the extra-terrestrial intensity I_o can be determined. From the radiometer measurements of I at two positions of the sun zenith angle it is possible to solve for I_o. The implicit assumption is that the aerosol characteristics have remained the same during the two measurements. In the absence of an actual extra-terrestrial measurement with the same instrument this is perhaps the best determination of I_o.

Due to the lateness of entry of our experiment in the GATE project it was not possible to obtain a stable platform for our instruments. Pointing errors due to the rolling of the boat were particularly serious to the extinction measurements. A bore sighted pin hole and image system was used to point the instrument at the sun and the voltage readings were frozen momentarily and the data recorded manually.

4. Results.

The radiometric measurements yielded a value of the optical depth of aerosols that greatly facilitated our search for a fit of the polarimeter data. For the entire set of data we assumed a ground reflectivity of A = 0.02. As we have noted elsewhere (Kuriyan et al. 1974a) in the measurement of downwelling radiation the reflectivity of the ground plays only a minor role and this value of A can be viewed as a calibration of the reflectivity of the ground. The derived aerosol parameters are displayed in Table I. The parameter b is related to the modal radius r_c by $b = \frac{2}{r_c}$. The errors in the determination of the various parameters are estimated to be $\Delta b = \pm 2$, $\Delta m = \pm .02$, $\Delta\tau$ (polarimeter) $= \pm .03$, $\Delta\tau$ (radiometer) $= \pm .03$. The large errors can be traced to the lack of a stable platform and the associated difficulties in pointing. Table I also provides the downward flux at the ground level $F_\downarrow$(ground) for π units of solar flux at the top of the atmosphere, the upward flux at the top of the atmosphere $F_\uparrow$ (top) and the monochromatic local albedo for the whole atmosphere $\frac{F_\uparrow \text{(top)}}{F_\downarrow \text{(top)}}$.

Eventhough the derived parameters are shown to have a real index of refraction most of the data are consistent with an imaginary part of about 0.02. In order to appreciate the effect on the albedo of the inclusion of aerosols we have also given in Table I the albedo for a dust free atmosphere (Rayleigh).

5. Conclusions.

The experimental set up left a lot to be desired and so only about half the data gathered was of sufficient quality to yield the equivalent aerosol optical parameters. The error bars were considerably larger than those from ground based measurements at UCLA. In spite of this the calculated flux divergences are at least as reliable as those obtained from the direct measurements of fluxes at two heights. This statement is predicated on the fact that the direct measurements

Table I

Date	Time UT	λ µm	aerosol optical depth: Radiometer	aerosol optical depth: Polarimeter	b	m	Fluxes: $F_{\downarrow}$ (ground)	Fluxes: $F_{\uparrow}$ (top)	Local Albedo $\frac{F_{\uparrow}(top)}{F_{\downarrow}(top)}$: Turbid	Local Albedo $\frac{F_{\uparrow}(top)}{F_{\downarrow}(top)}$: Rayleigh
7/5	11:15	.7	.09	.15	25	1.44	2.271	.117	.049	.022
		.575	.11	.15	25	1.44	2.21	.175	.073	.047
	12:15	.7	.07	.05	18	1.44	2.788	0.07	.024	.018
7/6	12:30	.7	.24	.25	18	1.44	2.821	.126	.043	.018
		.575	*	.25	18	1.44	2.752	0.194	.066	.040
	18:17	.7	.37	.37	18	1.44	.803	.239	.223	.042
7/9	13:50	.575	.16	.15	18	1.44	2.877	.165	.054	.038
	14:55	.7	.12	.15	18	1.44	2.847	.098	.033	.018
7/10	12:35	.7	.57	.6	18	1.56	2.683	.258	.087	.018
		.575	.67	.7	25	1.54	2.567	.366	.124	.039
7/11	15:00	.575	.25	.25	18	1.44	2.661	.195	.068	.040
7/12	9:06	.7	.14	.15	18	1.54	.898	.144	.134	.042

*Not available.

require an identity of experimental arrangements as well as a simultaneity of measurements. In most cases the results obtained from one wavelength matched those from another and this multispectral verification was a check on the consistency of the approach. It may be argued that in situ methods would yield the aerosol optical parameters without ambiguity and in a direct fashion. Such cavalier statements do not withstand a careful scrutiny of the assumptions underlying the in situ methods. The meticulous investigations of Hänel (1972a,b) in Bullrich's group stresses the crucial importance of relative humidity to in situ experiments. Their model calculations show that the optically important layers in the atmosphere are often those regions where the relative humidity is in excess of 80% and then, a determination of the size becomes possible only when the relative humidity can be measured with high precision. Thus, in situ methods will yield a reasonable representation of the actual state of affairs if the sampling is performed in the optically important layers where the precise value of the relative humidity is known. In view of the large errors that can be caused due to a bad choice of sample or improper techniques it is imperative that a consistency check be incorporated in such experiments. One such check on its consistency would be to calculate the fluxes using the derived parameters and to compare them against measured fluxes. A careful experiment of this nature is being undertaken at Mainz by Bullrich.

The difficulty in incorporating the radiative effects of aerosols has resulted in their omission in the numerical models of atmospheric circulations. Recent studies by Kondratyev (1972, 1973), Yamamoto and Tanaka (1972, 1974), Bullrich (1974), Eiden and Eschelbach (1973), Dave and Braslau (1973), Rasool and Schneider (1971), Grassl (1974), and Herman (1974) have stressed the influence of aerosols to the heat budget in the atmosphere. Quantitatively speaking the effect of the visible radiation interacting with the atmospheric particulates are of the same order of magnitude as the solar infrared radiation interacting with the atmospheric molecular (H_2O, CO_2) constituents. The circulation model calculations have included the effect of the latter while the former has been ignored. While general discussions of aerosol effects are (Landsberg 1970, Singer 1970, Wilson et al. 1971) available in the literature there is clearly a need for a numerical study on the climatic effects of aerosols on circulation patterns. If there is an observable effect, then it will be necessary to determine the effective optical parameters of atmospheric particulates and their global distribution. A network of ground based polarimeter stations or a satellite borne instrument as envisaged in AIRSAT could provide this information.

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