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PROCEEDINGS OF THE INTERDISCIPLINARY WORKSHOP ON VERTICAL RADIOMETRIC PROBING

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INTRODUCTION

On the 23rd and 24th of April 1965 an Interdisciplinary Workshop on Vertical Radiometric Probing was held at the GCA Corporation's facility at Bedford, Massachusetts. The participants, chosen by invitation, spanned the spectrum of scientists active in the field of electromagnetic sensing of the atmosphere by satellite.

The Workshop, jointly sponsored by the GCA Corporation and the NASA Goddard Space Flight Center, was convened to expose workers in satellite radiometry with inversion techniques which have recently proved successful in inferring atmospheric thermal structure from remotely sensed infrared observations. Since all radiometric structural inferences involve an inversion of data, the application of these techniques to spectral regions other than the far infrared was to be explored. Thus the theme of the Workshop was the development and application of methods designed to maximize atmospheric structural inferences from passive electromagnetic sensing by a satellite.

That the Workshop attained its immediate goal is attested by the lively and stimulating discussions in the pages to follow. That the long range results are controversial is perhaps appropriate to this exciting and still unplumbed field of satellite radiometry.

PARTICIPANTS

Mr. William Bandeen	National Aeronautics Space Administration/ Goddard Space Flight Center
Professor Alan Barrett	Massachusetts Institute of Technology
Dr. Kinsell Coulson	General Electric Space Sciences Laboratory
Dr. Jitendra Dave	National Center for Atmospheric Research
Dr. Diran Deirmendjian	RAND Corporation
Dr. S. Roland Drayson	University of Michigan
Dr. Edwin T. Florance	GCA Corporation
Mr. B. Richard Fow	Massachusetts Institute of Technology
Dr. Robert Fraser	Space Technology Laboratory
Dr. Rudolf Hanel	National Aeronautics Space Administration/ Goddard Space Flight Center
Dr. Frederick B. House	GCA Corporation
Dr. Jean I. F. King	GCA Corporation
Dr. Virgil Kunde	National Aeronautics Space Administration/ Goddard Space Flight Center
Mr. William B. Lenoir	Massachusetts Institute of Technology
Dr. M. Linton Meeks	M.I.T., Lincoln Laboratory
Dr. William Nordberg	National Aeronautics Space Administration/ Goddard Space Flight Center
Dr. George Ohring	GCA Corporation
Dr. Robert Samuelson	National Aeronautics Space Administration/ Goddard Space Flight Center
Professor Zdenek Sekera	University of California, Los Angeles
Dr. David Staelin	Massachusetts Institute of Technology
Dr. Sean Twomey	U.S. Naval Research Laboratory
Dr. Russell Walker	Air Force Cambridge Research Laboratories
Dr. David Q. Wark	United States Weather Bureau/ National Weather Satellite Center

OPENING REMARKS

Dr. William Nordberg of NASA Goddard Space Flight Center opened the Workshop by stressing that substantial progress has been made on the theoretical problem of inverting radiance data to obtain vertical atmospheric structure. He mentioned specifically the work of Dr. Jean King of GCA Corporation and Dr. David Wark of the United States Weather Bureau, who have satisfactorily inferred temperature profiles from infrared radiance measurements, thus disproving the critics who said "it couldn't be done." On the instrumentation side infrared hardware of good spectral resolution and accuracy is presently available, said Dr. Nordberg. He also noted that similar progress in the visible region of the spectrum has not been as noticeable.

According to Dr. Nordberg, one purpose of the Workshop was to bring together workers in the microwave, ultraviolet and visible, and infrared regions of the spectrum. These specialists could then attempt to clarify future progress in satellite probing of the atmosphere in their respective spectral intervals. In view of the successful solution of the inversion problem in the IR, Dr. Nordberg suggested that inversion would provide a challenge to other regions of the spectrum which would tend to unify different approaches to radiometric probing.

LINEAR INVERSION METHODS

Dr. David Wark of the Weather Bureau, National Weather Satellite Center reported the results of his work on the inversion problem. He discussed the assumptions which have to be made to reduce the transfer equation for the emitted thermal radiation to a linear integral equation of the first kind. Frequency variation of the Planck function B over the 15 micron carbon dioxide band was accounted for by linear interpolation about a reference frequency. Transmittances for six spectrometer openings of width 5 wavenumbers were calculated. The transmittance depends weakly on the vertical temperature distribution, but Dr. Wark noted that errors in the transmittance produced controllable changes in the inferred thermal profile.

The inversion problem, as stated by Dr. Wark, consisted of the inference of a continuous function $f(x)$ from the integral equation

$$g(y) = \int K(x,y)\ f(x)\ dx$$

when only six or possibly seven values of g are known. The weighting function or kernel K, when plotted against the variable log p, showed considerable overlapping for different spectrometer channels. Dr. Wark indicated how weighted temperatures could be defined for each channel, but that such effective temperatures were not of meteorological interest, because of the amount of overlapping.

The effect of noise in the measurements limits the number of usable channels which can resolve the thermal structure of the atmosphere, said Dr. Wark. He pointed out that mathematically speaking the matrix used in his inversion method was ill-conditioned and hence the solution vector was extremely sensitive to errors in the raw data. This instability of linear inversion could be overcome by employing the minimization methods of Phillips and Twomey [1,2]*. Dr. Wark briefly described the end result of this smoothing technique and how the smoothing parameter γ was selected. He showed that γ could be fixed rather unambiguously by plotting a quantity measuring the error in the inferred temperature profile versus γ.

Dr. Wark also reported on his group's attempt to fit the temperature profile with empirical functions. These functions are derived from a set of temperature soundings by a least-squares procedure. The higher order empirical functions, which measure deviations of the profile from the mean, had been giving trouble in the inversion method, according to Dr. Wark.

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*Numbers in [ ] throughout the text indicate reference numbers.

Dr. Wark presented his inferred thermal profiles from data taken on the 11 September 1964 balloon flight at Palestine, Texas [3]. He also showed an inferred profile from less satisfactory data gathered on a flight over Sioux Falls, South Dakota on 10 March 1965.

Dr. W. Nordberg remarked on the good results obtained by his group when mapping the mean temperature of the lower stratosphere based on data from the 15 micron channel of TIROS VII [4].

Dr. D. Deirmendjian (RAND) asked if stratospheric temperatures could be inferred satisfactorily by the linear inversion technique or if more structure than the standard atmosphere could be discerned from the data. He also inquired about the propagation of *a priori* knowledge about the temperature sounding into the inferred profile. Dr. Wark replied that no inferences could be made for pressures less than 10 millibars because the weighting functions employed in IR measurements "run out of information" there. He emphasized that the linear technique could infer more information than the climatological pressure and temperature of the tropopause but admitted that the pressure points of discontinuity were selected with the actual sounding in mind because the linear method was still in the initial stages of development. He indicated that in the future the data would be processed "more blindly" before the inferred profile was plotted against the actual sounding. This sort of "blind" processing had to be done when clouds were present on the Palestine flight.

Dr. J. Dave (NCAR) asked if the presence of water vapor would affect measurements in the 15 micron carbon dioxide band. Several participants confirmed that water vapor was negligible even at 709 wavenumbers.

NONLINEAR INVERSION METHODS

Dr. Jean King of the GCA Technology Division presented the results of his nonlinear inversion algorithm applied to the Palestine balloon flight data. He described how, by assuming an exponential-type model for the transmittances of five spectrometer channels (the Q branch was not used), the inversion problem simplifies to the inversion of a Laplace transform. With the assumption that the Planck function can be represented by three isothermal slabs or ramps of varying thickness, the problem reduces to the solution of nonlinear algebraic equations [5]. Dr. King then showed that this set of moment equations is uniquely solvable by Prony's algorithm if the effective channel absorption coefficients are chosen according to a prescribed formula.

The central difficulty in the inversion problem, according to Dr. King, is the response of the inferred profile to noise in the data. To test the sensitivity of the nonlinear algorithm to noise, it was applied to a model atmosphere of simple analytic form with random errors added to the moments. Dr. King showed the results of this test; he found that the Prony algorithm responds to noise by giving roots of the Prony polynomial which correspond to nonphysical slab boundaries. These inadmissible roots, however, carry with them Gaussian-Christoffel weights that are very small compared to the weights of admissible roots. Since a Gaussian weight corresponds physically to the jump in the Planck function at the associated slab boundary, Dr. King stressed the fact that the slab profile derived from the admissible roots alone was still a satisfactory representation of the continuous profile. He also indicated that the nonlinear algorithm was able to extract all of the essential information in the data, while rejecting the noise.

Dr. King then showed his inferred temperature profiles based on the Palestine balloon flight data [6]. He pointed out that the disagreement of the inferred pressure and temperature of the tropopause with the sounding might be due to the rather crude transmittance model he had used. He showed that the choice of initial boundary conditions did not strongly affect the inferred thermal profile. A particularly pleasing result of the nonlinear inversion algorithm, according to Dr. King, was the inference of cloud-top pressure and temperature from the noonday radiance data. He indicated that this success was encouraging, and that the prospect of inferring atmospheric cloudiness from meteorological satellite observations in the IR may be eventually realized.

Dr. D. Wark inquired whether the nonlinear algorithm could extract additional information if more data points were supplied. He also asked if the assumption of an exponential form for the transmittance were not limiting. Dr. King replied that the limits of the nonlinear algorithm had not yet been determined.

Dr. S. Twomey (NRL) commented that Yamamoto had run into trouble when he tried to fit empirical transmittances to a sum of exponentials [7]. Yamamoto abandoned the attempt when he got bad roots of the Prony polynomial.

Professor Z. Sekera (UCLA) asked about the presence and effect of aerosols on the IR measurements. He was assured that very clear conditions prevailed during the Palestine flight, and that one would not expect much effect. Dr. K. Coulson (G.E.) remarked that W. E. Marlatt [8] presented results at the Washington A.G.U. meeting which showed the comparison between surface temperatures measured with thermistors and the Barnes radiometer. Marlatt found only 1 degree K discrepancy under clear conditions, but noted a discrepancy of 12 degrees when aerosols were present.

Dr. Fred House of GCA Technology Division next summarized the nonlinear inference of temperature profiles from Adel's ozone emission data at 9.6 microns. He attempted to infer three ramps by interpolating the data to five integral values of the secant of zenith angle. It was found that only two ramps could be inferred, leading to the conclusion that the data could not be pushed further. Dr. House concluded that the nonlinear algorithm could deduce meaningful information from quite noisy data, since inferred parameters such as total ozone optical depth and mean stratospheric temperature were in rough agreement with expected values.

An example was shown to indicate the effect of uncritical smoothing on the nonlinear algorithm. Dr. House warned that smoothing applied carelessly to the data could lead to incorrect and unphysical results.

Dr. W. Nordberg asked if interpolation was not in fact a type of smoothing. Dr. King replied that "smoothing is a more violent procedure" than the interpolation which is necessary in application of the Prony algorithm.

Dr. D. Wark remarked that one data point in Figure 4 of Reference 6 seemed to correspond to 688 wavenumbers, where a faint Q branch was avoided in choosing spectrometer channels. He asked if the presence of the Q branch would invalidate that point. Dr. E. Florance (GCA Corporation) replied that the point in question did not correspond to a particular frequency, but was simply a way of representing the data in terms of exponential transmittances. If other channels were chosen, he said, the required point might not appear equivalent to 688 wavenumbers.

PASSIVE MICROWAVE RADIOMETRY

Dr. M. L. Meeks of Lincoln Laboratory reported on his work in collaboration with Richard Fow of M.I.T. concerning the inversion problem in the microwave region of the spectrum [9]. As an illustration of the effect of the atmosphere on the oxygen spectrum, Dr. Meeks showed that the shape of individual lines is strongly dependent on height. Because of the high frequency resolution of microwave radiometers, one uses a monochromatic absorption coefficient which, Dr. Meeks emphasized, is not a weak function of the temperature profile to be inferred. The absorption coefficient was calculated using the van Vleck-Weisskopf line shape. The strong dependence of transmittance on temperature in the microwave region contrasts with weak dependence in the IR. From the observed antenna temperature at several different frequencies, the thermal profile in the atmosphere T(h) can be inferred by iterative solution of a nonlinear integral equation.

The inversion problem was studied by simulating the emission from a 1962 standard atmosphere. Dr. Meeks said that a set of five weighting functions was chosen with the least amount of overlapping, while still eliminating any emission from the ground. The inferred T(h) was expressed as a polynomial; with this choice, divergent results were obtained until boundary conditions were imposed at the ground and the maximum altitude. Dr. Meeks showed that the resulting solutions were not too sensitive to the boundary conditions except where the weighting functions were practically negligible.

The effects of noise were simulated by adding random errors appropriate to antenna noise temperature of 1500 degrees, 3000 degrees, and 5000 degrees K. The results, according to Dr. Meeks, indicated that the rms temperature deviations in the output are proportional to the antenna noise temperature. He concluded that this proportionality implied stability of the inversion problem.

Dr. Meeks then discussed the choice of observing frequencies in terms of the peak height and half-width of the appropriate weighting functions. He showed by plotting peak heights over the oxygen spectrum that the logical choice of frequency for broad bandwidth corresponds to minimum peak height between lines. In order to probe the lower atmosphere one may use a bandwidth of 200-300 megacycles. The weighting function with a peak height around 30 kilometers would require a bandwidth of 10-20 megacycles.

Dr. S. Twomey asked whether the nonlinear form of the integral equation for T(h) leads to systematic error in the iterated solution. Dr. Meeks answered that they had compared a polynomial fit to the standard atmosphere with the inferred polynomial profile from inversion and that the comparison was satisfactory.

Dr. D. Wark commented that he had tried to impose boundary conditions on the temperature profile, but discovered the solution was "like a snake". He traced this difference to the strongly overlapping kernels which he had to employ. Dr. Twomey then noted that the widely separated kernels used in the microwave study should lead to more stability in the solution and inquired whether these kernels could be realized physically. Dr. Meeks replied that the kernels could be realized subject to the requirements on instrument bandwidth which he had discussed.

Dr. W. Nordberg asked if the assumed antenna temperatures were typical of those found in practice. Professor A. Barrett (M.I.T.) replied that actual noise temperatures were in the vicinity of 20,000 degrees K.

William Lenoir of M.I.T. described his work on the Zeeman splitting of oxygen lines. He showed that the line shape depends on latitude and on the state of polarization of the observed radiation. At the magnetic equator he found a weighting function with a peak height of 72 kilometers and width of 20-25 kilometers by assuming a 1.5 megacycle bandwidth filter; inferred rms accuracy of about 5 degrees K could be obtained with this weighting function. Over the magnetic pole the situation changes; only circularly polarized components are observable. If one can separate right from left circular modes, then the appropriate weighting function has peak height 60 kilometers and width 30-35 kilometers, he said.

Dr. W. Nordberg remarked that if one could get a temperature measurement at 72 kilometers with 5 degrees K accuracy, this information would be very useful to geophysical theories of mesospheric heating. At high latitudes inversion would seem impossible if no better than 25 degrees K accuracy could be had. Professor A. Barrett suggested that uncertainty in the temperature profile be reduced by running up the integration time.

Dr. R. Hanel (NASA/GSFC) wondered about meaningful temperature inferences at altitudes of 65-70 kilometers since local thermodynamic equilibrium does not hold there in the infrared region. Professor A. Barrett replied that thermodynamic equilibrium was not a problem, since the spontaneous emission term in the microwave region was very small because of its cubic dependence on frequency.

Dr. David Staelin (M.I.T.) presented the results of his attempt to invert data on the absorption spectrum of water vapor. Using a 5 channel radiometer centered around 1 centimeter wavelength, he measured the attenuation of the solar flux as the sun was setting and simultaneously measured water vapor content with a radiosonde. Dr. Staelin pointed out that observed attenuation was greater than expected from theory using the radiosonde data, possibly because of the hygristor's failure to measure water vapor at high altitudes.

To infer the vertical distribution of water vapor from the measured optical depth Dr. Staelin broke the atmosphere into two 6 kilometer blocks to give mean tropospheric and stratospheric contents. He reported that an error of 10 degrees K in the atmospheric temperature would generate less than 3 percent error in optical depth. He also discussed the problem of detecting integrated cloud density with a microwave radiometer. By selecting two frequencies with equivalent weighting functions in water vapor, one could determine the cloud density by its differential effect on both channels. Dr. Staelin suggested that in this way clouds could be detected from a satellite.

William Lenoir (M.I.T.) summarized an inversion of the 9^+ oxygen line emission as measured from a balloon. By observing with antennas fixed at 60 and 75 degrees from the zenith and at frequencies of 20, 60, and 200 megacycles from the line center, he obtained six data points from which six isothermal slabs were inferred. The weighting functions in this case were all of exponential type. The results were not too satisfactory, and Lenoir thought that the assumption of a van Vleck-Weisskopf line shape was in error. This assumption, he believed, could be tested in the laboratory or possibly deduced from emission data if T(h) were known.

Dr. S. Drayson (U. of Michigan) commented that a group in England working around 300 microns found more absorption than was predicted by the van Vleck-Weisskopf line shape. Lenoir added that the difficulty arose mainly in the wings of a line and that for that reason measurements at the line center were preferable. Dr. W. Nordberg remarked that it seemed the inversion problem was a less serious difficulty than the question of proper line shape.

Professor A. Barrett added that in the microwave region one has to know the constants of a single line. In the infrared one averages over several lines and the details of the transmittance are not too important. Professor Barrett emphasized that the van Vleck-Weisskopf line shape is suspect for microwave frequencies, but that a new line shape theory developed by Soviet workers [10] seems to remove most of the discrepancy with experiment. He concluded that he had grave doubts about any inversion results with the present state of knowledge of the oxygen line.

RAYLEIGH AND MIE SCATTERING

Professor Zdenek Sekera of UCLA reported on the state-of-the-art in scattering theory with particular emphasis on the inference of meteorological parameters. He stressed the much greater mathematical difficulty in analysing the visible and ultraviolet measurements than was the case with emission data.

According to Professor Sekera, the analysis of Rayleigh scattering yields the total Rayleigh optical depth of the atmosphere and thereby the ground pressure. Similar treatment of non-Rayleigh scattering would lead to an inferred aerosol concentration as a function of optical depth. If one could measure the effects of absorption, one would be able to infer the mixing ratio of ozone. The reflection of sunlight from the ground gives no meteorological information, but Professor Sekera indicated that ground reflection is nevertheless an important element in theory and observation.

As an illustration of possible inferences, Professor Sekera discussed the case of pure Rayleigh scattering [11,12]. He indicated the problem of possible inferences from measuring the intensity and polarization of either down-going or up-welling radiation. Measurement of the neutral points, which are insensitive to reflectance from the ground, gives immediately the total optical depth and hence the pressure at the ground. The maximum amount of polarization then enables one to calculate the effect of ground reflection.

With absorption one has the possibility of inferring the mixing ratio of ozone by inversion of a Laplace transform. Professor Sekera noted that if one knew the dependence of optical depth on pressure, one could invert the observed X-function to find the height distribution of ozone [13].

Professor Sekera continued his discussion by considering non-Rayleigh scattering by aerosol distributions. He remarked that the results of studies assuming different size and vertical distributions of aerosols had demonstrated the insensitivity of measured intensities to these distributions. In the Mie scattering region one has to deal with the strong forward diffraction peak in the scattering function and its effect on multiple scattering. Professor Sekera showed that expansion of the scattering function in Legendre polynomials was an inefficient way to handle the problem. He indicated that the forward peak must be treated separately in the scattering problem.

The state-of-the-art includes the finding that aerosol scattering is very important in the visible and near IR. Professor Sekera described a theoretical model in which a turbid layer is introduced on either the bottom or top of a Rayleigh atmosphere [14]. The calculated results of this model on the position of the neutral points agreed quite well with observed displacement of neutral points in the presence of a low turbid layer or a stratospheric dust layer of volcanic origin. Upper turbidity shows greater polarization in the blue than in the red.

Professor Sekera stressed that a comparison of theoretical and experimental results is sufficient to give one information about non-Rayleigh scattering; in particular one could detect the presence and location of turbid layers in the atmosphere.

Dr. D. Staelin wondered if an intermediate turbid layer could be distinguished from the simultaneous occurrence of an upper and lower layer. Professor Sekera replied that the wavelength dependence of the polarization should enable one to make the distinction. Dr. D. Deirmendjian explained the difference between upper and lower turbid layers by pointing out that the polarization depends on whether non-Rayleigh scattering occurs before or after Rayleigh scattering.

Dr. D. Wark asked if the size distribution of aerosols in upper and lower layers were not expected to be different. Professor Sekera affirmed that when the distributions of both layers were assumed to be the same, the results for the upper layer did not agree as well with observations.

Dr. W. Nordberg inquired about the possibility of inferring size and vertical distribution of aerosol particles. Professor Sekera thought this could be done, but the appropriate expressions had not been evaluated yet. He suggested that a search be undertaken for sky positions where the effects of aerosols would be most noticeable. Dr. K. Coulson said that there is a real question of how to interpret the large observed variation in polarization across the sky. This variation has not yet been explained satisfactorily, but may contain much valuable information.

Dr. D. Wark remarked that the non-Rayleigh scatterers of interest were not Mie scatterers, and he gave ice particles as an example. Professor Sekera stated that the small dependence of calculated results on the size or shape of the scatterers had been surprising, but that this insensitivity was doubtless due to the fact that the forward peak is predominantly a diffraction effect. He also thought that stratospheric ice particles would be in frozen drop form.

Dr. D. Staelin wondered if one could get better inferences by measuring all four polarization parameters. Professor Sekera agreed that it would be better to measure all the parameters which occur in the theory.

Dr. R. Hanel asked how cloud particles might affect IR inversion methods. Dr. D. Deirmendjian replied that effects of aerosols may persist down to 20 microns, but that Rayleigh scattering would be negligible.

Dr. Robert Fraser of Space Technology Laboratory reported on his study of the effects of Lambert and Fresnel laws on the ground reflection problem. He showed clearly that looking from the bottom or top of the atmosphere was essentially the same. He found that Lambert and Fresnel reflection could be distinguished only for small total optical thickness.

Dr. Kinsell Coulson of General Electric Space Sciences Laboratory described the results of his experiments on the reflectance of natural surfaces. Measured polarization curves for artificial clay surfaces show a strong similarity to curves for a Rayleigh atmosphere. The neutral points are noted to shift with wavelength. Dr. Coulson also showed polarization curves computed for a Rayleigh atmosphere on top of a plane clay surface. Except near the limb, only the effect of direct reflection is important [15].

Dr. Robert Samuelson of NASA Goddard Space Flight Center discussed the effects of scattering on emitted radiation from clouds. He calculated limb-darkening curves at 8.5 and 11.2 microns for clouds of varying optical thickness by solving the radiative transfer equation with the method of discrete ordinates [16,17]. Dr. Samuelson's results show that the forward scattering peak tends to increase the emissivity of the cloud, i.e., make it "blacker". For a cloud top pressure of 950 millibars the limb-darkening curve is not appreciably affected by scattering, but for a cloud at 417 millibars, scattering causes a strong limb-darkening.

Dr. R. Fraser wondered if this was the first time that scattering had been taken into account for cloud emission. Dr. Samuelson replied that previous work had been confined to a two stream model. Dr. D. Deirmendjian remarked that the limb-darkening curves reminded him of the Venus curves of Murray, Wildey and Westphal [18].

Dr. J. King brought up the question of separating the effects of thermal emission and scattering on the limb-darkening curve. Dr. D. Staelin asked if polarization measurements could be used to detect scattering effects alone. Dr. Samuelson answered that the polarization would be too small to measure.

Dr. D. Wark noted that a statistical study of TIROS limb-darkening data demonstrated essentially the same curves at all latitudes. The similarity of limb-darkening curves was noted by Dr. Russell Walker (AFCRL), who mentioned the fact that only very near the limb could one notice a difference. Mr. W. Bandeen (NASA/GSFC) remarked that the statistical treatment of TIROS data had indicated a stronger limb-darkening than predicted by theory [19]. Professor Sekera noted that the assumption of a plane parallel atmosphere was not a good approximation in this situation and that the sphericity of the earth should be taken into account.

Dr. W. Nordberg asked how the presence of clouds with scattering taken into consideration would affect outgoing radiation. Dr. Samuelson replied that for clouds around 900 millibars scattering could be treated as absorption and reemission, thus modelling the cloud as a grey slab. However, for clouds near 417 millibars, the scattered intensity is greater than predicted by a grey body assumption.

Dr. J. Dave of the National Center for Atmospheric Research presented his recent work on multiple-scattering theory applied to the inference of atmospheric ozone from Umkehr measurements [21]. He stated that by iterating the auxiliary equation instead of using X and Y functions, one obtains physically reasonable results [20]. Dr. Dave showed that the geometric series approximation is bad about solar zenith angles of 90 degrees where the Umkehr method is giving one considerable information. He noted the effect of ozone distributions of widely different type on the multiple-scattering correction was not easy to interpret. However, application of the Umkehr measurements with the new corrections gave much closer agreement with the ozone distribution predicted by the photochemical theory.

Dr. Dave noted that the problems associated with satellite observations of the vertical ozone distribution were somewhat worse than those involved in Umkehr measurements. But he thought that it was time to begin thinking about instrumentation for satellite ozone inferences. Dr. Dave felt the variable slab method might be applied to Umkehr measurements, since the absorption coefficient in the ultraviolet was a smooth function of wavelength and appropriate wavelengths could be selected to satisfy the data requirements of the nonlinear algorithm. He was not sure that sufficient accuracy was possible to infer a double ozone maximum.

Dr. J. King said that inversion is an error analysis problem; if one has only two place accuracy, it is possible to infer no more than two ramps. Dr. S. Twomey noted that Mateer [22] had found only four basic patterns from world Umkehr data, which would seem to show that only four coefficients can describe the vertical ozone profile.

Dr. D. Staelin said the big problem here seemed to be the vertical distribution of scatterers. He asked if laser radar would be useful. Dr. D. Wark replied that a satellite would be so far away from scatterers that insufficient power would be returned. Dr. D. Deirmendjian remarked that laser backscatter is so complicated that one can only hope to extract certain kinds of information from the weak return. Microwave radar returns contain more information because of the longer wavelength. Dr. W. Nordberg said in summary that a laser is most useful for ranging, but that it is difficult to separate the effects of aerosol size and concentration in the returned signal.

GENERAL DISCUSSION

Dr. W. Nordberg opened the discussion session by emphasizing two points: (1) the results of emission measurements show promise that inversion will be successful; and (2) the only apparent application of inversion in the short wavelength scattering problem is the inference of vertical ozone distribution by Umkehr or satellite [23] measurements. The development of a good inversion method is not an immediate problem at short wavelengths, Dr. Nordberg remarked, since only semi-quantitative application of theory has been made so far. He stated that the problem of backscattered radiation is now in a similar position of resolution to that of infrared measurements circa several years ago. The remark was intended not to discourage work on inversion, but to point up present necessities.

Professor Z. Sekera again stressed the importance of aerosol scattering in the abosrption band of water vapor. He said that the effects of aerosols might be significant to studies of atmospheric heat balance. Dr. J. Dave thought that means should be developed to instrument future satellites in order to check the effect of aerosols on absorption measurements. Dr. Nordberg questioned whether a good mathematical inversion method could be overthrown when scattering corrections were included. He was assured by Dr. D. Wark that scattering corrections would not be an essential change in the linear inversion method since a day's data could be processed in about 10 minutes of computer time.

Dr. Nordberg indicated that he would like to see all the inversion methods which had been proposed working on the same problem with the same amount of a priori information. He also raised the question of tolerable error in the data: what resolution would be necessary to infer given vertical structure. It seemed that in both the infrared and microwave regions the resolution was fixed more or less by experimental considerations. Dr. S. Twomey stated that there was a close connection between the accuracy of data and the number of independent parameters which could be inferred.

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