Airborne measurements of European atmospheric scattering coefficients

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Abstract

A discussion of a series of airborne measurements of atmospheric optical properties in Europe. Visible spectrum measurements made using an instrumented C-130 aircraft between 0.5 and approximately 6 km above ground level are described with respect to experimental procedures, results and application of the data to the determination of atmospheric contrast transmission. Data locations are illustrated as are the primary radiometer systems utilized to make the measurements. Sample data from flights conducted during 1976 and 1977 are presented illustrating irradiance levels beneath scattered to broken cloud decks, and total volume scattering coefficient variations as a function of altitude above ground level. Comparisons between scattering coefficient and relative humidity profiles are illustrated and the data base availability is reviewed.

Introduction

The Visibility Laboratory, a sub-division of Scripps Institution of Oceanography at the University of California, San Diego, has for a good number of years conducted an airborne measurement program in cooperation with and under the sponsorship of the Air Force Geophysics Laboratory. This jointly conducted experimental program has for the most part, been directed toward developing a body of data suitable for applications requiring the determination of visible spectrum contrast transmittance through the lower atmosphere. For the last several years it has been conducted as an independent but cooperative effort in conjunction with the NATO OPAQUE Program where OPAQUE is the acronym for OPTICAL ATMOSPHERIC QUANTITIES IN EUROPE. And in that context, five two-month deployments have been made to the European area, the first in the Spring of 1976, and the most recent in the Summer of 1978.

The purpose of this paper is to present a short review of the program's general procedures, its primary instrumentation, and a sample of some typical results.

Flight Procedures

The basic procedure has been to put an instrumented C-130 aircraft into the test environment, and measure those optical atmospheric properties that will most influence visual or electro optical performances with respect to image transmission through that environment. For this visually oriented program, the C-130 system was designed to acquire the data necessary for the determination of universal contrast transmittance as defined in Eqs. (1) and (2), the derivations for which are described most recently in Duntley, *et al.* 1978a[1].

$$R_r^*(z,\theta,\phi) = \frac{\pi\; N_r^*(z,\theta,\phi)}{H_{(z_t)}\; T_r(z,\theta,\phi)}\;. \qquad (1)$$

Eq. (1), for directional path reflectance, R_r^*, illustrates those optical atmospheric properties which must be determinable from the airborne measurements in order to generate the desired contrast transmittances. They are, path radiance along the path of sight $N_r^*(z,\theta,\phi)$ total downwelling irradiance, $H_{(z_t)}$ and beam transmittance along the path, $T_r(z,\theta,\phi)$, where the parenthetical modifiers in all cases, define altitude, z, and the zenith angle θ and azimuth ϕ of the path of sight.

$$_b\tau_r(z,\theta,\phi) = \frac{1}{1 + \dfrac{R_r^*(z,\theta,\phi)}{_bR_o(z,\theta,\phi)}}\;. \qquad (2)$$

Eq. (2), for contrast transmittance, $_b\tau_r$, is in a ratio form that is found convenient for use, in that the two reflectance terms R_r^* and $_bR_o$, isolate the properties of the transmitting medium, and the properties of the background into two separate quantities which can be independently determined. The R_r^* term characterizing the atmospherics, and the R_o term the inherent directional reflectance of the background.

The flight program's goal therefore, has been to acquire a set of measurements, suitable for use in these generalized equations, which represent a broad spectrum of geographical and temporal situations. In the recently completed series of OPAQUE deployments, data flights were accomplished in the areas illustrated in Fig. 1. Data missions were flown as far south as the west coast of Sicily in the Mediterranean, and as far north as the southern coast of Denmark in the Baltic. The geographical distribution of the data flights and their related ground based measurements is further identified in Table 1, where each site is listed in order of increasing latitude.

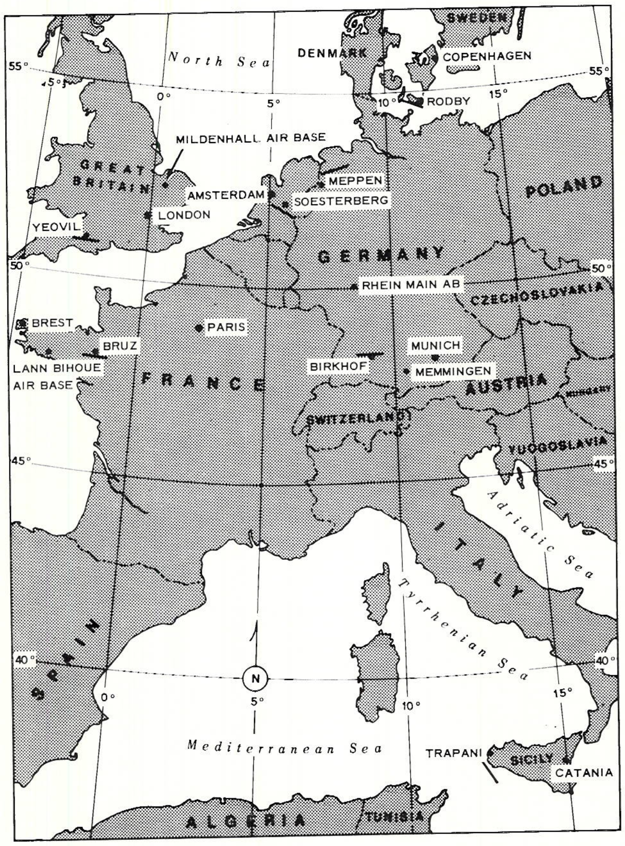

Table 1.

Project OPAQUE Flight Track & Ground Sites Location & Ground Elevations

Geographical Reference and Site Identification Code		Center of Flight Track		Ground Site		Approx Gnd Elev along track
		Latitude	Longitude	Latitude	Longitude	
Ground Sites						
Catania, Sicily	(CT)	-	-	37°24'N	14°55'E	-
Trapani, Sicily	(TR)	-	-	37°55'N	12°29'E	-
Bruz, France	(BR)	-	-	48°01'N	1°45'W	-
Birkhof, Germany	(BK)	-	-	48°13'N	9°11'E	-
Yeovilton, England	(YO)	-	-	51°01'N	2°37'W	-
Soesterberg, Netherlands	(SØ)	-	-	52°08'N	5°17'E	-
Meppen, Germany	(MP)	-	-	52°52'N	7°23'E	-
Flight Tracks						
Sigonella, Sicily	(SG)	37°24'N	15°20'E	-	-	Sea Level
Trapani, Sicily	(TR)	37°33'N	12°30'E	-	-	Sea Level
Bruz, France	(BR)	48°01	1°41'W	-	-	50 m
Birkhof, Germany	(BK)	48°15'N	9°05'E	-	-	762 m
Yeovil, England	(YO)	50°56'N	2°27'W	-	-	60 m
Soesterberg, Netherlands	(SØ)	51°56'N	5°35'E	-	-	6 m
Mildenhall, England	(ML)	52°24'N	1°41'E	-	-	Sea Level
Ahlhorn, Germany	(AL)	52°53'N	7°51'E	-	-	18 m
Meppen, Germany	(MP)	53°00'N	7°37'E	-	-	18 m
Rodby, Denmark	(RB)	54°41'N	11°08'E	-	-	Sea Level

⇦ Fig. 1: Project OPAQUE Site Location Map

With this introduction to the intent of the general procedures, let us proceed to a brief description of some of the primary instrumentation with which the radiometric measurements were made during each flight. Fig. 2 illustrates the C-130 as it appeared during the OPAQUE III deployment to France in the Summer of 1977. As the annotation implies, the aircraft carried six different varieties of radiometers, two camera systems, several meteorological probes and a Royco particle counting system.

The primary radiometers were the integrating nephelometer used for the measurement of total volume scattering coefficients, and the upper and lower hemisphere radiance scanners used for the measurement of sky and terrain radiance distributions. The nephelometer, upper hemisphere scanner and upper hemisphere camera were mounted in the modified upper radome as a composite assembly illustrated in Fig. 3.

The upper and lower hemisphere scanners are servo controlled 5° field of view telescope assemblies which have been programmed to scan a hemisphere in a series of 18 ten second revolutions. The radiance distribution measurements are later sorted and averaged to yield an average radiance value for each 6° in azimuth and each 5° in zenith angle.

The integrating nephelometer is enclosed in the large shroud assembly in the foreground of Fig. 3. It is a folded path device designed and built at the Visibility Laboratory several years ago for an earlier program, but modified to its present configuration for use on the OPAQUE deployments. The operational components are illustrated in Fig. 4 with the shroud open, showing the projector and detector assemblies, however the system characteristics are more clearly illustrated in the artist's conception shown as Fig. 5. This nephelometer has several features which make it a particularly attractive experimental tool. First, the optical system uses a cylindrically limited projector beam, stopped to provide a rectangular beam cross section which provides a good geometrical definition of the illuminated volume. Second, the detector assembly's primary channel uses a cosine corrected irradiometer head which performs the optical integration over all scattering angles between 5° and 172° minimizing truncation losses. And third, the detector assembly's secondary channels measure relatively narrow angle directional scattering at both 30° and 150° which allows the determination of a forward to back scattering ratio that can be used to more thoroughly characterize the sample aerosol.

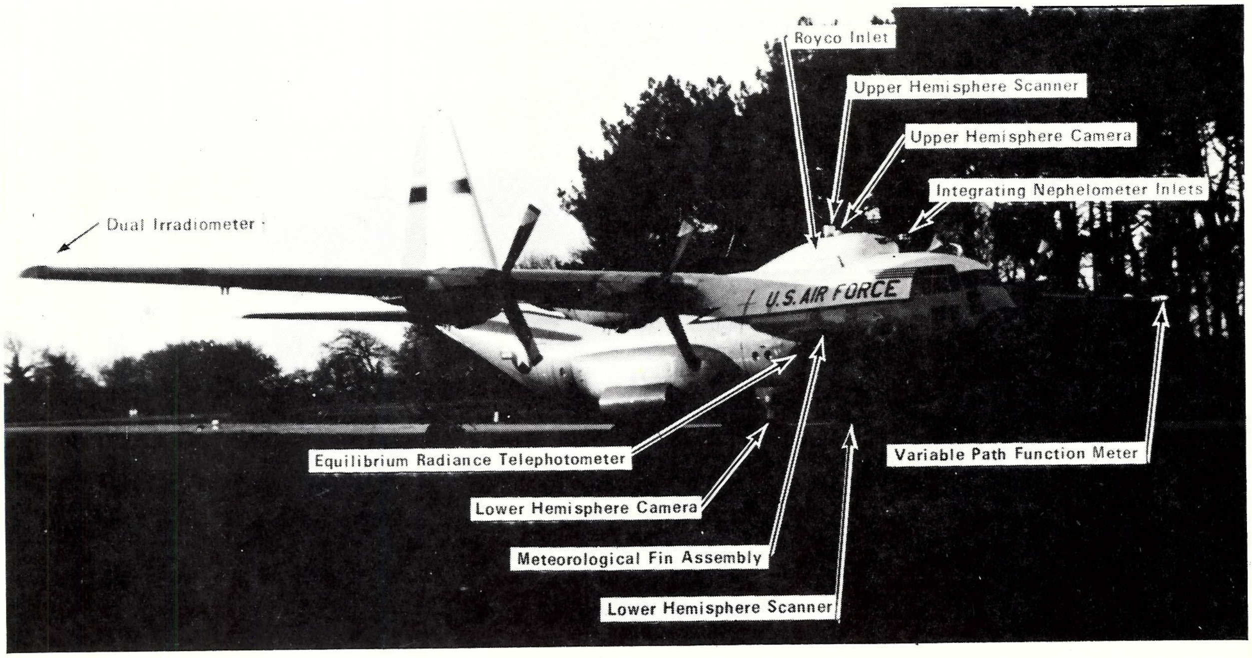

Fig. 2. Airborne Instrumentation System

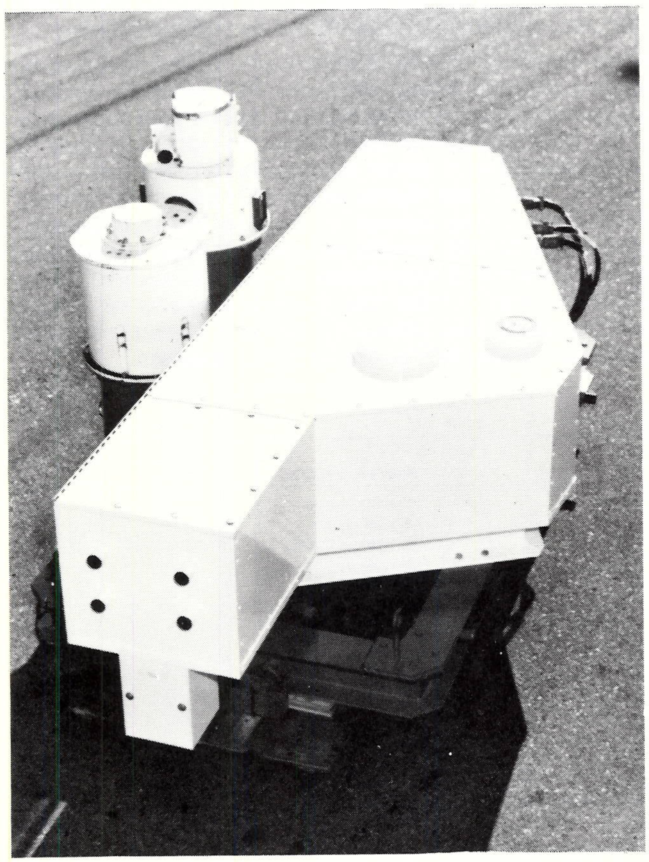

Fig. 3. Integrating Nephelometer Assembly

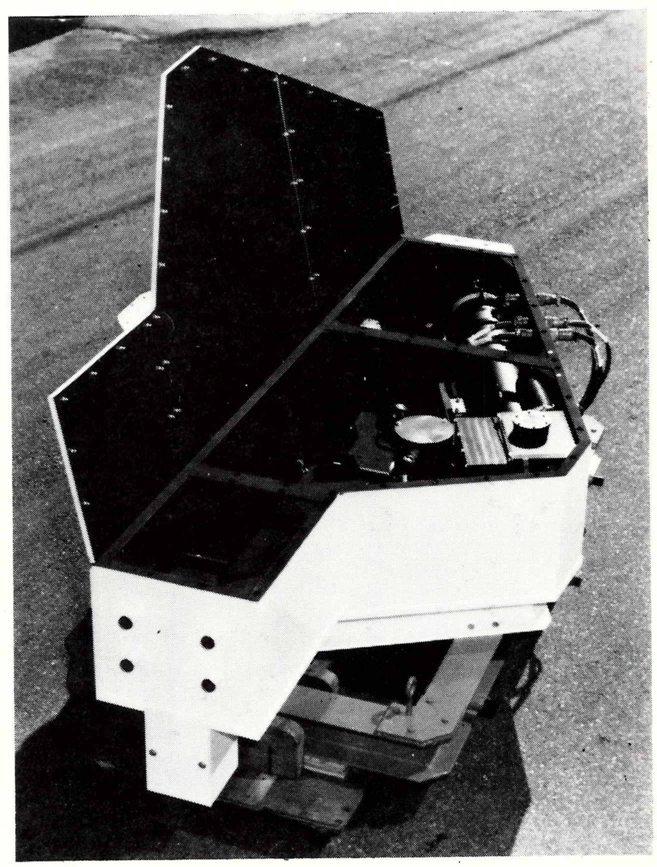

Fig. 4. Nephelometer Internal Arrangement

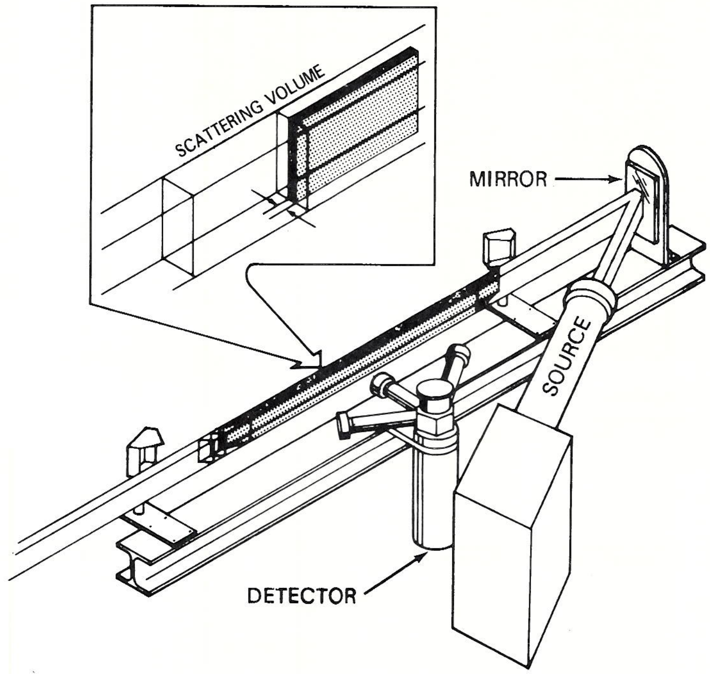

Fig. 5. Nephelometer Schematic Representation

All of the six radiometer channels utilize S-20 photomultipliers fitted with spectral filters to yield the spectral responses illustrated in Fig. 6. The filter number 4 represents the pseudo photopic response which is similar to the response used for many of the OPAQUE ground based measurements. It is also the response which closely approximates the visual response of the human observer, and thus generates the data used in visual search and detection problems.

The nominal flight profile for a clear day mission is shown in Fig. 7. The pattern illustrated requires about an hour and forty-five minutes to complete, and would yield data describing sky and terrain radiances plus scattering coefficient profiles in any two of the four available spectral bands. The flight pattern must be flown twice to acquire equivalent data in all four spectral bands. During the five OPAQUE deployments, the high incidence of low ceilings and generally poor VFR flying conditions precluded the use of this nominal pattern, and restricted data missions to modified profiles that could be completed between ground level and the cloud bases. Consequently, many data flights terminate somewhere between 5 and 10 thousand feet, rather than the twenty shown in the illustration. If one chooses to abandon the requirement for determining contrast transmittance from the data, and is willing to settle for the simpler radiance or beam transmittance, then the automatic scanner data which are used primarily for the computation of path radiances, are not required, and the flight pattern can be simplified to contain only the ascent and descent legs. Under this much less restrictive situation, where nephelometer profile data is the only item of real concern, successful data collection has been accomplished under rather severe weather conditions. These simplified profiles represent just under 30% of the OPAQUE data set.

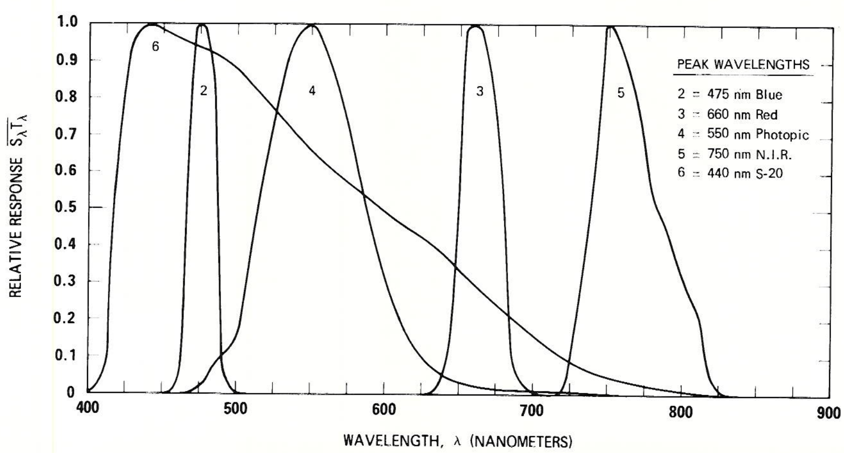

Fig. 6. Radiometer Spectral Response Curves

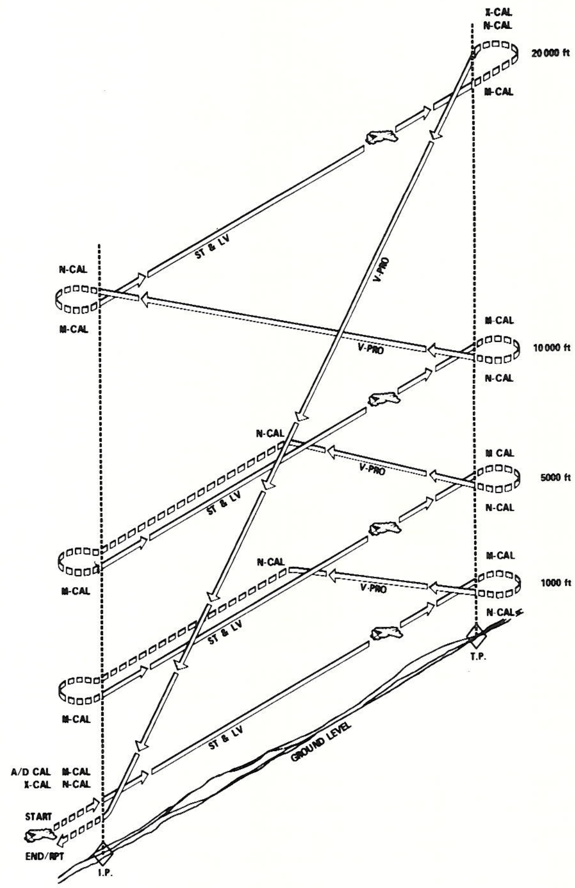

Fig. 7. Nominal Clear Day Flight Profile

Data Summary

The following groups of figures have been chosen to represent typical samples of the data collected with the C-130 system during the first three OPAQUE deployments.

The first group of three figures are data from flight C-416 which was made on the Rodby track off southern Denmark during OPAQUE III. These are typical of data appearing in Duntley, *et al.* 1978b[2]. Flight C-416 was an afternoon flight with partly cloudy skies. There were scattered low cumulus with some high thin cirrus.

Fig. 8 illustrates measurements of total downwelling irradiance made as a function of altitude in each of the four spectral bands during the ascent and descent portions of the flight. The irradiances are generally stable with an occasional downscale kick due to a cloud coming between the aircraft and the sun. The photopic illumination, converted from the 1100 $w/m^2\mu$ shown in the plot, is just under 80,000 lux.

Fig. 9 illustrates the structure of the total volume scattering coefficient as a function of altitude in the same spectral bands. Except for the clutter occurring in the middle altitudes around 2 to 3 km where the aircraft was flying through cloud debris, these profiles illustrate the normally anticipated spectral separations. That is greater scattering in the filter 2 blue band, scaling down to the lesser values in the filter 3 and 5 red bands. The degree of fine structure in the data that is attributable to instrumentation and system noise is generally not more than ±5% of the reading, which at this scale is a band slightly wider than the square symbol used to identify the filter 2 data. Radiometer least counts range between ±0.5 and ±1.5%.

The low altitude filter 4 scattering coefficient of $1.8\mathrm{x}10^{-4}\mathrm{m}^{-1}$ or $0.18\ \mathrm{km}^{-1}$ indicates an approximate visibility of 17 km with nearby stations calling 15 to 20.

The vertical beam transmittances calculated from these scattering coefficient profiles are illustrated in Fig. 10. In this presentation the curves represent the vertical beam transmittance from any selected altitude to the ground in each of the four spectral bands. The crossover between the filter 3 and 4 curves basically is the result of the nonsimultanaity in the measurement of the scattering coefficient structure. This crossover will often occur when a series of measurements is made over a several hour time period under scattered cloud conditions, and can be considered to some degree a measure of the temporal and geographical non-uniformity of the sample environment.

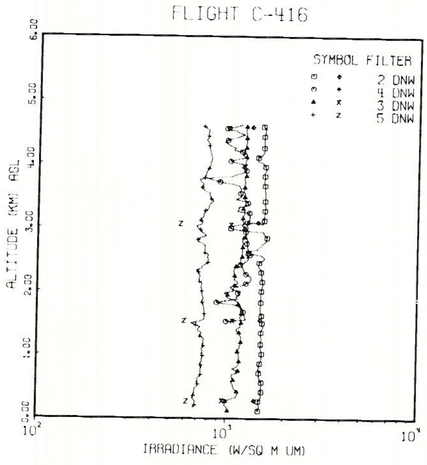

Fig. 8.

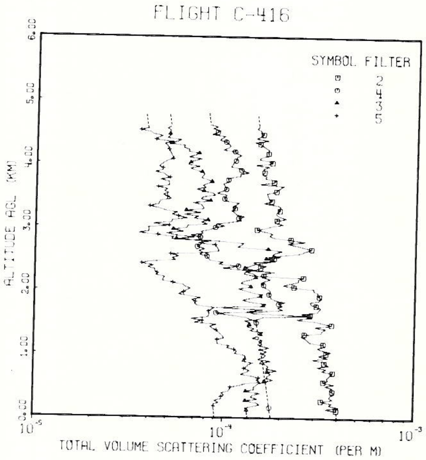

Fig. 9.

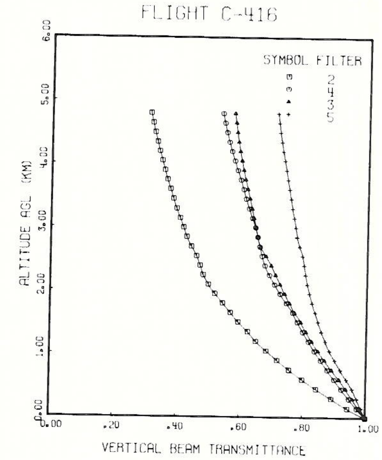

Fig. 10.

Three Sets of Sample Data from Flight C-416, Rodby, Denmark

The airborne measurements of upper and lower hemisphere radiance distributions made by the automatic scanner systems are not included in the report format currently in use by this program, but they represent a most valuable data resource. They are essential, of course, for the computation of the R* directional path reflectance components and the resultant contrast transmittances as illustrated in Eqs. (1) and (2). During each standard mission, sky and terrain radiance distributions are measured from four different altitudes in each of four spectral bands. Each of these thirty two radiance distributions is represented by an array containing approximately 1000 data points. In order to simplify the presentation and possible codification of these arrays we have developed the isoradiance plot illustrated in Fig. 11. These data were measured over the Meppen site during an earlier program, but are typical of the 35 sets of flight data in the taped data bank. In this polar display the plotted lines represent points of equal radiance with the center of the plot representing the zenith, and the outer periphery the horizon. In the matching terrain plot, the center would represent the nadir.

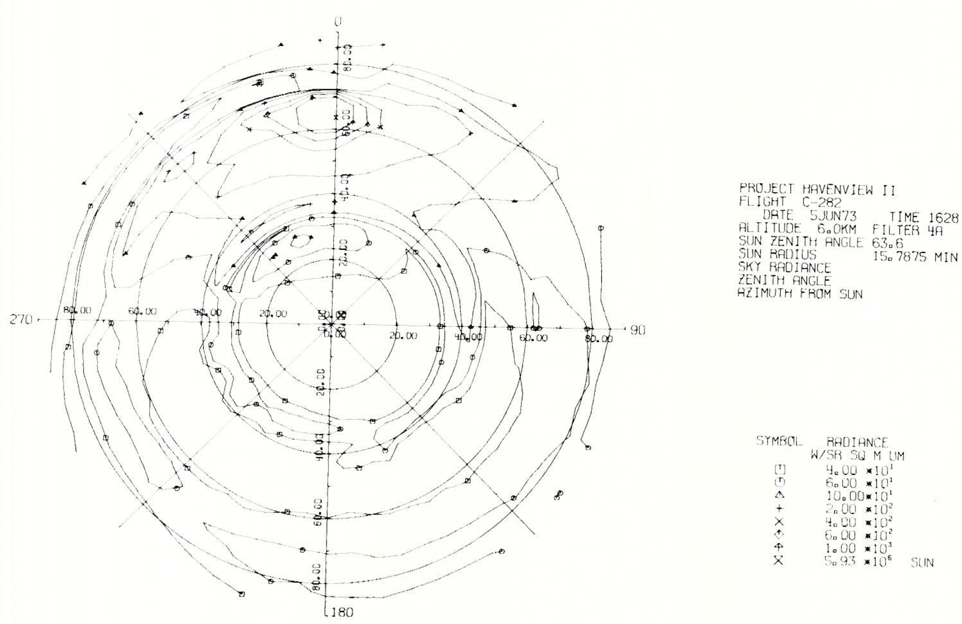

Fig. 11: Upper Hemisphere Isoradiance Plot

Typical Comparison Data

This second group of figures represent composite plots which are typical of the summary displays appearing in each of the OPAQUE deployment Technical Reports. They contain the same basic data that appears in the individual flight displays, but by grouping several flights together on one plot it is often easier for the analyst to visualize the overall character of the deployment.

The first illustration Fig. 12, is a grouping of the average temperature profiles measured during each of the OPAQUE I flights. These eight profiles are coded by Latitude in the legend and represent data from the flight tracks in the Netherlands, England, northern Germany and Denmark. The solid uncoded lines represent the anticipated temperature profiles as listed in the U.S. Standard Atmosphere Supplements.

The second summary plot Fig. 13, illustrates total downwelling irradiance profiles measured with the pseudo photopic response during the OPAQUE III flights. The generally cluttered structure in the profiles contrasts sharply with the relatively constant values associated with clear day flights. The cloud cover coding in the legend for the most part explains the irregularity, as all flights were made under scattered to broken or worse cloud conditions. The short profile for flight C-422 represents the illumination under full overcast conditions on a Rodby flight made in heavy haze between sea level and the 2 km ceiling.

The third and last summary plot Fig. 14, represents total volume scattering coefficients measured with the pseudo-photopic response during the OPAQUE II flights. The general characteristic best illustrated in this set is the low altitude haze layer that typifies so many of these profiles. The low altitude changes in scattering coefficient can easily exceed a factor of ten within the last 1000 meters. The magnitude and altitude of this often abrupt haze boundary are obviously major influences upon the determination of slant path transmittances through this lower altitude regime, and can be ignored only at the peril of major error in our determinations.

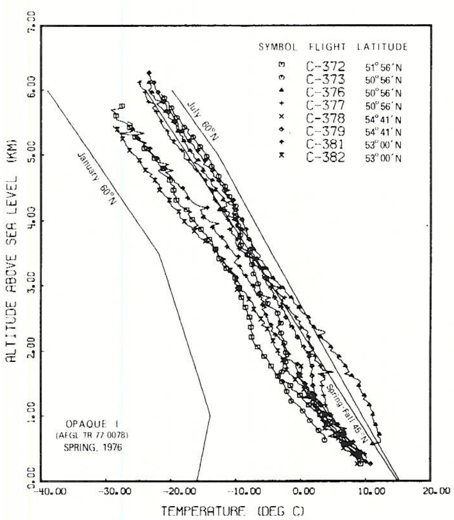

Fig. 12.

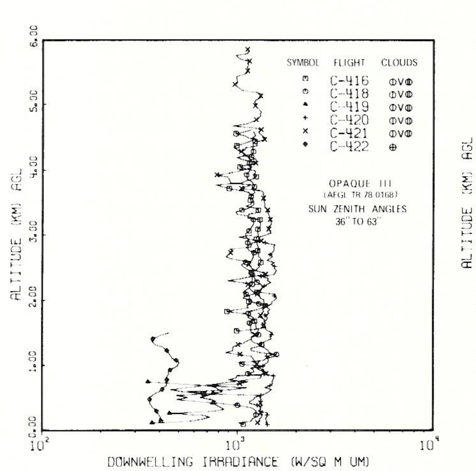

Fig. 13.

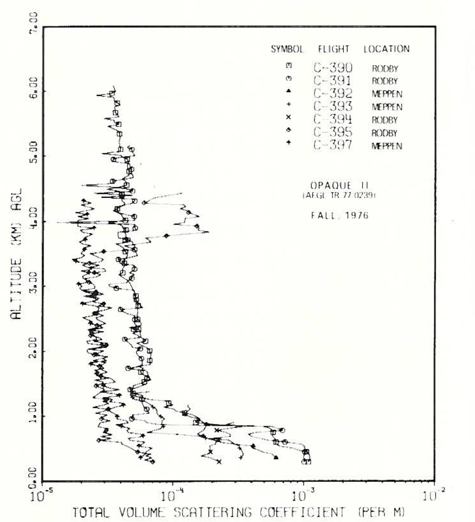

Fig. 14.

Three Plots of Summarized Data Displays

This final set of three figures illustrates several automatic displays which are being generated to aid in the analysis of the C-130 profile measurements. The displays are produced for each flight and are intended to form the data base for further studies into the relationships between atmospheric humidity and aerosol scattering.

Figure 15 contains the pseudo photopic scattering coefficient and relative humidity profiles measured on flight C-412. These data were selected to point up the close similarity in the major structural characteristics between the two sets of measurements, a common feature found on many flights both within the OPAQUE and other previously collected data sets.

Figure 16 represents the same basic data displayed as a scatter diagram, but with the scattering data pseudo normalized by displaying it as the ratio of the total to the Rayleigh scattering. This ratio of "s" to "s_R" is referred to by some investigators as equivalent ground level scattering. If the display were sorted by spectral filter, then the clearly strong correlation could be recognized quite readily.

Fig. 17 again represents the same basic data, but with the relative humidity converted to absolute humidity and the scattering data adjusted to represent only the Mie component. The flexibility and convenience of these automatic displays has provided an increasingly useful and powerful tool in the analysis of these flight data, and the determination of their applicability to the overall task of developing operational optical forecasting.

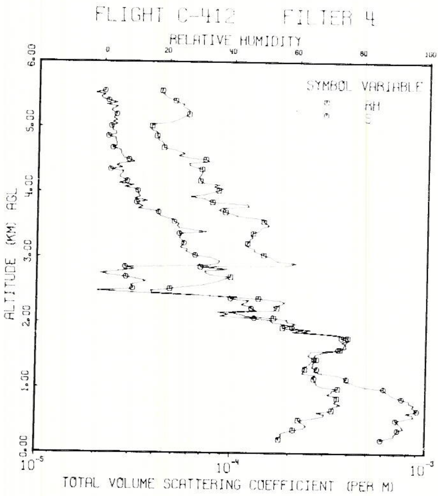

Fig. 15.

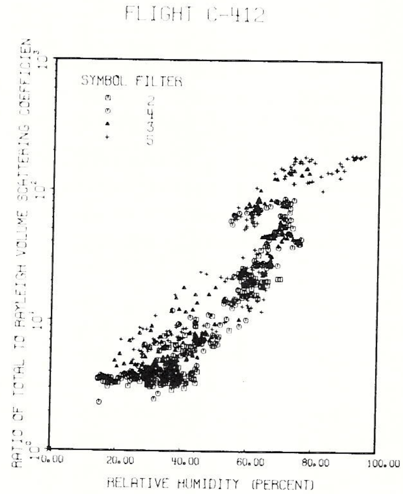

Fig. 16.

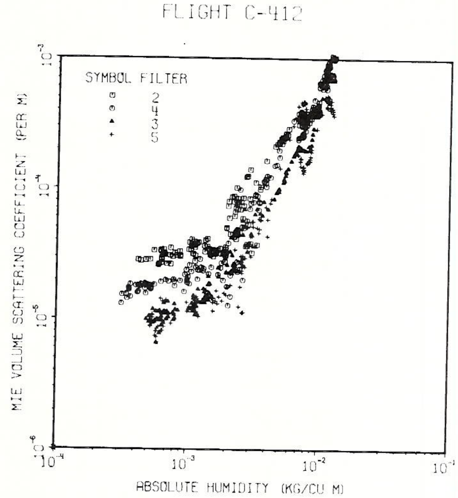

Fig. 17.

Three Plots of Alternate Displays for Analysis

Summary

Atmospheric measurements of the type illustrated herein have been made during five European deployments on a total of 10 different flight tracks in six different countries. Geographically, the 86 flights are relatively evenly distributed with the minimum of six occurring in the Netherlands, the maximum of 21 occurring in northern Germany, and the remaining five sites averaging 12 flights each. Temporally, the flights represent all four seasonal conditions during daylight hours between mid-morning and late afternoon.

These vertical profile data in conjunction with the extensive ground based data collected by the European scientific community represent a major step forward in the coordinated documentation of the optical and meteorological properties of the European operational environment. They provide a well specified data base upon which extensive analysis will build a more thorough understanding of the linkages between the optical and meteorological conditions and processes.

Acknowledgements

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2. Duntley, S. Q., R. W. Johnson, and J. I. Gordon (1978b), "Airborne Measurements of Atmospheric Volume Scattering Coefficients in Northern Europe, Summer, 1977", University of California, San Diego, Scripps Institution of Oceanography, Visibility Laboratory, SIO Ref. 78-28, AFGL-TR-78-0168.