AD-A106 387 PHOTOMETRICS INC WOBURN MA F/G 4/1
DETERMINATION OF UPPER ATMOSPHERIC WINDS AND TURBULENT DIFFUSIO--ETC(U)
JUL 81 C A TROWBRIDGE F19628-78-C-0171
UNCLASSIFIED PHM-04-81 AFGL-TR-81-0200 NL

1 OF 1
AD
A106387

END
DATE
FILMED
11-81
DTIC

LEVEL II

AFGL-TR-81-0200

AD A106387

DETERMINATION OF UPPER ATMOSPHERIC WINDS AND TURBULENT DIFFUSION AND DISSIPATION FROM ARTIFICIAL CLOUD EXPANSION AND GROWTH

Christian A. Trowbridge

PhotoMetrics, Inc.
4 Arrow Drive, Woburn, MA 01801

22 July 1981

Final Report for Period 22 June 1978 - 21 June 1981

Approved for public release; distribution unlimited.

Prepared for

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFGL-TR-81-0200	2. GOVT ACCESSION NO: AD-A106 387	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): DETERMINATION OF UPPER ATMOSPHERIC WINDS AND TURBULENT DIFFUSION AND DISSIPATION FROM ARTIFICIAL CLOUD EXPANSION AND GROWTH		5. TYPE OF REPORT & PERIOD COVERED: Final Report. 22 Jun 78 — 21 Jun 81
		6. PERFORMING ORG. REPORT NUMBER: PhM-04-81
7. AUTHOR(s): Christian A. Trowbridge		8. CONTRACT OR GRANT NUMBER(s): F19628-78-C-0171
9. PERFORMING ORGANIZATION NAME AND ADDRESS: PhotoMetrics, Inc. 4 Arrow Drive Woburn, MA 01801		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62101F 669007AD
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Geophysics Laboratory Hanscom AFB, MA 01731 Contract Manager, S.P. Zimmerman/LKB		12. REPORT DATE: 22 July 1981
		13. NUMBER OF PAGES: 25
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS (of this report): Unclassified
		15a. DECLASSIFICATION DOWNGRADING SCHEDULE: N/A

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbulence
Turbulent Diffusivity
Reduction of Photographic Images
Atmospheric Heating
Fourier Analysis
Chemical Releases
Upper Atmosphere

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Microdensitometric reduction and computer analysis were applied in analyzing radiometrically and photogrammetrically calibrated photographic images of chemical and particulate tracers in the stratosphere, mesosphere and thermosphere. Digitized optical density distributions were processed by Fourier and configuration space analyses to determine turbulent atmospheric heating rates, diffusion coefficients, and other parameters descriptive of upper-atmospheric turbulence.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19. Key Words (continued)

Atmospheric Winds

20. Abstract (Continued)

Richardson numbers, heating, and turbulent diffusivity were also determined from wind data derived by the smoke trail method.

FOREWORD

The program described here consisted of determination of heating rates and diffusion coefficients for the turbulent atmosphere through photometric and photogrammetric reduction and computer analysis of photographs of chemical releases. Related earlier work by the PhotoMetrics research group is described in References 1,2,3 and 5.

The author wishes to express his thanks to Mr. Samuel P. Zimmerman (Contract Manager) of AFGL for his continued encouragement and support, to Z. Reinhardt and J. Lander for assistance in the data analysis, and to Dr. I.L. Kofsky and C.C. Rice who also made important contributions to the studies described in this report.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

The objective of the program described here is the determination of parameters which characterize turbulence in the upper atmosphere. These include, but are not limited to, turbulent diffusion coefficients and atmospheric heating rates derived from analyses of transport and surface brightness distributions of tracer chemical clouds. Microdensitometric scanning is used to sample the radiance distributions of mainly sunlight-scattering artificial clouds which have been recorded by radiometrically calibrated photography. These brightness data are then analyzed by digital computer methods to determine both Fourier-transform and configuration-space statistical descriptors of the fluctuating component of the surface brightness. Features of the one dimensional energy spectra which are indicative of turbulence are further analyzed to determine heating rates (rate of dissipation of turbulent kinetic energy) and diffusion coefficients as described in Section II. Measurements of the horizontal wind field by photographic triangulation were also used to obtain further estimates of heating and diffusion (Section III). Support tasks and an inverse triangulation scheme are discussed in Section IV.

A summary of the tracer release cloud data analyzed is shown in Table 1, and a partial listing of results from the "Aladdin 1974" (through the night release series -- Wallops I., VA) in Table 2. The results of these and other analyses were reported as they were completed to AFGL scientists for their immediate use in the interpretation of atmospheric turbulence phenomena.

Table 1. Summary of Analyses

Release*	Trail Positions	Energy Spectra	Heating Rates	Diffusion	Shears And Richardson Numbers
BONNIE	Yes	Yes	Yes	Yes	Yes
QUEENIE	Yes	Yes	Yes	Yes	Yes
RUBY	Yes	Yes	Yes	Yes	Yes
ALICE	Yes	Yes	Yes	Yes	Yes
LOUISE	Yes	Yes	Yes	Yes	Yes
BLANCHE	Yes	Yes	Yes	Yes	Yes
PAULA	Yes	Yes	Yes	Yes	Yes
HELEN	No	Yes	Yes	Yes	Yes
ETTY	No	Yes	Yes	Yes	Yes
HERTA	No	Yes	Yes	Yes	Yes
JOAN	No	Yes	Yes	Yes	Yes
KAM	No	Yes	Yes	Yes	Yes
WINTER ANOMALY	Yes	No	Yes	Yes	Yes
Stratospheric Trail					
FLORA	Yes	No	Yes	Yes	Yes

----

*Code name of atmospheric chemical release.

SECTION II

DETERMINATION OF HEATING RATES AND EDDY DIFFUSION

Characterization of turbulent flow in the atmosphere may be accomplished by analyzing surface brightness distributions of chemiluminescent or sunlight scattering tracers released from rockets (Ref 1-6). Statistical or Fourier methods may be applied to the mean brightness distribution or to the fluctuations of brightness about the mean distribution to extract information about the structure present.

The released atoms, molecules, or particulates very quickly reach pressure and temperature equilibrium with ambient species and are found from experience to conform to the flow field. The spatial characteristics of the flow are frozen in time by radiometrically and photogrammetrically calibrated photography from ground stations. Analysis starts with microdensitometer scans across the images of this frozen flow field, which are assumed (by the ergodic hypothesis) statistically equivalent to the time resolved output of a fixed physical sensor as the flow field proceeds across it. The resulting digital density information is converted to scene brightness through the H&D characteristic of the film, with appropriate corrections applied to account for reciprocity effects in exposure duration, spectral sensitivity of the film, lens T-stop, and varying sky background (Ref 3).

Further corrections are also performed to account for the transfer function of the microdensitometer's finite sampling aperture and for the modulation transfer function of the microdensitometer itself, which is a function of the temporal scanning rate of the instrument. The importance of utilizing a scanning system with true microdensitometer optics, is explained in Ref 11. Briefly, to obtain the precision and accuracy needed for these analyses the response of the instrument must be temporally and spatially stationary. Distortion of the calculated power spectra can result from nonuniform reproduction of the photographically recorded data.

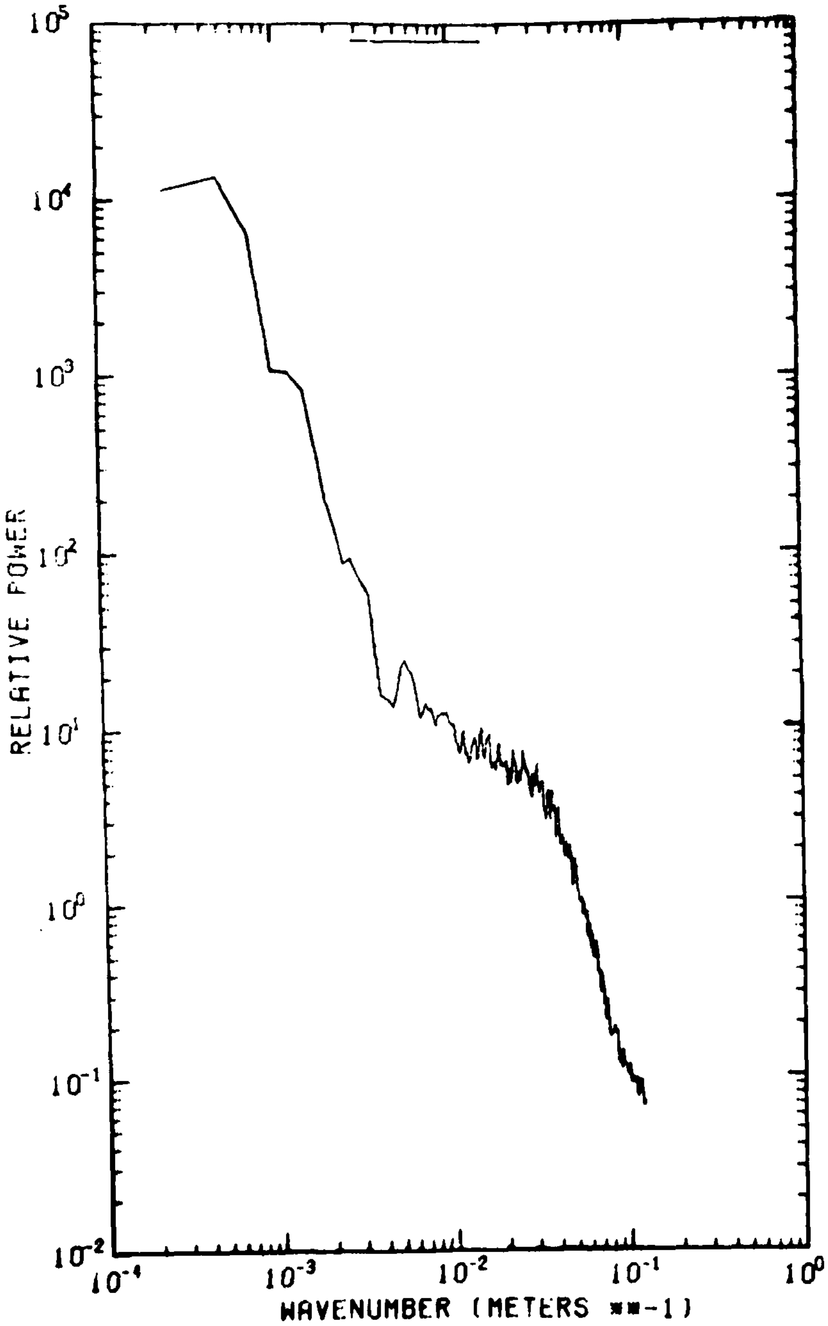


Figure 1. Turbulence spectrum at 99 km altitude for release ETTY (Aladdin 1974) determined by "FFT" techniques.

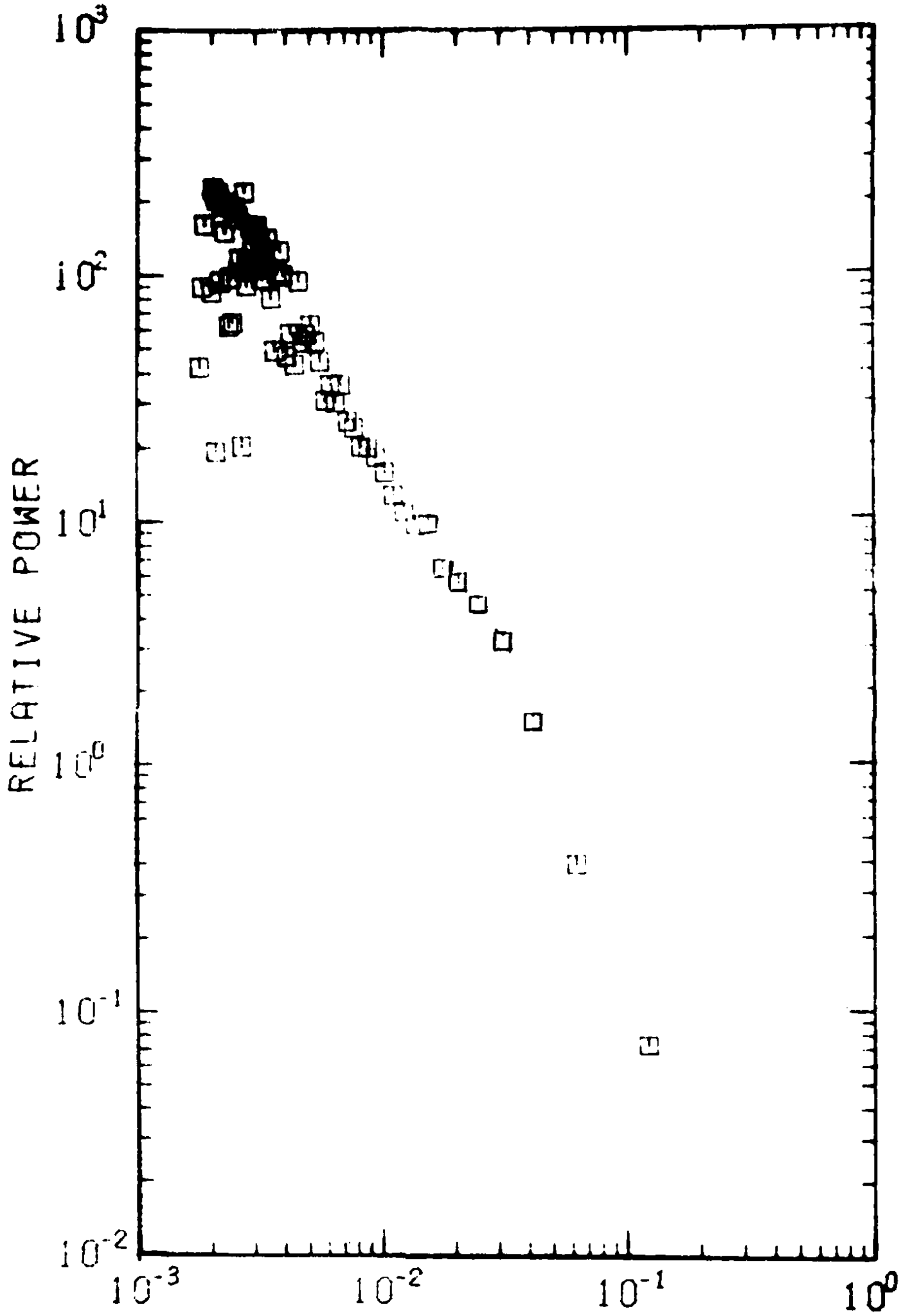


Figure 2. Turbulence spectrum for release ETTY found by the "count" method.

Photogrammetric calibration of the imagery is also required (next section) to determine the altitudes of the points of measurement and to convert film plane measurements to distance scales at the glow. Time sequential analyses often require a correction of scale factor due to the range variation produced by cloud movement by the mean wind field. Finally, the corrected brightness data are analyzed by Fourier (or other statistical) methods. Fourier analysis, or calculation of one dimensional turbulent energy spectra is carried out by one of three methods -- standard Fourier analysis, "fast" Fourier Transform (FFT), or a simple summation process (counting method, Ref 8) which determines the spectral energy in discrete, nonuniform wavenumber bands. Each of these methods requires large amounts of input data to achieve a desired statistical accuracy (Ref 10), usually 20 to 50 parallel microdensitometer scans through the turbulent region of interest. Depending upon analysis method, the average energy spectrum is obtained by segmental averaging or by averaging of individual scan spectra. Examples of FFT and "count" energy spectra for release ETTY are shown in Figures 1 and 2.

The one dimensional scalar energy spectrum E(k) as a function of wavenumber k may be utilized to determine the Fourier characteristics of turbulent flow. E(k) often exhibits power law dependencies on wavenumber, the most well known being the Kolmogoroff or inertial spectral range where

$$E(k) \propto k^{-5/3}$$

which implies, from dimensional arguments, that turbulent energy is being fed at a constant rate from large cells into small ones in the subrange of cell dimensions in which this slope obtains. A further application of the energy spectrum is its capability of isolating features of characteristic wavelength -- for example internal atmospheric gravity waves.

When an inertial spectral range is present the heating rate or rate of viscous dissipation of turbulent kinetic energy ε may be found from

$$= \frac{A \epsilon_n^3}{E^3 (k_1) k_1^5} \qquad (1)$$

where A is a constant. $E(k_1)$ is the energy at wavenumber k_1 located within the inertial subrange, and ϵ_n is the scalar rate of decay of density fluctuations (n') due to molecular diffusion

$$\epsilon_n = 6D \left(\frac{\partial n'}{\partial x}\right)^2 = \int_0^\infty k^2 E(k) dk. \qquad (2)$$

here

D = the molecular diffusion coefficient, and

$\frac{\partial n'}{\partial X}$ = space rate of change of turbulent density fluctuations of tracer material in the release.

$<(\frac{\partial n'}{\partial X})^2>$ is usually determined by numerical differentiation of the brightness data and may also be obtained by the integral formulation (2). Frequently $< (\frac{\partial n'}{\partial x})^2 >$ (and thus ϵ) is biased toward lower values because of limited spectral extent in the integral approximation, or by inclusion of smooth regions of sky background in the numerical method. The power law form of E(k) is a -5/3 to 0.2 k_ν where a transition to a larger negative slope occurs (-3 or greater); $k_\nu = (\epsilon/\nu^3)^{1/4}$ is the limiting wavenumber for viscous dissipation, and ν the kinematic viscosity. Limited spatial resolution of the photography determines the spectral extent and the upper integration limit of equation 2. If this limit is less than 0.2 k_ν it is evident that $<(\partial n'/\partial x^2)>$ may be substantially smaller than expected and estimates of ϵ will also be low. The above method has been used successfully to determine ϵ near the turbopuase (Ref 6 and 12). If the energy spectrum extends beyond 0.2 k_ν an accurate determination of the constant A in (1) may be made (Ref 13). The scalar energy spectrum in the inertial range is

$$E(k) = A\epsilon_n \epsilon^{-1/3} k^{-5/3}$$

which may be made nondimensional using Kolmogorov scaling

$$E_1(k) = \frac{k_\nu^{\,3}\,\nu}{\varepsilon_n}\;E(k) = k_\nu^{\,3}\,\nu\,A\varepsilon^{-1/3}\,k^{-5/3}\,.$$

Further scaling the spectrum by $\left(\frac{k}{k_\nu}\right)^{5/3}$

$$N(k) = Ak_\nu^{\,4/3}\,\nu\varepsilon^{-1/3}$$

or

$$A^3 = \frac{N^3(k)}{k_\nu^{\,4}\,\nu^3\,\varepsilon^{-1}}$$

but

$$\varepsilon = k_\nu^{\,4}\,\nu^3$$

and

$$A = N(k) = E(k)\,\frac{k_\nu^{\,3}\nu}{\varepsilon_n}\,\left(\frac{k}{k_\nu}\right)^{5/3}$$

Alternatively, since k is known, and assuming the constant A is known, ν may be calculated from

$$\nu = \left(\frac{\varepsilon}{k_\nu^{\,4}}\right)^{1/3} \qquad (3)$$

Equations used by atmospheric modelers to calculate altitude profiles of ν become increasingly inaccurate at very high or low temperatures or under conditions occurring at high altitudes (above 32 km), standard atmosphere calculations of kinematic (and dynamic) viscosity are presently tabulated only to 86 km. Further experimental determination of the behavior of kinematic viscosity at high altitude could provide the opportunity to refine the model equations.

Another possible formulation analogous to the spectral form for the average potential temperature may be used

$$E_n(k) = \alpha\,\frac{\bar{n}}{g}\,\frac{\partial \bar{n}}{\partial z}\,\varepsilon^{\,2/3}\,k^{-5/3} \qquad (4)$$

where n is the mean density, $\frac{\partial \bar{n}}{\partial z}$ the gradient of the mean, α is a constant, and g the gravitational constant.

One further method of calculating ε may be utilized: The average of the square of the turbulent density fluctuations $\overline{n'^2}$ is calculated for several times after the initial release. Then

$$\varepsilon_n = \frac{\partial(\overline{n'^2})}{\partial t}$$

and the rate of turbulent dissipation is calculated from equation (1). This formulation for decaying turbulence should be applicable to tracer pulse or trails in any altitude region.

Evaluation of the eddy diffusion coefficient K may now be accomplished utilizing turbulent heating rates. Reference 7 shows that eddy diffusion may be expressed as

$$K = C\,\varepsilon^{1/3}\,k_o^{-4/3} \qquad (5)$$

where C is a constant and k_o is the low wavenumber limiting the inertial spectral range, which is determined by inspection of the turbulence spectrum. Wavenumber k_o can also be calculated as

$$k_o = \frac{\int_o^{\infty} E(k)\,dk}{\int_o^{\infty} k^{-1}\,E(k)\,dk}$$

if the spectral range experimentally extends beyond 0.2 k_ν.

If the Brunt Vaisala frequency N of the atmosphere is known, the eddy diffusion coefficient may be calculated as (Ref 14)

$$K = \frac{1}{3}\,\varepsilon/N^2 \qquad (6)$$

Alternatively, Equation (6) can also be used to determine N^2 when K and ε are known.

Table 2. Partial Tabulation of Typical Analysis Results, Alladin 1974

Release	Altitude (km)	k_o (m^{-1})	ε ($m^2\ sec^{-3}$)	K ($m^2\ sec^{-1}$)	k_ν (m^{-1})	ν ($m^2\ sec^{-1}$)	R_i
KAM	90	1.3×10^{-3}	2.1	6.3×10^{3}	0.15	16.0	0.074
JOAN	98	1.5×10^{-3}	8.29	8.22×10^{3}	.23	14.3	.15
JOAN	98	1.8×10^{-3}	7.22	6.16×10^{3}	.18	18.9	.17
ETTY	99	2.2×10^{-3}	1.42	2.74×10^{3}	.125	17.9	.24
JOAN	102	2.0×10^{-3}	7.88	5.51×10^{3}	.175	20.2	.44
JOAN	102	3.2×10^{-3}	4.79	2.49×10^{3}	.155	20.1	.59
HERTA	104	3.5×10^{-3}	4.21	2.12×10^{3}	.125	25.7	.14
JOAN	108	3.4×10^{-3}	9.16	2.85×10^{3}	.13	37.2	1.28
JOAN	108	3.4×10^{-3}	13.12	3.22×10^{3}	.125	35.6	1.62

----

k_o = large scale wavenumber limit of the inertial range of turbulence

ε = rate of turbulent dissipation

K = turbulent diffusion coefficient

k_ν = wavenumber limit for viscous dissipation of turbulence

ν = kinematic viscosity

R_i = Richardson number.

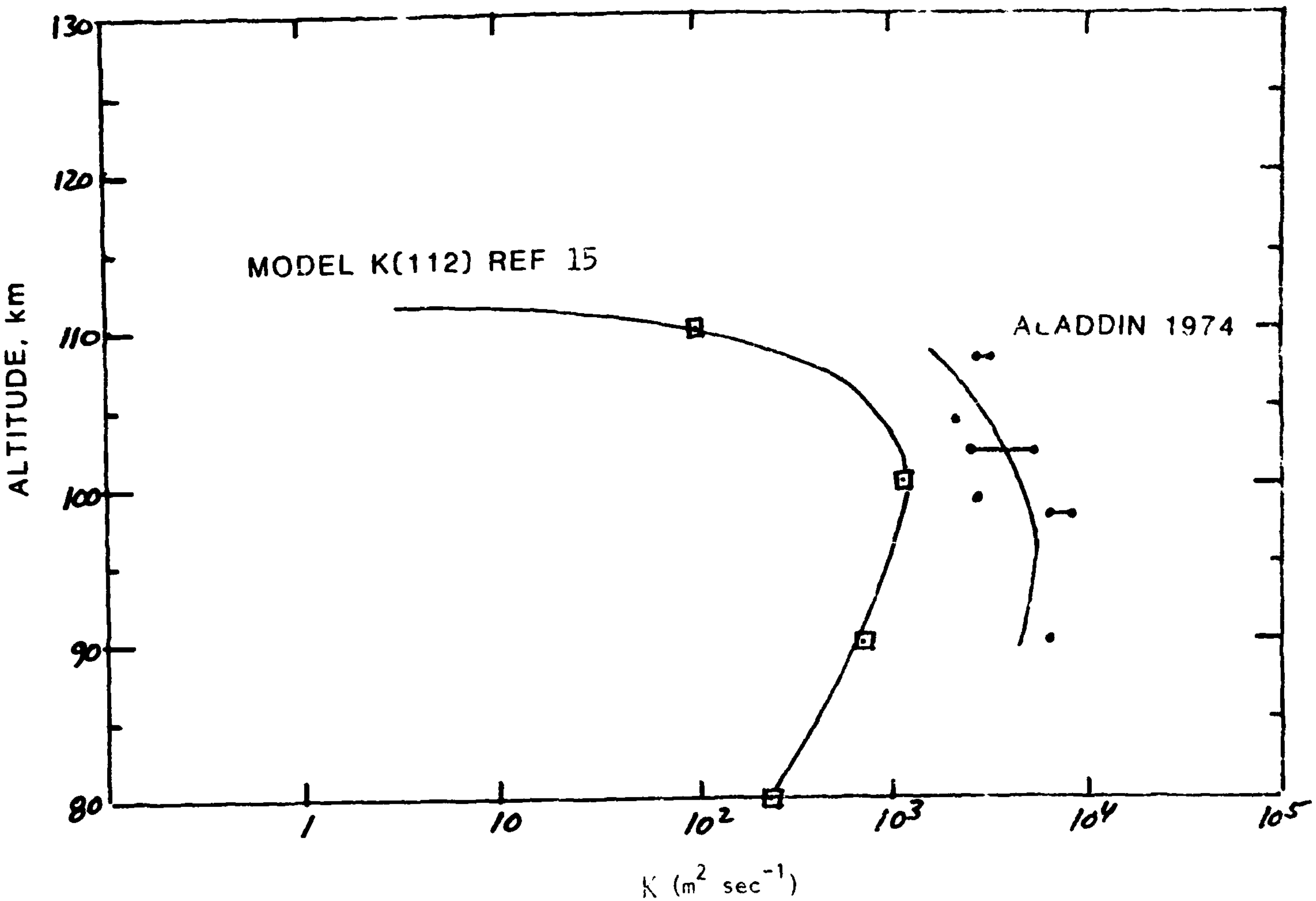


Figure 3. Turbulent diffusion coefficients derived from the Aladdin 1974 series of releases.

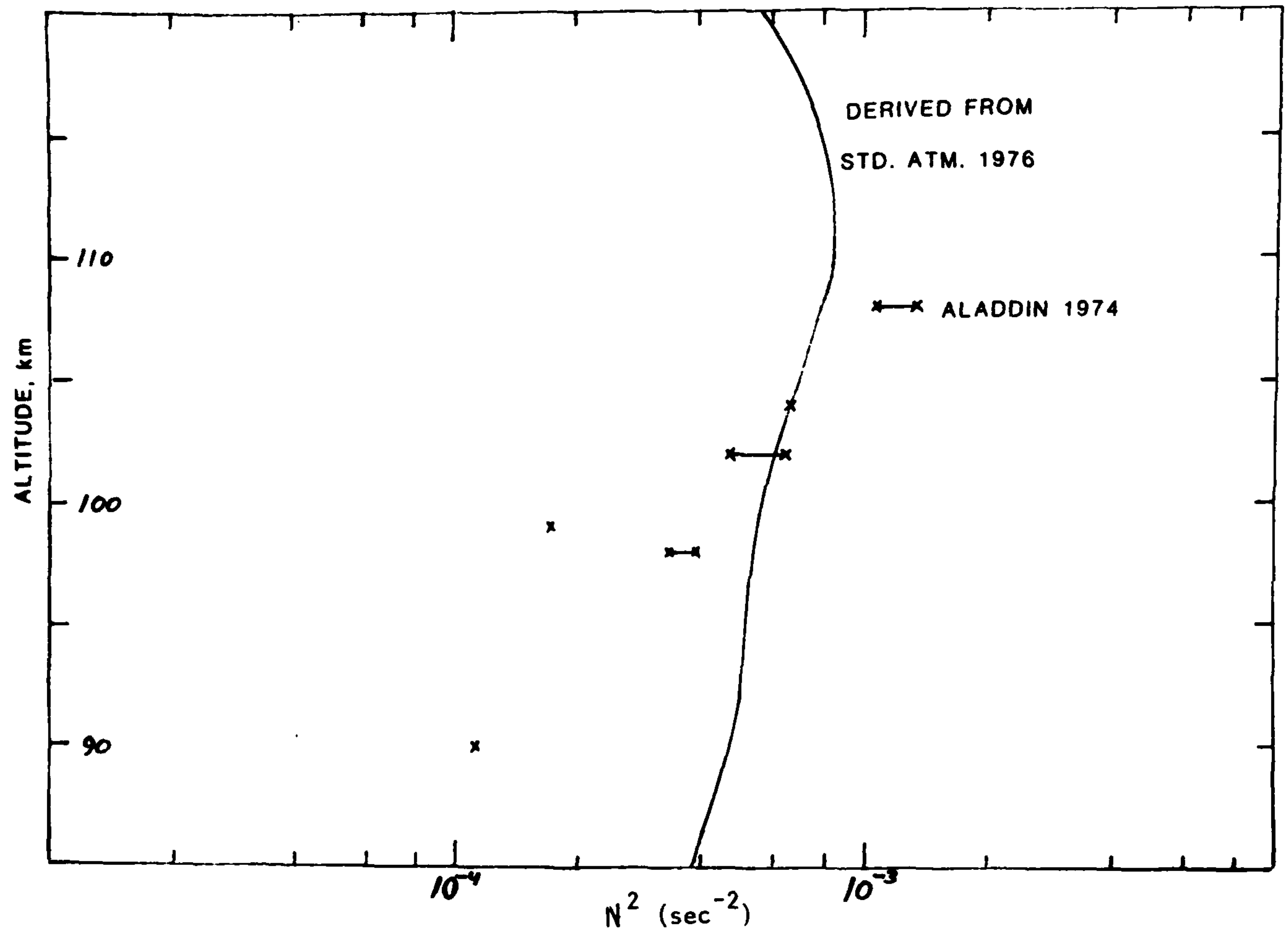


Figure 4. Brunt Vaisala frequencies calculated for the Aladdin 1974 series of releases.

The data in Table 2 (Alladin 1974-Wallops I., VA) are typical of the analysis results; ε was determined using Equation (4) and K from Equation (5), k_ν was estimated from the spectra and ν calculated from Equation (3). Figure 3 shows the calculated eddy diffusion compared to a diffusion model with turbopause at 112 km (Ref 15). Figure 4 compares N^2 determined from Equation (6) to N^2 determined from 1976 U.S. Standard Atmosphere.

Knowledge of the atmospheric wind field may also be used to determine ε and K (Section III), or time sequences of low frequency power spectra may be analyzed by methods analogous to those used to determine molecular diffusion (Ref 1), however, this latter method is only useful when the tracer cloud retains a roughly gaussian structure.

SECTION III

PHOTOGRAPHIC TRIANGULATION

The use of photographic photometry to determine quantitative measures of atmospheric turbulence requires that accurate photogrammetric calibration be performed as well. Triangulation determines spatial locations on the tracer release as a function of time as it is transported by the mean wind field. The position of the glow and its range determine the conversion from image scale to dimensions on the three-dimensional object itself. Procedures used to perform these calibrations are detailed in References 16 and 17, and are briefly covered below.

Photogrammetric triangulation to distant objects from appropriately separated ground stations is based upon accurate knowledge of each station location (in latitude, longitude and altitude above a reference ellipsoid) and also the orientation of the camera film plane at each station. Determination of camera orientation is accomplished by analysis of photographs of star fields. Film plane coordinates of star images and equatorial coordinates of the stars at the exact time of exposure are related through vector equations which are solved to determine the exact focal length of the camera and the direction of the camera optic axis in right ascension and declination, and also the rotation of the film plane needed for coincidence of the stars and their images. The orientation may be readily expressed in any other coordinate system (e.g., horizon or geocentric) by rotations about the coordinate axes which effect the coordinate transformation.

The digital film plane positions of the tracer cloud as viewed from two photographic sites are then related to determine the spatial location of the glow. Film plane coordinates of the glow are determined using an automatic scanning densitometer which can locate and digitize the centerline of a trail or puff release (Ref 18) or determine the location of small dots drawn on the negative in the region of interest. The latter method must often be used for turbulent portions of releases where the automatic scanner cannot define a centerline of the release.

Vector lines of sight for each film plane release point are calculated and an iterative procedure determines the best match of each Site 1 point with a Site 2 point. The spatial position of the trail is determined by calculating the latitude, longitude and altitude of the intersection of the vector lines of sight of matched points. Some of the problems which are associated with the implementation of the method are detailed in Reference 19. An inverse of this triangulation method was used to approximately project altitude grids onto the film plane records of older releases given the known wind profile (Section IV).

Measurements of the horizontal wind field are accomplished by analysis of the motion of the trail for several frames over total durations of one to two minutes. Least squares analysis of trail position as a function of time at each altitude yields the average positional change and average velocity components.

Further detail of atmospheric turbulence, heating rates, and diffusion may be studied with the aid of these horizontal winds. Richardson number shown in Table 2, which is a measure of the local stability or instability of the atmosphere, was determined from

$$R_i = N^2/(\partial v/\partial Z)^2$$

where $\partial V/\partial Z$ is the vertical shear of the horizontal wind. Usually $R_i > 1/4$ indicates stability, $R_i < 1/4$ instability or turbulence. Whenever winds are used as a basis for measuring turbulent heating and diffusion the value of R_i must be less than 1/4 in the region of the measurements. The shear used for the data in Table 2 is an average over two km altitude segments; a smaller increment in altitude would produce a larger shear and decreased R_i. The energy deposition rate per unit mass due to the vertical shear of the horizontal wind, $\varepsilon = \frac{1}{2}\nu(\partial v/\partial z)^2$ is an additional measure of heating. For turbulent layers, turbulent velocity fluctuation v' about the mean velocity may be calculated and heating may be expressed as

$$\varepsilon = A V'^{3} / \ell_o$$

where ℓ_o is the outer length of the turbulence and A' is a constant of order unity. Under certain conditions the one dimensional energy balance equation may be solved to provide a vertical diffusivity

$$K(z) = \frac{\varepsilon}{(\partial v/\partial z)^2} \cong K_m$$

where K_m is the momentum transfer coefficient.

SECTION IV

SUPPORT TASKS

The work described in this Section relates directly to determining reliable turbulence spectra at a series of known atmospheric altitudes. It involves choosing photographic records of past releases which 1) show turbulent structure, and 2) have the appropriate photogrammetric and radiometric calibrations, or are amenable to reconstruction of these calibrations, for quantitative analysis.

First, we surveyed and cataloged a library of film records of AFGL chemical releases dating from 1962 to 1974. Of an estimated 1700 rolls of film that were available for this purpose 866 received preliminary examination to determine those releases which could be candidates for useful analyses. Of these 235 were judged to contain no evidence of atmospheric turbulence, and another 319 were found to be duplicates (more than one camera is usually operated at each photographic site). The remaining 312 films were carefully examined and numbered, and a log of data prepared containing the following information: Log Number, Release Name or identification, Date, Site, Camera Number, Film Type, Wavelength Filter, Launch Time, Release Material, Type of Release (trail or puff), whether a calibration stepwedge had been made, whether the film had been previously used for triangulation, frame numbers or time code where turbulence was present, and comments or description of the turbulence.

Of the films in the catalog 77 were found which had turbulence present and also had the necessary calibrations for meaningful analyses. The amount of data which was suitable for analysis was considerably more than could be analyzed during the course of the work and the cataloging procedure was halted at this point. Photographic prints of the turbulent areas were made which could be annotated to preserve a record of areas which were digitized for analysis; as this is part of the working data, these images are not reproduced here.

A major problem was encountered with these older data (all pre-1975). All of these releases chosen for analysis had been previously triangulated to determine release position as a function of time and altitude, and wind profiles had been calculated from these positions. It was expected that we would correlate the computer printouts of trail position with the triangulation photographs, on which were marked altitude-identifying dots, to determine the altitudes of regions to be analyzed. However, these printouts proved to be no longer available either from AFGL or from the contractor who had performed the wind determination. The only printout data available were tabulations of horizontal wind profiles contained in reports. A lengthy procedure (a sort of inverse triangulation) was programmed to circumvent this problem by utilizing known or estimated camera site and orientation data, and estimated release rocket trajectories.

Tabular wind profiles were first entered into computer files at one kilometer altitude intervals. Then using the known site location, approximate camera viewing angles, and an approximate latitude, longitude location for the release, the computer program created a model release along an interpolated rocket trajectory (from the few position data points available), and then transported this release volume using the known wind profile. At predetermined increments of time after injection of the tracer, the program utilized vector triangulation methods to reconstruct and plot at 1 km intervals the image plane view for the particular camera used. The plotted view could then be overlaid on the film to determine altitudes.

The estimated error for this procedure proved to be large since some of the input parameters must be estimated. If the site location, camera orientation, and rocket trajectory were all known, the error would be on the order of ½ km in altitude. The resulting error for the data analyzed, however, appears to be closer to 2 to 4 km.

SECTION V

CONCLUSIONS

Calculation of turbulent atmospheric heating rates and turbulent diffusion coefficients were made from data extracted from photographic records of releases in the stratosphere, mesosphere, and lower thermosphere. Analysis methods which proved most useful were Fourier energy spectra to characterize this turbulence, numerical analysis to determine the gradient of the mean, and analysis of horizontal winds and shears. The combination of spectrally derived parameters coupled with the measurement of the gradient of the mean has produced the most reliable determinations of heating and diffusivity. Improvements in spectral technique have allowed the spectral regime transition at 0.2 k_ν to be determined and thus ν may also be found. The Brunt-Vaisala frequency may also be evaluated directly from the spectral data without recourse to temperature measurements.

Calibration data for many of the older releases (pre 1975) were found to be only marginally adequate, as reconstruction of the calibrations was time consuming and also subject to errors on the order of 2 to 4 km in altitude. Although this was a disappointing finding, approximately 50 percent of these trails do have sufficient calibration information to determine altitudes to approximately one km accuracy.

Results of data analysis reported here (refer to Tables 1 and 2) are representative only, and do not reflect the large volume of data reduced and analyzed, whose results were reported to AFGL scientists as they were obtained.

REFERENCES

1. C.A. Trowbridge, I.L. Kofsky, Densitometric Analysis to Determine Artificial Cloud Expansion Characteristics, AFCRL-TR-75-0147, 14 Mar 1975.

2. C.A. Trowbridge, Densitometric Analyses to Determine Artificial Cloud Expansion Characteristics, AFGL-TR-78-0075, 15 Mar 1978.

3. I.L. Kofsky, C.A. Trowbridge, R.H. Johnson, Analysis of Chemical and Smoke Releases in the Atmosphere, AFCRL-TR-74-0102, 31 Jan 1974.

4. S.P. Zimmerman, J. Appl. Meteorol. 4, 279 (1965).

5. C.A. Trowbridge, I.L. Kofsky, R.H. Johnson, Measurement of Turbulence and Diffusion in High-Altitude Chemical Clouds, AFCRL-68-0382, 30 July 1968.

6. S.P. Zimmerman, C.A. Trowbridge, The Measurement of Turbulent Spectra and Diffusion Coefficients in the Altitude Region 95 to ~110 km, Space Research XII (1973).

7. S.P. Zimmerman, N.V. Loving, Turbulent Dissipation and Diffusivities in the Stratosphere, CIAP-DOT, Volume 1, The Natural Stratosphere (1974)

8. S.P. Zimmerman, Turbulence Observed in Electron Density Fluctuations in Equatorial E Region over Thumba, India, J. Geophys. Res. 81, Oct 1976.

9. S.P. Zimmerman, A.F. Quesada, V.L. Corbin, C.A. Trowbridge, R. Olsen, Dept of Transportation, CIAP Sponsored Research Final Report.

10. P.I. Richards, Computing Reliable Power Spectra, IEEE Spectrum, 4, January 1967.

11. I.L. Kofsky, Reduction of Pictorial Data by Microdensitometry, Chapter in book "Aerospace Measurement Techniques," NASA SP-132, January 1967.

12. S.P. Zimmerman, N.W. Rosenberg, A.C. Faire, D. Golomb, E.A. Murphy, W.K. Vickery, C.A. Trowbridge, D. Rees, The Aladdin II Experiment: Part I, Dynamics, Space Research XIV (1974).

13. R.J. Hill, Models of the scalar spectrum for turbulent advection J. Fluid Mech. 88, 541-562, 1978.

14. D.K. Lilly, D.E. Waco, S.I. Adelfang, Stratospheric Mixing Estimated from High-Altitude Turbulence Measurements, J. Appl. Metro. 13, 448-493, 1974.

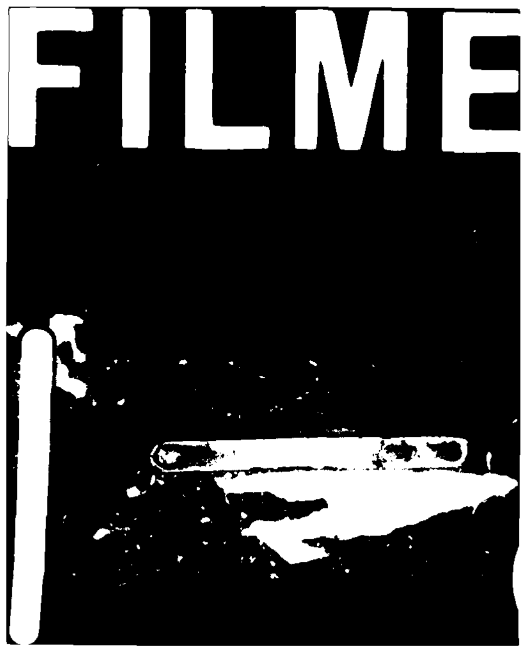
15. J.D. George, S.P. Zimmerman, T.J. Keneshea, The Latitudinal Variation of Major and Minor Neutral Species in the Upper Atmosphere, Space Research XII (1972).

16. A.F. Quesada, Vector Evaluation of Triangulation Camera Parameters from Star Photographs, AFCRL-TR-0451, 21 Aug 1975.

17. A.F. Quesada, Application of Vector and Matrix Methods to Triangulation of Chemical Releases in the Upper Atmosphere, AFCRL-71-0233, 23 April 1971.

18. C.A. Trowbridge, W.S. Andrus, An Automated Coordinate Measurement System for Smoke Trail Photographs, AFGL-TR-78-0231, 29 Sept 1978.

19. C.A. Trowbridge, I.L. Kofsky, R.H. Johnson, Recording and Analysis of Optical Data from Stratospheric Dynamics Experiments, AFGL-TR-78-0015, 14 Jan 1978.


FILME