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Atmospheric Turbulence Measurements from a Subsonic Aircraft

L. J. Otten,* A. L. Pavel,† W. C. Rose,‡ and W. E. Finley†
Air Force Weapons Laboratory, Kirtland Air Force Base, N. Mex.

Nomenclature

f	= frequency
M	= Mach number
t	= total or stagnation conditions
T	= fluid temperature
u	= velocity
v	= signal voltage
ρ	= fluid density
ℓ	= correlation length
C_n^2	= structure constant parameter for index of refraction
$()'$	= fluctuation in a quantity
$\overline{(\ )}$	= time average of a quantity
$\langle(\ )\rangle$	= rms of a quantity

Abstract

THE operation of constant-temperature and constant-current fine wire and thin film anemometers on an aircraft is discussed. Instrumentation has allowed data with a 10-kHz bandwidth to be gathered. Atmospheric turbulence data, gathered at flight Mach numbers of 0.28 and 0.83 and operating altitudes of 3.6-12.5 km, are presented. Samples of results from studies of stratospheric turbulence, and the turbulence structure of the tropopause boundary, are described.

Contents

The Earth's atmosphere is rich in various scale sizes of turbulent motion. The largest scale size of interest in atmospheric turbulence exceeds 1 km, and the smallest can be as small as 1 mm. The frequency requirements on an airborne system for detecting this range of turbulence scales are solely dependent on how fast one flies through the turbulence. For example, to resolve turbulent bursts of 500 to 5 mm at high subsonic speeds requires a frequency response of 100 Hz to 10 kHz. This band becomes even more formidable when one considers the dynamic span of the turbulent fluctuations encountered. For a Kolmogoroff "$-5/3$" one-dimensional energy decay over the required five orders of magnitude in frequency, one would encounter just slightly less than an 84-dB change in turbulence intensities. A sensor system that has the capabilities to measure these ranges of turbulence is a fine wire or thin film anemometer.

A fine wire heated to a temperature only slightly above ambient (i.e., $T_{\text{wire}}/T_{\text{ambient}} = 1.0002$) will sense the desired fluctuations in static temperature.[1] For increasing Mach numbers, the values of the velocity fluctuations present in the atmosphere will contribute to the measured temperature values.[2] This behavior comes about through the aircraft's flight Mach number and is not a function of the motions and variations present in the atmosphere. Thus if one were to use only a single, unheated wire, it would be impossible to measure the value of fluid temperature fluctuations from a high-speed aircraft.

To surmount this apparent impasse, another wire, heated to at least twice the freestream absolute temperature, is required. This wire, when cooled by the airflow, becomes sensitive only to the mass flows (ρu).[1] The heated wire produces a signal proportional to the sum of two desired turbulence quantities ρ' and u'.[2] Once again, if one were to operate only a single heated wire, it would, in general, be impossible to determine the magnitude of the velocity fluctuations. This is true independent of the aircraft's flight Mach number. Spectra can be obtained, however, under the assumption that the spectra of ρ' and u' are identical.

We therefore have the situations that at high speeds we have two systems capable of measuring two fluid parameters, neither of which is sufficient by itself, to deduce information about the atmosphere. In high-speed wind tunnel testing, it has been shown that combining the two measurements can yield the desired information about the fluctuating velocity, temperature, or density.[1,2]

Based on this knowledge, an NC-135A aircraft was equipped with such a dual-probe anemometer system. Both constant-temperature (for the hot wire) and constant-current (for the unheated wire) anemometers were used. The sensors were either fine wires, 5-μm tungsten (Ref. 3) or thin films deposited over quartz rods. Data from the atmospheric research aircraft were found to have a relatively low signal level with large discrete noise levels (from engine compressors, for example) beyond 10 kHz. Because of this, all data from this aircraft were filtered at 10 kHz. To reduce the large dynamic range of the data for recording, and for inflight analysis purposes, the signal was dual processed. An ac-coupled signal was taken to resolve data from about 10 Hz to 10 kHz and a dc-coupled signal was used for the frequencies from about 0.1 to 10 Hz.

The probe tips were installed in a tapered support structure that provided a rigid mounting and a means of placing the sensors well into the freestream and parallel to the aircraft potential flowfield. Flowfield accelerations around the aircraft were assumed to have no effect on normalized freestream turbulence, a reasonable assumption in view of the very small pressure gradient in the vicinity of the probe.

Samples of representative results from flights at various Mach numbers and altitudes are shown in Table. 1. The data reduction techniques are found in Refs. 2 and 4. Table 1 clearly shows the compensation for aircraft speed and the ability of this system to measure relatively small turbulence variations.

A typical spectrum of the mass flux and total temperature in the frequency domain from one of these points is shown in Fig. 1. A $-5/3$ slope is evident for frequencies as low as 10 Hz and continues to the noise level at about 5 kHz. Since both the total temperature and mass flux fluctuations follow the Kolmogoroff energy cascade, so will both the velocity and density fluctuations. For the flight speeds shown in Table 1, these frequencies correspond to scales from 10 m to 10 mm. In some applications, the integral scale of the density fluc-

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*Major, U.S. Air Force. Member AIAA.
†Major, U.S. Air Force.
‡Consultant, President of Rose Engineering. Associate Fellow AIAA.

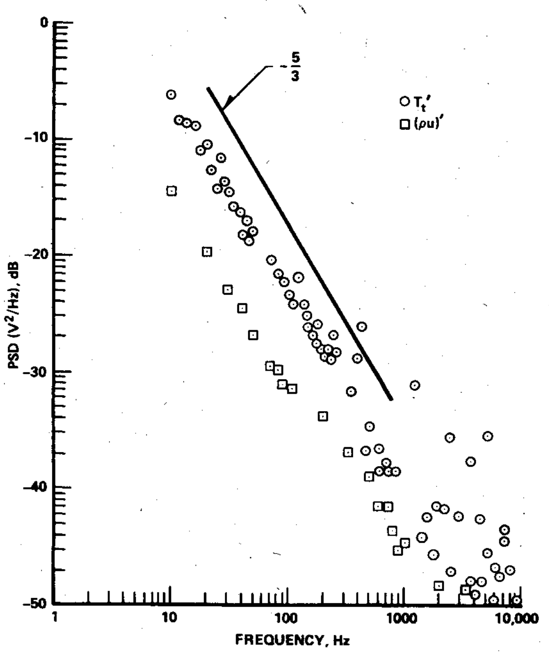

Fig. 1 Spectra of mass flux and total temperature fluctuations, 3.6 km, $M = 0.57$, Feb. 1979.

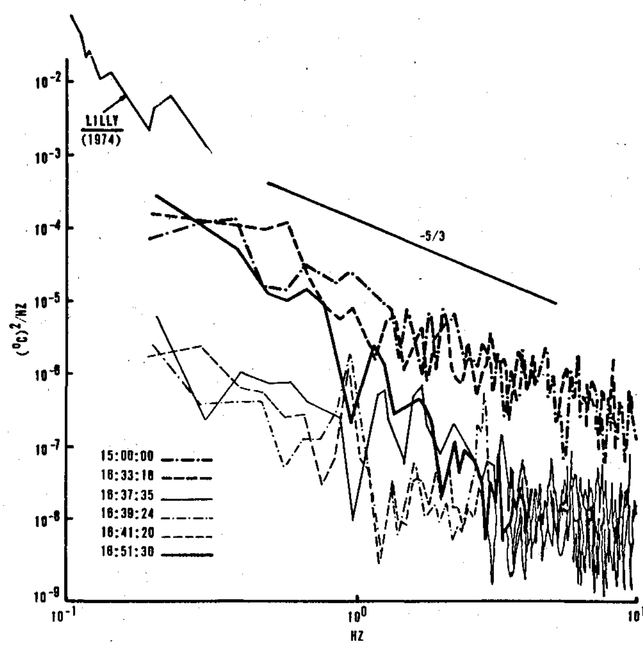

Fig. 3 Atmospheric turbulence during the 1970 solar eclipse.

Table 1 Representative turbulence data

Altitude, km	u, m/s	M	ℓ, m	$\frac{\langle(\rho u)\rangle}{\bar{\rho}\bar{u}}$, %	$\frac{\langle T'\rangle}{\bar{T}}$, %	$\frac{\langle\rho'\rangle}{\rho}$, %
3.66	234	0.57	6.0	0.028	0.014	0.014
3.66	153	0.48	—	0.026	0.011	0.011
3.66	124	0.37	—	0.023	0.007	0.007
3.66	93	0.28	—	0.025	0.006	0.006
8.84	271	0.83	7.1	0.026	0.021	0.019
11.89	237	0.80	10.9	0.021	0.006	0.007

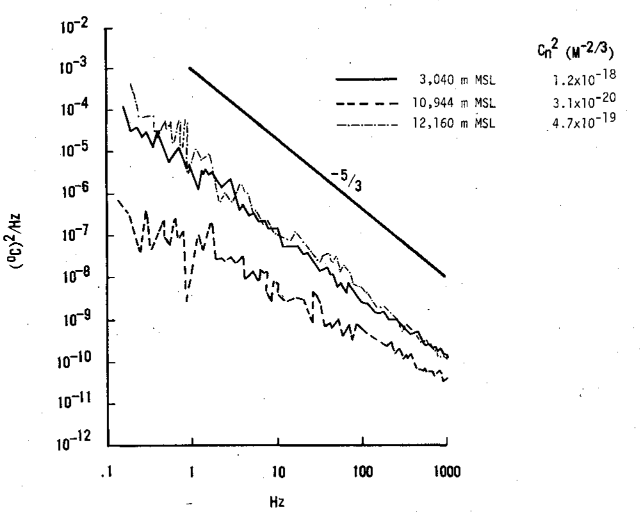

Fig. 2 Atmospheric turbulence through the tropopause.

tuations, ℓ, are of interest and these can be obtained by integrating the time autocorrelation function of either the mass flux or the total temperature to obtain the integral time scale and then using the mean velocity through the turbulence to calculate the integral spatial scale. Spatial scales found for the present data, assuming an exponential decay for the autocorrelation function, are given in Table 1. Several applications of these types of data are found in Ref. 6.

A sample of upper atmospheric data is shown next. Meteorological data from a concurrent rawinsonde flight indicated the tropopause to be at approximately 11,552 m. (Data showing the changing levels of turbulence as the aircraft climbed through the tropopause are shown in Fig. 2.) Just above the balloon-measured level of the tropopause, the level of turbulence increased dramatically (12,160 m in Fig. 2) to an intensity comparable to values seen at the top of the atmospheric boundary layer (approximately 1670 m above the surface). Noted in the increased turbulence was a pronounced component at the fractional hertz frequencies. The C_n^2 values, also shown in Fig. 3, for these data were obtained by the techniques discussed in Refs. 2 and 4.

Samples of high-frequency transient atmospheric effects superimposed in a low-frequency background are shown in Fig. 3. During the total solar eclipse that occurred in February 1979, a mission was flown about 608 m above the tropopause at 11,856 m MSL in the area of the eclipse. This provided a very uniform pre-eclipse turbulence background in the stratosphere, as shown by the 14:00:00 and 16:33:18 time lines in Fig. 3. These levels can be contrasted with another measurement of stratosphere turbulence in the line labeled "Lilly."[5] As the sun entered totality the level of turbulence clearly decreased, as shown by the 16:37:35, 16:39:24, and 16:41:20 time lines in Fig. 3. After the sun emerged, the level of turbulence gradually returned to previous levels, the 16:51:30 time line. The passage of a simultaneous, relatively rapid low-temperature spike was also noted.

Atmospheric turbulence measurement using fine wire anemometry offers a wealth of knowledge to a broad range of investigations. Through proper handling of the resultant two-sensor data very precise and versatile atmospheric turbulence measurements can be made from a highly mobile station.

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