Power spectra of turbulence in the free atmosphere[1]

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(Manuscript received January 17, 1966)

ABSTRACT

Presently known data on the spectrum distribution of turbulence energy in the free atmosphere near jet-stream level are combined from various Russian, Australian and American sources. A comparison is made between these data. Special attention is given to the phenomenon of clear-air turbulence (CAT).

1. Introduction

Clear-air turbulence (CAT) still presents one of the major hazards of aviation. Although a large volume of statistical data on CAT occurrence is available and has led to useful correlations between CAT and macro-scale weather patterns (COLSON, 1963; PINUS & SHMETER, 1962; PCHELKO, 1962; REITER, 1961, 1963), the physical nature of CAT remained unexplored until very recently. Research flights conducted by specially instrumented aircraft over the USSR (SHUR, 1962; VINNICHENKO *et al.*, 1965) and Australia (REITER & BURNS, 1965) produced sets of power spectra of CAT near jet-stream level which, for the first time, give indications of the processes that lead to the formation of turbulent flight conditions in clear air.

Although there are some differences between the USSR and the Australian (TOPCAT) measurements, they agree in certain ways for wave lengths in the CAT region of conventional jet aircraft, i.e., for $L < 300$ m. These points of agreement and disagreement will be discussed in detail farther below.

In addition to these detailed surveys of the atmospheric microstructure, meso-scale wind fluctuations in the jet-stream region were spectrum analyzed, using aircraft measurements of wind vectors obtained from Doppler navigational systems (PINUS, 1963; KAO & WOODS, 1964). Thus, for the first time, we have turbulence spectra available for the free atmosphere at jet stream level, ranging from approximately 50 m of wave length to 800–900 km.

Although turbulence data from high levels in the atmosphere still have to be considered sparse, the authors find it worthwhile to take stock of our present knowledge on flow disturbances in the free atmosphere. Using the subsequent survey as a starting point, avenues of further research will be pointed out.

2. Measurements of turbulence in the free atmosphere

Since the composite picture of atmospheric turbulence for $5 \times 10 < L < 1 \times 10^6$ m has to rely on various data sources, a brief description of the methods of measurement appear in order.

(1) *Accelerometer records. The aircraft as "sensor"*

When an aircraft penetrates a zone of developed turbulence, it experiences bumps. With accelerometers mounted in certain points of the air frame, and knowing the response functions for these points, it is possible to transform the recorded loads into atmospheric gusts. Methods and equipment have been described in detail by SHUR (1959). In summary the procedure is as follows: Airplane loads are measured, coded and recorded on magnetic tape. For analysis (under stationary laboratory conditions) the record is played back, decoded and connected with the input of the spectrum analyzer. The output signal of every filter is divided by a coefficient, equal to the squared modulus of the response function for the given middle fre-

[1] This report resulted from discussions held between the authors during the International Colloquium on the Fine-scale Structure of the Atmosphere, Moscow, June 15–22, 1965.

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quency of the filter. Thus, after processing one arrives at the true power spectrum of atmospheric turbulence. Measurements of the w-component of turbulence were made by means of this method beginning from 1960, using a TU-104 aircraft. Flights consisted of traverses at constant height and airspeed. Pilots were instructed not to handle the controls if possible while measurements were taken.

(2) *Gust records. The aircraft as "platform"*

The TOPCAT measurements were carried out over Australia (MIZON, 1964; REITER, 1964) with a Canberra B-6 aircraft, instrumented with a gust probe mounted on a nose boom and measuring differential pressure variations in three coordinate directions. The original instrumentation, described by BURNS (1963), had to be modified slightly in order to adapt it to higher altitude measurements (BURNS & RIDER, 1965). The instrumentation appears to be similar to the "inclinometer" recently constructed and described by PAKHOMOV (1962) and used for studying atmospheric motions in clouds.

From the pressure-probe records power spectra of all three components of atmospheric gusts were derived. Vertical velocities were determined from the air flow sensed by the probe, and from aircraft motions using reduction equations developed by CHILTON (1954) and CRANE *et al.* (1956). The longitudinal turbulence components were derived under the assumption that the ground speed of the aircraft remained constant, i.e., that all variations in air speed were due to turbulence. Comparisons with tower measurements at Darmstadt, Germany, suggest that this assumption is justified at least at low altitudes.

Measurements of the lateral turbulence component presented more of a problem. BURNS & RIDER (1965) attribute the usefulness of the Australian data to the installation of tip tanks which reduced the "Dutch roll" motion of the aircraft, and to empirical corrections established from gust records of artifically induced "Dutch roll". A small error in the v-component of turbulence still remained at long wave lengths, simulating slightly to high kinetic energy.

Investigations of the horizontal wind speed fluctuations at scales $L < 3000$ m were carried out in the U.S.S.R. from aircraft equipped with hot-wire anemometer. Using this device, described by VINNICHENKO (1964), the spectra of u-component were obtained in clear air at scales from 20 m up to 3000 m.

(3) *Doppler-wind measurements*

By means of Doppler radar and analog computers wind records may be obtained almost continuously by measuring ground speed, heading, and drift angle. Aircraft motions will affect the accuracy of measurements, especially at high altitudes. Since these motions are, however, of sufficiently small period, they may be filtered out easily by computing mean values over several successive points of measurement. This has been done successfully with "Project Jet Stream" data, limiting the resolution of wind and temperature data to approximately 20 km (REITER, 1962).

Usually larger aircraft maneuvers such as wide turns, etc., automatically block the Doppler systems and actual data points are lost during such operations. Allowance has to be made for this fact in the spectrum analysis of such data.

By flying as straight as possible with a constant power setting of the engines, Doppler radar measurements in the U.S.S.R. allowed to extend the range of representative data to smaller scales (4–5 km) (PINUS, 1964).

3. Power spectra of turbulence

The results from the measurements described before have been combined in Fig. 1, using $(km/hr)^2/(rad/km)$ as basic unit for spectral density, and (rad/km) for wave number (meters for wave lengths). The sources and characteristics of the various spectra entered schematically in this diagram (omitting some of the small and insignificant details) are listed in Table 1.[1] One can see that data from various airborne devices cover practically the whole range of wave lengths from 50 m to ~ 1000 km.

From the evidence presented in Fig. 1, we may draw several conclusions:

(i) Even though wave lengths of almost 1000 km are described by spectrum analysis, the

[1] The various units of measurement for power spectral density used by different authors have been converted to $(km/hr)^2/(rad/km)$ in the following way:

$$1[\text{cycle}] = 2\pi\ [\text{rad}],$$

$$1[(m^2/sec^2)/(cycle/km)] = 2.06[(km^2/hr^2)/(rad/km)]$$ (KAO & WOODS),

$$1[(ft^2/sec^2)/(cycle/ft)] = 5.84 \times 10^{-5}[km^2/hr^2)/(rad/km)]$$ (REITER & BURNS).

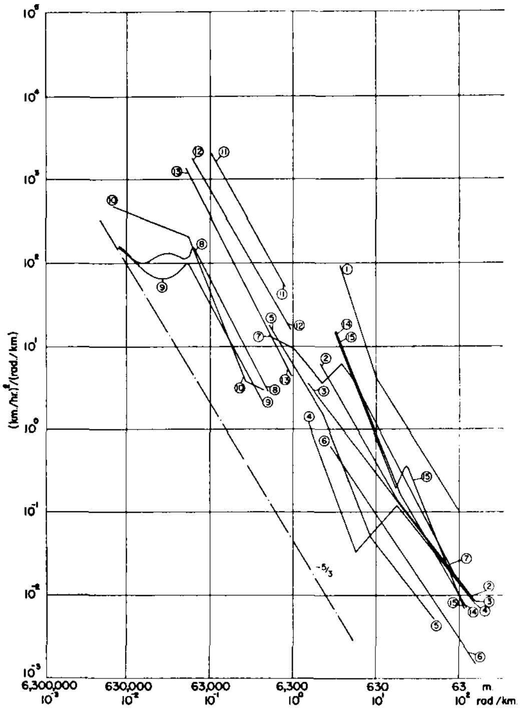

Fig. 1. Power spectra of atmospheric turbulence (see Table 1).

ultimate input region of turbulent energy into the atmosphere is not yet established by present measurements.

(ii) The spectral intensities obtained under "severe CAT" conditions may be ten (or even more) times larger than those measured under "light CAT" at a given frequency.

It is worth noting that spectra Nos. 8, 9, and 10 (Kao & Woods) agree reasonably well with spectra Nos. 11, 12, and 13 (Pinus). The latter show a slightly higher intensity. The U.S.S.R. data have been classified into spectra for severe (No. 11), moderate (No. 12) and light (No. 13) CAT, whereas the U.S. data have been broken down into measurements taken during flights parallel (Nos. 8 and 9) and normal to the jet stream (No. 10). Some CAT was experienced during these flights, but on the average probably not as much as during the flights contributing to spectrum No. 11 (see e.g. Reiter, 1962).

The slight discrepancies between the two sets of data may be due to:

(*a*) different methods of analysis. Pinus used the fluctuations of the total wind speed for the spectral density computations whereas Kao and Woods considered separately the velocity components normal and parallel to the direction of strongest wind encountered during the flight;

(*b*) different geographic locations. Jet streams over the eastern United States, on the average, are perhaps steadier than over the U.S.S.R., and consequently might give rise to different mesoscale perturbations. The quasipermanent upper trough in the lee of the Rocky Mountains, and the confluence of cold arctic air and moist tropical air in the southwesterly flow east of this trough might give rise to a certain "bias" of the U.S. data (Kao & Taylor, 1964).

(iii) Experimental power spectra obtained by different authors follow, in general, the " $-5/3$" law up to scales ~ 100 km. However, in some parts of the spectra there may be significant deviations from this law.

These deviations may be regarded as evidence that within the investigated range of scales there are sources and sinks of turbulent energy in the free atmosphere. In the authors' opinion unstable gravity waves and Archimedian forces should be considered as factors which may cause the observed deviations from a " $-5/3$" law.

Buoyant subrange

Spectrum No. 1 was obtained over the U.S.S.R. under conditions of severe CAT. It is typical for large spectral intensities in a stably stratified atmosphere.The spectrum curve is. steeper than " $-5/3$" at wave lengths $L > 600$ m. A similar change of slope of the spectral curve may be seen in spectrum No. 14, which is typical for the w-component under moderate CAT, and in spectra Nos. 2 and 5 for the u- and v-components.

The steeper slope of the spectrum curve at wave lengths $L > 600$ m had been attributed by Shur (1962) to the energy-dissipating effect of buoyant forces in a thermally stable environment. The increase of slope in the "buoyant subrange" was also derived theoretically (Bolgiano, 1959, 1962; Lumley, 1965; Monin, 1964).

The other spectra in the short-wave region of Fig. 1 do not corroborate the existence of a "buoyant subrange", even though some of them were measured under thermally stable conditions (see Table 1).

From recent discussions at the International

Table 1. *Power spectra of turbulence in the free atmosphere.*

Spectrum No.	Source	Characteristics (turbulence components given with respect to course of aircraft)
1	Shur, 1962	w-component, severe CAT, near jet stream level, stable stratification
2	Reiter & Burns, 1965	u, v-components, moderate CAT, jet stream level, stable stratification
3	Reiter & Burns, 1965	w-component, flight parallel to wind, moderate CAT, jet stream level, stable stratification
4	Reiter & Burns, 1966	w-component, flight nearly normal to wind, moderate CAT, jet stream level, stable stratification
5	Vinnichenko, Pinus & Shur, 1965	u-component, no CAT, near jet stream level, stable stratification
6	Reiter & Burns, 1965	u, v, w-components, light turbulence at 100 m altitude, unstable stratification
7	Vinnichenko, Pinus & Shur, 1965	u-component, light turbulence at 1000 m altitude, unstable stratification
8	Kao & Woods, 1964	u-component, at jet stream level, flight parallel to jet stream
9	Kao & Woods, 1964	v-component, at jet stream level, flight parallel to jet stream
10	Kao & Woods, 1964	u, v-components, at jet stream level, flight normal to jet stream
11	Pinus, 1963	u-component, severe CAT, under core of jet stream, flight normal to jet stream
12	Pinus, 1963	u-component, moderate CAT, under core of jet stream, flight normal to jet stream
13	Pinus, 1963	u-component, light CAT, over core of jet stream, flight normal to jet stream
14	Shur, 1963	w-component, moderate CAT, at jet stream level, stable stratification
15	Shur, 1962	w-component, moderate CAT, at jet stream level, stable stratification

Colloquium on the Fine-Scale Structure of the Atmosphere in Moscow several opinions on the "buoyant subrange" were formed:

(i) The "buoyant subrange" may exist under conditions of stable stratification and may be seen from scales of about 30–100 m up to scales where the energy sources (of unspecified nature) balance the buoyant forces. The slope of the spectral density curve may be equal to either "$-11/5$" (Bolgiano) or "-3" (Lumley), depending on different assumptions about the relation between the rate of energy transfer through the spectrum and the Archimedian forces.

(ii) The "buoyant subrange" may also exist under conditions of stable stratification at scales $L > 600$ m with a slope of the spectral curve approaching "-3" (Shur). This seems to be corroborated by experimental data, some of which are shown in Fig. 1.

(iii) The "buoyant subrange" does not exist as a "pure" phenomenon. Similarity considerations in the theoretical derivation of the spectrum slope in the "buoyant subrange" only take into account the turbulence alleviating Archimedian forces under thermally stable conditions, but not the generating forces of vertical wind shear. Under real conditions in the atmosphere, shearing forces may closely balance buoyant forces over a wide range of wave lengths, thus leaving no room for the development of a "buoyancy subrange". Mathematical theory taking into account the effects of vertical shear on turbulence spectra has yet to be formulated.

In view of these arguments one may accept as reasonable:

(i) the complex form of spectral curves in the short-wave region of turbulence in the free atmosphere;

(ii) the existence of a quasi-inertial region at scales where the "buoyant subrange" could be expected according to present theory;

(iii) the existence of a "buoyant subrange" at scales other than those which are predicted by theory.

4. Generation of clear-air turbulence

The spectra presented schematically in Fig. 1 allow to identify several sources of energy affecting the CAT region. (The latter may be identified as roughly 600 m $>L>$ 10 m for standard-design jet aircraft presently in operation.)

According to modern views atmospheric turbulence is due to instability of the general planetary flow. As it was mentioned above this original input region of energy into the power spectra is not yet established by present aircraft measurements. Thus, we can consider in this paper only such generators (or sources) of turbulent energy which act on smaller scales, and which produce "humps" in the spectrum curves at certain wave numbers.

At wave lengths $L \sim 100$ km KAO & WOODS find a significant difference in the spectrum curves between measurements parallel and normal to the jet streams (Spectra Nos. 8, 9, 10 in Fig. 1). The latter show higher spectral densities than the former, in agreement with the characteristic "striated" pattern of jet streams. The peak in the spectrum curves near 100 km suggests a wave-length region of turbulent energy input directly associated with jet fingers. The wave motions associated with these horizontal scales would be gravity-inertial waves. Another input region seems to exist at inertia wave modes >1000 km. NEWTON (1959) has shown that jet maxima may be explained as resulting from quasi-inertial oscillations.

As it is seen in Fig. 1, there is a rather poor connection (or even a gap) of the experimental spectra between 20 km $>L>$ 5 km. This deficiency is produced by measurement difficulties between micro- and mesoscale, using either accelerometers or hot-wire anemometers, or Doppler radar. It is possible that a source of turbulent energy may act in this very region. Especially spectra No. 1, 14, and 15 suggest higher kinetic energy at smaller wave lengths than shown, for instance, by spectra Nos. 11, 12 or 13. Such mesoscale wave lengths of the scale indicated above are in agreement with orographic lee waves, and with dimensions of some of the cloud streaks and banks observed from TIROS satellites (REITER, BERAN *et al.*, 1965). Not before this meso-structural spectrum region of the free-atmospheric flow is better understood, its micro-structure, especially CAT, can be located and forecast more efficiently.

Another source of energy for turbulence affecting aircraft may be identified in convective motions within thermally unstable atmospheric layers. A typical spectrum under such conditions is No. 7. It was obtained from aircraft measurements in moderate turbulence in well-developed convection at approximately 1 km altitude. This spectrum indicates a "hump" at waves of about 1.2 km. Apparently convective bubbles acted as a turbulent energy source, raising the energy level of velocity fluctuations beyond what should be expected from the decay of mesoscale wind fluctuations. The dimensions of these bubbles appear to be of the same scale as the thickness of the convective layer beneath the aircraft. Such conditions will mainly be found close to the ground, or near convective cloud systems. Both instances would usually be ruled out as CAT, because turbulence in these regions is either anticipated by the pilot, or it will not occur in *clear* air.

Special interest rests with those cases in which additional energy sources appear under stable stratification in the free atmosphere.

Spectrum No. 4 which is typical of some of the CAT measurements at jet stream level over Australia, shows a marked "hump" at wave lengths between 300 and 1 km. The appearance of the "hump" depends very strongly on the angle between wind direction and aircraft course. Flights at relatively large angle to the wind seemed to produce a pronounced hump, while flights conducted nearly parallel to the wind showed no hump and much higher energy levels at wave lengths $L>1$ km, even though the same turbulent region was explored (spectrum No. 3). The "hump", if present, appeared mainly in the w-component and not nearly as well developed in the u- and v-components. A similar "hump" can be seen in spectrum No. 15, which was obtained over the U.S.S.R. near the jet stream. Unfortunately, the dependence of the "hump" on the angle between wind and flight direction was not explored in this case.

From this observational evidence the conclusion had to be drawn that the presence of strongly anisotropic gravity waves suppressed turbulent energy at the scale of their wave length when flying parallel to the wave crests.

Turbulent energy was contributed at the long-wave end of the isotropic inertial subrange in cases of moderate to severe CAT. We have to expect that faster aircraft may, on occasion, have to face considerable gustiness up to, and beyond, speeds of Mach 3, especially when flying normal to the wave fronts of the breaking gravity waves because under such flight conditions the " $-5/3$" slope of the spectrum curves seems to extend to considerable wave length.

Critical conditions under which gravity waves on a thermally stable interface with vertical wind shear become unstable by increasing their amplitudes exponentially with time, may be evaluated from perturbation theory (HAURWITZ, 1941), The phase velocity of gravity waves is given as

$$c=\frac{\varrho_0\bar{u}_0+\varrho_1\bar{u}_1}{\varrho_0+\varrho_1}\pm\sqrt{\frac{g}{k}\frac{\varrho_0-\varrho_1}{\varrho_0+\varrho_1}-\frac{\varrho_0\varrho_1}{(\varrho_0+\varrho_1)^2}(\bar{u}_0-\bar{u}_1)^2}. \qquad (1)$$

Subscripts 0 indicate conditions in the lower layer, subscripts 1 those in the upper layer. ϱ stands for density, ū for mean wind speed, $k=(2\pi)/L$ for wave number, and g for acceleration of gravity. Flow conditions become unstable if the argument under the square-root becomes negative. Critical conditions, thus, may be formulated as (REITER, 1961, 1963)

$$\mathrm{R}\equiv\Delta\varrho-\frac{k\bar{\varrho}}{2g}(\Delta\bar{u})^2\lesssim 0 \quad \begin{matrix}\text{unstable}\\ \text{stable}\end{matrix}. \qquad (2)$$

The following abbreviations have been used in this expression:

$$\Delta\varrho=\varrho_0-\varrho_1;\quad \bar{\varrho}=\frac{\varrho_0+\varrho_1}{2};\quad \Delta\bar{u}=\bar{u}_1-\bar{u}_0.$$

The instability criterion (2) is similar to Richardson's criterion

$$\mathrm{Ri}=\frac{g}{\theta}\frac{\partial\theta}{\partial z}\Big/\left(\frac{\partial u}{\partial z}\right)^2 \qquad (3)$$

(θ = potential temperature), it is however wave-length dependent: Under suitable conditions of $\Delta\varrho$ and $\Delta\bar{u}$, there will be a critical wave number k, beyond which gravity waves become unstable. Breaking gravity waves have been observed in layers of cirrus clouds (REITER & HAYMAN, 1962). From evidence presented in Fig. 1 this breakdown seems to generate isotropic turbulence characteristic of the inertial subrange.

5. Correlation between subjective and objective turbulence data

The power spectra shown in Fig. 1 reveal a spread over more than two orders of magnitude of spectral density in the wave length region of CAT. This is a somewhat larger variation of turbulence kinetic energy than is indicated by the mesoscale disturbances of $L>10$ km shown in the same diagram.

Spectral densities reveal a systematic increase from flights reporting "no CAT" (No. 5), to those with "light CAT" (No. 6), "moderate CAT" (Nos. 2, 3, 4, 14, 15) and "severe CAT" (No. 1). Even though observations were made with two different aircraft (TU-104 and Canberra B-6), the agreement between subjective pilot's reports and objective gust measurements is remarkable. The only spectrum which disagrees with the rest of the data is No. 7. It was measured at low levels (1000 m) and was classified as "light turbulence" although its spectral densities lie well within the range of "moderate CAT". Since bumpy flight conditions usually are expected at low levels with thermal convection, it might very well have been that the pilot was prepared to encounter stronger gusts than actually found. Thus his judgment was biassed in favor of lower turbulence intensities.

From the foregoing it appears that a universally applicable comparison of subjective pilot reports of CAT with objective turbulence measurements may be made if one allows for psychological reactions by the pilot. Response characteristics of the aircraft have to be incorporated into such a correlation if large differences in design and airspeed characterize the various measuring platforms (MACCREADY, 1964).

6. Conclusions and outlook for future research

In spite of the sparsity of data available on the turbulent energy distribution in the free atmosphere, past measurements indicate the presence of distinct input regions of energy at certain wave-length ranges. Energy input seems to occur at wave lengths ~1000 km, corresponding to planetary inertial waves in the general circulation; at wave lengths somewhat larger than 100 km, corresponding to jet streams and gravity-inertial wave modes; at wave lengths somewhat shorter than 60 km, corresponding to meso-scale phenomena of long gravity or lee waves; and at wave lengths near 1 km, corresponding to short gravity-shearing waves in a stable environment, and to the dimension of convective "bubbles" in unstable layers.

It will be necessary to differentiate between those portions of spectra with a " $-5/3$" slope, where there is a real inertial transfer of energy through the spectrum according to the Kolmogorov-Obukhov theory, and those spectrum regions with the same slope, however with various sources and sinks of turbulent energy in balance with each other. In a manner of speaking, as suggested by Lumley, in the first case there is only a "transport" of energy through the spectrum, whereas in the second case there is a compensation of energy "export" from the spectrum due to some mechanism, by energy "import" due to another mechanism. Thus, it becomes evident that a standardization of atmospheric turbulence spectra without taking into account "particularities" of real spectra can give only rough results.

Although from the spectra presented in Fig. 1a break-down of gravity waves into isotropic turbulence experienced as CAT is indicated, the precise mechanism of such a transformation of wave-energy into turbulent energy is still unknown.

A theoretical solution of problems in question has to be corroborated by representative experimental data. Turbulent regions and their surroundings have to be measured at least in three space coordinates, preferably also in their changes with time. The detailed structure of the temperature and density field will have to be determined together with the structure of the wind field. It would be highly desirable to carry out thorough simultaneous measurements of turbulence spectra in the whole available range of scales. This would greatly facilitate the connecting of data from different spectral ranges. Such measurements would call for more sophisticated instrumentation than has been available on aircraft so far. More than just one measuring platform should be employed simultaneously to allow measurements in all dimensions.

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СПЕКТРЫ ЭНЕРГИИ ТУРБУЛЕНТНОСТИ В СВОБОДНОЙ АТМОСФЕРЕ

Известные в настоящее время спектральные распределения энергии турбулентности в свободной атмосфере вблизи струйных течений собраны вместе из различных советских, австралийских и американских источников. Производится сравнение этих данных. Специальное внимание уделяется турбулентности в ясном небе.