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A PERSPECTIVE ON THE STATUS OF MEASUREMENT OF ATMOSPHERIC TURBULENCE IN THE U.S.

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PRESENTATION TOPICS

- Characterization studies
  - Integral scale value
  - Spanwise gradient
  - Modeling
- Encounter studies
  - VGH
  - Special encounters
- Other
  - Ground-based measurement
  - Other in-situ measurement
  - Simulation
  - Active control
  - Workshop
- Summary

The purpose of this "pilot" paper is to review some recent efforts related to studies of atmospheric turbulence with primary emphasis on measurements. While not a comprehensive treatise, it is believed that this selected information can contribute to the general planning for a future specialist meeting. The content of the paper is given in the first figure. A discussion of a NASA measurement program aimed at characterization of atmospheric turbulence along with some modeling implications is the major content of the paper. Refs. 1-13 apply to this portion of the paper.

Other work discussed briefly includes statistics on turbulence encounters for various types of aircraft operations (refs. 14-15), studies of special severe encounters (ref. 16) and reference to remote sensing (ref. 17). Wind shear is considered to be a special topic and is not treated here.

N86-11193 #

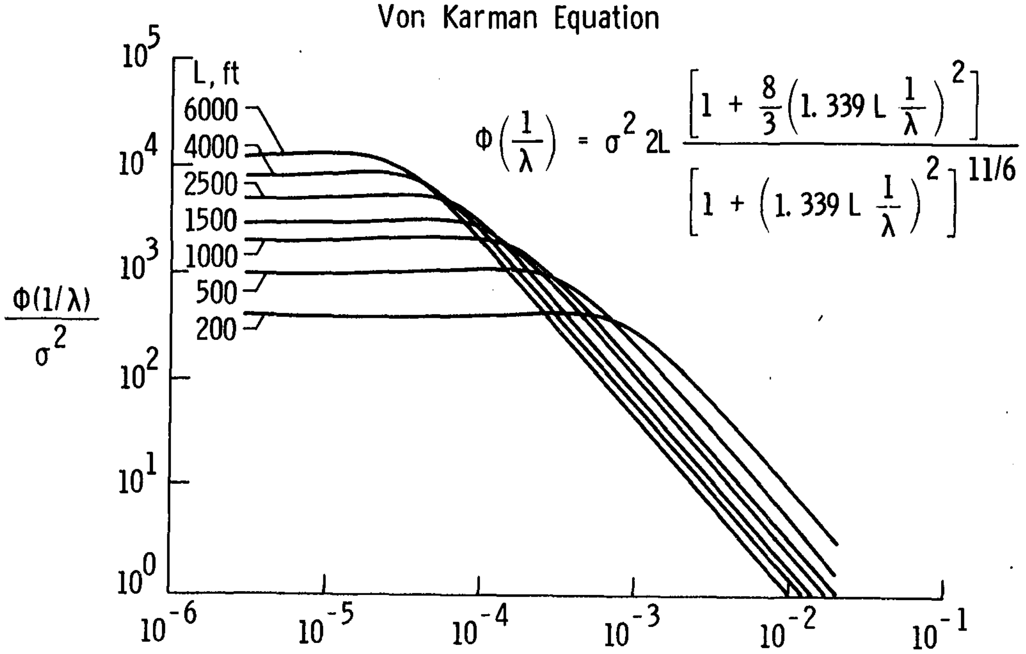
MAT PROJECT GOAL

Obtain atmospheric turbulence power spectra and determine appropriate values of L for different meteorological conditions (jet stream, low altitude clear air, mountain waves, near thunder storms) over an altitude range from near sea level to about 65,000 feet. Utilize same instrumentation system and data reduction procedure for all measurements.

The objectives of the NASA Measurement of Atmospheric Turbulence (MAT) program are stated here. Very low frequency measurements were required since the emphasis was on long wavelength portion of the power spectrum in order to estimate values of the integral scale value, L.

THEORETICAL TRANSVERSE POWER SPECTRA

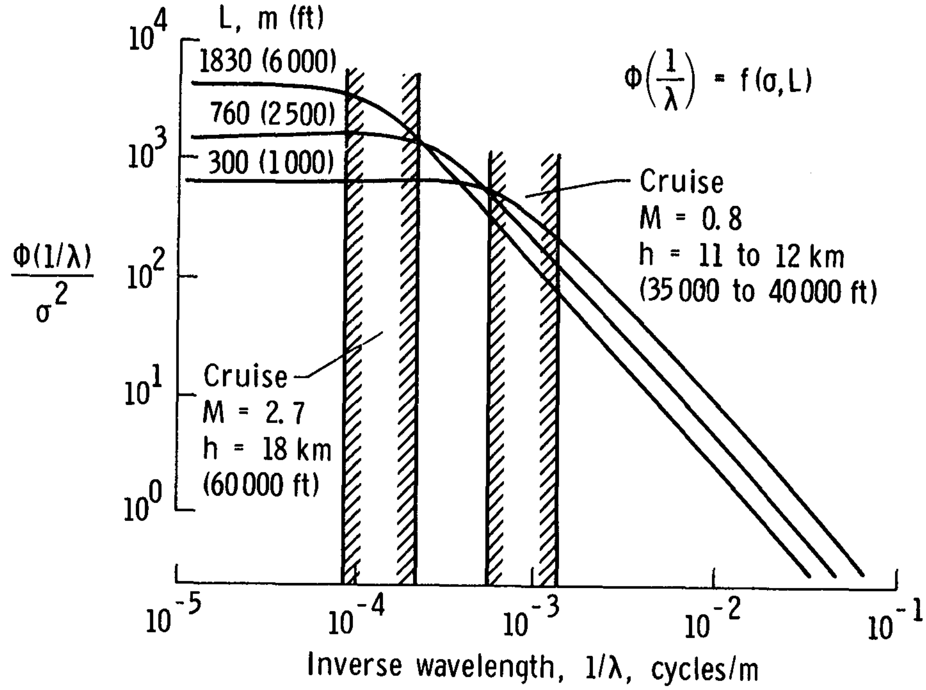
Von Karman Equation



The classical von Karman expression is given on this figure and shows that two parameters are required to describe a power spectrum, σ, related to the intensity, and L, related to the scale of the turbulence sample. The family of curves shown are normalized with respect to intensity and show how the location of the "knee" or flattening of the power spectrum changes with L. Some design specifications designate that L = 2500 ft. be utilized if power spectral analysis techniques are to be used.

THEORETICAL POWER SPECTRA

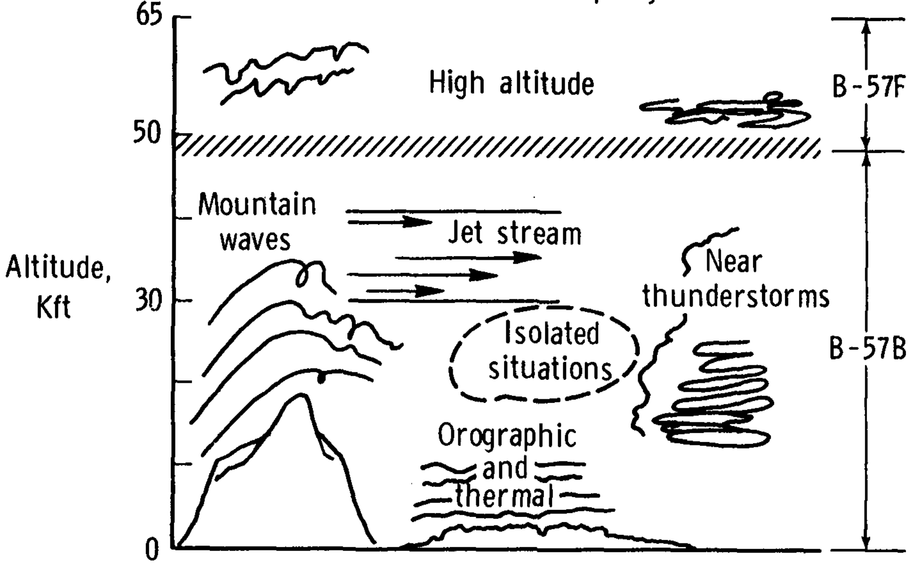
Von Karman Turbulence Model



Tne gust response characteristics of most contemporary aircraft are in a frequency range that knowledge of an appropriate L value is not needed; however for large, flexible supersonic aircraft the principal response is at much lower frequencies. Thus the aircraft response can be significantly different for the same intensity turbulence (note the log scales on the figure), and utilization of an appropriate L for design is important.

MAT PROJECT

Clear Air Turbulence Samplings



An instrumented B-57B Canberra aircraft was utilized as the sampling airplane. Samples of clear air turbulence were obtained for conditions shown. While the instrumentation was later installed on a B-57F for higher altitude samplings, due to various difficulties, data sufficient for publication were not acquired.

EQUATIONS FOR THE DETERMINATION OF GUST VELOCITY COMPONENT TIME HISTORIES

$$\text{Gust velocity component} = \left[\text{Primary measurement}\right] + \left[\text{Aircraft motion corrections}\right]$$

Longitudinal

$$u_g = \left[\Delta V\right] + \left[v_{ax} \sin \bar{\psi} + v_{ay} \cos \bar{\psi}\right]$$

Lateral

$$v_g = \left[V\beta\right] + \left[-V\Delta\psi + v_{ax} \cos \bar{\psi} - v_{ay} \sin \bar{\psi} + l\dot{\psi} + V\alpha\Phi\right]$$

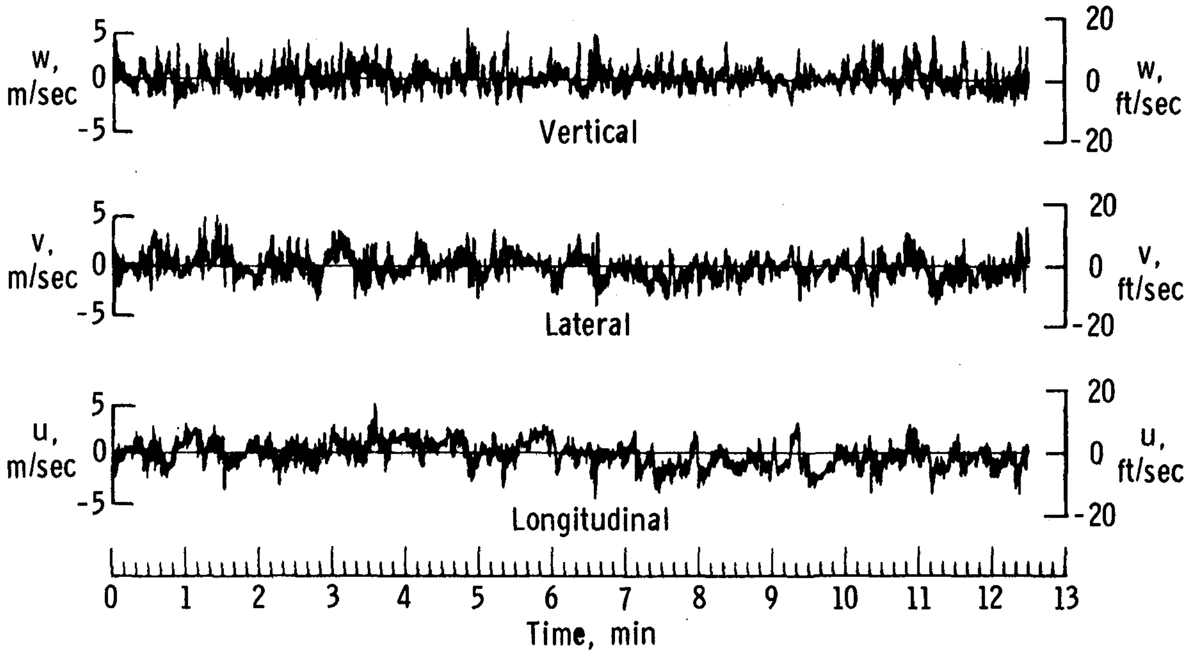
Vertical

$$w_g = \left[V\alpha\right] + \left[-V\theta + v_{az} + l\dot{\theta} - V\beta\Phi\right]$$

The equations on this figure show how the primary measurements made by balsa flow vanes and a sensitive airspeed device were corrected by use of instrumentation that measured aircraft motion to result in three components of gust velocity, longitudinal, lateral, and vertical with respect to the sampling aircraft.

CONVECTIVE CASE

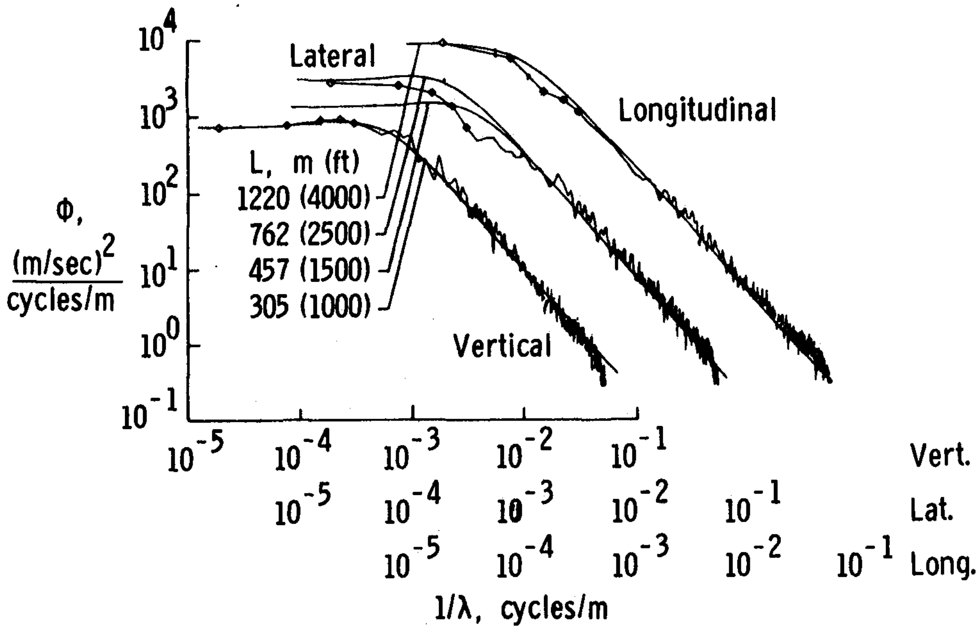
Turbulence Time History



The next four figures give example true gust velocity time histories measured under different meteorological conditions. Four cases were selected by a research meteorologist as representing turbulence caused by low altitude convective activity, mountain wave action, high altitude wind shear, and so-called rotor action with sampling in the lee of rather sharp mountain peaks in the presence of strong wind. The convective case shown here resulted from a run extending for approximately 150 miles at 1000 ft. altitude near the Virginia-North Carolina line and exhibits similar characteristics for all three components and their σ values ranged from 3.78 to 4.41 ft/sec.

CONVECTIVE CASE

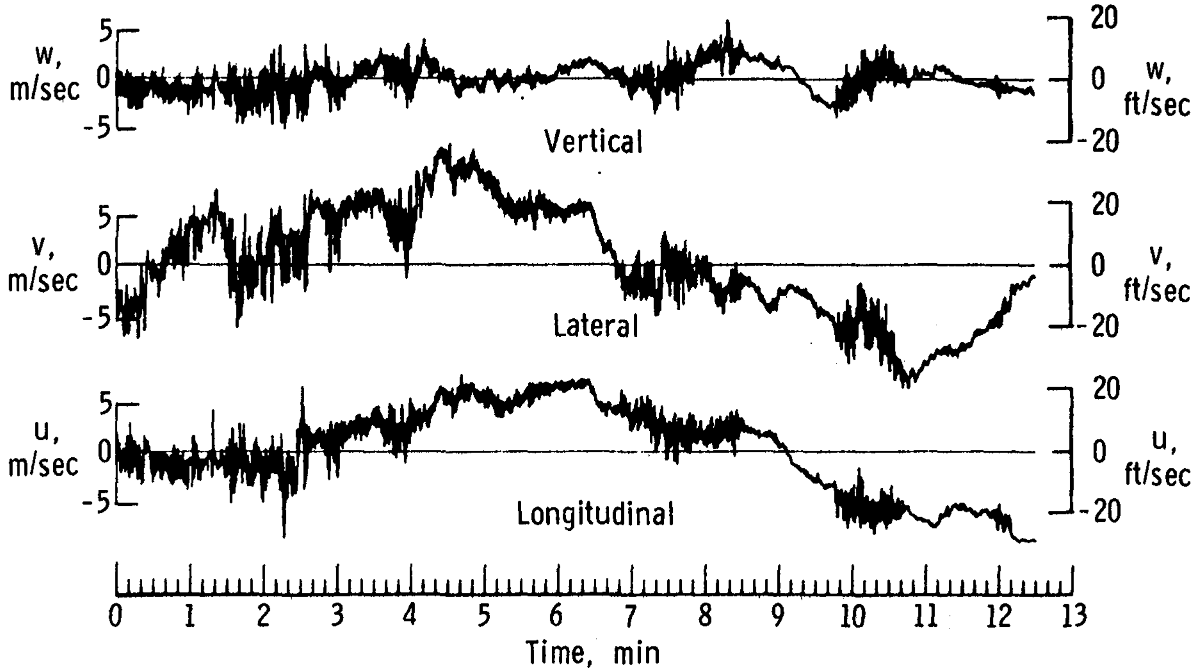
Power Spectral Density



The shape of the spectra for the convective case are reasonably close to the von Karman representation, (shown by the solid lines superimposed on the data curves) however, in order to have a reasonable fit, L values of 1000 ft., 2000 ft., and 4000 ft. appear appropriate for the vertical, lateral, and longitudinal components, respectively.

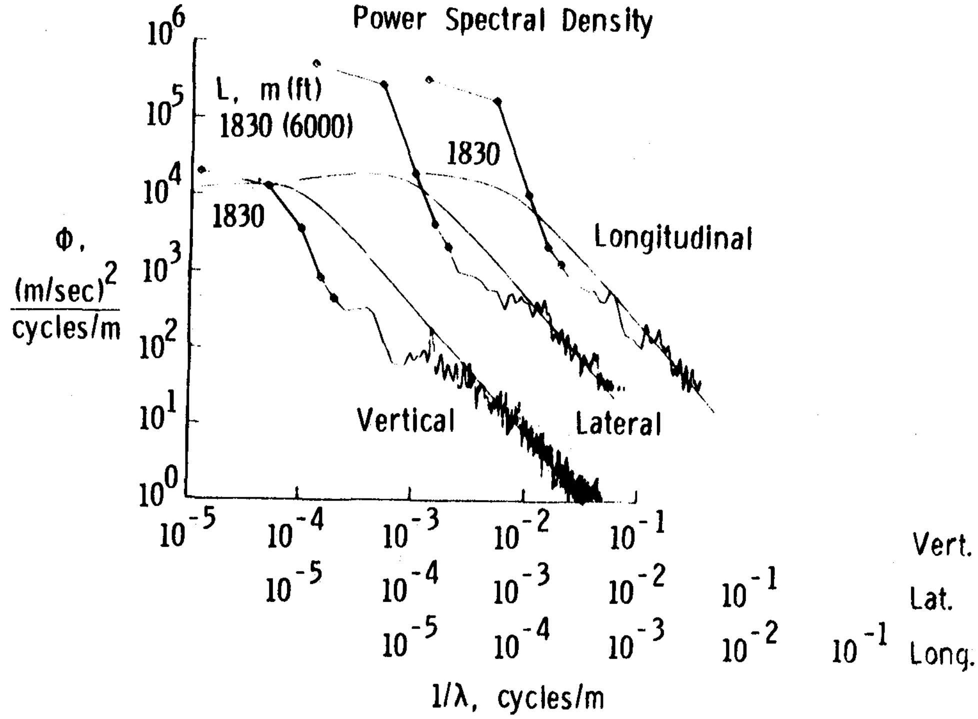
MOUNTAIN WAVE CASE

Turbulence Time History



Time histories for the mountain wave case are distinctively different in that major long wavelength content is obvious. At least three wave cycles are obvious in the 12 minute run for the vertical component - approximately one longer wave is noted on the horizontal components. The high frequency content is variable in intensity and for this and other mountain wave samples appears to intensify during positive swings in vertical gust velocity.

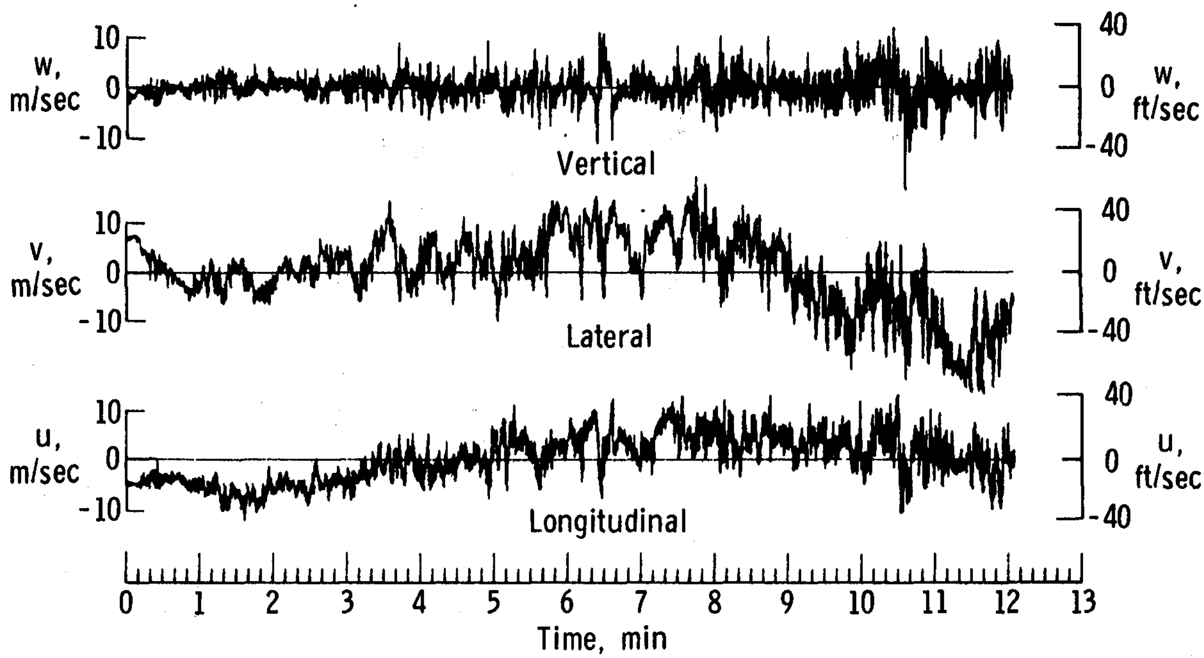
MOUNTAIN-WAVE CASE



The power spectra for the mountain wave case emphasize the observations noted on the time histories. High power is evident at long wavelengths and fitting a von Karman representation to the data is very difficult. It should also be noted that the higher frequency data exhibit the expected 5/3 slope, then tend to flatten, and then rise sharply in power at lower frequencies.

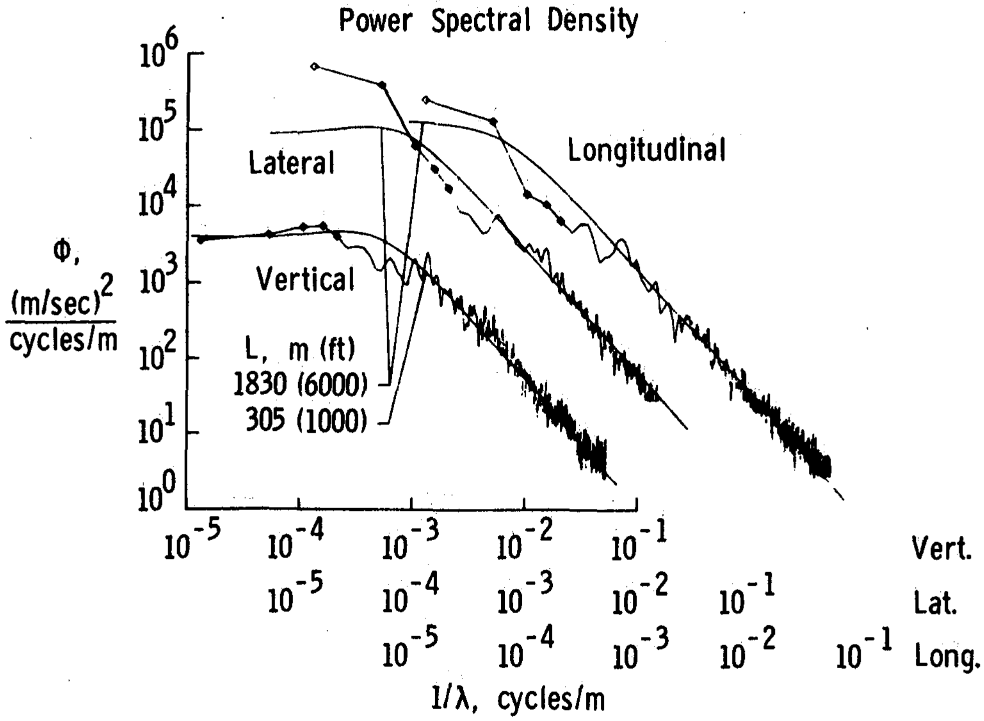
HIGH-ALTITUDE WIND-SHEAR CASE

Turbulence Time History



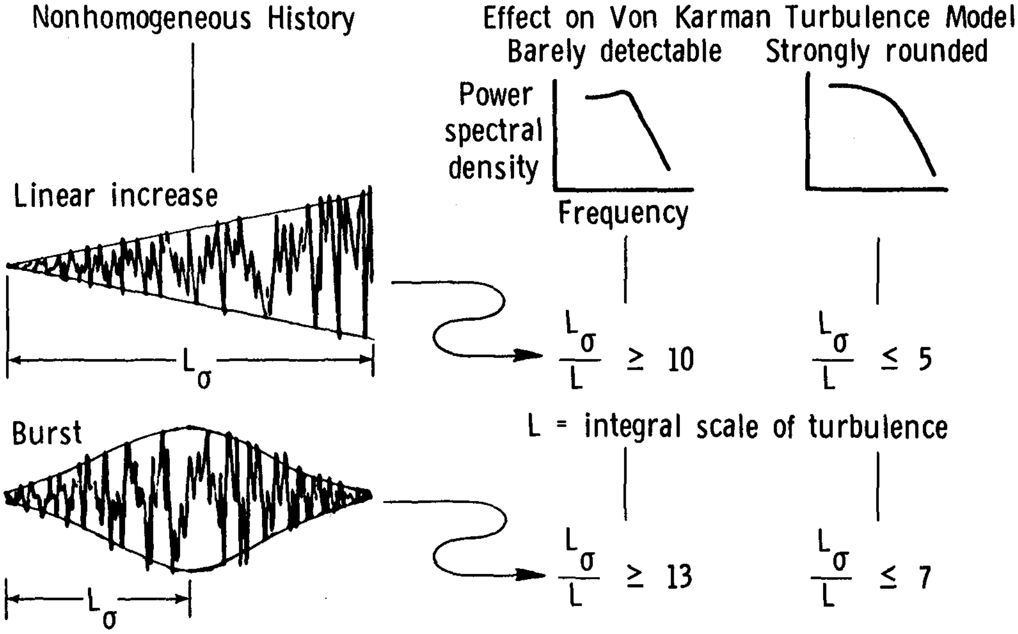
Observation of time histories indicate that the wind shear case characteristics, in general, seem to fit between the convective and mountain wave cases with intensity varying gradually with time. It is known that this nonhomogeneous or nonstationary behavior will affect the "knee" of the corresponding power spectrum. An assessment of this affect will be shown later.

HIGH-ALTITUDE WIND-SHEAR CASE



The power spectra for the wind shear case indicate more power content in the horizontal components at low frequencies than the vertical component and intermediate flattening noted in the mountain wave case is apparent, but much less severe. The von Karman model can be made to fit reasonably well, especially for the vertical component. Appropriate integral scale values are in the range of 6000 ft. for the horizontal components and 1000 ft. for the vertical component.

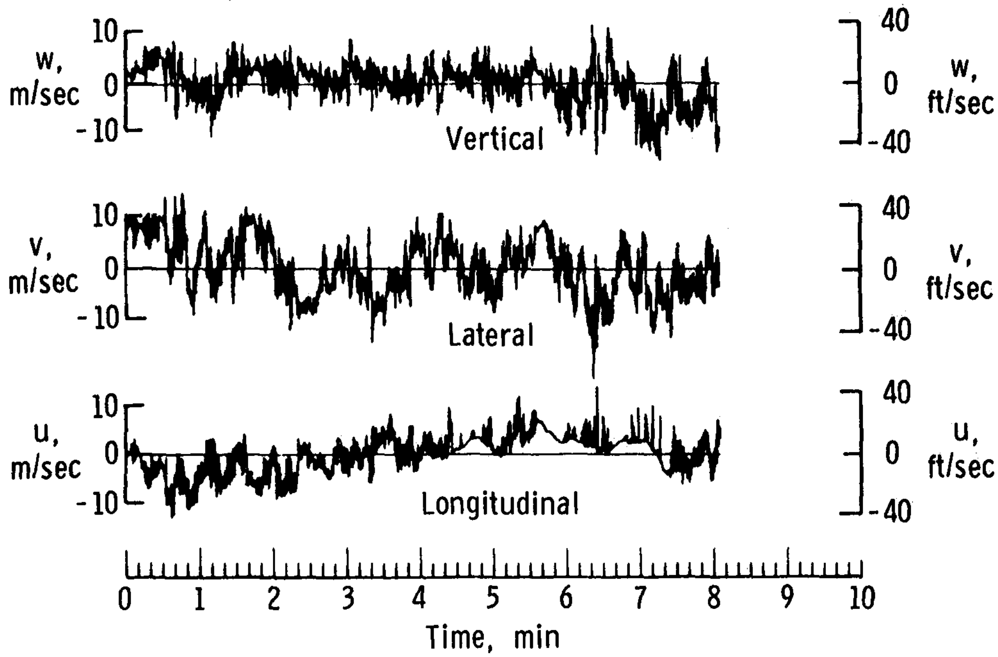
EFFECTS OF NONHOMOGENEOUS BEHAVIOR ON THE POWER SPECTRA OF ATMOSPHERIC TURBULENCE



The results on this figure were obtained in an analytical study by Dr. William Mark of Bolt, Beranek and Newman and provide "rule of thumb" guidance on the effects of intensity variation on the resulting power spectrum. Here, L_σ is the spatial length of the sampling run for a linear increase and one half the spatial length for an intensity burst, and L is the integral scale value of the turbulence. For the ratio of L_σ/L greater than 10 to 13 the effect on the power spectrum is barely detectable whereas for ratios below 5 to 7 a strongly rounding effect will be present.

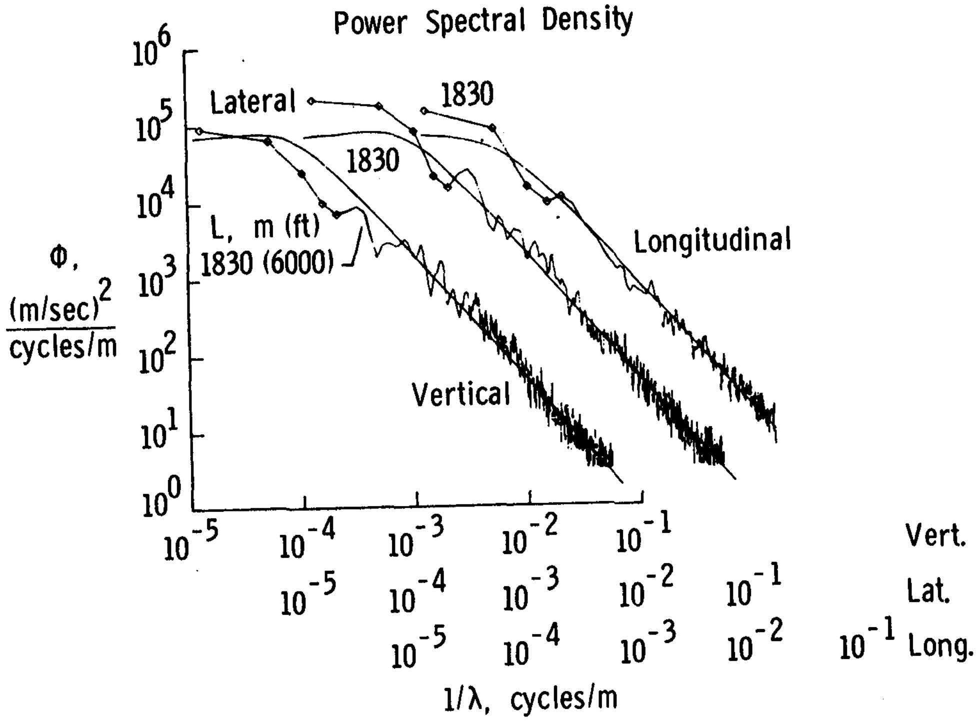
ROTOR CASE

Turbulence Time Histories



The time histories for the rotor case exhibit continual high intensity-high frequency turbulence and some long wavelength content is obviously included. The standard deviation, σ, for the vertical gust velocity component is 12.5 ft/sec. - more than 50% greater than any other sample acquired. Acceleration increments of 1g were equaled or exceeded 80 times in this traverse with maximum incremental accelerations of +2.2g and -1.8g.

ROTOR CASE



The power spectra for the rotor case are shown here. It appears that an integral scale value of 6000 ft. for the von Karman expression would approximate the spectra reasonably well.

FOUR SELECTED CASES

Meteorological condition	Altitude, km (ft)	Run length min	Run length km (miles)	Statistical d. f. for power spectra	$\sigma_{w'}$ m/sec (ft/sec)	$\sigma_{v'}$ m/sec (ft/sec)	$\sigma_{u'}$ m/sec (ft/sec)
Convective	0.3 (1000)	19.1	148 (91.7)	45	1.15 (3.78)	1.18 (3.86)	1.35 (4.41)
Wind shear	13.0 (42600)	12.2	137 (85.1)	29	2.45 (8.05)	7.33 (24.04)	4.48 (14.70)
Rotor	3.9 (12800)	8.1	88.5 (55.0)	19	3.82 (12.52)	5.51 (18.09)	3.57 (11.73)
Mountain wave	14.3 (46800)	12.6	149 (92.4)	29	1.34 (4.41)	5.39 (17.69)	4.30 (14.11)

d. f. = f(bandwidth, length)

This table summarizes the four cases shown previously with respect to altitude, length of run (in both time and miles), the statistical degrees of freedom applicable for the power spectra, and values of standard deviation for the three gust velocity components.

ASSESSMENT OF INTEGRAL SCALE VALUE

- RESULTS FROM FOUR SAMPLE CASES

  -5/3 SLOPE CORRECT FOR SHORT WAVELENGTHS

  CONVECTIVE

  L = 1000 VERTICAL
  L = 2000 LATERAL
  L = 4000 LONGITUDINAL

  HIGH ALTITUDE WIND SHEAR

  L = 1000 VERTICAL
  L > 6000 LATERAL, LONGITUDINAL

  ROTOR

  L > 6000 ALL COMPONENTS

  MOUNTAIN WAVE CASE NOT CONTINUOUS; SPECTRAL REPRESENTATION QUESTIONABLE

This figure summarizes the approximate relative integral scale values for the four cases. Because the turbulence in the mountain-wave case is not continuous, the use of power spectra for characterization is somewhat questionable. Results of modeling studies with this case will be shown later.

TURBULENCE MODELING

"Reeves"-type model:

$$w(t) = w_s(t) + \sigma_f(t)\, z(t)$$

(wind) (ordinary turbulence)

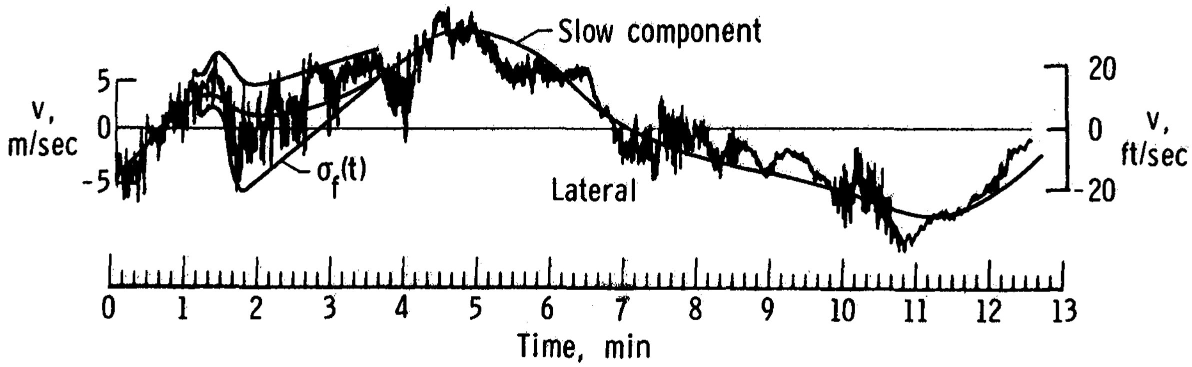
where:

$w_s(t)$ = "slow" component

$\sigma_f(t)$ = intensity variation component

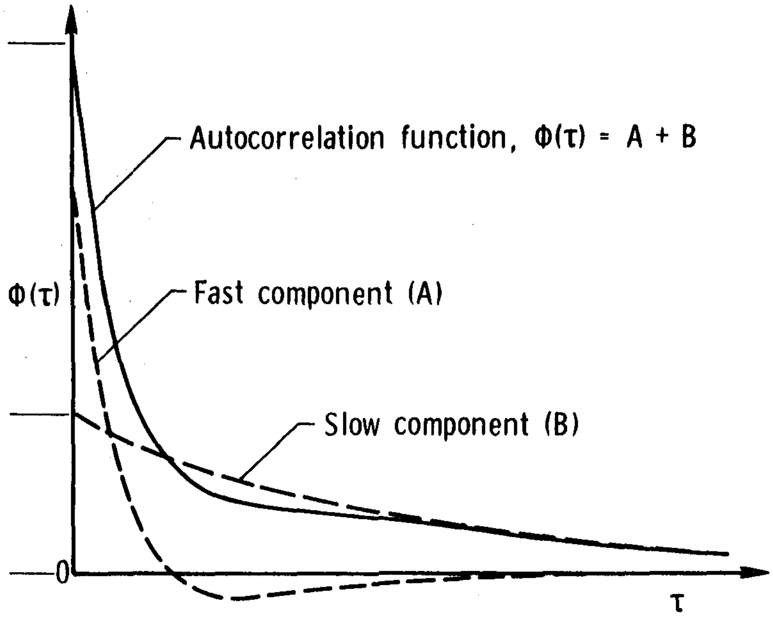
$z(t)$ = Gaussian component

Example case from mountain-wave sampling:



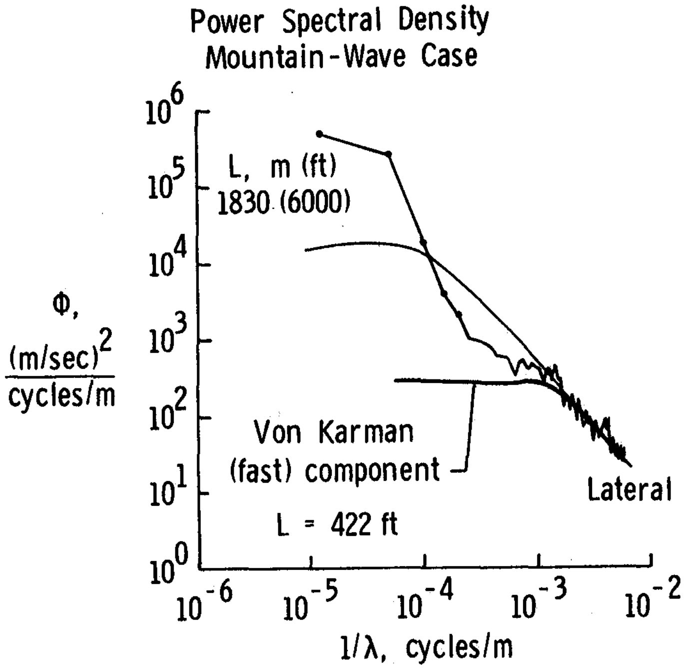
Some turbulence modeling studies by Sidwell and Mark based on early work by Reeves are in the list of references. Basically, the model includes a slowly varying component added to a rapidly varying qaussian component with an intensity variation. As shown by Mark, if the slow component and fast component are determined from the autocorrelation function, then the von Karman portion of the spectrum can be defined. The example mountain wave case is shown here and on the next two figures.

TWO COMPONENT MAKEUP OF AUTOCORRELATION FUNCTION



This is an idealized sketch of an autocorrelation function. In ref. 13 the assumption is made that the von Karman or fast component and the slow component are mutually independent. The autocorrelations are then additive.

DERIVED VON KARMAN COMPONENT SUPERIMPOSED ON TOTAL POWER SPECTRUM



The procedure described in ref. 13 was applied to the mountain-wave case shown earlier. Results are given in ref. 12 and shown here for the lateral component. In this case, a von Karman or "fast" component with an integral scale value of 422 ft. is defined, and the corresponding long wavelength or "slow" component has a scale value of 12,562 ft. In this case about 75 percent of the response of a large aircraft flying at M = 2.7 and 60,000 ft. would result from the slow component, assuming minimum influence by the pilot or control system.

SPANWISE GRADIENT (SPAN-MAT) RESEARCH

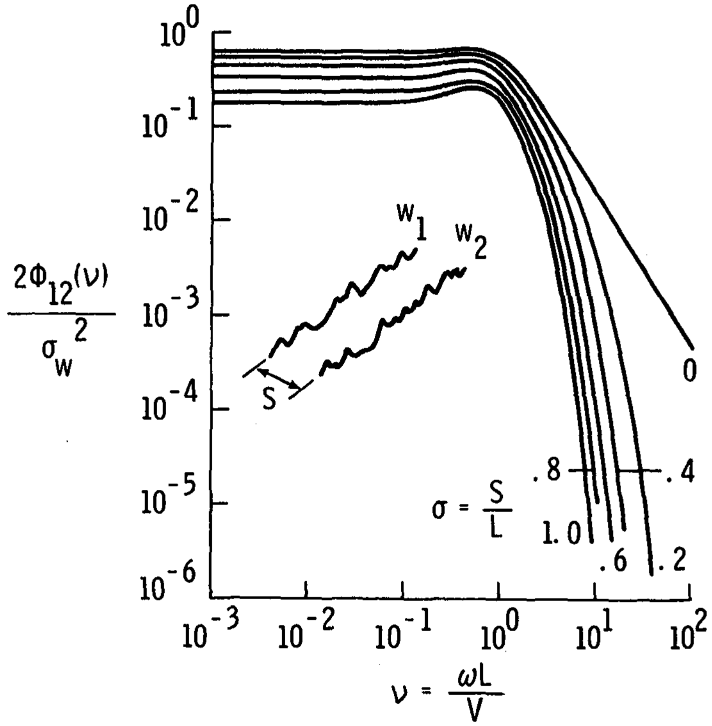
Objective: Acquisition of in-situ atmospheric turbulence data for correlation with analytical models, for use in simulations, and for comparison with data obtained from remote sensing techniques.

- Measure spanwise gust gradients applicable to terminal area operations
- Characterize wind shear, severe strom outflows and low altitude turbulence in utilitarian terms

The objectives of the sampling program with the additional probes at the wing tips are given on the figure. It is interesting to note that whereas the emphasis in the MAT program was on the low frequency portion of the power spectrum, the emphasis here is at the higher frequencies.

A B-57B was utilized as the sampling test bed. The aircraft was selected because of its rugged design, broad flight envelope, ease of flying and availability. The wing tip probes located 60 ft. apart are mounted at locations designed to accept fuel pods.

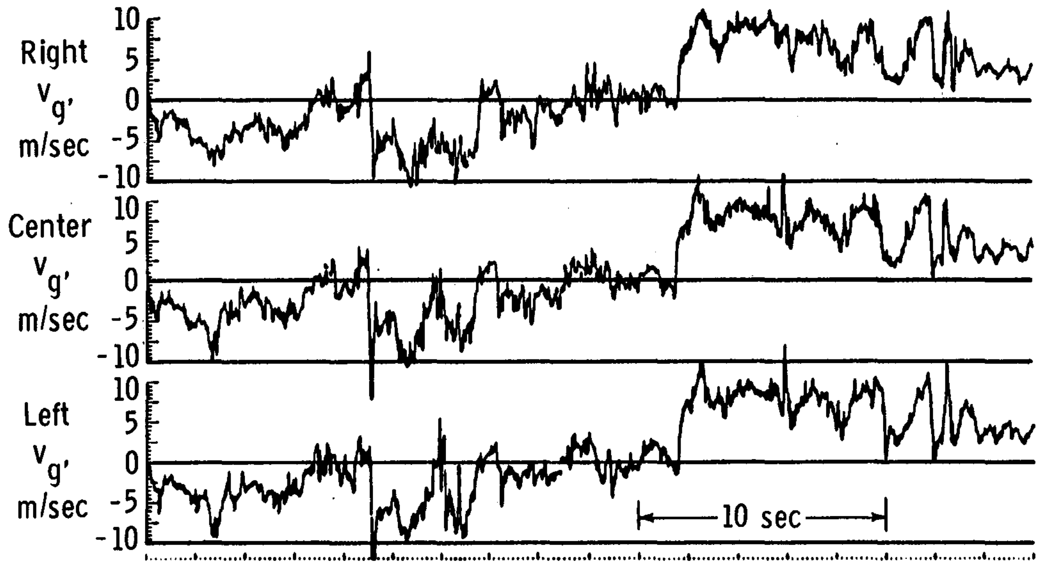
CROSS SPECTRA FOR TREATMENT OF NONUNIFORM SPANWISE GUSTS



This figure from NASA CR-2011 (J. Houbolt and A. Sen) shows theoretical prediction of the cross-spectra for the same gust component a distance S apart, assuming homogeneous isotropic turbulence. The curves are for various ratios of S/L where L is the integral scale value. Note that for S = S/L = 0, the curve would be a von Karman spectrum with a -5/3 slope at higher frequencies. Flights are being made at low altitude where L is expected to be small and thus get an expected deviation from S/L = 0, and this region is appropriate since the spanwise effects are especially important for pilot workload in the terminal area.

SPAN-MAT GUST VELOCITY TIME HISTORIES

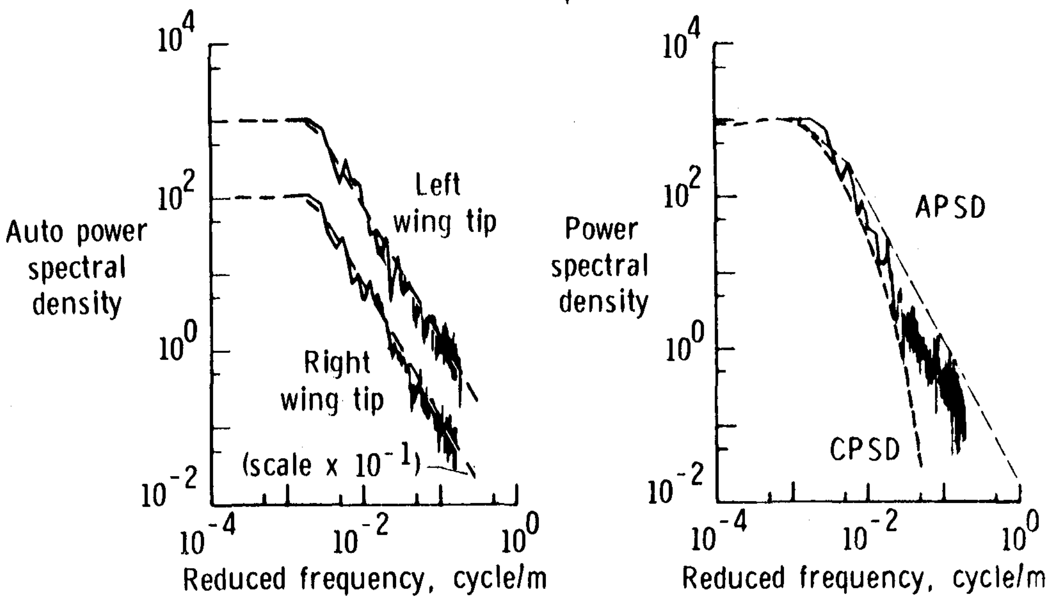
Lateral Components



This figure shows some example time histories from the two wing tips and the centerline. While the general and long wavelength characteristics are similar, significant differences are evident in the mid and higher frequency region.

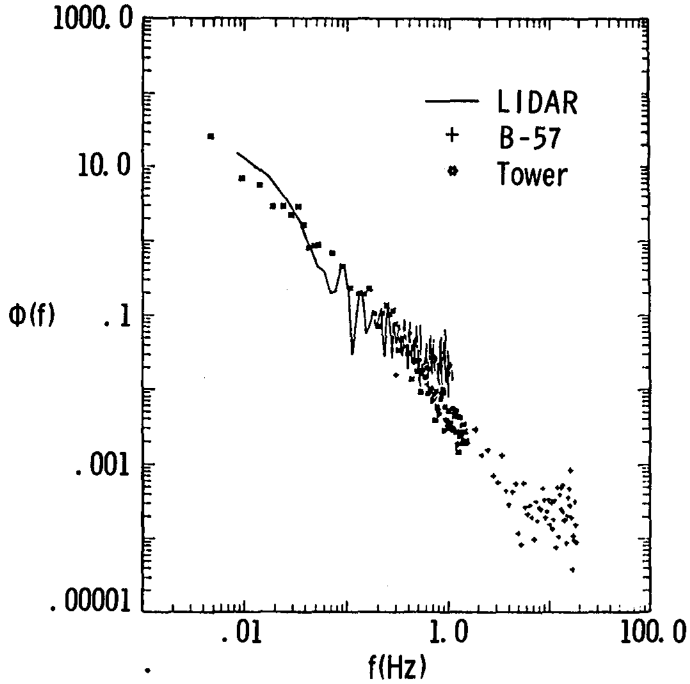
GUST VELOCITY POWER SPECTRA

Vertical Component



The left part of this figure shows the power spectra (APSD) for each wing tip with a fitted von Karman spectrum superimposed on the measured data. The L value from the fitted spectrum is used to provide the theoretical curve for cross spectra (labeled CPSD) on the right hand side of the figure. An example case of flight data is also shown. In this case the data deviate further from the prediction at the higher frequencies. The effects of filtering and data processing are presently under study.

COMPARISON OF GROUND-BASED AND IN-SITU MEASUREMENTS



Significant R&D efforts are underway in the remote sensing area. The use of doppler radar and lidar (LIght Detection And Ranging) is encouraging. Some example data are shown here where power spectral estimates from ground-based lidar, in-situ aircraft measurements, and tower measurements are shown. Lidar data are shown up to a frequency of 1 Hz, however the agreement deteriorates above about 0.1 Hz. The authors of ref. 17 attribute this to decrease in signal-to-noise ratio for the lidar data. The development and application of airborne units is expected to expand in the near future.

NASA VGH PROGRAM

- On-board recorders provide time history records of indicated airspeed, pressure altitude, and normal acceleration
- Derived gust velocity, U_{DE}, computed for acceleration peaks
  - U_{DE} = f(normal accel., equivalent airspeed, lift curve slope, weight, wing area, and gust alleviation factor)
- Recorders installed on numerous transport aircraft beginning in 1950's
  - Program terminated in early 1970's
  - Last report published 1977 on comparison of wide and narrow body long-haul turbine-powered transports
- General aviation program 1960-1982
  - Operation types included single- and twin-executive, personal, instructional, aerial applic., forest fighting, pipeline patrol, commercial fish-spotting, aerobatic, commuter, and float
  - Total of 42,155 hours of data collected from 105 airplanes

The NASA VG and VGH program was a continuing effort to obtain pertinent statistical information on transport aircraft turbulence encounters. Recorders were installed on many aircraft over a 20-year period. From time history records of indicated airspeed, pressure altitude, and normal acceleration, peak values of derived gust velocity were determined. This program has been terminated, and the last report was published in 1977. A general aviation program was conducted in the 1960-82 period where various operation types were studied. Data were obtained for a total of 42,155 hr. from 105 airplanes. Reporting is nearly complete.

DIGITAL VGH

- Feasibility of utilizing data available from transport crash recorders demonstrated
  - Data includes normal and lateral c.g. accel., indicated airspeed, pressure altitude, trailing edge flap and spoiler/drag brake position, and autopilot status
  - Data from wide body transports have been edited, processed and compiled (total of 2341 flights and 5067 hours flight time)
- Smart recorder
  - Instrument developed capable of recording, storing, and providing specified flight and ground data in desired format (statistical or time history)

NASA contact: N. Crabill, NASA Langley Research Center
Hampton, VA 23665-5225

The feasibility of utilizing data available from transport crash recorders to provide VGH-type information has been demonstrated. In addition, an instrument has been developed that can record, store and provide statistical data in a desired format. At the present time, there is no on-going activity in these areas.

SPECIAL CLEAR AIR TURBULENCE ENCOUNTERS BY COMMERCIAL AIRLINERS

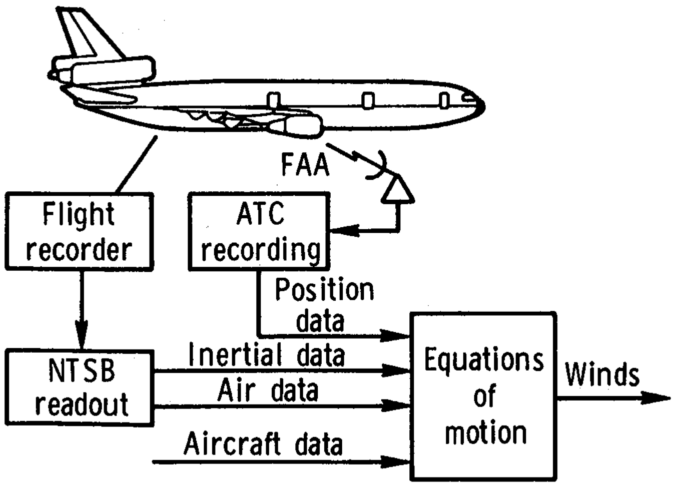
- Detailed analysis of encounters based on flight data recorders
  - Convert response data to atmospheric description
  - Correlation with meteorological phenomena
  - Establish model and install on simulator
  - Study response of different aircraft
- Study to data indicates that:
  - Strong shear layers destablished by storm passage or mountain waves provide disturbance
  - Turbulence is not of random nature, but of periodic large vortex flow

NASA contact: R. Wingrove, NASA Ames Research Center
Moffett Field, CA 94035

Special analyses are being conducted of severe turbulence encounters utilizing data from on-board flight data recorders. The procedure, which is shown on the following figure involves applying measured inertial and air data to equations of motion with parametric values appropriate for the particular aircraft involved. The derived atmospheric disturbance data can then be installed on a simulator for study of response of various aircraft to that disturbance.

Results to date for several high altitude cases indicate that a strong shear layer has been destabilized either by storm passage or mountain waves. For these cases, the disturbance is not of continuous random nature, but periodic large vortex flow.

WIDE BODY AIRLINE ACCIDENTS/INCIDENTS INVOLVING ATMOSPHERIC DISTURBANCES AT CRUISE ALTITUDES



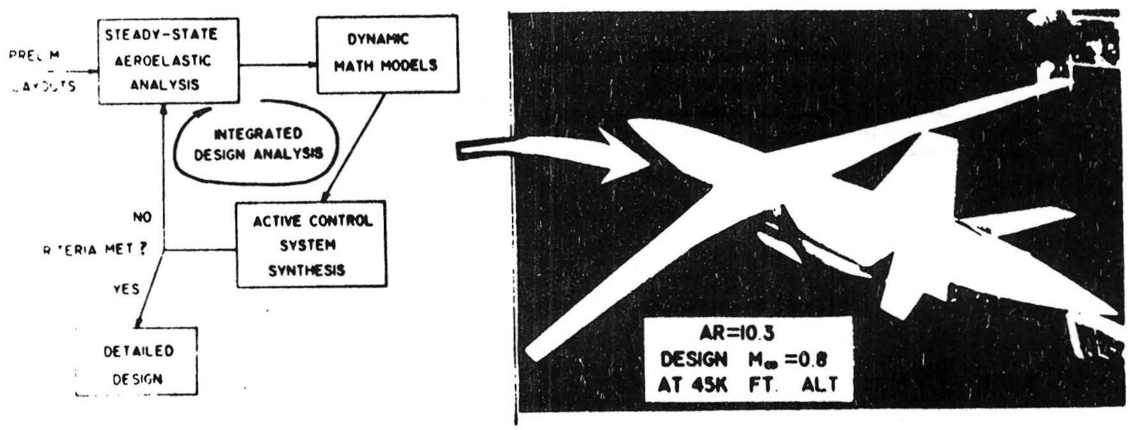
- Eight cases available for analysis
  - All at altitudes between 33000 and 41000 ft
  - Ocurrances in 1975, 1981, 1982, 1983(2) and 1985(3)
  - Locations from California to Greenland

This figure gives a block diagram of the analysis procedure and lists cases of wide body special severe encounters for which data are presently available.

DRONES FOR AERODYNAMIC AND STRUCTURAL TESTING (DAST)

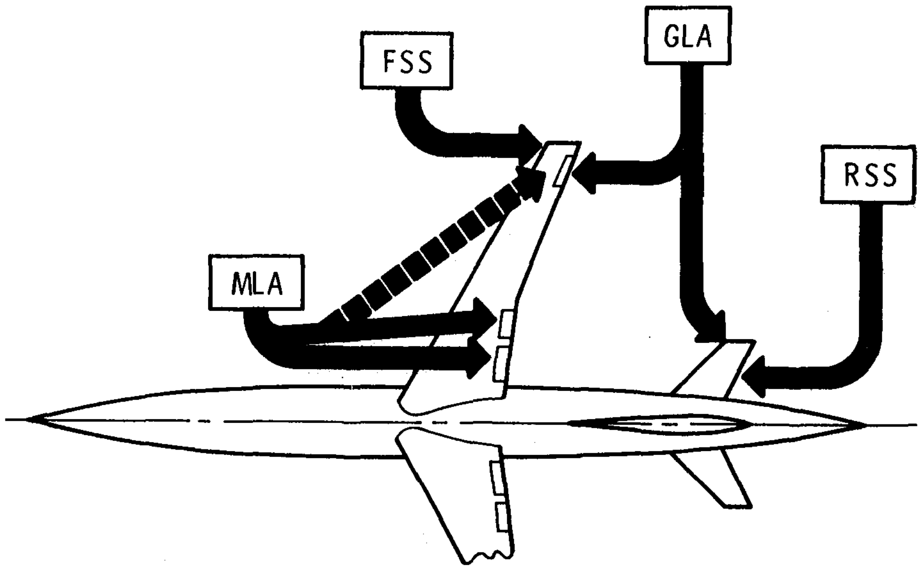
AEROELASTIC RESEARCH WING NO 2 (ARW-2)

- DEVELOP INTEGRATED DESIGN PROCESS TO INCLUDE STRUCTURES, AERODYNAMICS, AND CONTROL SYSTEMS DISCIPLINES
- STUDY AEROELASTIC EFFECTS PERTINENT TO FUEL-CONSERVATIVE AIRCRAFT
  - DESIGN WING WITH MULTIPLE ACTIVE CONTROLS
  - CONDUCT WIND TUNNEL AND FLIGHT TESTS FOR CORRELATION WITH ANALYSES



Significant emphasis is being given toward utilization of active control systems for load alleviation in new aircraft designs. An example of a research program is described here where an integrated design analysis procedure was applied in an iterative loop to provide design of a high aspect ratio fuel-conservative transport-type wing. The resulting wing design, which includes gust and maneuver load alleviation, flutter suppression and reduced static stability, requires the active control systems to be operating to fly within the design envelope. Flights of the research wing which has a span of 18 ft. are to be on an unmanned target drone test bed vehicle. The simultaneous operation of the multiple active control systems will be studied.

CONTROL SURFACE FUNCTIONS FOR THE DAST FUEL-CONSERVATIVE TYPE WING (ARW-2)



Control surface functions for the various active control systems are shown here. The wing and systems have been designed and fabricated and flight testing is presently pending funding support to develop improved systems to enhance the reliability of the flight vehicle. The wing is instrumented to measure bending, shear, and torsion structural loads, and both steady and unsteady surface pressure distributions.

ATMOSPHERIC TURBULENCE WORKSHOP

Date: Early CY 1986

At NASA Langley Research Center

Sponsored by NASA and DOD

Theme: Understanding, Predicting, Measuring, and Modeling

Interactive working sessions

Overview papers

Fixed committees - predicting, measuring, understanding, modeling

Floating committees - design, simulation, operations,
research & ops. from space platforms

Committee reports to yield information on
- needs
- present knowledge and practices
- information exchange
- future goals

A NASA-sponsored workshop on atmospheric turbulence is planned in early 1986. Attendees active in the areas of design and specifications, flight planning and operations, modeling, measurements (remote and in-situ), detection, and meteorological research and forecasting will be invited. Interaction between floating committees and fixed committees is intended, yielding in addition to broad information exchange, a general concensus on future goals in the area.

SUMMARY

- Flight sampling for characterization diminishing
- Measurements for correlation with earth science studies on-going
- VGH work inactive
- Ground-based sensing encouraging
- Special encounters being studied
- Realistic simulation work active
- Consideration for future work
  - Forecasting
  - Detection (for avoidance)
  - Design techniques
  - GLA systems design/validation

To summarize the status of measurement of atmospheric turbulence, it appears that no new measurements for characterization of clear air turbulence are being planned, however measurements, perhaps with less severe requirements, are being made to support other atmospheric measurement programs. The VGH work is inactive, however, if funding were available, a new recorder could be utilized that would greatly simplify the process of converting the data to publication form. Remote sensing developments are expected to continue and results to date are encouraging. A better understanding of unexpected high altitude encounters should result from incident studies utilizing on-board recorder information, and results from this, spanwise gradient measurements and others should lead to more realistic simulation work.

It is expected that turbulence measurements will continue to be made in the future to support further developments in forecasting, development of detection devices, and to evaluate design techniques and the validation of gust alleviation systems.

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16. Abstract

A perspective on status of measurement of atmospheric turbulence is presented. Details are given for turbulence characteristics measured in four distinct meteorological conditions. The emphasis is on identifying appropriate values of L, the integral scale value in the von Karman expression. On-going activity to measure spanwise gradients of turbulence at low altitudes is described. A resume of the NASA VGH program is given, as well as on-going utilization of flight recorder data on wide-body transports to reconstruct special turbulence encounters. Reference is made to some other activities regarding sensing, measurement, modeling, and alleviation.

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