SURVEY ON EFFECT OF SURFACE WINDS ON AIRCRAFT DESIGN AND OPERATION AND RECOMMENDATIONS FOR NEEDED WIND RESEARCH

by John C. Houbolt

1. REPORT NO. NASA CR-2360	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE Survey on Effect of Surface Winds on Aircraft Design and Operation and Recommendations for Needed Wind Research		5. REPORT DATE December 1973	
		6. PERFORMING ORGANIZATION CODE M123	
7. AUTHOR(S) John C. Houbolt		8. PERFORMING ORGANIZATION REPORT # ARAP 194	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Aeronautical Research Association of Princeton, Inc. 50 Washington Road Princeton, New Jersey 08540		10. WORK UNIT NO.	
		11. CONTRACT OR GRANT NO. NAS8-28136	
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D. C. 20546		13. TYPE OF REPORT & PERIOD COVERED Dec. 1971 – Aug. 1973 Contractor Final	
		14. SPONSORING AGENCY CODE	

15. SUPPLEMENTARY NOTES

This report was prepared under the technical monitorship of the Aerospace Environment Division, Aero-Astrodynamics Laboratory, NASA-Marshall Space Flight Center.

16. ABSTRACT

Results are presented of a survey of the effect of environmental surface winds and gusts on aircraft design and operation. A listing of the very large number of problems that are encountered is given. Attention is called to the many studies that have been made on surface winds and gusts, but development in the engineering application of these results to aeronautical problems is pointed out to be still in the embryonic stage. Control of the aircraft is of paramount concern. Mathematical models and their application in simulation studies of airplane operation and control are discussed, and an attempt is made to identify their main gaps or deficiencies. Key reference material is cited. The need for better exchange between the meteorologist and the aeronautical engineer is discussed. Suggestions for improvements in the wind and gust models are made. Needed research effort that was indicated by the survey is recommended. Key deficiencies are: a lack of knowledge of spatial correlation functions that are critical to aircraft response, lack of development or understanding of unusual and severe wind shear and cross winds, and inadequate modeling.

17. KEY WORDS Aircraft Response Atmospheric Turbulence Wind Shear Aircraft Design and Operations		18. DISTRIBUTION STATEMENT 20		
19. SECURITY CLASSIF. (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified		21. NO. OF PAGES 79	22. PRICE Domestic, $3.75 Foreign, $6.25

MSFC - Form 3292 (Rev December 1972)   For sale by National Technical Information Service, Springfield, Virginia 22151

FOREWORD

The motivation for the preparation of this report was the need of a definitive statement of the requirements of the aeronautical and aerospace communities relative to low level (altitudes $\lesssim 600$ m) wind inputs for the design and safe operation of aeronautical systems. It is hoped that this report will aid the aeronautical and atmospheric science communities in the development of programs aimed at the development of low level wind inputs for aeronautical applications by identifying the deficiencies that exist in our information. It is also hoped that this report will help to stimulate the needed dialogue between the engineering and atmospheric science communities relative to the needs and application of natural environment inputs to engineering problems.

Although this report is intended to identify the deficiencies in low level wind inputs for the next ten years, it is believed that it should be updated in approximately five years from now to incorporate the possible unforeseen needs which will undoubtly arise due to developments and advances in the state-of-the-art in the design and operation of aeronautical systems. This hopefully will guide the atmospheric scientist in his research program planning so as to satisfy these needs.

ACKNOWLEDGMENT

TABLE OF CONTENTS

LIST OF FIGURES

SURVEY ON
EFFECT OF SURFACE WINDS ON AIRCRAFT DESIGN AND OPERATION
AND RECOMMENDATIONS FOR NEEDED WIND RESEARCH

by

John C. Houbolt

INTRODUCTION

Much work has been done on the problem of the flight of
aircraft in atmospheric turbulence for flight levels above the
planetary boundary layer, that is, for altitudes above 300 to
600 meters (1000 - 2000 ft). Effort has been concentrated along
three main lines: collection and analysis of turbulence data,
mathematical modeling of the turbulence environment, and on the
development of methods for establishing the structural response
and design of aircraft due to this turbulence. References 1-25
represent a few of the many reports that may be found relative
to these studies.

By contrast, the effort that has been spent on winds and
gusts in the surface boundary layer (altitudes up to ~ 30 to 90
meters (100-300 ft)) and through the planetary layer (~ 300 to
1000 m (1000-3000 ft))is markedly different in nature. A tre-
mendous amount of work has been done on measuring the environ-
mental winds and gusts in these lower altitudes, in associating
and correlating the evidence with meteorological measurements,
and in developing mathematical descriptions. Developments in
the engineering application of these surface wind and gust
statistics to aircraft design and operations problems, however,
are for the most part still in a formative stage.

Environmental surface winds and gusts are known to have a
strong influence on the design and operation of aerospace ve-
hicles. At cruising altitudes gusts are of main concern; winds
enter primarily only in the way they affect navigation. At the
surface, however, winds and gusts are both of special concern to
aircraft operations. A few recognized examples may illustrate in
general some of the problems that arise. Cross winds represent a
hazard during approach and landing and may even preclude landing.
Gust encounter is most prevalent and can be very severe near the
surface. Wind shear complicates the approach to landing and
leads to undershoot or overshoot of the touchdown area, and in
some cases causes the landing to be aborted or even impossible.

The winds and gusts not only affect aircraft structural design and passenger comfort, but in particular cause serious aircraft control problems. Carrier operations are influenced strongly by the winds. In special missions, such as high-speed, low-level penetration, limitations often arise due to winds or gusts because of excessive loading on the pilot or deteriorated aircraft pointing or aiming accuracy. For VSTOL aircraft and helicopters, stability and control and handling qualities represent accute design problems, even in quiescent air. Operation in the presence of ground winds aggravate considerably these already severe problems. Small search or survey aircraft are limited in their operation because of excessive winds. Rocket-propelled vehicles launched from open pads are often designed in part by quasi-steady winds encountered prior to launch, and fixes must often be made to the configuration to prevent or minimize self-induced type instabilities, such as associated with vortex shedding. The prelaunch wind load problem has in fact been studied rather extensively, and there is now probably a better understanding of the problem area than any other of the ground winds problems of aircraft and space vehicles; see reference 26 and the references cited in reference 27.

As an aside, it is mentioned that ground winds and gusts are of concern in many areas beside aerospace endeavors. Winds often limit traffic operations on turnpikes or high-speed road systems. The wind "whistling through the mountains" is of concern to high-speed rail transportation systems. For years winds have been of paramount concern in the design of certain type bridges. Likewise, the design and structural response of buildings and structures due to winds is of central concern, references 28-33. Boating operations are hampered by the winds. The dispersion of contaminants and pollutants due to winds and gusts has become of increasing concern in recent years. Even the study of the formation of sand dunes by winds commands interest, reference 34.

In spite of the fact that surface winds represent a real factor in the design and operation of aerospace vehicles, there is no unified documentation on their treatment. Each problem area is treated somewhat independently of the other, and input winds description may vary widely, both with respect to mathematical modeling and degree of accuracy. Even for a given vehicle, the description may vary according to the problem being treated. For flight simulation, or the design of the thrust vector control system, for example, detailed time histories of wing inputs may be used. Yet for other response problems, such as structural excitation due to gusts, a power spectral representation may be preferred.

In general, there is no clear overall picture or integrated understanding of how winds enter into the design and operation of aerospace vehicles and, for the future, the picture is even more nebulous. Various questions exist. What are the current problems that are brought about by surface winds and gusts, and

2

what new problems are likely to become of importance in the future? What should the engineer know about winds and gusts to solve these problems? What mathematical models are appropriate? These questions appear worthy of evaluation. In turn, further questions arise. Are the current needs of the engineer with respect to surface wind problems being satisfied and, if not, what should be done to satisfy these needs? In addition, wind and gust information is usually collected by meteorologists who may have little knowledge or interest of what the aerospace engineer needs. Perhaps the most appropriate data are not being collected; perhaps the most suitable data for engineering use are not being presented to the engineer. Improvements in communication between the aerospace engineer and the meteorologist may be needed so that the needs of the engineer are better satisfied.

In an attempt to identify and evaluate these various problems more clearly, a survey was undertaken; specifically, the survey had the objective of making a critical evaluation of our knowledge of surface winds and gusts and their description, and how they influence and are taken into account in the design and operation of aerospace vehicles.

The survey consisted of a literature search and, in particular, personal visits to members of various groups, including industry, universities, and government agencies, see Appendix. The cross section of aerospace vehicles was included as much as possible, including rocket-powered vehicles, conventional and special purpose aircraft, and helicopters and VSTOL aircraft. Needs and requirements for now and up to ten years in the future were sought. Emphasis was placed more on aircraft-type vehicles than on launch vehicles, but implications with respect to space shuttle operations were also included.

QUESTIONS FORMING BASE OF SURVEY

In an attempt to ferret out and promote discussion on the problems that are brought about by environmental surface winds and gusts, questions of the following type were presented to the various individuals and groups that were contacted.

For the vehicle:

1. What problems arise and might arise as a result of surface winds, and in what ways does the engineer need wind and gust information?

2. What response calculations are made?

3. To what extent is design influenced? Operation?

For the input:

    4. How are the surface winds characterized and modeled?

    5. Is information of adequate form?

With respect to adequacy:

    6. What criteria and requirements exist currently?

    7. Are current needs of the engineer being satisfied?

    8. What are the gaps and deficiencies?

    9. If needs are not being satisfied, what should be obtained?

   10. What programs should be undertaken to obtain information to satisfy needs?

For the meteorologist:

   11. Is the meteorology community acquainted with the needs of the aerospace engineer?

   12. What information should the meteorologist be obtaining to help the engineer, to define the earth's boundary layer better?

There was an attempt to emphasize certain areas of the aircraft operation problems that were envisioned to be most significant; specifically:

    1) On the role of Specifications and Criteria

    2) Handling Qualities and Stability and Control aspects

    3) The presence of a pilot in the loop or the use of automatic approach control

    4) The role and use of simulators

It is of interest to note that even though the questions listed in this section were presented to the various individuals contacted as a means for starting a discussion, the questions were soon bypassed. Very quickly, the individuals or group contacted began to present ground winds and gust problems as they see them, or as represented by their experience. It is mainly on this spontaneous response that this report is based.

CITED PROBLEMS ASSOCIATED WITH SURFACE WINDS AND GUSTS

This section presents a listing, almost verbatim, of the various problems that were cited by individuals contacted in the survey. It was felt that such a listing is a direct, simple way of bringing out clearly the various problems that are considered significant and what certain notions towards these problems are. The main screening that has been done is to separate the comments into the seven basic categories that are indicated. It will be seen that the surface winds and gusts problems encountered are diverse and extensive, and are more in number than one might have imagined. It will also be seen that many of the problems are not even defined well as yet, that much more information is needed about the input surface winds and gusts, and that development of definitive design procedures - on input modeling, on engineering-type applications, on design implications - are very much needed. References 35, 36 and 37 also present discussions of the overall nature of the ground winds problem and are suggested for reading.

A. Ground-Type Operations, Including Parking, Taxiing, and Hovering

1. The military is concerned with the effect of ground winds on all equipment; standards are presently being revised.

2. Tornadoes and hurricanes present aircraft fly-away problems at all airports in their paths.

3. Stops or snubbers must be designed into tabs and elevators to prevent "banging" due to tail winds; improved fatigue life is also obtained.

4. Gusts are a concern for cargo doors; motors are designed to stall for winds greater than 33.4 m/s (65 knts).

5. Canopy design and wing fold design is influenced by winds; locks must be secured in many configurations, for example, for winds greater than 20.6 m/s (40 knts).

6. For 18 m/s (35 knts) winds and in a hovering condition, control power is the key problem.

7. Taxiing from the lee protection of a building into a strong wind represents a hazard.

8. Winds and gusts blowing across the face of large fan engines may lead to large blade stresses.

9. The recirculation or reingestion of hot engine gases leading to reduced engine power or compressor stall represents a severe problem for many VSTOL configurations, reference 38; winds affect this problem greatly.

10. The Harrier (a fixed wing, vectored-thrust VSTOL aircraft) generally takes off into the wind, but if no wind, take-off is made with a forward roll of 4.5 m/s (10 mph) to avoid ingestion problems. Also, this aircraft has only $8°$ for tail clearance, so gusts can create quite a hazard at operations near the ground.

11. Winds present a problem to rotor blades in shut-down condition; "gust locks" must be added in many configurations.

12. Parked rotors must be tied down to prevent auto-rotation due to winds; flapping may be severe if controls are not left in a correct position.

13. Blade flapping may be excessive during helicopter runup in presence of winds; stops or fuselage may be hit. Blade flapping is in general aggravated by winds. Some helicopters have placarded use in winds; for example, in winds greater than 11.2 m/s (25 mph), cyclic control must be displaced to cause rotor to be tilted into the wind; or collec- tive pitch must not be used to stop rotor when winds are blowing.

14. Gusts and winds are too strong at times for certain helicopters, such as the H56A; limits are, however, really not known.

15. Helicopters must not hover near open hanger doors due to self-generated destabilizing wind currents.

16. Deflected slip stream configurations of low-wing loading are very susceptible to winds; different control systems, such as spoilers for roll, re- action jets for yaw, appear a necessity.

17. The inboard landing configuration of a three-fan STOL configuration was hard to handle in the presence of winds, tipped over at times; outboard landing configuration by contrast was considered very good.

18. Tilt wing aircraft may have various blade in-
    stabilities; winds may be expected to aggravate
    these instabilities.

19. Arresting equipment may be required in elevated
    STOL ports because of winds.

20. "Taxiing" up to a dock in a seaplane with
    different relative wind and water movements is
    hazardous.

B. Approach and Landing (Cross-winds and wind shear)

1. In general, cross winds, wind shear, and gusts
   encountered during approach and landing pose
   significant design and operational problems to all
   aircraft, but for VSTOL configurations they are of
   critical concern (see references 39 and 40 as
   examples).

2. If the cross winds are too large, aircraft may be
   blown off the runway; some STOL configurations are
   much more susceptible than others.

3. Control power, especially roll power, is perhaps
   the item of major concern during take-off and
   landing.

4. The control power required to handle ground winds
   and gusts is really not known, especially for low-
   wing loading high-aspect ratio STOL configurations.

5. Cross-wind information is not adequate; gusts
   should be included. With the thousands of different
   cross winds that are to be found throughout the
   world, what types should be considered for design,
   and what characteristics are significant in their
   description (reference 41).

6. There is a need for a cross-wind rationale for
   approach and landing in areas where there is a
   high density of buildings and other obstructions,
   since cross winds may be altered into discrete and
   unusual patterns.

7. Stability derivatives must be such to give desired
   control at low speeds; there usually is much
   difficulty in calculating these derivatives, and
   often in order to achieve desired values, perform-
   ance may be compromised.

8. Because wind shear affects the power to be used, and because stability derivatives are influenced by power, there is a dependence of stability derivatives on wind shear for nearly all powered-type lift systems.

9. With some configurations, flight is not made if cross winds exceed 15.4 m/s (30 knts) because of difficulty with the drag landing parachute; in other instances, the parachute is released after landing to avoid dragging aircraft.

10. Air-cushion landing systems are considered by many to be ideal for cross-wind landings (reference 42).

11. Severe cross winds 35 days of a year are believed to be a strong factor as to why the STOL strip project in Manhattan was stopped.

12. The thrust-drag control system studied on an Otter aircraft was judged to have worked very well in combating the wind shear problem.

13. Inversions or other meteorological changes between day and night may cause a significant change in the wind velocity profile. Instead of the characteristic monotonic increase in velocity with altitude, some profiles have been found wherein the velocity peaks (a low-level jet stream), then falls off with increasing altitude, even reversing directions in some instances. The landing problem associated with wind shear is thus greatly aggravated. Much more information is needed on the various profiles that may be encountered - their detail and as to when and where they occur.

14. In wind and gusty conditions, it may be better to let a helicopter "fly itself"; pilots often aggravate the motions. Some opinion was expressed that helicopters are hard to fly in cross winds and gusts; others expressed the contrasing observation that helicopters aren't affected greatly by winds or gusts.

15. The Stability Augmentation System (SAS) on helicopters is considered to represent also a good gust alleviator.

16. The approach to landing with a helicopter on the top of a tall building in the presence of winds is considered to be a problem.

17. Ground handling, cross-winds, automatic approach systems represent problem areas of unknown scope for all remotely piloted vehicles.

18. The winds and gusts that should be used in landing studies of the space shuttle are unknowns.

19. Gust alleviation systems are considered important to STOL configurations which may cruise at M = 0.7 to 0.8 but are able to land on 610 m (2000 ft) strips at approach speeds of 41.2 m/s (80 knts).

20. Simulation studies of advanced transport configurations (6 engines, 6 fans) indicate that winds and gust significantly degrade approach control.

21. Studies of the DO31 configuration indicate control is relatively unaffected by gusts, but why this might be so is not known.

22. The Breguet and Harrier have had trouble in some cross-wind landings.

23. The A-7 is not flown if the cross winds exceed 10.3 m/s (20 knts); the A-8 is restricted for cross winds greater than 9.3 m/s (18 knts).

24. The X-14 was not flown in winds above 2.6 m/s (5 knts).

25. Low-wing loading aircraft (U-2) are known to be difficult to fly in gusty winds.

26. Winds and gusts severely restrict crop dusting operations.

C. Carrier Operations

1. Calm winds or winds greater than 15.4 m/s (30 knts) are a hazard in aircraft carrier landing operations. For calm conditions the carrier must steam at 15.4 m/s (30 knts), forming thereby a strong turbulent burble behind the carrier. For winds greater than 15.4 m/s (30 knts), steerage way becomes a problem; the seas are usually rough in these conditions, carrier motions become a big factor, and carrier steerage may be restricted because of other ships in proximity.

2. Extensive studies of wakes behind carriers have been made. (Specific references are discussed in a later section.)

9

3. An angle of attack approach is usually used. When gusts are present, an increment of 1/2 the maximum gust velocities is added to the nominal approach speed of 1.18 V_s , where V_s denotes stall speed.

4. The angle of attack approach gives difficulty when strong drafts are present. Navy is making extensive study using q (dynamic pressure) and power control for difficult situations. A matrix has been established to indicate when conditions are satisfactory to use the power control system; pilot takes over when conditions are exceeded.

D. Sensors, Instruments

1. In cross winds and wind shear conditions, the cues given to the pilot are very important.

2. Displays giving information on the nature of the cross winds or wind shears are difficult to make. Much work is needed to develop sensors, instruments, and displays to detect cross winds and wind shears, and in turn to indicate what should be done to counteract these inputs (references 43 and 44).

3. Good sensing systems and displays are needed to indicate the winds relative to the aircraft. With the air flow over the aircraft, all forms of downwash and local air flow disturbances, it is very difficult to establish how the wind is blowing relative to the aircraft.

4. Work is needed to develop instruments beyond that used in fixed wing aircraft, such as better altimeters, top of trees indicator, relative wind indicator (as mentioned in item 3). Since most airspeed indicators don't give information until a relative speed of 15.4 m/s (30 knts) is reached, there is also a need for a relative air speed indicator for speeds between 0 and 15.4 m/s (30 knts). At present, pilots must rely on visual cues for this range. Proper display to the pilot is considered most important.

5. In the use of the new microwave landing system, what are the parameters that should be monitored.

6. The Harrier aircraft must be flown with care in cross winds. The use of a side-slip vane, in the form of a visual display to the pilot and also through an automatic control in the rudder control system, is being studied at present as a possible means for improving flight safety in cross-wind situations.

E. Measurements

1. There is a lack of standardization in the various wind and gust measurements that are made. Aspects include time of averaging, heights of measurements, location (that is, are measurements in a free space or in the lee of a building), directional properties of the winds.

2. LOCAT and other tower data appear to apply mainly to the so-called "good day"; stormy days are not included in general.

3. More measurement should be made on "discrete gust" effects behind obstacles.

4. Better wind reporting at airports is needed (reference 45).

5. Measurements are needed to indicate when critical conditions arise. Additional information on shear is needed at times by the pilots. An example, as obtained from a FAA spokesman, illustrates the need. In a short period of time near the beginning of 1973, 9 aborted landing attempts were made at the JFK airport; 3 of these involved a single 747 aircraft, which finally diverted 1500 miles to make a landing. A very unusual wind shear condition in which wind direction actually changed was later diagnosed to be the cause of the trouble.

F. Turbulence Models and Simulation

1. It is unanimous that better wind and gust models are needed for use in analytical and simulation studies; there is at the same time a big disagreement as to what is needed.

2. Turbulence and wind inputs are considered by some to be essential or the most important ingredient in simulation studies of aircraft approach and landing. Many felt, in fact, that the kind of modeling made will probably "make or break" a STOL system that is under consideration.

3. Gust models based on high altitude turbulence are in general found to be too severe and unrealistic. Based on pilot reactions from both fixed base and flight simulation studies, much lower values of gust severity and integral scale are indicated relative to those often quoted. Values of 1 m/s

(3 fps) for rms severity, instead of 1.8 or 2.4 m/s (6 or 8 fps), and L = 60 - 90 m (200-300 ft) rather than 760 m (2500 ft), were found to be much more realistic.

4. Some felt that any well spelled out set of models would be acceptable.

5. Some felt that a "stable" of wind and gust models were needed, dependent on application; the thought was also expressed that perhaps only the more severe half of any measured set of wind profiles should be used for modeling purposes.

6. Some felt that perhaps a sophisticated model was not really needed; the alternative suggested was to pick some of the more severe winds and gust conditions that might be encountered and to study whether the airplane could be flown or not, or at least find out what problems might be indicated.

7. Gaussian-type gust inputs were not considered realistic by some pilots. Nonstationary gust effects were considered a most essential item. Patchiness, in fact, is often simulated simply by turning the gust generator on and off.

8. Models in various specifications all appear different. All specifications or guidelines are considered in need of improvement. No distinction is made between conventional, STOL, or helicopter aircraft. The model and configuration interface may be important; models, for example, should perhaps be tailored to the configuration. In a broader context, three basic notions are of concern:

   1) Are gust and wind models configuration-dependent?

   2) The ability for a given design group to utilize a model is an important factor.

   3) The design group philosophy also has an important bearing with respect to what models are used.

9. Many questions about the detail of the models need study:

   1) Are results affected greatly by different spectral shapes?

   2) Is the use of different integral scale values for the u, v, and w components important?

3) Is it necessary to consider correlation effects between the u, v, and w components?

4) How important are the cross correlation effects that might arise in the low altitude turbulence as a result of obstructions such as trees, cliffs, or buildings, as contrasted to the use of isotropic-type turbulence?

5) Are geographical and seasonal changes in spectral content significant?

10. What are realistic environmental and load limits?

11. Is it important to model discrete gust effects such as might arise behind obstacles?

12. The flow behind an aircraft carrier has been studied extensively and some excellent models of the approach environment has been made.

G. Specifications and Criteria.- A few comments are made here with respect to the statements and guidelines that are set forth in specification and criteria documents relative to the treatment of surface winds and gusts, references 46-61. Not many statements were offered by the individuals contacted, but the few that were made are listed here. The statements are not intended to be critical of the specifications that exist. Rather, the lack of detailed coverage that exists in various specifications may be concluded as due to the fact that models, procedures and techniques for handling ground winds and gusts are still in the embryonic stage of development. With few exceptions, such as reference 46 and certain internal NASA documents, guidelines for handling gusts, if presented at all, are based mostly on high altitude turbulence models. Even these models are subject to question. Only a relatively few attempts have been made to develop realistic low-altitude turbulence models. Applications, and attempts to feed back results of these applications to develop better input models, are few. It is thus not possible to set down definite, well though out, proven and acceptable low-altitude turbulence models and application procedures at the moment, and it is thus no wonder that models cannot be stated in specifications. Observations offered by individuals went as follows:

1) The specifications give mainly only general statements with respect to handling gusts and winds, usually in terms of control motions, such as "control motion should not be excessive when winds and gusts are present;" or "hover is to be made with collective pitch not exceeding $\pm$ 1 in. calm air ($<$ 1.5 m/s or $<$ 3 knts)."

2) Each new Request for Proposal (RFP) has specific requirements spelled out, usually pertaining to control rates or other control characteristics; no specific wind or gust requirements are indicated.

3) For carrier operations, statements such as the following appear: "Operation in the island wake should be kept to a minimum," "hover behind the carrier should be avoided," "launch and recovery should be made in relative wind less than 23 m/s (45 knts)."

STUDIES OF THE LOW ALTITUDE WINDS AND GUSTS

The ability to apply information on environmental surface winds and gusts to evaluate design and operational problems of aeronautical systems, and to interpret results meaningful, is at present somewhat limited. Methods and procedures are still in the developmental stage, and only recently are questions being raised with respect to whether the proper type of information is being collected. In spite of this situation with respect to aeronautical problems, the amount of study that has been made of surface winds and gusts is staggering. This section presents a sampling of the many references that may be found reporting these studies. It is recognized that it is not practical to study all of the references indicated; as an aid to the reader, therefore, a few key papers which present representative information will be singled out in a later section of this paper. As an arbitrary breakdown, the references listed herein on environmental studies are given in three groups.

Books.- References 62 through 67 represent a sampling of the excellent textbooks that may be found relating to low-level atmospheric turbulence.

Measurement techniques.- A sampling indicating the types of studies that have been made on sensors and measurement techniques is given by references 68 through 85.

Data gathering and analysis and basic meteorological studies.- Studies of the surface wind and gust environment may be classified broadly into two types. One is associated with the sampling and analysis of statistical data on the winds and gusts. The others tend to be more the basic research type, wherein the attempt is to collect the statistics on the winds and gusts and various meteorological parameters as well, to analyze the data in terms of the meteorology, and then to try to collapse all the data into simple generalized or universal form. References 86 through 221 represent these studies.

Some current measurement programs.- Mention is made here of a few measurement programs that are under consideration or that may have been started. These programs are mentioned simply as efforts to keep in mind which possibly might have some input toward understanding the surface winds and gusts problem better.

1. A large joint effort by the Environmental Sciences Service Administration (ESSA) and the Canadians measuring winds over Lake Erie, both horizontally and vertically; main objective is to try to understand weather patterns better.

2. A line of 15 towers, spaced at 300 m (1000 ft), along the 4600 m (1500 ft) runway at Edwards Air Force Base Towers are to be 90 m (300 ft) off the center line of the runway; anemometers at 3 m (10 ft) elevation will measure u and v components. The study is for operational purposes, not research.

3. Tethered balloon experiment to be conducted in Minnesota to obtain information up to the 1 kilometer altitude (sponsor AFCRL). Three instruments are to be mounted on the tether at low altitudes to measure surface friction; five additional sensors are to be used at the higher altitudes.

4. A FAA program being conducted by Battelle, Northwest, in the Seattle area. One of the objectives of the program is to attempt, by tower measurements, to identify the meteorological information of significance to VSTOL aircraft and their operation.

MODELS OF SURFACE WINDS AND GUSTS

Considerable effort has been made to derive mathematical models of the surface winds and gusts for use in aerospace engineering applications. It is observed, however, that only a relatively few individuals have tried to utilize these models, or are even familiar with them. There appears to be greater familiarity with the higher altitude gust models and as a consequence, these models have often been applied, inappropriately, to study aircraft problems at boundary layer altitudes; results obtained have usually been judged as being "unrealistic." There is thus a need for education on the need for and use of surface layer models.

References 46, 47, 114, 160, and 222 through 238 are representative of studies dealing with the development of surface layer models. It is not the intent of this survey to give an in-depth review of these models, since this has been done in part elsewhere; reference 46 gives a very extensive coverage of

various wind and gust models; references 234 and 235 present excellent reviews. It is felt appropriate, however, to indicate their nature. The figures that are presented are intended to be pictorial and not definitive in nature. Thus, not too much attention should be paid to the units or the nomenclature used Differences in units and in nomenclature represent, in fact, a major reason why it is presently difficult to compare one model to another

Figure 1, taken from reference 235, and presented in many forms elsewhere, is a version of a popular but typical presentation on the spectrum of wind speed that has been obtained from tower measurements over a long time observation. The portion of the curve showing peaks in the period range of one week and one day is associated with the winds; these winds are quasi-steady in nature to the airplane and create the cross wind and wind shear problems encountered during take-off and landing. The broad dip in the period range of one hour has been termed the spectrum gap. The portion in the period range of one minute to one second is associated with the atmospheric gusts or turbulence that has been created in the main by the winds. This turbulence, which acts in superimposed fashion to the winds, gives rise to the rapidly fluctuating disturbances that are encountered during take-off and landing.

In contrast to a negligible correlation between the u and w turbulence components at higher altitudes, there is a strong correlation between u and w in the surface boundary layer, leading to the definition

$$u_\tau = \sqrt{-\overline{uw}} \tag{1}$$

and a surface stress

$$\tau_o = \rho u_\tau^2$$

where $\overline{uw}$ represents a time average of the product uw. The value u_τ is used extensively in models as a basic reference value.

In the surface boundary layer, and for neutral atmospheric stability conditions, the mean wind velocity profile U as a function of height z is found to be represented well by the equation

$$\frac{U}{u_\tau} = \frac{1}{k} \ln \frac{z}{z_o} \tag{2}$$

16

where k is von Kármán's constant (≈ 0.4), and z_0 is a
roughness length, which is roughly 1/30 the dimension of the
typical roughness particle (references 46 and 235). For non-
neutral conditions, a modification to this equation is employed
utilizing a universal-type function which is dependent on
stability conditions, reference 65. For the entire boundary
layer a power law profile is often used, of the type

$$\frac{U}{U_1} = \left(\frac{z}{z_1}\right)^{\alpha}$$
(3)

where U_1 is the velocity at some reference height z_1 . The
value α is dependent on z_0 and atmospheric-stability, see
references 32 and 235. Figure 2 indicates example profiles as
derived from this equation. Peak wind profiles at selected
locations, in contrast to mean profiles, are treated extensively
in reference 46 by an equation similar to equation (3); gust
factors, the ratio of peak winds to mean winds, are also pre-
sented.

The mean velocity profile is of concern in the approach to
landing, since it requires the pilot to make power and attitude
changes in order to maintain a given air speed. Fluctuations
about the mean profile are perhaps of even greater concern,
since they lead to hazardous flight conditions (likelihood of
stall, control difficulty in general) and in turn to large dis-
persions in the touchdown point, or even aborted landings.
Figure 3, taken from reference 237, indicates the magnitude of
these fluctuations that are possible. In many instances unusual
velocity profiles of the type indicated in Figure 4 develop; the
approach and landing problems for these unusual profiles are in
general much more severe than the statistical average case.
Little is known, however, with respect how to anticipate or
detect these profiles, and how to cope with them when en-
countered. Much study on these odd or unusual profiles is
therefore needed to establish representative sets of profiles,
to understand their cause and how to detect them, and what
operational procedures should be followed, if possible, when
they are detected.

Cross-wind models, associated with the fact that the mean
wind flows at an angle to the runway, have also been developed,
references 41, 59 and 60. The more unusual or severe cross
winds have not received much attention, however. As an example,
if an obstruction intervenes such as a group of trees, or a
hill, or a building, then sharp, discrete-type disturbances may
develop in the cross wind, which may cause serious control
difficulty; a rapid change in wind direction with altitude is

another example.[*] In general, more study is needed of cross winds relating to their magnitude and directional variability, and on the form they may take.

Modeling of the turbulence is usually made in spectral form, although discrete gust models continue also to be examined, references 11 and 226. Some representations are based on the so-called von Kármán form, given by the equations

$$\phi_u(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{\left[1 + (1.339 L_v \Omega)^2\right]^{5/6}} \tag{4}$$

$$\phi_v(\Omega) = \sigma_v^2 \frac{2L_v}{\pi} \frac{1 + \frac{8}{3}(1.339 \cdot 2L_v \Omega)^2}{\left[1 + (1.339 \cdot 2L_v \Omega)^2\right]^{11/6}} \tag{5}$$

$$\phi_w(\Omega) = \sigma_w^2 \frac{2L_w}{\pi} \frac{1 + \frac{8}{3}(1.339 \cdot 2L_w \Omega)^2}{\left[1 + (1.339 \cdot 2L_w \Omega)^2\right]^{11/6}} \tag{6}$$

Other representations use the Dryden form

$$\phi_u(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{1 + L_u^2 \Omega^2} \tag{7}$$

$$\phi_v(\Omega) = \sigma_v^2 \frac{2L_v}{\pi} \frac{1 + 3(2L_v)^2 \Omega^2}{\left[1 + (2L_v)^2 \Omega^2\right]^2} \tag{8}$$

$$\phi_w(\Omega) = \sigma_w^2 \frac{2L_w}{\pi} \frac{1 + 3(2L_w)^2 \Omega^2}{\left[1 + (2L_w)^2 \Omega^2\right]^2} \tag{9}$$

---

[*]The shear stresses act in combination with the Coriolis Forces due to the earth's rotation and cause a systematic deflection of the mean wind; results of a fairly simple theory by Ekman are commonly referred to as the Ekman Spiral.

In these equations $\Omega = \frac{\omega}{V}$, where ω is circular frequency and V is velocity. In high altitude models the wind speed is tacitly ignored and V is normally taken as the speed of the aircraft. For low altitude situations, particularly with VSTOL aircraft, the airplane speed may be of the same order as the wind speed, even lower, and thus V must be defined differently; only a few seem to recognize this fact. Specifically, the relative velocity between the aircraft and the wind should be used for V as a good approximation. A generalized correlation distance will be proposed in a later section of this report which inherently includes consideration of both the wind and aircraft velocities.

Theoretically, and because better agreement is found with measured results, equations (4)-(6) are preferred model choices. Since equations (7)-(9) represent rational functions, however, they can be represented much easier in simulator studies; that is, a white noise generator with simple filters can be used to duplicate their spectral makeup, references 47 and 234. The Dryden equations are therefore usually chosen for use in simulator studies.

A common way to express the rms turbulence severity values σ_u , σ_v , σ_w , in the earth's boundary layer is in terms of the friction velocity u_τ , equation (1). Representative values are given in references 46 and 235. As an example, the following values are indicated below at an altitude of about 20 m

$$\sigma_u = 2.5 \, u_\tau \qquad (10)$$

$$\sigma_v = 2.0 \, u_\tau \qquad (11)$$

$$\sigma_w = 1.3 \, u_\tau \qquad (12)$$

As the altitude increases the constants in these relations approach one another, specifically a value of about 1.25. Above the boundary layer the friction velocity u_τ falls to zero. At such altitudes, equations (10)-(12) imply that the rms values for the turbulence components also vanish. The mechanism for turbulence generation is different, however, and equations of the type given by equations (10)-(12) do not apply. The turbulence tends to isotropy, with σ_u , σ_v and σ_w all about equal.

Integral scale values L_v , L_u , L_v , for the boundary layer are given in references 46 and 235. In general, the scale values are observed to increase with altitude up to about 300 m (1000 ft); above this altitude the scale values seem to be constant. It should be noted that the scale values that are

derived from data are quite sensitive to the derivation technique used, or on spectral function choice that is made, see reference 25. Thus, care should be exercised in comparing the scale values obtained by different investigators.

In an attempt to take into account the time delay between wing and tail gust encounter, and the nonuniformity of the gusts in the spanwise direction, spectra models of "equivalent" airplane angular velocities have been advanced, reference 47. The problem is essentially that of taking into account the correlation of the gust velocities that act over one portion of the aircraft with the gusts that act over another portion. In general, the models that have been advanced aren't adequate, and much more study of these "cross correlation" effects is needed. This aspect of the gust encounter problem should be regarded, in fact, as one of the top priority problems that should be studied next.

APPLICATION OF MODELS IN AIRCRAFT STUDIES

It is the consensus that all flight and fixed-based simulator studies of aircraft involving stability and control and flying qualities evaluation should include turbulence as an input. This inclusion, in fact, is considered essential or a must. Thus, simulated turbulence inputs are to be found in nearly all flight or simulator studies of aircraft. This section lists a few of the studies that have been made.

Simulator or flight studies.- References 234 and 239 through 252 are examples of flight and simulator studies of aircraft which included turbulence as a prime input. Generally, the turbulence input is obtained by passing the signal from a white noise generator through simple electrical filters so that a desired spectral shape is obtained. Most of the earlier studies were based on the high altitude gust models and the Dryden-type spectra. Invariably, the investigators found that the turbulence severity values and scale of turbulence as indicated in these models were too large; the main reaction from the pilots was that the turbulence simulation did not seem "realistic." Downward adjustment of both the σ and L values usually led to a better reaction to the turbulence simulation. It is of interest to note that the values arrived at by a trial and error process, σ of about 1 m/s instead of 3 m/s and L of around 100 m instead of 800 m, are in conformity with several low altitude gust models. A better awareness of boundary layer gust models is thus indicated. Another fault in many applications is that cross-correlation effects (nonuniformity of the gust over the dimensions of the aircraft) are not included. It is being realized, however, that these effects must be included.

20

One of the best treatments relating to the development of a low-level turbulence model and with respect to use in a simulator study of a particular aircraft configuration is reference 234. The development considers (a) the average head-on and vertical gusts on the wing, on the fuselage, and the tail, (b) the average side gusts on the fuselage and on the tail, and (c) the spanwise shear of head-on and vertical gusts across the wing. The various forces and moments that act on the aircraft due to gusts were simulated through use of 8 independent gust generators. Study of the behavior of the airplane when flying along a flight path that is at an angle to the mean wind direction was also included.

The patchy nature of the turbulence environment is another item of key concern in simulation studies. Some feel that in order to achieve realistic results that this patchiness is one of the most important items to be included in simulation studies. The terms nonstationary, non-Gaussian, or intermittent character, are often used to describe the phenomenon. Reference 233 presents a study of ways for developing a non-Gaussian gust signal. Reference 229 presents some results comparing reactions of pilots to Gaussian and non-Gaussian inputs.

Carrier operation. References 253 through 259, and the references contained therein, deal with the modeling of the wake behind an aircraft carrier and with simulation studies of the flight of aircraft in these wakes. Wake studies have been rather thorough and from these studies very sophisticated winds and turbulence models have been developed. The models are usually given in terms of three separable but superposable components: steady-state flow angularity, ship-motion-induced disturbances, and random turbulence. Oddly, it appears that the models developed for carrier wakes are much better and in much greater detail than for the models of winds and turbulence over land. Since the wake is dependent on the configuration of the carrier, however, continuing model developments are required.

Analytical studies.- Besides simulator studies there are studies which examine certain other problems associated with aircraft operation in winds and turbulence. Some of these studies are mentioned here. In references 229 and 260, the wind shear problem is considered; the approach to landing of an airplane along a flight path at an angle to the ground is treated, and results giving the probability of encountering a given wind shear within a given altitude increment are derived. The nature of the analysis given in reference 260 is pioneering, and much more work along such lines is needed.

Reference 261 is an interesting and detailed treatment of the approach to landing of a helicopter on the top of a tall building. Very thorough measurements were made in wind tunnel studies to establish the wind pattern and turbulence that is caused by the building. An analytical study of the effect of wind pattern of a helicopter approaching the building top was then made.

21

Reference 262 gives an analytical treatment of the stability and response characteristics of an STOL aircraft in a gust environment.

Wind tunnel projects.- It is of interest to note that in the United States and Canada, many wind tunnels have been converted to study wind flow over various obstacles. Flows over cities, actually modeled on the wind tunnel floor, are of special interest. Much effort has gone into means for simulating the earth's boundary layer. The basic problem is the difficulty of simultaneously simulating the mean velocity profile and the turbulence characteristics. References 263 through 266 are some reports dealing with wind tunnel simulation. In some tunnels studies are being made of an airplane immersed in a simulated earth's boundary layer (both the wind profile and turbulence), in an attempt to measure the forces and moments that develop on the airplane from the turbulence. This project could be most significant. Reference 267 is an example of the type of wind studies that are also made in wind tunnels.

SELECTED REFERENCES REPRESENTING OVERVIEW OF GROUND WINDS PROBLEMS

The long list of references given in this report is in the nature of a shopping list. A study of all the reports listed is in general not practical. It was felt worthwhile, therefore, as an aid to the reader, to select a few references which, if read, would give a fairly complete picture of the various facets of the surface winds problem. This section indicates these references.

General insight to aircraft problems. References 35 and 36.

Measurement and analysis of surface winds and turbulence.- Reference 223 is a good example describing the measurements, the analysis, and the results that were obtained in a very extensive test program investigating surface winds and gusts. References 152, 204 and 217 represent good examples of reports that are to be found wherein attention is focused mainly on the study of various meteorological parameters and laws which appear fundamental to the analysis of surface winds and gusts.

Mathematical descriptions and models.- References 46, 234 and 235 present excellent descriptions of mathematical models that are used to characterize surface winds and gusts. Reference 225 develops extensive spectral turbulence models, while reference 135 analyzes in detail the differences in longitudinal velocity fluctuations between two vertically spaced points. Intermittency and the use of discrete gusts models are treated in reference 226. References 114 and 229 are also significant with respect to model development.

22

Flight and fixed-based simulator studies.- Random gust simulation and analysis are treated in reference 47. One of the best and most extensive model developments and simulation efforts is that covered in reference 234. Other simulation studies which include turbulence as an input, in various degrees of detail, are represented by references 240, 241, 242, 246, 250 and 251.

Carrier approach.- References 253 and 254 represent good examples indicating the modeling and treatment of winds and gusts during approach to carrier landings.

Other response studies.- References 229, 260 and 261 represent treatments of various other problems that are due to surface winds and gusts.

THE METEOROLOGIST AND THE AERONAUTICAL ENGINEER

In general, the aeronautical engineer or scientist and the meteorologist have different points of view towards the analysis of surface winds and gusts. (Here, aeronautical engineer refers mainly to the structural dynamist, not necessarily to the fluid dynamist.) An attempt is made in this section to identify some of these differences.

The aeronautical engineer wants the models spelled out in simple terms; for example, he wants the rms gust severity value, the integral scale of turbulence, and the spectral shape specified. The meteorologist speaks in different terms. He is concerned mainly with energy budgets, and with the search for the basic meteorological parameters which cause data to condense to a universal form. He is accustomed to such parameters as

z height

U mean wind velocity

u_* friction velocity (another way of designating equation (1)

Θ mean potential temperature

θ fluctuating component of potential temperature

$\bar{\Theta}$ average potential temperature for entire layer

k von Kármán's constant

T_* a scaling temperature, $-\dfrac{\overline{w\theta}}{u_*}$

ϵ dissipation rate

In terms of these parameters the meteorologist defines certain basic nondimensional terms:

$$f = \frac{nz}{U}$$ a dimensionless frequency

$$\frac{z}{L} = \frac{kzgT_*}{\bar{\Theta}u_*^2}$$ a dimensionless height

$$\phi_\epsilon = \frac{kz\epsilon}{u_*^3}$$ a dimensionless dissipation rate

$$\phi_m = \frac{kz}{u_*}\frac{dU}{dz}$$ a dimensionless velocity gradient

$$\phi_h = \frac{kz}{T_*}\frac{d\Theta}{dz}$$ a dimensionless temperature gradient

$$R_i = \frac{g\frac{d\Theta}{dz}}{\Theta\left(\frac{dU}{dz}\right)^2}$$ the Richardson number

When an aeronautical engineer looks at reports by meteorologists he is apt to become confused. Often the notation is inconsistent from one report to another; the use of u_τ or u_* for friction velocity, for example. Even the basic non-dimensional parameters are defined in alternative, but equivalent, forms. When the aeronautical engineer sees the dimensionless height $\frac{z}{L}$ he may at first think that L represents an integral scale value of the turbulence; to the meteorologist, L is a basic stability parameter called the Monin-Obukhov stability scale length.

The aeronautical engineer usually thinks of spectral representation in terms of $\phi(\Omega L)$ vs. ΩL, figure 5, where $\Omega = \frac{\omega}{V}$, σ_w is the rms value of turbulence intensity, ω the circular frequency, L the integral scale, and V the speed of the aircraft. The meteorologist's presentation is usually as shown in figure 6, for neutral stability conditions of the atmosphere. The friction velocity u_* is used "as a more basic parameter" in place of σ_u, σ_v, or σ_w, the height z is used in place of L, and the mean wind speed U is used instead of the airplane speed V.

When the engineer thinks further about u_* he becomes further confused. He sees that it involves the covariance value between u and w, yet, because he is accustomed to thinking in terms of the assumption of isotropy, he thinks that $\overline{uw}$ should be zero, not a basic reference value.

24

When the atmosphere is unstable, the meteorologist introduces the parameter ϕ_m , as shown in figure 7, to help collapse the data; sometimes, instead, he introduces ϕ_ϵ . The engineer wonders why ϕ_m is used in some instances, ϕ_ϵ in others, and what is their connection. Often the meteorologist introduces various frequency scaling parameters for the abscissa scale, such as $\frac{f}{f_m}$, where f_m is an empirical factor found to make a chosen analytical function type fit a given set of spectral data.

The meteorologist studies various correlation functions such as the two-argument correlation function shown in figure 8; τ is the correlation time lag, while ξ represents the spatial distance between two measuring points which, in this case, fall essentially along the direction of the mean wind flow. The correlation contours obtained, resembling ellipses, are sometimes referred to as isopleths. The alignment of the line $\xi = \bar{U}\tau$ along the main axis of these "ellipses" is taken as a measure of the validity of Taylor's hypothesis, or the frozen gust field concept.

In general, the correlation functions studied by the meteorologist are not the functions of concern to the aeronautical engineer. As an example, the engineer wants to know the correlation between the vertical gust velocities at two different spanwise stations; from these functions he can deduce the rolling moment that is generated on the aircraft by the gusts. Likewise, he wishes to know whether the correlations between u , v , and w at different points of the airplane are significant from a response point of view. But if he does not have these functions he cannot evaluate their importance. The following example is given to illustrate how cross-correlation effects enter into airplane response considerations. Consider an aircraft to be acted upon by three distinct random inputs w_1 , w_2 , and v_1 , as depicted in the following sketch.
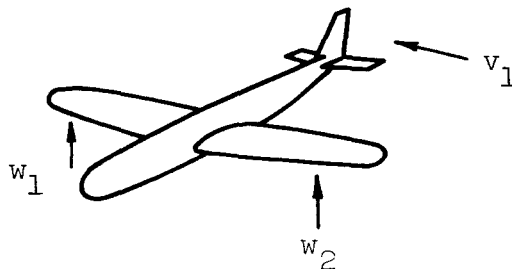
The value of any response quantity, such as rolling motion, may then be written as

$$y = \int_{-\infty}^{t} w_1(\tau) h_1(t - \tau) d\tau + \int_{-\infty}^{t} w_2(\tau) h_2(t - \tau) d\tau$$

$$+ \int_{-\infty}^{t} v_1(\tau) g_1(t - \tau) d\tau$$

where h_1 is the response due to a unit impulse input for w_1, and similarly for h_2 and g_1. The Fourier integral transform of this equation is

$$F_y = F_{w_1} H_1 + F_{w_2} H_2 + F_{v_1} G_1$$

where H_1, H_2, and G_1 represent the frequency response functions for y for sinusoidal inputs at w_1, w_2 and v_1. The spectrum for y follows in turn as

$$\phi_y = \phi_{w_1} H_1 \bar{H}_1 + \phi_{w_2 w_1} \bar{H}_2 H_1 + \phi_{w_1 w_2} \bar{H}_1 H_2 + \phi_{w_2} H_2 \bar{H}_2$$

$$+ 2 \mathrm{Re}(\phi_{v_1 w_1} \bar{G}_1 H_1 + \phi_{v_1 w_2} \bar{G}_1 H_2)$$

$$+ \phi_{v_1} G_1 \bar{G}_1 \tag{10}$$

It is noted that the response depends not only on the spectra for w_1, w_2 and v_1, but on the cross spectrum $\phi_{w_1 w_2}$ between w_1 and w_2 and the cross spectra $\phi_{v_1 w_1}$ and $\phi_{v_1 w_2}$ between w_1 and v_1 and between w_2 and v_1 as well. The cross spectrum between the w_1 and w_2 components is known to be significant to the response. The cross spectrum between w_1 and v_1, or w_2 and v_1, normally has been taken as zero (isotropy); it is not known, however, whether these cross spectra can be ignored for an aircraft immersed in surface layer turbulence. Studies to evaluate their importances are therefore needed. If the component u had been introduced also, the response spectra would appear even more complicated; cross spectra between u and v and between u and w would appear in addition, but again their importance would not be known. Certain cross correlations are known to be of significance in the formation of the boundary layer - the vw correlation appears important in the Ekman layer, for example - but these cross correlations may not be significant in determining aircraft response. It could be that the u and w correlation

26

is significant for response considerations, since the uw correlation is strong in the boundary layer, but that other correlations are of negligible importance.

It may be said in general that a better communication is needed between the meteorologist and the aeronautical engineer. Each must learn the language of the other better. The meteorologist must become better acquainted with the needs of the engineer, and steps must be taken to ensure that measurements taken are the type that can be used in the study of aircraft design and operational problems.

SUGGESTED FORM OF MODELS

It is not the intent of this paper to analyze various models or develop them further. It is felt appropriate, however, to state notions on the form that newer models should take. Hopefully, these comments will help make clearer where areas of weakness lie, and where future efforts should be directed in the study of surface winds and gusts. Attention is given mostly to the turbulence models, since they appear to be in the less developed state. Some comments are offered, however, to the wind models by way of emphasizing comments made in previous sections of this report.

The wind models described in references 46 and 235 are considered good. Attention should not concentrate or be restricted to the mean wind profiles; specifically, more work is needed to develop the unusual and severe profiles that occur from time to time - those profiles which have a "nonclassical" behavior of wind speed with height. Involved are such aspects as diurnal variations, stability considerations, occurrence of a two-layer structure, conditions with low ceilings, gust factor variability. Reference 114 is a good report to read in this connection. With respect to profiles in general, whether mean or odd in shape, more work of the type indicated in reference 260 on wind shear is needed. For cross winds, a better understanding is needed of their variability and, in particular, what discrete disturbances are introduced in their make-up by obstructions such as buildings, hills, or trees.

The remainder of this section touches upon surface turbulence. In reading through these comments, references 23, 24, 268 and 269 should also be studied, since the concepts studied in these references are directly related to the notions set forth here. Reference 23 considers the 3-dimensional gust encounter problem, and evaluates the gust components and, in turn, the gust forces and moments that are significant from a response point of view for conventional aircraft. Work along the line given in this report is needed for various STOL configurations,

since the mechanism for force and moment generation due to gusts may be different for these configurations than for conventional configurations. Reference 268 develops certain cross-spectral functions of the type that are needed in response considerations. Reference 24 derives the general technique for handling multiple random inputs, which is the characteristic situation for aircraft in the surface layer. Reference 269 demonstrates the application of cross spectra by considering a one-degree-of-freedom roll response case.

It is the belief of the author that the major reasons for failing to achieve realism in many simulator studies are as follows:

1) Use of excessive gust severity values (the use of rms values of around 9 fps nearly always led to "unrealistic" response behavior; the use of the more appropriate values around 3 fps gave a more realistic feel).

2) Use of excessive integral scale values (the use of scale values of around 2500 ft gave unrealistic results, as with the high severity values; the use of scale values of only several hundred feet, as is more appropriate, gave a much better response interpretation).

3) In particular, the appropriate forcing inputs due to the gusts (forces and moments) were not used.

Many feel that the question of intermittency or nonstationarity has a lot to do with achieving realism. It is felt, however, that if the three items listed had been handled more realistically, then nonstationarity aspects may not be important.

With these comments in mind, and with references 46, 47, 223, 234 and 235 as a guide, the following turbulence model is suggested. If analytical studies are being made, use the von Kármán spectral functions, equations (4), (5) and (6). If inflight simulation or fixed-based simulators are being used, use the Dryden equations, simply because spectral shaping is accomplished easier. For the turbulence severity values use

$$\sigma_u = 1.7 \text{ m/sec} \qquad 5.8 \text{ ft/sec}$$

$$\sigma_v = 1.4 \qquad 4.6$$

$$\sigma_w = 0.9 \qquad 3$$

with variations from one-half to double these values. For integral scale use

$$L = L_u = 2L_v = 2L_w = 0.8z$$

28

up to 300 meters altitude; use 250 m (800 ft) at higher altitudes.

Force and moment spectra due to the turbulence inputs should be established in accordance with the configuration. In general, the following force and moment spectra will dominate, figure 9.

1) Vertical force spectrum due to w

2) Pitching moment spectrum due to w

3) Yawing moment spectrum due to v

4) Rolling moment spectrum due to spanwise variation in w

For some configurations, the rolling moment due to a spanwise variation in u may be significant. On the basis of these input force and moment spectra, input gust generators may be derived for use in simulation. Each input is handled by an independent gust generator, with the shaping filters being chosen such that the output duplicates or approximates the spectral nature of the input being represented.

It is believed that if this model approach is used, the inclusion of the nonstationarity nature of the gusts may not be significant. Nonstationarity may be introduced, however, if judged lacking, either by simply switching the generators on and off in random fashion, or by randomly varying the gain of the generators.

Some comments about a possible, or interim, generalized correlation distance for possible use in deriving a general gust covariance tensor are given to close out this section. The treatment or derivation of this interim generalized correlation distance is not within the scope of this effort, but the advancement of certain notions relative to such a function may be of interest. There are two principal reasons or motivations for deriving a basic correlation distance measure:

1) To allow the derivation of appropriate cross-spectral functions (even though they may be approximations).

2) To be able to treat the case where the flight path of the aircraft is at an angle to the wind direction.

With reference to figure 10, and without giving the derivation, or the logic behind its meaning, the following is suggested as a basic correlation distance.

$$r = \left[(U_a t - x)^2 + y^2 + \eta^2 U^2 t^2 \right]^{1/2} \tag{11}$$

which may be rewritten

$$r = \left[\left(U_e t - \frac{U_a x}{U_e}\right)^2 + y^2 + \frac{\eta^2 U^2}{U_e^2} x^2\right]^{1/2} \tag{12}$$

in which

$$U_a = (U^2 - 2UV \cos \psi + V^2)^{1/2}$$

$$U_e = (U_a^2 + \eta^2 U^2)^{1/2}$$

where, as indicated in figure 10, U is the wind speed, V the speed of the aircraft relative to the ground, ψ the angle between the positive U and V directions; U_a is seen to be the relative velocity between the aircraft and the wind. Suppose that it is desired to establish the time cross-correlation function between, for example, the vertical gust velocities at point 2 and at point 1, where x is the separation distance in the flight direction and y is the separation distance normal to this direction. It is postulated that r, given by equation (12), can be used to derive the cross-correlation function and in turn the cross spectrum.

The following touches upon the general way to utilize r. On the assumption that isotropy is present, it can be shown that the cross-correlation function for w between points 2 and 1 is given by the point correlation function $g(r)$. The $g(r)$ function by the Dryden formulation, for example, is

$$g(r) = \left(1 - \frac{r}{2L}\right)e^{-\frac{r}{L}}$$; for the von Kármán form, g is given in

terms of Bessel functions, reference 20. If r, given by equation (12), is substituted in $g(r)$, and the Fourier integral transform taken, then a cross-spectrum function for w between the two points will result. For the u_a components, the turbulence components in the direction of the relative wind U_a, it may be shown, again on the assumption of isotropy, that the cross-correlation function is given by

$$R(r) = f(r) + \frac{y^2}{2r}\frac{\partial f}{\partial r}$$

where f is the point correlation for u, given, for example, as $f(r) = e^{-\frac{r}{L}}$ for the Dryden model. The Fourier integral transform of R, with r given as by equation (12), then gives a cross-spectrum function for the u_a components. The cross-spectral functions generated in this way can be used to establish the spectral functions for the gust forcing moments on the aircraft.

It should be observed that equation (12) takes into account convective effects, spatial separation effects, and the time-varying nature of turbulence. With reference to equation (11), if y is zero, then the use of r would lead to two-function correlation functions very similar to that shown in figure 8. If the aircraft is drifting with the wind, $U_a = 0$, and $x = 0$, $y = 0$, then r reduces simply to the $\eta U t$ term, which is associated with the time-varying property of the turbulence (along the $\xi = U t$ line in figure 8). Values of η are not known, but an estimate given here is $\eta \approx 0.4$. When V becomes large relative to the wind, the nature of r complies with the frozen gust field concept.

PROBABILITY CONSIDERATIONS IN MODELS

A point of interest noted during the course of the survey was the fact that there was virtually no mention of probability aspects of surface wind and gust encounter. This fact is considered significant and merits separate discussion. Mention was frequently made of design wind and gust values, or of the lack of knowledge of what the values should be, but discussion of the values in terms of probability considerations was notably absent.

A primary reason for the lack of reference to probability numbers is probably due to the fact that most of the individuals contacted represented the aeronautics community. Traditionally, aircraft structural design people have worked in terms of specified design values, but rarely do they deal with associated probability considerations. A few examples may be given by way of illustration. As mentioned earlier in this report, aircraft cargo doors are designed to operate in winds up to 65 mph; the probability of encountering such winds is not considered. For years, aircraft design for gust encounter has been based upon a specified gust shape and a specified maximum gust velocity (usually 50 fps). The probability of encountering this design velocity is not known, nor considered. For commercial type aircraft, landing gears are designed and tested to withstand a landing vertical impact speed of 10 fps; for carrier operation, a design vertical velocity has been 25 fps. In some instances, design values that have appeared suitable for years may become inadequate because newer configurations are introduced or because increased performance is demanded. Inadequacy is judged on the basis that the number of operational failures have become "excessive;" there usually is no hard and firm rule, however, as to what is meant by "excessive." If design values are found to be inadequate, they are graded upward. An example case is that of carrier landing operations. For certain configurations, the design sinking speed of 25 fps was found inadequate; a new design value of 31 fps was therefore introduced. (Usually, a number of operational tests and measurements are made and analyzed as a help in establishing how much of an increase should be made.)

The fact that many aircraft design procedures are stated simply in terms of specified numbers does not necessarily mean that no consideration was given to the statistics of the design problem. Often a large body of statistics on the problem are gathered. These data are analyzed and from the analysis a design value is selected. Thereafter, the statistics of the problem are set aside. The probability of encountering the design value is not considered. In some instances, certain of the statistics are used for design purposes. In the more recent treatments on gust encounter, for example, specific consideration is given to load exceedance curves, which indicate the number of times per second, on the average, that given load levels are reached. Inherently contained in the curves is the proportion of time turbulence is encountered on the average, and the overall rms value of the turbulence severity.

It is to be noted that some investigations deal specifically with probability considerations. References 21 and 260 are examples. Reference 21 contains a fundamental derivation which shows how the gust load exceedance curves may be used to establish the probability that a given load will be encountered in a specified flight time. Reference 260 analyzes the probability of encountering given wind shear values in the landing approach. There appears to be no application of such analyses, however, for aircraft design purposes.

By contrast, launch vehicle and space flight technology has developed with a strong attention being given to probability aspects. Design philosophy depends on the mission under consideration, on the component of the system that is being studied, and particularly on the phase of the development cycle that is on hand. Sometimes, a certain overall vehicle performance capability in terms of probability may be mentioned as a guideline, but it is realized that because of the many unknowns in the vehicle characteristics and design criteria, it is not realistic to expect a design to be developed that will precisely meet the specified performance capability. On the other hand, there are specific questions on probability aspects that are of primary concern in the design, mission planning, and operation of space vehicles. In the discussion on surface winds in reference 46, for example, such questions as the following are brought out and discussed.

1) How probable is it that the peak surface wind at some specified reference height will exceed (or not exceed) a given magnitude in some specified time period?

2) Given a design wind profile in terms of peak wind speed versus height from 10 to 150 meters, how probable is it that the design wind profile will be exceeded in some specified time period?

32

Much information is given in reference 46 on the first question at selected geographic locations. The second question, being more complex, is treated in a limited way. Reference 46 also discusses and presents much information on the concept of including exposure period probabilities in the design and operation of space vehicles. As an example, if an operation requires one hour to complete, and if the critical wind loads on the space vehicle can be defined in terms of the peak wind speed, then it is the probability of occurrence of the peak speed during a 1-hour period that gives a measure of the probable risk of the occurrence of structural failure.

The main purpose of this section is to point out that the philosophy used for the design of aircraft to winds appears different than that used for space vehicles. It would seem desirable to bring the two design communities together to exchange viewpoints, and to bring out the merits of each individual design approach. Specific consideration should be given to the form that design models for winds and gusts should take, particularly with respect to the degree that probability aspects are included.

CONCLUSIONS AND RECOMMENDATIONS

Some of the main conclusions that may be drawn from the survey are the following:

1. As anticipated, environmental surface winds and gusts create many design and operational problems for all aircraft. The listing in the section entitled "Cited Problems" serves as a convenient reminder to these problems.

2. The problem of maintaining control of the aircraft, particularly during hover, take-off, approach and landing, is probably the most critical design and operational problem that is due to surface winds and gusts.

3. VTOL and STOL aircraft are most vulnerable; stability and control and handling qualities, especially as aggravated by surface winds and gusts, are the key factors of whether a STOL system is feasible or not; operational problems will increase in number in the future.

4. As with VSTOL configurations, wind shear and cross-winds effects must be studied carefully for exotic singular-type configurations as the Space Shuttle and remotely piloted vehicles (RPV); automatic approach systems in the presence of winds and gusts need much study.

5. Relatively little is known about the unusual wind profiles or wind shear patterns - their cause, their detection, and the ability to cope with them.

33

6. Likewise, unusual cross-wind situations, especially those having discrete and severe disturbances as a result of obstacle interference, are little understood.

7. Better sensors and cues or displays to the pilot are needed; it is very difficult for him to detect what the winds and gusts are doing, and what his aircraft motions are.

8. A better liaison between aeronautical design and operational people and meteorologists is needed.

9. There is a need for standardization in measurement of winds and gusts, especially in the measurement and reporting of winds at airports.

10. The cross-correlation measurements made in surface gust studies are usually not appropriate for aircraft response studies; there is a critical need to measure the spatial correlation functions that are of concern to airplane control, such as the spanwise variation in the u and w components. The significance of the correlation between the u, v, and w components must also be evaluated.

11. Certain wind and turbulence models exist, but on the whole they are not adequate; the ability to develop gust input moments is a key ingredient missing; much effort should be expended to develop appropriate models for use in simulation and design studies.

12. There is an uncertainty with respect to how specific probability considerations should be included in design models for winds and gusts. Aircraft design procedures are based primarily on stipulated values of wind or gust severity; by contrast, space vehicle design often gives explicit consideration to the probability of an event occurring in a specified time.

13. Although certain models exist, only a relatively few individuals are aware of them.

14. Gust inputs are essential in simulation studies, fixed-based or in-flight simulation; techniques for including gusts are in need of much improvement.

15. It is not known whether a well developed model will serve all aircraft configurations, or whether models should be "tailored" to the type of configuration.

These 15 items serve as some of the important conclusions that can be made from the survey. The recommendation follows that these items need study and development. Priority items are: (1) measurement and analysis of spatial correlation effects pertinent to airplane operation, (2) study of unusual and severe

wind shear and cross-wind conditions, and (3) development of better models, with better dissemination.

The following additional specific recommendations are made:

1. Improved analytical means for studying the dynamic behavior of the atmosphere at low altitude are needed.

2. Study the importance of the u, v, and w components on different type configurations (for example, u may be important to some, but not to others).

3. Analytically develop key cross-spectral functions on the basis of information known today and on plausible assumptions.

4. With (2), develop the force and moment spectra that are applicable to various configurations, for use in simulation and analytical response studies; at the same time, develop experimental procedures to measure these forces and moments.

5. Develop procedures for investigating landing dispersions or other factors of concern operationally, due to wind shear and cross winds.

6. Study and develop better models (possibly along the lines advanced herein).

7. Preparation of a handbook on surface winds and gusts should be considered, which would serve the meteorologist and the aeronautical engineer on an equal basis, and help close the language gap between them.

8. Finally, it seems highly desirable to have a conference on surface winds and gusts. This conference would bring together the meteorologist and the aeronautical design communities, allow for an exchange of notions, show where developments stand today, point out the need for better models and, most importantly, would make a much larger number of individuals aware of the surface wind and gust problems. If successful, which seems certain, scheduling of such conferences on a regular basis, such as every three years, should be made.

APPENDIX

LIST OF ORGANIZATIONS AND INDIVIDUALS CONTACTED

Many groups are known to exist which could have provided an input to this survey. It was not possible to contact the majority of these groups due to lack of time, and thus a sampling, hopefully representative, was selected. The organizations and some of the individuals that were contacted are indicated in this appendix.

1. Air Force Cambridge Research Laboratories
   Hanscom Field, Mass.

   Rene V. Cormier
   Donald D. Grantham
   Duane Haugen
   Norman Sissenwine
   Paul Tattleman

2. Battelle Memorial Institute (N.W.)
   Richland, Washington

   A. G. Dunbar
   G. E. Elderkin
   T. W. Horst
   D. C. Powell
   J. V. Ramsdell

3. Bell Aerospace
   Buffalo, N.Y.

   Desmond Earl
   David Grupe
   Robert Kaiser
   Neil Sullivan

   Fort Worth, Texas

   Meijer Drees
   Troy Gaffey
   Leo Kingston
   L. Rohrbough
   Dora Strother

4. The Boeing Company
   Seattle, Washington

   James Fuller
   John Rogers
   Dwight R. Schaeffer
   Howard W. Smith
   Leroy Topp

5. Colorado State University
    Fort Collins, Colorado

       Prof. J. E. Cermak

6. Cornell Aeronautical Laboratory, Inc.
    Buffalo, N.Y.

       Warren Hall
       David Key
       Victor Lebacqz
       Roger Smith

7. de Havilland Aircraft of Canada, Ltd.
    Toronto, Canada

       Richard Batch
       Jack P. Uffen

8. Federal Aviation Agency
    Washington, D.C.

       Edmund Bromley, Jr.
       Arthur Hilsenrod
       Kenneth Kraus

9. General Dynamics Corp.
    Fort Worth, Texas

       R. L. Haller
       R. P. Peloubet

10. Ling-Tempco-Vought
    Dallas, Texas

       B. J. Brock
       Lee Head
       Robert E. Rostine
       Mack Shields

11. Lockheed-California Company
    Burbank, California

       Edward Ashburn
       Fred Hoblit
       Maurice D. Lamoru
       John Lewolt
       Alfred Potthart
       Roger H. Shaar

12. Massachusetts Institute of Technology
    Cambridge, Mass.

       Prof. Rene Miller

13. National Aeronautics and Space Administration
    Ames Research Center, Moffett Field, Calif.

        Seth Anderson
        Jack Franklin
        Ron Gerdes
        Richard Kurkowski
        Maurry White

    Langley Research Center, Hampton, Va.

        Jack Reeder

    Manned Spacecraft Center, Houston, Texas

        Jake Klinar
        Bernie Marcantel
        Rudolph L. Saldana

    Marshall Space Flight Center, Ala.

        George H. Fichtl
        William W. Vaughan

14. National Severe Storms Laboratory
    Norman, Oklahoma

        Edwin Kessler
        Jean Lee

15. Pennsylvania State University
    State College, Pa.

        Stan Hillard
        Prof. J. L. Lumley
        Prof. M. M. Sevick

16. Ryan Aeronautical Company
    San Diego, Calif.

        William Anderson
        W. Bert Davis
        H. B. Starkey

17. Systems Technology, Inc.
    Hawthorne, Calif.

        Irving L. Askenas
        Duane T. McRuer

18. University of Toronto
    Toronto, Canada

        Prof. B. Etkin
        H. W. Teunissen

19. University of Wisconsin
    Madison, Wisconsin

    Prof. H. Lettau

20. Wright-Patterson Air Force Base, Ohio

    Evard H. Flinn

REFERENCES

Grouping of References

In a rough sense, the references given herein are grouped in various categories. This grouping is indicated here as a possible aid to the reader in surveying the reference list.

Refs.

1-25	General gust studies, mainly for higher altitudes
26-27	Wind loads on launch vehicles
28-34	Wind loads on structures
35-36	General notions on the aircraft operational problems in surface winds and gusts
37-45	Assorted studies of wind and gust problems
46-61	Specifications, criteria, and guidelines
62-67	Books
68-85	Sensors and measurement techniques
86-221	Data acquisition and analysis, statistical inference, meteorological aspects, basic research of surface winds and gusts
222-238	Model developments
239-252	Simulation studies
253-260	Carrier wake studies
261-263	Analytical response studies
264-268	Wind tunnel studies
269-270	Cross-spectra and response

REFERENCE LIST

1. Press, Harry; Meadows, May T.; and Hadlock, Ivan: A Re-
    Evaluation of Data on Atmospheric Turbulence and Airplane
    Gust Loads for Application in Spectral Calculations.
    NACA Rept. 1272, 1956.

2. Atmospheric Turbulence and Its Relation to Aircraft.
    Proceedings of a Symposium, The Royal Aircraft Establishment,
    Farnborough, England, 16th November 1961.

3. Meeting on Aircraft Response to Turbulence. Compilation of
    papers presented at the NASA Langley Research Center,
    September 24-25, 1968.

4. Jones, J.W.; Mielke, R.H.; Jones, G.W.; et al.: Low Altitude
    Atmospheric Turbulence, LO-LOCAT Phase III, Vol. I, Parts 1
    and 2, Vol. II, Parts 1 and 2, AFFDL-TR-70-10, November 1970.

5. Crooks, W.M.; et al.: Project HICAT High Altitude Clear Air
    Turbulence Measurements and Meteorological Correlations.
    (AFFDL-TR-68-127, Vol. 1), AF Flight Dynamics Laboratory,
    Wright-Patterson AFB, Ohio, 1968.

6. Ashburn, E.V.; et al.: Development of High Altitude Clear
    Air Turbulence Models. (AFFDL-TR-69-70), AF Flight Dynamics
    Laboratory, Wright-Patterson AFB, Ohio, 1969.

7. Pritchard, F.E.; Easterbrook, C.C.; and McVehil, G.:
    Spectral and Exceedance Probability Models of Atmospheric
    Turbulence for Use in Aircraft Design and Operations.
    (AFFDL-TR-65-112), AF Flight Dynamics Laboratory, Wright-
    Patterson AFB, Ohio, November 1965.

8. Saxton, D.W.: The Nature and Causes of Clear-Air Turbulence.
    AIAA Paper No. 66-966, presented at the AIAA 3rd Annual
    Meeting (Boston, Mass.), November 29-December 2, 1966.

9. O'Hara, F.; and Burnham, J.: The Atmospheric Environment
    and Aircraft--Now and the Future. Aeronautical J., vol. 72,
    June 1968, pp. 467-480.

10. Jones, J.G.: A Theory for Extreme Gust Loads on an Aircraft
    based on the Representation of the Atmosphere as a Self-
    Similar Intermittent Random Process. RAE Technical Report
    68030 1968

11. Jones, J.G.: A Unified Discrete Gust and Power Spectrum
    Treatment of Atmospheric Turbulence. RAeS/AIAA/CASI
    International Conference on Atmospheric Turbulence, London,
    May 1971.

12. Etkin, B.: Theory of the Flight Airplanes in Isotropic Turbulence; Review and Extension. University of Toronto Report No. 72, February 1961.

13. Etkin, B.: Dynamics of Flight: Stability and Control. Wiley, N.Y., 1959.

14. Zbrozek, J.K.: Atmospheric Gusts. Present State of the Art and Further Research. J. Royal Aero. Soc., vol. 69, no. 649, 1965.

15. Diederich, Franklin W.: The Response of an Airplane to Random Atmospheric Distrubances. NACA Report 1345, 1958.

16. Eichenbaum, Frederick D.: A General Theory of Aircraft Response to Three-Dimensional Turbulence. J. Aircraft, vol. 8, no. 5, May 1971, pp. 353-360.

17. Porter, Richard F.; and Robinson, Alfred C.: A Proposed Criterion for Aircraft Flight in Turbulence. Battelle Columbus Laboratories, Columbus, Ohio.

18. Hoblit, F.M.; Paul, N.; Shelton, J.D.; and Ashford, F.E.: Development of a Power-Spectral Gust Design Procedure for Civil Aircraft. FAA-ADS-53, January 1966.

19. Dutton, John A.: Broadening Horizons in Prediction of the Effects of Atmospheric Turbulence on Aeronautical Systems. AIAA Paper 68-1065, presented at the AIAA Annual Meeting and Technical Display, Philadelphia, Pa., Oct. 21-24, 1968; also AIAA Selected Reprints Series, vol. XIII.

20. Houbolt, John C.; Steiner, Roy; and Pratt, Kermit G.: Dynamic Response of Airplanes to Atmospheric Turbulence Including Flight Data on Input and Response. NASA TR R-199, June 1964.

21. Houbolt, John C.: Gust Design Procedures Based on Power Spectral Techniques. AFFDL-TR-67-74, August 1967.

22. Houbolt, John C.: Design Manual for Vertical Gusts Based on Power Spectral Techniques. AFFDL-TR-70-106, December 1970.

23. Houbolt, John C.: On the Response of Airplanes in a 3-Dimensional Gust Field. A.R.A.P. Report No. 161, Aeronautical Research Associates of Princeton, Inc., Princeton, N.J., July 1971.

24. Houbolt, John C.: On the Response of Structures Having Multiple Random Inputs. Jahr. 1957 der WGL, Friedr. Vieweg & Sohn (Braunschweig), pp. 296-305.

25. Houbolt, John C.: Atmospheric Turbulence. AIAA Paper No. 72-219, presented at AIAA 10th Aerospace Sciences Meeting, San Diego, Calif., January 17-19, 1972.

26. Meeting on Ground Wind Load Problems in Relation to Launch Vehicles. Compilation of papers presented at the NASA Langley Research Center, June 7-8, 1966.

27. Prelaunch Ground Wind Loads. NASA Space Vehicle Design Criteria. NASA SP-8008, November 1965.

28. Fichtl, George H.; Kaufman, John W.; and Vaughan, William W.: The Characteristics of Atmospheric Turbulence as Related to Wind Loads on Tall Structures. National Bureau of Standards, Dept. of Commerce Building Science Series 30, 1970.

29. Anon.: Wind Effects on Buildings and Structures. University of Toronto Press, Toronto, 1968, 2 vols.

30. Davenport, A.G.: The Relationship of Wind Structure to Wind Loading. Paper 2, Symp. 16, Proceeding of Conference on "Wind Effects on Buildings and Structures" at NPL in June 1963. HMSO, London, 1965.

31. Davenport, A.G.: The Buffeting of Large Superficial Structures by Atmospheric Turbulence. Reprinted from the Annals of the New York Academy of Sciences, vol. 116, article 2, June 1964, pp. 135-159.

32. Davenport, A.G.: Rationale for Determining Design Wind Velocities. J. Struct. Div., Proc. Amer. Soc. Civil Eng., May 1960.

33. Harris, R.I.: The Nature of the Wind. Presented at the Construction Industry Research and Information Association Seminar on the Modern Design of Wind-Sensitive Structures at London, England, June 18, 1970.

34. Hanna, S.R.: The Formation of Longitudinal Sand Dunes by Large Helical Eddies in the Atmosphere. J. of Applied Meteorology, vol. 8, 1969, pp. 874-883.

35. Flinn, E.H.: Low Altitude Turbulence and V/STOL Gust Response. AFFDL/FGC-TM-70-3, September 1970.

36. Davis, H.M.; and Flinn, E.H.: Research Requirements for V/STOL Gust Response and Low Altitude Turbulence Model. AFFDL-FDCC TM 66-11, October 1966.

37. McElreath, Capt. Kenneth W., ed.: Research and Development Programs of the Flight Control Division. AF Flight Dynamics Laboratory (FGS), Wright-Patterson Air Force Base, Ohio, prepared for the SAE, January 1972.

38. Some Comments on Reingestion - Ames Wind Tunnel Test Results. XV-5A Datum - No. 4, 1 September 1963.

39. Snyder, C. Thomas: Analog Study of the Longitudinal Response of a Swept-Wing Transport Airplane to Wind Shear and Sustained Gusts During Landing Approach. NASA TN D-4477, 1968.

40. Cockayne, William; and Rusnak, Walter: Study of Automatic Flare and Decrab Guidance and Control System for the Space Shuttle Vehicle. NASA CR-114436, July 1971.

41. Crutcher, H.L.: Project Crosswinds. Unpublished paper of the National Climatic Center, U.S. Dept. of Commerce, NOAA, Environmental Data Service, Federal Building, Asheville, N.C. 28801.

42. Ryken, John M.: A Study of Air Cushion Landing System for Space Shuttle Vehicles. NASA CR 11803.

43. McElreath, Capt. K.W.: True Airspeed Sensor for V/STOL Aircraft. AFFDL-TR-72-131, December 1972.

44. V/STOL Displays for Approach and Landing. AGARD Report No. 594, July 1972.

45. Measurement and Reporting of Surface Wind and Vertical Wind Shear at Aerodromes. Attachment to State Letter AN 10/11.9-72/19, 5th Air Navigation Conference, Montreal, 1967.

46. Daniels, Glenn E., ed.: Terrestrial Environment (Climatic) Criteria Guidelines for use in Space Vehicle Development, 1971 Revision. NASA Technical Memorandum TM X-64589, May 10, 1971.

47. Chalk, C.R.; Neal, T.P.; et al.: Background Information and User Guide for MIL-F-8785B(ASG), "Military Specification - Flying Qualities of Piloted Airplanes." AFFDL-TR-69-72, August 1969.

48. Flying Qualities of Piloted Airplanes. Military Spec. No. MIL-F-8785B(ASG), Interim Amendment-1(USAF), 31 March 1971.

49. Flying Qualities of Piloted V/STOL Aircraft. Military Spec. No. MIL-F-83300, 31 December 1970, used in lieu of MIL-H-8501A.

50. Airplane Strength and Rigidity, General Specification For. Military Spec. No. MIL-A-008860A(USAF), 31 March 1971, used in lieu of MIL-A-8860(ASG).

51. Airplane Strength and Rigidity, Flight Loads. Military Spec. MIL-A-008861A(USAF), 31 March 1971, used in lieu of MIL-A-8861(ASG).

52. Airplane Strength and Rigidity, Miscellaneous Loads. Military Spec. MIL-A-008865A(USAF), 31 March 1971, used in lieu of MIL-A-8865(ASG).

53. Airplane Strength and Rigidity, Reliability Requirements, Repeated Loads, and Fatigue. Military Spec. MIL-A-008866A (USAF), 31 March 1971, used in lieu of MIL-A-8866(ASG).

54. Airplane Strength and Rigidity, Vibration. Military Spec. MIL-A-8892(USAF), Amendment 1, 16 November 1971.

55. Airplane Strength and Rigidity, Flight Loads. Military Spec. MIL-A-8861(ASG), 18 Mary 1960, supersedes in part the MIL-S-5700 series specs and in part Spec. MIL-A-8629.

56. Airplane Strength and Rigidity, Miscellaneous Loads. Military Spec. MIL-A-8865(ASG), 18 May 1960, supersedes in part the MIL-S-5700 series specs. and in part Spec. MIL-A-8629.

57. Airplane Strength and Rigidity, Reliability Requirements, Repeated Loads, and Fatigue. Military Spec. MIL-A-8866(ASG), 18 May 1960, see superseding data in section 6 of Spec. MIL-A-8629.

58. Climatic Extremes for Military Equipment. Military Std. MIL-STD-210A, 2 August 1957, superseding MIL-STD-210, 1 June 1953.

59. Automatic Landing Systems (ALS). Department of Transp., Federal Aviation Administration, Advisory Circular No. 20-57A, 12 January 1971.

60. Air Registration Board. Airworthiness Requirements for Automatic Landing in Restricted Visibility Down to Category 3, British Civil Airworthiness Requirements, Paper No. 367, Issue 3, Working Draft, June 1970.

61. Anon.: Tentative Airworthiness Standards for Powered Lift Transport Category Aircraft. Federal Aviation Administration, Department of Transportation, 1970.

62. Batchelor, G.K.: The Theory of Homogeneous Turbulence. Cambridge University Press, Cambridge, 1959.

63. Hinze, J.O.: Turbulence. McGraw-Hill, New York, 1959.

64. Lettau, Heinz; and Davidson, Ben: Exploring the Atmosphere's First Mile. Pergamon, 1957, 2 vols.

65. Lumley, J.L.; and Panofsky, H.A.: The Structure of Atmospheric Turbulence. Wiley, New York, 1964.

66. Priestley, C.H.B.: Turbulent Transfer in the Lower Atmosphere. University of Chicago Press, Chicago, 1959.

67. Sutton, O.G.: Micrometeorology: A Study of Physical Processes in the Lowest Layers of the Earth's Atmosphere. McGraw-Hill, New York, 1953.

68. Barnes, Stanley L.; Henderson, James H.; and Ketchum, Robert J.: Rawinsonde Observation and Processing Techniques at the National Severe Storms Laboratory. NOAA Tech. Memo. ERL NSSL-53, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, April 1971.

69. Bradley, E.F.: A Shearing Stress Meter for Micrometeorological Studies. Quart. J.R. Met. Soc., vol. 94, 1968, pp. 380-387.

70. Brown, Rodger A.; Bumgarner, William C.; et al: Preliminary Doppler Velocity Measurements in a Developing Radar Hook Echo. Bulletin of the Amer. Meteorological Society, vol. 52, no. 12, December 1971, pp. 1186-1188.

71. Camp, Dennis W.; Turner, Robert E.; and Gilchrist, Luke P.: Response Tests of Cup, Vane, and Propeller Wind Sensors. NASA Technical Memo. NASA TM X-64522, May 18, 1970.

72. Carter, John K.: The Meteorologically Instrumented WKY-TV Tower Facility. NOAA Tech. Memo. ERLTM-NSSL 50, U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, October 1970.

73. Cermack, J.E.; and Horn, J.D.: The Tower Shadow Effect. Atm. Sci. Lab., U.S. Army Electronics Command, White Sands, N.M., August 1966.

74. Fichtl, George H.: The Responses of Balloon and Falling Sphere Wind Sensors in Turbulent Flows. NASA TN D-7049, February 1971.

75. Fichtl, George H.; DeMandel, R.E.; and Krivo, S.J.: Aerodynamic Properties of Rough Spherical Balloon Wind Sensors. NASA TN D-6373, June 1971.

76. Horst, T.W.: Corrections for Response Errors in a Three-Component Propeller Anemometer. Battelle Memorial Institute, Pacific Northwest Labs., Richland, Wash., BNWL-SA-4262, March 1971.

77. Hsi, G.; and Cermak, J.E.: Meteorological-Tower Induced
     Wind-Field Perturbations. College of Engrg., Colorado St.
     Univ., Fort Collins, Colo., October 1959, AD 623-946.

78. Kaimal, J.C.; Wyngaard, J.C.; and Haugen, D.A.: Deriving
     Power Spectra from a Three-Component Sonic Anemometer.
     Journal of Applied Meteorology, vol. 7, no. 5, October 1968,
     pp. 827-837.

79. Kaimal, J.C.; Haugen, D.A.; and Newman, J.T.: A Computer
     Controlled Mobile Micrometeorological Observation System.
     Journal of Applied Meteorology, vol. 5, 1966, pp. 411-420.

80. Lee, Jean T.: Thunderstorm Turbulence Measurements by Air-
     craft and Concurrent Radar Echo Evaluations. Severe Storm
     Detection and Circumnavigation, National Severe Storm
     Project, June 1963.

81. MacCready, Jr., P.B.; and Rex, H.R.: Response Characteristics
     and Meteorological Utilization of Propeller and Vane Wind
     Sensors. Journal Applied Meteorology, vol. 3, no. 2,
     April 1964, pp. 182-193.

82. NOAA Technical Memorandum ERL NSSL-55. The NSSL Surface
     Network and Observations of Hazardous Wind Gusts, June 1971.

83. Oliver, Vincent J.; and Parmenter, Frances C.: Weather
     Forecasting with the Aid of Satellite Data. Presented at
     the 9th Annual Meeting of the American Institute of Aero-
     nautics and Astrophysics, Wash., D.C., January 8-10, 1973.

84. Sirmans, D.; Watts, W.L.; and Horwedel, J.H.: Weather
     Radar Signal Processing and Recording at the National
     Severe Storms Laboratory IEEE Transactions on Geoscience
     Electronics, vol. GE-8, no. 2, April 1970, pp. 88-94.

85. Woodruff, R.K.; and Dunbar, A.G.: The Development and
     Testing of a Stable Buoy and Instrument System for Studies
     at the Sea-Air Interface. Pacific Northwest Laboratory
     Annual Report for 1969, Vol. II: Physical Sciencies, Part 1:
     Atmospheric Sciences, BNWL-1307, Battelle-Northwest,
     Richland, Wash., June 1970, pp. 46-53.

86. Adelfang, Stanley; Prophet, David T.: Turbulence and Wind
     Structure Studies, Measurements of the Intensity and
     Spectrum of Atmospheric Turbulence at Palmdale Airport.
     Report No. LR-23341, Lockheed California Company,
     December 1969.

87. Adelfang, S.I.; and Court, A.: Jimsphere Wind and
     Turbulence Exceedance Statistics. NASA CR-2118, August 1972.

88. Appleby, J.F.; and Ohmstede, W.D.: Numerical Solution of the Distribution of Wind and Turbulence in the Planetary Boundary Layer. DDC No. 66-424, September 1964.

89. Appleby, J.F.; and Dries, T.H.: Wind Variability Over a Complex Surface. AMS/AISS Paper No. 66-335, March 1966.

90. Atlas, D.; Metcalf, J.I.; Richter, J.H.; and Gossard, E.E.: The Birth of CAT and Microscale Turbulence. J. Atmospheric Sci., vol. 27, no. 6, September 1970, pp. 903-913.

91. Berman, S.: Estimating the Longitudinal Wind Spectrum Near the Ground. Qu. J. Roy. Met. Soc., vol. 91, 1965, pp. 302-317.

92. Bernstein, A.B.: Dimensional Analysis Applied to the Wind Distribution in the Planetary Boundary Layer. Monthly Weather Review, vol. 93, October 1965.

93. Blackador,A.K.; et al.: Structure of Turbulence and Mean Wind Profiles Within the Atmospheric Boundary Layer. Dept. of Meterology, Penn. St. Univ., University Park, Penn., Astia No. AD259-571, October 1960.

94. Blackador, A.K.; and Chaplin, A.S.: Wind Profiles, Spectra and Cross-Spectra Over Homogeneous Terrain. TRECOM 01388-1, U.S. Army Electronics Command, Fort Monmouth, N.J., February 1967.

95. Blackador, A.K.: The Vertical Distribution of Wind and Turbulent Exchange in a Neutral Atmosphere. Jour. Geophys. Research, vol. 87, no. 8, July 1962.

96. Boston, N.: An Investigation of High Wave Number, Temperature and Velocity Spectra in Air. Ph.D. Thesis, University of British Columbia, 1971.

97. Bowne, N.E.; and Anderson, G.E.: Take-off and Landing Critical Atmospheric Turbulence, Analytical Investigation, AFFDL-TR-68-23, Wright-Patterson Air Force Base, Ohio, April 1968.

98. Brooke, R.R.; and Spillane, K.T.: On the Variation of Maximum Wind Gusts with Height. Journal of Applied Meteorology, vol. 9.

99. Burnham, J.; and Colmer, M.J.: On Large and Rapid Wind Fluctuations which Occur when the Wind had Previously been Relatively Light. RAE Technical Report 69261, 1969.

100. Burnham, J.: Atmospheric Gusts--A Review of the Results of Some Recent Research at the Royal Aircraft Establishment. Monthly Weather Review, vol. 98, no. 10, October 1970, pp. 723-734.

101. Burns, A.: Power Spectra of Low Level Atmospheric Turbulence Measured from an Aircraft. RAE Tech. Note No. Structures 329, April 1963.

102. Burns, A.: Power Spectra of the Vertical Component of Atmospheric Turbulence Obtained from Concurrent Measurements on an Aircraft and at Fixed Points. RAE Tech. Note No. Structures 325, January 1963.

103. Busch, N.E.; and Panofsky, H.A.: Recent Spectra of Atmospheric Turbulence. Proc. Unguided Rocket Ballistics Meteorology Conference, New Mexico State Univ., 1967, pp. 215-257.

104. Busch, N.E.; and Panofsky, H.A.: Recent Spectra of Atmospheric Turbulence. To appear in Qtr. Jour. of Royal Meteorological Soc.

105. Businger, J.A.; Wyngaard, J.C.; et al.: Flux-Profile Relationships in the Atmospheric Surface Layer. Jour. of Atmospheric Sciences, vol. 28, no. 2, March 1, 1972, pp. 181-189.

106. Byzova, N.L., ed.: Investigation of the Bottom 300 Meter Layer of the Atmosphere. Translation from Russian, NASA Scientific & Tech. Info. Facility, No. N66-18972.

107. Calder, K.L.: Concerning the Similarity Theory of A.S. Monin and A.M. Obukov for the Turbulent Structure of the Thermally Stratified Surface Layer of the Atmosphere. Qtr. Jour., Royal Meteorological Soc., vol. 92, no. 391, January 1966.

108. Canadian Aero. Journal, Article by Warlow on Surface Wind Studies.

109. Cashmore, R.A.: Severe Turbulence at Low Levels Over the United Kingdom. Meteorological Mag., vol. 95, January 1966.

110. Clarke, R.H.: Observational Studies in the Atmospheric Boundary Layer. Qtr. Jour. Royal Meteorological Soc., vol. 96, 1970, pp. 91-114.

111. Colmer, M.J.: Some Full-Scale Measurements of the Flow in the Wake of a Hangar. RAE Technical Report 70202, 1970.

112. Colmer, M.J.: On the Character of Thunderstorm Gust Fronts. RAeS/AIAA/CASI International Conference on Atmospheric Turbulence, London, May 1971.

113. Colmer, M.J.: An Analysis of Measurements of Horizontal Windspeed and Gustiness made at Several Levels on a 30 m Tower. RAE Technical Report (to be published).

114. Cormier, Rene V.: A Proposed Dissertation on the Temporal and Spatial Variability of Integrated Boundary Layer Winds. Ph.D. Thesis, Dept. of Earth and Eng. Sciences, St. Louis Univ., St. Louis, Mo., March 31, 1972.

115. Corrsin, S.: On the Spectrum of Isotropic Temperature Fluctuations in an Isotropic Turbulence. Jour. Appl. Phys., vol. 22, 1951, pp. 469-473.

116. Cramer, H.E.; and Record, F.A.: Properties of Turbulent Energy Spectra and Cospectra in the Atmospheric Surface Layer. ECOM-64-G1-F, M.I.T., Dept. of Meteor., 1969.

117. Crawford, Kenneth C.; and Hudson, Horace R.: Behavior of Winds in the Lowest 1500 Feet in Central Oklahoma: June 1966 - May 1967. ESSA Tech. Memo. ERLTM-NSSL 48, August 1970.

118. Danard, M.B.: On the Dependence of Wind Variability on Surface Wind Speed; Richardson No., and Height Above Terrain. Jour. of Appl. Meteor., vol. 4, no. 3, June 1965.

119. Davenport, A.G.: The Spectrum of Horizontal Gustiness Near the Ground in High Winds. Qtr. Jour. of Royal Meteor. Soc., vol. 87, April 1961, pp. 194-211.

120. Davidson, et al.: Local Wind Circulations - Final Report, Volume II: Studies of the Field of Turbulence in the Lee of Mountain Ridges and Tree Lines. N.Y.U., September 1961, AD 275-611.

121. Deardorff, J.W.: Numerical Investigation of Neutral and Unstable Planetary Boundary Layers. Jour. of the Atmospheric Sciences, vol. 29, 1972, pp. 91-115.

122. Derrickson, Jr., R.J.: Structure of Atmospheric Turbulence in the Surface Layer. Ph.D. Thesis, Dept. of Meteorology, M.I.T., May 1964.

123. Dwyer, J.; and Tucker, F.L.: Summary of One Year of Data from the Cape Kennedy WIND System. Air Force Cambridge Research Laboratories, Bedford, Mass., August 1965. AFCRL-65-637.

124. Elderkin, G.E.: Experimental Investigation of the Turbulence Structure in the Lower Atmosphere. Battelle-Northwest Report 329, Pacific Northwest Laboratory, Richland, Wash., December 1966.

125. Elderkin, C.E.; Powell, D.C.; Dunbar, A.G.; and Horst, T.W.: Take-Off and Landing Critical Atmospheric Turbulence (TOLCAT) Experimental Investigation. Technical Report AFFDL-TR-70-117, Wright-Patterson Air Force Base, Ohio, May 1971.

126. Elderkin, C.E.: Diabatic Effects on Atmospheric Turbulence Spectra. Pacific Northwest Laboratory Annual Report for 1970 to the USAEC Division of Biology and Medicine. BNWL-1551, vol. II, part 1, Battelle Pacific Northwest Laboratories, Richland, Wash., June 1971, pp. 143-147.

127. Elderkin, C.E.: Measurements and Graphs of Turbulence Autocorrelations in Space and in Time. BNWL-SA-4086, presented at the Symposium on Air Pollution Turbulence and Diffusion, Las Cruces, New Mexico, December 7-9, 1971.

128. Elderkin, C.E.: Atmospheric Turbulence Studies. Pacific Northwest Laboratory Annual Report for 1967 to the USAEC Division of Biology and Medicine, Volume II: Physical Sciences, Part 3. Atmospheric Sciences. BNWL-715-3, October 1968.

129. Exploring the Atmospheres First Mile: Proceedings of the Great Plains Turbulence Field Program, O'Neil, Nebraska, 1 August to 8 September 1953.

130. Faller, A.J.: Large Eddies in the Atmospheric Boundary Layer and their Possible Role in the Formation of Cloud Rows. Jour. Atmos. Sci., vol. 22, March 1965, pp. 176-184.

131. Favre, A.J.: Review on Space-Time Correlations in Turbulent Fluids. Transactions of ASME, Jour. App. Mech., 1965.

132. Fichtl, George H.: Third and Fourth Moments of Vertical Two-Point Differences of Turbulent Velocity Fluctuations in the Atmospheric Boundary Layer. Presented at the Intl. Conf. on Aerospace and Aeronautical Meteorology (ICAAM), Washington, D.C., May 22-26, 1972.

133. Fichtl, G.H.; and McVehil, G.E.: Longitudinal and Lateral Spectra of Turbulence in the Atmospheric Boundary Layer. NASA TN D-5584, February 1970. Also Jour. of Applied Meteor., vol. 9, no. 1, February 1971, pp. 51-63.

134. Fichtl, George H.: On the Relationship between Small-Scale Wind Shears and Wind Profile Power Spectra. NASA TM X-64562, October 27, 1970.

135. Fichtl, George H.: Standard Deviation of Vertical Two-Point Longitudinal Velocity Differences in the Atmospheric Boundary Layer. Boundary-Layer Meteorology, vol. 2, 1971. pp. 137-151.

136. Fichtl, G.H.: Probability Distribution of Vertical Longitudinal Shear Fluctuations. Jour. of Applied Meteor., vol. 11, 1972, pp. 918-925.

137. Frenkiel, F.N.; and Klebanoff, P.S.: Higher Order Correlations in a Turbulence Field. Physics of Fluids, vol. 10, March 1967.

138. Gibson, C.H.; and Schwarz, W.Z.: The Universal Equilibrium Spectra of Turbulent Velocity and Scalar Fields. Jour. Fluid Mech., vol. 16, 1963, pp. 365-384.

139. Gifford, F.A.: A Study of Low-Level Air Trajectories at Oak Ridge, Tennessee. Monthly Weather Review, vol. 81, 1953, pp. 179-192.

140. Grant, H.L.: The Large Eddies of Turbulent Motion. Jour. Fluid Mech., vol. 4, 1958, pp. 149-190.

141. Grant, H.L.; Hughes, B.A.; Vogel, W.M.; and Moilliet, A.: The Spectrum of Temperature Fluctuations in Turbulent Flow. Jour. Fluid Mech., vol. 34, 1968, pp. 423-442.

142. Gunter, D.E.; Jones, G.W.; et al.: Low Altitude Atmospheric Turbulence, LO-LOCAT Phases 1 & 11. ASD-TR-69-12, Wright-Patterson Air Force Base, Ohio, February 1969.

143. Hanson, F.V.; and Hanson, P.S.: The Formation of an Interval Boundary Over Heteorogeneous Terrain. U.S. Army Electronics Command, Fort Monmouth, N.J., 66.348, November 1965.

144. Hanson, F.V.: Turbulence Characteristics of the First 62 Meters of the Atmosphere. White Sands Missile Range, December 1963, AD 426-681.

145. Harris, R.I.: On the Spectrum and Auto-Correlation Function of Gustiness in High Winds. E.R.A. Tech. Rep. 5273, Leatherhead, England, 1968.

146. Harris, R.I.: Measurements of Wind Structure at Heights up to 598 ft. Above Ground Level. E.R.A. Tech. Rept. 5258, Leatherhead, England, 1968.

147. Hasofer, A.M.; and Sharpe, K.: The Analysis of Wind Gusts. Australian Meteor. Magazine, vol. 17, December 1969, pp. 198-214.

148. Hasseltine, C.: Cape Kennedy Low Level Wind Study for September 23-25, 1963. George C. Marshall Space Flight Center, Huntsville, Ala. NASA TM X-532027, 1964.

149. Henry, R.M.: A Study of the Effects of Wind Speed, Lapse Rate, and Altitude on the Spectrum of Atmospheric Turbulence at Low Altitude. IAS Report No. 59-43, January 1959.

150. Kaimal, J.C.; and Haugen, D.A.: Characteristics of Vertical Velocity Fluctuations Observed on a 430 m Tower. Quar. Jour. Royal Meteor. Soc., vol. 93, 1967, p. 305.

151. Kaimal, J.C.: Measurement of Momentum and Heat Flux Variations in the Surface Boundary Layer. Radio Science, vol. 4, no. 12, December 1969, pp. 1147-1153

152. Kaimal, J.C.; Wyngaard, J.C.; et al.: Spectral Characteristics of Surface Layer Turbulence. Air Force Cambridge Research Laboratories, Bedford, Mass.

153. Kaimal, J.C.; and Businger, J.A.: Case Studies of a Convective Plume and a Dust Devil. Jour. Appl. Meteor., vol. 9, 1970, pp. 612-620.

154. Kaufman, John W.; and Hill, Kelly: Inphase Characteristics of Winds to 150 Meters. Aerospace Environment Division, Aero-Astrodynamics Laboratory, Marshall Space Flight Center, Alabama.

155. Klebanoff, P.S.: Characteristics of Turbulence in a Boundary Layer with Zero Pressure Gradient. NACA Report 1247, 1955.

156. Kravchenko, I.M.: On the Wind Profile in the Mean-Ground Layer of the Atmosphere. Bulletin, Geophysics Series, Acad. of Sci. (USSR), March 1963.

157. Kukharets, V.P.; and Tsvang, L.R.: Spectra of Turbulent Heat Flux in the Atmospheric Boundary Layer. Izv. Atm. and Oceanic Physics, vol. 5, 1969, pp. 1132-1142.

158. Lappe, U.O.; Davidson, B.; and Notess, C.B.: Analysis of Atmospheric Turbulence Spectra Obtained from Concurrent Airplane and Tower Measurements. IAS Report No. 59-44, January 1959.

159. Lappe, U.O.; and Davidson, B.: On the Range of Validity of Taylor's Hypothesis and the Kolmogoroff Spectral Law. Jour. Atmos. Sci., vol. 20, November 1963, pp. 569-576.

160. Lappe, U. Oscar: A Climatological-Wind Turbulence Model for Estimating Low Altitude Gust Loads. AFFDL-TR-67-122, January 1968.

161. Lemon, et al.: The Energy Budget at the Earth's Surface, Part II. U.S. Dept. of Agriculture, AD 605-527, 1963.

162. LeMone, P.: The Structure and Dynamics of Horizontal Vortices in the Planetary Boundary Layer. University of Washington, 1972. (Unpublished Ph.D. Thesis)

163. Lettau, et al.: Studies of the Three-Dimensional Structure of the Planetary Boundary Layer. Dept. of Meteorology, Univ. of Wisconsin, August 1961.

164. Lin, C.C.: On Taylor's Hypothesis and the Acceleration Terms in the Navier-Stokes Equations. Quar. Appl. Math., vol. 10, 1953, pp. 295-306.

165. Lumley, J.L.: The Spectrum of Nearly Inertial Turbulence in a Stably Stratified Fluid. Jour. Atmos. Sci., vol. 21, January 1964, pp. 99-102.

166. Luna, R.E.; and Church, H.W.: A Comparison of Turbulence Intensity and Stability Ratio Measurements to Pasquill Stability Classes. Jour. of Appl. Meteor., vol. 11, 1972, pp. 663-669.

167. McBean, G.A.: The Turbulent Transfer Mechanisms in the Atmospheric Surface Layer. Ph.D. Thesis, University of British Columbia, Canada, 1970.

168. McBean, G.A.: The Variations of the Statistics of Wind Temperature and Humidity Fluctuations with Stability. Boundary Layer Meteorology, vol. 2, 1971, pp. 438-457.

169. McVehil, G.E.: Wind and Temperature Profiles Near the Ground in Stable Stratification. Quar. Jour. Royal Meteor. Soc., vol. 91, 1964.

170. Mitchell, L.W.: Wind Shear and Turbulence over Selected Stations of the Air Force Western Test Range. Air Weather Service (MAC), USAF, December 1966, TR 189.

171. Miyako, M.; Stewart, R.W.; and Burling, R.W.: Spectra and Cospectra of Turbulence over Water. Quar. Jour. Royal Meteor. Soc., vol. 96, 1970, pp. 138-143.

172. Monin, A.S.: The Structure of the Wind-Velocity and Temperature Fields in the Atmospheric Surface Boundary Layer. Translated from Trudy, Institut Fiziki Atmosfery, No. 4-5-20, Akademiia Nauk SSSR, 1962.

173. Monin, A.S.: Empirical Data on Turbulence in the Surface Layer of the Atmospher : Jour. of Geophysical Research, vol. 67, no. 8, July 1962.

174. Monson, K.R.; Jones, G.W.; Mielke, R.H.; et al.: Low Altitude Atmospheric Turbulence LO-LOCAT Phase III Interim Report. Vol. I: Data Acquisition and Analysis. Technical Report AFFDL-TR-69-63, Vol. 1, Wright-Patterson Air Force Base, Ohio, 1969.

175. Newton, C.W.: Movements and Patterns of Development of
      Thunderstorms. Severe Storm Detection and Circumnavigation,
      U.S. Dept. of Commerce National Severe Storms Project,
      Final Report, 1963.

176. Notess, C.B.: Analysis of Turbulence Data Measured in
      Flight at Altitudes up to 1600 Feet above Three Different
      Types of Terrain. Cornell Aero. Lab. Report No.
      TE-1215-F-1, April 1959.

177. O'Brien, J.J.: Investigation of the Diabatic Wind Profile
      of the Atmospheric Boundary Layer. Jour. of Geophysical
      Research, vol. 70, no. 10, May 1965.

178. Obukov, A.M.: Some Specific Features of Atmospheric
      Turbulence. Jour. of Fluid Mech., vol. 13, 1962.

179. Obukhov, A.M.: Turbulence in an Atmosphere with Non-
      uniform Temperature. (English translation of original)
      Boundary Layer Meteor., vol. 2, 1971, pp. 7-29.

180. Panofsky, H.A.: Scale Analysis of Atmospheric Turbulence
      at 2m. Quar. Jour. Royal Meteor. Soc., vol. 88, 1962,
      pp. 57-69.

181. Panofsky, H.A.; and McCormack, R.A.: The Spectrum of
      Vertical Velocity Near the Surface. IAS Report No. 59-6,
      January 1959.

182. Panofsky, H.A.: A Survey of Recent Ideas on Low Level
      Atmospheric Turbulence. Symp. on the Theory and Meas. of
      Atmos. Turbulence and Diffusion in the Planetary Boundary
      Layer. Reprint, Sandia Laboratories, SC-M-67-2931, 1967.

183. Panofsky, H.A.; and Townsend, A.A.: Change of Terrain
      Roughness and the Wind Profile. Quar. Jour. Royal Meteor.
      Soc., vol. 90, 1964, pp. 147-155.

184. Panofsky, H.A.; and van der Hoven, I.: Spectra and Cross-
      Spectra of Velocity Components in the Meso-Meteorological
      Range. Quar. Jour. Royal Meteor. Soc., vol. 81, 1955,
      pp. 603-606.

185. Panofsky, H.A.: Determination of Stress from Wind and
      Temperature Measurements. Quar. Jour. Royal Meteor. Soc.,
      vol. 89, 1963, pp. 85-94.

186. Panofsky, H.A.: The Relation between Eulerian Time and
      Space Spectra. Quar. Jour. Royal Meteor. Soc., vol. 84,
      1958, pp. 270-273.

187. Panofsky, H.A.: The Structure of Atmospheric Shear Flows,
      Paper 1, Aerodynamics of Atmospheric Shear Flows, AGARD
      Conf. Proceedings No. 48, February 1970.

188. Panofsky, H.A.; and Prasad, B.: Similarity Theories and Diffusion. Int. Jour. Air Water Pollution, Pergamon Press, vol. 9, 1965, pp. 419-430.

189. Panofsky, H.A.: The Spectrum of Temperature. Radio Science, vol. 4, 1969, pp. 1143-1146.

190. Panofsky, H.A.; and Mares, E.: Recent Measurements of Co-spectra for Heat Flux and Stress. Quar. Jour. Royal Meteor. Soc., vol. 94, 1968, pp. 581-584.

191. Panofsky, H.A.; Blackador, A.K.; and McVehil, G.E.: The Diabatic Wind Profile. Quar. Jour. Royal Meteor. Soc., vol. 86, 1960.

192. Pao, Y.H.: Undulance and Turbulence in Stably Stratified Media. Symposium on Clear Air Turbulence and Its Detection, Seattle, Wash., August 14-16, 1969, Science Research Laboratories, D1-82-0740, 1969.

193. Paquin, J.E.; and Pond, S.: The Determination of Kolmogoroff Constants for Velocity, Temperature and Humidity Fluctuations from Second and Third Order Structure Functions. (Submitted to Jour. of Fluid Mechanics.) 1971.

194. Pasquill, F.: Wind Structure in the Atmospheric Boundary Layer. Philosophical Transactions Soc., London A269, 1971.

195. Plate, B.J.: Aerodynamic Characteristics of Atmospheric Boundary Layers. Atomic Energy Commission, Division of Technical Information.

196. Pond; et al.: Turbulence Spectra in the Wind over Waves. Jour. of Atmospheric Sciences, vol. 20, July 1963.

197. Potter, T.D.: Wind Structure in the Lowest 1500 Feet in Convective Conditions. Ph.D. Thesis, Dept. of Meteorology, Penn. State Univ., Univ. Park, Penn., 1962.

198. Powell, D.C.: Diabatic Effects on Profiles of the Shear Stress. Pacific Northwest Laboratory Annual Report for 1970 to the USAEC Division of Biology and Medicine, BNWL-1551, Vol. II, Part 1, Battelle, Pacific Northwest Labs., Richland, Wash., June 1971, pp. 143-147.

199. Proceedings of the Symposium on Mountain Meteorology. Atmospheric Science Paper No. 122, Fort Collins, Colorado, 26 June, 1967 (edited by E.R. Reiter and J.L. Rasmussen).

200. Roth, R.: Turbulence Spectra with Two Separated Regions of Production. Jour. of Appl. Meteor., vol. 10, no. 3, June 1971, pp. 430-432.

201. Saunders, K.D.: B-66B Low Level Gust Study, Vol. 1. WADD Tech. Report 60-305, Wright-Patterson Air Force Base, Ohio, March 1960.

202. Scoggins, James R.: Some Properties of Low Altitude Atmospheric Turbulence at Cape Kennedy, Florida. Dept. of Meteor., Texas A&M University.

203. Shiotani, M.: Lateral Structures of Gusts in High Winds. Physical Science Lab., Nihon Univ. at Namashino, Funabashi, Chiba, Japan, March 1967.

204. Simpson, C.L.; and Staff Members of the Atmospheric Resources Dept.: Pacific Northwest Laboratory Annual Report for 1970 to the USAEC Division of Biology and Medicine, BNWL-1551, Vol. II, Part 1: Atmospheric Sciences, Battelle, Pacific Northwest Labs, Richland, Wash., June 1971.

205. Singer, I.A.: Wind Gust Spectra. N.Y. Academy of Sci., vol. 116, art. 1, June 1964, pp. 116-133.

206. Singer, I.A.: A Study of the Wind Profile in the Lowest 400 Feet of the Atmosphere. Brookhaven National Laboratory, Prog. Report No. 2, January 1959; Prog. Report No. 3, October 1959; Prog. Report No. 4, January 1960.

207. Sitaraman: V.: Spectra and Cospectra of Turbulence in the Atmospheric Surface Layer. Quar. Jour. Royal Meteor. Soc., vol. 96, 1970, pp. 744-749.

208. Taylor, P.A.: On Wind and Shear Stress Profiles above a Change in Surface Roughness. Quar. Jour. Royal Meteor. Soc., vol. 95, 1969.

209. Townsend, A.A.: Natural Convection in the Earth's Boundary Layer. Quar. Jour. Royal Meteor. Soc., vol. 88, 1962, pp. 51-56.

210. Tsvang; et al.: Measurement of Some Properties of Turbulence in the Lowest 300 Meters of the Atmosphere. Bulletin, Geophysics Series, Acad. of Sci. (USSR), 1963.

211. van der Hoven, I.: Power Spectrum of Horizontal Wind Speed in the Frequency Range from 0.0007 to 900 Cycles Per Hour. Jour. Meteor., vol. 14, April 1957, pp. 160-164.

212. Webb, E.K. Autocorrelations and Energy Spectra of Atmospheric Turbulence. C.S.I.R.O. Div. Meteor. Phys. Tech. Paper No. 5, Melbourne, Australia, 1955.

213. Webb, E.K.: Profile Relationships: The Log-Linear Range, and Extension to Strong Stability. Quar. Jour. Royal Meteor. Soc., vol. 96, 1970.

214. Wood, J.D.: On Richardson's Number as a Criterion for Laminar-Turbulent-Laminar Transition in the Ocean and Atmosphere. Radio Science, vol. 4, no. 12, December 1969, pp. 1289-1298.

215. Wyngaard, J.C.; and Pao, Y.H.: Some Measurements of the Fine Structure of Large Reynolds Number Turbulence. Proceedings, Symposium on Statistical Models and Turbulence LaJolla, Calif., 1971. (To be published in series "Lecture Notes in Physics," Springer-Verlag.)

216. Wyngaard, J.C.; and Coté, O.R.: Cospectral Similarity in the Atmospheric Surface Layer. Air Force Cambridge Research Laboratories, Bedford, Mass.

217. Wyngaard, J.C.; Coté, O.R.; and Izumi, Y.: Local Free Convection, Similarity, and the Budgets of Shear Stress and Heat Flux. Jour. of Atmospheric Sciences, vol. 28, no. 7, October 1971, pp. 1171-1182.

218. Wyngaard, J.C.; and Coté, O.R.: The Budgets of Turbulent Kinetic Energy and Temperature Variance in the Atmospheric Sciences, vol. 28, no. 2, March 1, 1972, pp. 190-201.

219. Zilitinkevich, S.S.: Non-stationary Turbulent Regime in the Surface Layer of the Atmosphere. Translation from Russian, DDC No. AD 628-972, September 1965.

220. Zilitinkevich, S.S.; et al.: Review--Dynamics of the Atmospheric Boundary Layer. Academy of Sciences of the USSR Institute of Oceanography, Jour. of Atmospheric and Oceanic Physics, vol. 3, no. 3, 1967, pp. 297-333.

221. Zubkovsky, S.L.; and Koprov, B.M.: Experimental Investigation of the Structure of the Turbulent Heat and Momentum Fluxes in the Atmospheric Surface Layer. Izv. Atmos. and Oceanic Physics, vol. 5, 1969, pp. 323-331.

222. Case, E.R.; Maritan, P.A.; and Gorjup, M.: Development of a Low Altitude Gust Model and Its Application to STOL Aircraft Response Studies. de Havilland Aircraft of Canada, DHC-DIR 68-15, May 1969.

223. Elderkin, C.E.; Powell, D.C.; Dunbar, A.G.; and Horst, T.W.: Take-Off and Landing Critical Atmospheric Turbulence (TOLCAT) - Experiments and Analysis. AFFDL-TR-71-172, Wright-Patterson Air Force Base, Ohio, April 1972.

224. Elderkin, C.E.; Powell, D.C.; and Horst, T.W.: Modeling of Wind Component Spectra. Pacific Northwest Laboratory Annual Report for 1970 to the USAEC Division of Biology and Medicine, BNWL-1551, vol. II, part 1, Battelle, Pacific Northwest Laboratories, Richland, Wash., June 1971, pp. 148-153.

225. Fichtl, G.H.: Design Ground Wind Spectra of Atmospheric Turbulence. Memorandum from Atmospheric Dynamics Branch, S&E-AERO-YE, George C. Marshall Space Flight Center, Huntsville, Ala., March 14, 1969.

226. Jones, J.G.: Turbulence Models for the Assessment of Handling Qualities During Take-Off and Landing. Prepared for AGARD Flight Mechanics Panel Specialists' Meeting on Flight Handling Qualities Criteria, Ottawa, September-October 1971.

227. Jones, J.G.: The Representation of Low Altitude Atmospheric Turbulence in Piloted Ground-Based Simulators. RAE Technical Report (to be published).

228. Jones, J.G.: Gradient Properties of a Model of Stationary Random Turbulence. ARC CP 998, 1967.

229. Kurkowski, Richard L.; Fichtl, George H.; and Gera, Joseph: Development of Turbulence and Wind Shear Models for Simulation Application. NASA Aircraft Safety and Operating Problems Conference, Vol. I, NASA SP-270, 1971.

230. McVehil, G.E.; et al.: On the Feasibility of Modeling Small Scale Atmospheric Motions. CAL Report No. ZB-2328-P-1, April 1967.

231. Paulson, C.A.: The Mathematical Representation of Wind Speed and Temperature Profiles in the Unstable Atmospheric Surface Layer. J. Appl. Meteor., vol. 9, 1970, pp. 857-861.

232. Pritchard, F.E.: The Turbulence and Terrain Environments Affecting Low-Altitude High Speed Flight. Cornell Aeronautical Laboratory, Buffalo, N.Y., July 1966.

233. Reeves, Paul M.: A Non-Gaussian Turbulence Simulation. AFFDL-TR-69-67, Wright-Patterson Air Force Base, Ohio, 1969.

234. Skelton, Grant B.: Investigation of the Effects of Gusts on V/STOL Craft in Transition and Hover. AFFDL-TR-68-85, Wright-Patterson Air Force Base, Ohio, June 1968.

235. Teunissen, H.W.: Characteristics of the Mean Wind and Turbulence in the Planetary Boundary Layer. UTIAS Review No. 32, University of Toronto, Institute for Aerospace Studies, October 1970.

236. Lappe, U.Oscar: Design of a Low Altitude Turbulence Model for Estimating Gust Loads on Aircraft. AFFDL-TR-64-170, Wright-Patterson Air Force Base, Ohio, March 1965.

237. Lappe, U.O.; Thuillier, R.H.; and Reeves, R.W.: Development of a Low Altitude Turbulence Model for Estimating Gust Loads on Aircraft. ASD-TDR-63-318, Wright-Patterson Air Force Base, Ohio, July 1963.

238. Watson, I.A.: Report of an Investigation into Low-Altitude Wind Structure for Automatic Landing. Aeronautical Meteorology, WMO Technical Note No. 95, World Meteorological Organization, Geneva, Switzerland, October 1969.

239. Franklin, James A.: Turbulence and Lateral-Directional Flying Qualities. NASA CR-1718, April 1971.

240. Franklin, James A.: Flight Investigation of the Influence of Turbulence on Lateral-Directional Flying Qualities. Jour. Aircraft, vol. 8, no. 10, October 1971.

241. Hall, G. Warren; and Boothe, Edward M.: An In-Flight Investigation of Lateral-Directional Dynamics for the Landing Approach. AFFDL-TR-70-145, October 1970.

242. Johnson, W.A.; and McRuer, D.T.: A System Model for Low-Level Approach. Jour. of Aircraft, vol. 8, no. 12, December 1971, pp. 983-988.

243. Jones, J.G.: The Speed Response of an Aircraft Constrained to Fly Along a Straight Path in the Presence of Turbulence at Low Altitude. ARC R&M 3563, 1967.

244. Klein, J.A.: Yaw Axis Control as a Means of Improving V/STOL Aircraft Performance. AFFDL-TR-72-99, Wright-Patterson Air Force Base, Ohio, September 1972.

245. LaPlant, II, Porter; and Baldwind, Robert L.: Flight Evaluation of the XV-5A V/STOL Aircraft. Technical Report No. 66-30, AD 810 922, Air Force Flight Test Center, March 1967.

246. McRuer, D.T.; Weir, D.H.; and Klein, R.H.: A Pilot-Vehicle Systems Approach to Longitudinal Flight Director Design. Jour. of Aircraft, vol. 8, no. 11, November 1971, pp. 890-897.

247. Onstott, E.D.; and Salmon, E.P.: Airplane Flying Characteristics in Turbulence. AFFDL-TR-70-143, Wright-Patterson Air Force Base, Ohio, February 1971.

248. Perry, D.H.; Warton, L.H.; and Welbourn, C.E.: A Flight Simulator for Research into Aircraft Handling Characteristics. RAE Technical Report 66373, ARC R&M 3566, 1966.

249. Porter, Richard F.; Loomis, James P.; and Robinson, Alfred C.: A Procedure for Assessing Aircraft Turbulence-Penetration Performance. NASA CR-1510, March 1970.

250. Schuler, J.M.; Smith, R.E.; and Lebacqz, J.V.: An Experimental Investigation of STOL Longitudinal Flying Qualities in the Landing Approach Using the Variable Stability X-22A Aircraft. Presented at the 28th Annual National Forum of the American Helicopter Society, Wash., D.C., May 1972.

251. Schuler, J.M.; Kroll, Jr., J.; and Key, D.L.: VTOL Flying Qualities and the Flight Research use of VTOL Variable Stability Airplanes. Canadian Aeronautics and Space Jour., vol. 12, no. 6, June 1966.

252. Tomlinson, B.N.: The Simulation of Turbulence and Its Influence on the Pilot. RAeS/AIAA/CASI International Conference on Atmospheric Turbulence, London, May 1971.

253. Durand, Tulvio S.; and Wasicko, Richard J.: Factors Influencing Glide Path Control in Carrier Landing. Jour. Aircraft, vol. 4, no. 2, March-April 1967.

254. Durand, Tulvio S.: Carrier Landing Analyses. STI Tech. Report No. 137-2, Systems Technology Inc., Hawthorne, Calif., February 1967.

255. Hooks, Jr., J.T.; Mattlage, C.E.; et al.: A Carrier Approach Simulator, Simulation of Night Carrier Landing Approach. Vought Aeronautics Div., LTV Aerospace Corp., September 1968.

256. Lehman, A.F.: An Experimental Study of the Dynamics and Steady-State Flow Disturbances Encountered by Aircraft During a Carrier Landing Approach. Oceanics, Inc. Report 64-16, September 1964.

257. Lehman, A.F.; and Kaplan, P.: Experimental Model Studies of the Dynamic Velocity Fluctuations Existing in the Air Wake of an Aircraft Carrier. Oceanics, Inc. Report 65-21, Parts I and II, March 1965.

258. Barnett, W.F.; and White, H.E.: Comparison of the Airflow Characteristics of Several Aircraft Carrier. David Taylor Model Basin Aero. Report 1008, May 1963.

259. Oldmixon, W.J.: The Acquisition, Reduction, and Analysis of Turbulence Data Associated with PA Configuration Approaches to Carrier Landings. Report No. 653, Princeton University, Dept. of Aero. Eng., July 1963.

260. Fichtl, George H.: Wind Shear Near the Ground and Aircraft Operations. Jour. Aircraft, vol. 9, no. 11, November 1972.

62

261. Krynytzky, Alexander Josaphat: Helicopter Response to Flows Induced by Tall Buildings. Submitted in partial fulfillment for the Degree of Master of Science at the Mass. Institute of Technology, August 1972.

262. Pinsker, W.J.G.: Theoretical Assessment of the General Stability and Gust Response Characteristics of STOL Aircraft. RAE Technical Report 71028, 1971.

263. Campbell, G.S.; and Standen, N.M.: Progress Report II on Simulation of Earth's Surface Winds by Artificially Thickened Wind Tunnel Boundary Layers. National Research Council of Canada, NAE Report LTR-LA-37, July 1969.

264. Cermak, J.E.; and Arya, S.P.S.: Problems of Atmospheric Shear Flows and Their Laboratory Simulation. Paper 12, Aerodynamics of Atmospheric Shear Flows, AGARD Conference Proceedings No. 48, February 1970.

265. Counihan, J.: An Improved Method of Simulating an Atmospheric Boundary Layer in a Wind Tunnel. Atmospheric Environment, vol. 3, 1969, pp. 197-214.

266. Templin, R.J.: Interim Progress Note on Simulation of Earth's Surface Winds by Artificially Thickened Wind Tunnel Boundary Layers. National Research Council of Canada, NAE Report LTR-LA-22, February 1969.

267. Durgin, Frank H.; and Tong, Pin: The Effect of Twist Motion on the Dynamic Multimode Response of a Building. Presented at the Symposium on Flow-Induced Structural Vibrations, sponsored by IUTAM and IAHR at Karlsruhe, Germany, August 14-16, 1972.

268. Houbolt, John C.; and Sen, Asim: Cross-Spectral Functions Based on von Kármán's Spectral Equation. NASA CR-2011, March 1972.

269. Houbolt, John C.; and Sen, Asim: Single-Degree-of-Freedom Roll Response due to Two-Dimensional Vertical Gusts. NASA CR-111966, July 1971.
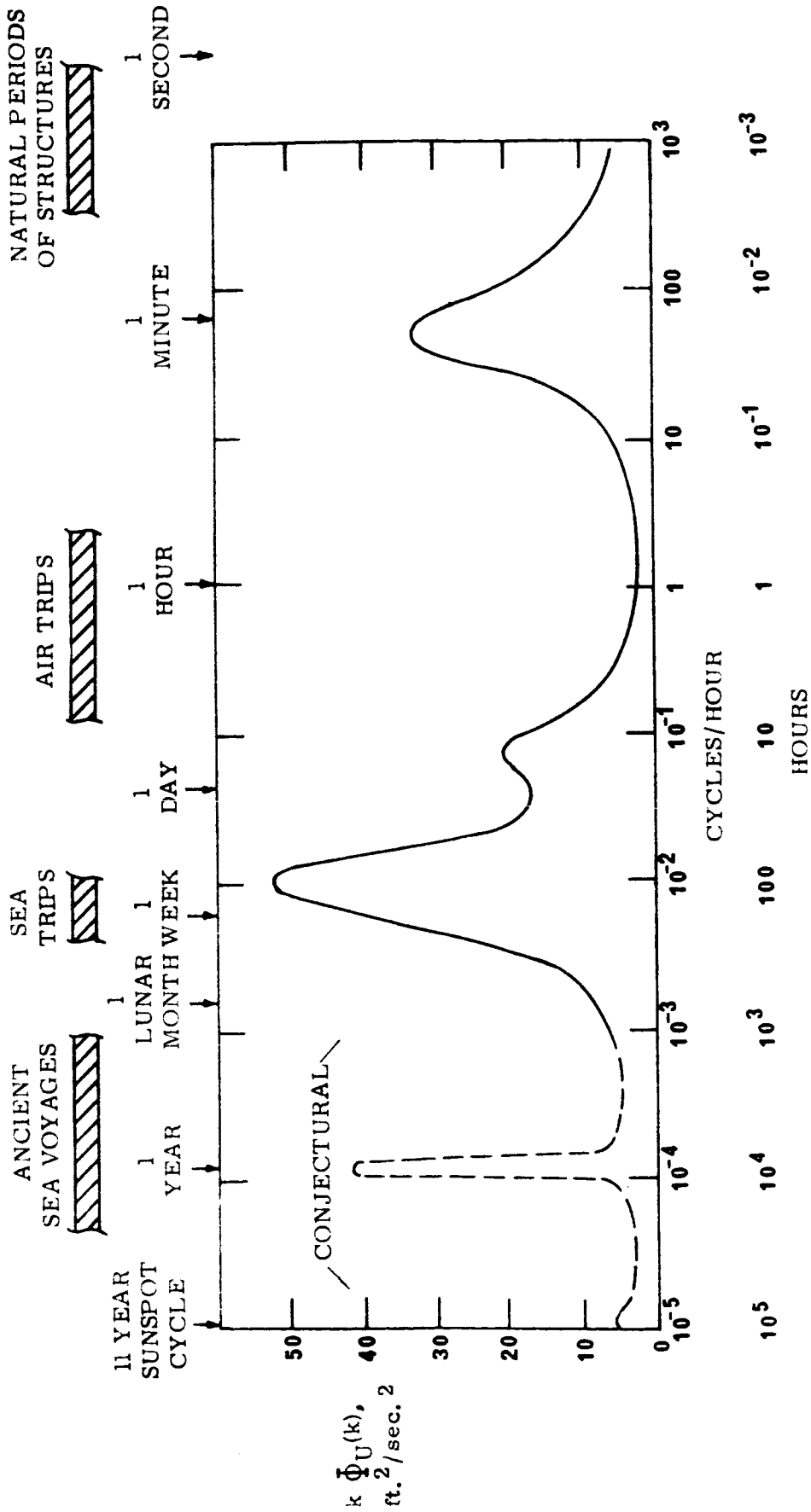
FIGURE 1. Spectrum of Wind Speed at Brookhaven, New York, U.S.A.
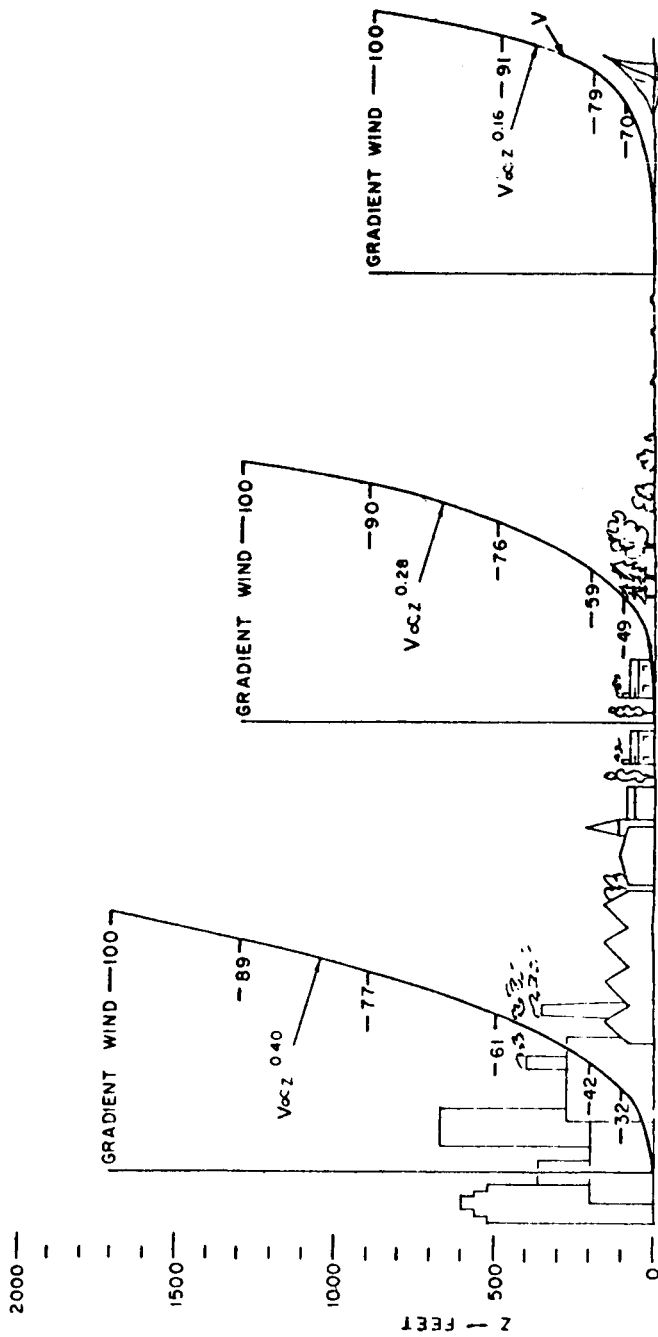(From Refs. 235 and 267)

65

FIGURE 2. Typical Mean Profiles over Terrains of Differing Roughness (From Refs. 235 and 30)
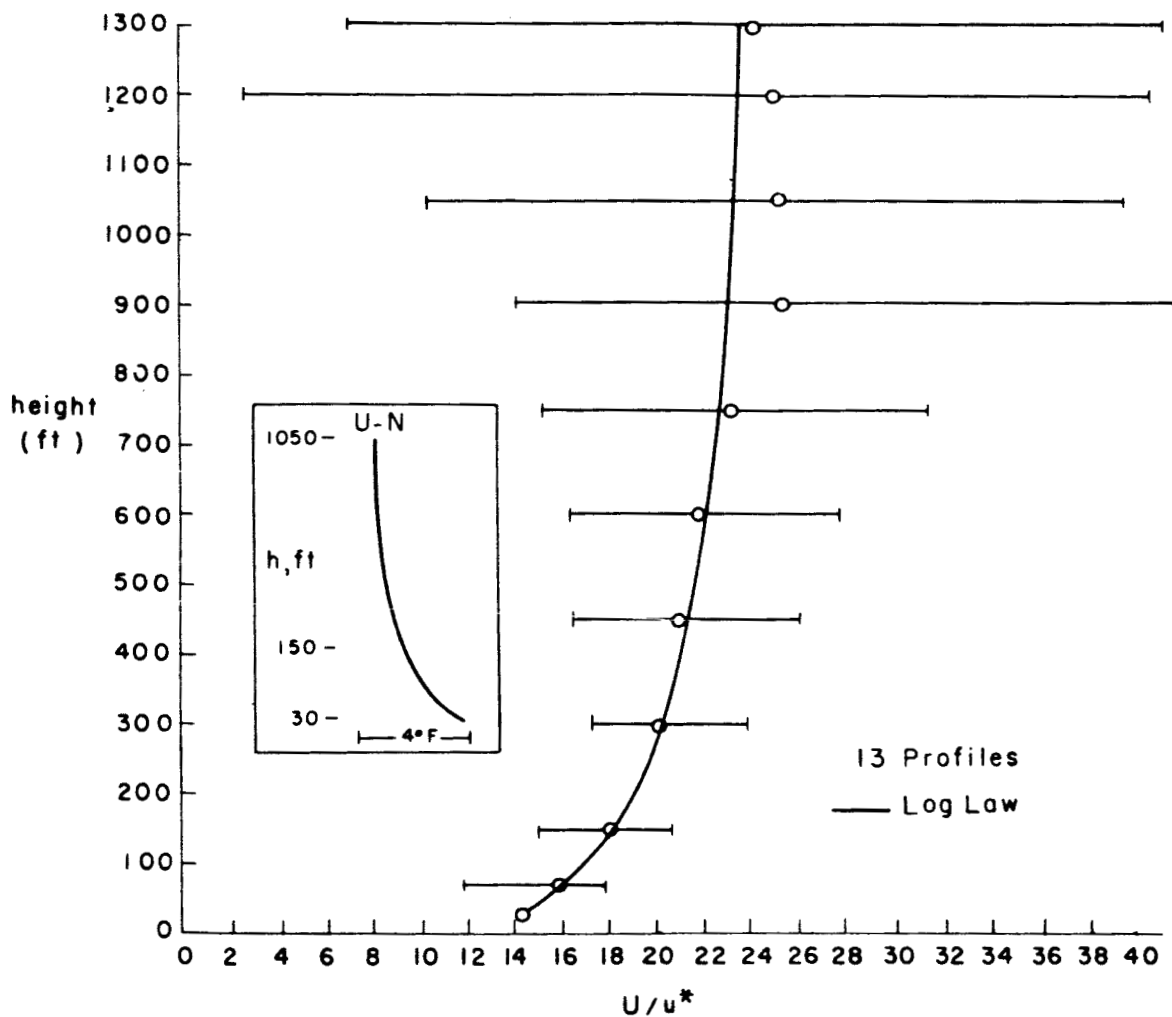
66

FIGURE 3. Average Values of Cedar Hill Tower Wind Profiles
for Combined Unstable-Neutral Lapse Rate
(From Ref. 237)

FIGURE 4. Examples of Nonclassical Wind Profiles
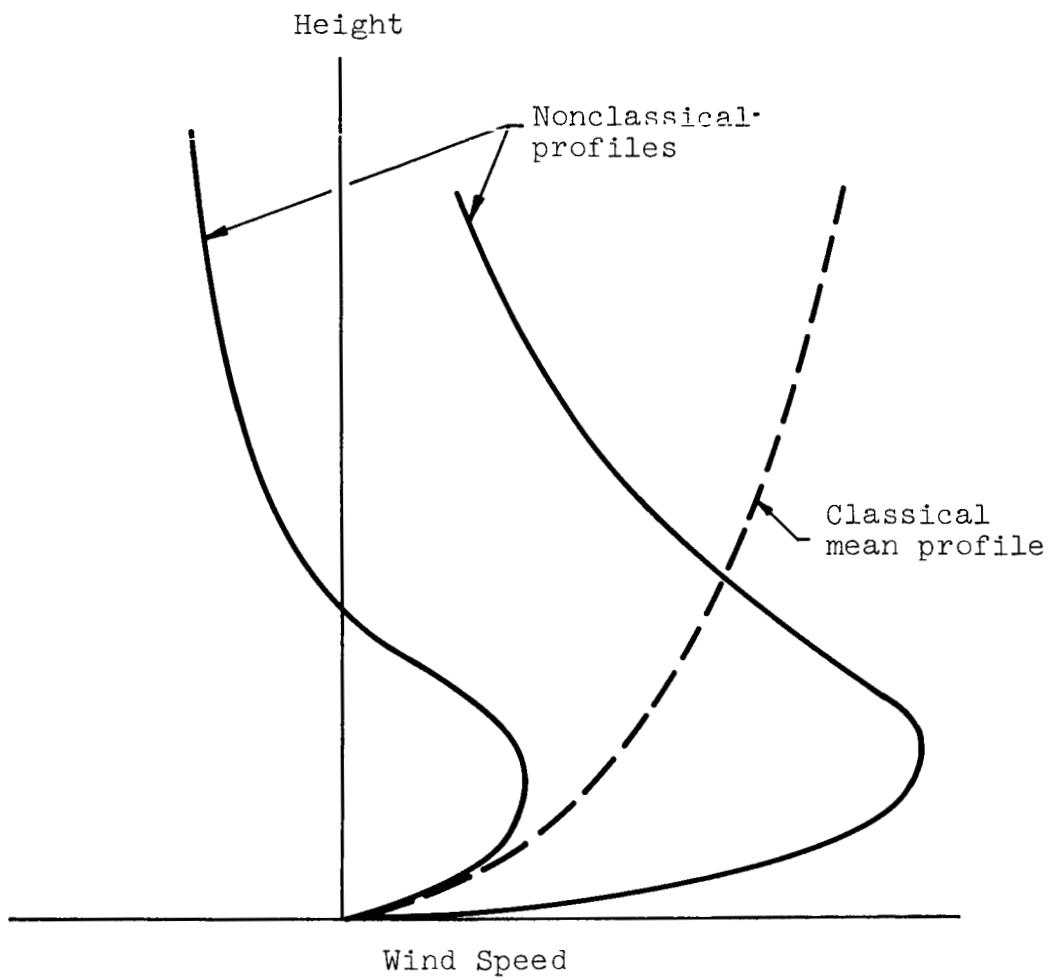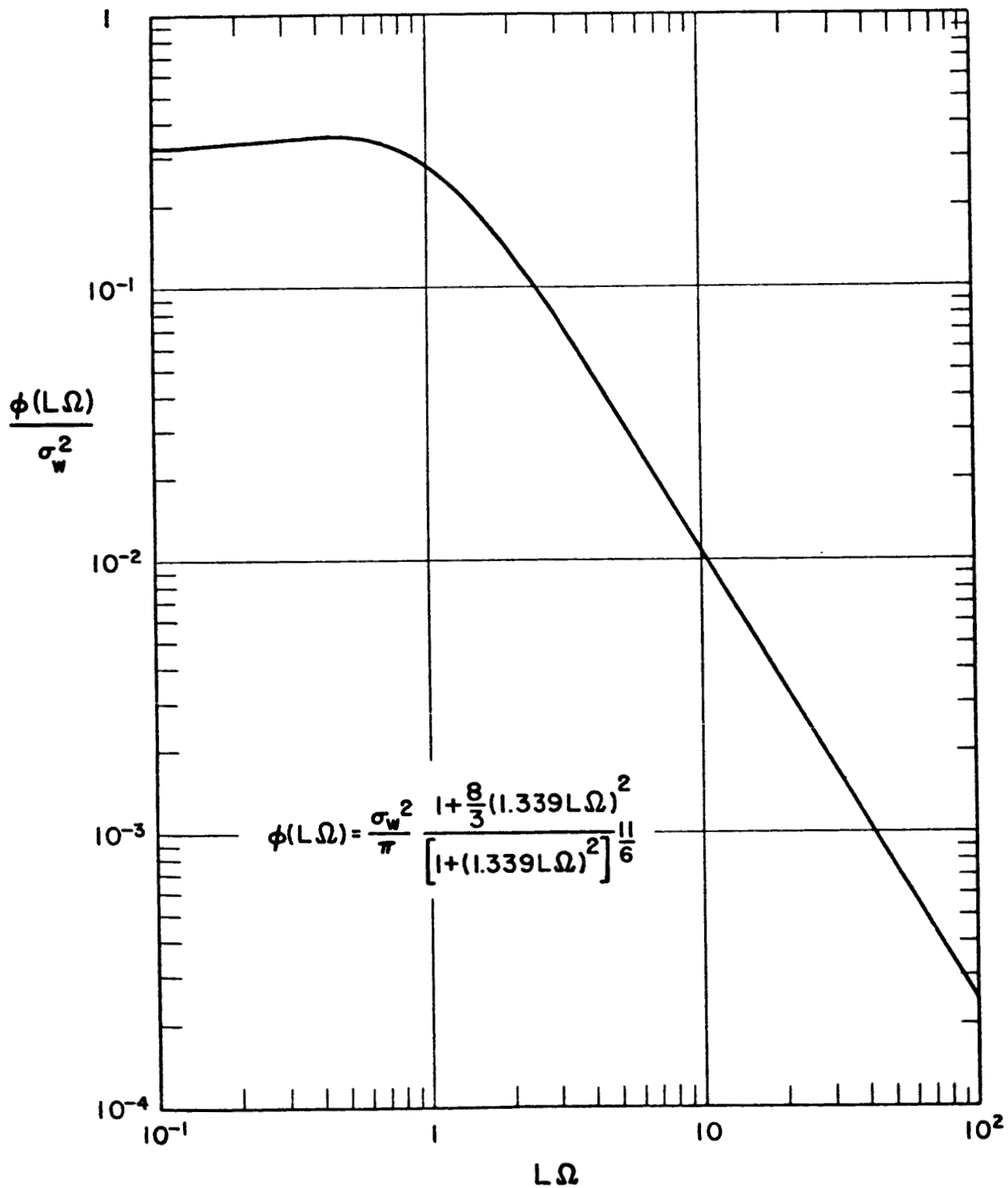
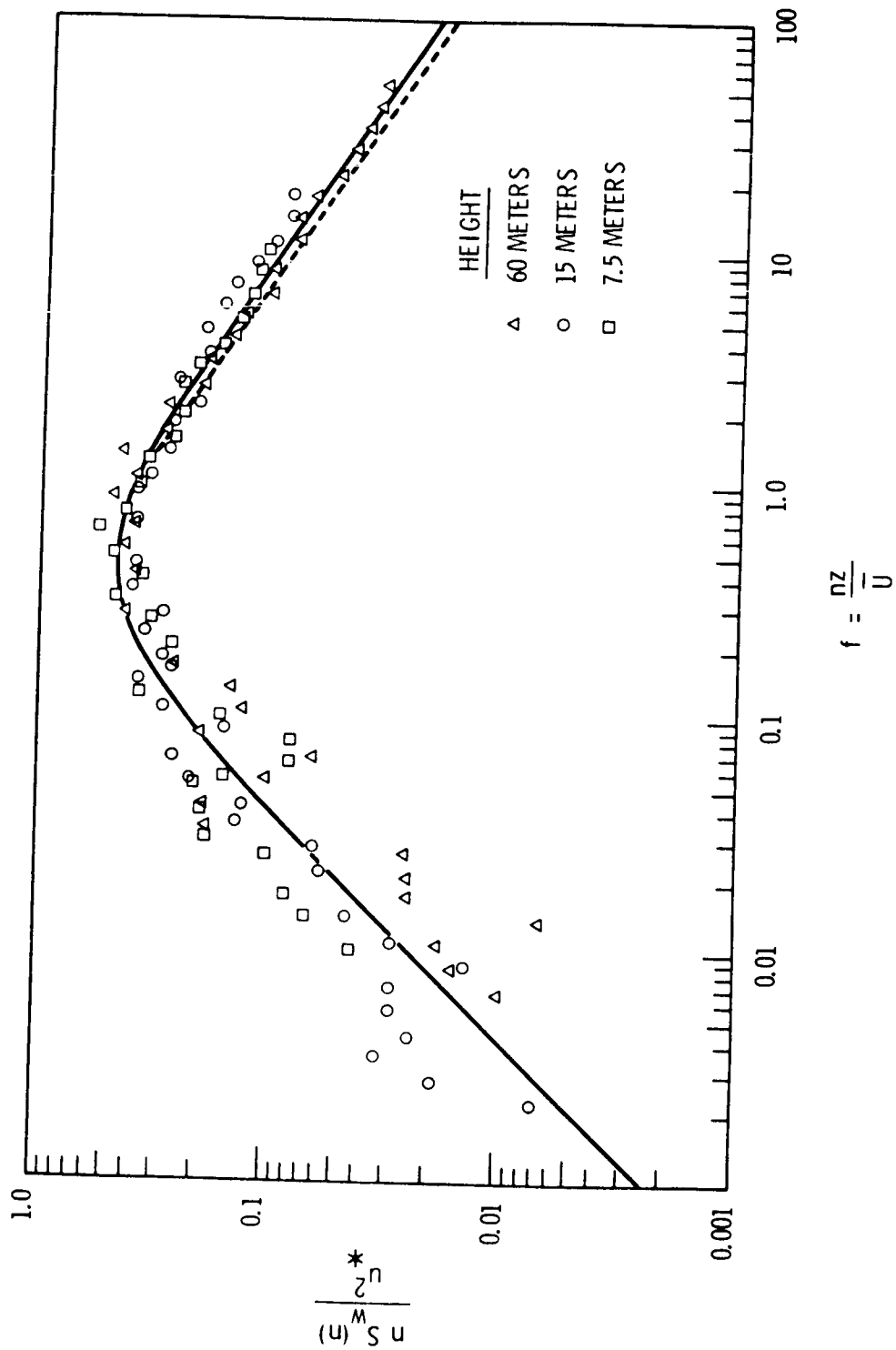FIGURE 5. Gust Spectrum Function for w

$$\phi(L\Omega) = \frac{\sigma_w^2}{\pi} \frac{1 + \frac{8}{3}(1.339L\Omega)^2}{\left[1 + (1.339L\Omega)^2\right]^{\frac{11}{6}}}$$

69

FIGURE 6. Nondimensional w Spectra - Neutral Case (From Ref. 223)
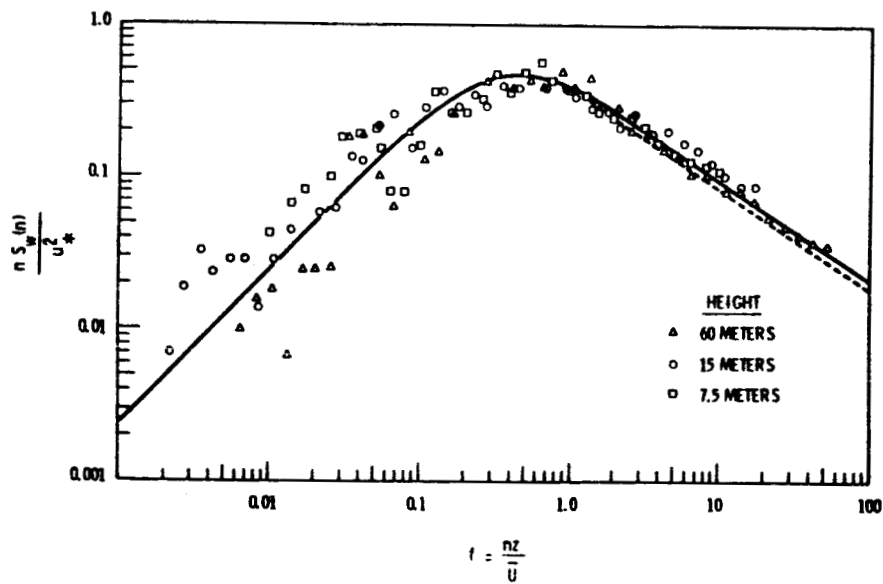
FIGURE 7. Nondimensional w Spectra - Two Unstable Cases
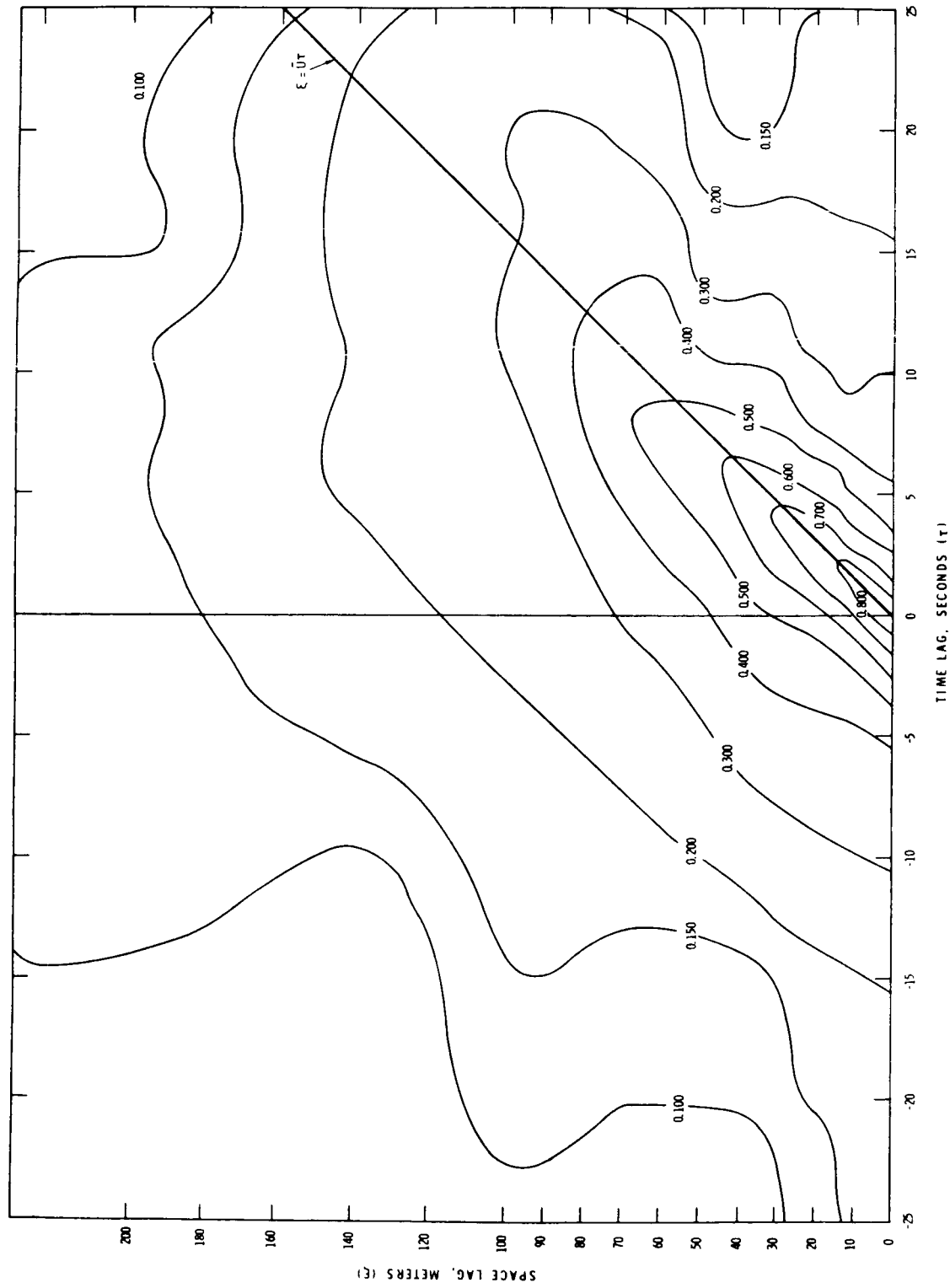
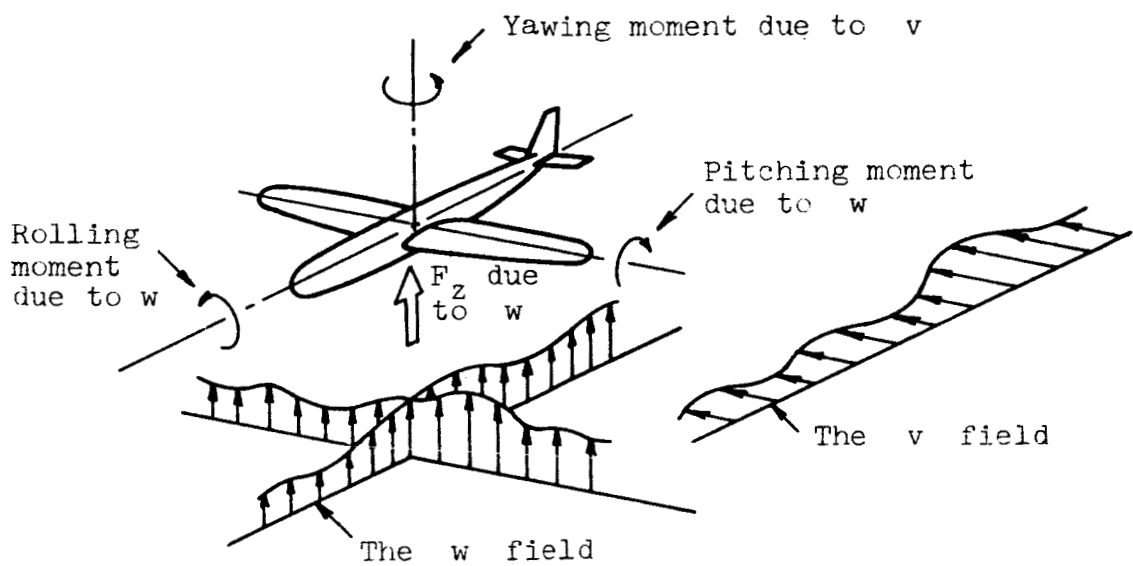FIGURE 8. Two-Argument Correlation Function of u in Time and Space (From Ref. 22B)
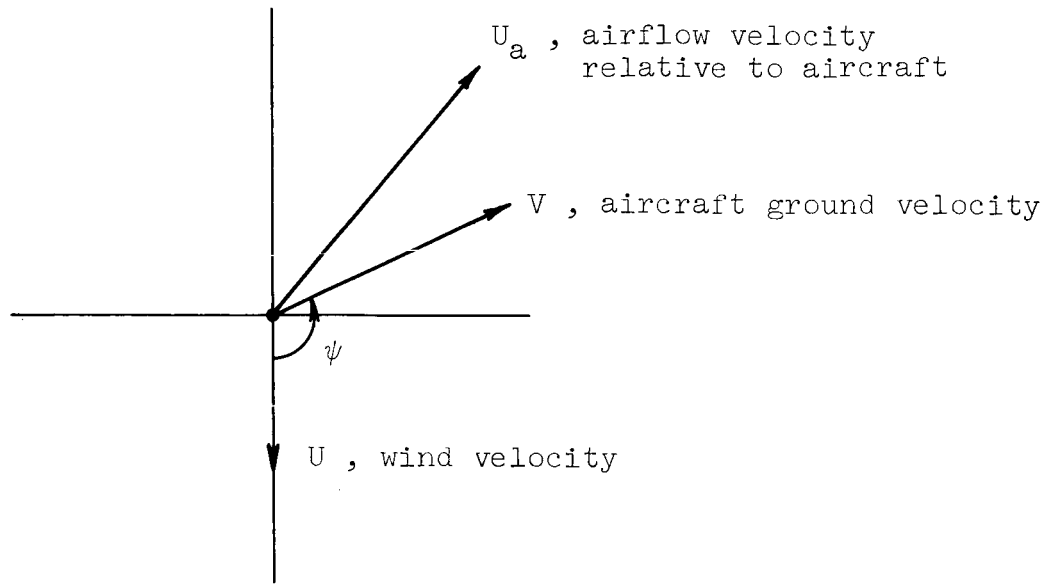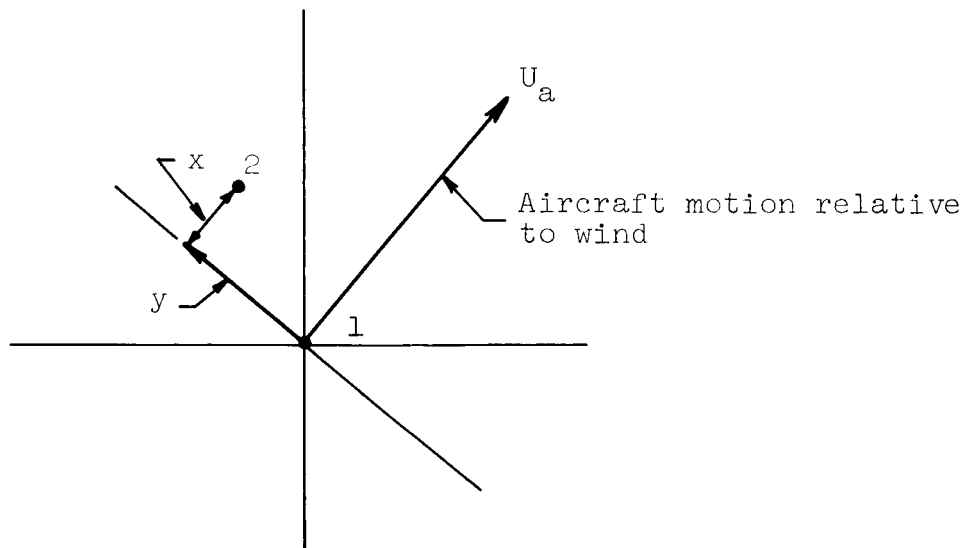
FIGURE 9. Predominant Force and Moments that Act on an Airplane in Turbulence

(a) The airflow vector U_a

(b) Relative location of two points

FIGURE 10. Geometry Involved in Considering the Correlation of
Turbulence Velocities between Two Points for Aircraft
Flight Path not Aligned with Wind Direction