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NASA Conference Publication 2468

Atmospheric Turbulence Relative to Aviation, Missile, and Space Programs

Proceedings of a workshop held at
Langley Research Center
Hampton, Virginia
April 2-4, 1986

NASA

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Atmospheric Turbulence Relative to Aviation, Missile, and Space Programs

Edited by
Dennis W. Camp and Walter Frost
FWG Associates, Incorporated
Tullahoma, Tennessee

Proceedings of a workshop sponsored by the
National Aeronautics and Space Administration
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Langley Research Center
Hampton, Virginia
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PREFACE

A portion of NASA's aviation safety activities has involved obtaining a clearer understanding of weather-related phenomena. Atmospheric turbulence has always been of concern, not only for aircraft but also for missile and space programs as well.

In 1984, Richard Tobiason of the NASA Headquarters Office of Aeronautics and Space Technology (OAST) began urging that a workshop be conducted on the topic of atmospheric turbulence. This topic involves so many interrelated specialities (designers, operators, forecasters, modelers, flight measurement experimenters, regulator (design criteria) and statistical analysts) that a sharing of information and improved communication in general appeared to deserve special attention. Accordingly, FWG Associates was given responsibility for conducting a workshop, which was jointly sponsored by NASA and the Department of Defense.

The primary goals of the workshop were to assess the state of knowledge in the various discipline areas and identify efforts needed to alleviate weaknesses. Attendees were assigned to committees, and after interaction with other committees, their viewpoints were compiled; these viewpoints are included in the proceedings as committee summary reports. Dr. Walter Frost, Mr. Dennis W. Camp, and Mrs. Barbara Smith are to be commended for their work in planning and conducting the workshop.

Harold N. Murrow
Conference Coordinator

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EXECUTIVE SUMMARY

The purpose of the workshop was to bring together various disciplines of the aviation, missile, and space programs involved in predicting, measuring, modeling, and understanding the processes of atmospheric turbulence. Working committees re-examined the current state of knowledge, identified present and future needs, and documented and prioritized integrated and cooperative research programs. The details of the overall workshop are fully documented in the proceedings.

The workshop was sponsored by NASA and DoD and conducted by FWG Associates, Inc. The workshop was held at Langley Research Center, Hampton, Virginia, April 2-4, 1986. Issues addressed by an interdisciplinary group of professionals were: common user requirements, common existing research facilities, as well as new facility requirements, current status of our knowledge of turbulence processes, forecasting and prediction techniques, computational algorithms, measurement capabilities, potential future instrumentation, and design criteria.

Invited papers provided an overview on the current status of turbulence modeling theories, measurement techniques, and operational and design needs. The papers are documented in the proceedings.

The results of the committee working sessions and interactive discussions are summarized in Tables 1 through 4. Recommendations as related to user needs and research areas are tabulated under the broader areas of operations, design, simulation, and space needs. Detailed descriptions of the research needs and suggestions as to agencies responsible for the research areas are given in the committee summary reports.

TABLE 1

OPERATIONS

1. Establish a clear definition of operational objectives for understanding turbulence.
2. Standardize turbulence terminology and reporting procedures.

UNDERSTANDING

1. Prepare a survey paper on the state-of-the-art in understanding turbulence:
   a) Frequency of occurrence
   b) Duration
   c) Spatial/temporal distribution
2. Establish high-altitude turbulence data and understanding.
3. Assemble a comprehensive sensor system to provide cost-effective flight research.
4. Support development of high-resolution CFD research models.
5. Several agencies and sectors of the industry should work together to develop and disseminate a standard that clearly encompasses all aspects of aircraft turbulence.

MODELING

1. New parameterization models should be investigated.
2. Modelers should establish more direct contact with the remote sensing community.
3. The lidar community should define and present their needs to modeling community.

MEASURING

1. Develop measurement techniques to distinguish gravity waves from turbulent fluctuations.
2. Develop turbulence avoidance techniques:
   a) Airborne measurement
   b) Ground-based measurement
   c) Prediction
   d) Current on-board information
3. Refine techniques for detecting turbulence using VAS sounding data.
4. Investigate methods of direct sensing of turbulence from ground-based lidar and radar for long-range implementation.
5. Document present state of knowledge on the use of profilers for monitoring turbulence aloft.

PREDICTING

1. Focus on various pieces of turbulence problem for numerical prediction since current grid resolution will not allow mesoscale effects to be operationally computed:
   a) Mountain waves
   b) Convection
   c) Etc.
2. Use existing forecast fields to provide higher resolution through the development of subgrid nesting techniques.
3. Verify and indentify most effective forecast techniques.
4. Resolve presently used rules of thumb forecasting methods into valid and standard techniques and publish the results.
5. Continue the development of liders for use on space platforms.
6. Determine if aircraft, VAS, or profiler data will improve numerical models.
7. Continue the development of equipment and algorithms for accessing and determining turbulence encounters from flight recorder data.
8. Establish a centrally located automated PIREPS assimilation center.
9. Train users and operators to interpret turbulence data from NEXRAD radars.

TABLE 2

DESIGN

1. Re-assess TARC 78-55:
   a) Turbulence prediction techniques
   b) Design approach
   c) Airline meteorology prediction

UNDERSTANDING

1. Analyze and establish a national repository of turbulence data:
   a) Inventory current data base
   b) Expand as needed
   c) Analyze
   d) Develop a catalog
2. Determine benefits or effects on the increased life span of aircraft due to improved clear-air turbulence forecasts and/or warning and avoidance systems.
3. Develop detailed flow visualization and/or measurements of unsteady atmospheric phenomena.
4. Calculate the evolution of three-dimensional vortices and their effects on flow near the ground plane.
5. Investigate (research and measure) the response of aircraft with multi-surface control systems during turbulence penetration.

MODELING

MEASURING

1. Develop turbulence measurement techniques for altitudes greater than 30 km.
2. Develop a low-cost "g" meter which permits easy visual readout and reset capability.
3. Expand research, development, and validation in the area of avoidance and awareness.

PREDICTING

TABLE 3

SIMULATION

1. Review current MIL spec models for structural, flying qualities, and flight control applications.
2. Provide explicit guidance on how to implement turbulence models.

UNDERSTANDING

1. Generate data for modeling the probability density function of turbulence.
2. Analytically investigate the effect on lidar sensing due to multi-phases (i.e., snow, rain, etc.).
3. Verify physical soundness of superimposing turbulence on wind shear (i.e., quasi-steady) flow models.
4. Systematically investigate and determine the various effects or scales of turbulence (i.e., non-Gaussian coherence, spectrum form, etc.) which can be preceived by pilots and their relative level of importance.
5. Study the necessity of a three-dimensional wind shear/turbulence model for training application.
6. Develop an understanding of the most important types of wind shear/turbulence near airports and/or topographical features.

MODELING

1. Investigate the general Monte Carlo turbulence simulation problems and consider potenetial coupling with CFD models.
2. Develop models of anisotropic turbulence associated with various forms of wind shear (particularly microbursts).
3. Develop suitable turbulence models for rotary wing design and simulation.
4. Develop realistic turbulence models below 500 ft:
   a) Wind shear
   b) Fronts
   c) Sea breeze
   d) Other local scales

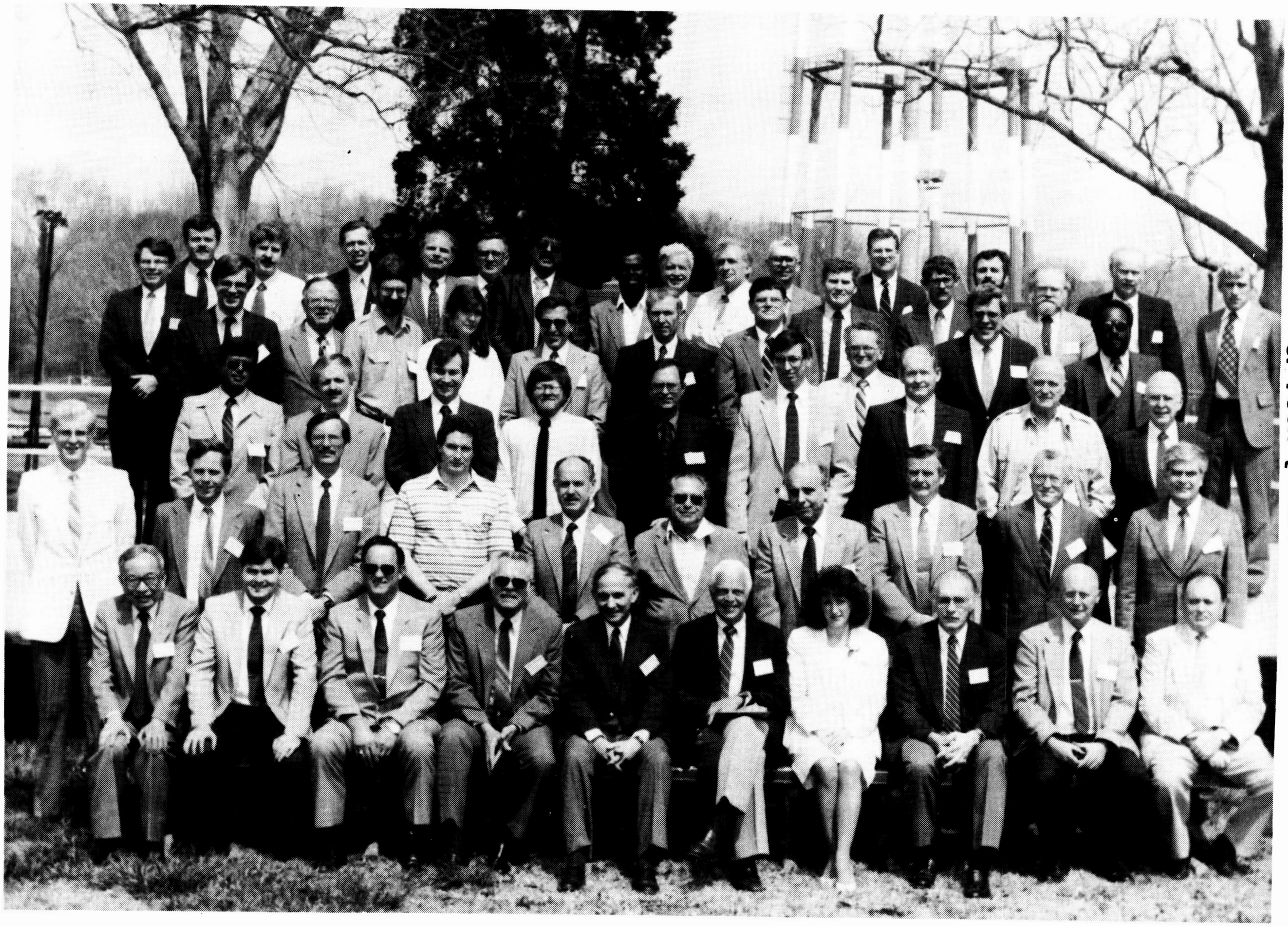
MEASURING

PREDICTING

TABLE 4

SPACE

UNDERSTANDING	MODELING	MEASURING	PREDICTING
		1. Develop remote sensing capability of measuring density at 70 to 120 km.	



WORKSHOP PARTICIPANTS

INTRODUCTION AND WELCOME

Jerry C. South
NASA Langley Research Center
Hampton, Virginia

It is my pleasure to welcome all of you to NASA Langley Research Center. We're very happy to co-host this workshop with the DoD. I was involved in my research days in a group that included atmospheric turbulence research and that's where I got to know Harold Murrow originally.

We host many workshops during the year, and if there is anything that we can do to make your stay more productive and comfortable, please let us know. Harold is the administrative chairman and can take care of any of your needs. If you have any questions or if you have some extra time and would like to have a tour of some of the facilities at Langley, Hal can probably arrange that, too. I'll get out of the way. I know your objective is transferring a lot of information and trying to look at research needs for the future, so get to it and have a good couple of days.

Harold N. Murrow
NASA Langley Research Center
Hampton, Virginia

As most of you know, atmospheric turbulence has always been of concern to the aerospace community and will continue to be. The very first NACA report* was on that subject. There are so many interrelated facets that, one to two years ago, several people thought that it would be profitable to try to bring together people with differing perspectives on the subject in a workshop arrangement. Probably the biggest initiator of that was Dick Tobiason, who was at NASA Headquarters, OAST, at that time. Later, further support was offered by John Theon, OSSA, and Captain Ed Harrison with the Secretary of Defense. So we, along with John Houbolt here at Langley and Dennis Camp at Marshall met with Walt Frost and formed an organizing committee which led to this workshop. We certainly appreciate the support, and we certainly hope that this will be profitable to everyone here.

*Wilson, E. B.: Theory of an Airplane Encountering Gusts. NACA Report 1, Part 2, 1915.

INVITED PAPERS

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COMMENTS ON THE PROBLEM OF TURBULENCE IN AVIATION

James C. McLean, Jr.
National Transportation Safety Board
Washington, D.C.

Since there has been aviation there has been a turbulence problem. The earliest aviators recognized several potentially turbulent situations such as strong low-level winds across rough terrain, convective turbulence due to solar heating and instability. They also had a great respect for the damaging turbulence associated with thunderstorms. Much of this knowledge was based on experience. It was not until the 1940's that much of the problem underwent scientific scrutiny. The Thunderstorm Project described the dynamics of the airmass thunderstorm, but as we now know, it did not address many of the ancillary characteristics that thunderstorms can generate. In the late 1950's the mountain wave was investigated and described.

With the advent of high-altitude jet aircraft in the 1950's, it was commonly thought that flight would be above all troublesome weather. The Air Force and, shortly thereafter, the airlines learned this was not so. A type of turbulence called CAT (Clear-Air Turbulence) reared its head and extended sharp claws. In February 1966 the joint military-civilian National Committee for Clear-Air Turbulence was established. This action, in part, led to a period of intensive research to both describe the phenomenon and to accurately forecast it.

In 1977, the downburst associated with thunderstorms was first described, and since that time there have been intensive efforts to identify the onset of this phenomenon and to give pilots a timely warning of the hazard.

In spite of all the efforts to improve the forecasting and detection of turbulence, the problem is still with us. Excerpts from the statistics of the most recent period of accident records compiled by the National Transportation Safety Board (NTSB) may give some insight into the magnitude of the problem.

Table 1 enumerates the accidents that occurred during the period from 1982 through 1984, the latest period that NTSB has complete records. It gives the total number of accidents for the three-year period for large commercial carriers--both scheduled and non-scheduled--operating under FAR Part 121, the commuter and air taxis operating under FAR Part 135, and general aviation, which includes corporate aircraft, operating under FAR Part 91. These accidents have, in turn, been subdivided into fatal and nonfatal accidents and subtotaled as weather-involved and, more specifically, as turbulence-involved accidents. The weather-involved accidents are accidents in which weather is listed as a cause or factor. Other casual factors such as those attributable to pilot actions or maintenance problems may have been assigned to the same accident.

More indicative of the magnitude of the weather hazard is Table 2 which gives the weather accidents as percentages of the total number of accidents and the turbulence-associated accidents as a percentage both of the total number of accidents and a percentage of weather-involved accidents. Most significant in these numbers is that the odds that an accident involving a large commercial carrier being in a weather accident are greater than for either the commuter and air taxi operations or for general aviation. This is probably due, at least in part, to the fact that the aircraft operated under FAR Part 121 are most sophisticated and more likely to have redundant systems than the smaller aircraft, and hence are less likely to suffer from catastrophic mechanical failure. Additionally, the pilots, as a group, have more experience and are less likely to become involved in situations attributable to operational errors. But based upon their scheduled operation, they do encounter all varieties of weather situations.

It is noteworthy that in all three operational categories, weather is a factor in a higher percentage of fatal accidents than it is in accidents overall, and in the case of FAR Part 121 operations, over half of all the fatal accidents are weather involved and they account for almost all of the fatalities. The common thread in this particular data sample is snow and/or ice, which was a factor in four of the five fatal accidents. Engine ice and ice and snow on the wings were major factors in the Air Florida accident in Washington, D.C., in January 1982 which killed 78 people. During the same month, two people were killed when a World Airways DC-10 ran off the runway into Boston harbor due to ice and snow on the runway. The other accidents were a Republic Airlines Convair 580 which ran into a snowbank in Brainerd, Minnesota, on January 9, 1983. A propeller disintegrated, fatally injuring a passenger. The other involved an Ozark Air Lines DC-9 which collided with a snow sweeper in Sioux Falls, South Dakota, on December 20, 1983, killing the sweeper operator. The fatal accident that was not involved with snow and/or ice was the wind shear encounter by Pan American Flight 759 on takeoff from New Orleans International Airport on July 9, 1982, which caused 153 fatalities.

Turbulence accounts for 24 percent of the accidents involving large commercial carriers and 54 percent (over half) of the weather-involved accidents. Fortunately during the 1982 through 1984 time period, there were no fatalities caused by turbulence encounters. This is not unique to the period. There have been no fatal accidents involving large commercial aircraft directly attributable to turbulence since the crash of a Braniff Airways Lockheed Electra on May 3, 1968, in which 85 people were killed. In this case, the aircraft suffered structural failure recovering from an unusual attitude induced by a thunderstorm. There have been two fatal turbulence accidents since that time: a Fairchild F-27 in December 1968 and a Lockheed Hercules in May 1974. In both cases, the structural failure was attributed to fatigue or pre-existing cracks in the airframe. This is not to imply that turbulence is not a hazard. During the 1982 to 1984 time period, there were 81 injuries in FAR Part 121 operations, 24 of them listed as serious. This represents both considerable pain and suffering to those involved and a significant financial liability to the airlines. Those generally at greatest hazard by turbulence are flight attendants who often continue cabin services when the seat belt sign is on and are injured both by being thrown about the aircraft's interior and by service equipment, such as food and drink carts and galley equipment. An additional problem is the large amount of loose luggage and other objects that are carried aboard airliners and improperly stowed. These objects often become missiles in severe turbulence.

In the categories operating under FAR Parts 135 and 91, the turbulence accidents only account for 2 percent of the total accidents and 6 and 7 percent of the weather-related accidents, respectively. The difference between the smaller commuter, air taxi, and general aviation aircraft and the larger commercial carriers is that turbulence-related accidents with the smaller aircraft are much more likely to be fatal. The reason for the lower percentage of turbulence accidents is readily explainable. In the smaller aircraft, the passengers and crew remain strapped in and there are generally not the loose and potentially hazardous objects in the passenger spaces. Consequently, the turbulence--so long as control of the aircraft is maintained--is a discomfort. The serious problem is when control is not maintained. The large majority of fatal turbulence encounters are a result of the pilot losing control of the aircraft due to extreme accelerations or disorientation and either colliding with the ground while out of control or by overstressing the aircraft during an attempted recovery from an unusual attitude which results in an in-flight breakup of the aircraft.

The NTSB has investigated several turbulence accidents and has made recommendations to improve the system in those instances where the Board believed that changes in procedures might serve to alleviate the problem to some degree. Unfortunately, the NTSB does not have the resources to investigate all turbulence encounters. It is limited to investigating those classified as accidents by the Board's definition, which means that there was serious injury to passengers or crew members or sufficient damage to the aircraft that its airworthiness was affected. The following paragraphs are synopses of some of the accidents investigated by the NTSB which are examples of the problems associated with turbulence.

On May 19, 1980, a Gates Learjet Model 25D was enroute from West Palm Beach to New Orleans on J-58. The aircraft reached its cruise altitude of 43,000 feet just prior to reaching Clovia Intersection, about 104 miles west of Sarasota. Shortly after the pilot had reported leveling off the controller at the Jacksonville Center, monitoring the frequency used by the Learjet, heard an unusual staccato sound followed about 18 seconds later by a report from the co-pilot, "Can't get it up...it's in a spin." About 33 seconds after the first staccato sounds, radio and radar contact with the aircraft were lost. Floating debris was found in the water in the vicinity of Clovia Intersection, but the two pilots were missing and presumed to have been killed. There were no passengers on board.

Another Learjet was following about 16 minutes behind the accident aircraft at the same altitude. In the vicinity of Clovia Intersection the pilot reported that he encountered the most severe turbulence he had ever encountered in a Learjet.

An analysis of the weather conditions in the vicinity of the accident showed an upper front or vertical discontinuity at the approximate altitude where the aircraft encountered the turbulence. This discontinuity appeared on the sounding of Bootheville, Louisiana, and Appalachicala and Tampa Bay, Florida, the three stations nearest to the accident. Additionally, there were strong vertical and horizontal wind shears in the vicinity of the discontinuity.

It was determined that this upper front was most likely the cause of the turbulence that led to the accident. The NTSB believed that the indicators of potential CAT may have been available prior to the accident and recommended that the National Oceanic and Atmospheric Administration (NOAA):

> Define the relationship between clear-air turbulence and upper fronts as analyzed by soundings and develop forecasting techniques to utilize the information to improve clear-air turbulence forecasts.

A CAT encounter by a United Airlines DC-10 over Morton, Wyoming, caused serious injuries to seven people and minor injuries to 19 others as well as causing damage to the aircraft, mostly to the interior from objects tossed about the aircraft.

A study of the weather data available showed that conditions were approaching those conducive to mountain wave development, but of several systems used to forecast the onset of a mountain wave only one would have forecast it and then only based upon the hourly data recorded about 2 minutes prior to the accident. Analysis also showed that there was a discontinuity below the tropopause with 10 kts of wind shear across it recorded at one sounding station. The conclusion was that the turbulence was caused by a combination of an incipient mountain wave and wind shear through an atmospheric discontinuity. It was also concluded that there were no known forecasting systems that would have predicted the turbulence.

There have been two accidents caused by turbulence that have been associated with strong upper level winds in the vicinity of intruding thunderstorms. These are the accidents involving a United Airlines DC-10 near Hannibal, Missouri, on April 3, 1981, and an Air Canada L-1011 about 60 miles south of Wilmington, North Carolina, over the Atlantic Ocean on November 24, 1983. In the United Airlines accident there were eight serious injuries, and in the Air Canada accident there were five serious injuries.

In both cases there were developed or developing thunderstorms in the vicinity of the jet stream, and the aircraft encountered the turbulence several miles downwind of the thunderstorm cell. The United pilot reported being in cirrus clouds, probably an anvil cloud. There have been several studies of these accidents with efforts to describe the atmospheric mechanics. Hopefully, these will lead to a better understanding of the phenomenon. In any event, the area downwind of a thunderstorm in a jet stream regime should be considered potentially turbulent. This is not a new idea. The Air Force has preached this gospel for many years and at least one airline recommends aircraft avoid thunderstorms downwind by at least one mile for every knot of wind speed at flight altitude.

As a result of its investigation of these two accidents, the NTSB recommended that NOAA:

Advise its weather forecasters to be alert for situations where there is a jet stream or strong upper level winds in association with lines of developing or developed thunderstorms which may produce an area of severe clear-air turbulence, and to issue appropriate warnings of this potential turbulence to pilots through area forecasts, SIGMET's, or other appropriate means of communication.

In spite of years of efforts, the problem is not solved and will probably never have a complete solution but improvements can be made. Instrumentation is being improved in quantum jumps and with this improvement will come better observations, a better understanding of the dynamics of turbulence, and in turn better forecasts with a better understanding of turbulence will come improved training helping pilots to recognize some turbulent situations and avoid them. This will help but will not be the total cure. The scale of some turbulence is too small for accurate forecasts. Here the answer may be on-board detectors that will give pilots a warning of turbulence ahead.

However, the problem is approached, the efforts of many scientists and engineers will be needed to help bring increased safety and comfort to those not always so-friendly skies.

TABLE 1. U.S. Civil Aviation Aircraft Accident Totals for the Time Period 1982 to 1984.

	Total accidents	Fatal accidents	Fatalities	Weather accidents	Fatal weather accidents	Weather fatalities	Turbulence accidents	Fatal turbulence accidents	Turbulence fatalities
FAR Part 121 large commercial	62	9	253	28	5	235	15	0	0
FAR Part 135 commuter and air taxi	485	96	260	154	43	106	9	5	17
FAR Part 91 general aviation	9,302	1,688	3,377	2,593	717	1,561	198	94	237

TABLE 2. U.S. Civil Aviation Weather Accident Percentages for the Time Period 1982 to 1984.

	Weather accidents, percent of all accidents	Fatal weather accidents, percent of all fatal accidents	Weather fatalities, percent of all fatalities	Turbulence accidents, percent of all accidents	Fatal turbulence accidents, percent of all fatal accidents	Turbulence fatalities, percent of all fatalities	Turbulence accidents, percent of all weather accidents	Fatal turbulence accidents, percent of all fatal weather accidents	Turbulence fatalities, percent of all weather fatalities
FAR Part 121 large commercial	45	56	93	24	0	0	54	0	0
FAR Part 135 commuter and air taxi	32	45	41	2	5	7	6	12	16
FAR part 91 general aviation	28	42	46	2	8	6	7	13	15

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DoD (USAF) TURBULENCE ACCIDENTS AND INCIDENTS

Douglas Miller
USAF Inspection and Safety Center
Norton AFB, California

This presentation is a summary of Air Force turbulence-related mishaps for the last ten years of Air Force mishaps from a perspective of where we have been, where we are now, and where we are going. In addition to accounts of major mishaps, a summary of what actions were taken to preclude future similar mishaps will be presented. Also, a discussion of some of the things being done now and being planned for the future to prevent turbulence-related mishaps will be presented.

Before presenting this summary, a short explanation of how mishaps are classified is in order. The mishaps to be discussed in detail fall into a Class A category. Class A mishaps are defined as a mishap resulting in:

1. Total cost of $500,000 or more for injury, occupational illness, and property damage, or
2. A fatality, or permanent total disability, or
3. Destruction of, or damage beyond economical repair to, an Air Force aircraft.

The DoD as a whole uses pretty much this same system.

The definition of our Class B mishap category is a mishap resulting in:

1. Total cost of $100,000 or more, but less than $500,000, for injury, occupational illness, and property damage, or
2. A permanent partial disability, or
3. Hospitalization of five or more personnel.

Do not pay much attention to the Class B parameters since none of the Air Force turbulence-related mishaps fell into this category.

The definition of our Class C mishap category is a mishap resulting in:

1. Total damage which costs $10,000 or more, but less than $100,000
2. Any injury or occupational illness which results in a lost workday case involving days away from work (i.e., 8 hours or greater), or
3. A mishap which does not meet the criteria above, but which Chapters 5 through 9 require reporting.

Until January 1, 1986, the dollar limits for Class C damage ranged from $1000 to $100,000 (the Air Force just recently raised the lower limit to $10,000).

To give a perspective on the size of flight operations during this study, in 1985 the Air Force has possessed 9,927 active aircraft and flew 3,488,000 flight hours since 1976.

Table 1 shows the total numbers of Classes A, B, and C mishaps we have experienced in the last ten years as well as the number of turbulence-related mishaps which we have experienced by mishap category. From a statistical point of view, a very small percentage of our mishaps are turbulence related. However, as shown in Table 2, there is a problem that the Air Force has taken seriously from actions taken in our Air Force turbulence-related Class A mishaps.

TABLE 1. Total Air Force Class A, B, and C Mishaps and Turbulence-Related Mishaps from 1976 to 1985.

CLASS A	CLASS B	CLASS C
782	931	36,729

TURBULENCE RELATED:

CLASS A	CLASS B	CLASS C
5	0	17

The first turbulence-related Class A mishap in my study occurred when one of our transport aircraft flew into or near a thunderstorm. The aircraft had departed home base with weather radar problems. The radar set was repaired prior to departure but failed again during the flight. Arriving near their destination, they found that there was significant weather between their position and their destination base. Civil air traffic control (ATC) advised them of a temporary radar failure, and that there was pretty solid cover between them and their destination. Ironically, military radar was tracking them and the Air Force possesses radar pictures of the weather conditions and aircraft for this flight. The controller stated, "There's no way I can get you around it." The aircrew indicated that they were in visual meteorological conditions (VMC) and would visually circumnavigate the thunderstorms. Two minutes later, the aircraft failed to respond to a transponder change. The aircraft broke apart in flight, went out of control, and crashed. Crew members and passengers perished in the crash. The aircraft had flown close to thunderstorm cells and, as a result, encountered extreme turbulence which failed the #4 pylon and right wing.

A lot of action was generated by this mishap. For example, the weather radar which had been experiencing a lot of reliability and maintainability problems was replaced with a much better and more reliable system. The Air Force came out with much more specific guidance on thunderstorm avoidance in our basic flight rules. Finally, there was a call for increased research in the area of severe weather avoidance.

A Multiagency Conference on Severe Convective Storms and Their Hazards to Aviation was held on February 16 and 17, 1977. A number of agencies were represented at this conference: National Weather Service, Environmental Research Labs, National Severe Storms Lab, National Severe Storms Forecast Center, FAA, NTSB, NASA, Lockheed, University of Chicago, and Air Force Inspection and Safety Center.

Some of the recommendations that came out of the conference are given in Table 3. With regards to the first recommendation, a number of studies have been conducted on thunderstorms by the National Severe Storms Lab and other agencies. For the second, the Air Force has acquired films on thunderstorm avoidance and other training aids. The third recommendation was covered in our corrective action. The fourth, a test program was established to see if full-time weather expertise would be useful at Kansas City Air Route Traffic Control Center. Flight simulation techniques have been developed for low-level wind shear and are used in Air Force cargo aircraft flight simulator programs. The last recommendation was covered in our corrective action.

The second major mishap occurred when a trainer aircraft penetrated a thunderstorm at high altitude. The mishap pilot accepted a routing from air traffic control which had more severe weather than what had been forecast for this flight planned route. When the pilot entered significant weather, he reported it to ATC. The controller offered the pilot a 180° turn as there were cells in all quadrants. The pilot received clearance to climb (even though the aircraft was already out of its engine operating envelope). At flight level 464, still in the cell, both engines flamed out. The aircraft traveled 5.4 nautical miles from its last radar painted position to its point of impact in 2 minutes 9 seconds. It was hypothesized that severe turbulence within the storm contributed to spatial disorientation and a delayed decision to eject. The aircraft did not have an on-board weather radar. The mishap pilot had significant flight experience, including being a graduate of Air Force Test Pilot School, but let his good judgment get side-tracked by intense motivation to get to his destination. There were no weather-related corrective actions taken as a result of this mishap.

Our third Class A mishap occurred in 1985 when a forward air controller (FAC) aircraft, encountered turbulence and downdrafts associated with a mountain wave phenomena. Mountain wave had not been forecast prior to the mishap flight. A pilot report of severe turbulence was issued by a helicopter after the mishap aircraft was airborne, but the information was not relayed to the mishap pilot. It was determined that the mishap aircraft got into an area of downdrafts which exceeded the aircraft's capability to climb to avoid terrain. Search for the crash site was hampered by severe turbulence in the area.

As a result of this mishap, a warning was put in the aircraft flight manual that in even moderate turbulence vertical gust velocities could exceed the aircraft's climb capabilities.

Less than two months later, another FAC aircraft was lost when it penetrated severe weather as it attempted to return to base during a weather recall. The mishap pilot whose visual routes of escape had been closed off by weather moving in from all directions decided to climb to 5,000 feet in instrument meteorological conditions (IMC) so that he could be radar vectored around the severe weather. During his IMC climb, he encountered a severe updraft which he interpreted as an attitude indicator failure. He then made a right descending turn to get back into visual (VMC) conditions. The mishap pilot then failed to reduce his high-power setting and the aircraft entered a nose-low, high-speed descent. The left wing failed at approximately 2,500 feet AGL due to high speed and turbulence. The aircraft entered a left uncontrollable roll and was completely destroyed on impact, fatally injuring the pilot.

Actions and suggestions coming from this mishap were similar to those of the other FAC aircraft mishaps. A warning regarding the dangers of flying low to medium performance aircraft in the vicinity of severe updrafts or downdrafts were recommended for Air Force Manual 51-12, "Weather for Aircrew," as well as a similar warning for the aircraft flight manual.

Finally, in our last turbulence-related mishap a transport aircraft was performing a medical evacuation mission into a remote site. Crosswinds on this approach were high requiring occasional full use of cross controls. A turbulent downdraft destabilized the aircraft a quarter mile from the runway. As this was a one-way site, one that requires that you fly your approach in one direction and your departure in the opposite direction--due to rising terrain in three quadrants--and they were already past the commit point (the point past which go-around is improbable), the pilot was committed to land. The aircraft touched down in a left drift and continued to drift left until it departed the runway. The aircraft sustained significant damage. There were no weather-related corrective actions taken as a result of this mishap. This concludes the look at our Class A turbulence-related mishaps.

Table 4 summarizes the last ten years of Class C turbulence-related mishaps. A Class C mishap is any damage that is between $1000 and $100,000. I will not go into detail on these mishaps unless someone has a particular question. Copies of our Class C investigations are not retained except for a brief narrative summary which is put into our computer. If the summary mentioned that turbulence was forecast, this was noted as a yes or no; if it was not mentioned, unknown (UNK) was noted. Also, if the airspeeds and altitudes at which the turbulence was encountered were contained in the summary, this is noted on the charts.

In reviewing the Class C mishaps, two major trends were noticed. First, that most of these mishaps occurred in large aircraft and second that most turbulence-related injuries were sustained by unrestrained occupants. In talking with fighter aircraft action officers (by the way, I am the C-130 action officer), their comment was that high-performance aircraft are not usually adversely affected by turbulence. Fighter aircraft are built for high "G" loading, and when they do hit turbulence, crew members are always well restrained.

I believe the reason we have a very good record in the area of turbulence-related mishaps is that our aircrews maintain a high level of awareness of severe weather. It is a frequent topic in our safety magazines, it is covered in pilot training, annual instrument refresher training, and aircrew briefings from our Air Weather Service people. Another factor is that good weather forecasting keeps us away from severe weather and turbulence.

Some areas where I see improvement for the future in turbulence avoidance includes better aircraft and ground-based weather radar. NEXRAD, which should come on line in the early 1990's, will have a turbulence algorithm. For improved forecasting, the Air Weather Service has recently completed a geophysical requirement for future turbulence research (defining Air Force and Army future forecasting needs). It is presently under review at Air Force Geophysics Labs. Dr. Dale Meyer from Air Weather Service, who was at this conference, is involved in this effort and has told me that he would be glad to give any of you who are interested in this geophysical requirement an overview of the project.

QUESTION: Dave O'Keefe (Lockheed). I noticed in your Class C you had an F105 where the vertical stabilizer broke apart or suffered damage due to turbulence. Was there any indication that there was a fatigue problem or there were corrosion problems? Were there any investigations as to why that stabilizer broke apart?

ANSWER: No, we do not retain copies of our Class C investigations. All I had to go on was a computer short summary. There were no indications at all of structural fatigue. The F105 is an old airplane, but it seems that if there had been indications, they would have been mentioned in our findings and they weren't.

QUESTION: Capt. Ed Harrison (The Pentagon). As the C130 action officer you should be well equipped to answer this one. I noticed the Air Force uses C130's for hurricane and typhoon reconnaissance. I was just curious as to their weather-related safety record. They are flying directly into the jaws of danger. Do they have a significant experience with turbulence-related incidents?

ANSWER: That is a good question. I know of one C130 mishap of a weather C130 flying into a typhoon in the Pacific in 1974. They never found the airplane so they were never able to determine what exactly caused the failure of the aircraft.

QUESTION: Mike Tomlinson (Air Weather Service). In your listing of the factors that you think are involved in a relatively good safety record, a factor that I didn't see that I think should be there is the need for pretty tight operational rules that specify when certain levels of turbulence are forecast. Do you think that is a significant factor, and because you're not out there when the forecast calls for severe turbulence, are you less likely to be exposed to those conditions and have resulting accidents?

ANSWER: Yes, you are. I guess I did fail to mention that as a result of that 1976 C141 accident, they did come up with very specific guidance on thunderstorm avoidance. And that has, unfortunately, been relaxed since that time. For a while the Air Force as a whole had a regulation telling you how far you had to stay away from thunderstorms. You had to be 20 miles downwind or 10 miles upwind, I don't remember the exact parameters. After that, the fighter community wanted different limitations. That parameter still exists in military airlift command supplement to 60-16, the general flight rules, but it is not in the Air Force regulation itself. But you're right. It is very true that we do have a lot of operating restrictions that keep us out of severe weather.

COMMENT: Dale Meyer (HQ Air Weather Service). As was pointed out, I will be glad to discuss our perspective of Air Force and Army requirements.

QUESTION: George Treviño (Michigan Tech). Will photocopies of all these slides and presentations be made available to the participants?

ANSWER: To answer your question on my briefing in particular, there are parts of it in which I went into specifics, such as places and types of aircraft, and they are "For Official Use Only." What I'm going to do is give to the workshop organization all of my briefing which is not restricted and present a summary that won't name the specific aircraft.

QUESTION: Al Bedard (NOAA). You have a criteria for classifying the strength of turbulence which I believe dealt with the G forces, if I read that slide correctly. Is that widely accepted by the defense community or is that your own internal classification?

ANSWER: That is something I think AWS would be better at answering. I think Dr. Meyer can probably answer that better than I can.

ANSWER: Dale Meyer (HQ Air Weather Service). We do have a procedure that was developed by the Air Force Wright Aeronautical Laboratories in 1981 that uses gust loading to classify all Air Force aircraft into four categories. We use that information operationally in tailoring our forecasts and interpreting PIREPS. I don't have the details with me but I have access to them.

TABLE 2. Air Force Turbulence-Related Class A Mishaps.

TRANSPORT AIRCRAFT IN-FLIGHT BREAKUP; NEAR THUNDERSTORM

TRAINER AIRCRAFT CONTROL LOSS; IN THUNDERSTORM

FORWARD AIR CONTROLLER (FAC) COLLISION WITH THE GROUND DURING MOUNTAIN WAVE ENCOUNTER

FAC AIRCRAFT IN-FLIGHT BREAKUP IN THUNDERSTORM UPDRAFTS AND TURBULENCE

TRANSPORT AIRCRAFT RUNWAY DEPARTURE AFTER APPROACH DESTABILIZED BY TURBULENT DOWNDRAFT

TABLE 3. Multiagency Conference on Severe Convective Storms and Their Hazards to Aviation.

RECOMMENDATIONS

- THE NEED FOR BASIC RESEARCH INTO THE LOCATION, DURATION, AND INTENSITY OF TURBULENCE IN THE VICINITY OF THUNDERSTORMS
- NEW AIRCREW TRAINING AIDS
- BETTER GROUND-BASED AND AIRBORNE-WEATHER RADAR
- ASSIGNING FULL-TIME WEATHER EXPERTISE IN THE AIR TRAFFIC CONTROL SYSTEM
- DEVELOP FLIGHT SIMULATION TECHNIQUES WITH REGARD TO LOW-LEVEL WIND SHEAR
- REVIEW AND STRENGTHEN REGULATIONS AND CRITERIA WITH REGARD TO PENETRATING HAZARDOUS WEATHER

TABLE 4. Class C Turbulence-Related Mishaps.

	WAS TURBULENCE FORECAST	ALTITUDE/AIRSPEED	DAMAGE
1976			
T-39A	NO	FL410/220 KIAS	ENGINE FLAMEOUT
EC-135J	UNK	FL310	CAT CAUSES OSCILLATIONS/FAILURE OF TRAILING WIRE ANTENNA
1977			
C-130B	UNK	FL110	CHAIN BOX LATCHES FAIL WHEN A/C ENCOUNTERS SEVERE TURBULENCE IN CLOUD
B-52G	YES/MOD	HIGH ALT/300 KIAS	SEVERE TURB THROWS CREW VIOLENTLY ABOUT
T-38A	UNK	FL210/300 KIAS	DAMAGE TO LEADING EDGES OF BOTH WINGS AND VERT STABILIZER WHEN AIRCRAFT ENTERED AREA OF HEAVY RAIN AND MODERATE TO SEVERE TURBULENCE
1978			
B-52G	YES	TRAFFIC PATTERN/	DAMAGE TO FLAPS WHEN A/C ENCOUNTERED MODERATE TURBULENCE IN RAINSHOWERS
1979			
C-130H	NO	LOW ALT	LOADMASTER BREAKS LEG WHEN A/C ENCOUNTERS SEVERE CAT
B-52H	YES	UNK	MODERATE TURBULENCE CAUSED DAMAGE TO BOMB DOORS, WHILE OPEN
EC-135H	UNK	FL330	TRAILING WIRE ANTENNA SEPARATES DUE TO CAT
1980			
C-130A	UNK	1000 AGL/125 KIAS	LOADMASTER BREAKS WRIST WHEN A/C ENCOUNTERS CAT
C-130B	NO	UNKNOWN	CREW CHIEF INJURES BACK WHEN A/C ENCOUNTERS MODERATE CAT
1981			
C-130A	UNK	FL180/240 KIAS	TWO CREWMEMBERS INJURED WHEN A/C ENCOUNTERS A SEVERE DOWNDRAFT

TABLE 4. (concluded).

	WAS TURBULENCE FORECAST	ALTITUDE/AIRSPEED	DAMAGE
1981			
F-105D	UNK	1000 FT AGL/ 500 KIAS	PART OF VERTICAL STABILIZER LOST WHEN A/C ENCOUNTERED SEVERE TURBULENCE EN ROUTE TO RANGE
C-130H	NO	FL160	TWO CREWMEMBERS INJURED WHEN A/C ENCOUNTERS ABRUPT SEVERE CAT
1982			
KC-135	YES	3000 MSL	PASSENGER INJURED WHEN A/C ENTERS AREA OF HEAVY WEATHER AND SEVERE TURBULENCE
1985			
KC-135A	UNK	FL220	A/C SUSTAINS CRACKS IN ALL FORWARD ENGINE MOUNTS WHEN A/C ENCOUNTERS SEVERE TURBULENCE
C-130B	YES	LOW LEVEL	FIVE AIRCREW SUSTAIN INJURIES WHEN A/C ENCOUNTERS MOUNTAIN WAVE

N87-22344

NEW GENERATION AIRCRAFT DESIGN PROBLEMS RELATIVE TO TURBULENCE STABILITY, AEROELASTIC LOADS, AND GUST ALLEVIATION

Richard M. Heimbaugh
Douglas Aircraft Co.
Long Beach, California

Figure 1 schematically illustrates past history, present status, and future of discrete gusts. Etkin [1] notes that the actual first discrete gust analysis was done in 1915 [2] where the equations and physical concepts related to gust response were derived. In the early 1930's the idea of using an aircraft as a measuring device based on a sharp-edged gust formula was initiated [3]. In the 1930's and 1940's, discrete gust data were collected and analyzed [4]. The present widely used mass parameter gust formula was published in the 1954 timeframe and subsequently resulted in the CAR-4B requirement for gusts [5]. Later the British introduced the idea of tuning a one minus cosine (1-cos) gust [6].

Figure 2 schematically illustrates a secondary line of development. In the early 1930's efforts were started to investigate the idea of gust gradients, and the importance of gradients was recognized. In fact, during this era, a dimensional analysis study showed that gust intensities are related to the cube root of the wavelength [7]. More recently, in the late 1960's, there was a probability analysis which showed that gust gradients and intensities are related and that the cube root type law is valid [8]. Finally, there was a survey that investigated the derived gust velocities of modern jet airplanes [9].

Figures 2 and 3 show there are basically two approaches to the gust analysis: discrete and spectral density. The roles of these two approaches to gust analyses will be discussed later in this presentation. In the early 1930's, von Karman derived the present spectral density characterization of the atmosphere [10], and the idea of using PSD (power spectral density) methods applied to gust analysis was introduced in the early 50's [11]. Again, a period of collecting and analyzing data and refining the approach followed in the 50's and 60's. The result was the FAA Report No. ADS-53 in 1966, which was the first serious attempt at trying to come up with a design criteria for sizing airplane structure based on the PSD gust [12]. Subsequently in 1980, the FAA Appendix G was introduced which requires PSD gust analysis [13]. Some other significant milestones are shown at the bottom of Figure 3. In a paper by Firebaugh [14] an analysis of data was presented which illustrated different conclusions in terms of what some of the gust parameters should be. Also, in the early 1970's the government (DoD) issued a MIL-008861A requirement for PSD type analysis [15].

The present discrete criteria (Figure 4) used by the FAA is based on the mass parameter gust derived in the 1950's [12]. It is a 1-degree-of-freedom analysis which is based on the airplane flying through an idealized 1-cosine gust that is 25 mean aerodynamic chords long. That type of analysis does not lend itself to a close-loop method such as would be done for gust alleviating systems or even if it were desired to analyze the effect of SCAS (Stability Control Augmentation System) systems. The criteria specifies design gust velocities based on the data derived in the 1930's and 1940's and, therefore, does not reflect the experience of modern aircraft.

The problem with discrete gust analysis is that it does not really address the question of gradients. Realistic gust gradients are needed if it is desired to evaluate the effects of short-period and dutch roll stability and how the stability of the airplane relates to the airplane response in gust (see Figure 5). Realistic gradients are needed to evaluate the effect of gusts in exciting vibration modes. Finally, realistic gradients are also needed for evaluating close-loop systems or load-alleviating systems. The steeper the gradients through which the airplane flies, the harder it is to design load-alleviating systems that are effective. So, to get a good prediction or analysis, you need to have realistic gradients; that is the main problem with the discrete gust formula.

As shown in Figure 6, the British recognized [6] some of the problems summarized in Figure 5, and in the early 1960's came up with this idea of tuning. In Reference 6 it was stated that realistically the airplane not only plunges but also pitches and it is also known that vibration modes can be excited. The British indicated that these types of parameters should be included in the analysis. At that time, they did not know what the gradients of the gust should be; thus, they required a survey of all possible gradients. Effectively, they were saying that all gradients are equally likely and it is necessary to tune an airplane to find the worst one. The design gust levels, however, were the same design gust velocities that were used by the mass parameter formula and the criteria as originally stated only mentions vertical gust; for some reason no mention of lateral gust was made. The wording of the criteria along with some additional information suggests that the British believe that the main driver in terms of determining the structural gust load should be the discrete gust. The PSD gust is considered secondary and they require it but only as a guide.

Again, the problem is that you do not have realistic gradients. There has been an analysis [10] which indicates that the gradients are, in fact, dependent on the gust intensity and the larger the gust intensity the smaller the gradients as shown in Figure 7. Another problem is that the design gust velocities were not recalibrated to reflect the significant changes in the analysis that the British required. They proposed [8] the original design velocities that were derived based on a simple mass formula parameter, which did not account for vibration modes and pitching of the airplane; they then applied those velocities to the new analysis. An additional problem is that the criteria need to be recalibrated based on the new analysis method.

In terms of the PSD gust, the basic criteria are based on the von Karman spectra which are defined in Figure 8. In this figure, L is the scale of turbulence and Ω refers to spatial frequency in radians per foot. If the airplane is flying through the turbulence at a particular speed, it can be related to a spectrum defined relative to frequency in Hz. The analysis is a linear one in which the gust varies only in a streamwise direction. The design parameters were developed with a somewhat different philosophy than was used for the discrete gusts. Discrete gust velocities were based on a probability approach where some level of turbulence was chosen such that an encounter was experienced every so many million miles as a basis for the design velocities. The PSD criteria were backed out based on the philosophy of providing equivalent strength to successful airplanes flying in the 1960's. Finally, the present criteria are also characterized by the fact that the various certifying agencies specify different parameters for many of the design parameters. The basic approach is the same but different agencies vary some of the details. Some of these details are significant.

In Figure 9, the PSD analyses are illustrated by two approaches: (1) a mission approach and (2) a design envelope approach. The mission approach seeks to represent the operational characteristics of the airplane in terms of how it is flown, what altitudes and speeds it is flown, what payloads, fuel loadings, and so forth. The design envelope approach is similar to the way other types of loads are computed in that you specify extreme conditions in terms of flying at speeds and altitudes that correspond to the limits of the flight envelope, investigating extreme payloads and fuel loadings, etc. There are various schools of thought within the community in terms of which approach is most desirable, and, in fact, there is a reluctance to really rely on any single approach. The feeling being perhaps that no single approach completely addresses all of the problems related to gust analysis. Presently, both approaches are used. One agency, the military, requires a mission approach; the FAA, however, allows only the use of a design envelope approach.

Presently, there is a question of whether to use discrete or PSD analysis to determine gust design loads. An illustration of these two is presented in Figure 10. The British tend to feel that discrete analysis should be the main thrust. However, the original ADS-53, perhaps reflecting a prejudice in the people who worked on it, indicated that PSD analysis should be the primary means for determining design gust loads [12]. Presently, there is not a specific detailed criteria in terms of how to certify active load-alleviating systems; however, there is an Advisory Circular that is very specific.

Presently, particularly with the FAA [13], both discrete and PSD analyses are required (Figure 11). The discrete mass parameter gust analysis by itself is not adequate since it does not account for dynamic effects. The shaded areas of Figure 11 indicate the parts of the airplane that are likely to be sensitive to dynamic effects. The engine pylons and perhaps wing tips are sensitive to exciting vibration modes which are not predicted by the mass parameter method. The tail is sensitive to dutch roll stability, which again is not accounted for in the mass parameter formula. Finally, the PSD approach has important applications in terms of supporting fatigue and damage tolerance analysis.

The PSD approach is basically a linear approach for analyzing active systems. The problem with approach is how to represent nonlinearities. Figure 12 indicates that you have a control system command and an actual control surface motion which are not necessarily linearly related to the command. An important parameter in PSD mission analysis is the zero crossing of the mean (N_0). The calculation of N_0 involves calculating the spectra of the rate of change of acceleration. A dot indicates a derivative of acceleration. With the streamwise gust model that we have today, the integral of the acceleration rate does not converge. You can get any value you want for N_0 depending on what you choose for the limits of integration.

As mentioned earlier, the vertical tail is particularly sensitive to dutch roll stability (see Figure 13). Modern transports generally have low dutch roll damping and as the damping approaches zero the PSD analysis will predict higher and higher loads on the vertical tail because the analysis assumes resonance at each solution frequency. Therefore, very large vertical tail loads are possible if you have a very low damped dutch roll mode and further assume no pilot interaction in terms of artificially supplying damping and also assume no yaw damper control system.

Historically, as shown in Figure 14, most of the data and criteria is based on using the airplane as a measuring device. The early discrete gust criteria is based on obtaining VG data recorded while flying through turbulence and analyzing that data by using the discrete gust formula. Based on that analysis, deducing what must be the gust velocities that the airplane experienced can be obtained. Then based on that data, coming up with a criteria in terms of design gust values that envelope all the experience or at least the likely experience is possible. The significance here is if it is desired to go the reverse way and re-create extreme acceleration data from the criteria and to change the analysis, it is not possible to get back the original acceleration data. The point to be made is that the criteria and the analysis are tied together and you really should not modify one without modifying the other. The same principle applies for the PSD approach where you are flying through random turbulence. The criteria is derived based on backing out the required design parameters such that the PSD analysis will predict loads consistent with the known strength of successful airplanes. Assume you wish to go the reverse direction using existing criteria but to do something to improve the analysis, if you were to analyze the original airplanes that the criteria was based on, different conclusions would be obtained. One might conclude that the reference airplanes were under-strength or over-strength. Thus, the need to relate the criteria and the analysis is realized. If there is some significant improvement to be made in the analysis, that improvement needs to be related to the criteria.

The basic goal of the criteria is to successfully extrapolate the experience of past airplanes. Illustrated in Figure 15 are old airplanes that are considered to be satisfactory from the structural point of view, are economically viable, and now you have some new airplane which needs to have the same characteristics. The new airplane should be structurally safe and economically viable. The analysis and the criteria primarily are ways of extrapolating the successful experience of old airplanes to new airplanes. The important question is how well the analysis and criteria predict the relative characteristics between the old and new so that significant changes are accounted for in the new design relative to the old design.

Generally, the criteria need to be integrated with modern analysis (Figure 16). Modern analysis refers to a method that accounts for dutch roll and short-period stability, and vibration modes along with the need to define realistic gust gradients. If those changes are made, then the design criteria should be reviewed in terms of what should be the design gust levels and also perhaps incorporate any experience we have with modern aircraft along with historic data from the 1930's and 1940's.

The main message is the need for standardization of approach and concensus in terms of what the approach should be (Figure 17). Some think PSD by itself is sufficient for determining design gust loads. There are other schools of thought that suggest if you have a realistic discrete gust approach, you do not need PSD gust for determining design loads. Is there something unique that the PSD gust analysis offers that is not part of the discrete gust analysis? Variations in the way mission and design envelope approaches to PSD gust are treated in criteria should be resolved.

There are various data, proposals, and interpretations of data in terms of how the scale of turbulence varies with altitude (Figure 18). Another question concerns the calculation of the zero crossing count, which is important in the mission analysis. As discussed earlier, the integral of the acceleration rate spectra does not converge; thus, we need to have a criteria that defines what the cutoff frequency is so that everyone is consistent. Another issue which is left up to the individual is whether one should analyze vertical gusts and lateral gusts independently or whether they should be combined.

Should there be some minimum standards concerning mission segments when the mission PSD approach is used (Figure 19)? In the extreme case you could define the mission as a single segment altitude, speed, and weight configuration. Or you could have many segments. Is there some minimum standards that could be imposed? Since the structures and controls disciplines are separate, there tends to evolve a separate description of the atmosphere that is used by controls engineers in terms of how they evaluate control system performance in turbulence versus the criteria the structural engineer uses in sizing the structure.

Shown on the top of Figure 20 is the formula that is used in the mission analysis for computing the crossings with positive slope of any load level L. As shown, it is a function of the N_0 mentioned earlier. P1 and P2 are the proportion of time in storm and non-storm turbulence, and b_1 and b_2 relate to the intensity of the storm and non-storm turbulence. If you change values for the scale of turbulence or cutoff frequency, the P's and b's should be recalibrated. This is true because the P's and b's were backed out to match flight experience, so the analysis and data are related. If the P's and b's are changed, you could conceivably come up with a different exceedance curve as indicated by the solid and dashed lines. The philosophy in the past has been to set the design crossing level (N_{DL}) to be consistent with known levels of limit load. The limit load is a known number that corresponds to the known strength of a previous airplane that has been successful. Now what would happen if you change the analysis to reflect a different exceedance curve? Y should back out a different N_{DL} as opposed to saying that the crossing exceedance relationship is different and therefore the design load level is now x percent bigger.

Relative to future airplanes that are going to be flying at higher altitudes than present aircraft: Probably we need to think about what should be the gust criteria at altitudes above 50,000 feet (Figure 21). The other question relates to the streamwise gust model. A lot of information indicates that at least at low altitudes the scale of turbulence is relatively small so that three-dimensional effects may be important at low altitudes. b/L is the span to scale of turbulence rates. There is perhaps some value for that parameter where you could say that three-dimensional effects are important and other values where three-dimensional effects can be neglected.

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QUESTION: Warren Campbell (BDM Corporation). One thing that you didn't address was what importance you place on the shape of your probability density distributions. I noticed that when you showed that exceedance curve, part of that exceedance curve was based on the assumption of the Gaussian distribution.

ANSWER: That is true.

CAMPBELL: Do you have any feel for the importance of probability distributions?

ANSWER: I guess I don't. As long as the distribution which, in turn, relates to that exceedance curve is a tool to back out the design values not an end in itself, I don't think it is terribly important but I don't really know.

CAMPBELL: One other question. When you design an aircraft, pardon my ignorance, do you consider fatigue in the PSD part.

ANSWER: Yes.

QUESTION: Bob Heffley (Manudyne Systems). From the standpoint of the designer, can you comment on how the pilot in the loop needs to be accounted for and what the implications are on the analysis methods that you describe, i.e., for both the discrete gust and power spectral density.

ANSWER: I guess in terms of the pilot the implications center on how he would respond to turbulence and how he would interact with it. Presently, the analysis generally doesn't account for that. You either do an open loop analysis in which you assume the pilot has no interaction at all or a closed loop analysis which again assumes the pilot isn't doing anything but the active system is doing all the feedback. I know in the controls area there are various pilot models that attempt to simulate delays and gains to represent the pilot as if he were a control law. I am not sure if there is a universal agreement as to what is a good pilot model. I guess it could be included if it could be represented as a control law, but right now they're not.

QUESTION: John Houbolt (NASA Langley). Richard, that was a nice rundown. I'd like to make this observation though. I wish I had a half hour to get up and give a follow-up talk to what you just said and place a lot of your notions in a little bit different context and from a little bit different perspective. There are a number of things that could be slanted differently than what you have done there. Let me just mention two of them. One of them is the power spectral density approach. You can do everything with that that you can do with the discrete gust approach but more and in a much rational way. So you can cover everything that the discrete gust approach has in it automatically in the power spectral density approach. And now the second thing I'd like to comment on is your comments on N_0, the zero crossing problem. If you do it right there is no problem getting N_0 correctly. It will converge very nicely and very rapidly. The reason I mention this is that this is one of the problems that we have at a conference of this sort. It's a heck of a time to disseminate certain pieces of information. Ten years ago I told people how to calculate N_0 in a proper way. That still hasn't gotten around the community and there is a reason for that. There is probably only one person in this audience, namely you, that is familiar with the N_0 problem and it is a difficult problem of getting this information around to the various people, because there is very little interest in it, but indeed if you do it properly, there is no problem whatsoever in calculating N_0. I think the sort of thing we need to take up in this conference is how do we get some of this information out of the group in a better way than we have presently been doing. This is an observation, not a question.

QUESTION: Jack Ehernberger (NASA Ames). Can you amplify briefly on your comment for a future requirment of more data characteristics above 50,000. Is that related to a specific inadequacy of previous data sets or some new unique design concepts?

ANSWER: Yes, I would think in terms of the discrete gust, the design gust velocities are functions of altitude and, as I remember, the discrete gust is only defined in military and civil regulations up to 50,000 feet. At the cruise speed, it is 50 ft/sec, up to 20,000 feet, and then it linearly reduces to some value at 50,000 feet. I'm raising the question that above 50,000 feet what do you do? Should structural analysts continue to allow it to linearly reduce to zero or assume a different function? I was thinking of what I had seen in the news about some of these hypersonic airplanes that are going to be flying at the edge of the atmosphere.

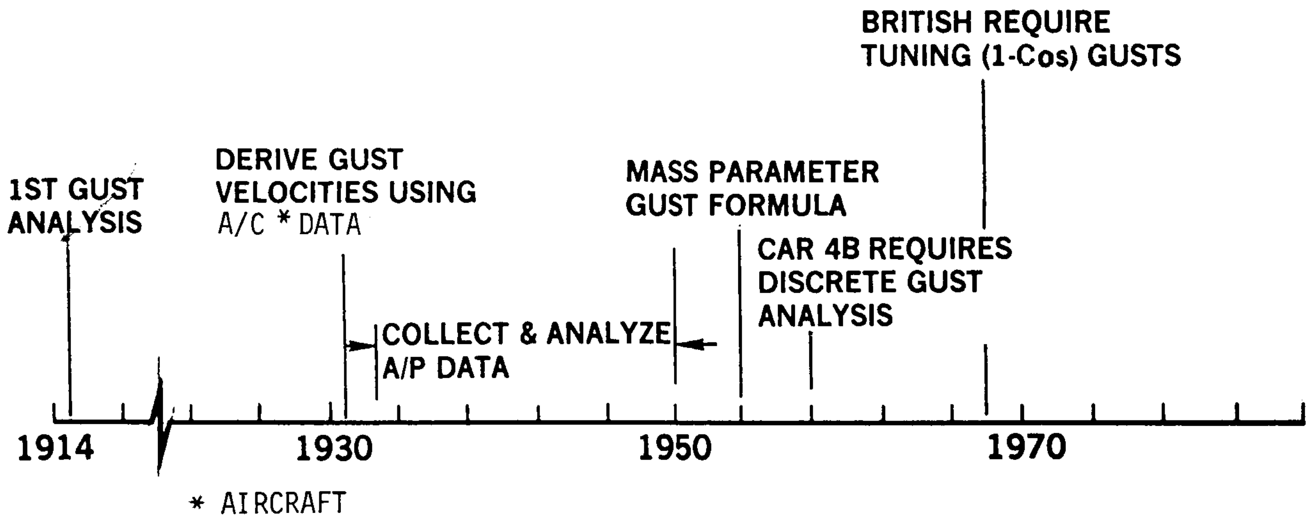


Figure 1. Development history of discrete-type gust description.

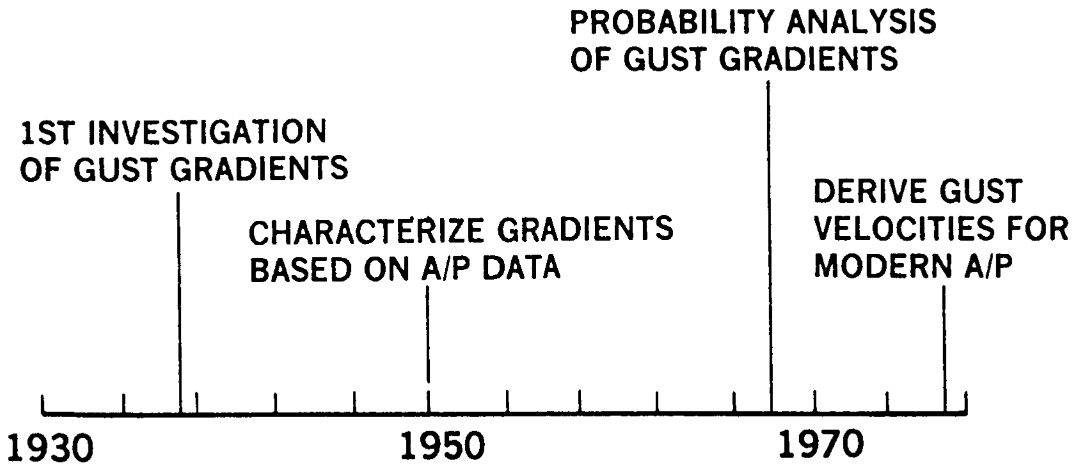


Figure 2. Time frame for gust gradient analysis development.

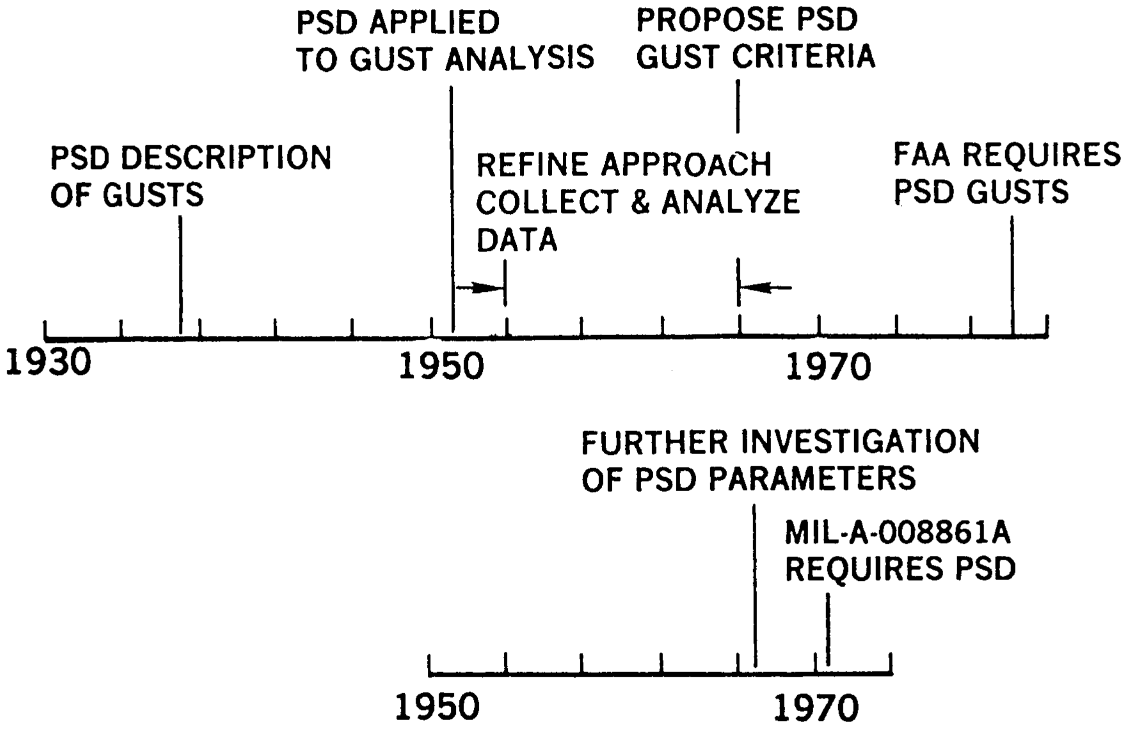
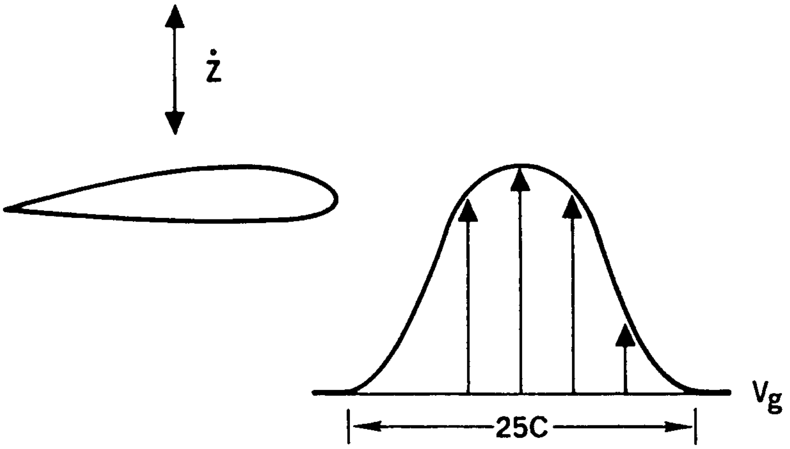


Figure 3. PSD gust history.



- BASED ON 1 DOF ANALYSIS
- BASED ON METHODOLOGY AND DATA 30-50 YEARS OLD
- DOES NOT PERMIT CLOSED-LOOP ANALYSIS
- DOES NOT REFLECT MODERN AIRCRAFT

Figure 4. Discrete gust--present criteria.

REALISTIC GUST GRADIENTS

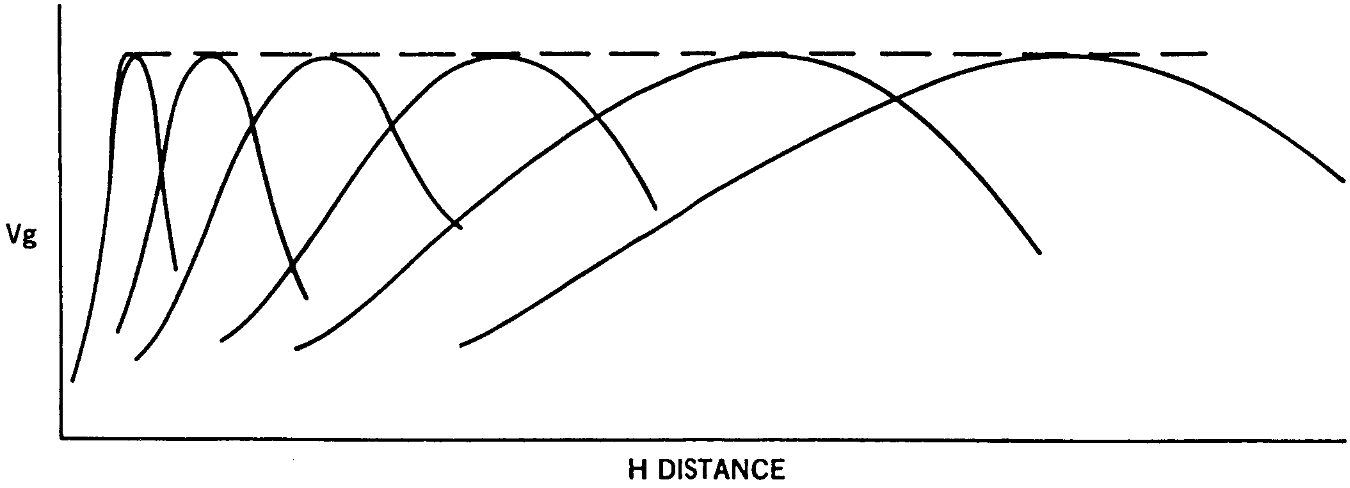
NEEDED TO EVALUATE A/P STABILITY

NEEDED TO EVALUATE VIBRATION MODES

NEEDED TO EVALUATE GLA SYSTEMS

Figure 5. Discrete gust--problems.

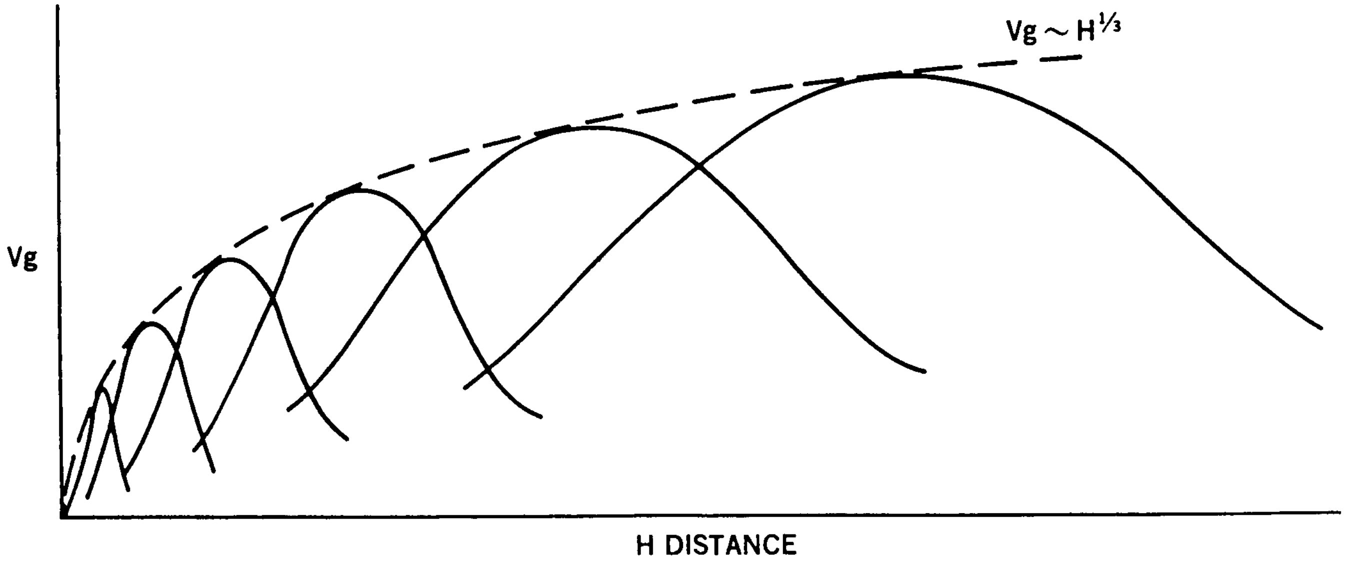
- REQUIRE MODERN METHODS TO "TUNE" 1 - Cos GUSTS



- USES MASS PARAMETER DERIVED GUST VELOCITIES
- "TUNING" SPECIFIED ONLY FOR VERTICAL GUSTS
- PSD GUSTS REQUIRED AS "GUIDE"

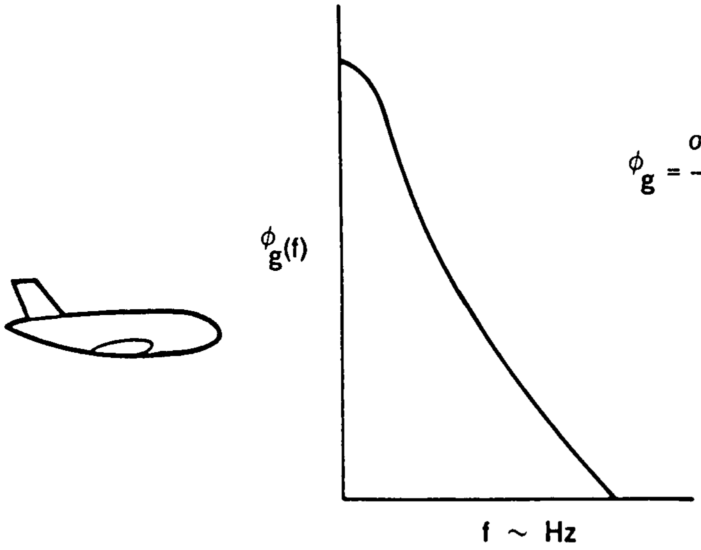
Figure 6. British discrete gust--present.

- "TUNING" DOES NOT PRODUCE REALISTIC GRADIENTS



- DESIGN VELOCITIES WERE NOT RECALIBRATED

Figure 7. British discrete gust--problems.



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

- LINEAR ANALYSIS OF STREAMWISE GUSTS
- STRENGTH EQUIVALENT TO 1960s AIRCRAFT
- VARIETY OF GUST CHARACTERIZATIONS

Figure 8. PSD gust--present criteria.

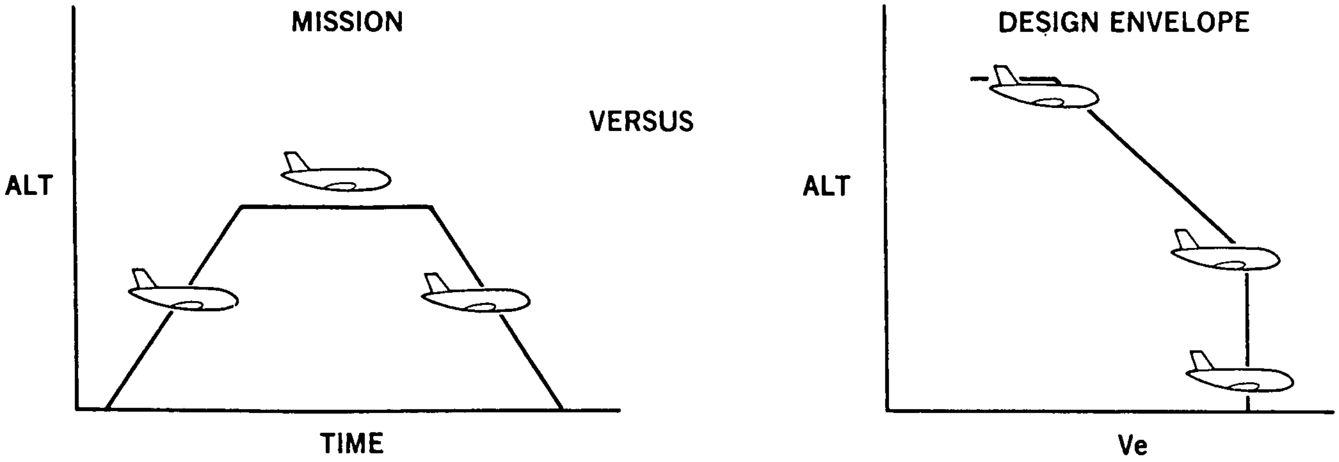
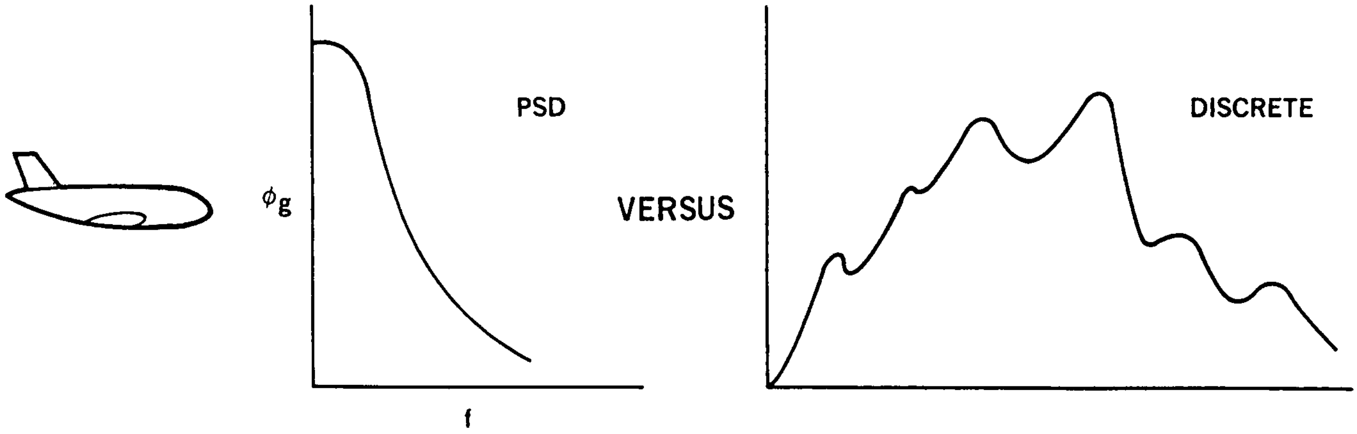


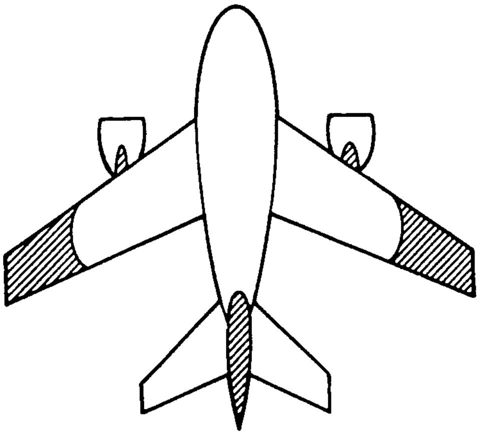
Figure 9. PSD gust--present criteria.



- FAA ADVISORY CIRCULAR ON ACTIVE CONTROLS FOR LOAD ALLEVIATION

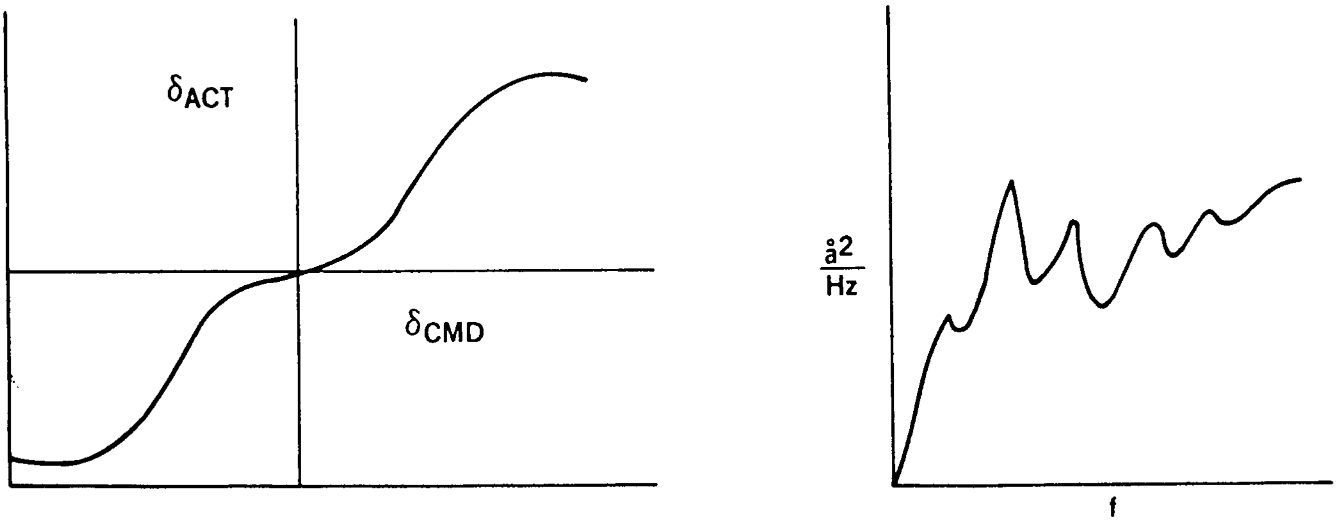
Figure 10. PSD gust--present criteria.

- **BOTH DISCRETE AND PSD REQUIRED**



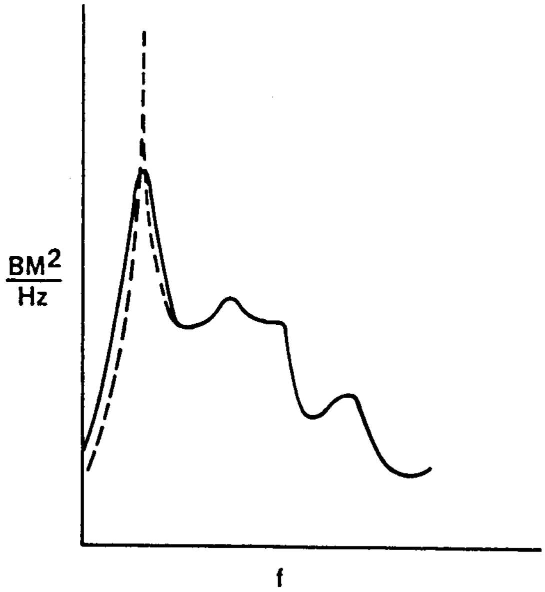
- **MASS PARAMETER GUSTS CANNOT REPRESENT A/P STABILITY AND VIBRATION MODES**
- **PSD IMPORTANT PART OF FATIGUE-DTA**

Figure 11. Gust criteria--present.



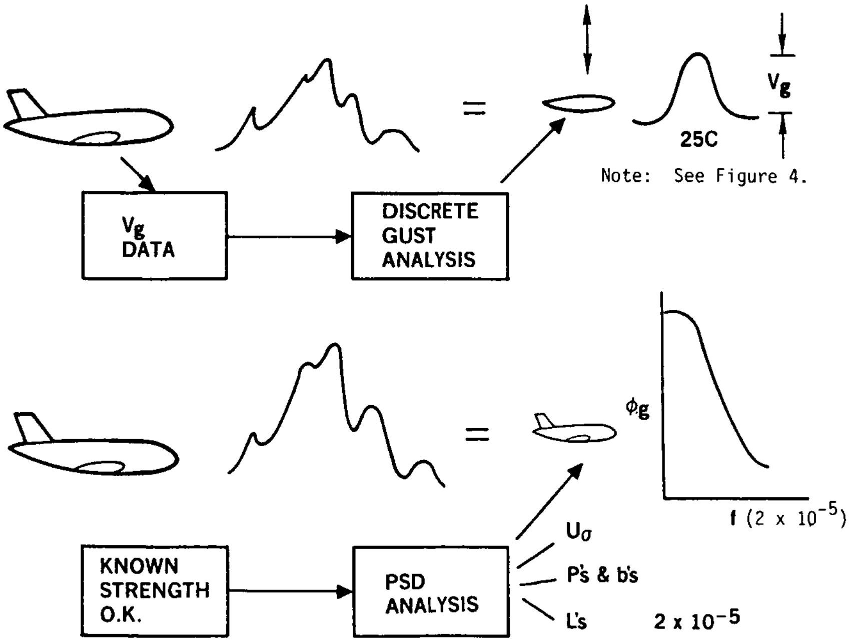
- **REPRESENTATIONS OF CONTROL SYSTEM NONLINEARITIES**
- **INTEGRATION FOR ACCELERATION No DOES NOT CONVERGE**

Figure 12. PSD--problems.



- PSD LOADS $\longrightarrow \infty$ AS $\xi_{DR} \longrightarrow 0$

Figure 13. PSD--problems.



Note: See Figure 4.

Figure 14. Criteria--background.

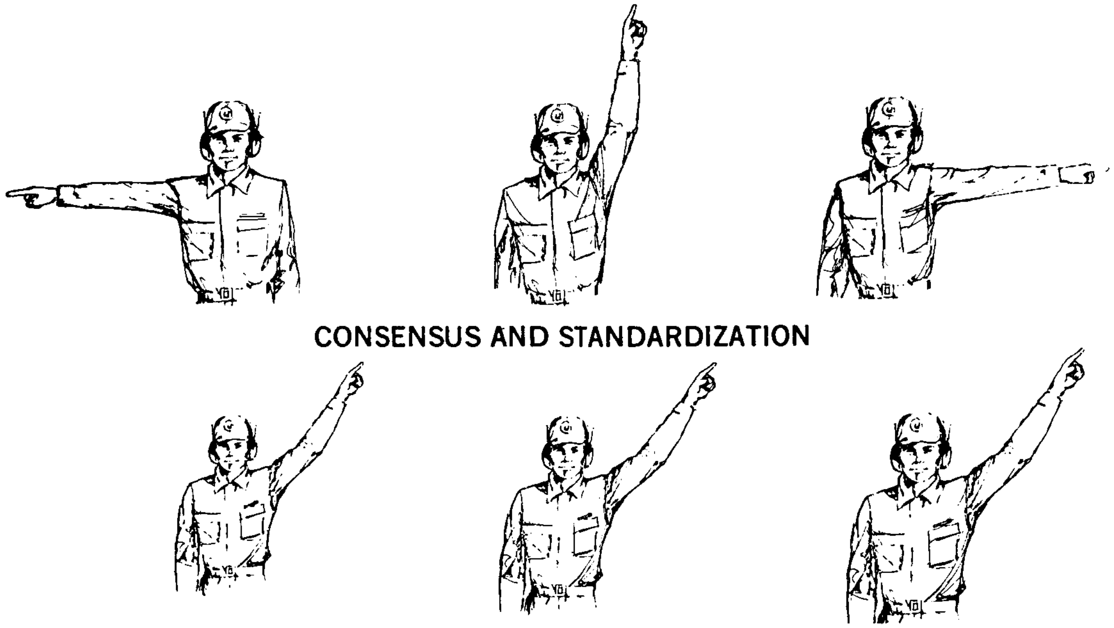
- **ANALYSIS/CRITERIA USED TO ASSURE EQUIVALENT LEVEL OF SAFETY**
- **RELATIVE CHARACTERISTICS ARE PREDICTED**

Figure 15. Criteria--philosophy.

- **INTEGRATE DISCRETE GUST CRITERIA WITH MODERN ANALYSIS**
- **DEFINE REALISTIC GRADIENTS**
- **RECALIBRATE DESIGN GUST LEVELS**

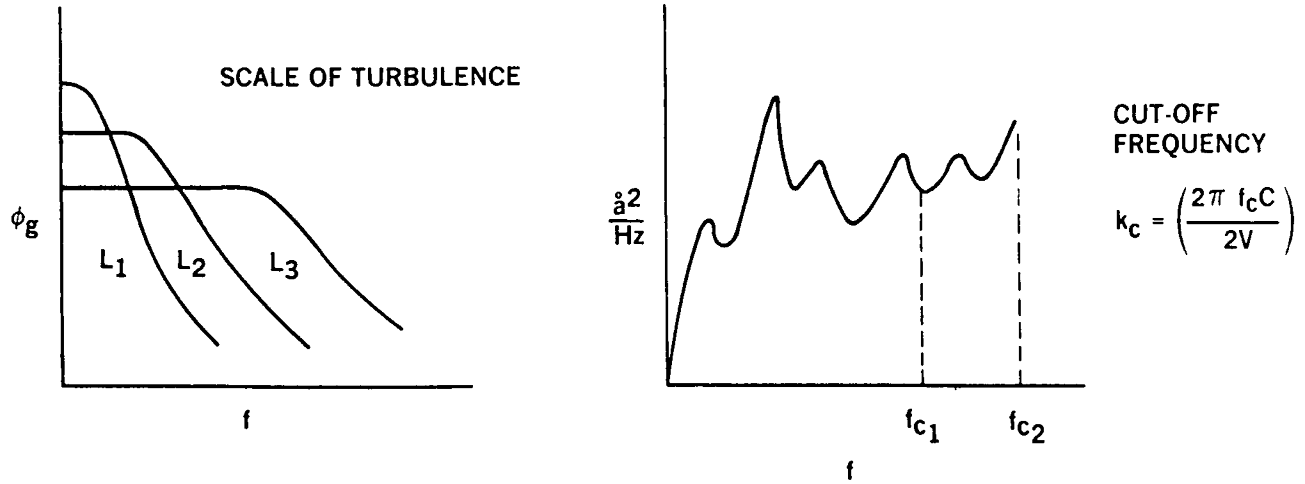
- **ACCOUNT FOR DATA ON MODERN AIRCRAFT**

Figure 16. Discrete gust--future.



- PSD GUST FOR DETERMINING DESIGN LOADS?
- MISSION VERSUS DESIGN ENVELOPE?

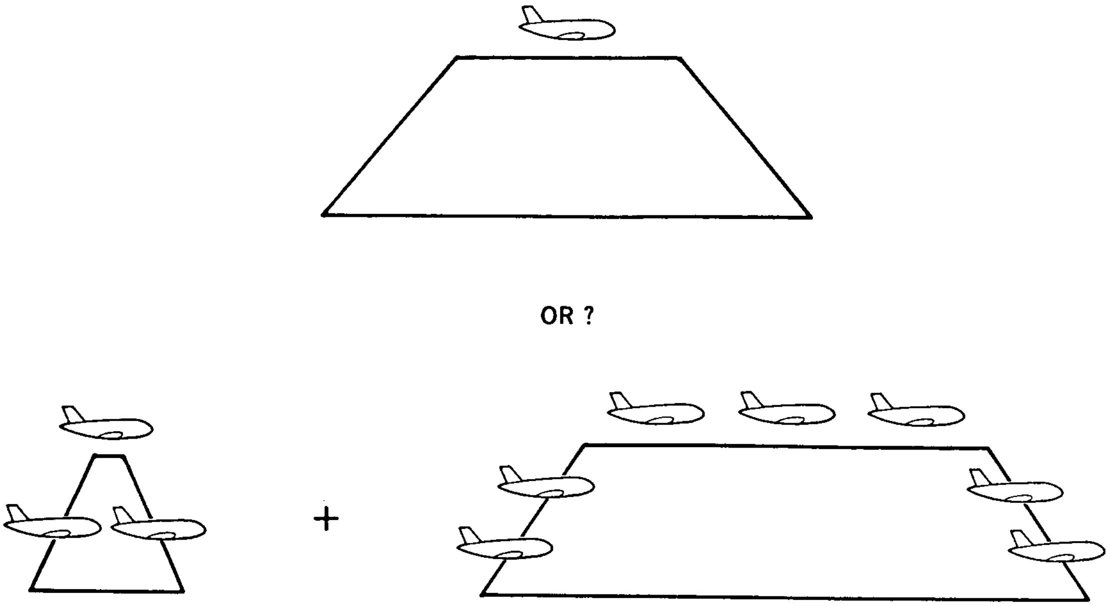
Figure 17. PSD gust--future.



- ISOLATED OR COMBINED VERTICAL-LATERAL GUSTS

Figure 18. PSD gust--standardization.

- MINIMUM STANDARDS FOR MISSION ANALYSIS



- SAME TURBULENCE FOR CONTROL AND STRUCTURAL ANALYSES

Figure 19. PSD gust--standardization.

$$N_{DL} = p_1 N_0 e^{-\left(\frac{L-L_{1G}}{\bar{A}b_1}\right)} + p_2 N_0 e^{-\left(\frac{L-L_{1G}}{\bar{A}b_2}\right)}$$

- RECALIBRATE p's AND b's
- RECALIBRATE DESIGN ENVELOPE DESIGN VELOCITIES
- RECALIBRATE N_{DL}

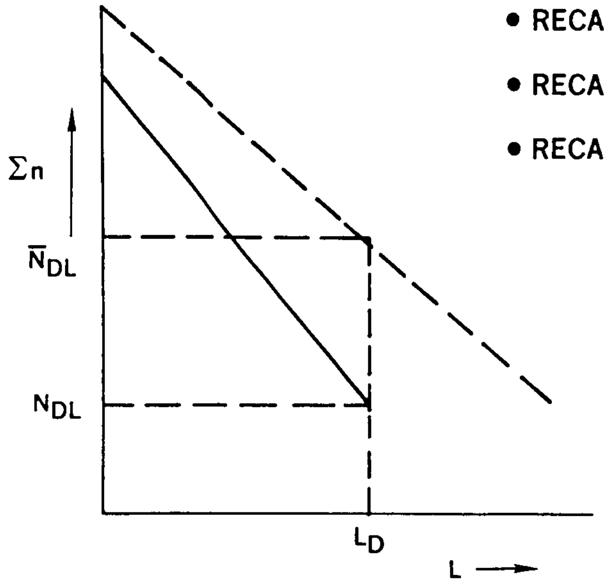


Figure 20. PSD gust--recalibration.

DESCRIBE GUST CHARACTERISTICS ABOVE 50,000 FT

ADEQUACY OF STREAMWISE GUST MODEL FOR LOW ALTITUDES

(b/L) WHERE 3-D EFFECTS BECOME IMPORTANT

Figure 21. Future--general.

N87-22345

TACTICAL MISSILE TURBULENCE PROBLEMS

Richard E. Dickson
U.S. Army Missile Command
Redstone Arsenal, Alabama

1. INTRODUCTION

Recently, the Missile Command acquired two new project offices: Remotely Piloted Vehicles (AQUILA) and Unmanned Aerial Vehicles. Usually, missile and rockets do not bank to turn so we are playing catch-up on winged vehicles.

Our usual bill of fare consists of free flight rockets and guided missiles. They range from direct fire systems to tactical ballistic missiles, with air defense thrown in for good measure.

Add to the above smart and dumb submunitions, and it is readily apparent that our interest is from the surface to the exoatmosphere. Of particular interest is atmospheric turbulence in the atmospheric boundary layer, since this affects both the launch and terminal phase of flight, and the total flight for direct fire systems.

2. ROCKET ARTILLERY BOOST WIND PROBLEMS

Rocket artillery, being unguided, is unable to correct for the effects of winds after launch. Cannon artillery is boosted in the tube, while rocket artillery is boosted outside the tube. When a rocket comes out of the launch tube it is moving rather slowly. Any crosswind will cause an aerodynamically stable rocket to cock into the crosswind; then the propulsion will drive the rocket upwind. All the wind has to do is turn the rocket; the propulsion does the rest. Most of this effect occurs in the rocket's first yaw wavelength, about 20 to 200 m, depending on the rocket's characteristics.

One technique to reduce this effect is to reduce the aerodynamic stability by delaying the opening of the fins till the rocket is going faster. Since neutrally stable rockets also have their problems, the time delay is chosen to trade off various error sources.

3. MEAN WIND CORRECTION

With tube artillery, a forward observer may adjust the fire onto the target. This is not practical for rocket artillery since the targets are deep in the enemy's territory. The Swiss company Contraves has developed the FIELDGUARD fire directing radar which is used by the Federal Republic of Germany (FRG) with their 110 m Light Artillery Rocket System (LARS).

The FIELDGUARD radar tracks three registration rounds to the target area and adjusts fire like a forward observer. Due to the time of flight of the rocket to the target, the FIELDGUARD can only reduce the effect of mean winds during boost and coast. Coast wind effects and wind effects after burnout are the same for rocket and cannon artillery.

4. TURBULENT BOOST WIND CORRECTION

The effects of turbulence during the first yaw wavelength are not corrected by FIELDGUARD. It has been proposed [1] that each round be tracked over the first yaw wavelength and this information then be used to correct the aiming of the next round. This is referred to as the Dynamically Aimed Free Flight Rocket (DAFFR) concept.

The coast wind effects could have already been determined by FIELDGUARD, or a MET message could be used as is done with tube artillery.

Of course, the ability of the DAFFR scheme to reduce the effects of turbulence during boost depends upon the correlation of turbulence over time [2,3] and the time between rounds.

The turbulence intensity which is a function of surface roughness can be quite large near the earth's surface. Cannon cockers like to fire from the tree line for concealment. The failure to consider surface roughness in the selection of rocket artillery launch sites could adversely affect system performance, particularly if that performance was determined in a benign turbulence environment. White Sands Missile Range could be considered a rather benign turbulence environment when compared with forested, mountainous, or urban regions of Europe.

5. THE DAFFR WIND FILTER

Assuming the longitudinal wind, u, is the sum of the mean wind, $\bar{u}$, and the turbulent wind, u', one has [2]:

$$u(t) = \bar{u} + u'(t)$$

The turbulent wind is related to its value at some previous time by [2]:

$$u'(t + \tau) = \rho(\tau)\, u'(t) + u''(t + \tau)$$

where ρ is the correlation coefficient for a time delay, τ, and u" is the random component of the turbulence. The variance of the random component is defined by the relationship [2]:

$$\sigma^2(u'') = \sigma^2(u')[1 - \rho^2(\tau)]$$

so that the turbulent energy is conserved with time.

With this wind model, it was possible to develop a discrete recursive filter, Figure 1. First, a discrete Kalman filter was developed and then the Kalman filter gains were simplified to a set of suboptimal gains (Figure 1).

The gain for the mean, 1/n, should be quite familiar. The gain for turbulence, (1 - 1/n), is reduced by epsilon to take into consideration the effects of the random component of the turbulence and measurement noise. Since the rocket is being used to sense the wind, its randomness constitutes measurement noise.

6. THE DAFFR TEST

The DAFFR concept, with a FIELDGUARD on loan from FRG, was demonstrated at Eglin Air Force Base, Florida, in the spring of 1983 and 1984.

Two equipment problems were encountered. The first was ionization in the rocket exhaust plume that attenuated the DAFFR radar signal to such an extent that tracking had to be delayed until after burnout. No tracking data were available during the first yaw wavelength. The second and more severe problem was the slowness of the "surplus" launcher drives to re-aim. The time between rounds was approximately 6 seconds while 2 to 3 seconds was desired.

Even at 6 seconds between rounds, some improvement (10 percent) was noted. More importantly, that improvement was in good agreement with the preflight prediction for a 6-second delay. It is hoped that with 2 or 3 seconds between rounds, a reduction of turbulence boost effects of 50 percent could be achieved.

An interesting adjoint to the test was Lockheed's Active Infrared Measurement (AIM), a laser Doppler velocimeter. Though used during the DAFFR test as range instrumentation to measure boost winds, Lockheed contends the AIM could be used to measure the wind prior to the launch of each round and correct aim based upon those measurements. There is no one best answer.

7. ROCKET WAKE TURBULENCE PROBLEMS

During boost, the exhaust plume forces the airflow around the rocket away from the rear of the rocket. This reduces the aerodynamic effectiveness of fins placed at the rear, thus reducing the stability.

Another problem of interest is wake interference. Following rockets cut across the exhaust plume of leading rockets if they are too close in space and time. The effect decays quite rapidly (in seconds) but it does limit how close together rockets may be fired. During the DAFFR test, Lockheed's AIM did sense the wake and its decay. The effect is not well understood.

8. CONCLUSIONS

Of course, many of the turbulence problems of rockets and missiles are common to those of aircraft, such as structural loading and control system design. This discussion has been primarily about a problem peculiar to free flight rockets, which has not been solved at this time.

Besides the correlation of turbulence over time, the correlation over space is also of interest. What relationship do measurements of wind at the launcher have to winds in front of the launcher? What effect does turbulence have on the impact angle of dumb submunitions?

Each new system will have new turbulence problems associated with it.

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1. McCorkle, Jr., W. C.; and Lilly, J. A.: An Adjusted Fire Technique for a Highly Accurate Free Flight Rocket Artillery System, U.S. Army Missile Command Technical Report RD-74-13, Redstone Arsenal, Ala., June 1974.

2. Hanna, S. R.: Some Statistics of Lagrangian and Eulerian Wind Fluctuations, *Journal of Applied Meteorology*, 18:518-525, April 1979.

3. Frost, W.; Long, B. H.; and Turner, R. E.: Engineering Handbook on the Atmospheric Environmental Guidelines for Use in Wind Turbine Generator Development, NASA TP-1359, Dec. 1978.

QUESTION: Warren Campbell (BDM Corporation). Can you tell me what the minimum range of the AIM Doppler lidar is? What is your first range gate?

ANSWER: I think the minimum range was just a few meters off the launcher, but I'd have to check. The range went out to 700 but we had lots of measurements in close and spread them out in a geometric progression because we were interested in the close-in effects. We kept doubling where the gates were as we went out. The first range gate was at 10 m.

CAMPBELL: I have just one comment: I don't know how you will ever get around the problems you have with trees. Of course, the fetch downstream where the internal boundary layer is developing is felt a long way downstream and that depends on where you are.

DICKSON: I have seen some work where it was as much as 400 m. One of my suggestions was that we get lawnmowers and chainsaws and go upwind and clear everything out. I might add one other thing, since you mentioned the LDV, we did see missile wake turbulence effects with the LDV. Of course, the AIM was using a conical scan and a Fast Fourier Transform. The missile wake turbulence just blew the AIM off the air, but when we went back to the raw data we could see the missile wake turbulence and its decay. We weren't instrumented or looking for it, but it was definitely there, and I see LDV's as tools for examining missile wake turbulence in addition to turbulence around airports and other things.

QUESTION: Bob Heffley (Manudyne Systems). I have one quick comment. There is an Army ECOM report circa 1966 (TR-ECOM-6019) which describes boundary layer profiles below tree lines and various kinds of vegetation. This was based on both wind tunnel and full scale measurements.

STATE:

$$\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_n = \begin{pmatrix}1 & 0\\ 0 & \rho\end{pmatrix}\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_{n-1} + \begin{pmatrix}0\\ U''\end{pmatrix}_n , \quad U''_n \sim N(0,\, q), \quad q = \sigma_{U'}^2(1-\rho^2)$$

OBSERVATION:

$$Z_n = (1,1)\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_n + V_n = U_n + V_n,\ Vn \sim N(0,\, r)$$

PREDICTION:

$$E\,(U)_n^- = (1,1)\,E\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_n^- = (1,1)\begin{pmatrix}1 & 0\\ 0 & \rho\end{pmatrix}E\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_{n-1}^+$$

FILTER:

$$E\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_n^+ = E\begin{pmatrix}\bar{U}\\ U'\end{pmatrix}_n^- + \begin{pmatrix}\frac{1}{n}\\ \left(1-\frac{1}{n}\right)\epsilon\end{pmatrix}\left[Z_n - E\,(U)_n^-\right]$$

$$\epsilon \simeq \frac{q}{q+r}$$

Figure 1. Discrete recursive filter.

N87-22346

REMOTE VERSUS IN SITU TURBULENCE MEASUREMENTS

Walter Frost
FWG Associates, Inc.
Tullahoma, Tennessee

Comparisons of in situ wind and turbulence measurements made with the NASA B-57 instrumented aircraft and those remotely made with both radar and lidar systems are presented. Turbulence measurements with a lidar or radar system as compared with those from an aircraft are the principal themes. However, some discussion of mean wind speed and direction measurements is presented.

First, the principle of measuring turbulence with Doppler lidar and radar is briefly and conceptually described. The comparisons with aircraft measurements are then discussed. Two studies in particular are addressed: One uses the JAWS Doppler radar data and the other uses data gathered both with the NASA Marshall Space Flight Center (NASA/MSFC) and the NOAA Wave Propagation Laboratory (NOAA/WPL) ground-based lidars. Finally, some conclusions and recommendations are made.

Figure 1 illustrates conceptually how Doppler radars and lidars measure winds. A pulse of microwave energy is transmitted into the atmosphere. The beam of energy spreads out in a conical manner. The transmitted signal is scattered back to a receiver by raindrops or, in clear air, by aerosols, bugs, or other materials which scatter back the signal. The signal is then recorded and processed. The volume element in space which the radar probes is conical in shape. It gets bigger as it moves out. The length of the volume element for a pulsed radar or lidar system is equal to the speed of sound, c, times the pulse duration, τ, divided by 2. Each volume element is called a range gate. There are several range gates that extend outward in space until the transmitted signal is too weak for further radiation to be scattered to the receiver. Typically τ is 1 µs, and with the speed of light being 300,000 m/s the range gate length is 150 m long. The length varies based on the system capabilities, and for lidars it is often 300 m long. Therefore, it is quite a long volume in space that the system interrogates. The lateral spread of the beam, d, depends on the divergence angle, θ, and the distance from the transmitter. The diameter of the volume element is thus variable becoming larger further from the transmitter. For radar the spread rate may be on the order of 17 m/km.

The signal scattered back to the receiver is from those particles which are within the volume element. The particles are assumed to move in equilibrium with the air and thus at the mean wind speed. Of course, due to turbulence and wind shear across the volume element, the particles will also be relative to one another.

The radar system signal processor records the Doppler frequency shift due to the velocity component of the particles away from or toward the receiver. The Doppler frequency is then related to each individual particle motion by the relationship $f_d = -2v_{ri}/\lambda$ where v_{ri} is the velocity component of the ith particle along the direction of the beam (i.e., the radial velocity component). The mean wind is essentially the average of the sum of all these motions. The subscript r in Figure 1 denotes the radial component either toward or away from the radar.

The processed signal of the Doppler frequency shift due to each particle is idealized as having a Gaussian shape. Thus, the signal represents a frequency spectrum. If the majority of the particles are moving with the mean air motion, then the most energy is scattered at the value of the mean Doppler shift frequency, f_d (see Figure 1). The mean frequency shift is then correlated with the mean velocity. Due to the fact that the particles are also moving randomly relative to one another because of the turbulence and other air motions, there is a spreading of the energy associated with the f_d. Thus, different amounts of energy are associated with different frequencies depending on how the particles are moving relative to each other. If you assume the signal is Gaussianly distributed, then a standard deviation (called the pulse standard deviation), σ_p (see Figure 1), can be defined and, in principle, is a measure of the chaotic motion due to turbulence within the volume element being sampled. Thus, the standard deviation of the Gaussian distribution or the spectral width of the return signal should be a measure of the atmospheric turbulence.

A pulsed lidar works on the same principle. A typical Doppler frequency shift spectrum from a lidar is shown in Figure 2. In practice, the signal does not have the nice Gaussian distribution that is assumed and generally several pulse signals are averaged to get meaningful results. If the pulse repetition is 100 cycles/sec and ten pulse returns are averaged, a 10 millisecond average measure of the wind is obtained.

Thus, with a radar or lidar measurement you are averaging the wind both spatially and with time which could be 0.5 to 2 seconds depending on how many pulses are averaged to obtain a good strong return. The beam spreading of a lidar is much smaller than that of a radar. The lidar signal at most spreads about 1 m for the range achievable. In effect, the spatial volume sensed by a lidar can be considered as a pencil line approximately 100 to 300 m long.

The spreading or spectral width of the time average signal for the lidar is also a measure of turbulence, i.e., the pulse standard deviation, σ_p. In turn, a time history of 0.5 to 2 seconds averaged wind speeds can be plotted from the lidar data as illustrated in Figure 2. From this time history, a standard deviation of the wind, σ_w, can be computed by conventional techniques. Thus, two standard deviations will be discussed; one is σ_p which represents the second moment or spectral width of the Doppler frequency lidar signal distribution and the other one is σ_w which is calculated as illustrated by the equation in Figure 2. Both measurements remember are turbulence averages over a relatively large spatial region in space due to the volume resolution of the radar or lidar.

Figure 3 is a sketch (approximately to scale) of a typical volume element that is 5 km from the transmitter at which point the volume element is 150 m long and 85 m in diameter. The size of a B-57 type aircraft relative to volume element is illustrated. The radar volume element overwhelmingly engulfs the entire aircraft. In turn, the lidar beam is more like a line through space, 300 m long.

To compare the aircraft measurement of turbulence, which is effectively a point measurement, with Doppler radar or lidar, you must fly along the beam and compare the data measured in each range gate with that measured by the aircraft while it is in or next to that portion of the beam (see Figure 4). The aircraft measurement is essentially the turbulence measured point by point along a line of flight. The different sampling volumes cause some problems in interpreting what turbulence is actually being compared. The aircraft turbulence intensity will, in general, be small because we compare measurements only for the period of time when the aircraft is "beside" the individual range gates. The time for an aircraft to travel the length of a range gate is about 1.5 to 2 seconds. Thus, when we compute the mean for each 1.5 to 2 second turbulence record, the mean is really turbulence itself. Turbulence intensities defined in this manner will be small compared to values computed typically from 45-minute to one-hour records normally reported in the literature.

In considering the pulse volume standard deviation, there are physical factors other than turbulence, which will cause the second moment of the Doppler signal frequency spectrum to broaden. Figure 4 lists four factors which cause spectral broadening. Various correction factors are also shown in the figure.

If there is a gradient in mean wind (i.e., wind shear) across the volume element, spectral broadening will occur. The magnitude of spectral broadening due to wind shear is estimated by the expression for σ_s in Figure 5.

There will be spectral broadening due to the fact that the radar is generally scanning. As the radar beam moves through space, spectral broadening occurs. Finally, there is spectral broadening from raindrops having different fall rates. The value of σ_t is of interest to our study. Therefore, it is necessary to correct the overall pulse spectral width, σ_p, by subtracting σ_s, σ_α, and σ_d. The radar data have been corrected in this paper, but the lidar data have not. At the bottom of Figure 5 you can again see the definition of the wind standard deviation as contrasted to the pulse standard deviation at the top of the figure.

First, some of the comparisons of aircraft data with Doppler-radar-measured turbulence are presented. Second-moment data from JAWS are used. Three cases are considered. During the JAWS Project in Colorado, three Doppler radars were used to measure the wind field throughout a huge volume in space. The location of these volumes is shown in Figure 6. The volumes are typically 2 km high and their areal extent is as illustrated in the figure. For the July 14 case, the region indicated on the figure was probed with both the CP-2 and CP-4 radars located as shown. Velocities from two directions for an overlapping volume in space were available from this experiment. During the JAWS Project, the NASA B-57 aircraft was flown in the experiment region to gather data on gust gradient across the wing span, which is described in Murrow's paper [1]. Although we were principally gathering data relatively to gust gradients, the opportunity to use the data for comparisons with Doppler radar turbulence measurements is a fringe benefit. Unfortunately, the only time flights actually coincided with the particular dual Doppler measurement was for the July 14 case. The problem we encountered in trying to operate the aircraft during the JAWS Project was that the JAWS experimental region encompassed Stapleton International Airport, Denver, Colorado. If there was any interesting weather like microbursts or thunderstorm activity, the aircraft was vectored out of that region because of traffic control problems. We, therefore, never really got the opportunity to fly repeatedly where the Doppler radar was probing a region that contained the aircraft flight path.

The July 14 case is the best data set available. For this case, three runs, Runs 23, 24, and 25, from Flight 6, as shown on Figure 7, were available where the aircraft flew through or close to the region the radar was scanning at that moment. Run 23 occurred slightly before the Doppler measurement was made. Run 24 corresponds exactly with the time the measurement was made. Run 25 also corresponds in time with the Doppler radar measurement but it is somewhat outside the radar volume element.

Characteristics of the flight path for Run 24, Flight 6, are shown in Figure 8. The flight occurred at approximately 6500 ft altitude which is about 500 to 600 ft above the terrain. The terrain was relatively uniform. The aircraft was flying in the direction indicated in the upper right-hand corner of the figure. A strong tailwind was encountered during this particular phase of the flight as shown by the arrows which represent one-second average horizontal wind vectors along the flight path during the run.

Figure 9 shows the results of the comparison of the turbulence measurements. The crosses are the second-moment data from the radar at each volume element or range gate. Strictly speaking, it is not exactly the value in each volume element. The data we used was provided to us by NCAR. The σ_p values were interpolated to a 200 m square grid system from the initial radial wind speed data. The zero's on the figure are the wind standard deviation, σ_w, which we calculated from the radar data from the formula given in Figure 7. The symbols *, L, and V are longitudinal, lateral, and vertical (relative to the aircraft) turbulence standard deviations. The aircraft measurements, in general, correspond with the wind standard deviation values. Notice that the values are low compared with normally reported values. This is because each σ represents the standard deviation about a spatial mean for the 150 m section of wind corresponding to the range gate or volume element through which the airplane flies.

The pulse volume standard deviation, σ_p, is higher than the other values by at least a factor of 2. The reason for this is not fully understood at this time. If the standard deviation for the three velocity components are computed from the total time history (87 seconds) while the airplane flies the entire length of the flight path for the July 14 case (i.e., not just through each range gate) and if the square root of the turbulence kinetic energy is taken as an effective value of σ, good agreement with the radar pulse standard deviation is achieved. I am not sure as of yet how to interpret this. Jean Lee from NOAA/NSSL compares dissipation rates, which are a measure of turbulence kinetic energy with their Doppler radar second-moment measurements.

Figure 10 offers an explanation of possibly why there is a major difference between radar turbulence and aircraft-measured turbulence. When you measure turbulence with an aircraft, even if you go right through the radar volume element, you are basically making point measurements along a line, say path A in the figure. There is some mean wind speed along that line in space during the period required to fly the path. The aircraft turbulence intensity reported here is the fluctuations about that particular mean. If we flew through another part of the volume element, say along path B, you might see quite a different mean wind speed or distribution about that mean for the short period of time required to fly along the path. The second-moment data from the radar, on the other hand, is an effective total spatial average throughout the entire volume element. The radar measurement is representative of the turbulence within that volume element because it is a spatial measurement. If we had a long enough time record and Taylor's hypothesis is valid, the aircraft measurement should, in principle, give the same result. The time records we are working with, however, are very short and work needs to be done to learn how to handle non-stationary turbulence resulting from sampling over very short times or regions of space.

Next, the Doppler lidar turbulence meaurements are addressed. Three studies have been carried out. The February 7 and 9 study is described here. This study was funded by NASA Goddard and carried out at Boulder, Colorado. Two things were of interest: (1) Measuring turbulence flux parameters relative to mountain-induced flows and (2) making comparisons with the NOAA/WPL ground-based lidar. Again, the NASA B-57 aircraft was used; the program was a joint effort between NASA Goddard (who provided the funds), NASA Langley (who reduced the data), NASA Dryden (who operated the aircraft), and NASA Marshall (who directed the program).

The flight patterns flown during the lidar comparison test are shown on Figure 11. The NOAA/WPL lidar was set up on Table Mountain. Interest was in turbulence due to winds blowing over the mountains and parallel to the mountains, respectively. The lidar beam was directed at approximately 4.5° elevation and 200° azimuth and an approach was made along this trajectory. The aircraft would then make a turn and at the same time the lidar beam was rotated to a 290° azimuth at the same 4.5° elevation. The aircraft would then climb out along that line of sight. Our intent was to make enough flights along each trajectory to do ensemble averaging. Turbulence in the boundary layer is not homogeneous, particularly over or in the vicinity of mountains. Several samples of turbulence corresponding to each range gate (roughly 300 m) was needed in order to analyze the data by ensemble averaging techniques. Roughly ten samples for each 300 m increment in space is needed. Ensemble statistical analysis can then be carried out with the data. That was the plan. However, Doppler lidar data of the time resolution needed was not recorded at corresponding times with flights as frequently as planned. Thus, we had a limited data set.

Figure 12 is a cross section in space of the lidar beam path relative to the terrain for the 4.5° elevation and 290° azimuth orientation. Each vertical line represents a range gate (300 m long). Data were taken at 0.5 seconds, i.e., pulsing 12 times per second and averaging six pulse returns. The vectors plotted along vertical lines are the time histories of 0.5-second averaged wind speeds. The vector length represents the magnitude of the wind speed and time is plotted in the vertical direction. In this particular case, the wind was getting stronger with time. The arrowheads show that there is a reverse flow over this mountain which is interesting. The wind is blowing toward the left-hand side of the figure in the upper range gates and is blowing to the right-hand side in the lower range gates. The flow pattern corresponds to a wake region such as readily observed in laboratory studies. Mountain flows obviously have flow separation regions as can be seen in these data.

Tables 1 and 2 list the data sets analyzed. The plan was to obtain eight to ten runs along each lidar beam so we could do ensemble averaging. However, we only got six for February 7 and four for February 9. In principle, to do ensemble statistics these are not enough records. However, if that is all the data you have, then you try to do the best you can.

Figures 13 and 14 show results from the February 7 and February 9 data sets. Mean wind speed (average wind speed for the period of time the aircraft is in that 300 m volume element) is compared with the time history from the radar signal for that same period of time in the left-hand side figures. There's general agreement here which we think is very good. You cannot expect one to one agreement since it is impossible to fly the aircraft directly along the beam. Moreover, because of the presence of the mountains, which can block or shed the wind, not measuring the wind at exactly the same region in space can cause large differences. Note also that because of the short averaging times of 1.5 to 3 seconds, the reported wind speed, are in themselves low-frequency turbulence.

The difference between Doppler mean winds and aircraft mean winds was on the order of 2 m/s. There are several other factors besides terrain effects and large-scale turbulence that could contribute to these differences. The inertial navigation system has a Schuler drift. If you are on the high side of the Schuler oscillation you can easily be 2 m/s off in inertial velocity. Also, one of the problems we were having with the lidar during this test was the pulse transmission frequency was varying slightly which would give a velocity error relative to the reference frequency. The right-hand side of that figure shows the measured turbulence intensity. A "*" designates aircraft-measured turbulence defined as previously described and a "+" designates the lidar spectral width turbulence. We did not take the wind shear out of the lidar data, and you will notice this right away. There is a very pronounced peak in the pulse volume data at corresponding positions of wind shear.

As with the radar data, the second moment data are roughly a factor of 2 greater than the aircraft data and the wind standard deviation data. I did not expect the lidar results to be a factor of 2 or 3 higher than the aircraft data because the beam from the lidar is at most 1 m thick in conical shape. Thus, the spatial volume sampled is small compared to the Doppler radar, which can have a sampling volume greater than 85 m in thickness. An explanation as to why the second-moment or spectral broadening of the lidar data are so much larger than the aircraft measurements is not presently clear.

Figure 15 shows turbulence spectra computed from the data. There is quite a bit of scatter in these data because of ensemble averaging of only a limited number of runs. The "*" represents the turbulence spectrum calculated using the aircraft data. The open circles are the spectra computed from the lidar data. In general, these agree pretty much with one another over the region where they overlap. The lidar is actually 0.5-second averages. With 0.5-second data, the maximum frequency that can be resolved is 1 Hz. The lidar data then have a frequency range from 1 Hz to about 0.01 Hz whereas the aircraft data, where we were sampling 40 times per second, range from 20 Hz to about 0.04 Hz. Typically, the computed spectrum follow roughly a -5/3 slope.

Preliminary conclusions are that lidar- and radar-measured winds generally agree with the aircraft-measured winds. Differences in agreement could be due to problems with comparing spatial and temporal data, Schuler drift in the INS system or to variation in the pulse transmission frequencies from the lidar system.

Not only does the magnitude of the winds agree reasonably well but also the profile shapes, in general, correspond. Other results from the NASA/MSFC lidar that are even better than these are available because at Marshall we made eight to ten runs with which we could carry out ensemble averaging. The results look quite a bit better. It is also concluded that the wind standard deviation turbulence intensity and aircraft standard deviations are in good agreement. This conclusion is based on the fact that the intensity is the correct order of magnitude and the spectrum overlap a -5/3 slope and follow. Maybe good agreement is too strong, but they are in agreement.

The spectral width or second-moment data which come directly from the radar or lidar signal is about two or three times larger than the aircraft measurement for both the lidar and radar. The reasons may be due to the fact that the radar is looking at a very large volume and the turbulence is a spatial measurement whereas the airplane is sampling along a line in space. Study is required, however, to resolve this difference. The variation of the spatial width standard deviation with height is very similar to the wind standard deviation and aircraft standard deviation values.

Recommendations are to plan and carry out research to fully resolve the issue of turbulence measurements with lidar and radar to establish a physical understanding of the temporal and spatial resolution of the turbulence data measured. There needs to be work done, although I understand there is work being done by the USAF/Geophysics Lab and NOAA/NSSL, in developing algorithms for operationally predicting or forecasting turbulence. Finally, I see great hope for the use of Doppler radar and lidar in numerical forecasting. If the point is ever reached where turbulence flux models are incorporated into these computational techniques and they are updated periodically with measurements, as currently done for wind speed and direction, it would be very useful to develop a scanning method using the Doppler lidar or radar which would provide measured momentum flux and perhaps heat and mass flux, also. The flux models in the numerical codes could then be updated routinely with actual measurements.

Reference

1. Murrow, Harold N.: Measurements of Atmospheric Turbulence, NASA CP-2468, pp. 73-92, 1987.

COMMENT: C. M. Tchen (City College of New York). It is found in atmospheric turbulence that the energy spectrum does not necessarily follow the Kolmogoroff -5/3 law, but it is often modified into the -1 law by wind shear. I noticed that your data in strong wind shear also show a milder slope than the -5/3 slope. The -1 spectrum can be broadened by the presence of rain or snow because of the added air-particle interaction. The recent turbulence measurements in the atmospheric surface layer in Scandinavian and the Russian laser measurements in atmospheric precipitation show this deviation from the Kolmogoroff law.

FROST: How were those measurements made?

TCHEN: The ORESUND Experiments 1985 by the northern European countries measured the atmospheric turbulence by means of a variety of instrumentations: hot-wire anemometers, cup anemometers, Doppler sodars, radiosonde microwave radiometers, and balloons. The Russian experiments measured the atmospheric turbulence in precipitation by means of laser intensity fluctuations.

QUESTION: Dave Emmitt (Simpson Weather Associates). Due to the length-to-diameter ratio of the lidar beam, at Marshall we tried to look at the difference in interpretation when we looked downwind versus crosswind with our beam and found there was some difference. You were looking at 200° and 290°. Did you detect any difference in trying to interpret data for those two directions?

FROST: We didn't look specifically at that problem but, if the effect was present, it was not obvious.

QUESTION: Bob McClatchey (AFGL). You didn't say much about clouds and precipitation in your comments. Lidar can't see through clouds and precipitation; radar has the hope of doing that. It wasn't obvious either whether the radars that were used in the Colorado experiment were looking at hydrometeors or whether they were looking at clear air and index of refraction changes. Can you comment on that, and whether in that context you conceive of a dual system involving both radar and lidar to really look at the whole regime? What's the maximum altitude range you can get with such ground-based systems.

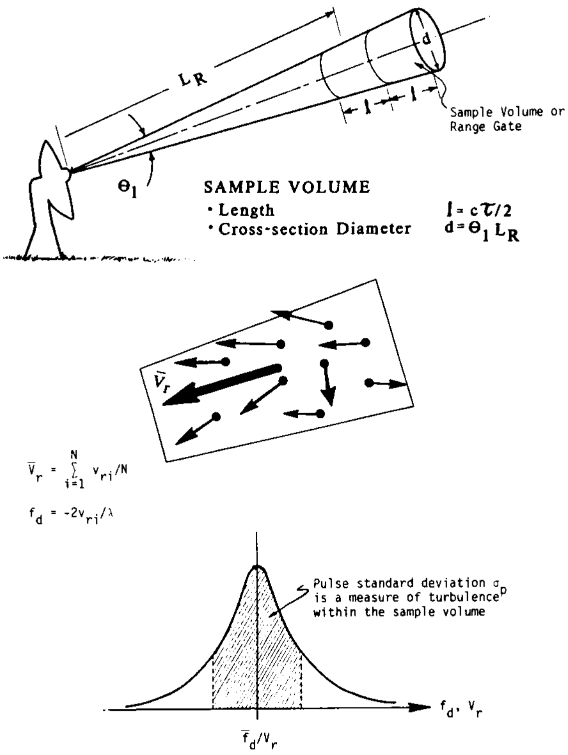
FROST: There was no rain or clouds in any of our experiments. The radar returns for the data we looked at were clear-air returns. As you say, the radar does look through the clouds and the lidar will not. If there is any cloud cover, then your measurements are basically limited to the elevation of the cloud cover with the lidar system.

TABLE 1. Selected Runs of the February 7 Test.

B-57B Aircraft Data			NOAA Lidar Data		
Run No.	Azimuth Angle	Sampling Time (MST) Start to End	PRF (Hz)	Number of Pulse Average	Sampling Time (MST) Start to End
2	290	11:46:42-11:49:19	12	6	11:46:53-11:49:04
3	200	11:56:42-12:00:27	12	6	11:57:59-12:00:06
4	290	12:02:03-12:03:59	12	6	12:00:50-12:02:55
5	200	12:12:01-12:15:56	12	6	12:12:17-12:16:41
6	290	12:17:48-12:21:29	12	6	12:16:43-12:19:50
7	200	12:27:51-12:31:49	12	6	12:27-00-12:29:35

TABLE 2. Selected Runs of the February 9 Test.

B-57B Aircraft Data			NOAA Lidar Data		
Run No.	Azimuth Angle	Sampling Time (MST) Start to End	PRF (Hz)	Number of Pulse Average	Sampling Time (MST) Start to End
9	200	12:14:06-12:17:45	12	48	12:13:39-12:17:23
10	290	12:19:30-12:23:09	12	24	12:17:45-12:22:13
11	200	12:28:05-12:31:43	12	24	12:28:49-12:30:53
12	290	12:33:25-12:37:09	12	24	12:33:47-12:36:49

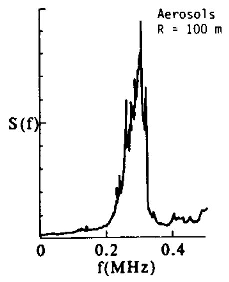


$$\bar{V}_r = \sum_{i=1}^{N} v_{ri}/N$$

$$f_d = -2v_{ri}/\lambda$$

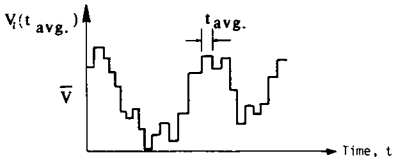
Figure 1. Doppler radar.

LIDAR SIGNAL SPECTRUM



SEVERAL SPECTRA ARE AVERAGED TO GIVE THE MEAN WIND SPEED AND SPECTRAL WIDTH. TYPICAL AVERAGING TIMES ARE 0.5 to 2 SECONDS.

TIME HISTORY OF RADIAL VELOCITY



WIND STANDARD DEVIATION

$$\sigma_w = \sum_{i=1}^{N} (V_i(t_{avg}) - \bar{V})/N$$

Figure 2. Lidar signal.

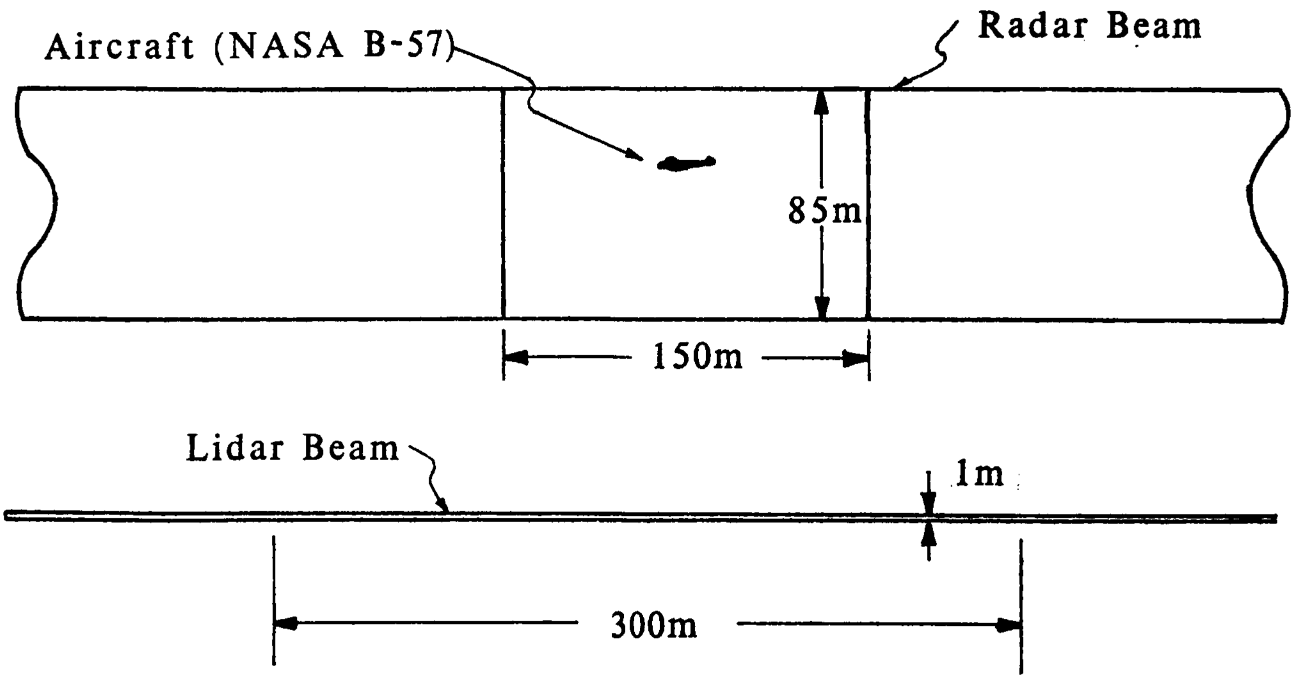


Figure 3. Sketch of relative sizes of aircraft, radar beam, and lidar beam. Scale 1 in = 50 m.

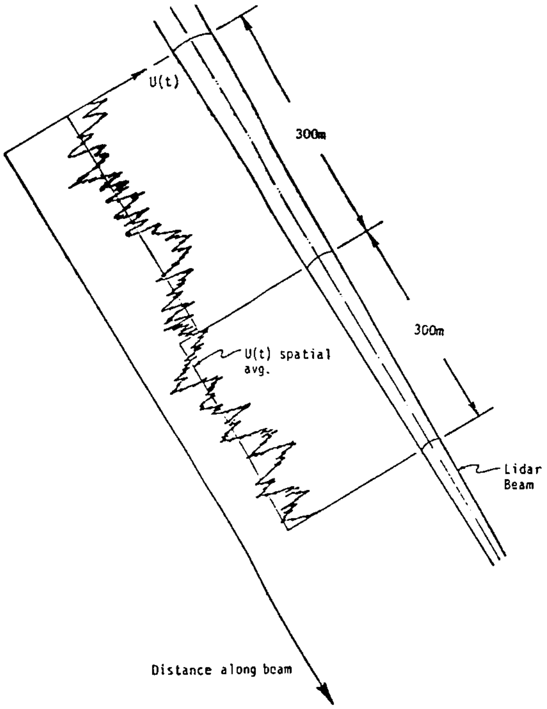


Figure 4. Aircraft measures turbulence along a line in space as compared to a lidar or radar which measures a spatial averaged turbulence in a conical volume element.

PULSE SD

- $\sigma_p = (\sigma_s^2 + \sigma_t^2 + \sigma_\alpha^2 + \sigma_d^2)^{1/2}$ in a pulse volume

where

σ_s = broadening due to radial wind shear

$= [(\sigma_r K_r)^2 + (R_o \sigma_\theta K_\theta)^2 + (R_o \sigma_\phi K_\phi)^2]^{1/2}$

σ_t = turbulence intensity

σ_α = broadening due to antenna motion

$= (\alpha\lambda \cos \theta_e / 2\pi\theta_1)\sqrt{\ell n 2}$

σ_d = contribution of different speeds of fall for various sized drops

$= \sigma_{do} \sin \theta_e$

$\sigma_\theta^2 = \sigma_\phi^2 = \theta_1/(16 \ell n 2)$

$\sigma_r^2 = (0.35\, c\tau/2)^2$

WIND SD

- $\sigma_w = \left(\frac{1}{N}\Sigma(V_r^2 - \overline{V_r^2})\right)^{1/2}$ in a grid volume (200 m x 200 m x 200 m)

Figure 5. Turbulence intensity.

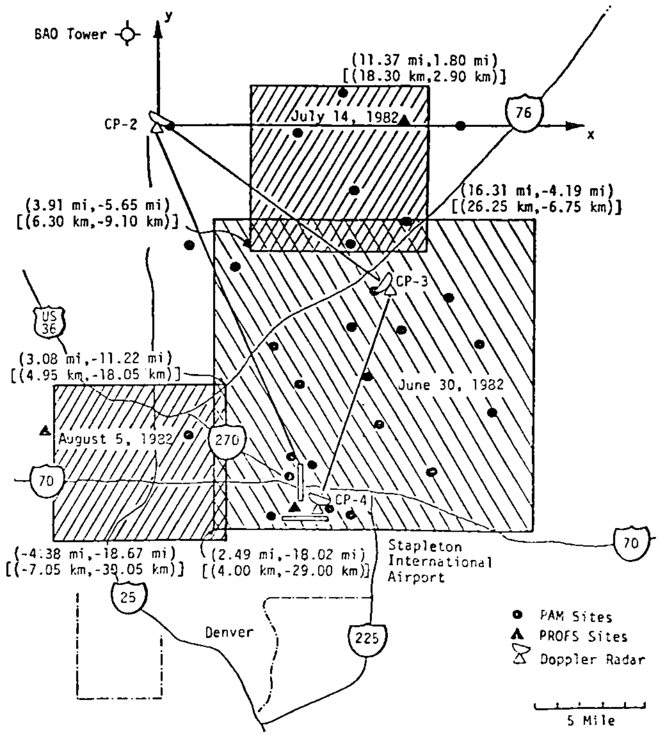


Figure 6. Location of spatial region for which JAWS data are available.

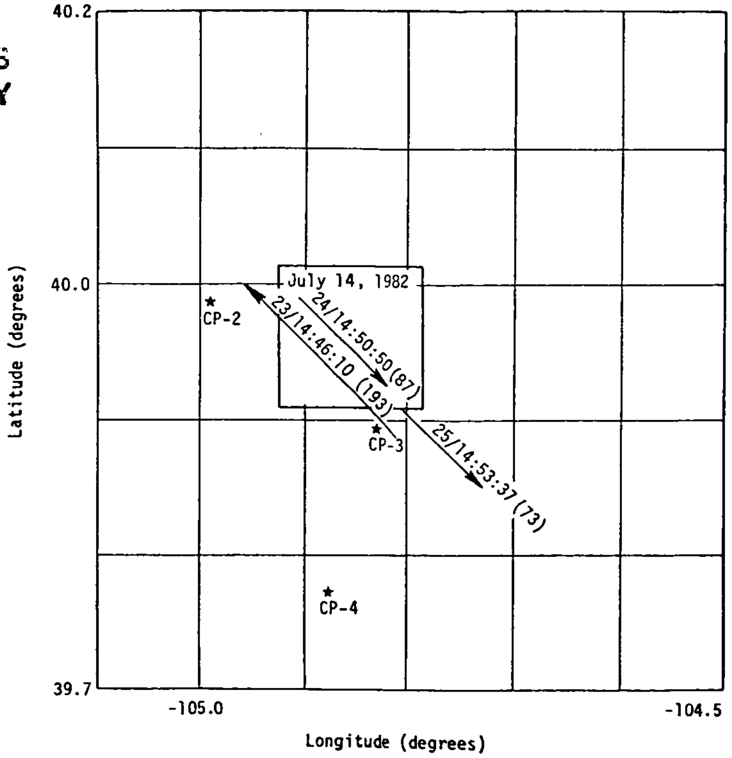


Figure 7. Relative positions of the JAWS July 14, 1982, microburst and the flight paths of Runs 23, 24, and 25 in Flight 6 of NASA B-57B aircraft.

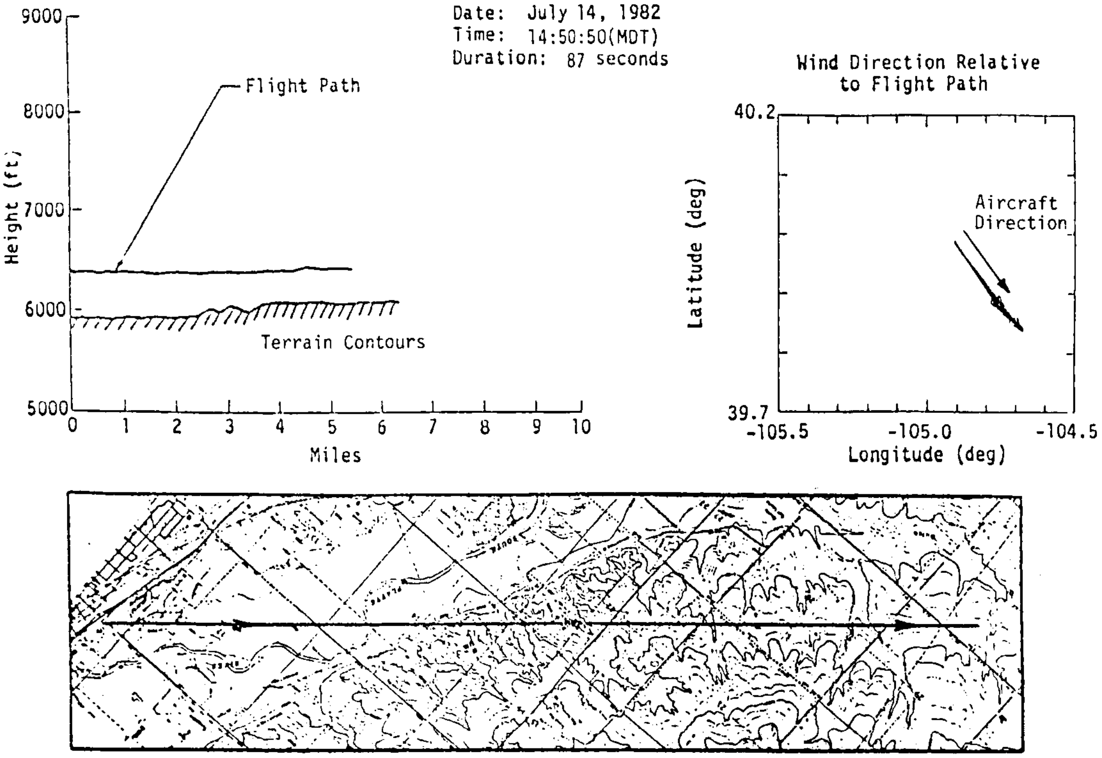


Figure 8. Flight path information: Flight 6, Run 24.

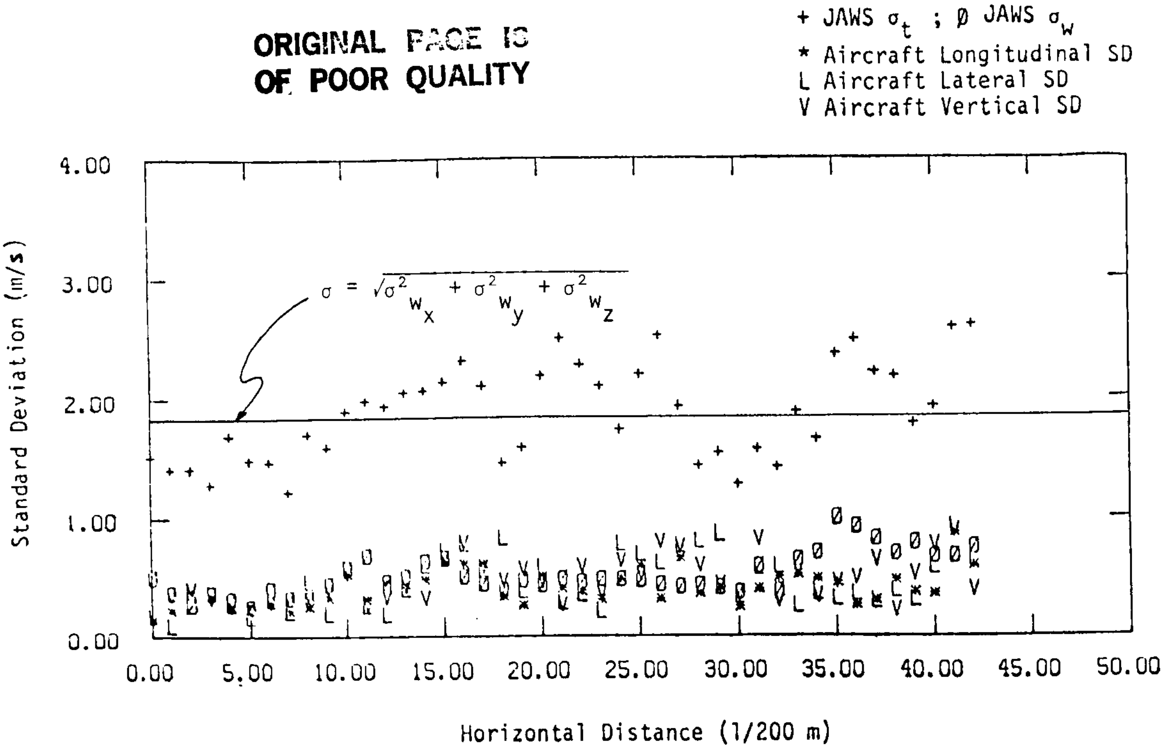


Figure 9. Comparison of σ_t with calculated turbulence intensities from NASA B-57B measurement (Run 24).

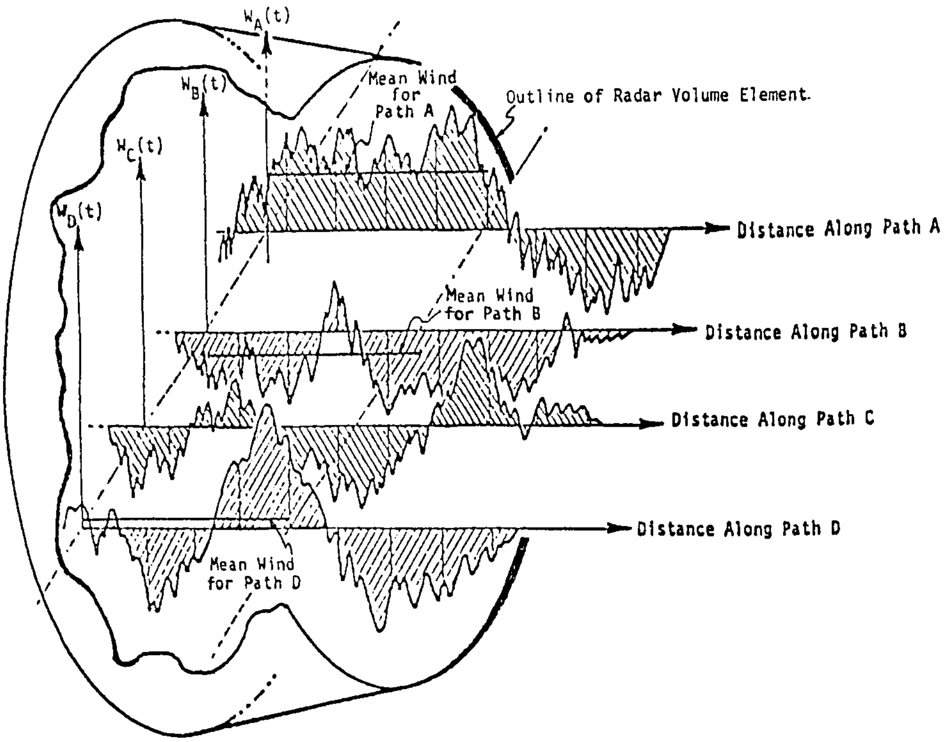


Figure 10. Schematic illustration of spatial extent of turbulence measurements from an aircraft and from a radar.

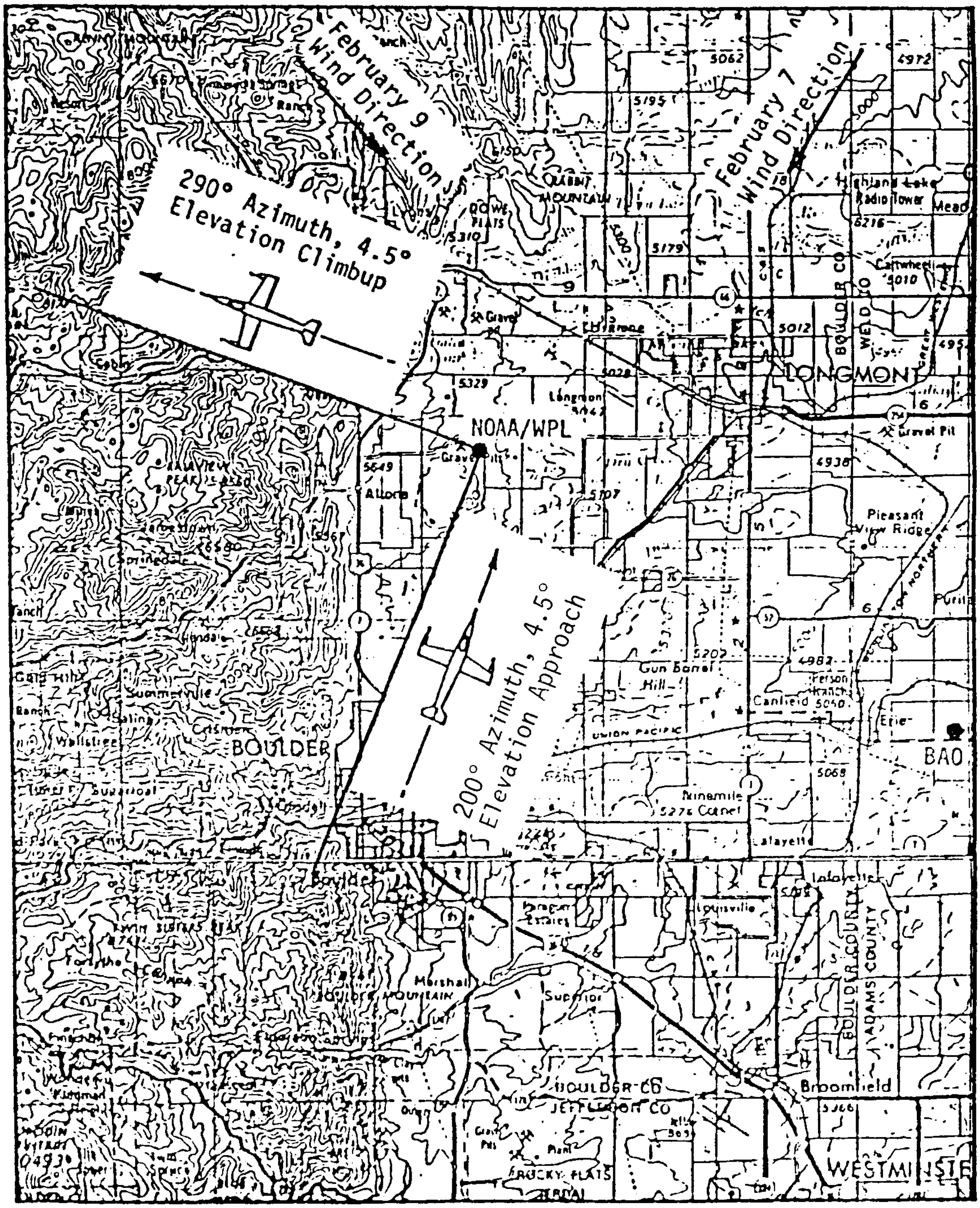


Figure 11. Flight paths relative to the lidar beam at 200° and 290° azimuth, respectively, at Boulder, Colorado, February 7 and 9, 1984.

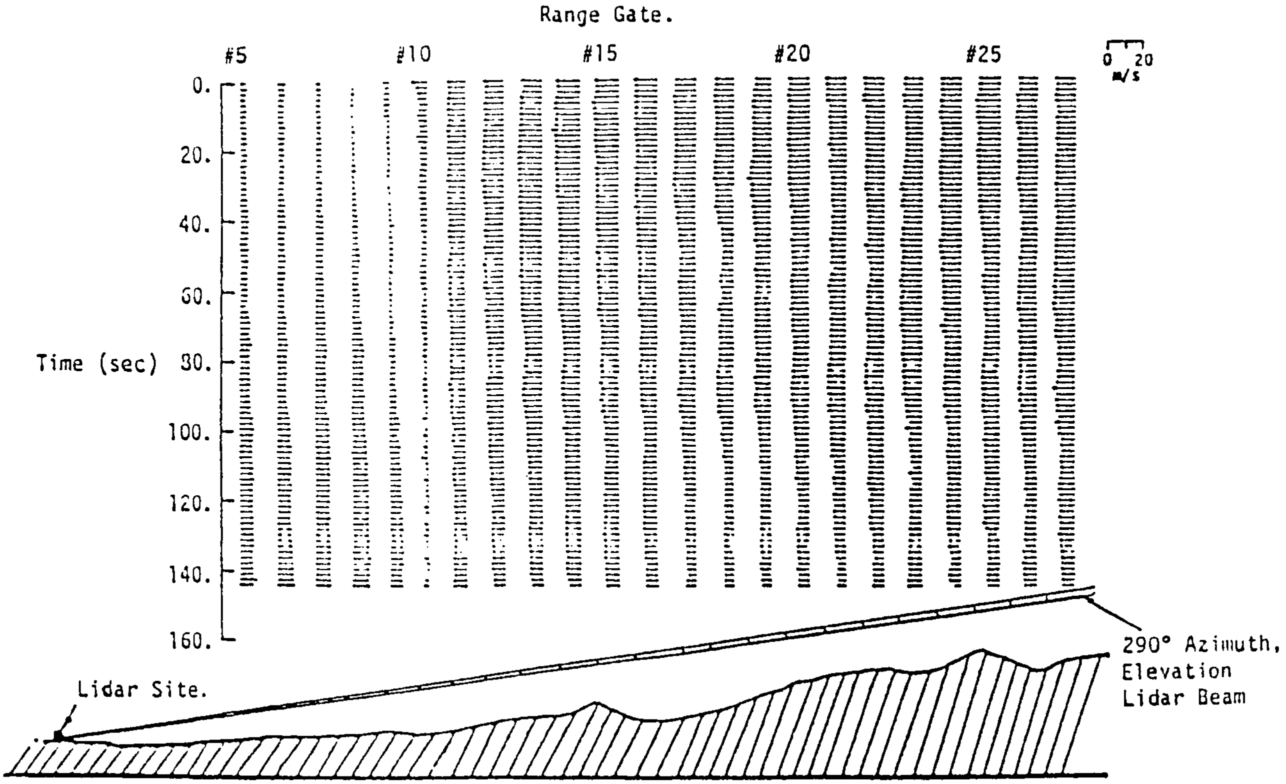


Figure 12. Time history of lidar-measured wind vector at 290° azimuth, 4.5° elevation relative to the terrain on February 9, 1984, Boulder, Colorado.

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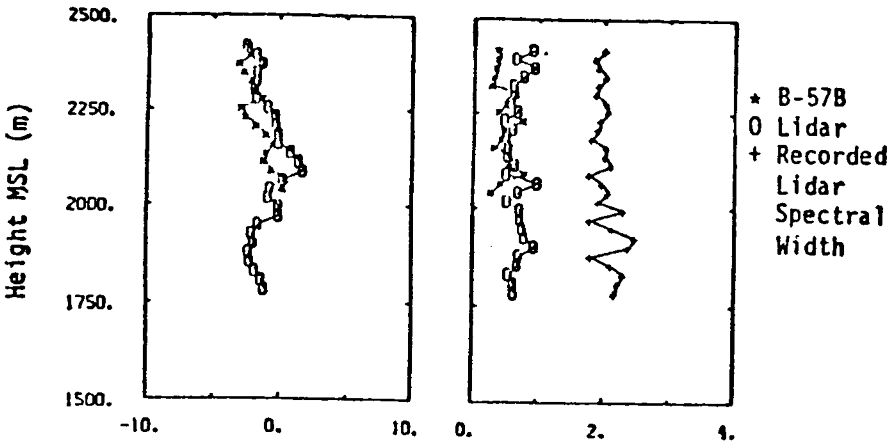
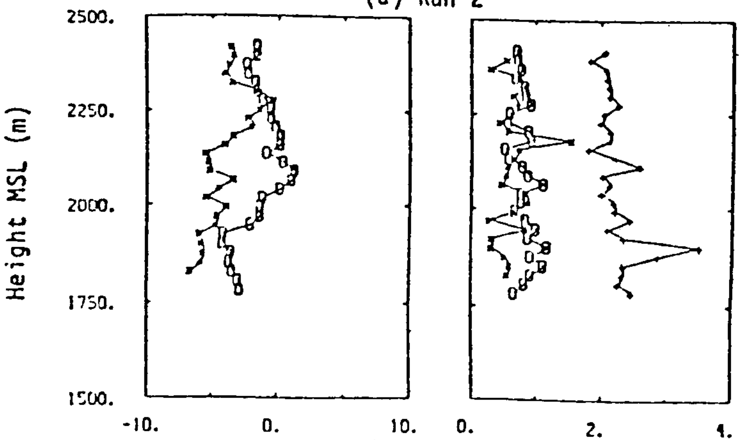
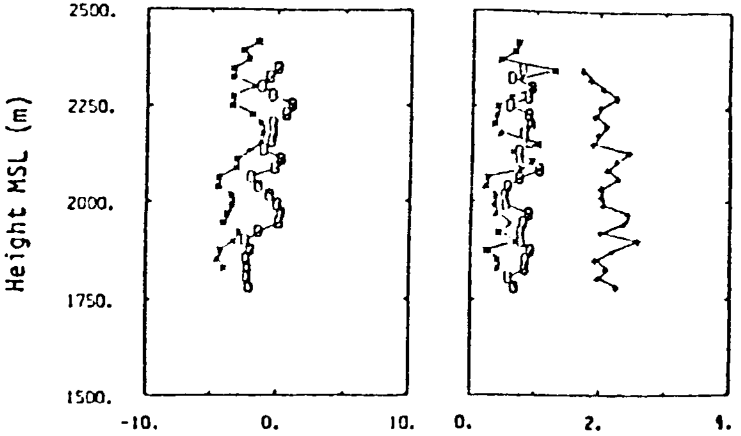


(a) Run 2

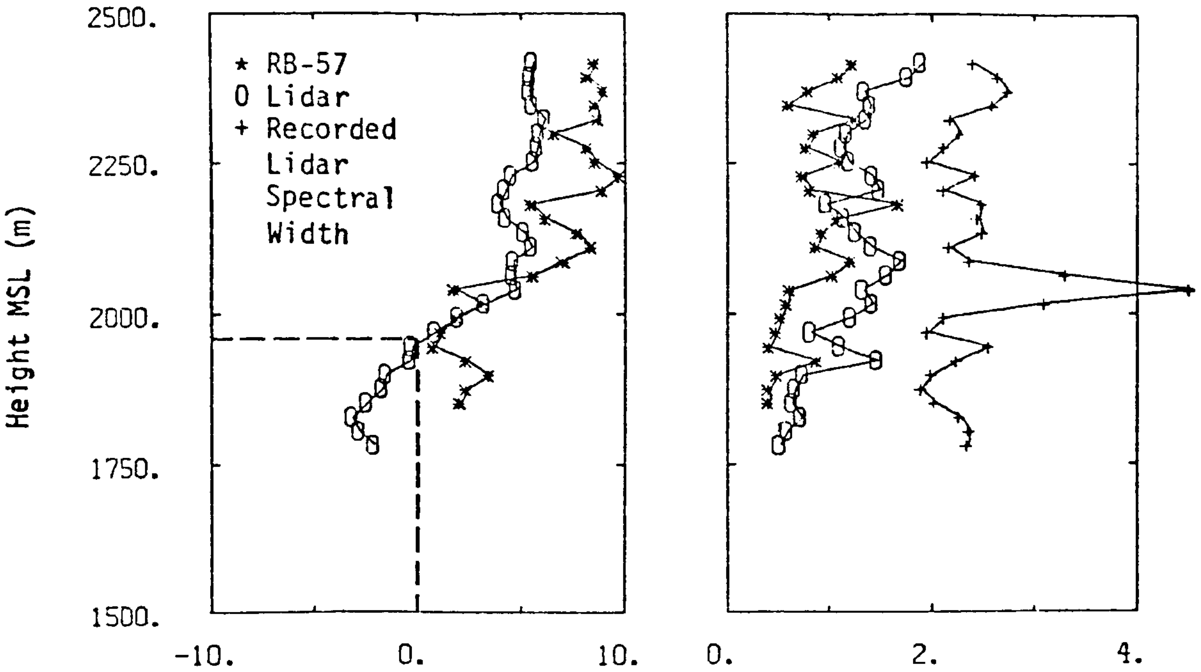


(b) Run 4

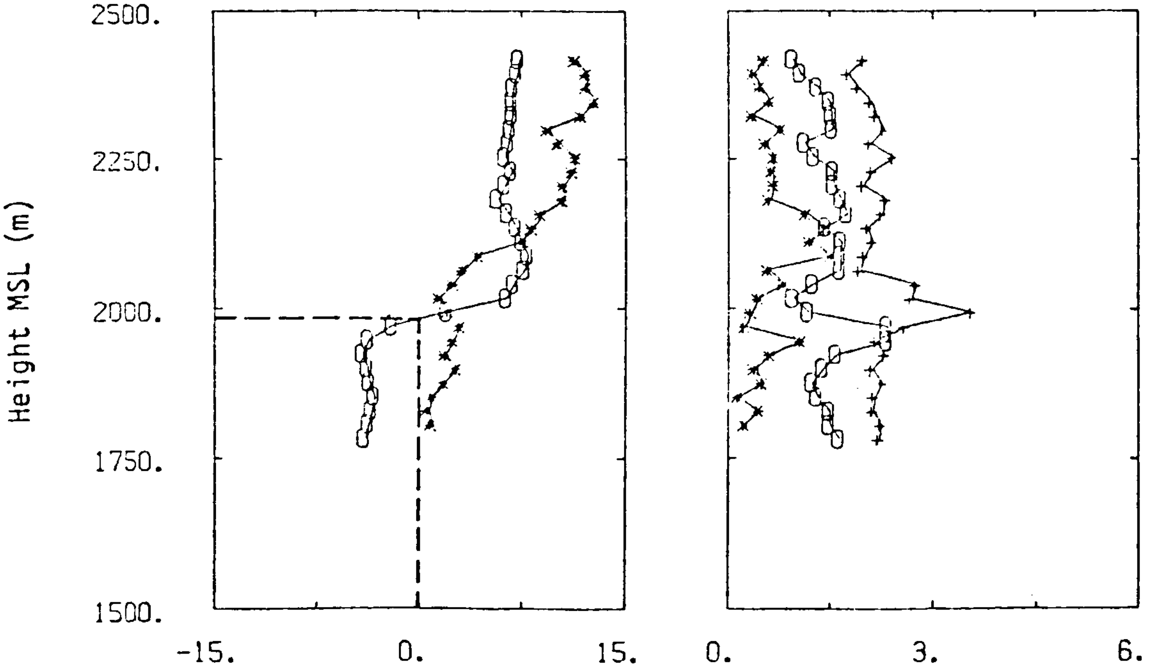


(c) Run 6

Figure 13. Comparison of radial mean wind velocity, calculated turbulence intensity, and lidar spectral width between aircraft measurement and lidar measurement on February 7, 1984 (280° azimuth).



(a) Run 10



(b) Run 12

Figure 14. Comparison of radial mean wind velocity, calculated turbulence intensity, and lidar spectral width between aircraft measurement and lidar measurement on February 9, 1984 (290° azimuth).

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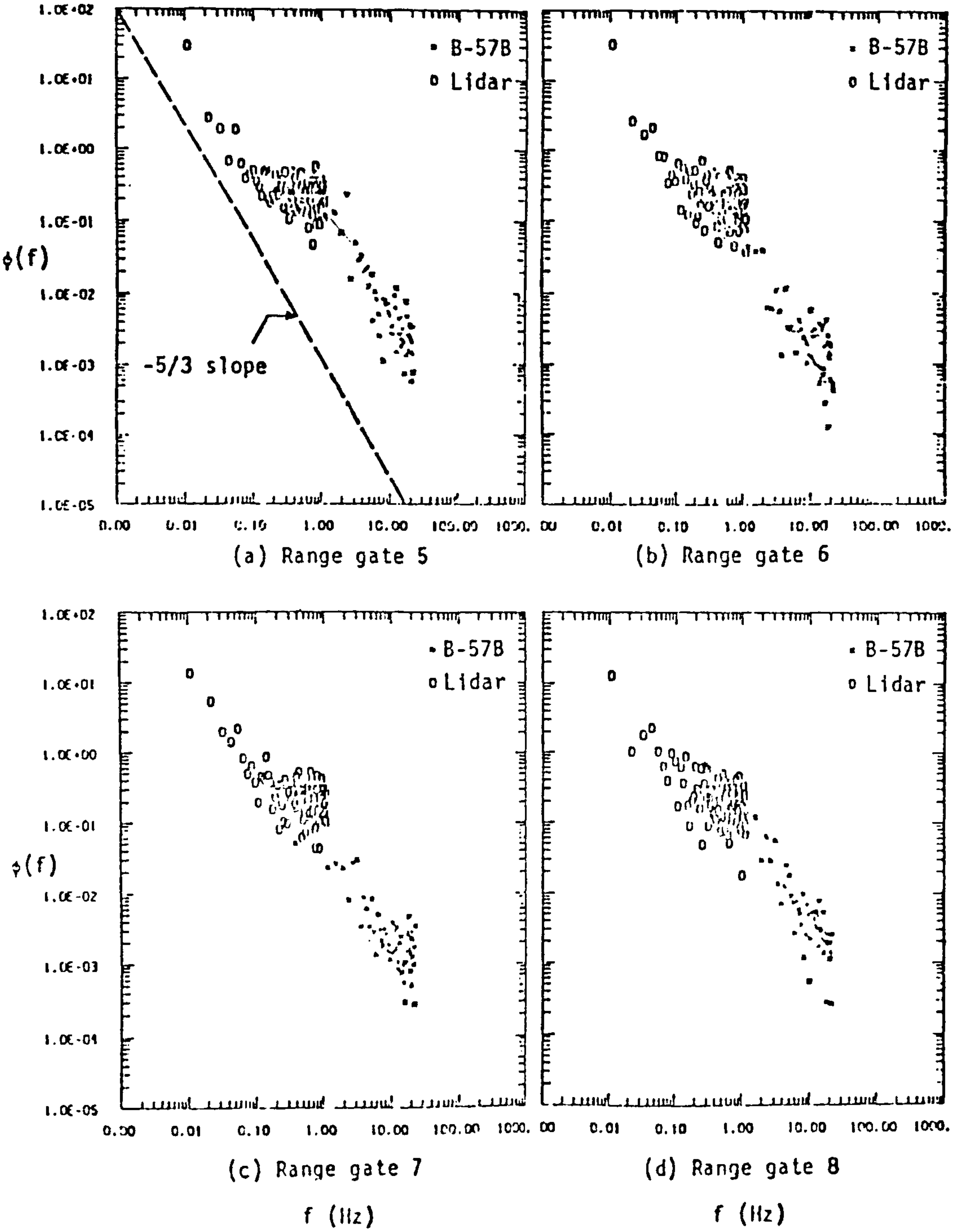

Figure 15. Computed radial turbulence spectra at 200° azimuth path.

N87-22347

MEASUREMENTS OF ATMOSPHERIC TURBULENCE

Harold N. Murrow
NASA Langley Research Center
Hampton, Virginia

This paper is intended to address various types of atmospheric turbulence measurements for the purpose of stimulating discussion during the interactive committee sessions of the workshop where measurement requirements relative to available data may be addressed. An outline of these various types of measurements is as follows:

1. Characterization studies
    a. Integral scale value
    b. Spanwise gradient
2. Encounter studies
    a. Velocity, vertical acceleration in g's, and pressure altitude
    b. Special encounters
3. Other
    a. Ground-based measurement
    b. Other in situ measurements
4. Summary

Some specific results of detailed characterization studies made at NASA Langley will be emphasized. References [1] through [13] are pertinent to these measurements and some modeling studies associated with them. Reference will be made to an existing program for measuring the spanwise gradient of gust velocity [14-17]. The most recent reports on statistics of turbulence encounters for various types of aircraft operations are summarized [18,19]. Special severe encounter studies [20] and reference to remote sensing [21] are also included. Wind shear is considered to be a special topic and is not covered here.

The objectives of the NASA Measurement of Atmospheric Turbulence (MAT) program are to obtain atmospheric turbulence power spectra and determine appropriate values of the integral scale length, L, for different meteorological conditions (jet stream, low altitude clear air, mountain waves, and near thunderstorms) over an altitude range from near sea level to about 65,000 feet. The same instrumentation system and data reduction procedure was to be utilized for all measurements. Very low frequency measurements were required since the emphasis was on the long wavelength portion of the power spectrum in order to estimate values of L.

The classical von Karman expression is given in Figure 1 and shows that two parameters are required to describe a power spectrum, σ, the intensity, and L, the scale of the turbulence sample. The family of curves shown is normalized with respect to intensity and shows how the location of the "knee" or flattening of the power spectrum changes with L. Some design

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specifications designate that L = 2500 ft be utilized if power spectral analysis techniques are to be used.

As shown in Figure 2, the gust characteristics of most contemporary aircraft are in a frequency range that knowledge of an appropriate L value is not needed; however, for large flexible supersonic aircraft, the principal response is at much lower frequencies. Thus, the aircraft response can be significantly different for the same intensity turbulence (note the log scales on the figure), and utilization of an appropriate L for design is important.

An instrumented B-57B Canberra aircraft was utilized as the sampling airplane. Samples of clear-air turbulence were obtained for conditions shown in Figure 3. While the instrumentation was later installed on a B-57F for higher altitude samplings, due to various difficulties, data sufficient for publication was not acquired.

The equations in Figure 4 show how the primary measurements made by balsa flow vanes and a sensitive airspeed device were corrected by use of instrumentation that measured aircraft motion to result in three components of gust velocity, longitudinal, lateral, and vertical with respect to the sampling aircraft.

Figures 5 through 8 give example true gust velocity time histories measured under different meteorological conditions. Four cases were selected by a research meteorologist as representing turbulence caused by low-altitude convective activity, mountain wave action, high-altitude wind shear, and so-called rotor action with sampling in the lee of rather sharp mountain peaks in the presence of strong wind. The convective case shown in Figure 5a resulted from a run extending for approximately 150 miles at 1000 ft altitude near the Virginia and North Carolina line and exhibits similar characteristics for all three components, and their σ values ranged from 3.78 to 4.41 ft/sec.

In Figure 5b the shape of the spectra for the convective case is reasonably close to the von Karman representation (shown by the solid lines superimposed on the data curves); however, in order to have a reasonable fit, L values of 1000, 2000, and 4000 ft appear appropriate for the vertical, lateral, and longitudinal components, respectively.

Time histories for the mountain wave case shown in Figure 6a are distinctively different in that major long wavelength content is obvious. At least three wave cycles are obvious in the 12-minute run for the vertical component--approximately one longer wave is noted on the horizontal components. The high-frequency content is variable in intensity and for this and other mountain wave samples it appears to intensify during positive swings in vertical gust velocity.

In Figure 6b the power spectra for the mountain wave case emphasize the observations noted on the time histories. High power is evident at long wavelengths and fitting a von Karman representation to the data is very difficult. It should also be noted that the higher frequency data exhibit the expected 5/3 slope, then tend to flatten, and then rise sharply in power at lower frequencies.

Observation of time histories shown in Figure 7a indicate that the wind shear case characteristics, in general, seem to fit between the convective and mountain wave cases with intensity varying gradually with time. It is known that this nonhomogeneous or nonstationary behavior will affect the "knee" of the corresponding power spectrum. An assessment of this effect will be shown later.

The power spectra for the wind shear case shown in Figure 7b indicate more power content in the horizontal components at low frequencies than the vertical component and less severe. The von Karman model can be made to fit reasonably well, especially for the vertical component. Appropriate integral scale values are in the range of 6000 ft for the horizontal components and 1000 ft for the vertical component.

The time histories for the rotor case shown in Figure 8a exhibit continual high-intensity, high-frequency turbulence and some long wavelength content is obviously included. The standard deviation, σ, for the vertical gust velocity component is 12.5 ft/sec--more than 50 percent greater than any other sample acquired. Acceleration increments of 1 g were equaled or exceeded 80 times in this traverse with maximum incremental accelerations of +2.2 g and -1.8 g.

The power spectra for the rotor case are shown in Figure 8b. It appears that an integral scale value of 6000 ft for the von Karman expression would approximate the spectra reasonably well.

Table 1 summarizes the four cases shown in Figures 5 through 8 with respect to altitude, length of run (in both time and miles), statistical degrees of freedom applicable for the power spectra, and values of standard deviation for the three gust velocity components.

The results of Figure 9 were obtained in an analytical study by Dr. William Mark of Bolt, Beranek, and Newman and provide "rule of thumb" guidance on the effects of intensity variation on the resulting power spectrum. Here, L_σ, is the spatial length of the sampling run for a linear increase and one half of the spatial length for an intensity burst, and L is the integral scale value of the turbulence. For the ratio of L_σ/L greater than 10 to 13, the effect on the power spectrum is barely detectable whereas for ratios below 5 to 7 a strongly rounding effect will be present.

Figure 10 summarizes the approximate relative integral scale values for the four cases. Because the turbulence in the mountain wave case is not continuous, the use of power spectra for characterization is somewhat questionable.

The objectives of the sampling program with the additional probes at the wing tips are given on Figure 11. It is interesting to note that whereas the emphasis in the MAT program was on the low-frequency portion of the power spectrum, the emphasis here is at the higher frequencies.

The B-57B was again utilized as the sampling test bed. The aircraft was selected because of its rugged design, broad flight envelope, ease of flying, and availability (see Figure 12). The wing tip probes located 60 feet apart are mounted at locations designed to accept fuel pods.

Figure 13 (taken from Houbolt and Sen [14]) shows theoretical prediction of the cross-spectra for the same gust component a distance S apart, assuming homogeneous isotropic turbulence. The curves are for various ratios of S/L where L is the integral scale value. Note that for $\sigma = S/L = 0$, the curve would be a von Karman spectrum with a -5/3 slope at higher frequencies. Flights are being made at low altitude where L is expected to be small and thus get an expected deviation from S/L = 0, and this region is appropriate since the spanwise effects are especially important for pilot workload in the terminal area.

Figure 14 shows some example time histories from the two wing tips and the centerline. While the general and long wavelength characteristics are similar, significant differences are evident in the mid and higher frequency region.

Figure 15a shows the auto-power spectra (APSD) for each wing tip with a fitted von Karman spectrum superimposed on the measured data. The L value from the fitted spectrum is used to provide the theoretical curve for cross-spectra (labeled CPSD) on Figure 15b. An example case of flight data is also shown. In this case the data deviate further from the prediction at the higher frequencies. The effects of filtering and data processing are presently under study.

Significant research and development efforts are under way in the remote sensing area. The use of Doppler radar and lidar (light detection and ranging) is encouraging. Some example data are shown in Figure 16 (from [21]) where power spectral estimates from ground-based lidar, in situ aircraft measurements, and tower measurements are shown. Lidar data are shown up to a frequency of 1 Hz; however, the agreement deteriorates above about 0.1 Hz. The authors of Reference [21] attribute this to a decrease in signal-to-noise ratio for the lidar data. The development and application of airborne units is expected to expand in the near future.

Figure 17 gives a summary of the NASA VG (velocity, vertical acceleration in g's) and VGH (velocity, vertical acceleration in g's, and pressure altitude) program. This program was a continuing effort to obtain pertinent statistical information on transport aircraft turbulence encounters. Recorders were installed on many aircraft over a 20-year period. From time history records of indicated airspeed, pressure altitude, and normal acceleration, peak values of derived gust velocity were determined. This program has been terminated, and the last report was published in 1977. A general aviation program was conducted in the 1960 to 1982 time period where various operation types were studied. Data were obtained for a total of 42,155 hours from 105 airplanes. Reporting is nearly complete.

The feasibility of utilizing data available from transport crash recorders to provide VGH-type information has been demonstrated and is outlined in Figure 18. In addition, an instrument has been developed that can record, store, and provide statistical data in a desired format. At the present time, there is no on-going activity in these areas.

Special analyses are being conducted of severe turbulence encounters utilizing data from on-board flight data recorders. A summary of these analyses is given in Figure 19. The procedure, which is shown on Figure 20, involves applying measured inertial and air data to equations of motion with parametric values appropriate for the particular aircraft involved. The derived atmospheric disturbance data can then be installed on a simulator for study of response of various aircraft to that disturbance. Figure 20 gives a block diagram of the analysis procedure and lists cases of wide-body special severe encounters for which data are presently available.

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

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

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

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Lidar:

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QUESTION: George Treviño (Michigan Tech). I saw by your measurements that you had some different scale lengths for the longitudinal scales and the vertical scales (6000 ft versus 1000 ft). That to me would indicate a very strong anistropy in the turbulence but yet you got some very good correlation with the theoretical isotropic von Karman spectra. How do explain that? Some of the data indicate a strong anistropy but yet you do get correlation with an isotropic curve?

ANSWER: As I mentioned earlier, I think that comes about because of the very high power content at the very low frequencies which is down to where you have wind effects. The question is where does the turbulence end and the wind begin? The high power content can be seen in the horizontal components but not in the vertical components. That's true if you are talking about frequencies that go all the way down to those low values or out to those long wavelengths.

TABLE 1. Four Selected Cases.

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

d.f. = f(bandwidth, length)

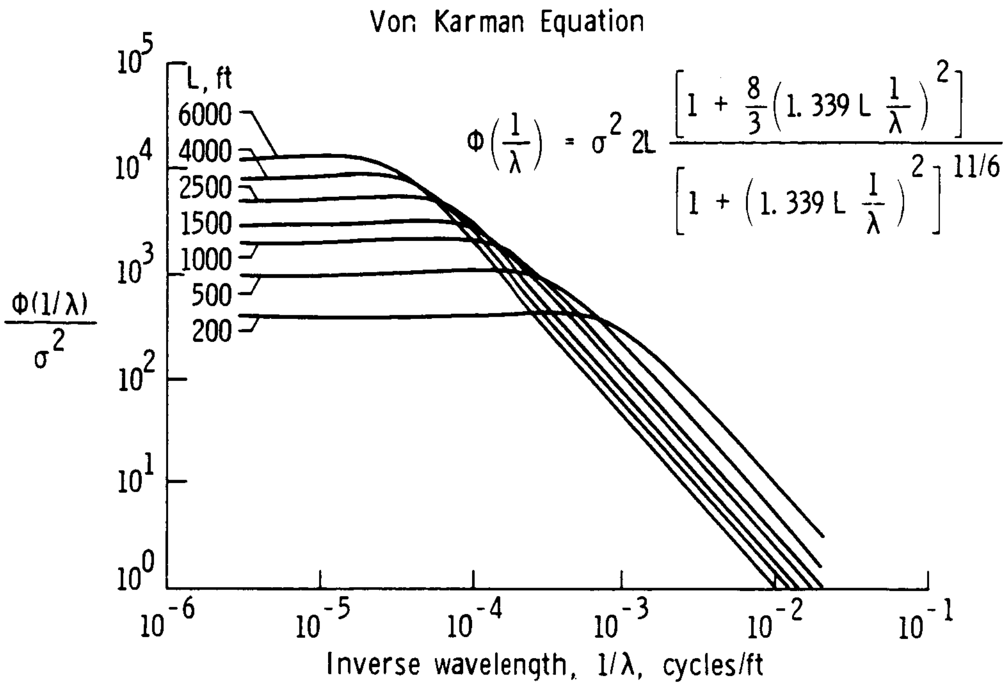


Figure 1. Theoretical transverse power spectra.

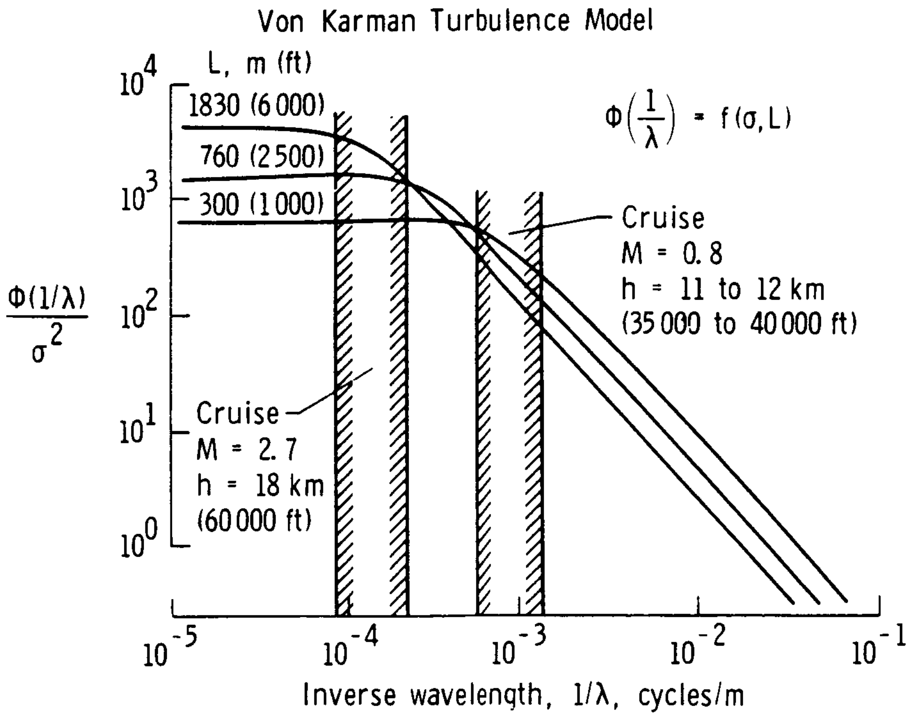


Figure 2. Theoretical power spectra.

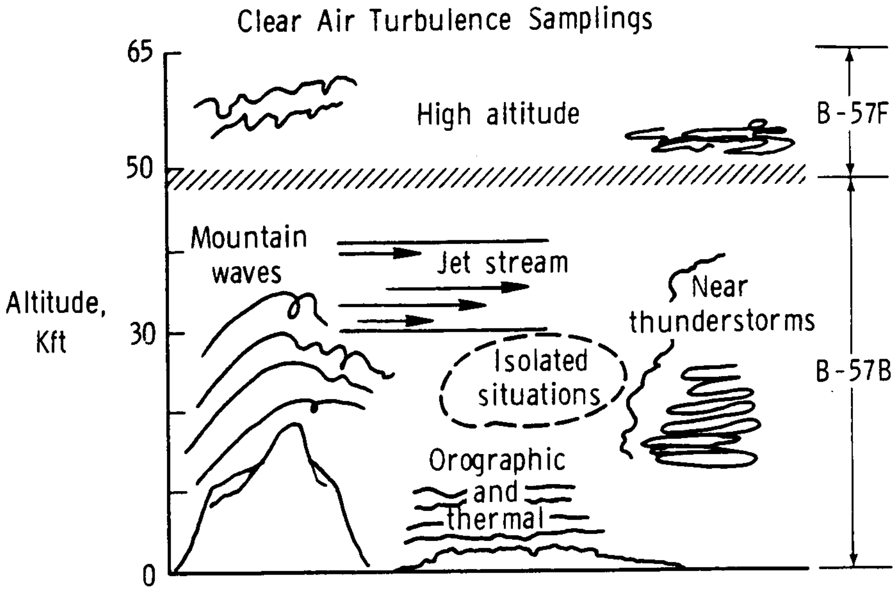


Figure 3. MAT project.

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

Longitudinal

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

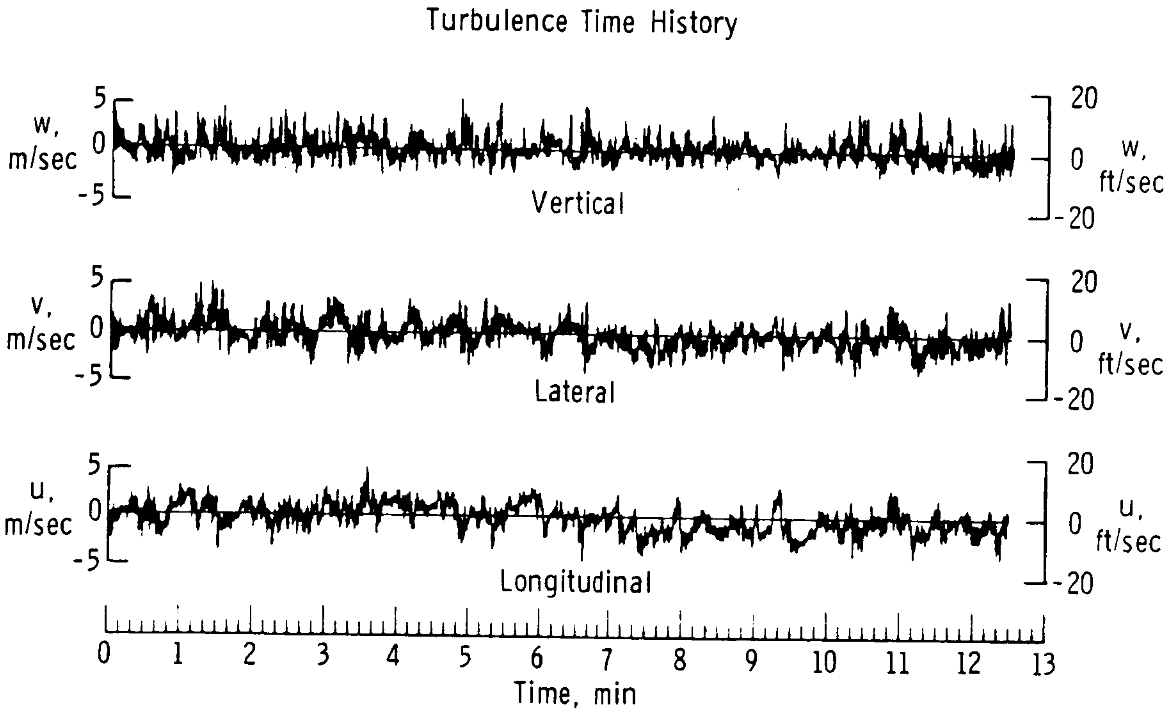
Lateral

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

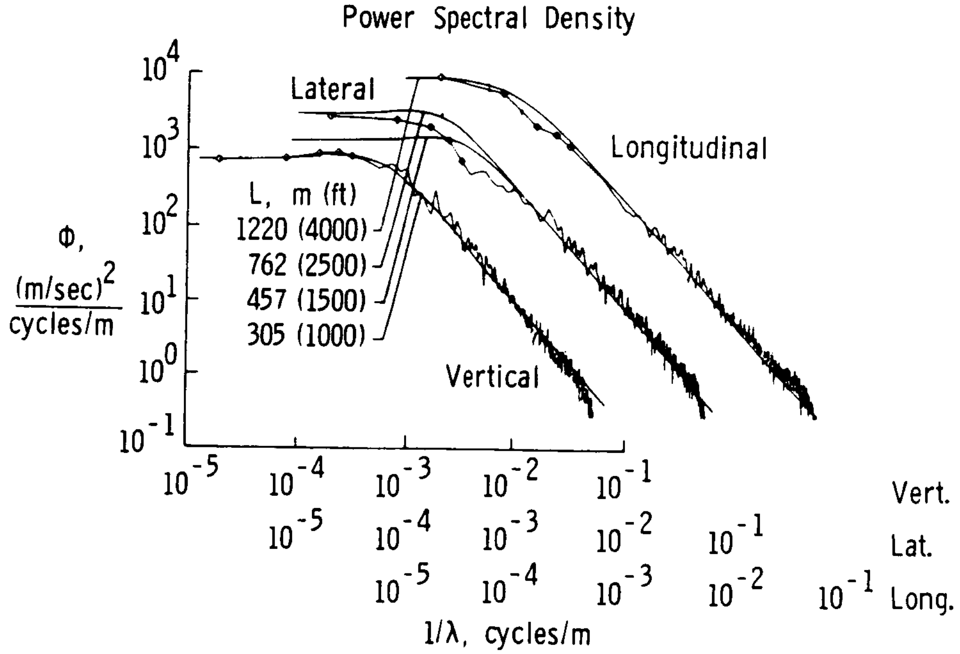
Vertical

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

Figure 4. Equations for the determination of gust velocity component time histories.

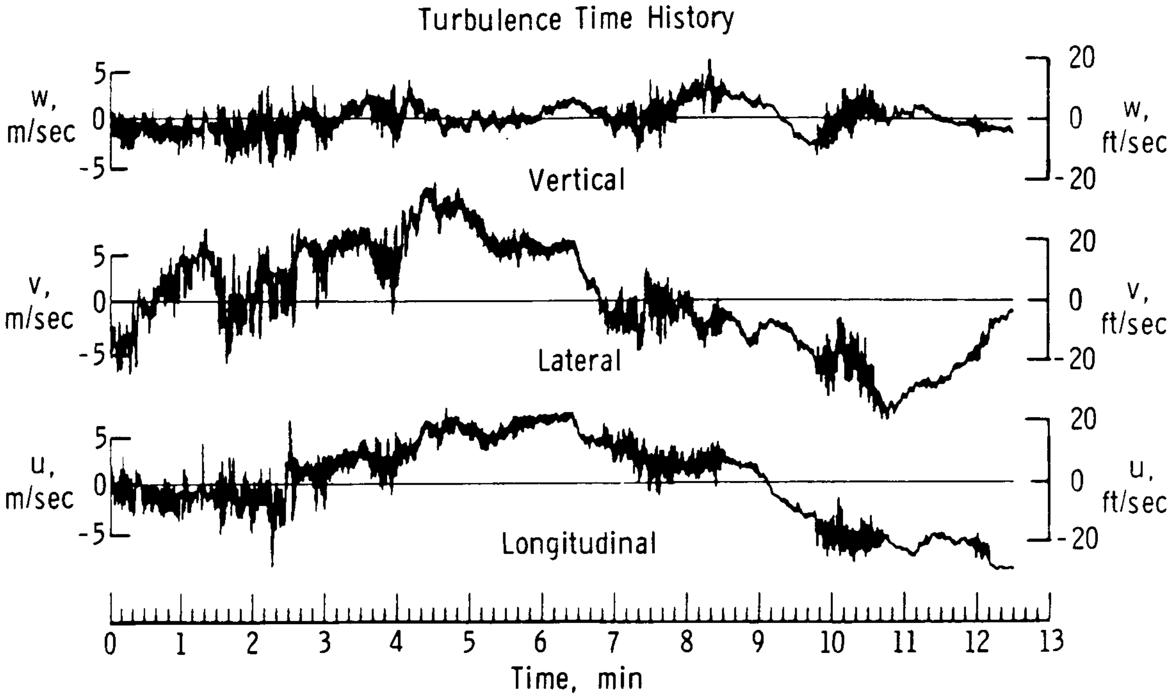


(a) Turbulence time history.

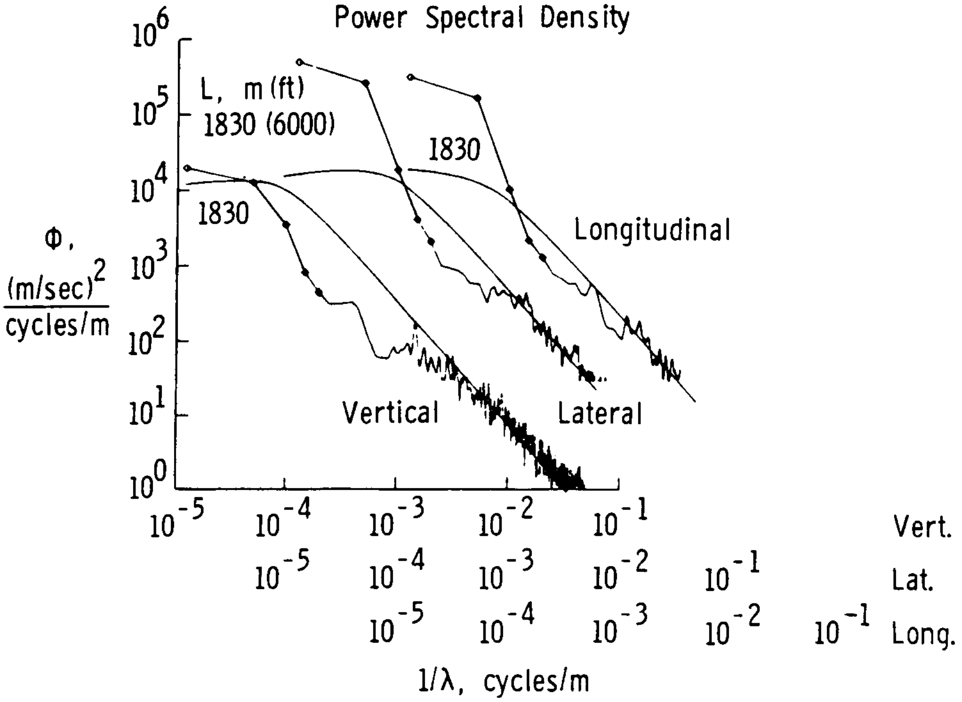


(b) Power spectral density.

Figure 5. Convective case.

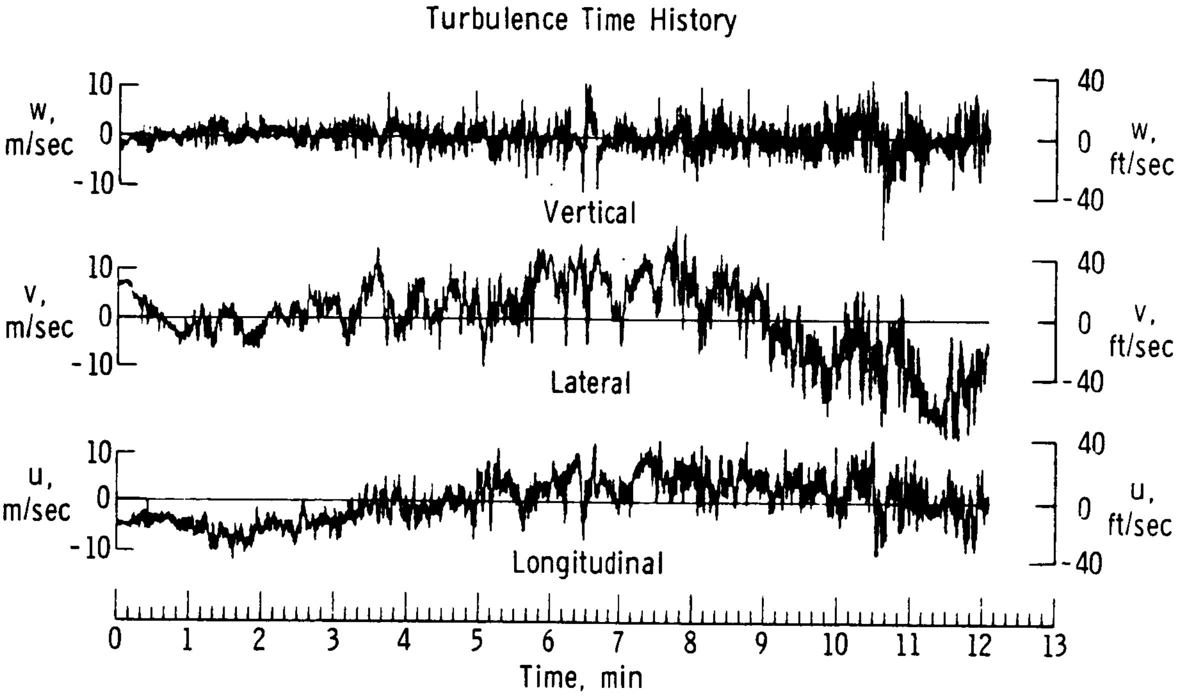


(a) Turbulence time history.

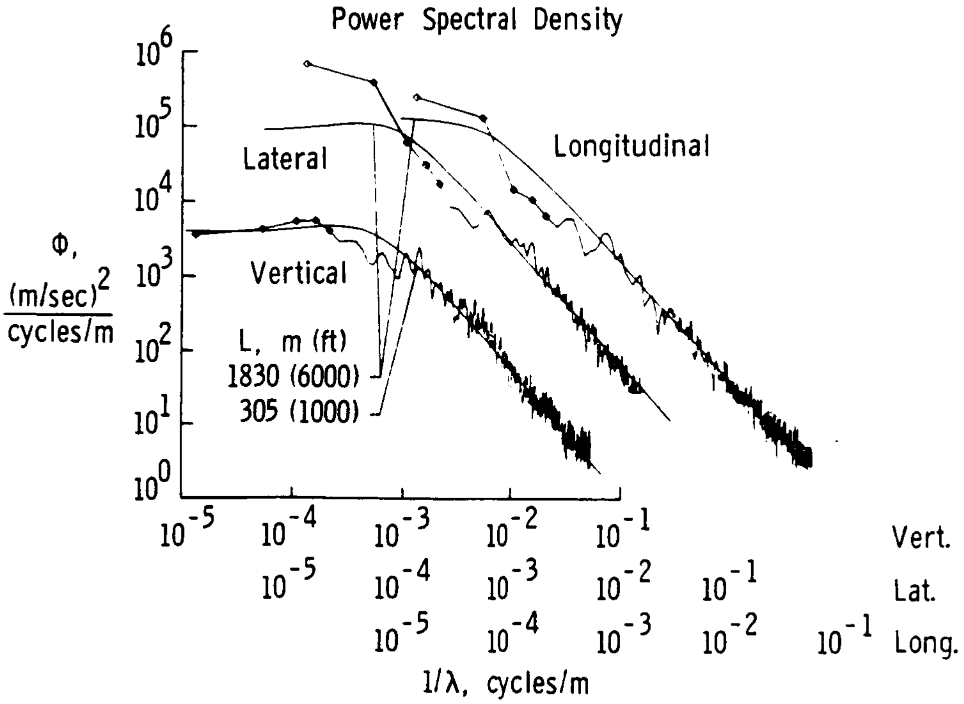


(b) Power spectral density.

Figure 6. Mountain wave case.

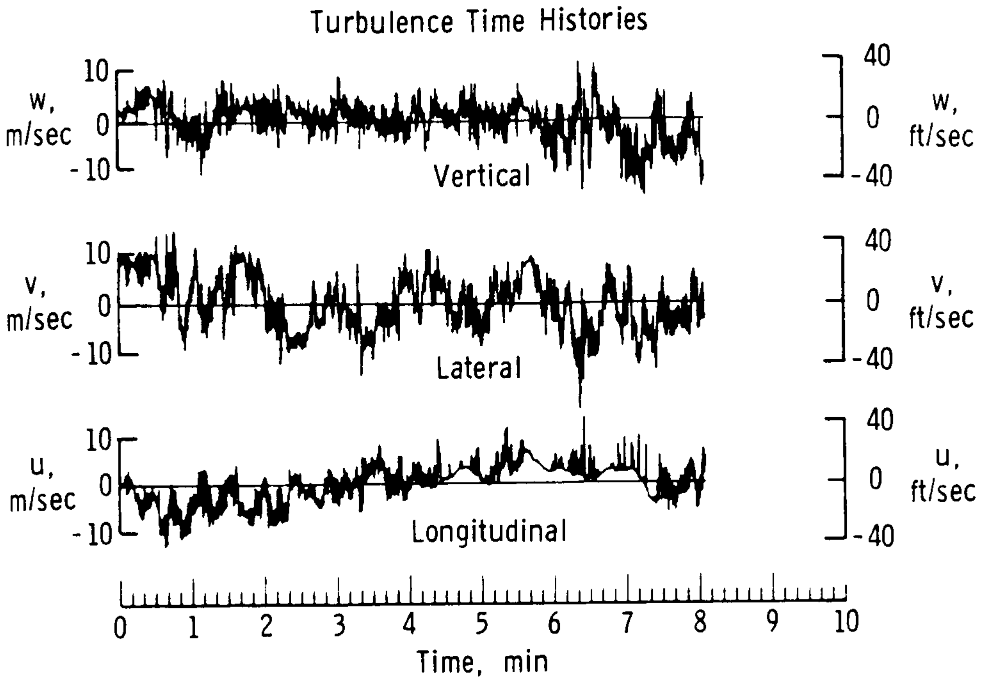


(a) Turbulence time history.

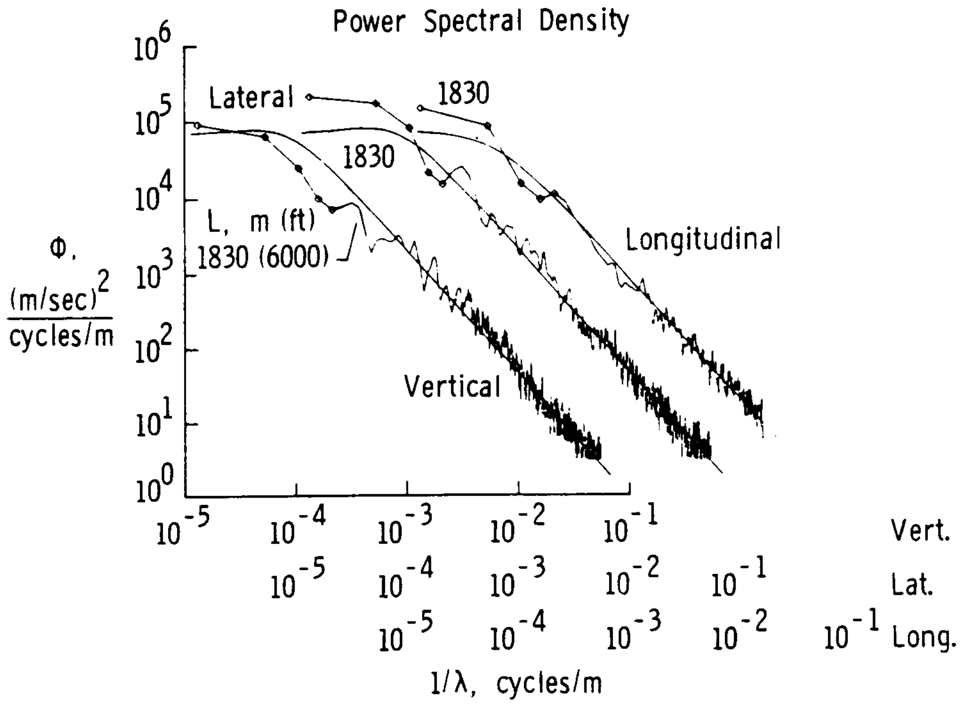


(b) Power spectral density.

Figure 7. High-altitude wind shear case.



(a) Turbulence time histories.



(b) Power spectral density.

Figure 8. Rotor case.

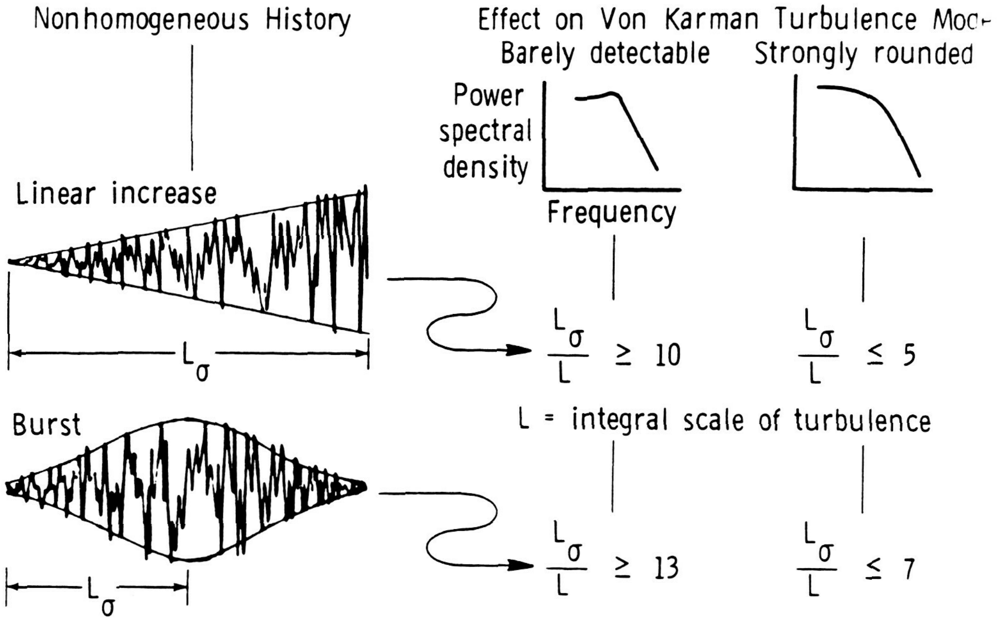


Figure 9. Effects of nonhomogeneous behavior on the power spectra of atmospheric turbulence.

- For wavelengths shorter than approx. 3000 ft, spectrum with -5/3 slope is reasonable
- For wavelengths greater than 3000 ft, appropriate integral scale value is variable
- In general, vertical component L smaller than that for lateral and longitudinal components

$$L_{vert} \cong 1000 \text{ ft}$$

$$L_{long,\ lat} \cong 6000 \text{ ft}$$

- Mountain wave cases not continuous: spectral representation questionable

Figure 10. Assessment of integral scale value (L).

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

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

Figure 11. Spanwise gradient (SPAN-MAT) research.

Figure 12. Test bed airplane.

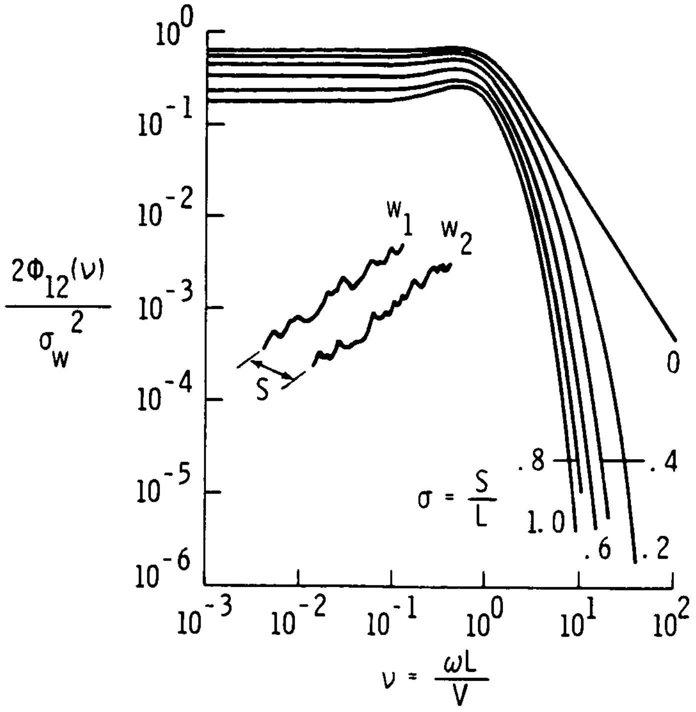


Figure 13. Cross-spectra for treatment of nonuniform spanwise gusts.

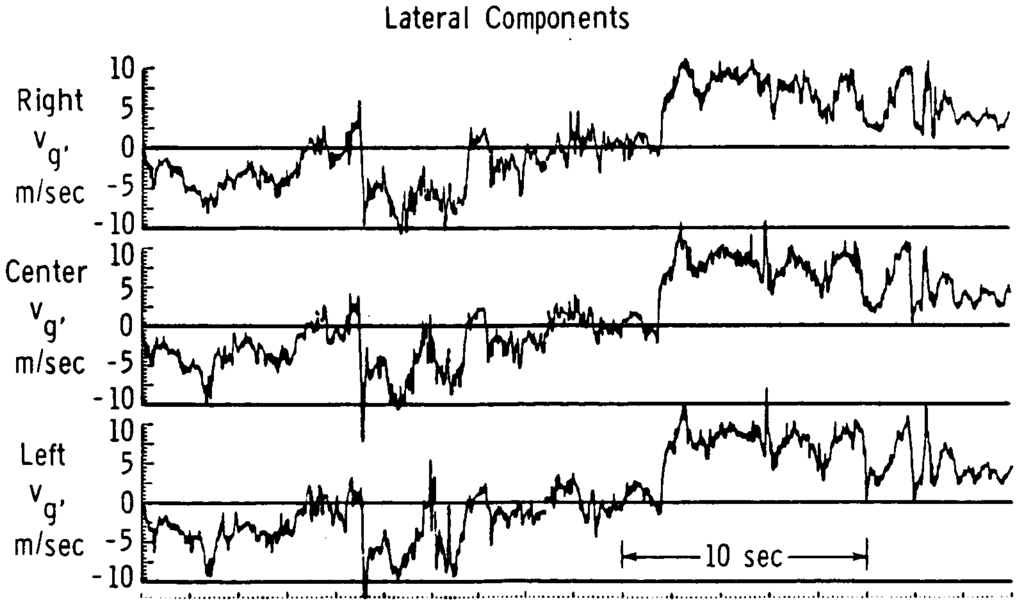


Figure 14.- SPAN-MAT gust velocity time histories.

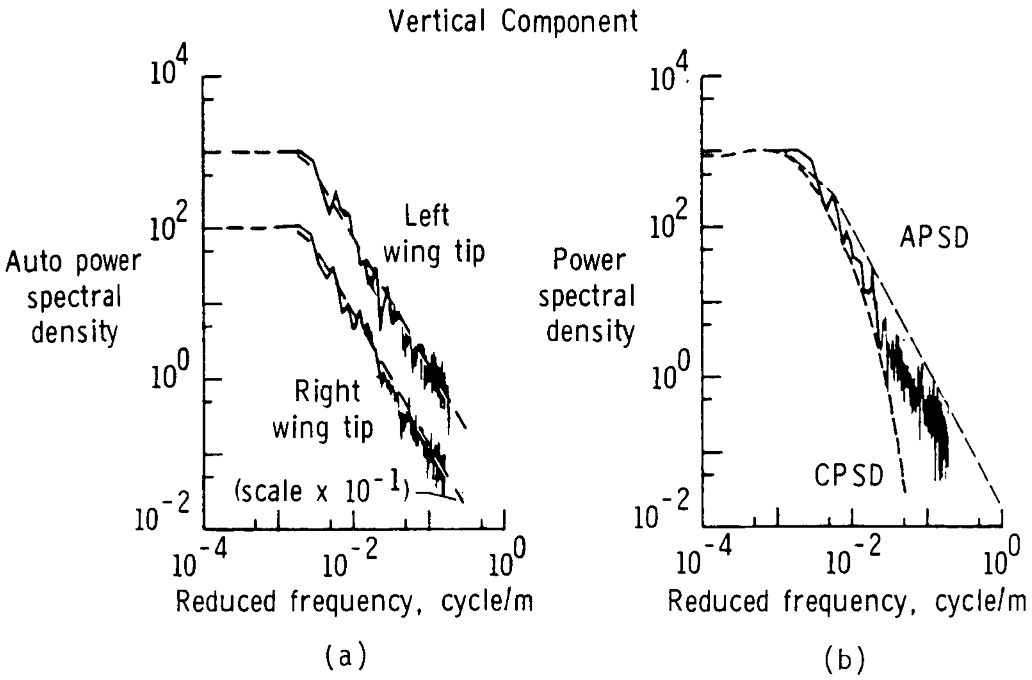


Figure 15. Gust velocity power spectra.

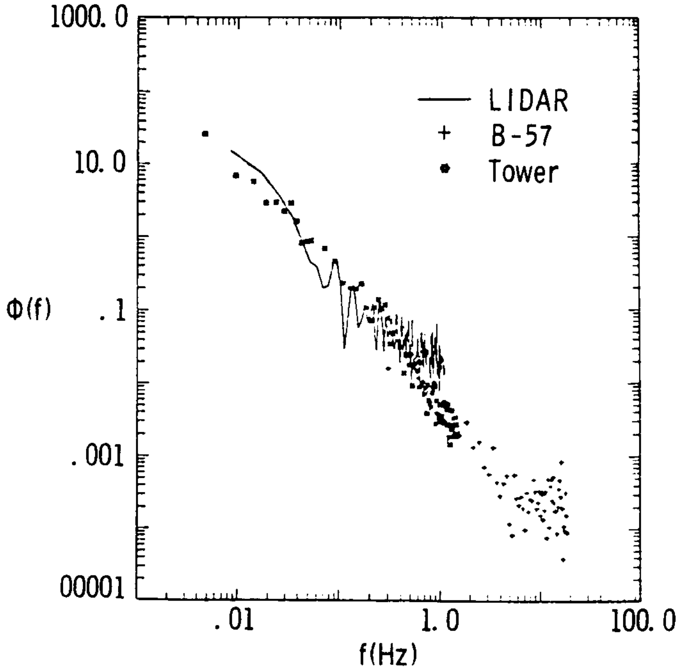


Figure 16. Comparison of ground-based and in situ measurements.

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

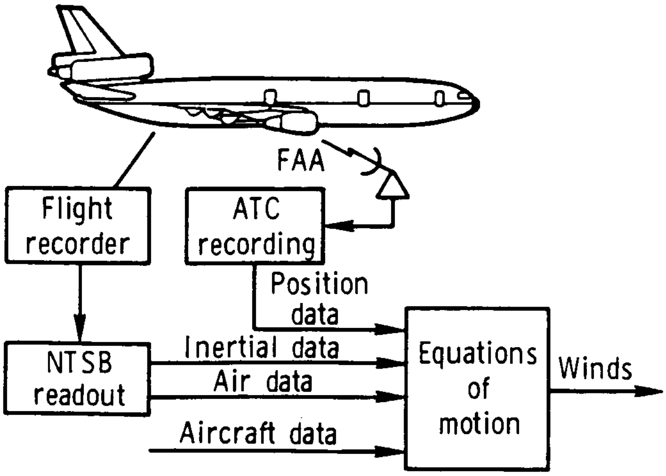
Figure 17. NASA VGH program.

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

Figure 18. Digital velocity, vertical acceleration in g's, and pressure altitude.

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

Figure 19. Special clear-air turbulence encounters by commercial airliners.



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

Figure 20. Wide body airline accidents/incidents involving atmospheric disturbances at cruise altitudes.

N87-22348

TURBULENCE AS OBSERVED BY CONCURRENT MEASUREMENTS MADE AT NSSL USING WEATHER RADAR, DOPPLER RADAR, DOPPLER LIDAR, AND AIRCRAFT

Jean T. Lee
National Severe Storms Laboratory
Norman, Oklahoma

ABSTRACT

As air traffic increases and aircraft capability increase as to range and operating altitude, the exposure to weather hazards increases. Turbulence and wind shears are two of the most important of these hazards that must be taken into account if safe flight operations are to be accomplished.

Beginning in the early 1960's, Project Rough Rider began thunderstorm investigations. This paper summarizes past and present efforts at the National Severe Storm Laboratory (NSSL) to measure these flight safety hazards and to describe the use of Doppler radar to detect and quantify these hazards. In particular, the evolution of the Doppler-measured radial velocity spectrum width and its applicability to the problem of safe flight is presented.

1. INTRODUCTION

Quantative data presentation and information assimilation are becoming increasingly important as Doppler radar evolves toward operational use by the weather services. Weather radar researchers have been faced with the development of techniques to identify and measure wind shear, vortices, and turbulence which constitute weather hazards to aviation. This paper summarizes past and present efforts at the NSSL in regards to weather hazards in convective cloud areas which can be encountered in aircraft operation.

2. BACKGROUND

Modern concepts of the internal structure of thunderstorms are developing mainly from multiple Doppler radar observations. Used in combinations of two or more, these radars now provide detailed portrayals of the precipitation-traced airflow in and beneath storm clouds and give new insights regarding the location of severe weather events. Furthermore, we can expect to see Doppler radar applications extended to include practical methods for measuring wind fields in optically clear air outside of storms for various altitudes [1]. The intensity of the radar return has been and still is used routinely by many to identify and track areas of heavy precipitation and hail (for examples see [2,3,4]), and operational tests have shown the great value of the radial velocity data in detecting mesocyclones and predicting tornadoes [5].

Thus, Doppler radar technology offers the unique opportunity to watch the complete development cycle of thunderstorms with a proven capability for

* C-2

early detection of aviation hazards and other severe weather events, and a likely capability to anticipate the rapid intensification which precedes severity [6].

The rationale for developing new diagnostic procedures is that:

1. Warnings will depend on real-time detection of singular events which provide controllers with criteria for advising pilots where dangerous conditions exist, and

2. Forecasts of severe weather events will depend on pattern recognition techniques which will provide aviation meteorologists, pilots, and air traffic personnel with criteria for predicting the likelihood (and locations) of hazardous weather events for flight and control planning.

Computer software to produce both types of products quickly and accurately depend on research studies which: (1) Objectively define data requirements, and (2) establish relationships among reflectivity, radial mean velocity, and spectral width with known weather hazards. Although this has been done and tested for mesocyclones and tornadoes, and to some extent for heavy rain and hail, work remains to better define the boundaries for turbulence, dangerous shear, strong directional outflow (gust fronts), and microburst.

2. HISTORY

The thunderstorm project of 1946 and 1947 was the first systematic documentation of these hazards at flight levels below 25,000 ft. In the 1950's, United Air Lines conducted studies in conjunction with commercial flights over the midwestern United States. With the advent of commercial jet aircraft operations at altitudes to 40,000 ft and increased air traffic density, accidents, and incidents involving aircraft in the vicinity of thunderstorms it was determined that a greater understanding of the thunderstorm was required. While a simple detour of all convective storms is the easiest way to avoid the associated hazards, the economics of civil aviation operations and non-combat military flights require a minimum disruption of service while safety is not compromised. Since the early 1960's, a cooperative research program involving the Federal Aviation Administration (FAA), National Aeronautics and Space Administration (NASA), U.S. Air Force (USAF), National Research Council (NRC) of Canada, the Royal Aircraft Establishment (RAE) at Bedford, England, and NSSL of the National Oceanographic and Atmospheric Administration (NOAA) has been in operation in Oklahoma. From 1960 to 1982 aircraft made controlled flights into thunderstorms of varying intensities (Figure 1) in order to determine the distribution of the hazards and their possible correlation with observations made by indirect probes such as weather radar and later with Doppler weather radar and lidars. In fact, we now recognize that radar correctly used and interpreted provides the best method known to date to improve the safety of flight near thunderstorms.

3. TURBULENCE

In the pre-Doppler era, over 500 penetrations of thunderstorms were made above 20,000 ft and a representative sample was obtained. In a second phase following the completion of the first phase, aircraft flights were confined to lower altitudes to obtain a sufficient sample size.

All aircraft were instrumented to measure and record the time, duration, and magnitude of the turbulence encountered during flight as well as other pertinent flight parameters. From these readings, derived gust velocities were calculated. The derived gust velocities are proportional to the change in acceleration (ΔN). The aircraft were tracked by the radar at Norman, and the position of the aircraft and the thunderstorm echo displayed on a Plan Position Indicator (PPI) scope were photographically recorded (Figure 2).

It was found early in the flight program that reflectivities of 10^5 mm^6m^{-3} (50 dBZ) were often associated with 3/4-inch diameter hail or layers [7], sizes that cause damage to an aircraft. Therefore, areas of indicated hail were avoided, and it may be possible that the gust velocities in these areas (Z_e values $\geq 10^5$ mm^6m^{-3}) exceed those measured outside of the area. Figures 3 and 4 are graphs of the distance from the center of the storm core when encounters of turbulence having derived gust velocities equal to or greater than 20 ft sec^{-1} were recorded. Storms of greater intensity were associated with greater gust velocities and with greater distances of significant turbulence from storm centers [8]. If one considers the average diameter of a severe thunderstorm to be 10 to 15 miles--a radius of 5 to 7.5 miles--it is apparent that severe turbulence can be encountered even near the edge of the visible cloud.

I would like to quote one conclusion from a report* by the National Research Council of Canada on flights conducted in Oklahoma:

> The results of this experiment are considered extremely important from an operational standpoint. It has been shown that at lower levels around squall lines and thunderstorms the return from weather radar provides insufficient information for avoidance of moderate and often severe turbulence, unless the aircraft is maneuvered in such a way as to avoid all radar echo by well over five miles. The intensity of turbulence encountered at this distance lends support to the view that echoes should be avoided by at least 10 miles and possibly more.

This view of turbulence differs from that of hail; the latter is closely related to echo intensity in a particular area because hailstones are themselves strong radar targets. At this time in our research we think of a thunderstorm system as a cluster of cells. The maximum radar reflectivity of which is an indicator of overall storm intensity, with the overall intensity determining the probability of hazardous turbulence, and the location of hail specifically indicated by the strong echo centers.

The two sampling phases (high and low altitude) produced similar statistics (Figure 5) which can be interpreted as meaning that turbulence

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*G. K. Mather and D. S. Treddenick: Turbulence Measurements at Low Levels Around Squall Lines, National Research Council of Canada Aeronautical Report LR-515, 1969.

encounters vary little with altitude. These sample penetrations also showed that turbulence could be related to radar reflectivity only in the broadest sense and that such a measure as reflectivity gradient was not the answer and, in fact, could be very misleading.

The next major stride was made when Doppler radar was applied to observe meteorological phenomena. Doppler radar offers the highest potential for further defining turbulence because turbulence is known to be related kinematically to features that are best measured remotely with a Doppler radar.

4. DOPPLER RADAR AND TURBULENCE

The NSSL staff began a series of experiments in 1973 using the Doppler radar in place of the conventional WSR-57 weather radar to study weather hazards to aviation. These joint experiments involved the USAF, FAA, NASA, Colorado State University, University of Oklahoma, and various NOAA components. Penetration aircraft (F-4-C, F-101, F-100, and F-106) suitably equipped to make in situ wind and turbulence measurements, were used simultaneously with the Doppler radar.

One of the first experiments used the Plan Shear Indicator (PSI) developed by the USAF Cambridge Research Laboratory (now known as the Air Force Geophysical Laboratory (AFGL); this device graphically depicts radial shear [9] (Figure 6).

Moderate or severe turbulence was encountered in all cases when the PSI displayed shear along the aircraft flight path, but shear was not indicated with all turbulence encounters, and it appears from these cases that moderate or less turbulence (derived gust velocities (U_{de}) $\leq$ 9.1 ms^{-1}) may escape detection by the PSI. This is not surprising since only the wind's radial component is measured by radar. Where severe turbulence (U_{de} > 9.1 ms^{-1}) repeatedly was encountered, the PSI showed transient shear areas along the flight path. Arc deformations apparently have an operational detectability threshold associated with wind shears $\geq 1.5 \times 10^{-2}s^{-1}$.

In 1974, a second-generation radar real-time display was developed at NSSL. The three spectral moments were presented as a field of arrows shown by a minicomputer-graphic display terminal interfaced to the NSSL Doppler radar [10]. Arrow length is proportional to the logarithm of received power, arrow direction displacement from a horizontal position is proportional to velocity (similar to a speedometer indicator) and the arrowhead size to Doppler spectrum width (Figure 7).

Using the new display for real-time analysis, we directed USAF Aeronautical System Command F-4-C aircraft in a number of thunderstorm penetrations, and successfully located areas where the aircraft experienced turbulence. In post-analysis, the data were searched for significant correlations between turbulence, radar reflectivity, and velocity data. Figure 8 is a time history of aircraft-recorded turbulence and Doppler velocity spectrum width along the flight path. Note how well the turbulence trend matches the trend in the spectrum width plot. A total of 45 such penetrations were analyzed; all show a similar relationship. During the 45 penetrations, there were 76 occurrences of moderate or greater turbulence. Ninety-five percent had spectrum widths of 4.0 ms^{-1} or greater [11]. There will be non-turbulent areas where the spectral width is large because the spectral width may be biased by wind shear and beam broadening [12]. However, in two tornadic storms studied, the cumulative probability for the spectrum width to be $\geq$4 ms^{-1} due to all factors is only about 30 percent [13]. For non-severe storms the probability is even less; thus, only a small portion of even a severe storm will have "false alarm" values.

In another set of experiments analyzed by Bohne [14], a correlation of 0.89 was obtained between the curves showing turbulence measured by aircraft and radar along a flight path. More importantly, for higher turbulence levels, which pose a greater flight hazard, the agreement between radar measurements and the turbulence actually experienced by the aircraft was nearly total. Other experiments have led to similar conclusions [15]. Judging from available information, it appears that a spectrum width threshold of 4 ms^{-1} may be associated with the onset of flight discomfort and 6 ms^{-1} with potential hazard. The Next Generation Radar (NEXRAD) is expected to estimate Doppler spectrum widths with an accuracy of 1 ms^{-1} down to a signal-to-noise ratio (SNR) of 5 dB [16]. For a radar of the NEXRAD type, this means that good estimates of spectrum width (turbulence) can be obtained out to the maximum range of 230 km even with very light precipitation, of the order of 0.3 mm hr^{-1}.

Aircraft penetration studies have further shown that extreme turbulence may occur as far as 20 nautical miles (36 km) from the edge of the radar contour of the center of severe thunderstorm clouds, and the FAA advises pilots to avoid all thunderstorms by a margin at least equal to this distance [17]. This is a safe procedure to follow in relatively uncrowded airspace. In airlanes with heavy traffic, however, it is desirable to keep detours to a minimum. NEXRAD can help in this content in two main ways. First, since it can accurately sense precipitation and turbulence, it can better define the boundaries of thunderstorms. Thus, uncertainties due to impressive edge definition will be minimized. Second, unlike present operational weather and ATC radars which scan the azimuth with fixed antenna elevations, NEXRAD will scann its surrounding space at several elevation angles providing a three-dimensional picture of storms. Thus, flights well above the tops of thunderstorms may not have to be disturbed.

In addition, turbulence appears to be nearly isotropic and therefore independent of viewing angle. Figure 9 shows a comparison of the spectrum widths in a storm being observed by both Norman and Cimerron radars which are separated by more than 40 km. We have looked at several storms with four to six elevations per case and have found essentially the same result. This also tends to substantiate the findings of isotrophicity in the turbulence data gathered during earlier penetration flights.

We have also looked at comparing Doppler-radar-measured turbulence with that measured by Doppler lidar and by a 444 m (1500 ft) instrumented KTVY-TV tower. Figure 10 shows the agreement in wind speed and direction and Figure

11 the comparison of the standard deviations (turbulence) of the horizontal velocity fluctuations [18]. The variances of the u and v components were computed for each lidar- and radar-estimated vector wind field and combined to find $\sigma_T = (\sigma_u^2 + \sigma_v^2)^{1/2}$, the standard deviation of the horizontal velocity fluctuations. The total variance is taken as being composed of the errors due to velocity estimates and that due to turbulence and small-scale flows. It can be seen that the horizontal velocity fluctuations measured by the three different systems is in remarkable agreement.

It also appears that turbulent areas in a storm are not randomly distributed (Figure 12). Figures 13 and 14 show how a NEXRAD algorithm of turbulence and a smoothing integration produces turbulent areas (volumes) which can be tracked in time and space thus making the output valuable for the aviation community.

Wind shear such as seen in gust fronts and downbursts are also amenable to Doppler radar use in their detection. However, there remains to be accomplished the numerical modeling of these features to determine if their formation, movement, and intensification (or decay) can be accurately predicted and this is the area in which NSSL is now engaged.

5. SUMMARY

Turbulence, wind shear, microburst, and hail are amenable to observation by Doppler radar. Techniques to obtain the information and present the probabilities of encounter in an effective manner is a goal of the NEXRAD system. Emphasis at NSSL has now shifted from aircraft in situ measurements to the corresponding remote sensor observation and the modeling of these hazards for use in the NEXRAD environment and in aircraft operations.

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QUESTION: Walter Frost (FWG Associates). I noticed in one of your plots that you compare intensities using $\sigma u^2 + \sigma v^2$. Do you always compare turbulence intensities in that fashion or do you ever compare individual radial components of turbulence intensities?

ANSWER: No we use various approaches. We compare individual radial components of the Doppler radar, lidar, and tower.

FROST: When you are comparing tower lidar and Doppler data for the NASA tests, how did you collocate those sigmas?

LEE: What we did was to place these data on a grid using the Taylor hypothesis to move the tower data downwind into a location being sampled by aircraft, Doppler lidar, and Doppler radar. We did some of the early experiements with the aircraft flying right down the Doppler radar radial in the vicinity of the tower. But we did not do the experiments that were done at Huntsville. Most of our data are located on a grid matrix (0.5 km size). Lidar measurements are approximately at 500 m spacing, the Doppler radar depth is 150 m, which was averaged to 0.5 km, and, of course, in range you have a spreading out of the beam so that we felt our grid size was obtained at 0.5 km grid both vertically and horizontally at about 40 km from NSSL. The comparisons were made using those grid values.

QUESTION: Mike Tomlinson (Air Weather Service). In putting together the information you have on precipitation and then adding the Doppler spectral width and turbulence, have you tried to correlate those locations with the lightning detection systems? There is some marketing going on that says lightning information can infer turbulence information. And I'm wondering if you had an opportunity to validate or invalidate that theory.

ANSWER: We were unable to determine the relationship between lightning and turbulence. All the research studies that have been conducted in our area and in other areas indicate that there is very little in the way of correlation. Similarly, the correlation of lightning and the severity of the storm is not apparent. We have had tornadic storms in which the lightning activity has been very light. We've had extremely heavy electrical activity in storms and have had no surface manifestations of any severe weather, neither heavy rain, hail, nor high winds. We are continuing research at NSSL. We do have the radars, we have three different lightning locating systems that we are working with, the LLP, the LPAT, and one which has a very high-frequency response so that we can actually watch the strokes develop. We are trying to find out where the lightning develops. Using the dual-Doppler system to monitor the storm buildup, we are attempting to find out what flow patterns cause the separation which then ends with a discharge. But right now we see no correlation; in fact, there almost seems to be a negative correlation between the activity and turbulence--if NASA's research is an indication of all systems. I have no reason to doubt that this is not true. When an aircraft flies where there is active lightning, its flight is relatively smooth. If it goes through another area where there is hardly any lightning, the aircraft may trigger the lightning.

QUESTION: Creighton Pendarvis (SimuFlite). I've enjoyed your presentation and found it most enlightening. I'm interested in your last statement that you are now able to keep an aircraft out of a hail shaft and also out of destructive turbulence. Is there any air traffic control (ATC) facility in this country at this time that you know that has the same capability?

ANSWER: No. The NEXRAD radar system is planned for the contract to be awarded in October 1986. Their prototype radar is to be installed at Norman by March 1987. The first production radar will come in the Oklahoma City area in 1988, and then by 1989 or 1990, other units will be distributed across the United States. The Doppler radars are coming; they will be installed. A main problem, of course, in the algorithm development and interpretation, is still going to be troublesome. I think there is still going to have to be a man in the loop.

QUESTION: C. M. Tchen (City College of New York). I am interested to know whether you see a difference in the spectral density without the rain and with the rain on the same site?

ANSWER: No, we do not see the difference in convective systems we have studied. In other words we do not see any affect of rain in the layers where data were obtained.

TCHEN: The theory on the two-phase turbulence where the droplets are suspended predicts a broadening of the k^{-1} spectral distribution by the precipitation in confirmation with the Russian laser experiments. Have you measured the spectral distributions in your experiments?

LEE: Yes. It may be that if we look specifically for that effect, we might find it.

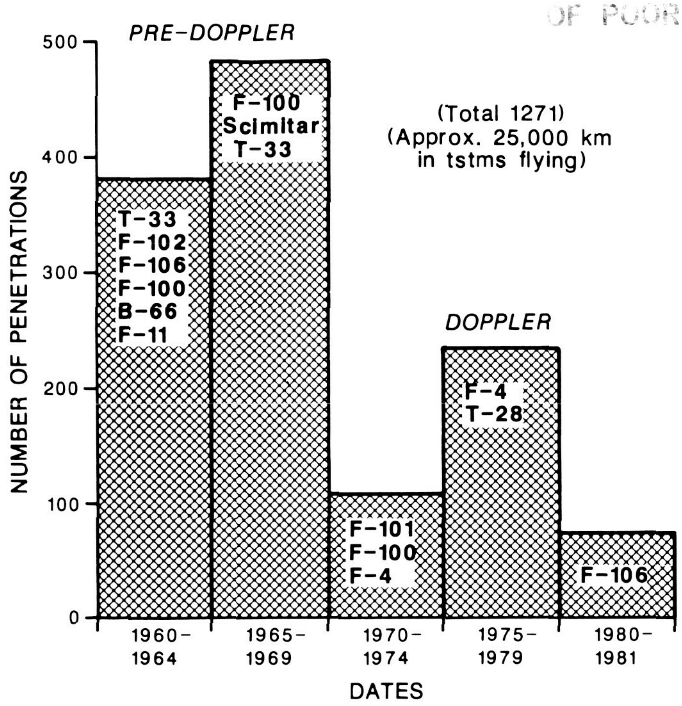


Figure 1. Number of thunderstorm penetrations made in Project Rough Rider 1960-1982 along with aircraft used in the data acquisition. Reduced numbers in 1970-1974 are results of no penetrations in 1970-1972 when emphasis was shifted to over thunderstorm flying using U-2 and RB-57F aircraft. In 1973 Doppler radar came into use and penetrations were once more initiated.

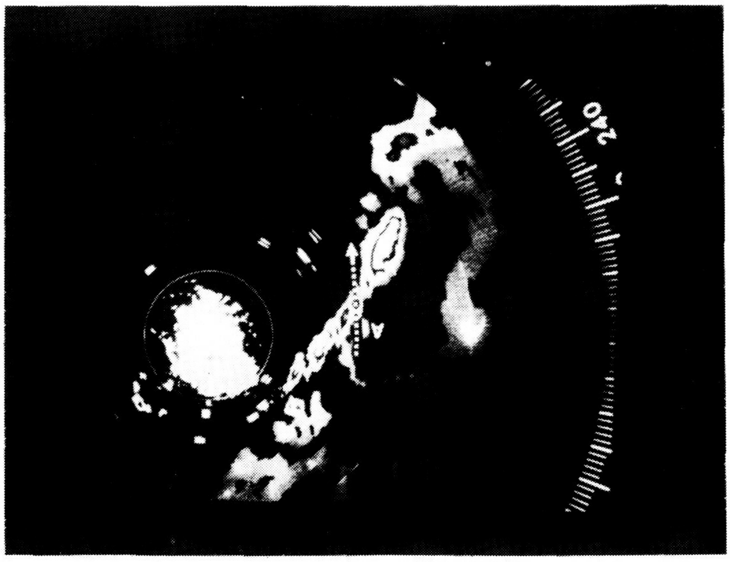


Figure 2. 16 June 1973 WSR-57 weather radar reflectivity iso-echo contour display with aircraft transponder beacons superimposed. Point "A" is the beacon return from the F-100 at 1357:25 CST; the dotted line indicates aircraft path. Range marks at 40 km intervals.

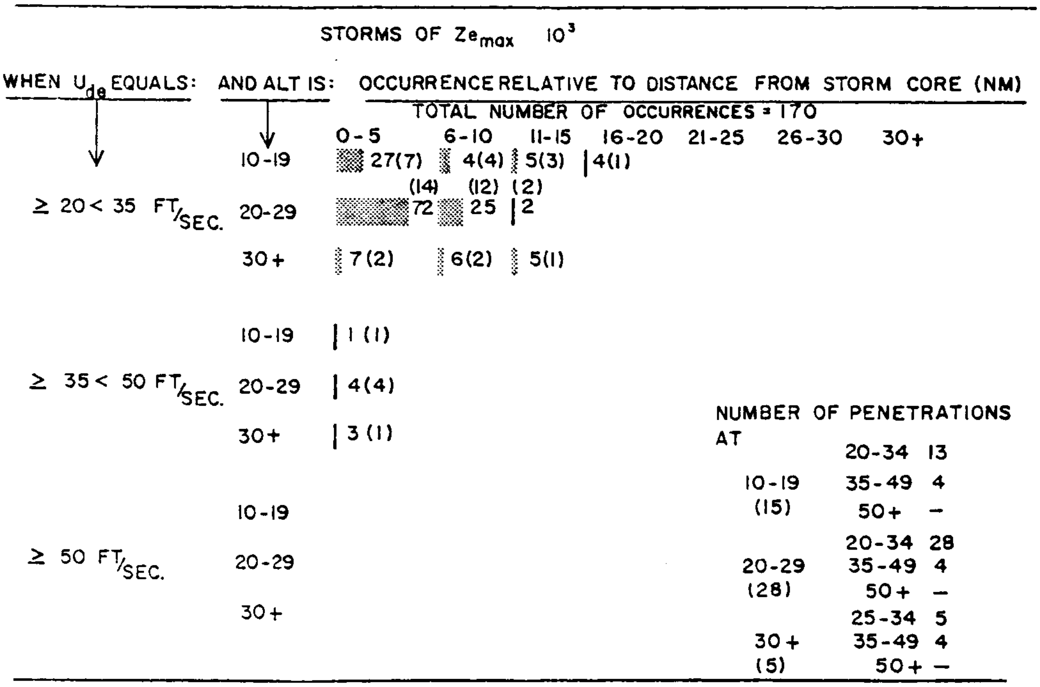


Figure 3. Distance from storm core with maximum reflectivity of $z_e = 10^3$ to 0.9×10^3 mm^{6}m^{-3} (30 dBZ). Turbulence is shown in three categories. Each turbulence category has penetrations divided into three altitude bands. The first indicates the number of separate occurrences while the number in parentheses indicates the number of penetrations. The occurrences are shown as a function of distance to core.

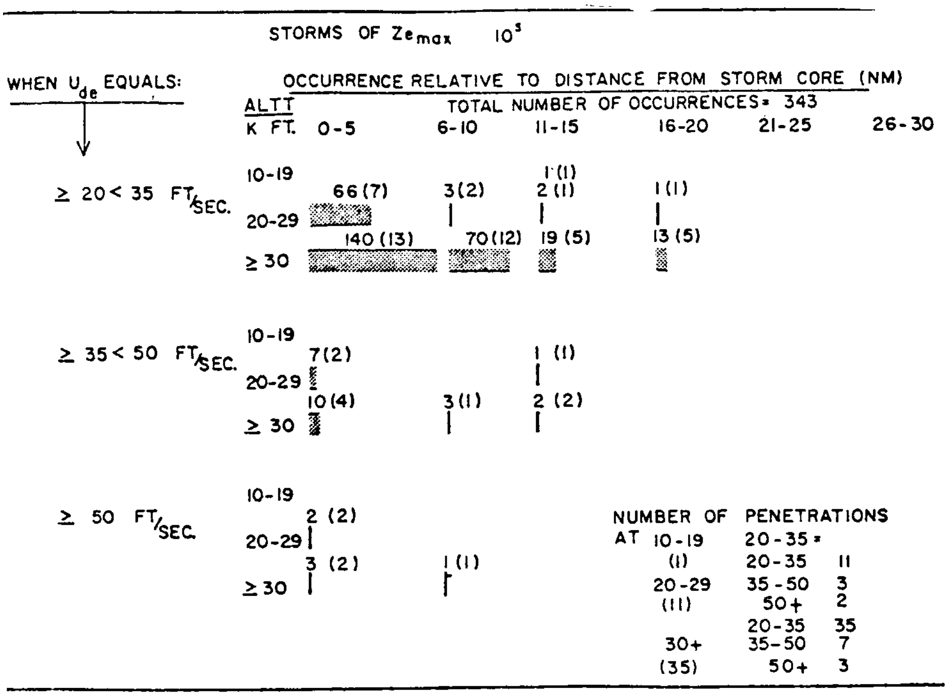


Figure 4. Distance from storm core with maximum reflectivity of 10^5 mm^{6}m^{-3} or more (≥50 dBZ). Turbulence is shown in three categories. Each turbulence category has penetrations divided into three altitude bands. The first indicates the number of separate occurrences while the number in parentheses indicates the number of penetrations. The occurrences are shown as a function of distance to core.

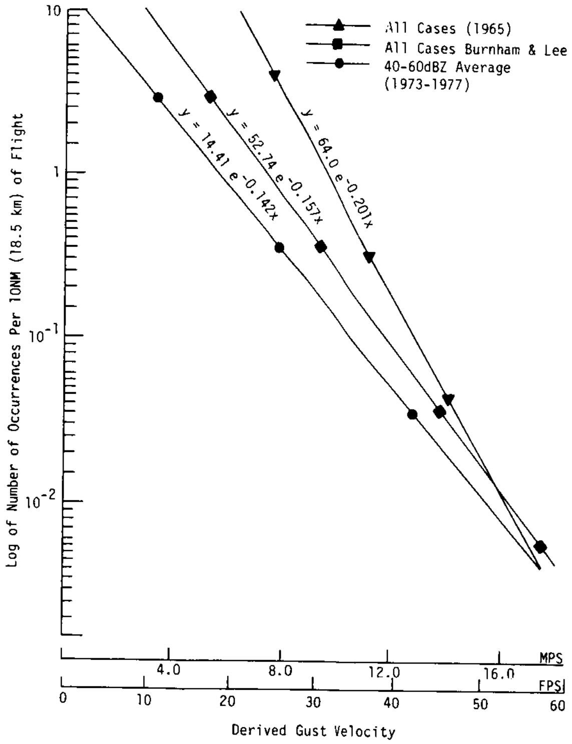


Figure 5. Frequency of turbulence encounters observed 1973-1977, as compared to observations made during the mid-1960's. Equations are exponential corresponding to the least-squares best fit for the data shown.

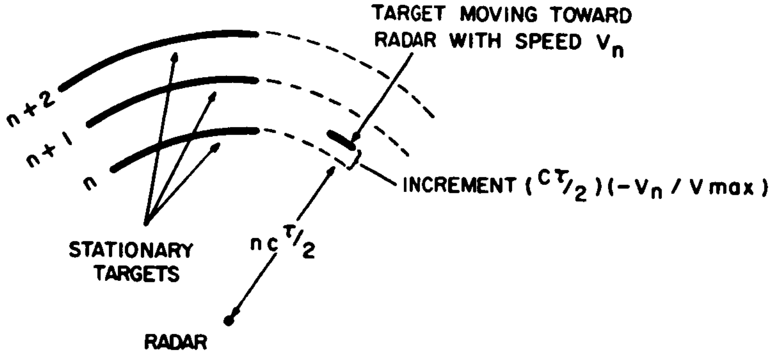


Figure 6. PSI display for stationary targets (left) and a moving target (right). The moving target is located at the same distance from the radar as the nearest stationary target (n) but is displaced from it on the PSI display by an increment proportional to its velocity.

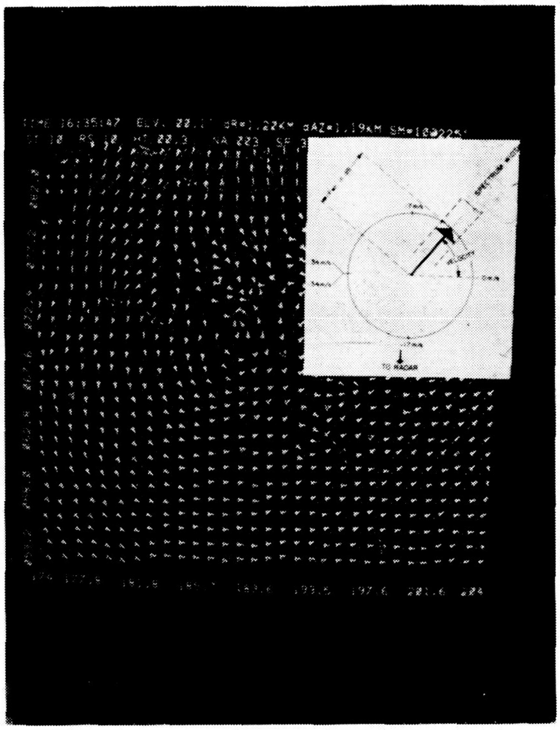


Figure 7. The multi-moment Doppler display of a mesocyclone. Each arrow contains information of the three principal Doppler spectrum moments for a resolution volume. For interpretation of arrows see insert in upper right corner (arrow length is proportional to received power, arrow direction to velocity and arrowhead size to Doppler spectrum width). Abscissa is azimuth and ordinate scale denotes range (km) from radar. Housekeeping information is at top of screen.

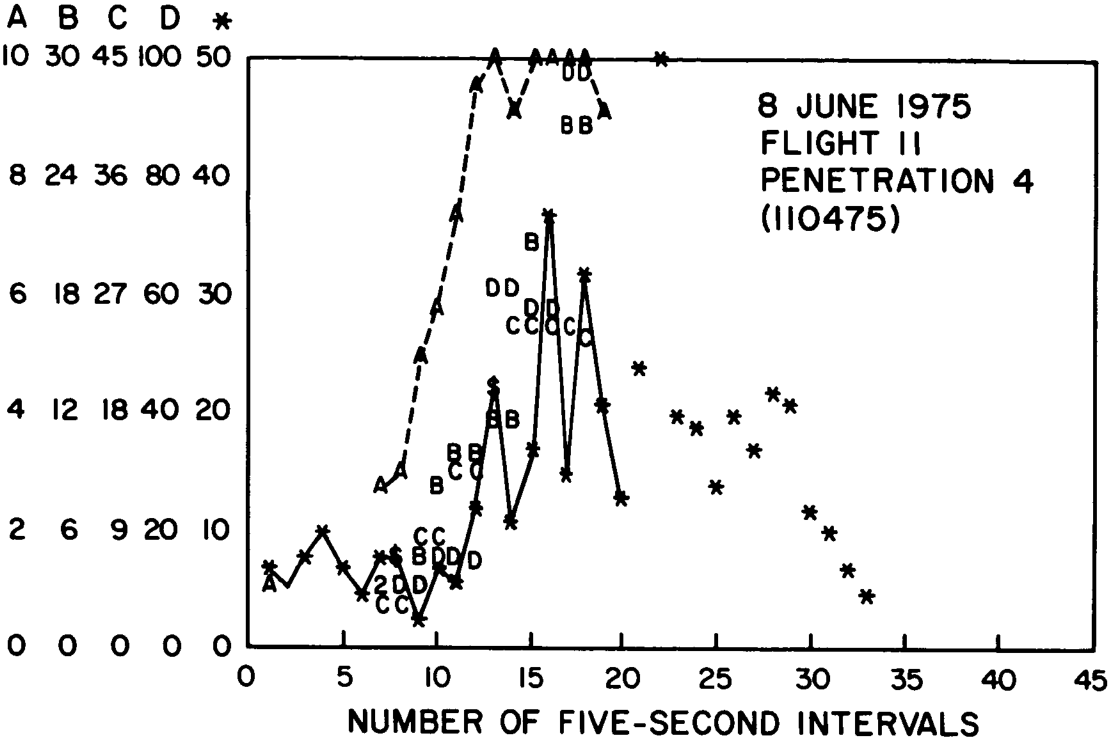


Figure 8. 8 June 1975 penetration number 4: Time (space) cross section for maximum values recorded for each five seconds of flight and corresponding Doppler radar data during penetration. Derived gust velocities in ft-1; spectrum width (A's) in ms-1; velocity gradient (B) in 1000 x s-1; Laplacian is "D." A number indicates the number of collocated data points. Dashed line connects values of spectrum width and solid line the derived gust velocities.

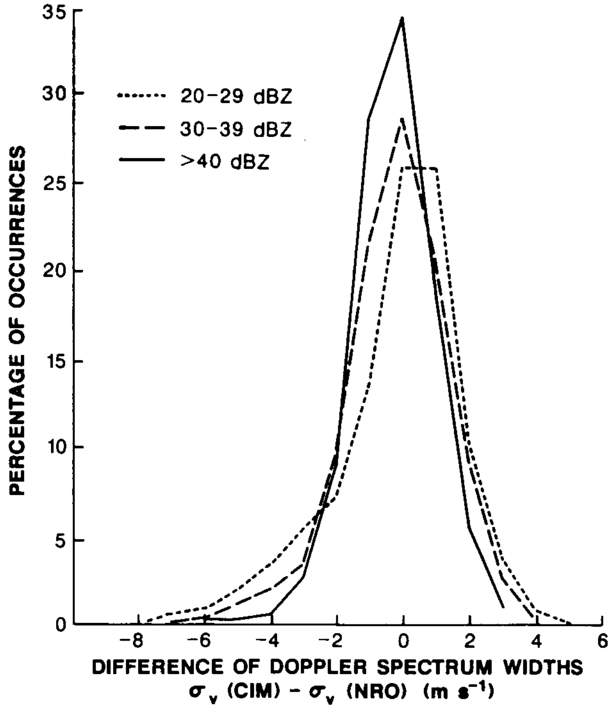
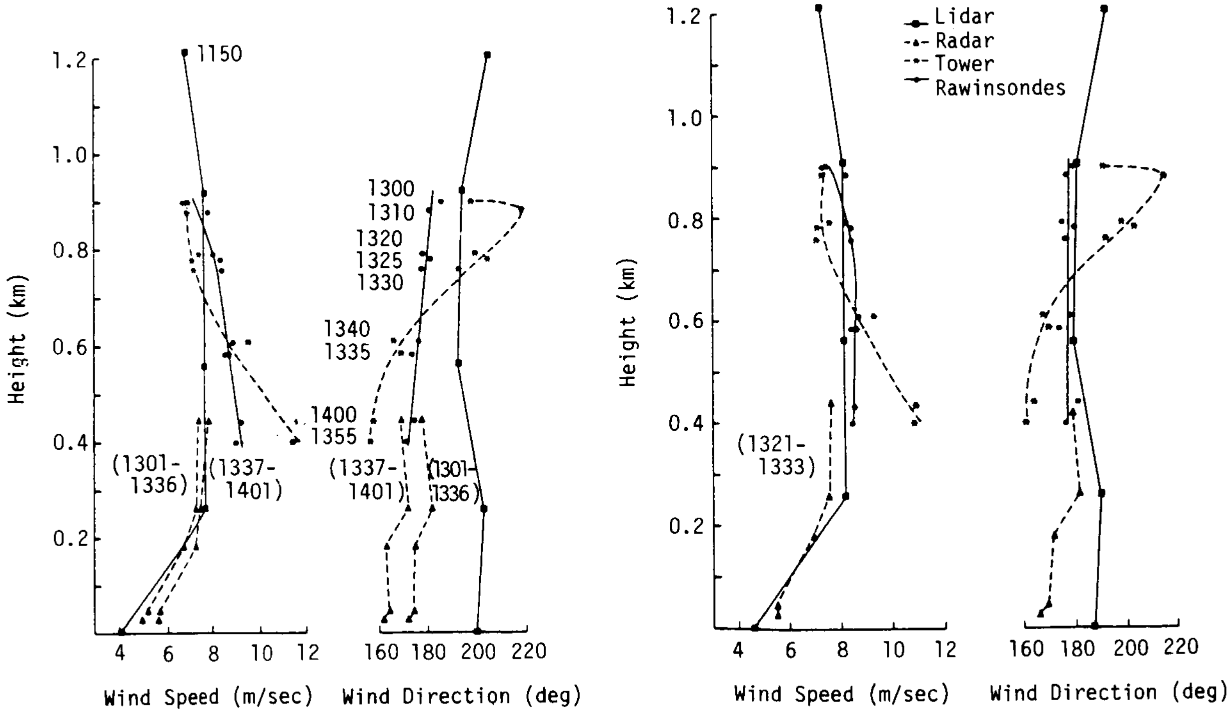


Figure 9. Comparison of spectrum widths obtained by two Doppler radars for various areas of reflectivity.



(a) Wind profiles measured by lidar, radar, tower, and rawinsondes

(b) Wind profiles measured by lidar, radar, tower, and rawinsondes adjusted to remove a time trend relative to 1330 CST. The tower profile was constructed from a 12-minute average of data from 1321-1333 CST.

Figure 10. Comparison of wind profiles.

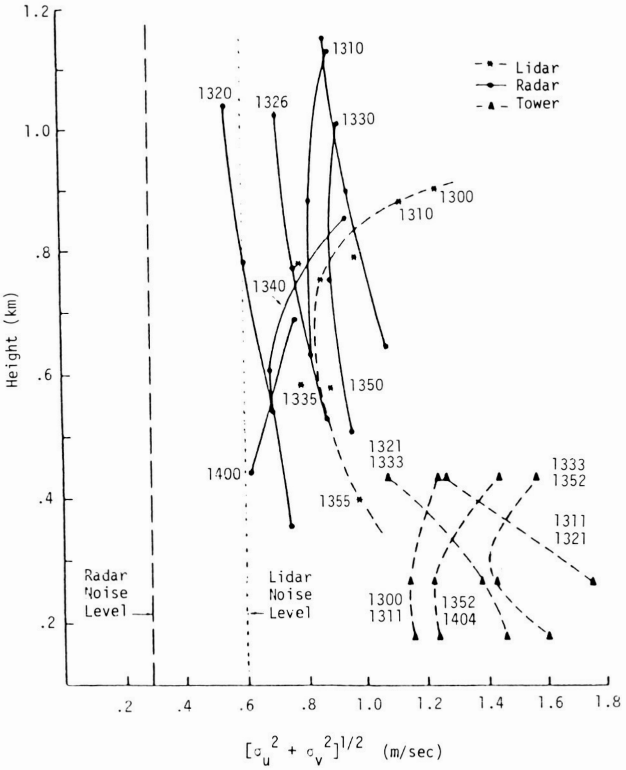
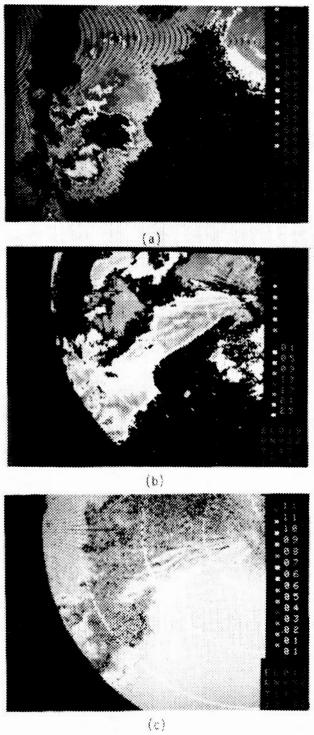


Figure 11. Standard deviation of the horizontal velocity fluctuations from lidar, radar, and tower.


(a)

(b)

(c)

Figure 12. Doppler radar display of (a) reflectivity, (b) velocity, and (c) spectrum width of a storm south of NSSL. Note displacement of the position of areas of maximum reflectivity, maximum velocities, and maximum spectrum widths relative to each other.

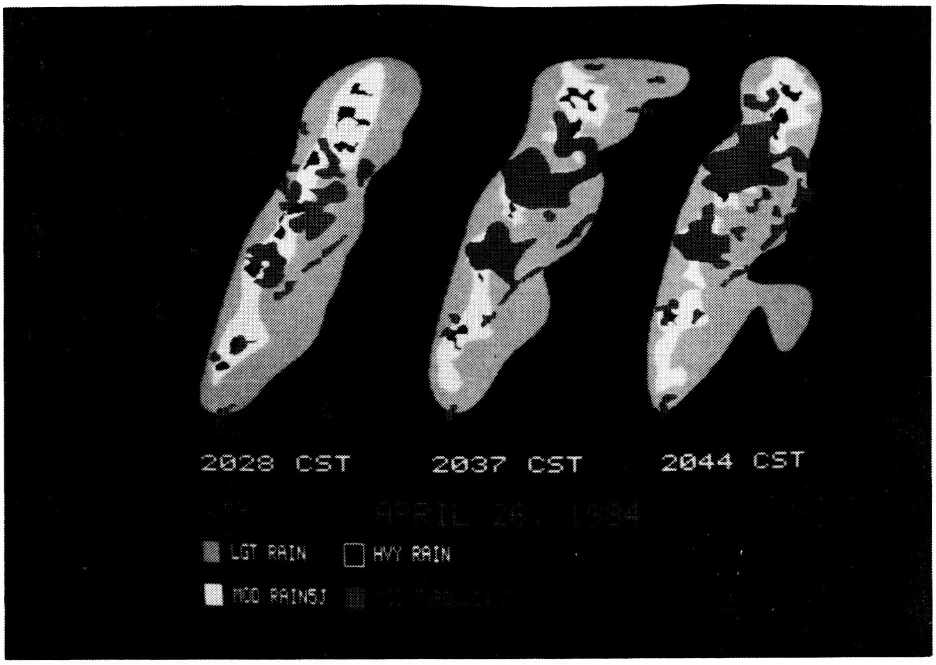


Figure 13. Storm hazard proposed NEXRAD display showing the use of a smoothing algorithm to delineate the hazard. Note time continuity of the hazards.

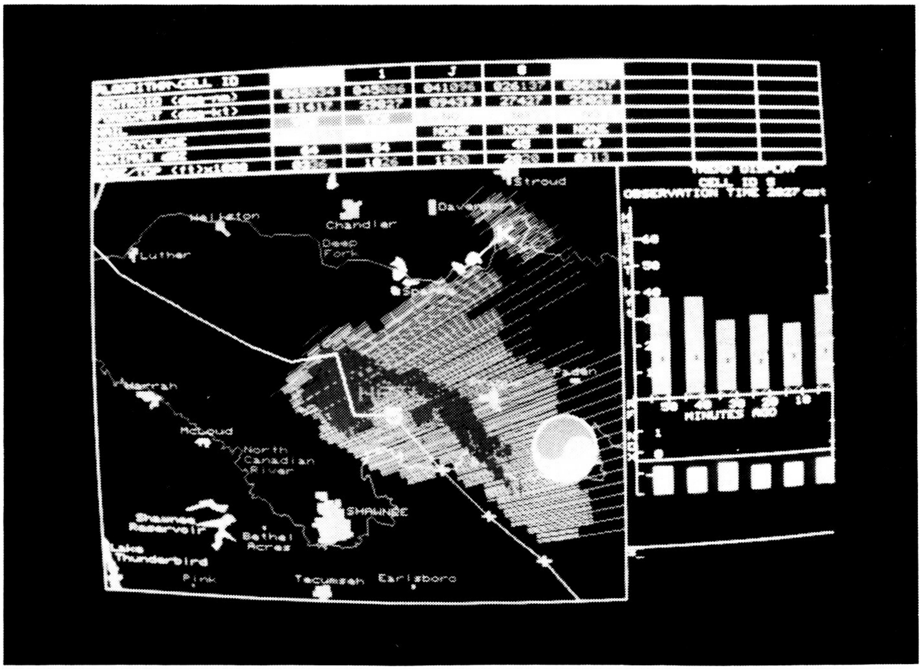


Figure 14. A second proposed type of NEXRAD display under development to provide pertinent information for a forecaster.

N87-22349

CAT-GENERATING MECHANISMS

Morton G. Wurtele
UCLA
Los Angeles, California

I'll begin with these three areas:

1. Development of instability configurations
2. The transition from unstable growth of these configurations into turbulence and a description of the nature of that turbulence
3. The question of decay of turbulence and one of the most controversial topics, the existence of what is called "fossil turbulence."

People involved in design and simulation want simple descriptions of turbulence that exists in the atmosphere and oceans, in these "clear-air" conditions. That description is not going to be forthcoming at this time. There are going to be all sorts of characteristics of these turbulent states. And, I might add, that it is amusing that the oceanographers have the advantage of us here. They are able to get in there and measure these things better than we can in the atmosphere now, when it comes to accurate measurements. And you want to keep your eye on what they are doing because a lot of the information that we gain is going to come from them.

As far as the existence of unstable configurations goes, of course, the vortex sheet has been known to be unstable for more than a century, but the first actual computation, beyond the simple fact of instability, was that of Rosenhead [1] in 1931 where he represented the vortex sheet as a sum of a lot of little vortices (Figure 1), each of which is acting on the others. And, of course, the vortex sheet is an equilibrium configuration until it is disturbed, and then the little vortices tend to move each other until it winds up in this familiar way. A lot of the literature refers to instability and/or wave breaking. These are very confusing terms really because this type of situation could conceivably be called a wave breaking. The next one (Figure 2) has totally different dynamics, namely, a wave on the surface of the ocean. Here is a laboratory wave breaking in the surface of water (Figure 2a). The dotted line is Longuet-Higgins' analytic solution to the problem [2]. Figure 2b is a picture from a surfing magazine which Longuet-Higgins picked up and fit his theoretical profile precisely to the pictured profile [3].

We are in a position to understand both of the mechanisms illustrated in Figure 2, even though they are quite different. The second one (Figure 2b) is so familiar, of course--the degeneration of that instability into a turbulent flow on the beach--that it may be surprising how little it has been studied. There are many pictures such as Figure 3 that depict the configuration of these roll-up type vortices in the atmosphere which have usually been visualized by cloud patterns [4]. This one is just off the coast of California. The atmosphere is known to have density differences like the water wave and vorticity in the basic flow like that studied by Rosenhead [1], but in both of these cases the atmosphere has the variable continuously distributed, rather than concentrated either in a vortex sheet or an interface between the fluids of different densities. Attempts at simulation have been made in the laboratory. Figure 4 is an early example of the fact that, if one takes high resolution rather than the characteristic radiosonde resolution, one can identify layers of low Richardson number in an overall stable layer [5]. In this case, the resolution is only 400 m and the Richardson number varies over four orders of magnitude and, of course, it can go to infinity as the shear goes to zero. This has been well known. We do not know exactly how these fine layers come about, but we can expect to find them.

In the laboratory, wave breaking can be represented, for example, in the early work of Thorpe [6] a very clever device was used (Figure 5). This is the two fluid system here and that is tilted so that you can get a shearing across the interface and these little waves develop, break, mixing occurs, and they die down. Thorpe suggested that the K-H mechanism looked like this. Compared to Rosenhead's calculation, Thorpe's work is in an earlier stage because we are only looking qualitatively and not doing numerical work. In Figure 6 we have the development of a roll-up. Then the next step is pure arm-waving: the whole thing breaks down in some fashion. Quite recently, in 1983, McEwan [7], by use of a paddle, produced a breaking wave in the fluid and was able to measure the density gradient throughout. McEwan's figures are in color and so cannot be reproduced here, but Figure 7 presents an idealization of his results, which are as follows. The sequence of events is:

1. The rolling-up process produces an unstable density gradient, heavy fluid over light.
2. The breakdown of this convectively unstable region occurs on a much smaller scale, permitting irreversible diffusion of density and momentum.
3. This microstructure persists after the restoration of gross stability. The experiment shows that by this stage the motions are three-dimensional. This stage is relatively long-lasting, and is referred to by some authors (though not by McEwan) as "fossil turbulence."
4. Finally, the stratified structure is reformed, although with a slightly reduced mean density gradient in the mixed region.

This is one of the first demonstrations, even though quite recent, that the breakdown is essentially three-dimensional in character. The sequence of events is a little more clear than it was in Thorpe [6] but still not numerical. In other words, we still have not gotten in there yet and measured the character of the turbulent exchange which goes on between the breakdown of an unstable situation and the final decay of the turbulence.

We now turn to another current research approach, that of numerical simulation. This method has the great advantage of providing vast quantities of accurate data. But there are compensating disadvantages: turbulence is three-dimensional and involves a range of scales larger than non-turbulent flows; as a result, true turbulence simulation requires, at present, unconscionable amounts of time on the largest computers. Thus, it may be some years before numerical simulation answers the questions concerning CAT that are being asked. However, progress is already evident.

In two articles, Klaassen and Peltier [8,9] have proceeded as follows. Beginning with an unstable K-H wave, they integrated numerically with a two-dimensional model. The expected roll-up occurs, bringing heavy fluid over light, but no breakdown takes place. Rather, the system oscillates, energy going back and forth between mean state and perturbation. Then, choosing a time in this development, which is of course highly nonlinear, they subject the given configuration to a three-dimensional linear stability analysis. The time development of the unstable wave is shown in Figure 8, the streamlines in the top panels and potential temperature in the bottom panels. The results of the stability analysis--which obviously requires extensive computation--are shown in Figure 9. The growth rate of the fundamental mode ω_0, at its maximum value corresponds to a wavelength in the (longitudinal) y-direction of about one-fourth the depth of the shear layer. If this maximum growth rate of this mode is converted to dimensional values, it turns out to be approximately equal to N, the Brunt frequency, showing that the breakdown is convective in its dynamics.

People who are more operationally inclined may be very impatient with these results. Of course, if you have heavy fluid over light fluid you expect a gravitational instability to result! Nevertheless, these steps are necessary in arriving at something that operationally concerned people will want to see. This is as far as the Klaassen-Peltier model can go (since it is not a simulation in itself, but the three-dimensional stability analysis of a two-dimensional configuration derived from an earlier simulation). The next step will presumably be a full-scale simulation of the turbulent breakdown, with parameterization of eddies of less than a certain scale. This would be the beginning of a quantitative characterization of the turbulence.

I will now proceed to discuss some of my own work, numerical simulations of a very different kind: the flow of a stratified fluid--e.g., the atmosphere--over an obstacle. This can be an obstacle on the ground, or an obstacle at any elevation, of course. The terrain is a natural obstacle to conceive of, but a frontal surface aloft could be the source of the disturbance, or a cloud mass. We first take a simple linear analytic solution. The wind is increasing linearly with elevation and the Brunt frequency is constant. We consider a small disturbance (Figure 10a). Nh/U_0 is the parameter which traditionally is taken to govern the linearity of the computation. If h is the height of the obstacle, the Brunt frequency is N, and the speed of the fluid at the level of which it encounters the obtacle is U_0. Here the ratio 0.1 suggests that it is a purely linear situation. And, therefore, the analytic solution is valid. The next figure will show the development of the Richardson number field from this particular streamline field (Figure 10b).

Here we have cells corresponding to the cells of the streamline field. In these cells, we have alternately Richardson number increases and decreases. You will notice there are more contour lines in the increase than in the decrease. In other words, the imposition of the gravity wave on the stable fluid increases the stability of the fluid more than it decreases the stability of the fluid. However, the fluid does have cells in which Ri decreases, and the next figure will show what happens when we increase the magnitude of the disturbance. In Figure 11, $Nh/U_0 = 3$, and now we can no longer use the analytic solution; we have to use a simulation code. Again, simulation means starting the motion from scratch and allowing the atmosphere to flow over the obstacle. In Figure 11a the signal has only gone as far downstream as the first crest. We see the streamlines are no longer sinusoidal but are beginning to get nearly vertical at points. Figure 11b shows the density field. So here we do get, not surprisingly, regions of overturning. The point is: where the wave is trapped by the increasing velocity, by the shear itself, the situation is so stabilized by that trapping that the instability exists only in highly local regions at approximately the height of the disturbance. Nothing terribly exciting can happen. You can get a rotor cloud, but you cannot get the vast outbreaks of instability and clear-air turbulence that are characteristic of certain situations. These two figures have represented the type of thing that can develop when increases with height in the atmosphere, therefore, providing a reflecting or trapping mechanism. We now take a case, and this is one that has been studied more than any in which the wind is constant and the stability is constant. The analytic solution is by Miles and Huppert [10]. Figure 12 is a flow over an ellipse where $Nh/U = 0.5$, a reasonably linear situation. Here is our simulated solution of the same situation and this is a special simulation code. I do not know of any other simulation in atmospheric sciences in which an orthogonal grid is generated numerically in order for the disturbing boundary to be a coordinate surface. The computation is then done with this new grid preserving the character of the equations but with the new coordinate surface and then transferring back into the old x,z system so that the ellipse shows as an ellipse. You simply get waves in this linear case. However, if the disturbing obstacle is increased in elevation, we get the pattern of Figure 13, with one vertical streamline. Nh/U in this case is 0.93, the critical value for this ellipse. Here we have simulation reproducing that situation, and we do get that vertical streamline precisely. The second vertical streamline, or almost vertical streamline, has lost some of its energy because the energy is spreading out in two dimensions. But that is simulated less well because the time is not long enough for the energy to fully straighten up that streamline.

The fact is, of course, that in nature the wind is not constant with height and the Brunt frequency is not constant with height. Either increasing or decreasing wind is the rule. We will now go to the situation in which we get a <u>decreasing</u> wind. If you have a wind that is linearly decreasing, it will eventually go through zero. This gives what is called a <u>critical level</u>; it has been much studied, but less simulated; and it is a situation that is highly productive of a nonlinear type of reflection. We have studied that first by taking a simple sinusoidal disturbance. That is a monochromatic disturbance; but the reflection from the critical layer produces many higher frequencies.

In Figure 14, however, the disturbance generates <u>all</u> frequencies. The left-hand panel represents the stream function; the mean flow is seen to reverse directions at 10 km elevation, the critical level. Well below this, at 6 to 8 km elevation, a reverse flow or rotor circulation is evident. The density field (right-hand panel) exhibits similarly a reverse density gradient. This would be a region of extreme turbulence. Note that almost no disturbance penetrates above the critical level.

However, it turns out that the existence of a critical level is not necessary to produce this type of nonlinear reflection. Figure 15 represents a similar result for a flow that decreases exponentially with elevation; in the diagrammed panels, the mean flow exceeds 10 m/s at all levels. The left-hand panel shows the total horizontal velocity. At elevations near 4 km, the oncoming flow of 25 to 30 m/s has reversed itself to -25 m/s just in the lee of the obstacle! The right-hand panel shows violent vertical updrafts and downdrafts of more than 14 m/s within the horizontal distance of a few kilometers. Again, a very turbulent region would result.

We conclude that the only thing necessary for the existence of a highly reflective and potentially turbulent situation is a reasonably deep layer of decreasing wind speed. (By decreasing I mean that it is lower at higher levels than at lower levels.) This is fairly characteristic of the stratosphere. So it suggests that the structure of the lowest stratosphere is often extremely pregnant as far as clear-air turbulence is concerned. The question is: Does the disturbance, which in these cases originates at the surface of the earth, actually propagate sufficiently into the stratosphere to produce this sort of turbulence? The answer is, sometimes it does and sometimes it does not. And it is surprising how little this question has been studied. It is what we in my group are devoting ourselves to now. To what extent does the flow structure in the troposphere plus the tropopause itself act as a barrier to gravity wave energy being propagated upward?

Figure 16 will show a situation in which this is the case. The simulation used the best data we could get from Jack Ehernberger and others upwind of the famous United Airlines episode over Hannibal in 1981 [11]. In this case, there was quite a bit of damage and injury inside the plane. We tried as best we could, but there is not any source of disturbance at the surface of the earth near Hannibal. But even if we exaggerated the profile of the terrain there, we could not propagate energy into the stratosphere. Nothing much happened. However, there was an enormous cumulonimbus cloud bank, which was really a very good two-dimensional obstacle to the flow at the time, and it extended to about 9 km. We assume the cloud bank to be the obstacle; and it was sufficient to produce this very large disturbance in the stratosphere. From about 11 km up we had rapidly decreasing wind speed. The hatched areas are areas of subcritical Richardson number. I believe the plane was flying at about 13,000 feet.

The two approaches I have outlined present, I think, the present position of our understanding. We understand how very stable atmospheric flows with large Richardson numbers can be rendered unstable. We understand the process of breakdown of this instability. We can watch the turbulence develop in the laboratory and distinguish between an active stage and a "fossil" stage. But we await detailed measurement and/or simulation of the turbulence.

I feel that this workshop was well conceived and should be repeated. Perhaps by the time of the next one, the scientists will be able to answer the questions asked by the engineers at this one.

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QUESTION: David Walker (Lehigh University). Could you say something about your simulation. Is it an inviscid simulation? You don't have the no-slip condition on the surface in those calculations? Is that correct? In those obstacles, I would expect that you would get a structured kind of eddy shedding off those obstacles that I didn't see in those results.

ANSWER: This is a completely inviscid model.

WALKER: The comment I would make is we've done a number of experiments involving obstacles of that nature at Lehigh. What in fact you get is a structured kind of hairpin vortex shedding off those kinds of obstacles that penetrates after a while well up above the ground plane.

WURTELE: These are not intended to represent the flow in the immediate region of the obstacle at all. In order to do that we would have to simulate the whole atmospheric boundary layer and we haven't attempted to do that. Really these solutions are valid at distances from the obstacle. Particularly it's the vertical propagation we are concerned with here.

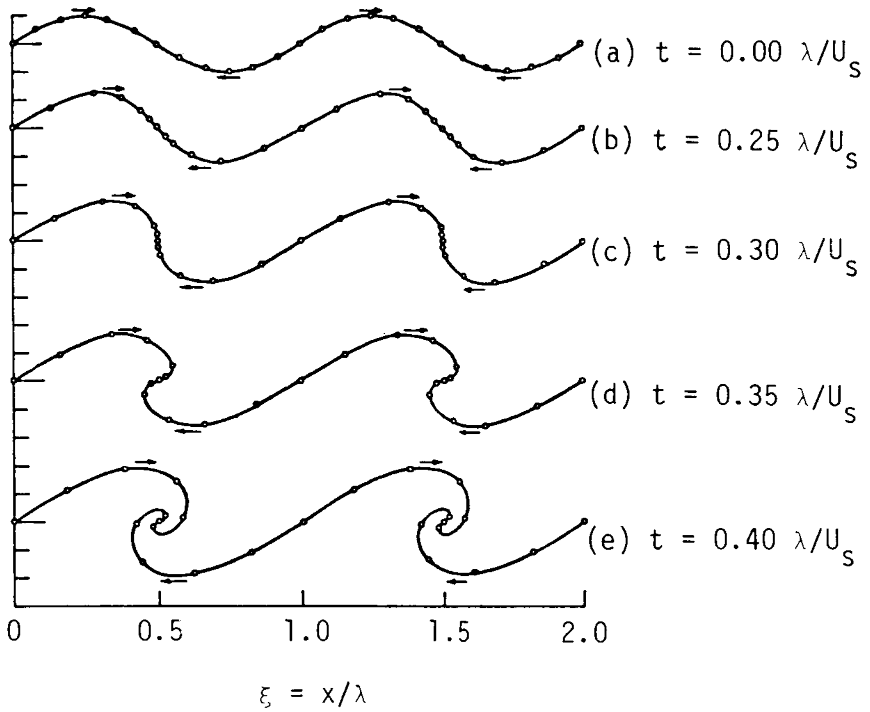
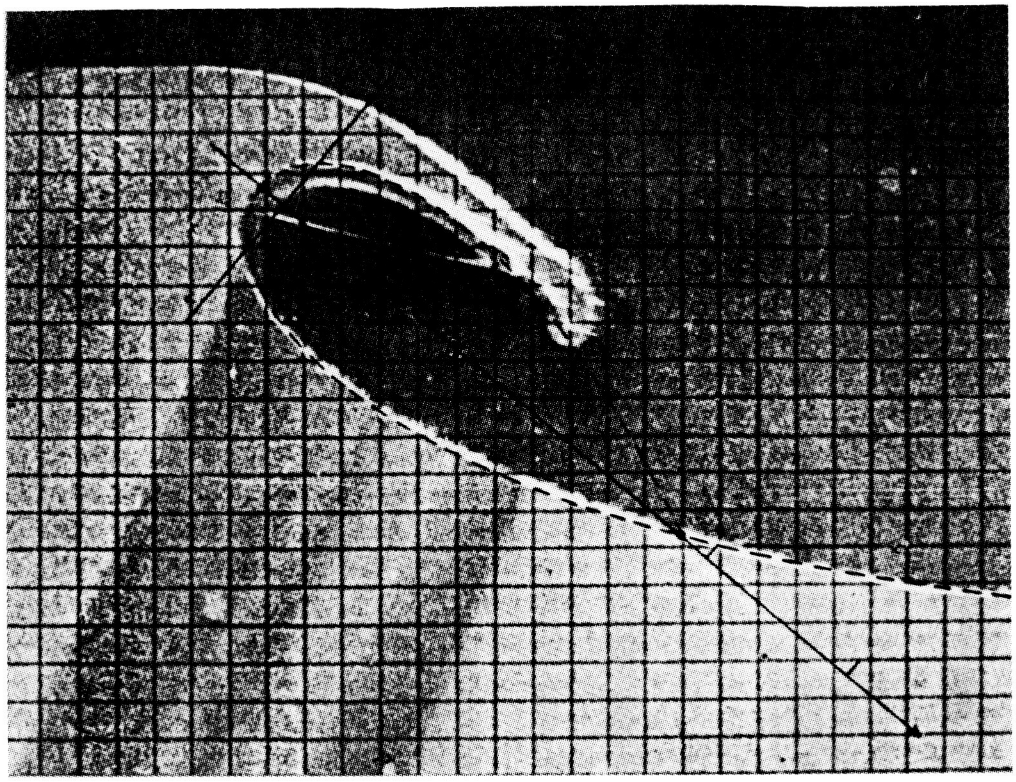
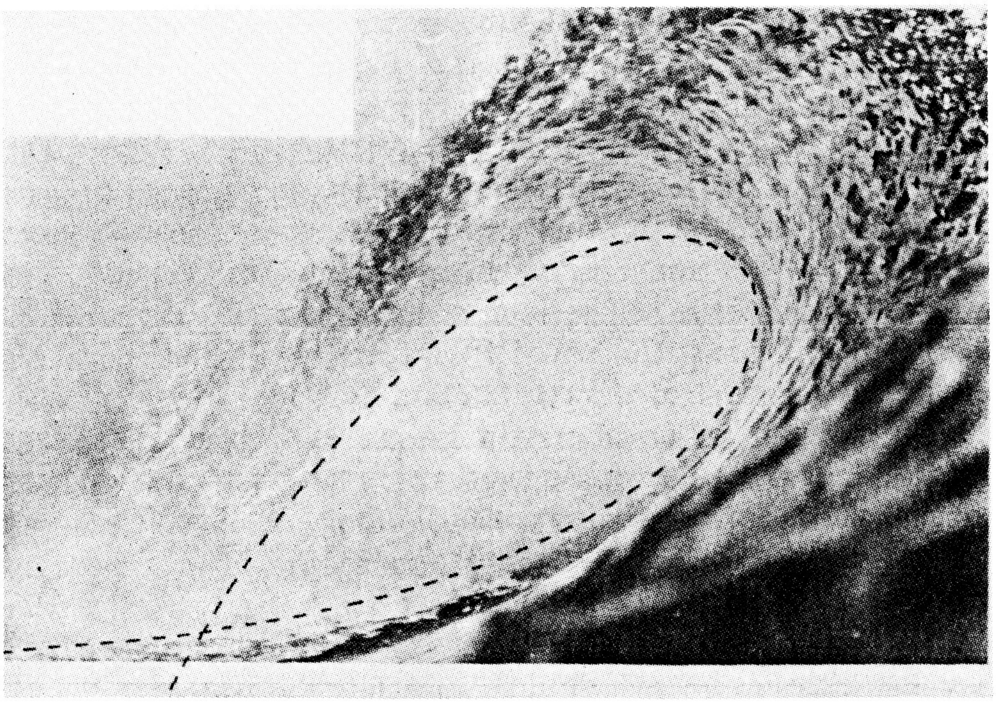


Figure 1. The rolling-up of a vortex sheet which has been given a small sinusoidal displacement [1].



(a) Laboratory wave breaking



(b) Longuet-Higgins [2] P_3 solution superimposed on a breaking wave

Figure 2. Surface waves breaking, with analytic solutions of Longuet-Higgins [2,3] superimposed.

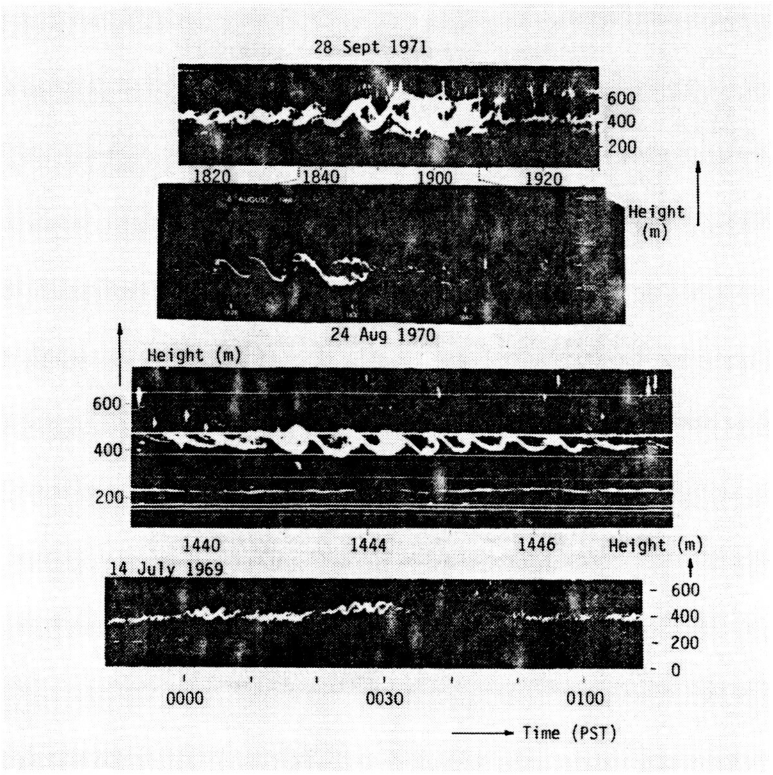
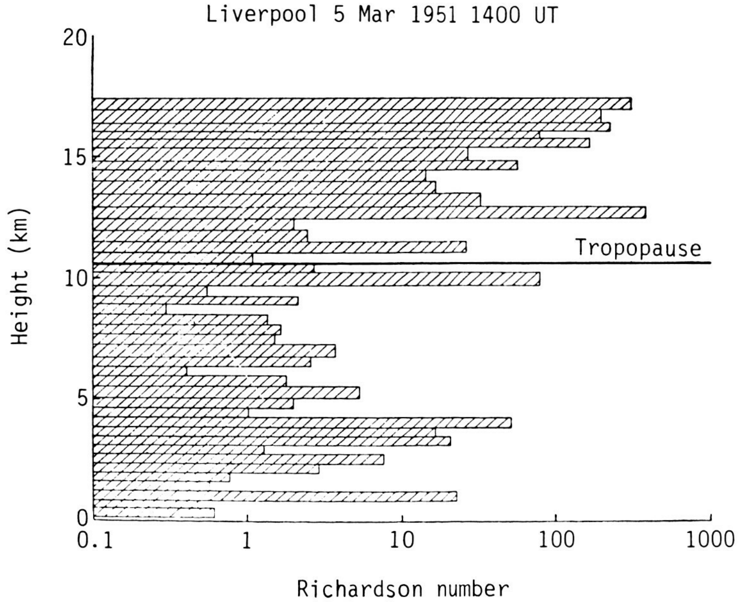
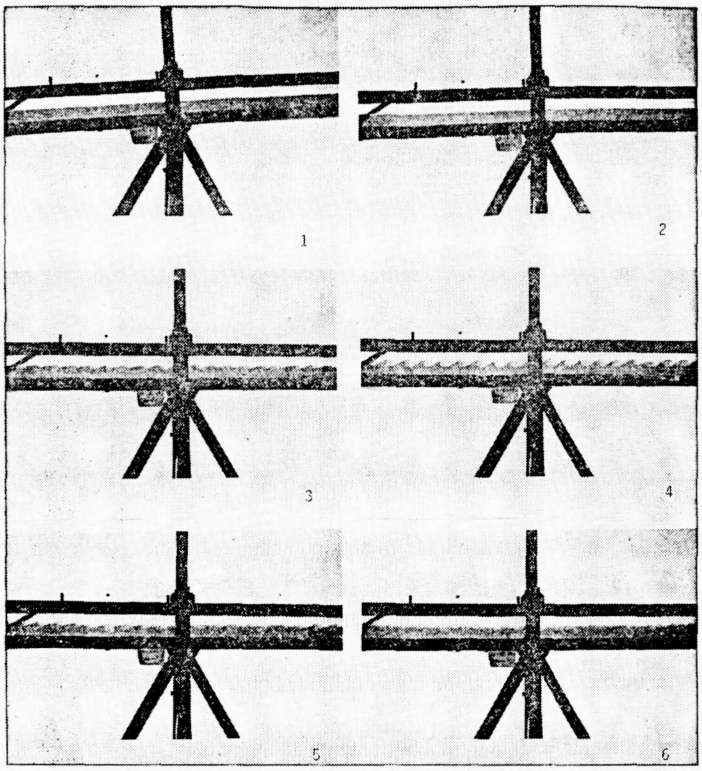


Figure 3. Kelvin-Helmholtz wave roll-up configurations as detected in the atmosphere by FM-CW radar [4].



A profile of gradient Richardson numbers in the atmosphere deduced from radiosonde wind and temperature data averaged over layers about 400 m thick.

Figure 4. High-resolution profile of Richardson number from Woods [5].



The growth of disturbances in a flow with J = 0.077 ± 0.01. The time between each successive photograph is about 0.5 sec and the length of the scale is 45 cm.

Figure 5. Breaking of unstable Kelvin-Helmholtz waves in the laboratory [6].

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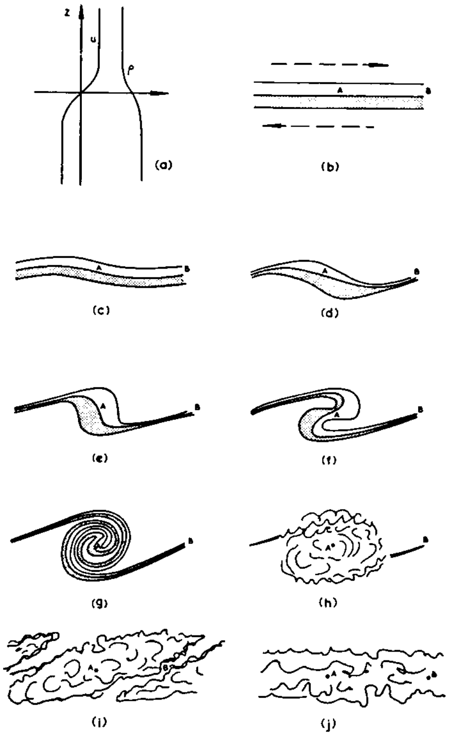
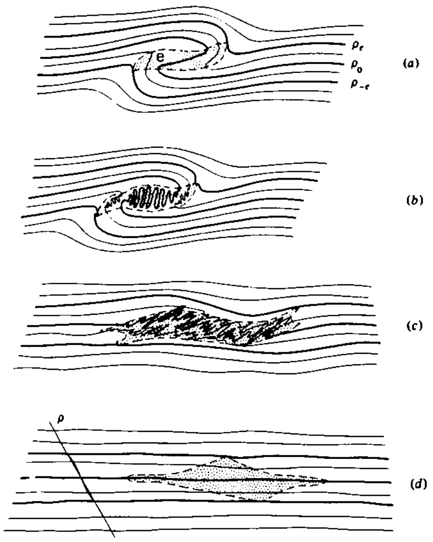


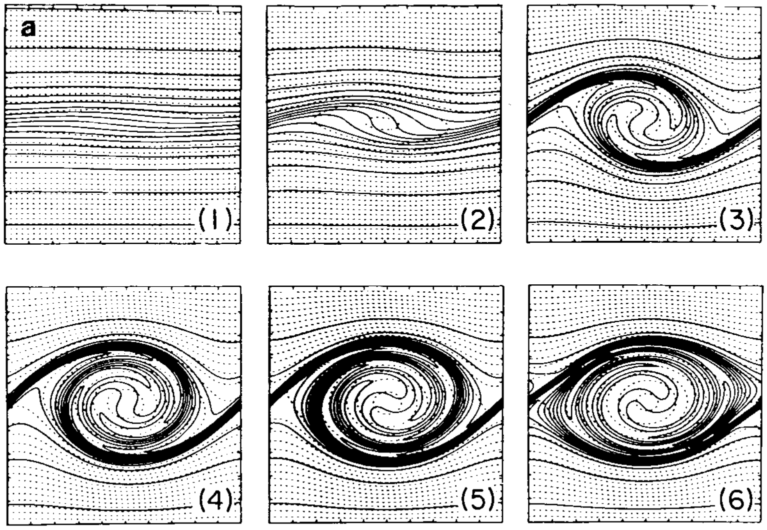
The growth of disturbances: (a) the density ρ and velocity u distributions; (b) the lines mark a fluid of constant density, points A and B are fixed, the arrows indicate the direction of flow; drawings (c) to (j) show the development of instability. The points A and B remain fixed, and the lines continue to mark a fluid of constant density.

Figure 6. Schematic of generation of turbulence from breaking of unstable Kelvin-Helmholtz waves [6].

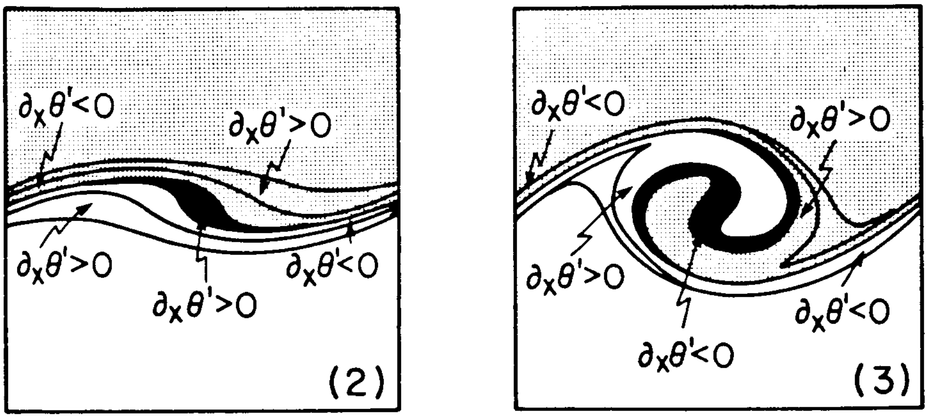


Idealization of a mixing event in a continuous stratification.
(a) Overturning. (b) Development of interleaving microstructure.
(c) Static stability is restored but microstructure is preserved.
(d) Gravitation to an equilibrium has changed the surrounding density profile between extremum isopycnals. The distortion of the profile is exaggerated for clarity. The intermediate isopycnals (fourth and sixth from the top) are displaced upwards and downwards respectively from their original positions, representing a gain in stratification potential energy.

Figure 7. Schematic of generation and decay of turbulence from breaking of unstable K-H waves [7]. Stage (c) is sometimes called "fossil turbulence."

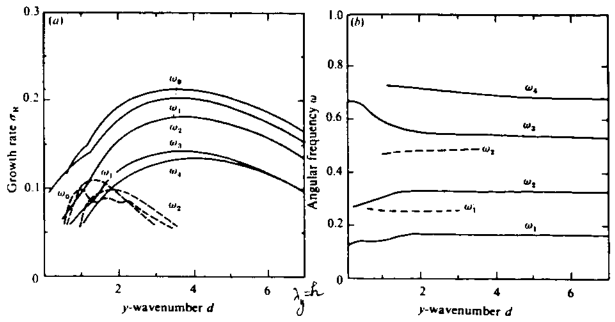


(a) Streamlines (dashed) have been overlaid on (a) the isentropes (solid), and (b) contours of the vorticity field (solid) illustrating evolution of the KH wave at Re = 500. Numerals 1-6 refer to key times. Contour intervals for the potential temperature field and streamfunction are all $\Delta\theta$ and $\Delta\psi$, respectively. The contour intervals for the vorticity field are $\Delta\zeta$ for (2) and $2\Delta\zeta$ for the remainder.



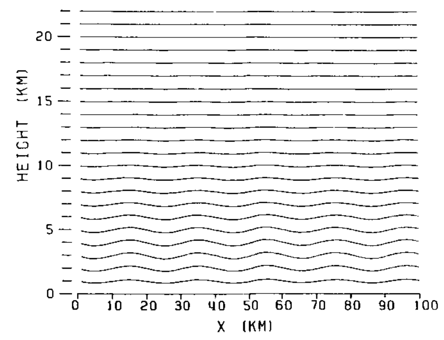
(b) Sketches of potential temperature field illustrating baroclinic sources and sinks of vorticity for a typical KH wave at key times (2) and (3) in the energy cycle. Median contour interval has been shaded darkly; regions with potential temperatures greater than the median value have been shaded lightly. Regions of baroclinic generation of vorticity $(\partial_x\theta' < 0)$ are found in the braids; regions of baroclinic destruction $(\partial_x > 0)$ are found at the right and left edges of the core.

Figure 8. Roll-up of unstable Kelvin-Helmholtz waves in simulation by Klaassen and Peltier [8]. Breakdown does not occur in two dimensions.

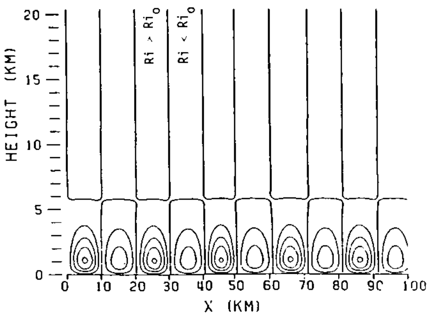


The growth rate σ_R and (b) angular frequency ω as functions of the spanwise wavenumber d for various longitudinal (b = 0) unstable modes of the Re = 500 KH wave at the key time (5) in its energy cycle. The sequency of modes labeled $\omega_0 \ldots \omega_4$ (solid lines) is associated with the primary SAR, while that for the $\omega_0' \ldots \omega_2'$ modes (dashed lines) is associated with the secondary SAR. The truncation level used was the maximum N = 19.

Figure 9. Growth rate of three-dimensional perturbation of unstable configuration of Figure 8 [9].

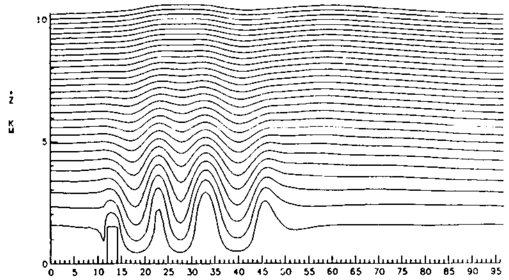


(a) Streamlines (Ri = 8, Nh/U = 0.1).

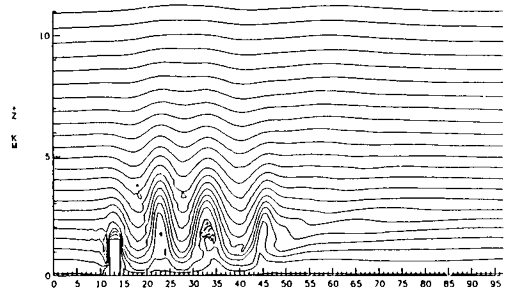


(b) Richardson number field perturbations (contours for quantity $(Ri - Ri_0)/Ri_0$ at intervals of 0.05).

Figure 10. Stratified shearing flow over an obstacle (small disturbance of height h) and corresponding perturbations of Richardson number field.

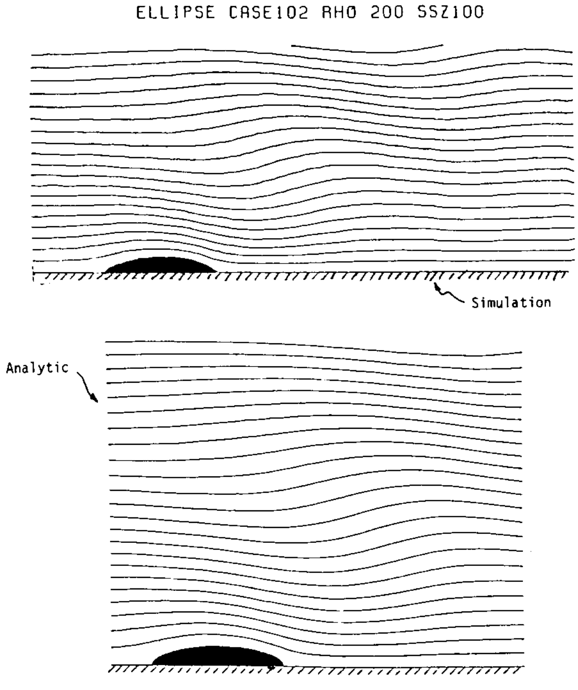


(a) Streamlines for flow of Figure 10a except that Nh/U = 3.0



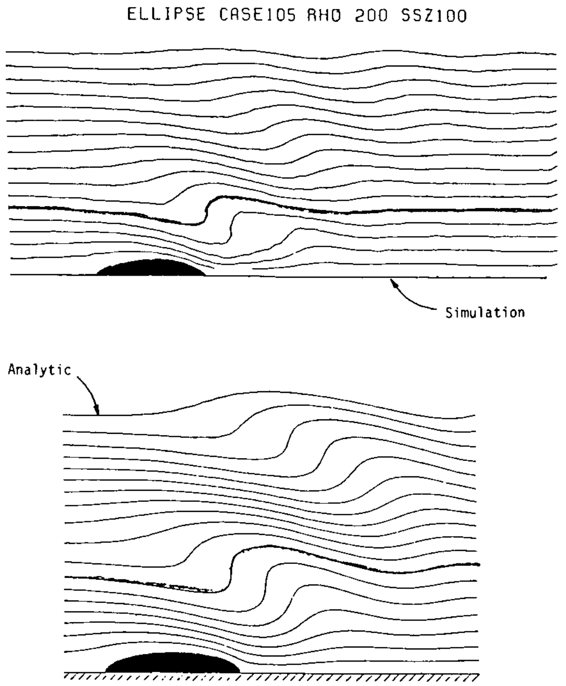
(b) Density field for flow of Figure 11a showing unstable regions

Figure 11. Streamlines and density field for flows.



Stratified shear flow over the semi-elliptical obstacle $\epsilon = 0.3$ for $\kappa = 0.5$

Figure 12. Flow over an ellipse of height h with Nh/U = 0.5. Upper panel: simulation. Lower panel: analytic [10].



Stratified shear flow over the semi-elliptical obstacle
$\kappa = \kappa_c = 0.93$

Figure 13. Same as Figure 12 but for Nh/U = 0.93. Unstable streamline is darkened. Upper panel: simulation. Lower panel: analytic [10].

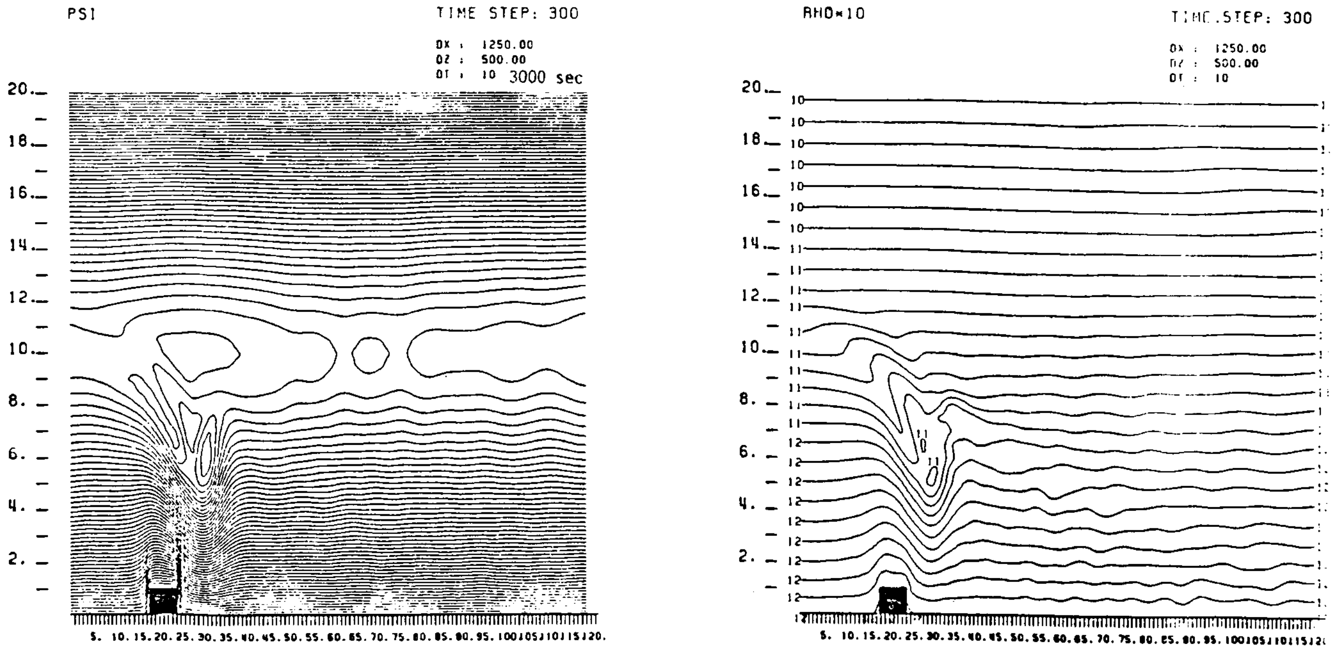


Figure 14. Stratified shear flow with critical level. Left-hand panel: streamlines. Right-hand panel: density.

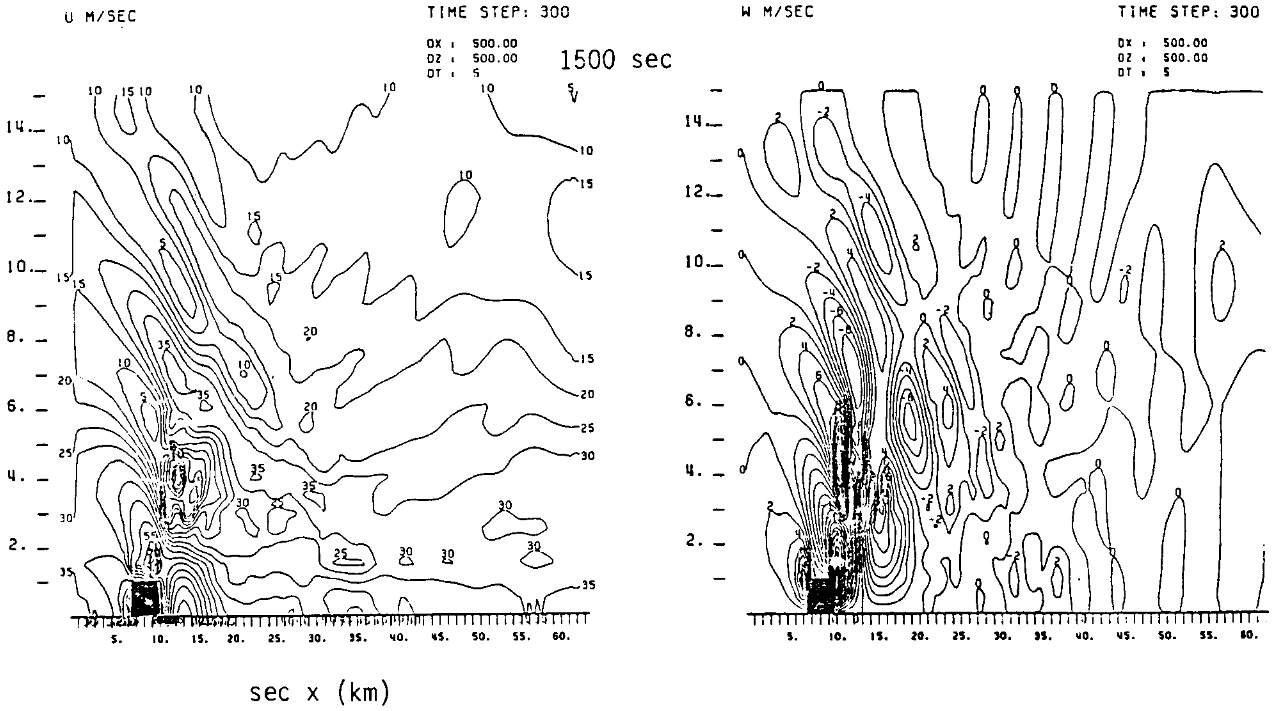


Figure 15. Stratified shear flow with exponentially decreasing speed. Left-hand panel: total horizontal velocity. Right-hand panel: vertical velocity.

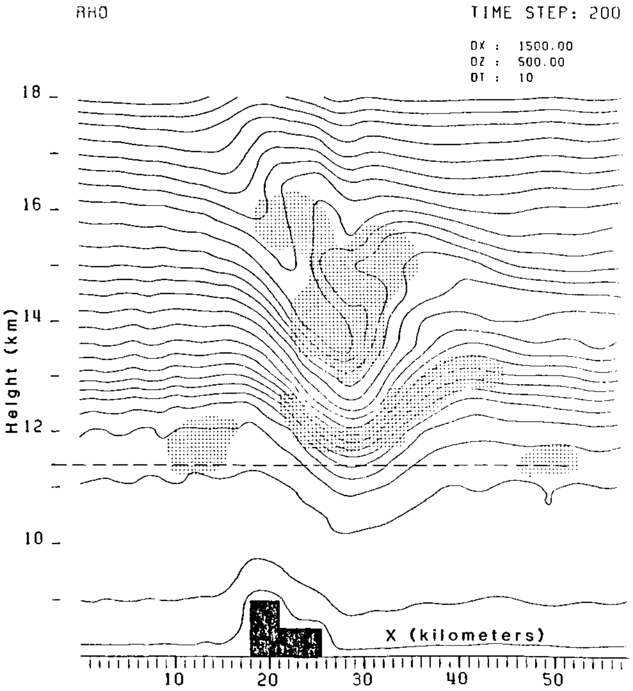


Figure 16. Simulation of conditions under which CAT-encounter occurred. Regions of Ri < 1 are hatched.

N87-22350

PHYSICAL MECHANISMS OF HEAT, MOMENTUM, AND TURBULENCE FLUXES

John S. Theon
NASA Headquarters
Washington, D.C.

This paper discusses, in a qualitative way, the physical mechanisms which generate fluxes of heat, momentum, and turbulence in the atmosphere. This material is presented to acquaint those people in attendance at the workshop who normally are involved in the aviation aspects of turbulence with the Earth science aspects of turbulence as important processes in the atmosphere.

To attempt to describe turbulent fluxes of heat, momentum, and moisture in precise mathematical detail becomes an intractable problem. It is burdened by an eighth order set of equations involving more variables than equations. It is a closure problem which requires complicated assumptions that are not necessarily always satisfied, variable boundary conditions, and sparse observational data. Therefore, we must approach the problem in a simplified manner to obtain any kind of solution involving the variables of shear, stress, and heat, moisture, and momentum fluxes. In general, the planetary boundary layer is small in comparison to the total depth of the atmosphere. Thus, in models which attempt to describe the entire atmosphere (for example, general circulation models), the planetary boundary layer can be ignored entirely because it does exert a fairly small influence over a short time scale. However, after about 12 hours or more, the dissipation processes in the planetary boundary layer become noticeable and when the model is applied to longer and longer forecast time periods of up to a week or ten days (as is now being done in Europe), then these effects must be included. They become very important in models describing the long-term behavior of the atmosphere, especially climate models.

There are other problems, of course, in which the inclusion of the planetary boundary layer is extremely important. Air pollution studies, air-sea exchanges, mesoscale models, and so on, must account for the planetary layer in very specific terms. Some of the physical mechanisms that are involved in generating fluxes are described in the following.

Figure 1 illustrates the scales of size and motion that are important in the generation of fluxes in the atmosphere (after Brown [1]). The top part of the figure shows the depth of the entire tropopause to be on the order of 10 to 20 km and the mixed layer depth about 1 km. An expanded view of the lowest kilometer shows this to be the level of the typical inversion (at 1 to 1.5 km), or the layer below which there is complete mixing with more or less stratified flow above. The important dimensions here in terms of roughness are of the order of 10 m high, but examination of the microscale in that layer involves concerns about such things as the trees, bushes, etc. Again, examination of an even smaller scale, perhaps the lowest 10 cm, which would normally be called a smooth surface on the planetary boundary layer scale, has within it roughness elements as well. These are very fine in detail and the turbulence they generate is also very small. Fortunately, it is not necessary to describe the smallest scales in that succession to obtain some benefit from the processes of heat, momentum, and moisture exchange. It is now recognized that the biosphere has a very important role in exchanging moisture, heat, and momentum with the atmosphere.

Let us consider some of the physical mechanisms for this exchange. Figure 2 shows, conceptually, some of the mechanisms for the generation of atmospheric turbulence which effect the fluxes of heat, momentum, and moisture. Of course, one of the most obvious mechanisms is vertical wind shear, shown in Figure 2(a). When there is a shearing action of any kind, turbulence can occur if the shear is sufficiently strong. This is a means for converting the energy in the larger scale flow into turbulence kinetic energy, and it is a mechanism that can generate turbulence anywhere in the atmosphere. Frequently, it is near the ground because strong shears occur in flows near a fixed boundary.

Differential heating is also a very important turbulence generating mechanism. The surfaces of the Earth are not uniform. Forests absorb solar energy quite differently from the oceans, and the highly reflective areas in the desert have quite a different capability for absorbing solar energy. In terms of thermal properties, the ocean has great heat capacity and is relatively stable in surface temperature both day and night. The reason is that the energy is absorbed through a deeper layer. Also, the heat capacity of water is large and can be mixed to a depth which virtually guarantees that the temperature of the surface will not change very much during the diurnal heating cycle. On the other hand, particularly barren land surfaces have very little thermal capacity. They have very poor conduction to the subsurface layers, and so the surface temperature over land can vary enormously from day to night. As shown in Figure 2(b), such temperature differences can generate vertical motions, literally heating or boiling the air that is lying in contact with the hot surfaces to generate turbulence. Flying in an aircraft in the boundary layer on a bright, sunny day produces a choppy ride from this kind of effect.

Even when there is a uniform surface temperature, surface roughness can generate turbulent flow. Figure 2(c) illustrates a stratified, laminar flow encountering a rough underlying surface which generates turbulence. This is the same kind of mechanism that occurs when an aerodynamic surface with rivets or surface debris on it trips a laminar flow into a turbulent flow.

Professor Wurtele [2] mentioned waves in the atmosphere that are set up by obstacles to the flow. Certainly, gravity waves can be generated by a number of phenomena in the atmosphere. Such waves can reach a state where their amplitudes are sufficiently large and the shear and buoyancy forces acting on them are conducive to the generation of turbulence. Figure 2(d) shows that the wave can literally destroy itself in turbulence. Professor Wurtele showed an example of Kelvin-Helmhotz waves that do produce overturning in the atmosphere, thereby generating turbulence.

It has been known for a long time that when the horizontal gradient is sufficiently severe in jet streams, and particularly if there is curvature in the flow, vortices can be shed to one side of the jet as illustrated in Figure 2(e). Such a phenomena is one cause of clear-air turbulence.

Differential advection often occurs in the midwest and southwest in the springtime. In such a case, a low-level flow from the south, which is quite warm and moisture laden, is overrun by a dry flow from the west across the Rockies, as illustrated in Figure 2(f). This situation can literally produce sufficient vertical instability so that there is natural overturning. Of course, when that happens, very severe turbulence occurs and the conditions are very conducive to producing thunderstorms and tornadoes.

The downburst is a phenomenon that in recent years has received a lot of attention. One type of downburst is thought to occur when a moist layer aloft drops precipitation through a fairly dry layer below it. The precipitation evaporates and in so doing cools the dry layer considerably. As shown in Figure 2(g), the resulting cold air is very dense, causing it to plunge downward rapidly toward the surface in a relatively confined region. This downburst generates turbulence as it shears through the horizontal flow on the way down, and when the plunging column of air hits the ground, it generates additional turbulence as well.

We heard yesterday how precipitation generates turbulence. This mechanism operates on a smaller scale, but hydrometeors falling through the air very definitely generate turbulence and alter the flow patterns that would otherwise occur in the vicinity of non-precipitating clouds. Figure 2(h) shows schematically the turbulence generated by falling precipitation.

Tropopause folds are a phenomenon which have been recognized for some years, but until recently no one believed that they occur as frequently as they do, nor was their role in transporting potential vorticity into the troposphere well understood previously. These folds generate turbulence because of the instability established when more buoyant stratospheric air is forced below heavier tropospheric air as shown schematically in Figure 2(i). Here, the air with higher potential temperature (θ) penetrates into the dense air below it in the fold and is then cut off. The instability thus generated is restored to more stable flow by turbulent processes.

We have already heard about the role of fronts in generating turbulence. Figure 2(j) shows a cold dome of air that has a reasonably coherent surface advancing into warmer, lighter air and actually stirring it up. Ahead of the front, squall lines or thunderstorms often develop. Thus, fronts are a source of turbulence and, though it is a moving mass of air, it could just as well be considered a solid obstacle that is moving along the surface generating turbulence ahead of it.

Orography is another important mechanism for generating turbulence, particularly in the boundary layer. Figure 2(k) shows the turbulence generated when flow crosses an orographic barrier. In this case, air is flowing over mountains, and a wake that contains considerable turbulence is generated right in the boundary layer. Rotor flows are generated in the wake at the top of the boundary layer, stirring additional turbulence themselves. There are gravity waves and mountain waves; gravity waves propagating away from the mountain and mountain waves standing on the lee side of the mountain at higher levels. Graphic examples of such waves were given in Dr. Wurtele's paper [2].

There is a class of stirring actions in the atmosphere that literally consists of convective instabilities. Here I am talking about air that might initially be stable but if slightly disturbed, it becomes unstable. In Figure 2(1), convergence is shown which lifts a parcel from near the surface to its original level. If the parcel contains enough moisture, the moisture starts to condense, releasing latent heat. Of course, that energy makes the parcel more buoyant, raising it further. This lifting mechanism can generate a great deal of turbulence. Once the process starts, it can accelerate, becoming less stable, and eventually generating thunderstorms with violent weather activity.

All of these mechanisms are somewhat localized in space and time. If you look at the atmosphere as a whole, you would probably say that the atmosphere is largely stratified, and it is. But these important turbulence generating mechanisms are exceptions to that stratification which really make the system what it is, and they cannot be neglected. Turbulence creates the fluxes of heat, momentum, and moisture which account for virtually all the interactions between the surface and the rest of the atmosphere.

There are a number of ways that people have attempted to handle all of these exchanges in models. Time does not permit me to talk about all of them, but I am going to mention one that is in current use today. It was developed in 1972 by Deardorff [3]. His method relies on a bulk parameterization scheme as follows:

1. Deardorff begins by estimating the mean values of wind velocity, potential temperature, and moisture in the boundary layer from the estimated height of the boundary layer and the lowest grid levels of the model.

2. Then he estimates the mean vertical fluxes of momentum, heat, and moisture from the bulk Richardson number (based upon the differences between the mean values of the boundary layer and the surface values).

3. Next, he estimates the direction of the surface wind using the surface pressure gradient to refine the mean wind velocity in the bulk Richardson number. If needed, these steps are iterated.

4. Finally, he obtains the height of the boundary layer as a function of x, y, $t + \Delta t$, given the height as a function of x, y, t (from the prognostic equation in unstable cases and a simple relationship in stable cases). This step uses model velocities and surface fluxes from step 2 above.

If you go through all the equations, you will find that it is still simple compared to a detailed description of the real processes that are involved.

This parameterization of the boundary layer is used in a number of models. Figure 3 is a schematic of the way it is used in the Goddard Laboratory for an atmosphere fourth-order, primitive equation, general circulation model. In this particular case, Deardorff's parameterization is used and the fluxes at the surface, indicated by F_s, are equated to the mean fluxes in the mixed layer, F_m. Inclusion of these fluxes actually makes a difference in the results of the model. It is a simplified accounting for all the processes described in Figure 2.

In Figure 4, a schematic diagram of a newer model called the global integrated biosphere model (by Sellers et al. [4]) is shown. This model has just recently been developed. The diagram shows how the fluxes develop from the surface, the ground cover, and the tree canopy, particularly the moisture and heat fluxes. The portion of Figure 4 outlined at the top of the page is the Deardorff parameterization, which describes the bulk flux parameterization between the surface and the atmosphere, but, in addition, there is a more elaborate system for describing the fluxes from the canopy and the ground cover and from the soil. The cavities represent the stomata of the plants. The symbolic resistances represent the resistance to the transport of moisture, in this case, through the biota. It is a complicated process which is empirically determined and accounts for both heat and moisture exchanges. Although it makes the model more complicated, it actually does produce visible results. From this approach, the surface stresses are computed in the model. The surface stress varies considerably according to the vegetation, soil type, roughness, etc.

Differences have been generated in the atmospheric portion of the model because soil moisture and vegetation do affect the behavior of the atmosphere. Precipitation is more realistically simulated because of the moisture mixing which is related to the vegetation. Soil moisture makes an enormous difference in how the model actually responds by producing precipitation which we hope will be realistic. It really does make a difference, particularly in climate models.

To summarize, although the atmospheric flow is basically stratified, there are a number of very important exceptions. In qualitative terms, these exceptions to that stratification make a significant difference in the way the atmosphere behaves. These exceptions enhance turbulent exchange processes and these turbulent exchange processes ultimately modify the behavior of the atmosphere over a wide range of spatial and temporal scales. Finally, the present methods for parameterizing turbulence and the fluxes they generate use bulk approximations. The question is: Are these adequate and can we improve them?

References

1. Brown, R. A.: *Analytical Methods in Planetary Boundary-Layer Modelling.* New York: John Wiley & Sons, Inc., 1974, 148 pp.

2. Wurtele, M. G.: "CAT-Generating Mechanisms," *Proceedings: Workshop on Atmospheric Turbulence Relative to Aviation, Missile, and Space Programs*, pp. 111-126, NASA CP-2468, 1987.

3. Deardorff, J. W.: "Parameterization of the Planetary Boundary Layer for Use in General Circulation Models," *Monthly Weather Review*, 100:93-106, 1972.

4. Sellers, P. J.; Mintz, Y.; Sud, Y. C.; and Dalcher, A.: "A Simple Biosphere Model (SiB) for Use within General Circulation Models," *Journal of the Atmospheric Sciences*, 43(6):505-531, March 15, 1986.

QUESTION: Jack Ehernberger (NASA Ames). You've indicated the importance of turbulence processes to the atmosphere. Can you characterize or has it been examined to any extent, the degree which the interest from the atmospheric prediction standpoint in simulation depends on turbulence as the turbulence intensity increases. In other words, the aircraft audience probably begins to be interested in an RMS value of 0.5 m/s and generally everyone who flies is interested in 1 m/s. The extreme incidents and accidents probably happen at a range of 3 or 5 m/s RMS. That doesn't infer that the larger the RMS is the more important it is to the atmospheric circulation. Has a breakdown been made or might it be made? Does your interest increase with the severity of the turbulence?

ANSWER: I don't think I have come across any cases in which in large-scale modeling or climate modeling that is a consideration. Certainly, if people are trying to model mesoscale processes they might be very concerned with it, and there are local scale models and cloud scale models that might account for turbulence. I think, in general terms, that even the smaller processes which occur more frequently are of great importance because they occur on a very widespread basis. For example, by changing the roughness of the Saudia Arabian peninsula, we were able to show that the Indian monsoon flow could be considerably altered. There is a very small-scale process (we are talking about turbulent flows over sand). It is generally concluded that sand does not produce much in the way of turbulence, but alter the roughness in the model slightly and increased surface stress actually produces curvature in the flow that leaves Saudia Arabia, thus changing the very important monsoon that occurs over India. So, the answer to your question is: I think not. I would like to emphasize the areas of mutual interest and perhaps overlook the divergence of interests at this meeting. With that intent, we attempted to convene the two communities, aviation and earth sciences.

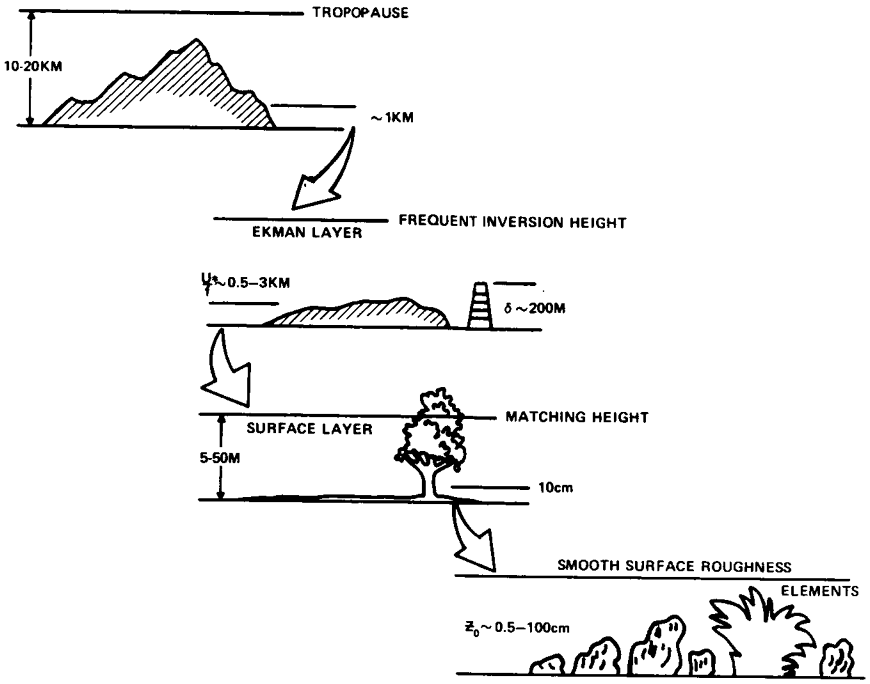
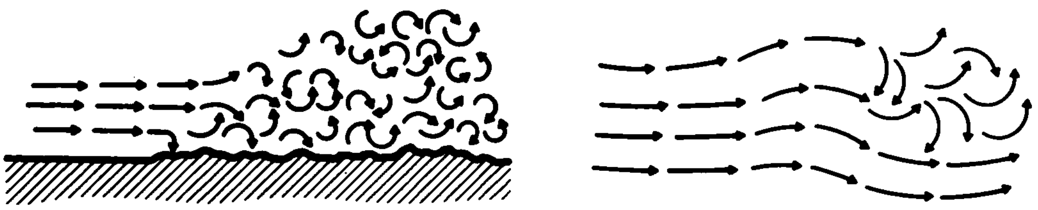


Figure 1. Turbulent scales of size and motion important to generation of fluxes (after Brown [1]).

(a) Vertical wind shear

(b) Temperature differences

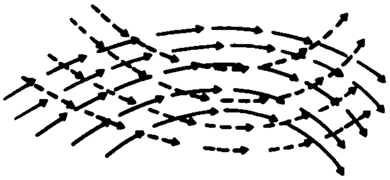


(c) Surface roughness

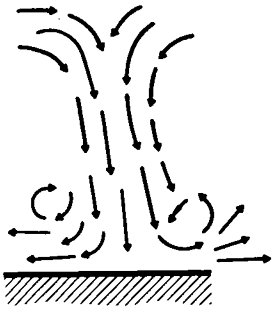
(d) Wave generated

Figure 2. Conceptual illustration of mechanisms for generation of atmospheric turbulence.

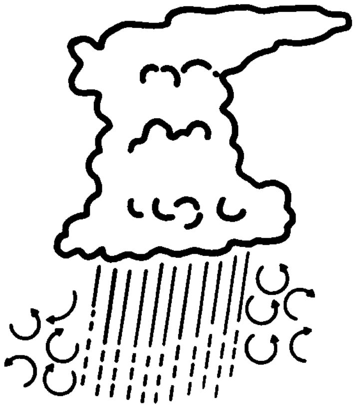
(e) Jet stream



(f) Differential advection

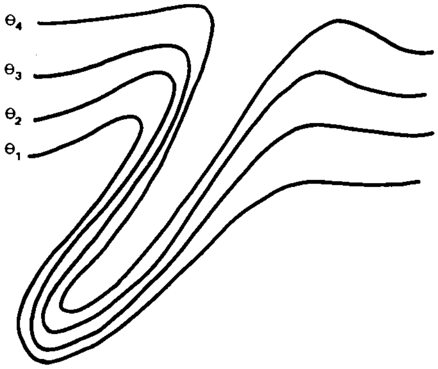


(g) Downburst

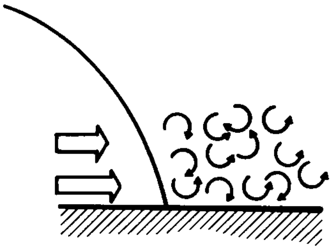


(h) Falling precipitation

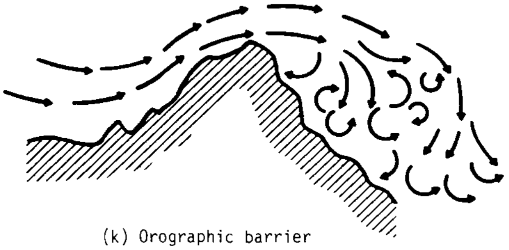
Figure 2. (continued).



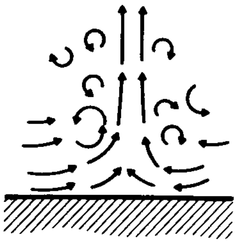
(i) Tropopause folding



(j) Frontal



(k) Orographic barrier



(l) Convective instabilities

Figure 2. (concluded).

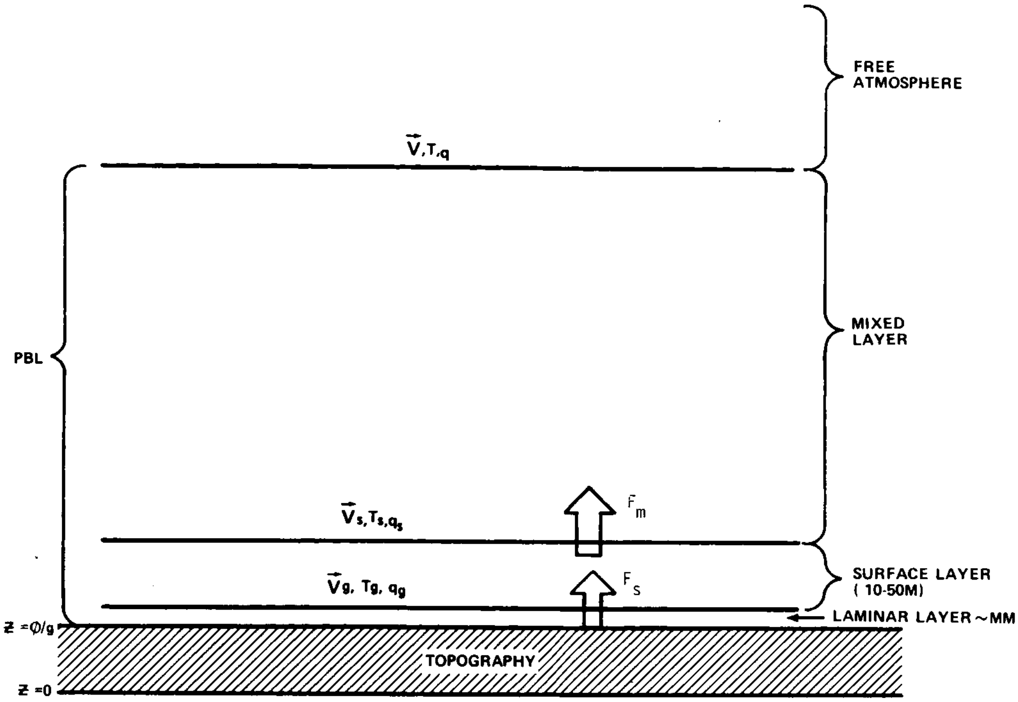


Figure 3. Schematic of parameterization model used by the Goddard Laboratory for Atmosphere.

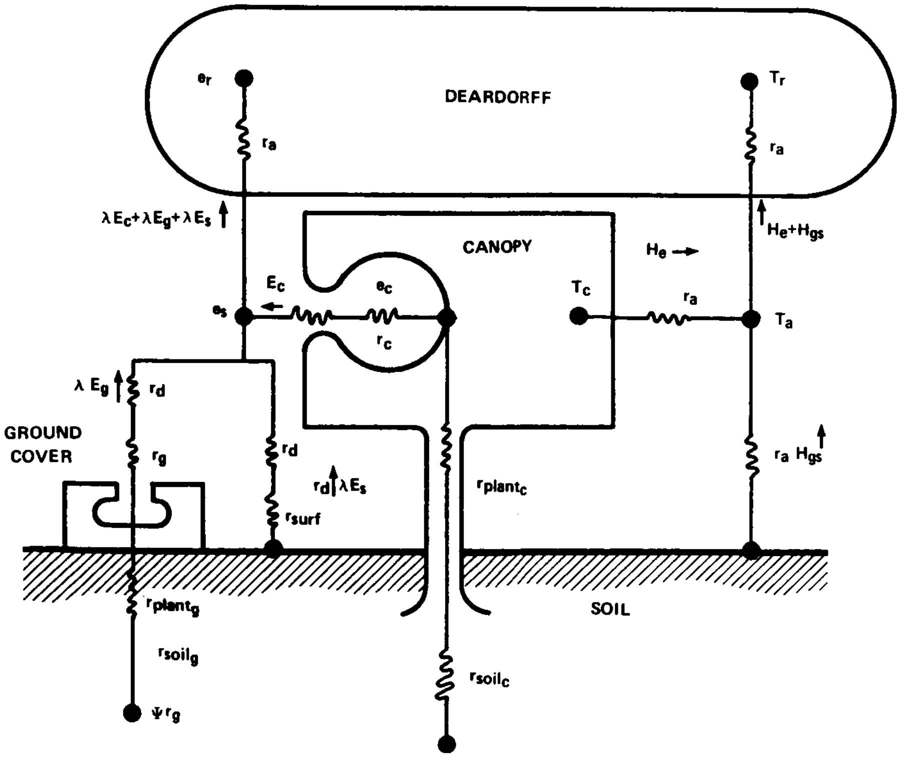


Figure 4. Global integrated biosphere model (by Sellars et al. [4]).

N87-22351

TURBULENCE FORECASTING

C. L. Chandler
Delta Air Lines
Atlanta, Georgia

In order to forecast turbulence, one needs to have an understanding of the cause of turbulence. Therefore, we shall attempt to show the atmospheric structure that often results when aircraft encounter moderate or greater turbulence. The following is based on thousands of hours of observations of flights over the past 39 years of aviation meteorology.

1. AIRMASS ANALYSIS

One of the best tools in analysis and forecasting turbulence is the frontal contour method of airmass analysis as perfected by the Canadians in the late 1940's and early 1950's.

In winter, on the average, one will find four major frontal zones (five airmasses) between about 20N and 50N latitude over the eastern United States. Figure 1 shows the mean position of the various surface fronts during an average winter. Large day-to-day variations often occur as well as mean year-to-year positions during the colder months. In summer, the Sub-Tropical surface front average position is just south of the Great Lakes and the upper air position is over the lakes. As before, there are large day-to-day variations in these positions. Figure 2 shows the same frontal positions but within the upper troposphere. Average temperatures are also shown at other MB (millibar) heights as well as mean heights/temperatures of the airmass tropopause.

We shall now look at vertical cross sections of the various frontal models and often associated wind maximums in winter. Figure 3 shows a typical model of the Arctic front with a wind maximum at about FL230* or near the 400 MB level. Southward, we find the Maritime Arctic frontal zone (often called Sub-Arctic) with a wind maximum much stronger at about FL290-300 or near 300 MB. This is shown in Figure 4. The next southward frontal zone is the polar front as shown in Figure 5. We see an average wind maximum of about the same strength as the Maritime Arctic but a maximum wind level of near FL340-350 near 250 MB. The most southern frontal zone (except in rare cases) we call the Sub-Tropical frontal zone. The height of this maximum moves up to near FL390 at 200 MB. This frontal model is shown in Figure 6.

At the higher levels above about 400 MB, we occasionally see a frontal zone south of the Sub-Tropical front in the temperature range of near -34° to -35° C at the 300 MB level. It appears now and then in the tropical areas in winter and even over the United States during the warmer months. Likewise, we occasionally see frontal zones north of the Arctic front in very cold airmasses and we call this frontal zone the Super Arctic.

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*FL230 = Flight level of 23,000 feet above mean sea level.

2. FRONTAL TURBULENCE

All of the frontal zones shown on Figures 1 through 6 may contain turbulence to some degree. Above about 12,000 ft, most of the turbulence will be of the clear-air type (CAT) due to descending air within the frontal zones. Figure 7 shows all four of the major frontal zones and the area of frequent, moderate, or greater CAT. As the altitude increases toward the "Z layer" (level of non-horizontal temperature gradient), the CAT will decrease reaching a minimum at the Z layer. This altitude of the reversal of the thermal wind, located at the level of maximum wind speed, is a desired level to fly for smooth air (jet core). One has only horizontal wind shear rather than vertical and horizontal shear. The altitude for maximum turbulence seems to at about two-thirds of the way from the surface front to the Z layer for each frontal model as shown in Figure 7. The colder the airmass, the lower the CAT zones within each frontal model. This is the reason that CAT is found at the lower altitudes in winter. Likewise, the lower latitudes result in the height of the CAT being found at higher altitudes within the frontal zones.

3. TROPOPAUSE TURBULENCE

Tropopause surfaces below about FL310 very seldom contain moderate or greater CAT. Cold airmasses north of the Maritime Arctic frontal zone result in sinking air. The resultant low tropopause does not contain enough of a temperature inversion and associated horizontal and vertical wind shear. Tropopause surfaces at and above about FL340 (250 MB) are the ones that often result in moderate or greater CAT within the ascending airmasses. Most CAT within tropopause surfaces will be found in temperatures colder than standard as well as temperature inversions, horizontal and vertical wind shear. Figure 8 shows various vertical temperature signatures through tropopause surfaces. Curves A and B seldom result in more than light CAT. Curves C and D often result in moderate or greater CAT at temperatures colder than standard if relative high wind speeds are present.

Figure 9 shows B, C, and D temperature curves across a typical frontal model and associated jetstream.

4. MOUNTAIN WAVES

The mountain wave is highly over-rated as a direct cause of clear-air turbulence. In fact, Delta Air Lines has been flying to the west coast for over 20 years from various cities east of the Rockies. We do not know of one case in which a Delta aircraft has encountered moderate or greater turbulence caused solely by a mountain wave when flying at altitudes above 25,000 feet. We have encountered turbulence many times over the mountains but the cause was determined to be upper front, tropopause, trough, or ridge lines when it was the CAT type. In some cases, the discontinuity was located within a wave condition and the turbulence within discontinuities may well be enhanced by mountain waves.

Figure 10 shows a mountain wave model with two frontal zones (three airmasses). As long as flights avoid the upper front and tropopause surfaces, flights are most always very smooth. In some cases, aircraft within the wave crest may well exceed the aircraft airframe speed limitations. In some of these cases, aerodynamic buffet may occur which no doubt results in often reported turbulence. Figure 11 shows that eastbound aircraft are more apt to experience this overspeed buffet due to the very sudden encounter due to high ground speeds. The example shows a 13-second difference between downwind versus upwind, which gives the headwind flight crews a much longer period in which to react to the ascending air.

5. CLOUD TURBULENCE

In this analysis, we will exempt all types of convective clouds except a few special cases of thunderstorms associated with widespread cirrus. As a general rule, cirrus results in only light turbulence in areas of relative light winds. Under moderate to strong winds, there is often found moderate turbulence near the cirrus tops and in this area there is a strong increase in wind speed near the cloud top. Most of the turbulence will be found within the last 1000 feet just before the top. This condition is shown in Figure 12. The cloud retards the horizontal wind flow (cloud drag) and as the top is approached, there is a sharp increase in wind speed as well as turbulence.

There is one condition that aircraft flying a higher levels encounter several times a year that result in passenger injuries. This is also shown in Figure 12 where the aircraft is flying on top in the clear. Below the cirrus, a thunderstorm has formed and the top has merged into the higher cirrus deck. The major updraft of the thunderstorm has created a bubble or ridge-row near the top of the cirrus deck. Flight crews often do not see this ridge-row or bubble and will just nick the top or pass through the wave effect just on top. In most cases, there is one sharp shock that results in a messy aircraft and/or injuries if seatbelts are not secured. To avoid this, weather radar tilt control tilted downward for the target should be used and then go either right or left of the target rather than the risk of flying the wave effect just on top.

6. TROUGHS AND RIDGES

Most always there will be some type of turbulence within trough lines. In most cases, it will be of short duration at any altitude and is more apt to be only light to moderate. Sloping trough lines seem to enhance the turbulence. Figures 13 and 14 show both a ridge line and trough line as it may appear on an upper air chart. In many cases, ridge lines give airborne aircraft many more problems than trough lines as often associated upper warm fronts, widespread cloud cover, and sharp cold air tropopause surfaces above the warmer airmasses below.

7. LOW-LEVEL CYCLONIC FRONTAL WAVES

Moderate to severe low-level turbulence is often caused during the cooler months by shallow, warm frontal cyclonic waves that may appear anywhere, but the severe cases favor the east coast of the United States as shown in Figure 15. Strong northeast surface winds with strong southwest winds above are only a few miles north and north-northeast of the center of the wave. Figure 16 shows a vertical cross section along the line AB as shown in Figure 15.

8. EXAMPLES OF FLOW PATTERNS THAT OFTEN RESULT IN MODERATE/SEVERE TURBULENCE

Figure 17 shows a very sharp upper warm front within a ridge line that most always will result in moderate to severe turbulence. Near the crest of the ridge line within the frontal zone, the warm front will produce the worst upper air turbulence within the tropopause than any other feature. Likewise, above the jet core and to the south toward the high pressure side, the cold tropopause will contain moderate to severe CAT in many cases.

Figure 18 shows a cold cut-off cold low with an upper jet front. The area north through northeast of the closed low is the area of frequent, moderate, or great CAT as we have two frontal zones, sharp trough line as well as cold sloping tropopause surface above the frontal zones. It is very important to fly the Z layer under this flow pattern or well above the tropopause. The lower levels in some cases may well prove to be relatively smooth. Figure 19 is a vertical cross section along the line AB which shows the areas of turbulence.

Figure 20 shows the position of the surface front and associated upper air position. The Coriolis effect comes into play as the cause of this type of turbulence, which in most cases will be only light but found at most all altitudes above about 15,000 feet. Cross contour flow is present above and near the surface position of the front.

9. FORECASTING TURBULENCE AT DELTA AIR LINES

In order to forecast turbulence, one has to have the proper analysis on large scale actual surface and upper air charts. Delta's actual upper air chart for 0000-1200 GMT contains computer-plotted data from 400, 300, 250, and 200 MB plus the height and temperature of the tropopause as well as maximum wind data. All this information is plotted on one large-scale chart and then the analysis is done by a Delta meteorologist. The actual charts also contain wind and temperature information from aircraft that has INS and ACARS equipment. This is hand plotted at present. Short-range forecasts are then made with the help of the Bracknell computer forecast of winds and temperatures at 12, 18, 24, and 30 hours from base data which also is plotted by computer at the same levels as the actual charts. Frontal analysis may be made on the forecast charts as on the actual with the corrected position of upper fronts and maximum wind. Both Suitland and Bracknell computers forecast the position of the maximum wind in error by about 60 miles too far on the high-pressure side in warm fronts in ridge lines. Both, also, underforecast the maximum wind speed by 30 to 40 knots in the case of Suitland and 15 to 25 knots in the case of Bracknell. The decrease in wind speed on the low-pressure side of the maximum is also in error by both Suitland and Bracknell but Bracknell will show a tighter gradient on the low-pressure side as it should be. Figure 21 shows the actual for 1200 GMT on March 31, 1986, for the Pacific Northwest with Maritime and polar fronts.

Figure 22 is a sample Delta turbulence alert that Delta's meteorologists enter into the Delta flight planning system by grid numbers, and if an aircraft passes through the area, it will be picked up by the Delta computer weather system and be placed on board the flight (B20). The second alert is for thunderstorms (T21).

For Delta's international flights, a more detailed flight forecast is made for turbulence by the Delta meteorologists as shown below:

> Delta 14/24 --- Lgt/Mdt CAT CLB FL 290-310 upper front --- Lgt CAT 40SW GVE FL330 trop temp rise --- Lgt CAT ACK trough FL350 --- Lgt/Mdt CAT FL370 50NE YYT trop temp drop --- Lgt 33W ridge line --- Lgt/Mdt CAT 30W CRK FL370 trop temp rise --- Lgt CAT DVR trough --- Lgt CAT descent FL290-280 trop --- Mdt CAT FL220-200 descent front.

Delta's meteorologists and flight dispatchers have access to company VHF for most of the route structure as well as HF for the international flights.

QUESTION: George Modica (AFGL). Do you have a large concern for tropopause folding type turbulence? And if so, what meteorological information do you look for?

ANSWER: We don't believe such turbulence really exists. In our practice at the Z layer, the "trop" is above it and the front is below it. If you want to extend that tropopause down into the top of the upper front, and you can do so, there is a lot of shear there. But if you go through at the Z layer horizontal, we hardly ever find any significant turbulence.

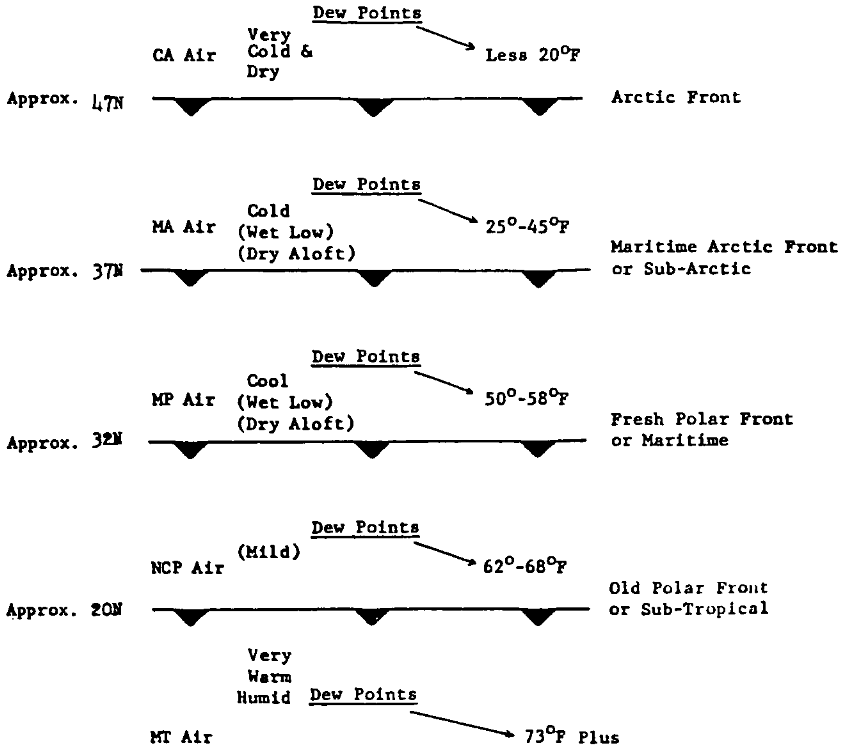


Figure 1. The mean position of the various surface fronts in the eastern United States during an average winter.

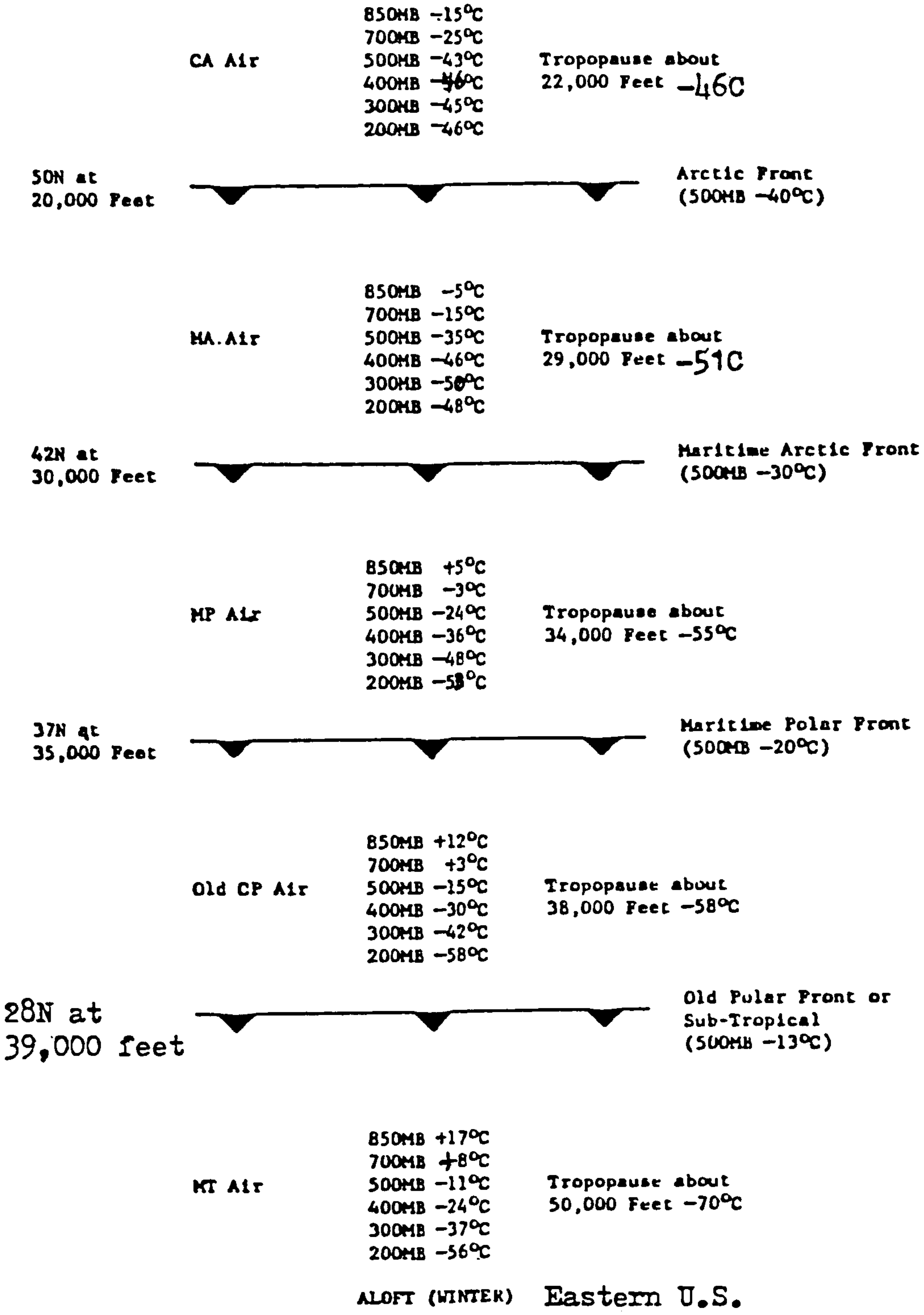


Figure 2. The mean position of the upper troposphere in the eastern United States during an average winter.

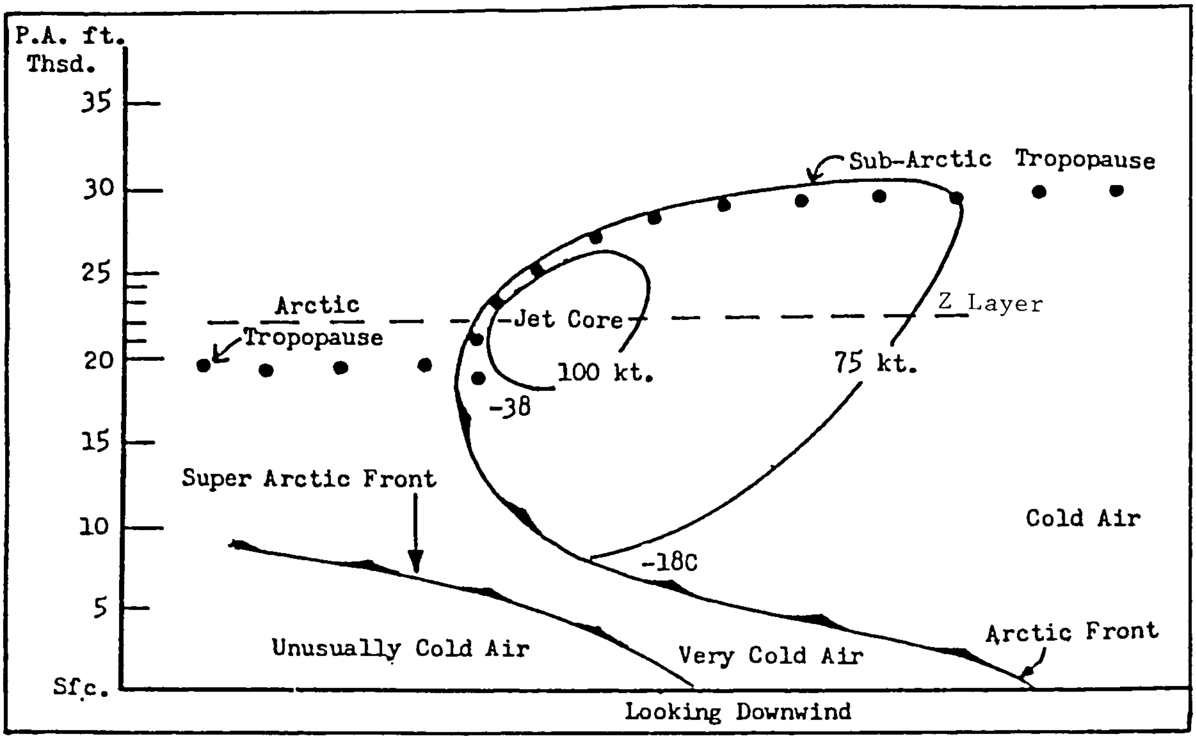


Figure 3. A typical model of the Arctic front with a wind maximum at about FL 230 or near the 400 MB level.

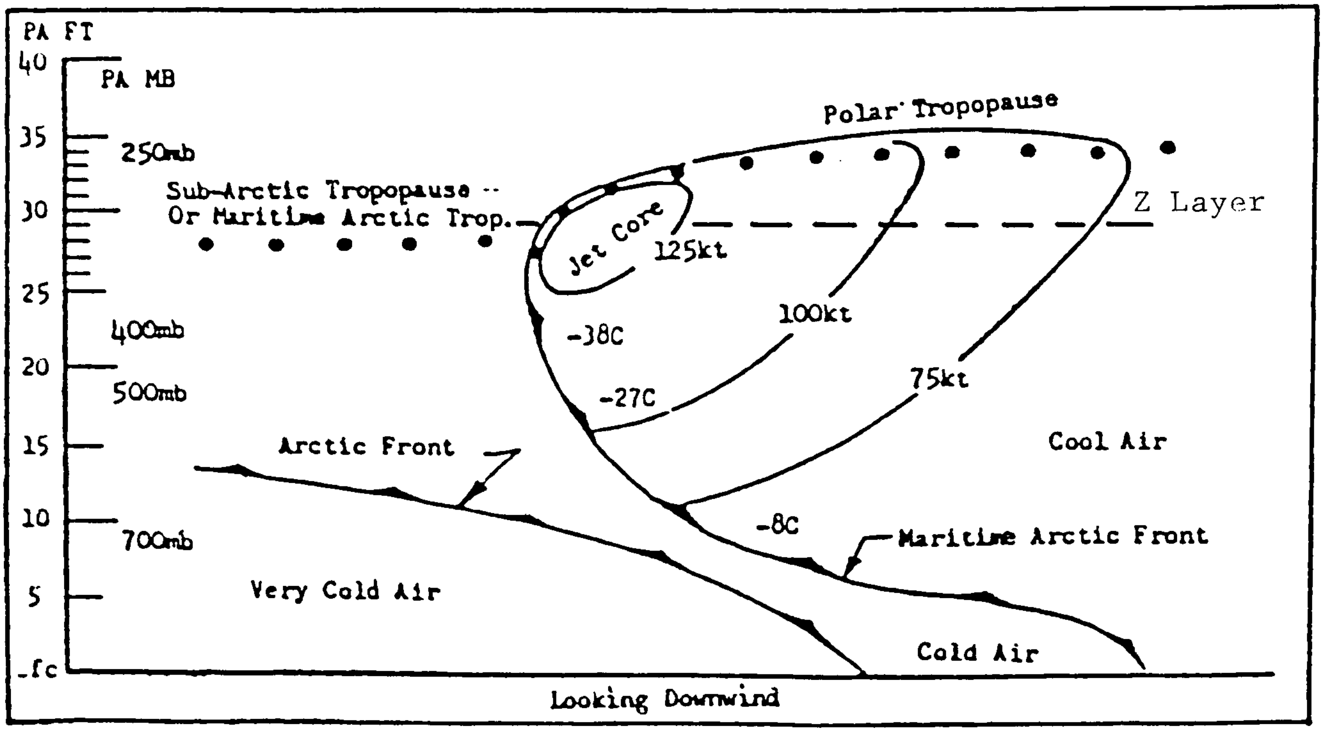


Figure 4. A typical model of the maritime Arctic frontal zone with a wind maximum at about FL290-300 or near 300 MB.

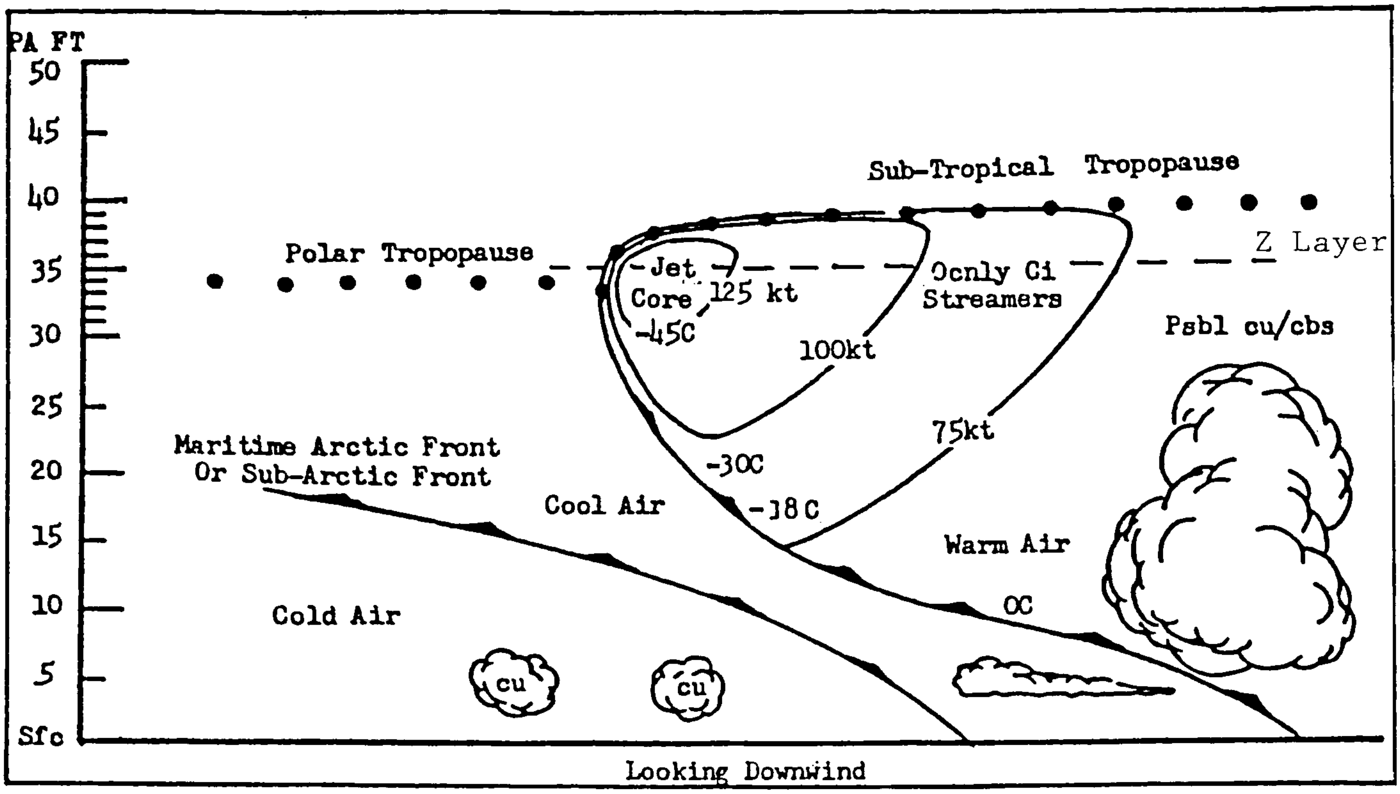


Figure 5. A typical model of the polar front with a maximum wind level of near FL340-350 at 250 MB.

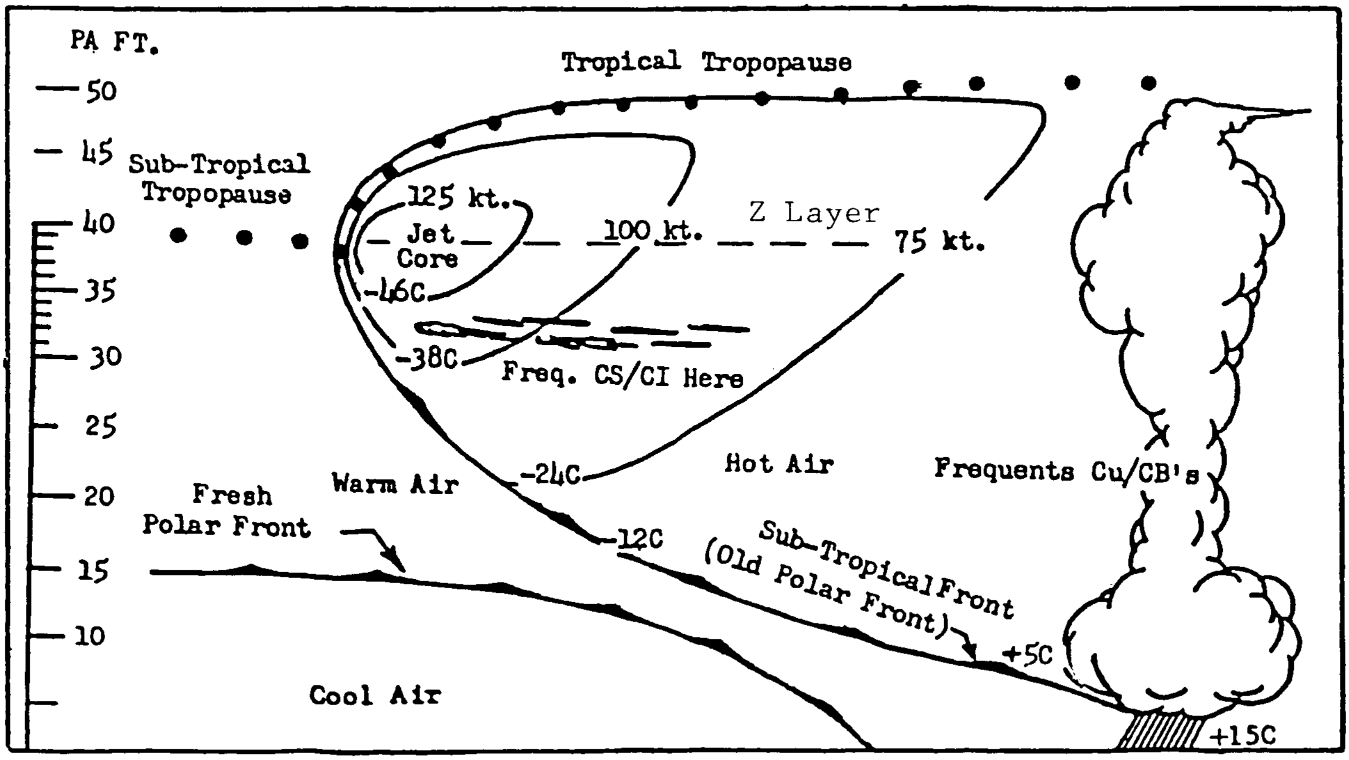


Figure 6. A typical model of the sub-tropical frontal zone with a wind maximum at about FL 390 at 200 MB.

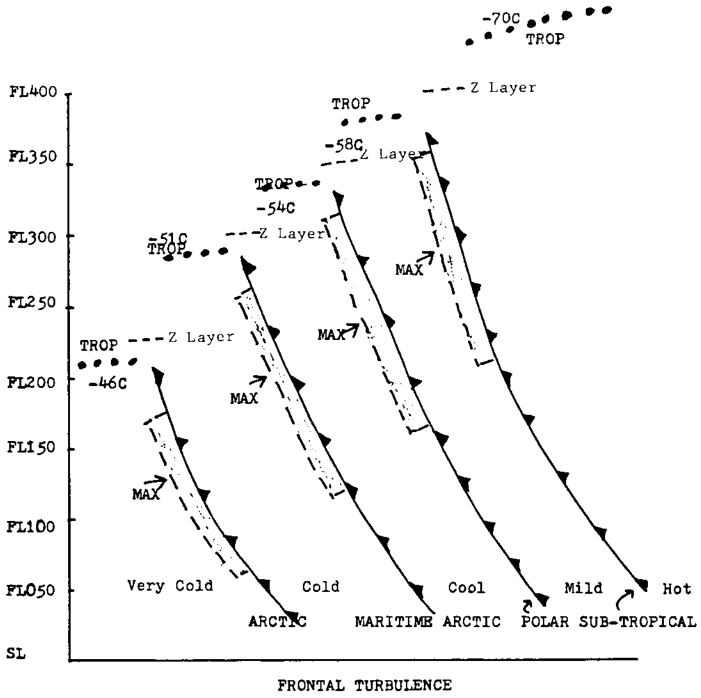


Figure 7. All four of the major frontal zones and the area of frequent, moderate, or great CAT.

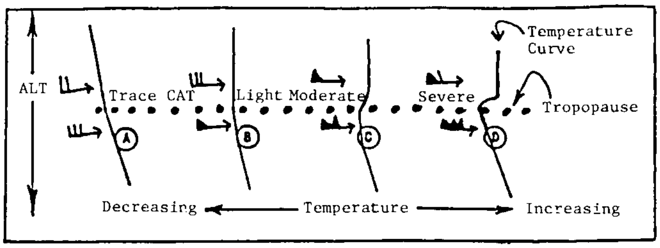


Figure 8. Various vertical temperature signatures through tropopause surfaces.

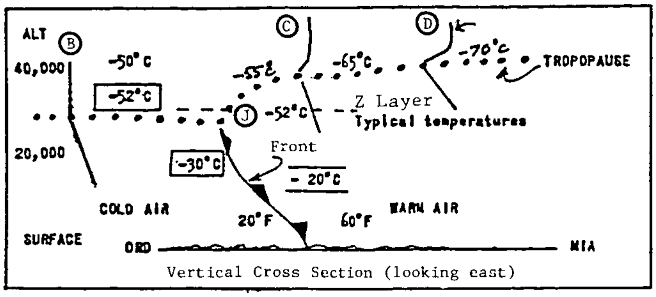


Figure 9. The B, C, and D temperature curves across a typical frontal model and associated jetstream.

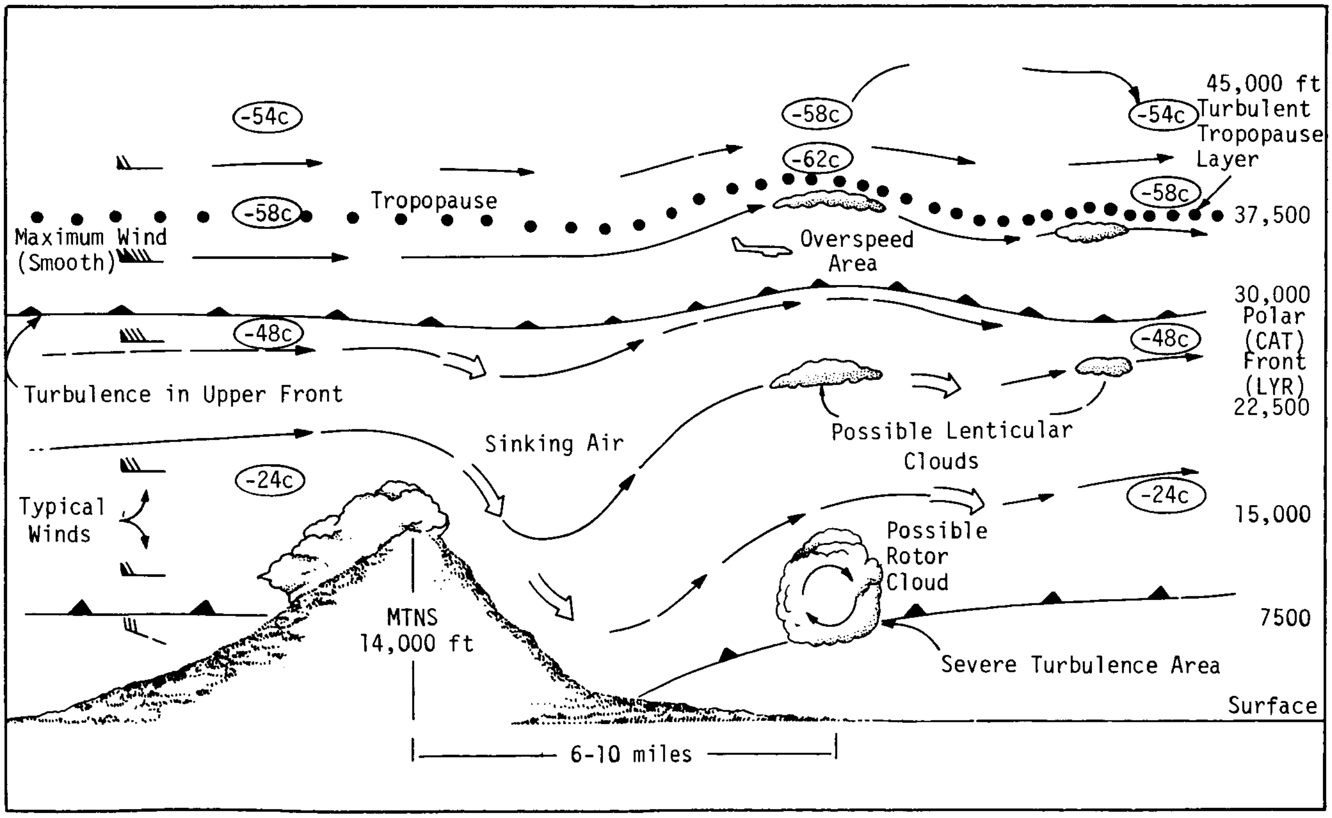


Figure 10. A classical model of a mountain wave.

Westbound GS 377 knots - Time in updraft 38.5 secs.

Eastbound GS 577 knots - Time in updraft 25.2 secs.

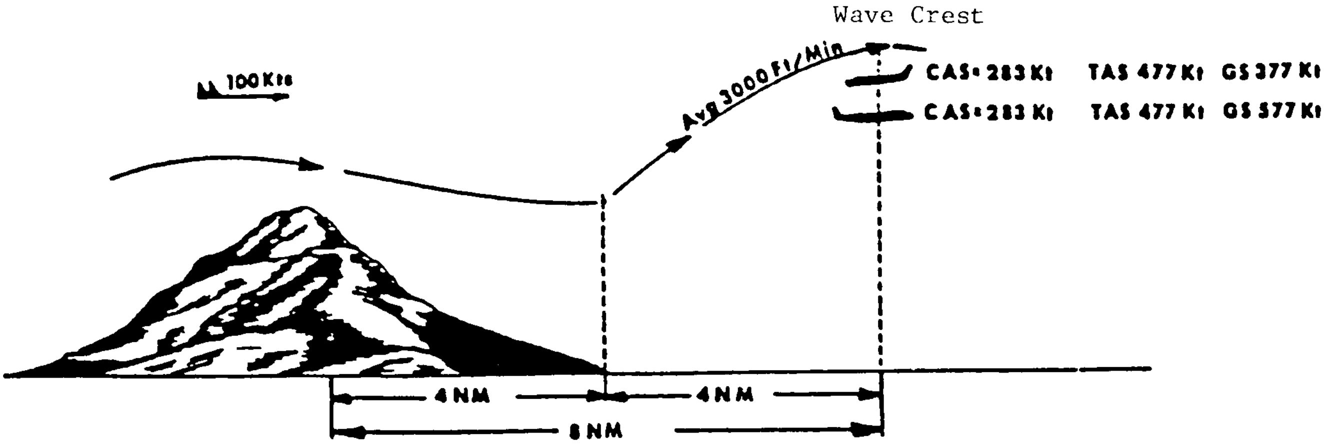


Figure 11. A typical wave with updraft.

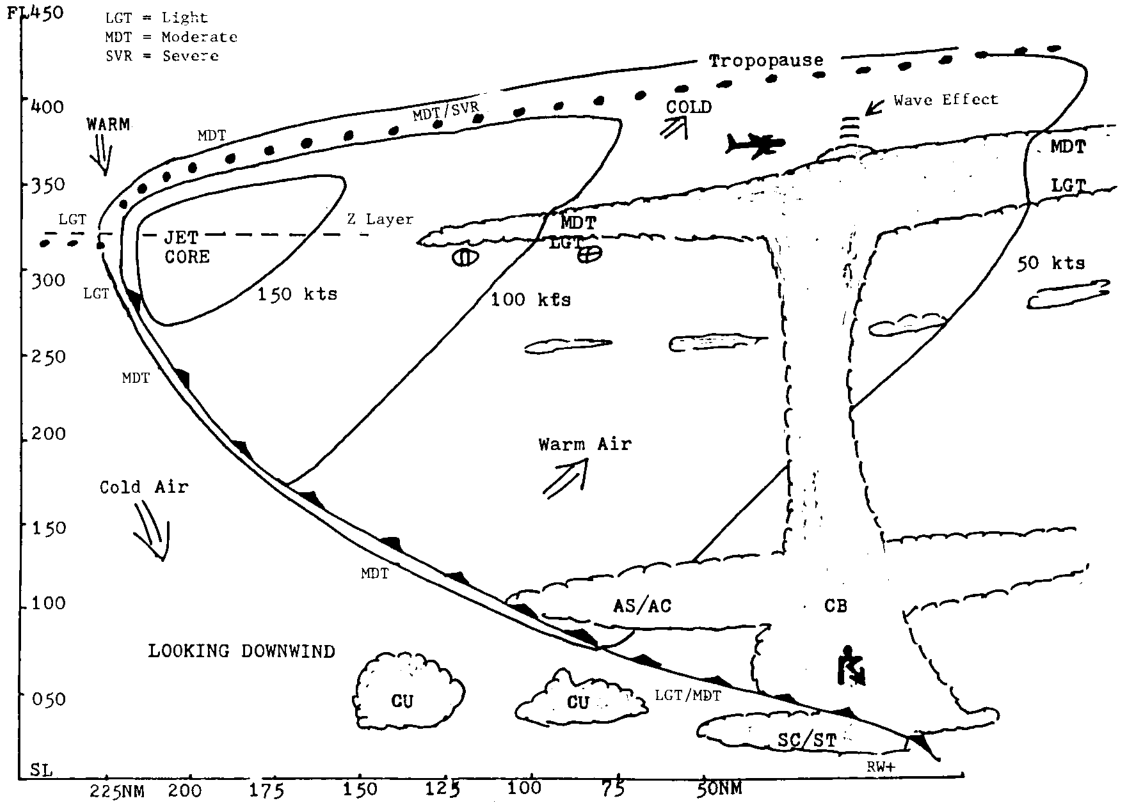


Figure 12. Cloud turbulence.

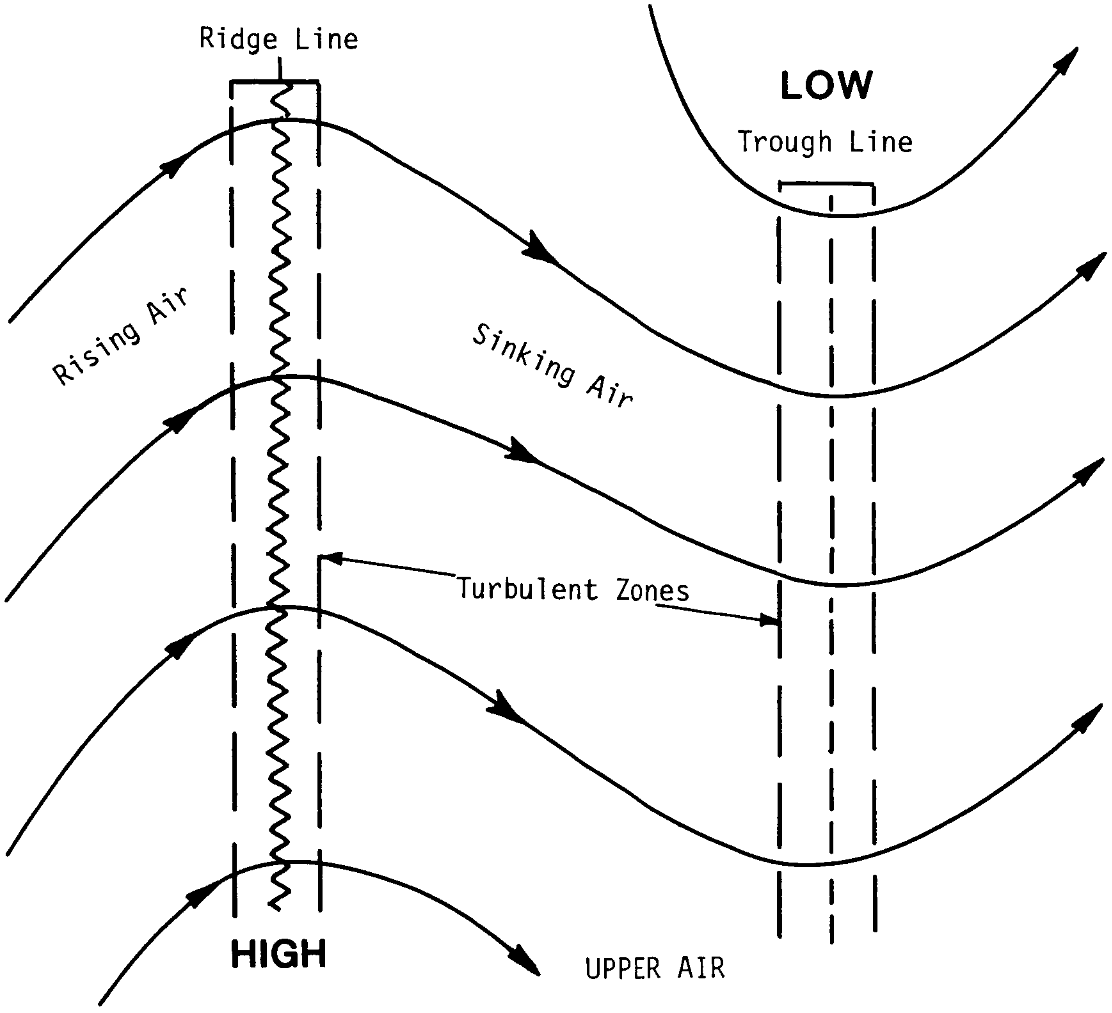


Figure 13. A ridge line as it may appear on an upper air chart.

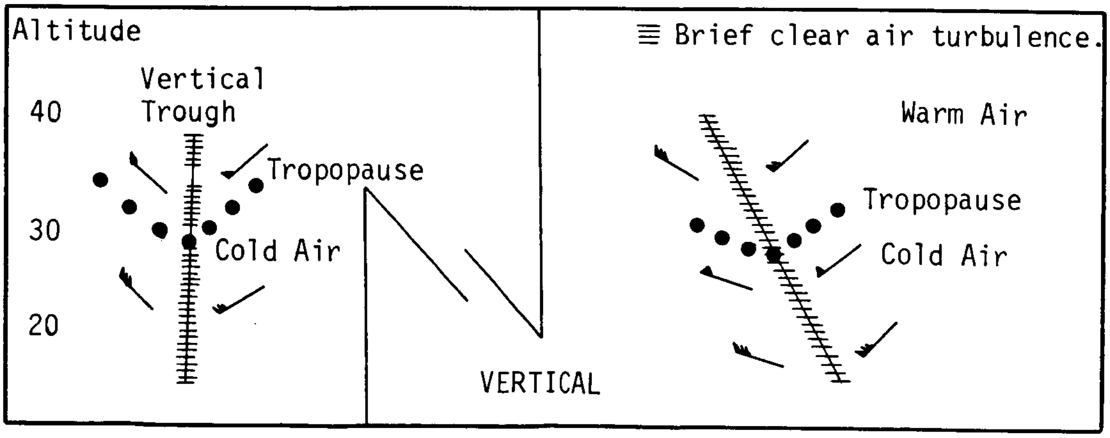


Figure 14. A trough line as it may appear on an upper air chart.

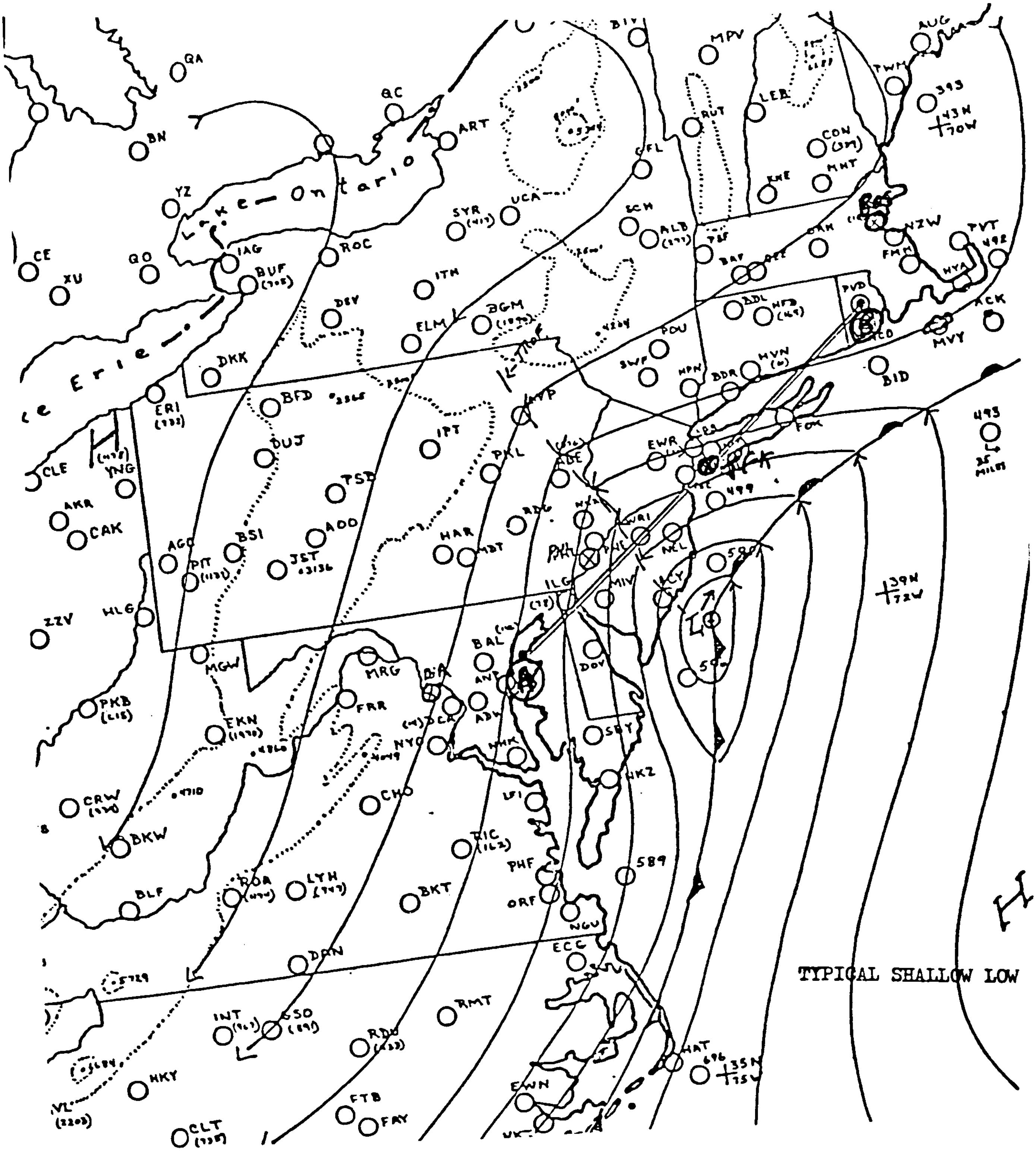
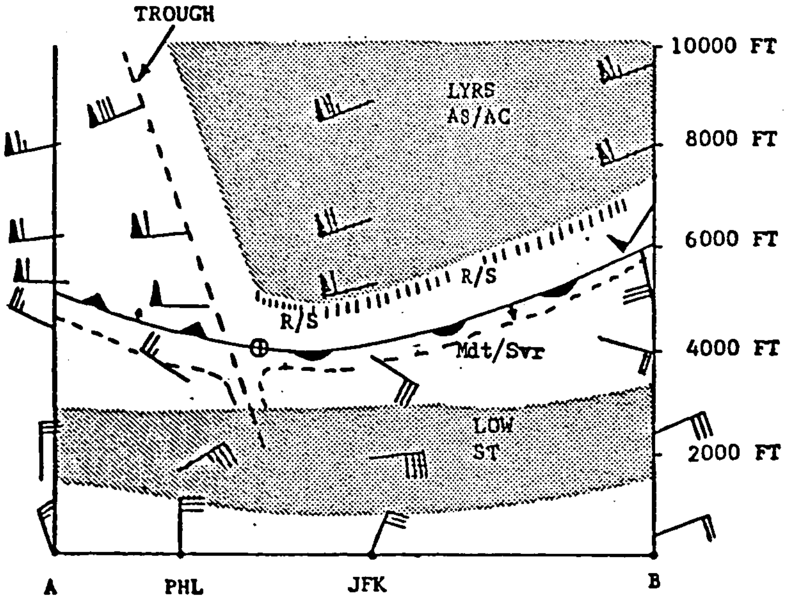


Figure 15. Severe cases of moderate to severe low-level turbulence in the east coast area of the United States.



Most of the turbulence would be found along the frontal zones (about 4000 ft at JFK and 6000 ft at B). Also, along the sloping trough line.

Figure 16. Vertical cross section along the line AB.

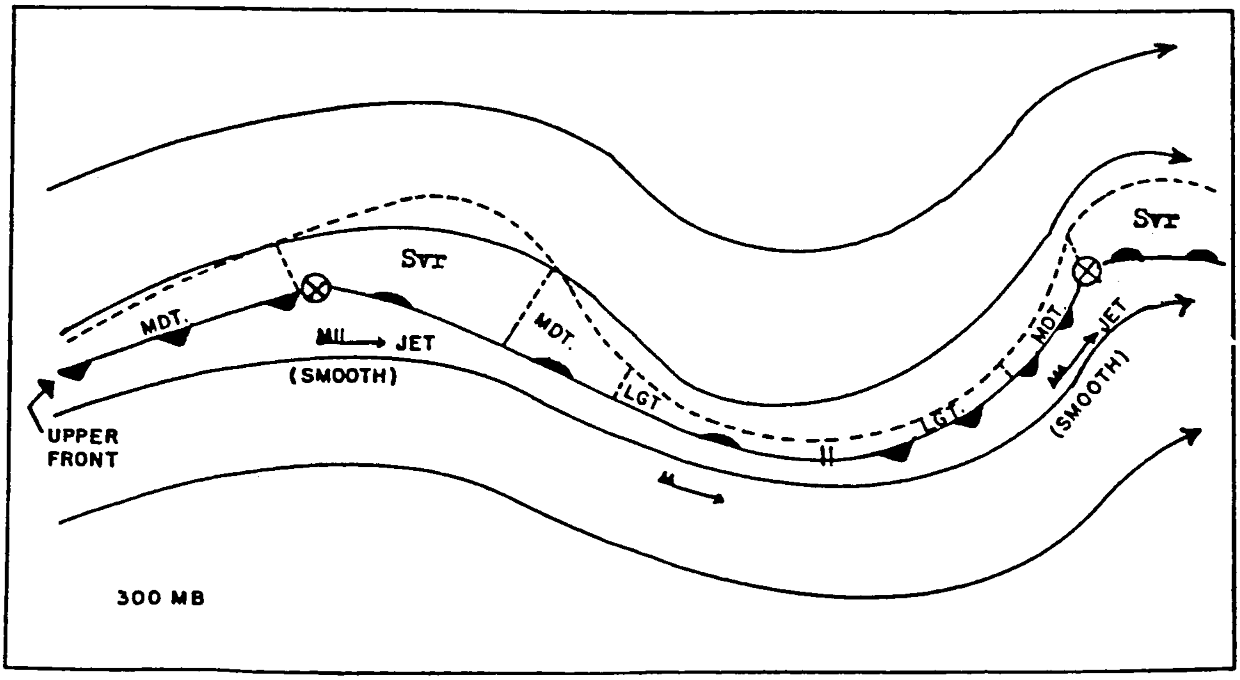


Figure 17. An illustration of a very sharp upper warm front within a ridge line that most always result in moderate to severe turbulence.

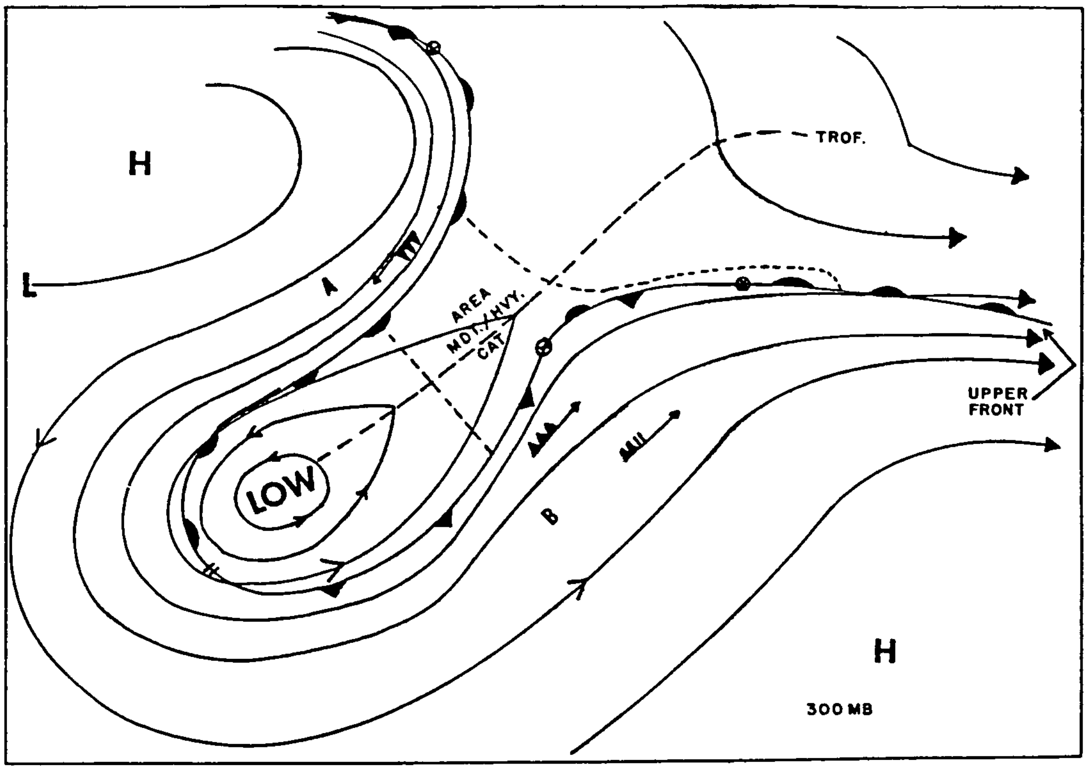


Figure 18. A cold cut-off cold low with an upper jet front.

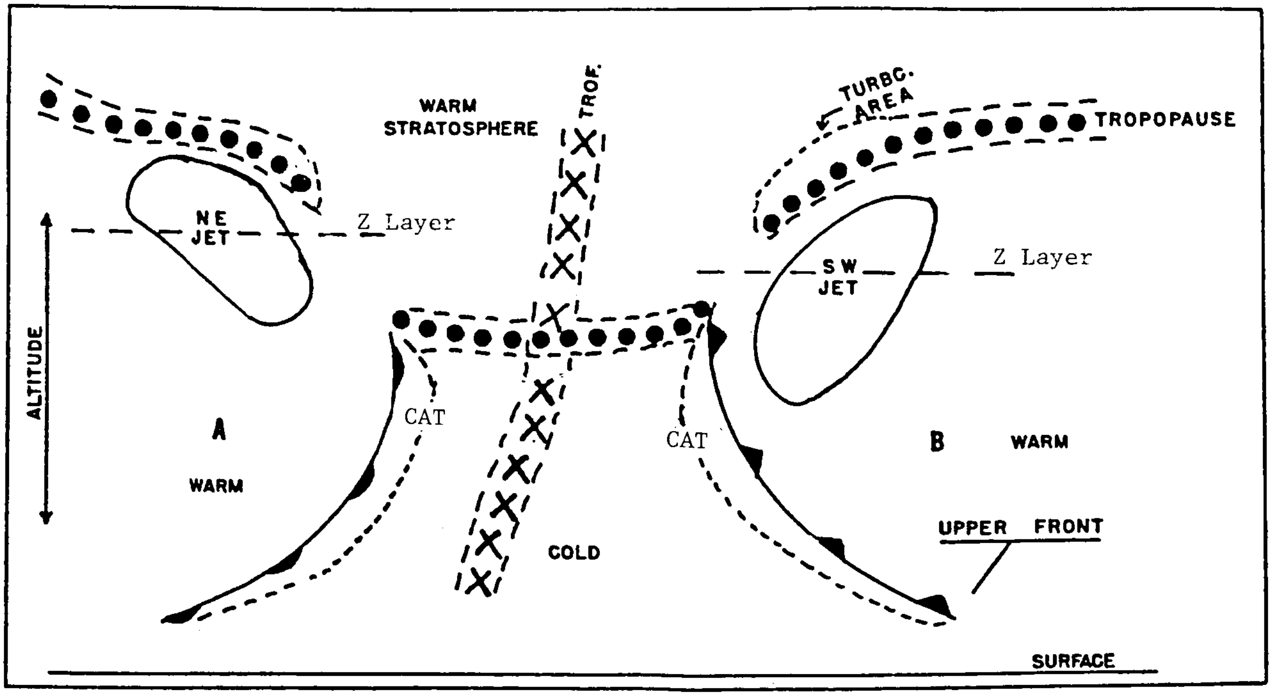


Figure 19. A vertical cross section along line AB which shows the areas of turbulence.

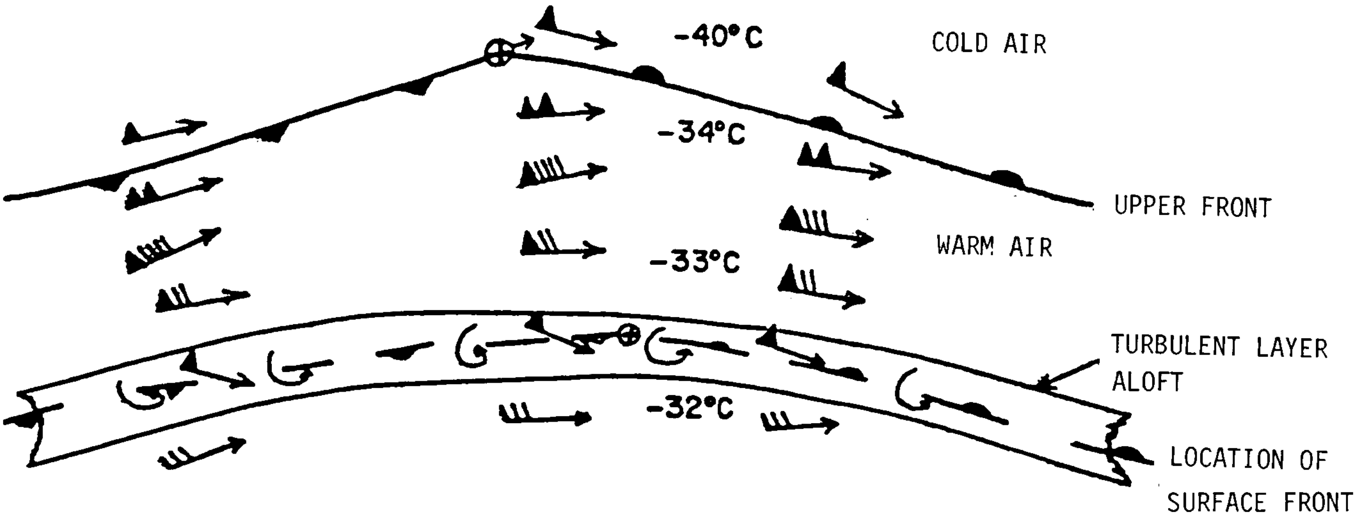


Figure 20. The position of the surface front and associated upper air position.

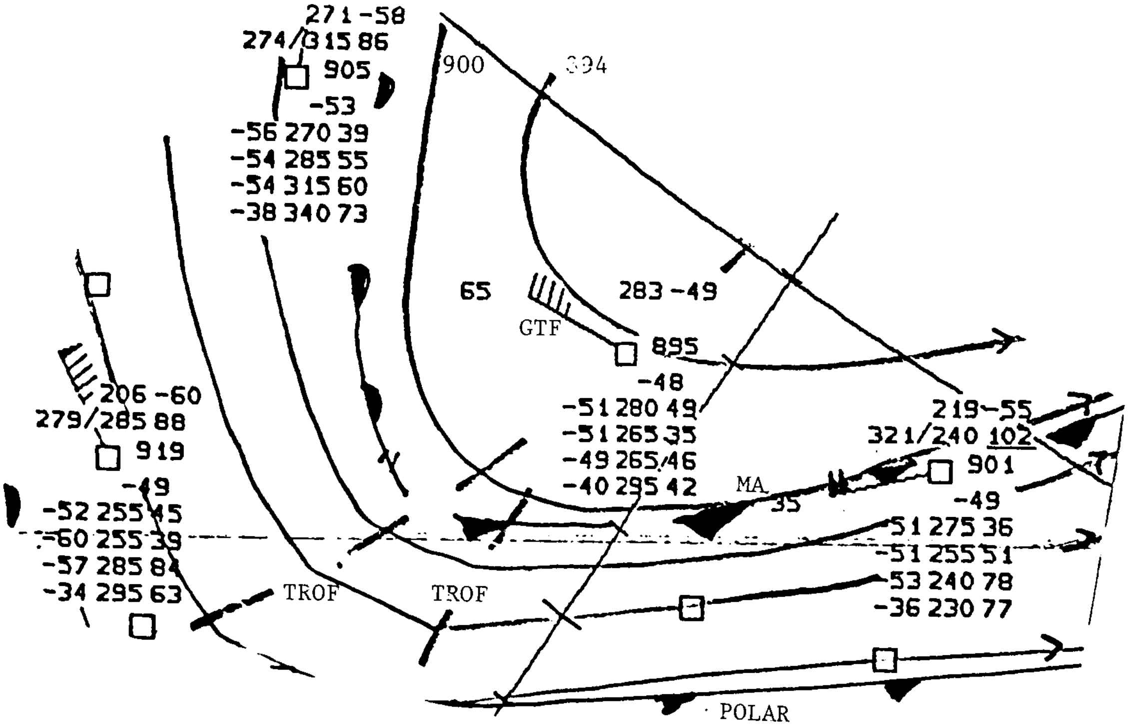


Figure 21. The actual for 1200Z on March 31, 1986, for the Pacific Northwest with maritime and polar fronts.

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 GBTA0000/29-0600/29B20/1552/1546/1545/1541/1544/1540/1187/1183/
1186/1182/1185/1181/1184/1180#

AT 29/0000Z AN UPPER FRNT AT FL320 EXTENDS FRM BIS SUX OMA
MCI TUL TO DFW.SLOPING DOWN TO THE EAST..THE TROP AT FL360
ABV THE FRNT SLOPES UP TO THE EAST....BY 29/0600Z THE FRNT AND
TROP WILL BE ALONG A LINE FAR RWF IRK 80W LIT TXK GGG CLL.

LOOK FOR MOSTLY MDT TURBC THRU THE FRONTAL SLOPE FL180 UP TO
FL260 AND LGT PSBL BRF MDT FL260 TO FL320..OCNL LGT TURBC THRU
THE SLOPE OF THE TROP.

FL330 AND FL350 THE Z LAYER SMOOTHEST WAY THRU..

A/C WEST BOUND BLO FL330 DESCEND AND ABV FL350 CLB FOR THE
FASTEST OUT....A/C EAST BOUND BLO FL330 CLB AND ABV FL350
DESCEND FOR FASTEST OUT..PATTON
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 GBTA0000/29-0600/29T21/1176/1181/1175/1180/1174/0823/0817#

AT 29/0000Z AN AREA OF SCTD TRW COVERS MOST OF MISS ALA THE
WESTERN FLA PANHANDLE AND WESTERN TENN..

A SCTD TO BRKN LINE OF TRW EXTENDS FRM MEM TO JAN AND MCB
TOPS IN THE LINE TO 400. THE CELLS ARE MOVING NE WHILE THE
LINE IS MOVING EAST. AND BY 29/03Z WILL EXTEND FRM 95SW BNA TO
MEI AND MSY TOPS NOW TO NEAR 470..BY 29/06Z THE LINE WILL EXTEND
FRM BNA TO BHM CKL MOB..TOPS NOW DOWN TO 410..LINE TO CONTINUE
EAST BEYOND FORECAST PERIOD.....PATTON
```

Figure 22. A sample Delta Air Lines turbulence alert that is entered into the flight planning system.

N87-22352

TRANSPORT MODELS FOR NUMERICAL FORECAST

Stephen D. Burk
Naval Environmental Prediction Research Facility
Monterey, California

The explosive growth of computing power, coupled with scientific and technological emphasis on the national scale, has led to significant major advances in operational numerical weather prediction (NWP) during the last two decades. There are about half a dozen major centers around the world running global NWP models operationally. Many more countries have operational hemispheric or limited-area models which provide weather forecasts. The global models typically have several hundred kilometer resolution, while the limited-area models usually have horizontal spacing of 50 to 100 km. Given the pace of burgeoning growth in this area, it seems warranted to occasionally take an overview of aspects of the field common to all modelers. In this note I take a brief look at the nature of subgrid scale turbulence transport parameterization, and some of the difficulties pertaining thereto, with particular emphasis on operational NWP models.

The Navier-Stokes equations describe the physics of atmospheric flow, and one might expect that it would be possible to numerically solve these equations in such a way as to yield near perfect depiction of all details of the flow, and hence, near perfect forecasts. It would be simply a matter of resolving all elements of the flow which have a significant impact on its evolution. While such direct simulations are possible for low Reynolds number flows, it can be demonstrated [1] that because of the wide range of scales of turbulent motion that are coupled nonlinearly, it would take roughly 10^{20} grid points to directly compute the flow over a region 10 km on a side. This is clearly beyond the capability of any dimly envisioned future computer.

Instead of trying to resolve all important eddy scales, one necessarily must address a less ambitious goal of forecasting the evolution of averaged values of the meteorological relevant quantities. Typically in operational NWP models, this means forecasting the value of a variable within a grid volume that may be 100 km on a side horizontally, and 50 to 100 mb thick vertically. Clearly, this grid will not have sufficient resolution to describe many interesting phenomena. A powerful thunderstorm having a horizontal scale of 10 km will not be resolved by this grid, nor will the details of a sea breeze, or clear-air turbulence, etc. But if the model cannot resolve these phenomena, and if we are only attempting to define averages on quite a large scale, do we really have to concern ourselves with such subgrid scale processes? The answer is a definite yes. These features of the turbulent flow, even though they be subgrid to our model, still interact in a complex, nonlinear manner with flow on the resolved scale. Thus we are led to the problem of parameterization, which in essence is the science (and to some degree, art) of properly representing subgrid scale influences on the model's resolvable scale variables.

There exists considerable diversity in the techniques used for parameterizing transport processes within NWP models. The earliest form of transport parameterization used in NWP models involved eddy-coefficient or K-theory. In K-theory the subgrid fluxes which one wishes to parameterize are assumed to be proportional to the local gradient of the relevant mean quantity. The proportionality factor is the eddy coefficient, K. The problem thus shifts from one of specifying unknown subgrid scale fluxes to that of defining "proper" eddy coefficients for the flow. In early treatments, the eddy coefficients generally were selected *a priori* according to some analytical function. Thus, to some extent one was determining the answer before beginning the integration. Current K-theory models often use eddy coefficients which depend in some manner on the stability of the flow (through deformation and buoyancy, or a bulk Richardson number, for example). Thus, the magnitude of K varies in time and space in a manner dependent on the evolution of the flow variables--a very desirable feature. Some weaknesses in K-theory, however, have led to the development of alternative approaches to transport modeling. For example, in convective situations where large eddies fill the atmospheric boundary layer (ABL) and are responsible for a significant fraction of the transport, the fluxes are not strongly related to the immediate local gradient. In fact, these eddies may transport heat counter to the local temperature gradient, which would imply nonphysical, negative eddy coefficients.

One of the alternate approaches to modeling transport processes within the atmospheric boundary layer takes advantage of the observation that often under convective situations the wind, potential temperature, and specific humidity are nearly constant with height from near the surface to near the boundary layer top--that is, these quantities are well-mixed within the convective ABL. Given such conditions, it is unnecessary to have many grid points in the vertical resolving the profiles, since their values within the mixed-layer can be defined by single mean values. It is, however, necessary to carefully define the fluxes at the top and base of the mixed-layer since these fluxes will determine how the mean values within the mixed-layer change with time. Since one does not have multiple grid points near the top of the ABL to help compute the entrainment flux in this type of complex, this is particularly true when the boundary layer contains clouds, because the presence of clouds has a major impact on turbulence, hence entrainment at ABL top. Thus, although initially attractive because of their apparent simplicity, the mixed-layer formulations can become complex and require considerable ingenuity to define entrainment fluxes in situations more complicated than the clear, convective ABL.

In R&D applications, second-order closure modeling has been widely used for parameterizing the transports due to turbulence. Second-order models, like K-theory models, require numerous grid points for their computations--making no *a priori* assumptions concerning the degree to which the ABL is well mixed. Unlike K-theory models, however, the fluxes are not assumed directly proportional to local mean gradients. Instead, dynamic equations for the fluxes are developed and added to the collection of model equations to be numerically integrated. A multiplicity of terms requiring closure arises from these new equations, and fundamental work in this area centers on improving and generalizing the closure expressions.

While the second-order models often permit greater realism in their description of ABL processes, a significant price must be paid in model complexity and computer time. (In a recent third-order closure calculation, Bougeault [2] was required to integrate 50 differential equations--this being feasible only because it was a one-dimensional model.) Currently, only substantial simplification will permit second-order modeling techniques to be incorporated into operational NWP models. It is possible, for example, to include a length scale equation and the turbulent kinetic energy equation in a NWP model to help in defining a generalized eddy coefficient, without carrying all of the second-moment differential equations.

Thus, the necessity for an operational NWP model to represent the atmosphere on a horizontal scale of many hundreds or even thousands of kilometers means that resolution of turbulence transport with the same detail as practiced is current R&D boundary layer models is impractical. However, transport parameterization in these NWP models, while necessarily somewhat crude, is still of great importance to the success of their forecasts. The important question here then becomes this:

> How do we take the advances being made in turbulence modeling research with high-resolution models, and with observation programs that focus on the details of local ABL turbulence, and use them to the best advantage in developing the physical parameterizations required in coarser-scale NWP models?

It clearly requires more than "scaling-up" the closure assumptions used on the fine scale to the larger scale. For example, a transport parameterization used for describing turbulent fluxes in a detiled cloud model cannot be expected to also represent the situation when towering cumulus, embedded in an otherwise nearly laminar troposphere above the ABL, become entirely subgrid to the model. And, indeed, entirely different phenomenological approaches have been developed for representing cumulus effects in synoptic scale models. But where are the bounds defining the types of transport scheme appropriate to a given model simulation? Or, to pose the problem slightly differently, if we begin with a fine-resolution three-dimensional model and gradually increase the grid spacing in successive simulations of the same situation, how should we gradually alter the parameterization algorithms so as to continuously represent the flow in a realistic manner at each scale? The demand for increased skill in sub-synoptic and mesoscale NWP models requires that such questions be addressed in a serious, extensive manner.

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2. Bougeault, P.: The Diurnal Cycle of the Marine Stratocumulus Layer: A Higher-Order Model Study, *Journal of the Atmospheric Sciences*, 42:2826-2843, 1986.

QUESTION: Warren Campbell (BDM Corporation). How do you calibrate the models that you use? Ordinarily when you start doing model equations you end up with a group of parameters and then you have to come up with solutions to those parameters. How do you go about actually making comparison with what's going on in the atmosphere in making those calibrations?

ANSWER: As far as the second-order closure models, most of that kind of thing is done first by using model calculations of laboratory flows to set the model constants. I have been working with the various versions of the Mellor and Yamada formulation, and they have a hierarchy of different order closure models. If you look at how they got the closure constants that are used, it traces back to laboratory flow simulations. So you don't have to change them for every new meteorological condition you are dealing with, which is a nice feature.

N87-22353

EXAMPLE ON HOW TO MODEL AND SIMULATE TURBULENCE FOR FLIGHT SIMULATORS

John C. Houbolt
NASA Langley Research Center
Hampton, Virginia

There has been a lot of analytical development on gust response in the past several years, but evidently the material has not been disseminated very well.

Therefore, I would like to first discuss length scale, L; using the spectrum differently; how σ and L form a combined parameter; why L is not important; and the exceedance number N_0.

Consider Figure 1 which deals with the scale of turbulence. Note that sometimes it is improper to derive an artificial or apparent value for turbulence length scale and then label it as the integral scale of turbulence. Suppose we have some data, as depicted in Figure 1, and then we curve fit an analytical function to the data. We do this specifically to deduce a value of L that makes the function fit the data. We should be very careful and not call this deduced value the integral scale of turbulence. Keep in mind that what we are doing is not only measuring the turbulence but also measuring the phemonenon that is causing the turbulence. The value of L may thus be misleading.

Figure 2 shows the power spectrum as obtained from measurements of turbulence and winds for very different intervals of sampling times ranging from 1 second to 1 minute, to an hour, to a day, to a week, to a month, to a year, and to five years. Just about all wavelengths of turbulence are possible in this representation of the turbulence spectra. If we fit a chosen function to the data, say a von Karman function, we might deduce a scale of turbulence on the order of 1000 miles. Thus, be very careful how you describe the scale of turbulence because it depends on the phenomenon and on the time interval of sampling. In the case of sampling over years, we are working with wavelengths that may be several thousand miles long.

For a number of years I have advocated that spectral functions should be looked at in a different way; that is, use the same spectrum function or functions that we have used before but interpret them differently. For example, we can rearrange the von Karman spectrum function so that is appears as shown in Figure 3. There is only a single line at the high frequencies. We combine both the severity and scale of turbulence to form a new parameter, designated as σ_1 in the figure. Non-dimensionalizing the spectrum with this parameter results in all the curves condensing to the elegant form shown. Working with this modified form of the analytical function greatly simplifies the rest of the analysis.

For example, suppose we have made measurements in a patch of turbulent air and have deduced the power spectrum shown schematically in Figure 4. If you make use of the function depicted in Figure 3, you can calculate automatically the combined parameter $\sigma_w/L^{1/3}$ by the equation:

$$\frac{\sigma_w}{L^{1/3}} = [1.919\ \Omega_1{}^{5/3}\ \phi_w(\Omega_1)]^{1/2} \tag{1}$$

This equation is obtained by simply going to the straight line portion of the curve, any place along it, and inserting the values of the abscissa, Ω_1, and ordinate, $\phi_w(\Omega_1)$, into the equation. Do not try to separate the severity from the scale in any more detail. They are combined in the parameter, σ_1, and they should be used that way.

Let's also make an inference from this observation. For a given set of data, $\sigma_w/L^{1/3}$ is a constant value. What does that infer? It infers the results shown in Figure 5.

From this figure we can, if indeed we want to, split it out and write σ_w as a function of L; specifically, $\sigma_w = CL^{1/3}$. It is not surprising then that the British have come up with the notion that the turbulence severity tends to vary according to the third power of the gust gradient distance. Spectral theory predicts this behavior if L is equated to gust gradient distance H as is often supposed. But again, I remind you, although this behavior can be inferred, it is not necessary to separate σ_w from L; σ_1 should be used as a combined parameter.

When we use the combined parameter, σ_1, we find the output spectrum of the vertical acceleration for an airplane as a function of the reduced frequency appears as shown in Figure 6. The influence of scale shows up only in a minor way at the lefthand tails of the curves; the influence is inconsequential with respect to the overall acceleration that the airplane feels because the primary airplane response takes place out in the region of frequency where scale is completely out of the picture. This observation is true for all the airplanes I have examined so far. As an aside, we should keep in mind that at the very low frequencies where scale does have a minor effect, we are dealing with wavelengths where the pilot, the autopilot, or the navigation system is controlling the airplane. The question of turbulence scale is thus a moot point.

Some questions have arisen about the number of zero crossing values, N_0, particularly with regard to certain pertinent integrals which do not converge. However, if it is done right, there is no problem getting a meaningful value of N_0. The N_0 integral will converge to a realistic value if the proper ingredients are included in the analysis. These are specifically the two functions shown in the middle of the equation on Figure 7. This equation depicts in simplified form the spectrum for the vertical acceleration of the center of gravity (c.g.). The first function on the right-hand side of the equation is a simplified form of the airplane transfer function. The last function represents the gust spectrum in simplified form. The second function takes into account gust penetration effects; notice the k^2 falloff at high frequency. The third term takes into account the effects of spanwise variation in turbulence. This avoids the usual assumption that the gusts are uniform in the spanwise direction. Observe how the effect of spanwise variation falls off inversely with k at the high frequency. Notice that the spanwise effects function also contains the aspect ratio A. When the two middle functions shown in Figure 7 are included, no problem is involved in determining the value of N_0.

Some simplified results for N_0 that have been obtained will now be discussed. To start the discussion, it is noted that the study of a number of airplanes indicates that the reduced frequency k_0 is related to the reduced short-period frequency by:

$$k_0 = 1.29\ k_s^{0.6} \tag{2}$$

where

$$k_s = \omega_s \frac{c}{2V} \tag{3}$$

In turn, the zero crossing value follows:

$$N_0 = \frac{V}{\pi c}\ k_0 \tag{4}$$

Consider now the history of the gust loads analysis. If we consider the load on an airplane when it enters a sharp-edged gust such as shown in Figure 8, the load or lift on the airplane is given by:

$$L = \frac{a}{2}\ \rho S V^2\ \frac{U}{V} \tag{5}$$

Equating this lift to an equivalent incremental acceleration gives:

$$\Delta n = \frac{L}{W} = \frac{a\rho SV}{2W}\ U \tag{6}$$

Note that the basic parameter which involves the combination of the variables a, ρ, s, V, and W is an equation we have seen and used for years. Its continued use, however, has led us into a trap. Later I will show that by rearranging the form of the basic parameter, our results will be greatly simplified. This equation is a first cut at establishing the vertical acceleration the airplane will feel when entering a sharp edge gust. We recognize, however, that gust penetration effects, non-steady lift effects, and the vertical motion of the aircraft tend to alleviate the load. In the early years--the 1940's--we introduced an alleviation factor (K) in the equation:

$$\Delta n = \frac{a\rho SV}{2W}\ K_g U \tag{7}$$

The factor was arbitrarily derived and was plotted as a function of the wing loading on the airplane as illustrated in Figure 9. We recognized, however, that the wing loading was not the right parameter to use when we started analyzing the acceleration in a more rational way, that is, when we began to include penetration effects, non-steady lift effects, and airplane motion effects.

When these various effects were taken into account the results shown in Figure 10 were obtained. The fundamental assumption leading to this figure is that the airplane is a point mass which moves in the vertical direction only; the gust was assumed uniform across the span. The incremental acceleration is noted to be of the same form as obtained for a sharp edge gust, except that a rationally derived alleviation factor, K_g, is introduced. K_g was found to be a function of the mass parameter μ. The gust shape assumed was a one minus cosine with a gust gradient distance H of 10 to 12 chords. U was taken to be on the order of 50 fps. Actually, there is nothing magic in the choice of the one-cosine gust; it is arbitrary. A triangle or half sine wave would have served equally well.

Progressing historically, the power spectral techniques for analyzing the response of aircraft in turbulence began to be introduced. Some basic results obtained are shown in Figure 11. The equation for vertical acceleration:

$$\begin{aligned}\sigma_{\Delta n} &= \frac{a\rho SV}{2W} K_\phi \, \sigma_w \\ &= \frac{V}{cg} \frac{K_\phi}{\mu} \sigma_w \qquad (8)\end{aligned}$$

is found to be analogous to the discrete gust equation, except that the gust severity and acceleration values are now expressed in rms units. The alleviation factor K_ϕ is also found to be a function of the mass parameter μ, and in addition is found to depend on 2L/c. This ratio L/c is analogous to the gust gradient distance in the discrete gust formulation. We should note that if the gust spectrum had been introduced as depicted in Figure 3 (i.e., as a function of σ_1), then the various curves in Figure 11 would collapse to nearly a single curve.

When everything is put together in a simple rational way, the gust response equation for acceleration can be shown to collapse to the very simple result:

$$\Delta n = 1.5 \sqrt{\frac{0.13}{\alpha}} \qquad (9)$$

However, Equation 9 is the complete equation for designing an airplane for gust penetrations; α is the angle of attack of the airplane necessary to maintain level flight, where α has the value at which $C_L = 0$. That is all there is. The equation automatically takes into account the altitude of the airplane, the speed of the airplane, the weight, all the alleviation factors, everything. I believe this to be a profound equation. People should be aware of it and it should be introduced into the regulations. We must note, however, that we have not been able to change the regulations for 40 years so the chances of getting this equation into the regulations appear slim.

Note the inferences from the equation. If you run into turbulence, one of the first things you want to do is slow down a little. To slow down but maintain altitude you've got to increase α. Increasing α gives you smaller incremental accelerations. As I mentioned, this is a fascinating equation, and I hope we can make the aviation community aware that it exists.

I also have derived generalized equations for N_0. If we had started with the von Karman expression, the N_0 value is simply given by:

$$N_0 = \frac{1.084}{\sqrt{c\alpha}} \qquad (10)$$

Again, all flight conditions are taken into account in this equation. The only item determining N_0 is α. If we had started with the Dryden spectrum, the same form of the result is found but the constant is different:

$$N_0 = \frac{0.858}{\sqrt{c\alpha}} \qquad (11)$$

Now consider the aspects of turbulence for simulator applications. There has been trouble in the past with the simulations of turbulence in flight simulators. This is primarily because only one component was used. There has been some attempt to alleviate this situation with added sophistication but overall this has not been realistic. Specifically, attempts have been made to include non-stationary turbulence such as a modulation times a stationary kind of random turbulence. But invariably when pilots fly the simulator they comment that "It does not seem realistic." It is not surprising that it does not seem realistic because the simulation is not very realistic. As I have mentioned on previous occasions, turbulence is three-dimensional in nature, and this must be taken into account.

For example, as shown in Figure 12 there are, in general, three forces and three moments due to turbulence. Not all these forces are important, not all the moments are important. There are three, in particular, that are significant. They are: (1) vertical force, (2) pitch moment, (3) rolling moment. In many cases, pitching and rolling moment have not been taken into account. We must look at the turbulence situation in a little more realistic fashion. We cannot have a rolling moment if we make the assumption that the turbulence is uniform in the spanwise direction. There is a spanwise gradient in the turbulence just like there is a variation in longitudinal direction of flight. When we take into account the spanwise gradient you will have rolling moments on an airplane. All pilots know this fact. During approach an airplane can suddenly be thrown into a 20 degree roll condition. So in simulation studies we should at least include the vertical force, pitch moment, and roll moment because these are the important ones. In general we have not done so. The question is, how do we do that? The remainder of the presentation gives a quick insight as to how we can introduce the vertical force and the two important moments into simulation studies in a very realistic way.

Figure 13 introduces the notion of cross spectra. Along paths W_1 and W_2 we have different turbulence time histories. We have, in turn, differing cross spectra according to the separation distances that are involved. Let's take this into account in deriving the equations that produce the vertical force and the rolling moment.

Consider the vertical force as an example. We can simulate this very rationally in a simulator. The lift is given by:

$$L = \frac{a}{2} \rho S V^2 \frac{W}{V} \tag{12}$$

or

$$L = \frac{1}{2} \rho V^2 S c_L \tag{13}$$

where

$$c_L = a \frac{W}{V} \tag{14}$$

The actual form of the equation for L is much more complicated than shown, but if we considered the equation in complete form and took the Fourier transform of the lift coefficient you would arrive at the F_{c_L} function:

$$F_{c_L}(\omega) = \frac{a}{V} (P + iQ)(R + iS) F_W(\omega) \tag{15}$$

Because we have non-steady lift effects, we work with complex numbers in the frequency plane; (P + iQ) gives the in-phase and out-of-phase lift components that are due to gust penetration effects; (R + iS) is a similar kind of function but it occurs due to the spanwise variation in turbulence. It would take a week of lectures to present the complete derivation of (R + iS) but I'll indicate its basic nature as a final result. Finally, in Equation 15 we have $F_W(\omega)$ the Fourier transform of the turbulence itself. From the Fourier transform we can readily deduce the power spectrum of the lift coefficient as:

$$\Phi_{c_L} = \frac{a^2}{V^2} (P^2 + Q^2)(R^2 + S^2)\Phi_W \tag{16}$$

An indication of the nature of some of these functions is given in Figure 14. If we penetrated a sharp-edged gust, the lift would grow as sketched in the upper part of the figure. Converting to the frequency plane, the $(P^2 + Q^2)$ function as shown is obtained.

The function $(R + iS)$ is the one term that comes about because of the explicit consideration of the spanwise variation in turbulence. It involves evaluating the integral:

$$R^2 + S^2 = 2 \int_0^2 \int_{-1}^{1-S} \frac{c(S+\eta)}{C_0} \frac{c(\eta)}{C_0} \phi_{12}(|S|,\omega) d\eta ds \qquad (17)$$

where c is wing chord and ϕ_{12} is the cross spectra. Evaluating the integral gives the function: $1/(1 + 0.55AK)$. A good approximation to this function is sketched in Figure 15.

For purposes of illustration, I have adapted:

$$\phi_W = \frac{\sigma_1{}^2 \left[\frac{2L}{c}\right]^2}{1 + \left[\frac{2L}{c} K\right]^2} \qquad (18)$$

as the power spectrum of the input gust. I have introduced σ_1, the combined severity and scale parameter, and this makes all the spectra for c_L fall at the same points at high frequency.

Figure 16 shows the power spectrum of the lift coefficient as a function of reduced frequency. When all the functions are put together the equation:

$$\phi_{c_L} = \frac{a^2}{V^2} \sigma_1{}^2 \frac{2500}{1 + 4743k^2 + 45357k^4} \qquad (19)$$

represents a quite accurate curve fit of the spectrum result. We now ask the question: Is there a differential equation which when considered could lead to this function? The answer is yes, and the equation is:

$$213\left(\frac{c}{2V}\right)^2 c_L + c_L = 50 \frac{a}{V} \sigma_1 W_n \qquad (20)$$

This is a differential equation that would yield the spectrum given by Equation 19. If we wish, we can have coefficients in the equation vary during an approach according to the way the speed of the airplane is varying. The W_n on the right-hand side of the equation is white noise as obtained from a white noise generator; the equation automatically shapes the white noise to an appropriate turbulence spectrum. The approach for simulation is illustrated in Figure 17. Utilizing a white noise generator, feed the white noise into the analog of this differential equation. A time-varying c_L is generated which you input into the simulator, specifically to the equation for vertical motion. A realistic simulation of vertical force on the airplane is thus obtained.

For rolling moment (see Figure 18), it is essential to take into account the spanwise variation in turbulence. The general equation for the spectrum of the rolling moment coefficient is:

$$\phi_{C_M} = \frac{a^2}{16V^2} \frac{A^2}{A_0^2} I \; (P^2 + Q^2)\phi_W \tag{21}$$

where

$$A = \frac{b^2}{S} \quad \text{and} \quad A_0 = \frac{b}{C_0}$$

The nature of the integral I of Equation 21 is:

$$I = 2 \int_0^2 \int_{-1}^{1-S} \frac{c(S + \eta)}{C_0} \frac{c(\eta)}{C_0} (S + \eta)\eta \; \phi_{12}(151,\omega)d\eta ds \tag{22}$$

is shown in Figure 19.

The rolling moment integral is a little more complicated than the vertical force integral because we have to take moment arms into account. The very definite pronounced peak in Figure 19 is associated with wavelengths near the span of the aircraft. Indeed a very good approximation to the value of k at which this peak occurs at π/A. A very useful and simple approximation to I is:

$$I = \frac{5.57\nu}{7.84 + \nu^2} \times \frac{0.32 - 0.26\varepsilon}{1 + 0.8\varepsilon} \tag{23}$$

where

$$\nu = \frac{c}{2L} A \sqrt{1 + \left[\frac{2L}{c} k\right]^2} \tag{24}$$

Note that a different frequency argument than k alone is found.

Figure 20 shows the spectrum for rolling moment coefficient as a function of a reduced frequency. The equation:

$$\phi_{C_M} = \frac{a^2}{16V^2} \frac{A^2}{A_0^2} \sigma_1^2 \frac{33.8}{1 + 685k^2 + 1473k^4} \tag{25}$$

fits that curve exceptionally well. There is a differential equation that can lead to this spectrum which we will discuss later.

Figure 21 is added here to show again the non-importance of L. The spectrum of the rolling moment coefficient is at the top of the figure. When we include the transfer function for the airplane, $|H|^2$, that is associated with roll dynamic behavior, you get the output spectrum for roll angle as shown at the bottom of the figure. The scale of turbulence is not important in the consideration because the predominant response is in the frequency range that is not influenced by the scale of turbulence.

The differential equation for the rolling moment coefficient is:

$$38\left(\frac{c}{2V}\right)^2 c_M + 28 \frac{c}{2V} \dot{c}_M + c_M = \frac{a}{4V} \frac{A}{A_0} 5.81 \, W_n \tag{26}$$

Again, as in the case of the vertical force (see Figure 22), you have a white noise generator, you feed its output into the analog of the differential equation (Equation 26), and out comes the time varying moment coefficient; you input this to your simulator, specifically to the rolling equation of motion. The simulation of the rolling moment due to a turbulence encounter will then automatically be taken into account.

QUESTION: Hal Murrow (NASA Langley). Two points I would like to make. On the spectrum correction factor, I agree that there needs to be a correction. The point that is unclear is the magnitude of the correction and probably the biggest reason for this is the fact that in our instrumentation system for the B-57B we have some anti-aliasing filters. Their effect has to also be taken into account to determine the magnitude of the correction to apply. The second point I wanted to make is that we are talking about hypersonic airplanes nowadays, the Orient Express, that sort of thing. If you think of the primary response of the airplane as being in the short-period mode and calculate what that would be, it would go down to the very low frequencies or wavelengths. In these regions it would make a difference as to what is the value of L. I'm not convinced that L and σ are directly related in all cases.

ANSWER: That is something we will argue about in the future. You will not get down to those low frequencies with any airplane.

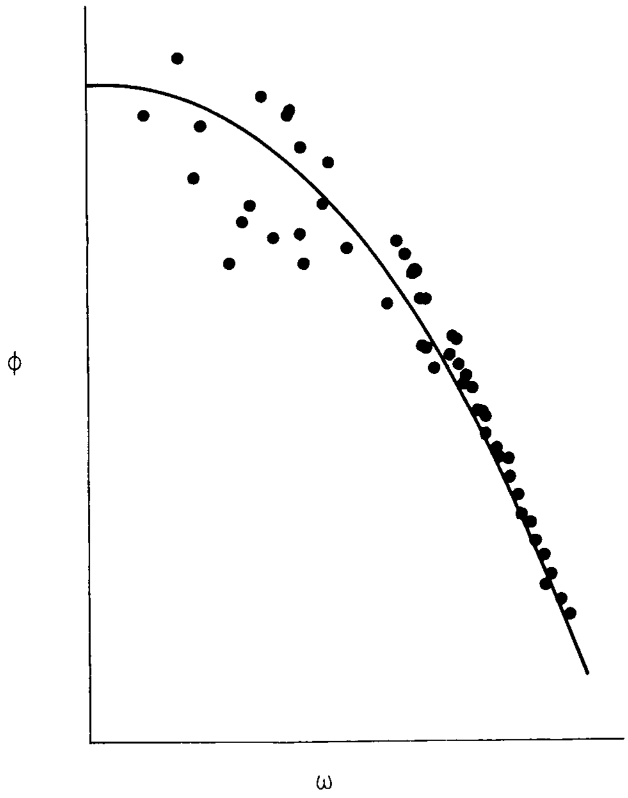


Figure 1. Curve fit of an analytical function to deduce a value for L.

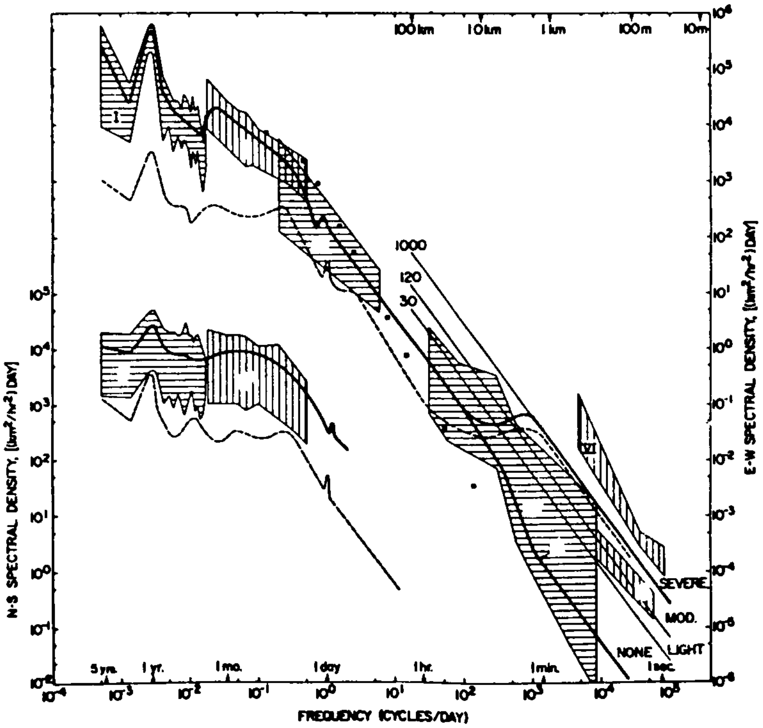


Figure 2. Power spectrum.

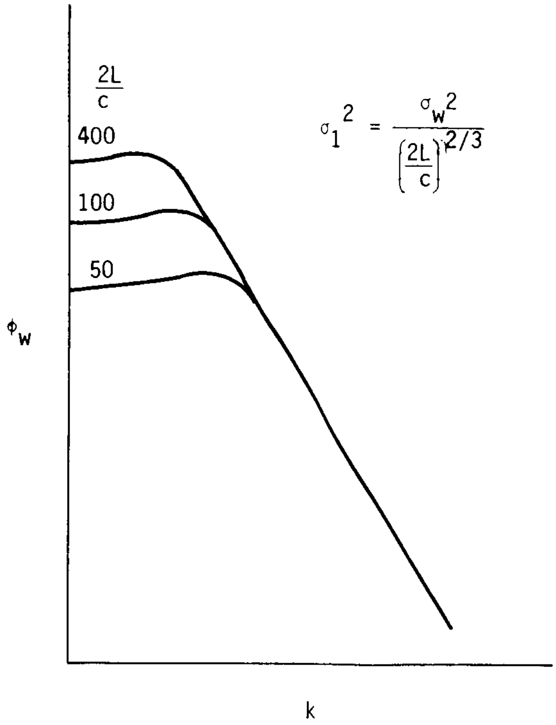


Figure 3. A von Karman spectrum.

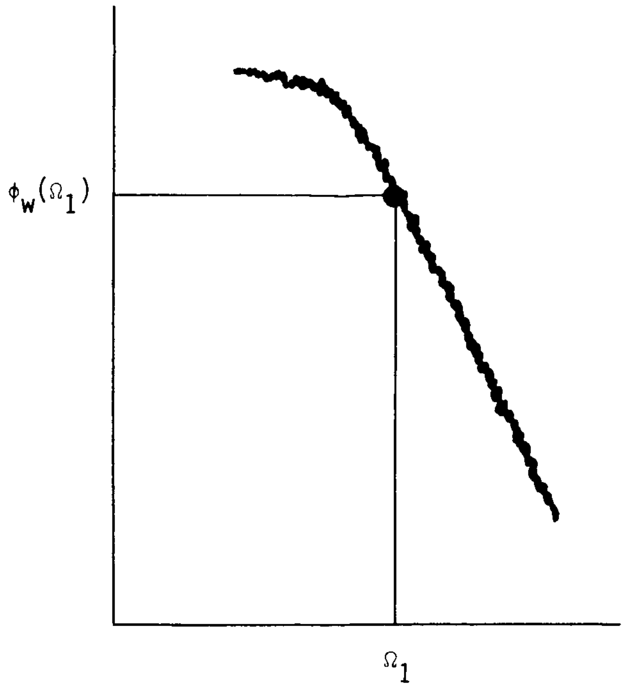


Figure 4. Example of a power spectrum for a patch of turbulent air.

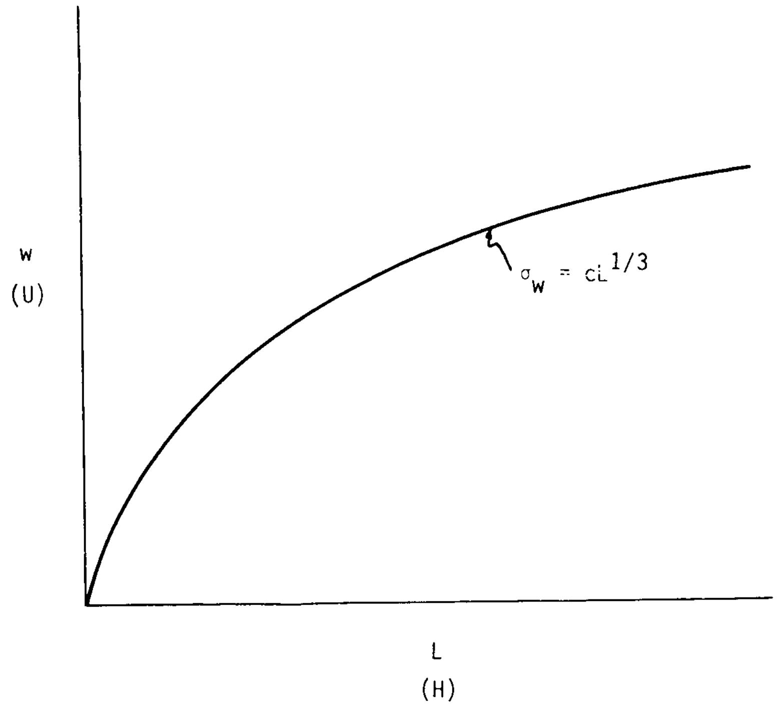


Figure 5. Influence from the relationship of σ_W, L, and C; namely, $C = \sigma/L^{1/3}$.

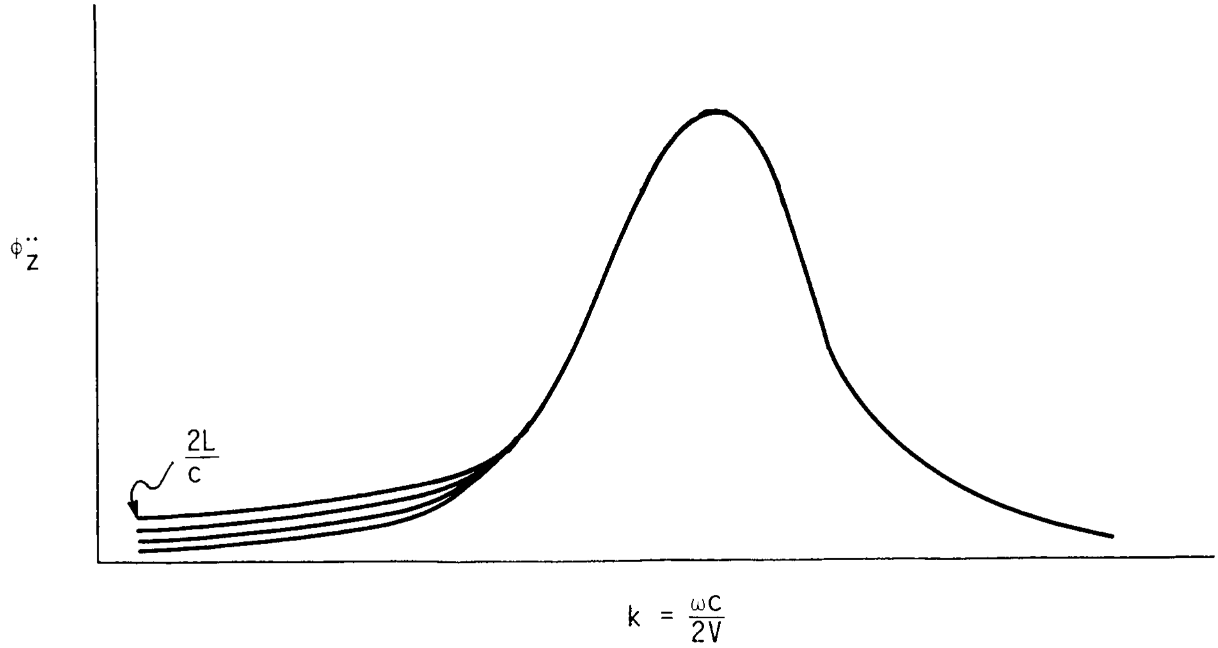


Figure 6. Example of an output spectrum for vertical acceleration of an airplane which illustrates the influence of the scale.

$$\phi_{\ddot{z}} = \underbrace{\frac{a_1 k^2}{1 + a_1 k^2}}_{\text{Transfer Function}} \times \underbrace{\frac{\beta^2}{\beta^2 + 1.5\pi k + \pi^2 M k^2}}_{\text{Gust Penetration Effects}} \times \underbrace{\frac{1}{1 + 0.55AK}}_{\text{Spanwise Effects}} \times \frac{\sigma_w^{\ 2}}{1 + \underbrace{\left(\frac{2L}{c}\, k\right)^{5/3}}_{\text{Gust Spectrum}}}$$

Figure 7. Simplified form of the spectrum of vertical acceleration of the center of gravity.

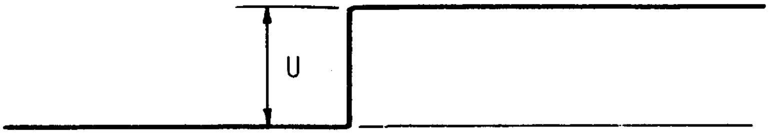


Figure 8. Sharp edge gust.

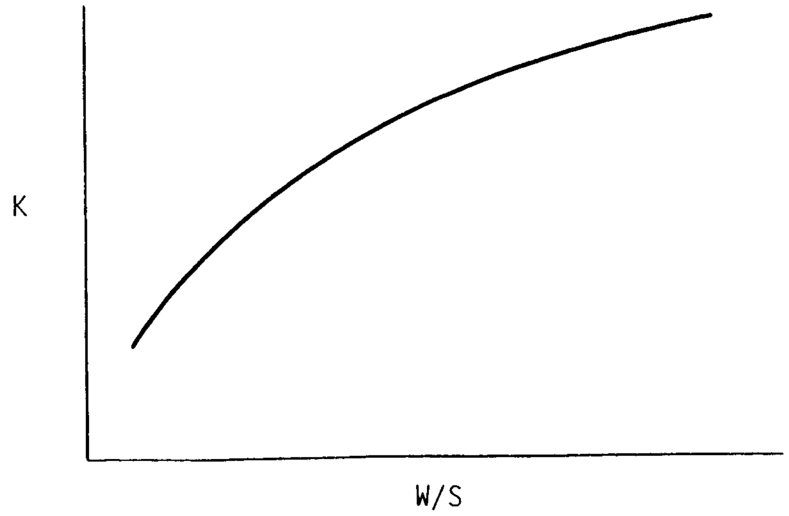


Figure 9. A 1940's version of the gust alleviation factor as a function of wing loading.

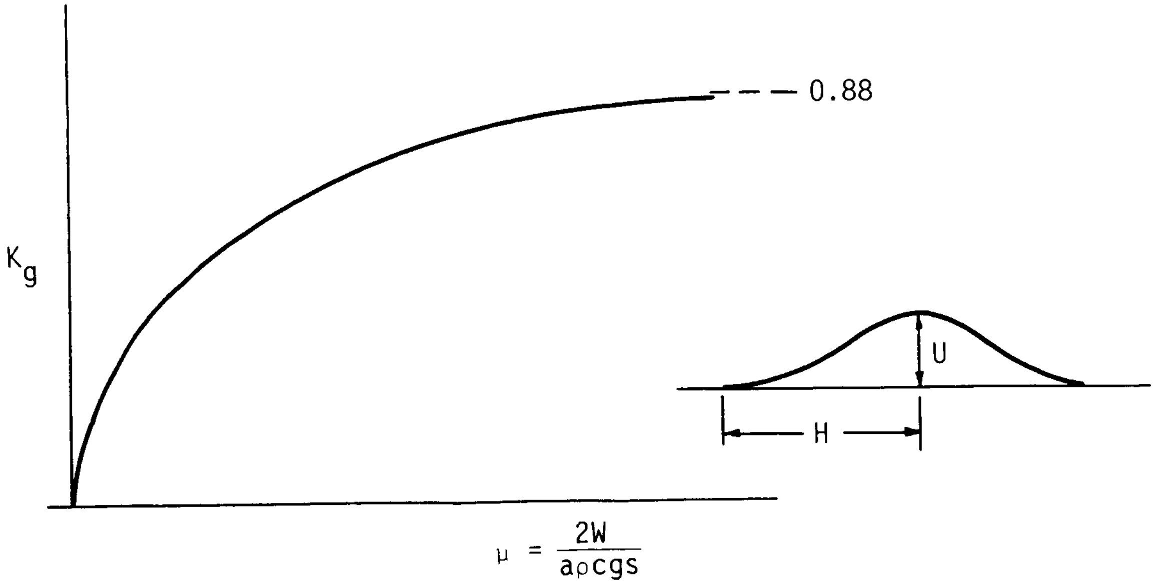


Figure 10. The gust alleviation factor as a function of mass parameter.

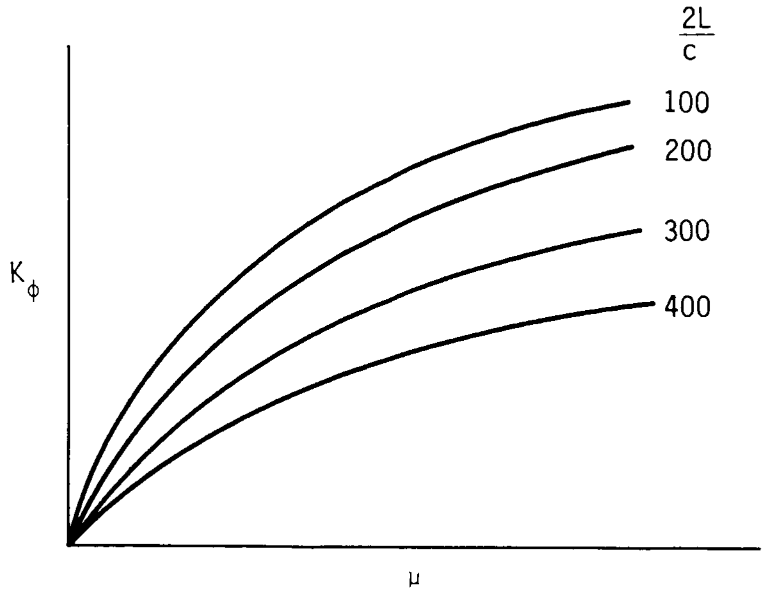


Figure 11. The gust alleviation factor as a function of the mass parameter as well as showing its dependence on gust gradient distance.

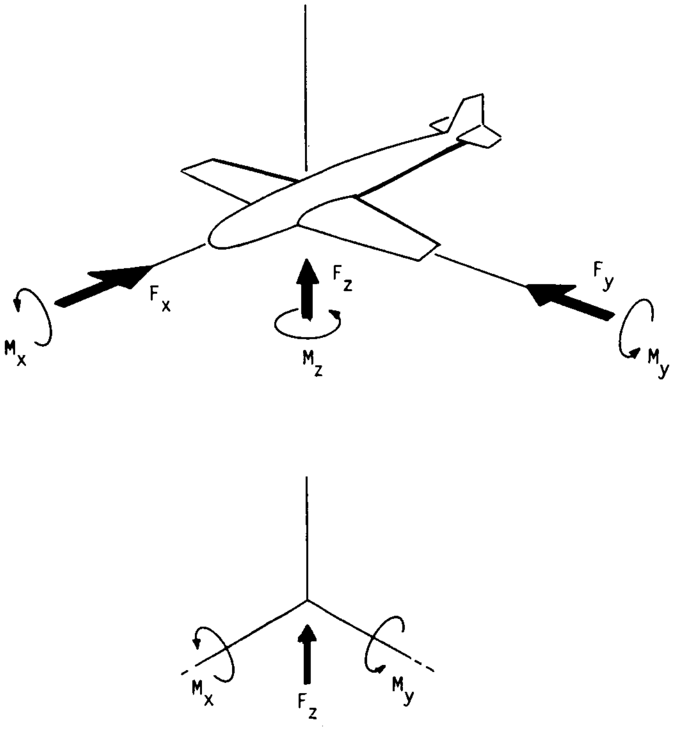


Figure 12. The forces and moments due to turbulence.

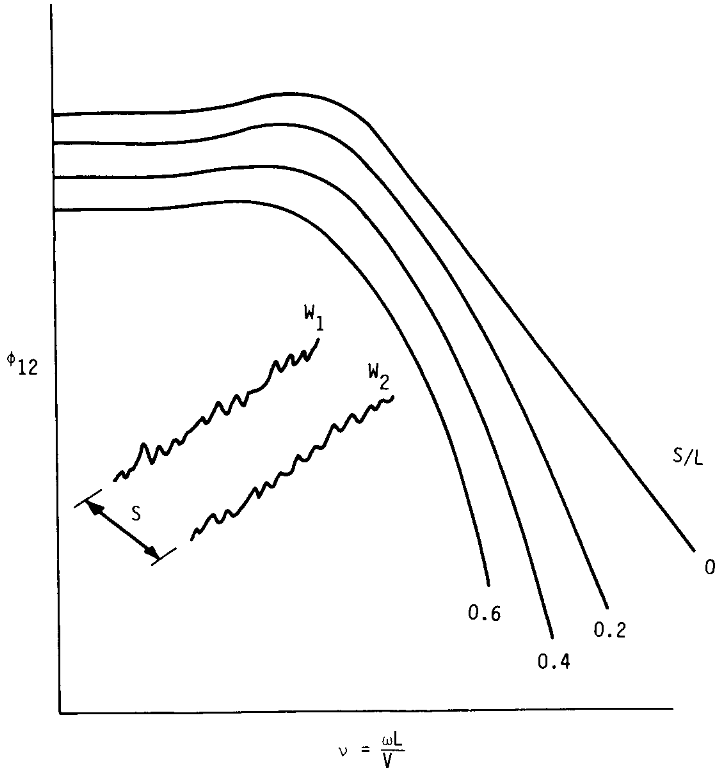
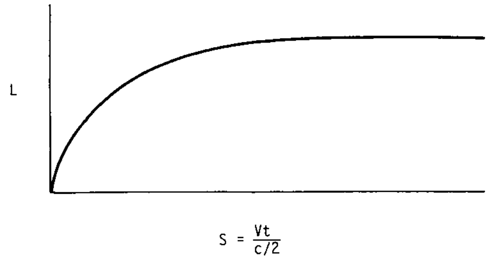
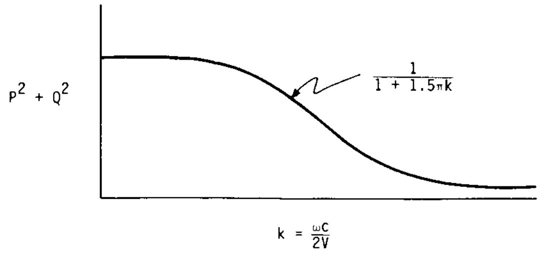


Figure 13. Illustrating the effect of separation distance on cross spectra.



(a) Time plane



(b) Frequency plane

Figure 14. Lift relationships as a function of time and frequency components.

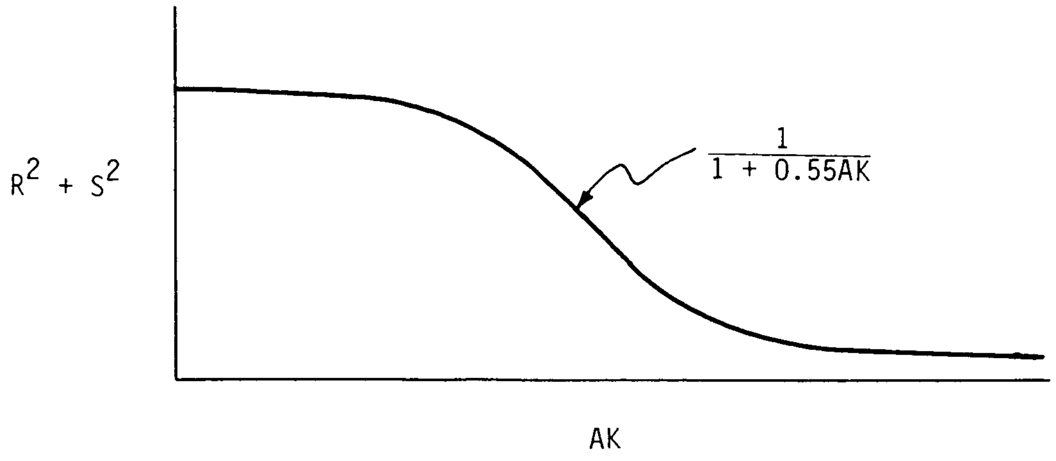


Figure 15. Spanwise variation effects with a consideration of cross spectra.

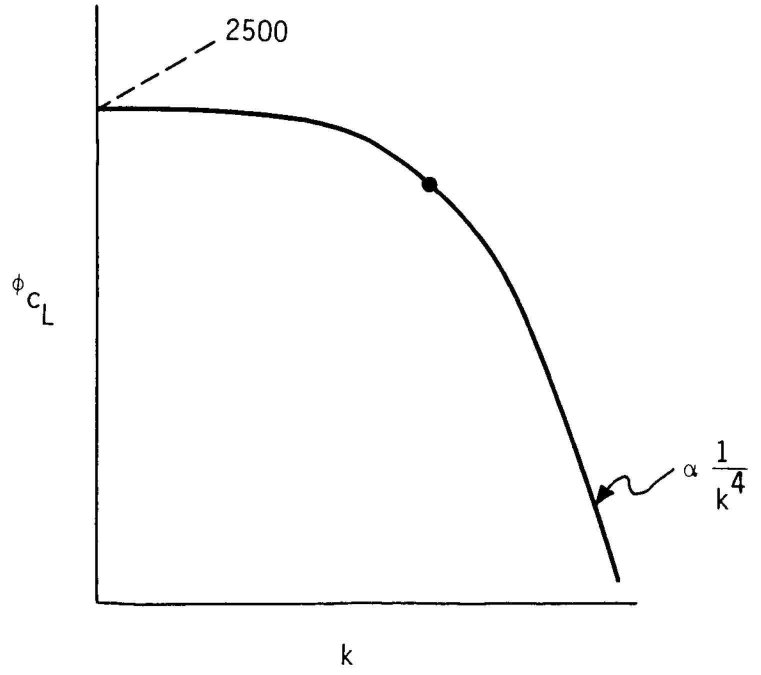


Figure 16. Power spectrum of the lift coefficient as a function of reduced frequency.

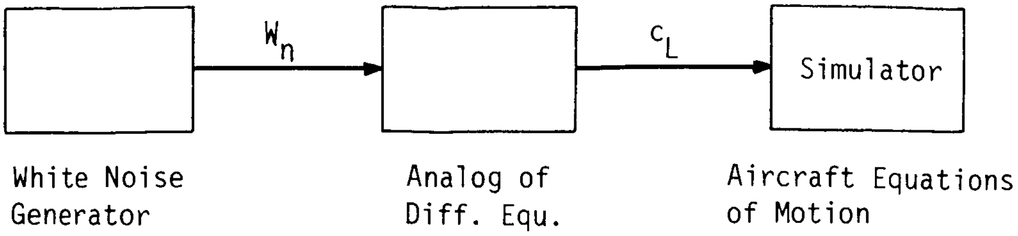


Figure 17. A realistic simulation approach.

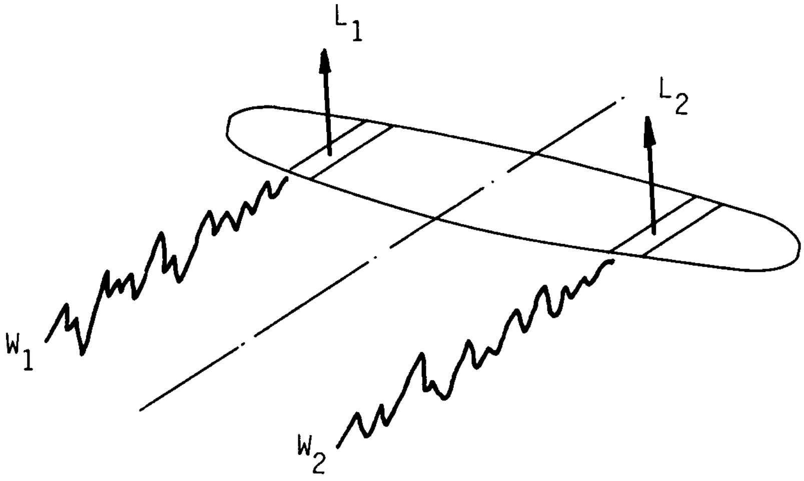


Figure 18. Spanwise variation in turbulence illustration.

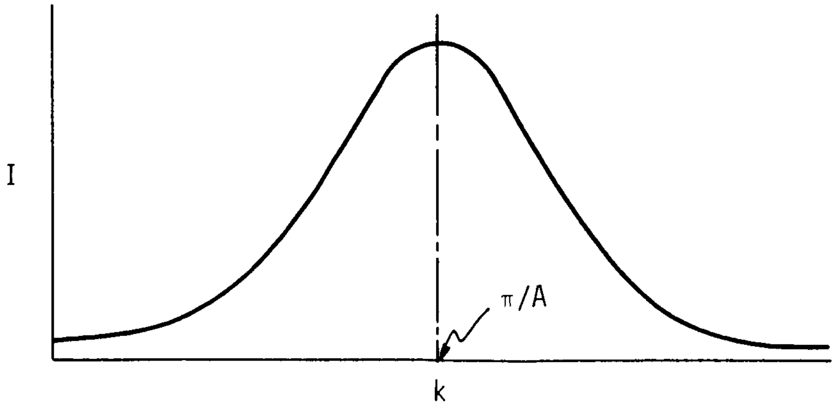


Figure 19. Rolling moment integral relationship to reduced frequency.

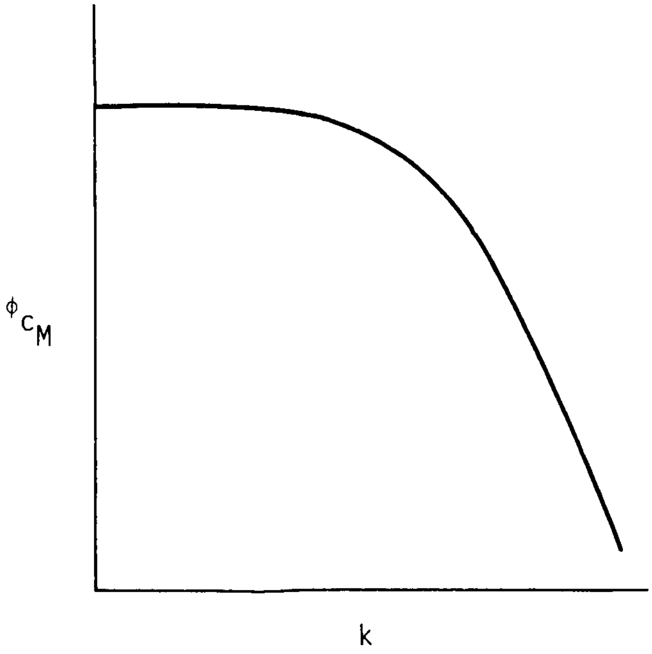


Figure 20. Rolling moment coefficient as a function of reduced frequency.

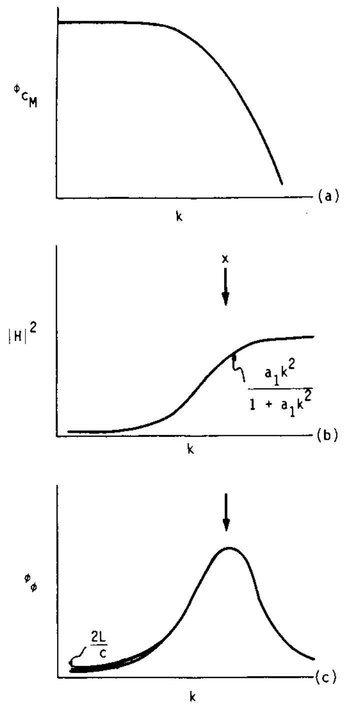


Figure 21. Output spectrum (ϕ_ϕ) obtained from spectrum of rolling moment coefficient (ϕ_{CM}) by a consideration of the transfer function $|H|^2$, i.e., $\phi_\phi = |H|^2\phi_{CM}$.

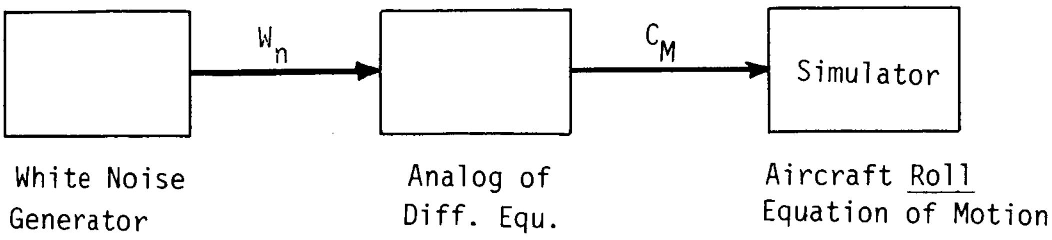


Figure 22. Roll behavior simulation.

N87-22354

IMPLEMENTATION OF TURBULENCE MODELS INTO SIMULATORS

Robert L. Ireland
United Airlines Flight Center
Denver, Colorado

In this paper, I discuss simulation of turbulence as it relates to the flight training environment. This is a remote discipline for many of you, and its requirements are significantly different from a research environment.

We find in flight training that an accurate depiction of the turbulence phenomenon is not a necessary end in itself. In fact, it is something that we do not often have the time or money to accomplish. Instead we are interested in a turbulence situation that feels good to the pilot, and perhaps what Dr. Houbolt was talking about was a very good description of where we need to go in that regard [1].

We consider all simulation enhancements in terms of training objectives. That is what we have to address, and we have a limited time to do it when a pilot that comes to the Training Center for only a three-day proficiency check each year. High-frequency sources of turbulence have to offer a distraction to the pilot. They should cause an oscillation of the instruments, and cause the simulator to move if it has a motion system. The exact scientific nature is really fairly unimportant. We do have some more specific training objectives, however, associated with the large magnitude large-scale turbulence that is often known as wind shear.

I will discuss the high-frequency turbulence issue first. We have several different examples of turbulence in the range of simulation at United Airlines at the present time. Our simulators range in age from 3 years to 25 years. Some of them merely put random white noise into the motion system, that is, of course, the most primitive. Some put random motion into the equations of motion and nothing else. There are two kinds of simulators that put the turbulence into the equations of motion. One type varies the period of the turbulence such that it does cause a disturbance of the instruments. It turns out to be pretty good. However, some newer simulators use white noise summed into the equations of motion but at the iteration rate of the simulator (30 Hz). As a result, nothing is seen in the instruments but the feel of the motion is good.

We do have two simulators in which we have implemented a more sophisticated approach. They are not limited to vertical turbulence but also incorporate pitch and roll moments. That, of course, is the best cost-effective depiction we have found. The tradeoff in implementation of turbulence in the flight training simulators comes with the interaction with the motion system. Motion systems are actually tuned so that gross maneuvers of the aircraft do not exceed the hardware limits. Consequently, in order to insert turbulence that feels adequate to the pilot, the levels are so high that they may be causing very undesirable effects in the aerodynamics. One thing that I am personally looking into at United at the present time is separately gaining the input of the turbulence to the motion system, so that a lower level of turbulence--a realistic level of turbulence--will also produce a realistic level of motion.

With regard to wind shear, we started putting some different kinds of wind shear models into our simulators about three years ago associated with specific training objectives. We find it very important in the training environment, with more than 2000 crews passing through our simulators each year, that we have some consistency of the training product. Therefore, a microburst model which can be flown through many different ways becomes as much a hindrance as it is a benefit. While it may be a very realistic depiction of the microburst phenomenon, it nevertheless provides no two pilots with the same training experience because it can be flown through an infinite number of ways. Therefore, we have moved to simplified models based on microburst phenomena. For example, a slice through the JAWS data could be programmed into the simulator in a one-dimensional fashion. This would allow us to know that every pilot received exactly the same training experience while at the same time making sure that a level of technical realism is maintained.

In closing, one point that I would like to reference is something that is missing from our simulations right now. No appropriate level of high-frequency turbulence to go along with the microburst models has been defined. I understand that there is some work out on that now. One problem we have with our simple simulation models of wind shear is that the recognition for the pilot is not difficult at all because the airspeed suddenly begins moving and he knows immediately that he is in a wind shear. We would like to add to our wind shear simulations some appropriate levels of high-frequency turbulence to mask that and get the pilot used to what he might have to recognize in the real world.

Reference

1. Houbolt, J. C.: Example on How to Model and Simulate Turbulence for Flight Simulators, *Proceedings: Workshop on Atmospheric Turbulence Relative to Aviation, Missile, and Space Programs*, NASA CP-2468, 1987, pp. 159-178.

N87-22355

THE STATUS OF MILITARY SPECIFICATIONS WITH REGARD TO ATMOSPHERIC TURBULENCE

David J. Moorhouse
USAF Wright Aeronautical Laboratories
Wright-Patterson AFB, Ohio

Robert K. Heffley
Manudyne Systems Inc.
Los Altos, California

1. INTRODUCTION

Atmospheric turbulence models are included in a number of military specifications although there is no military specification devoted solely to atmospheric turbulence models, *per se*. Perhaps the closest example of one is Reference 1, a compilation of maximum gust values for design of ground equipment. Aircraft design specifications which contain gust or turbulence models do so for different purposes. One series addresses the vehicle structural design to ensure sufficient strength when penetrating gusts and turbulence in flight. The turbulence model is expressed in terms of probability of encountering certain levels of disturbance, and has not been revised since the 1960's. Reference 2 contains a turbulence model for use in flight control system design. Again this model has not changed in recent revisions of the specification. The main emphasis of study has been on the interaction of a pilot with his aircraft in various forms of disturbances. This is manifested in the flying qualities specification [3] which contains an extensive model of winds, wind shear, turbulence, and gusts for use in aircraft design and development. It is used in flight stability and control augmentation development and as a simulator model for aircraft design. The model was updated significantly in 1980 [3] and is being further refined in the change from a Specification to a Standard [4]. The remainder of this paper will concentrate on the development and application of the "flying qualities atmospheric disturbance model."

The evaluation of the effects of atmospheric disturbances on airplane flying qualities has been approached in a diverse number of ways. The large volume of literature is evidence of this. At the same time, we have little guidance for choosing among these alternatives when specifying or examining a given airplane design. It is far too easy to become bogged down in the ill-defined tradeoffs between Dryden and von Karman turbulence forms, the need for non-Gaussian or non-stationary charcteristics, the debate over how and when to model wind shear effects, or whether shorter turbulence scale lengths are more realistic than longer ones. Airplane designers and simulator researchers continually face such questions, and while they may find answers suitable for one situation, the same questions can re-appear on a subsequent occasion.

The paper will first discuss the features of atmospheric disturbances that are significant to aircraft flying qualities. Next follows a survey of proposed models. Lastly, there is a discussion of the content and application of the model contained in the current flying qualities specification and the forthcoming MIL-Standard.

2. FLYING QUALITIES NEEDS

It is appropriate first to define what is meant by flying qualities, in order to keep the whole discussion in perspective. One accepted definition is "those airplane characteristics which govern the ease or precision with which the pilot can accomplish the mission" [5]. Further, flying qualities are often "measured" by subjective pilot opinion according to the Cooper-Harper rating scale [5] wherein it is stated that flying qualities are tied to accomplishing a specific task. Due consideration of environmental conditions is, in turn, implied. An airplane can have characteristics that make the task of landing relatively easy in calm air. The same task becomes very demanding in strong turbulence or even impossible in a violent thunderstorm, even though the airplane characteristics may not have changed. Thus, due consideration of atmospheric disturbances is implicit in any analysis of flying qualities.

For the purposes of the Flying Qualities Specification, an engineering model of the atmosphere may be considered as the simplest or minimum acceptable model which correctly identifies the primary parameters of particular interest. This is in contrast to the objectives of basic research into meteorological phemonena or the physics of atmospheric dynamics. Reference 6 discusses this dichotomy in more detail, with some indication of how the model is built up of components. Each component either exercises a particular feature of the man/machine combination or adds a particular aspect of realism to the piloting task. Let us, therefore, devote a few paragraphs to an overview of atmospheric disturbance features which are involved in flying qualities matters.

3. ATMOSPHERIC DISTURBANCE FEATURES

Prior to discussing atmospheric disturbance modeling needs, let us quickly review some of the basic features of all such models realizing that each claims some kind of uniqueness with regard to the following features. We shall discuss the nature of the variations in properties, but in general they can be viewed in terms of their engineering convenience versus their physical correctness. For example, the well-known von Karman turbulence form yields more correct spectral characteristics, but it is not as easily realized computationally as the more approximate Dryden form. The same kind of tradeoff between convenience and correctness is a dominant theme in several other respects as we shall discuss under the following subheadings.

3.1 Determinism Versus Randomness

Atmospheric disturbance models first can be separated according to their degree of determinism or randomness. At some level, the dynamics of the earth's atmosphere must be deterministic, but at our degree of understanding they frequently appear random. While characteristics such as mean wind and wind shear are normally handled on a deterministic basis, turbulence is usually modeled as a randomly occurring phenomenon. Nevertheless, wind velocity or wind shear can be just as well described in strictly probabilistic terms, and turbulence, conversely, can be described in wholly deterministic terms (as with gusts composed of summed sinusoids). In addition, random and deterministic models are often combined to suit the needs of a particular application [7,8]. Deterministic features are usually quantified directly using analytic functions or tables (e.g., mean wind respect to time or space). Random components, on the other hand, involve random variable sources having their own particular statistical properties of probability distribution and correlation. The differences are probably academic to a pilot, since either or both approaches can give a realistic mode; however, appropriate partition of model determinism versus randomness figures greatly in the success of any given application as we shall discuss shortly.

3.2 Probability Distribution

The probability distribution of gusts describes their range of amplitudes and frequency of occurrence. This can be quantified in terms of probability density, cumulative probability distribution, or a varying number of central moments (mean, variance, skewness, kurtosis, etc.). While the Gaussian distribution is mathematically convenient, several turbulence models having more correct non-Gaussian distributions have been developed in order to address the characteristics of patchiness and intermittency. Patchiness is frequently considered as corresponding to a proportionately higher rate of occurrence of very large magnitude gusts than found in a Gaussian distribution and is reflected by the higher order even central moments (fourth, sixth, etc.) [9]. Intermittency is the counterpart to patchiness when applied to gust velocity differences over a given time or space interval [10]. But the usefulness of these model features depends upon whether the specific application can accommodate a characteristic such as patchiness on a probabilistic basis. Pilots comment on the noticeable symmetry of the Gaussian distribution. Given only Gaussian-distribution turbulence, a perturbation is invariably followed by a correction so that he can allow the aircraft to fly "hands off." One way to look at this is that the time-average of the mean is comparatively short, even for manned simulations, which involve a limited duration time frame and a limited number of sample runs. Mathematically, the frequency of occurrence of the larger magnitude gusts is more in real life than in the Gaussian distribution. Models have been proposed to correct this discrepancy but those have the undesirable effect of increasing the variability from run to run.

3.3 Correlation

Correlation is the measure of the predictability of a gust component at some future time or point in space based on the knowledge of a current gust. Since the modeling of a random process such as turbulence consists of developing techniques for predicting the behavior of that process, it can be seen that correct duplication of the correlation can be important since these are measures of predictability. There are at least two ways of presenting correlation information, in the time or space domain (correlation functions) or in the frequency domain (spectral density functions).

C-3

The correlation function can be converted to the frequency-domain via a Fourier transformation resulting in the power spectral density function. A frequency domain representation is often useful because it permits comparison of the aircraft's spectral features with the spectral content of the turbulence. It is thereby possible to judge the degree to which the turbulence will affect the aircraft's motion, as described in Reference 11.

The two most common ways of describing gust correlation are the Dryden and von Karman power spectral density forms [3]. The correctness advantage of the von Karman form is not an issue unless the significant spectral content is centered in the microscale range about one decade or more above the integral scale break frequency. The microscale of turbulence is an indication of the distance of time separation over which gusts remain highly correlated, i.e., the initial subrange [12]. The von Karman turbulence involves a non-zero microscale--Dryden does not. The integral scale of turbulence is equal to the area under the normalized autocorrelation function and much larger than the microscale. Correct measurement of the integral scale depends on stationarity.

3.4 Dimensionality of Gust Field

A gust field can be described using various orders of dimensionality. The simplest is a one-dimensional-field model which involves just the three orthogonal velocity components taken at a single point (usually the aircraft center of gravity). The Taylor hypothesis (frozen field) can be applied, however, in order to approximate gust gradients with respect to the x-axis of the aircraft without increasing dimensionality. A two-dimensional field model is used to define a gust field in the aircraft x-y plane and can account for the size of the aircraft relative to gust scales. (A large aircraft relative to the gust scale attenuates gust gradient spectral power at high frequencies.) A two-dimensional field can lead to greatly increased mathematical complexity over a one-dimensional field [13], but some turbulence models simply define one-dimensional uniform velocity components and then add two-dimensional forms for gust gradients which contain aircraft size effects (as in Reference 3). These additional components are typically the first term in a Taylor expansion. More recent work [14] indicates that the correctness of these terms may be no better than ignoring them. A third dimension can be introduced in the form of an altitude-dependent wind shear [7,8], independent of the remainder of the model. Because of the inordinate increase in computational complexity, Reference 6 suggests that the gust gradient terms should be considered only if required by a specific piloting task.

3.5 Stationarity

A random gust is stationary if, for a collection of gust samples, the corresponding probability and correlation properties describe any additional gust sample which may be taken. Thus, stationarity implies an atmospheric disturbance having an invariant mean, variance, and correlation length (or time). There is no restriction on whether the probability distribution is Gaussian or not. In piloting terms, the effects are similar to the discussion of predictability that results from the probability distribution.

4. EVALUATING ATMOSPHERIC DISTURBANCE MODEL NEEDS

Atmospheric modeling needs vary greatly with the specific application, even for a single given aircraft and flight condition. Some analysis procedures require only a simple one-dimensional turbulence model (e.g., Dryden) and a single gust component. At the other extreme, elaborate simulation can involve a fully defined two-dimensional, non-stationary turbulence field along with a spatially or time varying mean wind field (i.e., wind shear). It is the role of References 4 and 6 to offer guidance in evaluating such needs and selecting appropriate disturbance model options among the variety of modeling choices and identifying the appropriate method of demonstrating compliance.

Some ways of viewing the modeling needs of a user include:

1. How disturbance components enter the airframe force and moment equations.
2. Inner/outer loop structure hierarchy for mission/aircraft centered features.
3. The need for determinism versus randomness in the flying qualities application.

Based on our knowledge of the various stability derivatives and respective gust component intensities, we can estimate the relative effect of various gust terms in order to judge:

1. Axis cross coupling (e.g., longitudinal and lateral-directional forces and moments are likely to be fairly well decoupled).
2. Translation motion (e.g., force equations are mainly affected by gust velocity components alone).
3. Rotational motion (e.g., moment equations are affected by gust velocity, time derivative, and gradient components).

The loop structure hierarchy in mission/aircraft centered features provides us with another way of judging atmospheric disturbance model needs. Figure 1 shows a spectral comparison of mission/aircraft-centered features against atmospheric disturbance features. Although the spectral boundaries of each feature are admittedly more ill-defined than shown, we can nevertheless illustrate a point. That is, any mission/aircraft features which are to be analyzed require the significant atmospheric disturbance features acting within the same spectral range. Conversely, atmospheric disturbance features outside that spectral range are superfluous. Taking the argument to the extreme, navigation considerations are not likely to involve the microscale or even integral scale range of turbulence. Likewise, flexibility effects would not require inclusion of mean wind or wind shear features.

Continuing in a similar vein, the results obtained from exciting an airplane by atmospheric disturbances depend greatly upon how the airplane is

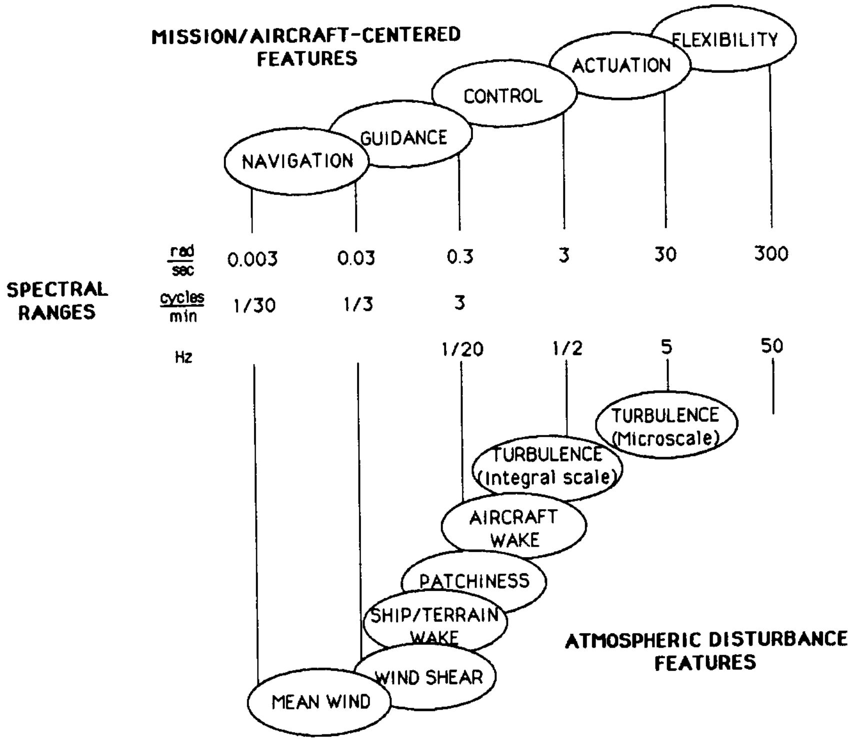


Figure 1. Spectral comparison of mission/aircraft-centered features against atmospheric disturbance features.

being operated, i.e., what the pilot is doing. The gust response can vary dramatically between hands-off operation and that involving tight regulation of attitudes and flight path. Frequently, the effects of wind shear are evaluated by measurement of the flight path excursion for a controls-fixed penetration of the shear. The phugoid is, of course, the dominant response mode in this case, and the result is a large-amplitude, undamped, roller-coaster-like flight path oscillation. But pilots do not characteristically operate hands-off in a wind shear environment. Rather, aircraft attitude is likely to be very well regulated by the pilot; hence, the flight path and airspeed modes would be exponentially decaying according to heave and speed damping stability derivatives (Z_w and X_u, respectively). Each of these two cases would lead one to vastly different conclusions regarding performance and identification of critical flying qualities parameters.

We need also to consider how determinism and randomness affect our choice of atmospheric disturbance models. Strict reliance upon a wholly random gust model for small-sample, short-term task evaluation is both impractical and improper. As investigators and evaluators, we desire to control disturbances well enough so that critical conditions and events can be staged especially in the case of manned simulation. This demands a fair degree of model determinism. On the other hand, pilot surprise and sensitivity to variation calls for a degree of randomness. Therefore, a compromise must be reached. This is an area which deserves to be addressed in a systematic way, but sometimes solutions must be based more upon experience than clear rationale.

5. PRACTICAL IMPLEMENTATION CONSIDERATIONS

The application of atmospheric disturbance models can involve a number of practical implementation problems--many associated with digital computer programming. One role of the Flying Qualities Handbook [4] will be to assist in answering some of the common implementation questions and to point out pitfalls frequently encountered. Some examples include:

1. Digital implementation of continuous spectral forms

2. Correct scaling of random noise sources

3. Evaluation of need for gradient components

4. Implementation of gust gradients, gust time derivatives, and gust transport lags.

Although these kinds of questions are based on fairly elementary mathematical or physical principles within the capacity of any practicing engineer, they are things which can nevertheless unnecessarily consume time and effort by flying qualities analysts. Table 1 illustrates some of the practical implementation matters addressed by the Flying Qualities Handbook [4].

TABLE 1. A List of Some Practical Implementation Topics from the Flying Qualities Handbook [4].

Implementation Item	**Handbook Method**	**Comments**
Digital implementation of continuous filter forms. Example: First-order Dryden form (applicable to u-gust or p-gust).	Spectral form: $\Phi_{uu} = \sigma_{u_g}^2 \, 2L_u/\pi \cdot \frac{1}{1 + (L_u\Omega)^2}$ Discrete realization: $u_g = c_1 u_g + c_2 \eta$ where $c_1 = \begin{cases} \text{either } \exp(-aT) & \text{(z-transform)} \\ \text{or } (1-aT) & \text{(Euler integration)} \\ \text{or } \frac{2-aT}{2+aT} & \text{(Tustin transform)} \end{cases}$ $a = V/L_u$ and $c_2 = \sqrt{1-c_1^2} \; \frac{\sigma_{u_g}}{\sigma_\eta}$ where η is a normally distributed random number with variance σ_η^2.	This matter can be confusing because spectral forms are written in a number of ways (e. g., one-sided or two-sided, spatial or temporal frequency, or in terms of angular or cyclical frequency). Furthermore, white noise in the continuous domain must be converted to random numbers in the discrete domain.
Determination of p-gust level of importance.	Criterion: p-gust is significant relative to v-gust if: $\sqrt{\frac{b}{L_w}} \cdot \lvert C_{l_p} \rvert > \lvert C_{l_\beta} \rvert$ or $\frac{2}{\sqrt{L_w b}} \cdot \lvert L_p \rvert > \lvert L_v \rvert$ where b is span and L_w is gust scale length.	The p-gust can be an important disturbance component in the roll axis, expecially if effective dihedral is small.
Determination of p-gust intensity.	Holley-Bryson model: $\sigma_{p_g} = \frac{2.15\,\sigma_{w_g}}{\sqrt{b\,L_w(1+b/L_w)}}$ MIL-F-8785C model: $\sigma_{p_g} = \frac{0.95\,\sigma_{w_g}}{\sqrt[3]{b^2 L_w}}$ Approximate intensity averaged over several models: $\sigma_{p_g} = \frac{1.9\,\sigma_{w_g}}{\sqrt{b\,L_w}}$	If the p-gust component is considered important, one must determine the intensity in order to implement the gust filter. A specific easy-to-compute value for intensity is seldom available. also the various p-gust model forms all have different ways of expressing model parameters.

6. A SURVEY OF EXISTING MODELS

A major task in the development of the Military Standard and Handbook was the review of existing atmospheric disturbance models and model forms. The objective was to examine how various models make the tradeoff between convenience and correctness and to search for strengths or deficiencies which could be important to a flying qualities investigator. Rather than arriving at a single most universal model to serve as the basis for the Military Standard, a variety of model forms appropriate for various applications were suggested. Table 2 lists some of the models which have been surveyed and offer some potential in flying qualities applications. For each table entry a few summary remarks are given along with a list of basic references.

7. THE CURRENT MILITARY SPECIFICATIONS FOR FLYING QUALITIES

Since our goal is discussion of the Flying Qualities Military Specifications, we should try to understand their weaknesses as well a their strengths. Prior to the existing specification, MIL-F-8785B presented a basic disturbance model consisting of turbulence and discrete gusts, but the requirements for its use were few in number and qualitative in nature. For the current version, the MIL-F-8785B model was extended and more explicit requirements were formulated. It is instructive to understand the background of this existing array of model components and how they are used in defining flying qualities requirements.

The effect of increasing disturbance intensity is typically an increase in pilot workload and/or a degradation in task performance. The effect on pilot rating is similar to a degradation in flying qualities from other causes. This consideration led heuristically to the specification of three disturbance intensities, which are qualitatively linked to the three levels of flying qualities. In attempting to formulate requirements for use of the models, it was proposed originally to incorporate the effects of disturbances into the levels of flying qualities. In the final version, "qualitative degrees of suitability" are defined to parallel the levels of flying qualities. A new section of the specification now contains requirements for use of the disturbance model. These are presented as a matrix of failure versus disturbance intensities for the different flight envelopes.

Both the von Karman and Dryden forms of the turbulence spectra are retained with specified intensities corresponding to probabilities of occurrence of 10^{-1}, 10^{-3}, and 10^{-5}. The "versine" (or 1-cosine) shape is retained for the discrete gust, except that only half a period is specified. In this way it can be used singly (e.g., representing a wind shear) or in pairs (as in the familiar discrete gust application) yielding more flexibility in application.

A completely new model is specified for low altitudes, with a more realistic variation of turbulence intensities and scale lengths with height above the gound. A mean wind having a logarithmic variation with height (planetary boundary layer) is specified. In order to account for the severe but less probable phenomena that cause difficulties close to the ground, a

TABLE 2. A Survey of Atmospheric Disturbance Models.

Model	Key Features	Sources*
Dryden turbulence	A convenient spectral form based on an exponential autocorrelation function for the axial component.	15
von Karman turbulence	A spectral form for which the autocorrelation function includes a finite microscale, thus the relative proportion of spectral power at high frequencies exceeds that of the Dryden.	16,17
Ornstein-Uhlenbeck turbulence	A spectral form with first-order longitudinal and transverse components.	18
Etkin one dimensional turbulence power spectra	The local turbulent velocity field is approximated by a truncated Taylor series which yields uniform and gradient components. High frequency spectral components eliminated on the basis of aircraft size. Based on Dryden form, but gradient spectra are non-realizable unless simplified.	13,19,20
Versine gust	A discrete gust waveform.	3
Lappe low-altitude turbulence model	Experimentally-obtained data of vertical gust spectra, mean wind speed, and lapse rate were used to develop a low-level turbulence model. The turbulence spectra are presented for different types of terrain, height, and meteorological conditions.	21
Multiple point source turbulence	A two-dimensional gust field generated from two or more noise sources having prescribed correlation functions and located spanwise or lengthwise on the vehicle.	22,23,24
Holley-Bryson random turbulence shaping filters	A matrix differential equation formulation of uniform and gradient components including aircraft size effects. Filter equation coefficients determined from least square fit to multi-point-source-derived correlation functions.	23
University of Washington non-Gaussian atmospheric turbulence model	Non-Gaussian model using modified Bessel functions to simulate the patchy characteristic of real-world turbulence. Spectral properties are Dryden and include gust gradients.	9,25

*Source numbers refer to references cited at end of paper.

TABLE 2. (continued).

Model	Key Features	Sources
Delft University of Technology non-Gaussian structure of the simulated turbulent environment	Non-Gaussian model similar in form to the University of Washington model, but uses the Hilbert transform to model intermittency as well as patchiness. Includes University of Washington model features extended to approximate transverse turbulence velocities and gradients.	26
Royal Aeronautical Establishment model of non-Gaussian turbulence	Non-Gaussian turbulence model with a variable probability distribution function and a novel digital filtering technique to simulate intermittency. Spectral form approximately von Karman.	27,28,29
The Netherlands National Aerospace Laboratory model of non-Gaussian turbulence	Similar to the Royal Aeronautical Establishment model, but extended to include patchiness and gust gradient components and transverse velocities.	30, 31
University of Virginia turbulence model	Models patchiness by randomizing gust variance and integral scale length of basic Dryden turbulence.	32
Mil Standard turbulence model	First order difference equation implementation of turbulence filters based on 8785 Dryden turbulence and refitted rolling gust intensity.	4
Indian Institute of Science non-stationary turbulence model	Nonstationary turbulence is obtained over <u>finite</u> time-windows by modulating a Gaussian process with either a deterministic or random process. The result is patchy-like turbulence similar to the University of Washington model except the time-varying statistics of the turbulence are presented for the deterministic modulating functions.	18
FAA wind shear models	Three-dimensional wind profiles for several weather system types including fronts, thunderstorms, and boundary layer. The profiles are available in table form.	7,33
STI wind shear model	Time and space domain models of mean wind and wind shear (ramp wave forms) are combined with MIL-F-8785C Dryden turbulence to obtain the total atmospheric disturbance. The magnitudes of the mean wind and wind shear are evaluated in terms of the aircraft's acceleration capabilities.	8,34

TABLE 2. (continued).

Model	Key Features	Sources
Sinclair frontal surface wind shear model	A generic model of frontal surface wind shear derived from a reduced-order from of Navier-Stokes equations. Relatively simple to use and can match the overall characteristics of measured wind shears.	35,36
MIL-F-8785B atmospheric disturbance model	Intensities and scale lengths are functions of altitude and use either Dryden on von Karman spectral forms or a one minus cosine discrete gust. Also spectral descriptions of rotary gusts.	37,38
MIL-F-8785C atmospheric disturbance model	Same as 8785B with the addition of a logarithmic planetary boundary layer wind, a vector shear, and a Naval carrier airwake model.	3
ESDU atmospheric turbulence	Rather general, but contains comprehensive descriptive data for turbulence intensity, spectra, and probability density	39,40
Boeing atmospheric disturbance model turbulence	A comprehensive model of atmospheric disturbances that includes mean wind, wind shear, and random turbulence. Turbulence is Gaussian and uses linear filters that closely approximate the von Karman spectral form. Mean wind and turbulence intensity are functions of meteorological parameters.	41
Wasicko carrier airwake model	Includes mean wind profile, effect of ship motion, and turbulence.	42
Naval ship airwake model	Includes free air turbulence filters plus steady, periodic, and random components of airwake which are functions of time and space.	3, 43
Vought airwake model for DD-963 class ships	Combined random and deterministic wind components for free air and ship airwake regions. Based on wind tunnel flow measurements.	44
STI Wake vortex encounter model	A two-dimensional model of the flow-field due to the wake vortex of an aircraft is presented. The parameters of the flow-field model are weight, size, and speed of the vortex-generating aircraft, and distance and orientation of the vortex-encountering aircraft. Strip theory is used to model the aerodynamics of the vortex-encountering aircraft.	45

TABLE 2. (concluded).

Model	Key Features	Sources
Cambell and Stanborne wind shear and turbulence model	Spatial model based on joint airport weather studies (JAWS) microburst data. Permits calculation of aerodynamic loads over body of aircraft.	46
Zhu and Etkin microburst model	Generic spatial model of microburst velocity components based on potential flow singularity distribution involving only three adjustable parameters.	47

vector shear is specified--a change in wind direction over a certain change in height. This is used in lieu of a particular wind profile or set of profiles. It is believed that varying the orientation and height of the specified vector shear covers an adequate range of aircraft responses for the landing task.

The specification of vector shear has the appearance of an engineering artifact, i.e., a 90° change in wind direction over a given height. It is, however, based on the wind conditions that existed at the time of an actual aircraft accident [48]. The winds did not compromise aircraft performance and had no obvious indication of dangerous conditions--they formed an insidious contribution to the busy landing task. The use intended by MIL-F-8785C is to produce a complex but realistic task in piloted ground-based simulation. As the wind changes from crosswind to headwind, or vice versa, the pilot is continually controlling both longitudinal and lateral/directional axes. The six-degrees-of-freedom aspect of this control task is frequently missing in simulation.

Based on meetings with the Navy, it became apparant that their atmospheric disturbance requirements were driven by the carrier landing task. The carrier airwake represents a severe environment. The disturbance model of MIL-F-8785C was completed by adding a carrier airwake model supplied by Nave of NADC [43]. We know that a degradation in pilot rating is accepted relative to landing in calm air; however, we do not yet know how the severity compares with the other portions of the disturbance model.

It should be emphasized strongly that the intent is not to add a whole new dimension to all the existing requirements. In MIL-F-8785B, the guidance was to establish the flying qualities and probabilities associated with critical flight conditions and failures. For MIL-F-8785C, the intent is to limit the degradation in flying qualities due to atmospheric disturbances for the critical cases. With the requirements contained in separate sections, they can be easily modified, emphasized, or even deleted by the procuring activity according to the mission needs. Reference 6 supports the existing specification with more detail on the items discussed herein.

8. IMPLICATIONS FOR THE FORTHCOMING MILITARY STANDARD

The foregoing discussions have tended to dwell on practical aspects of atmospheric disturbance modeling in flying qualities applications. We have described the existing military specification, a variety of modeling topics, and a partial list of modeling alternatives. Regarding atmospheric disturbance models, again we should note that it would be difficult, if not unwise, to embody in a single model all of the features which have been addressed in the existing body of models. Furthermore, to the extent that this could be done, the resulting model would then become "overkill" for many applications. In addition, since the Standard is just that--a standard--it is not necessary to apply a high fidelity facsimile of the real-world environment (assuming that we could ever reach agreement on what the "real world" is). Rather, it is only necessary to apply something good enough to permit a judgment or comparison in each specific context addressed by the Standard. Our inclination is therefore to recommend individualized modeling approaches which would be stylized for a particular application and which would draw upon the rich variety of existing models or modeling forms. This would be accomplished by setting forth an unquantified checklist of atmospheric disturbance properties in the Military Standard document. Specific qualification would then be made by the procuring agency on the basis of the application, vehicle type, mission, and expected environment. This would be done from consultation of the accompanying Handbook and recommended sources listed within. The same procedure could also be followed by the disturbance model user performing analysis or simulation not necessarily connected with aircraft procurement.

Flying qualities requirements set by the Military Standard must necessarily recognize the key role which atmospheric disturbances play in the piloting of an airplane. Hence, prescription of performance (amplitude of response) or workload (pilot opinion or other workload-related metrics) requirements must be made with an understanding of the combined pilot-vehicle disturbance system. This implies that more is needed than guidelines between, say, gust components and airframe aerodynamics. Due consideration must also be given to the piloting tasks and the effect that it has on modifying airplane dynamics and their sensitivity to atmospheric disturbances.

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QUESTION: Walter Frost (FWG Associates). In your spectral rolling moment, is there a problem with transferring from coordinate systems? Generally those are developed for?

ANSWER: Generally, I think there can be but it's one of these things where at this stage using something is much better than the absence of a model, which is really the case right now.

FROST: How do you recommend calculating L_w.

HEFFLEY: That is up to the model user, although the value typically used for low altitude is height above ground.

COMMITTEE SUMMARY REPORTS

COMMITTEE: DESIGN

CHAIRMAN: David O'Keefe

MEMBERS: Ben F. Dotson
Richard Heimbaugh
John C. Houbolt
Robert T. Meyer
Richard N. Moon
Joe J. Nishikawa
Elijah Turner

ISSUE:

Two primary issues:

1. How Accurate Gust Measurements or Predictions Do We Need; and What is the Impact on Gust Analysis?
2. How Can Data be Obtained for High Altitudes?

DISCUSSION:

1. First, gusts are statistical in nature and thus it is not possible to define a "worst possible" gust and then design for this gust. Second, criteria and design analysis are intertwined, that is, design levels are based upon the strength of existing satisfactory airplanes. The limit design frequency of exceedance is set such that if loads are determined for existing airplanes in accordance with proposed criteria, these loads will correspond to the limit strength of the airplane. Gust intensity profiles then are essentially backed out of known data in accordance with this criteria.

   If accurate "real time" gust measurements were suddenly available, then the entire inter-related criteria/design process would have to be reassessed in accordance with the airplane limit strength loads concept.

   The basic question may be: How and what data base can be used to update the information originally used in establishing the design criteria given in FAA-ADS-53?

2. High-altitude clear-air turbulence data are not well established. Vehicle operations in this regime appear likely within the next decade. Trans-atmosphere vehicles (TAV), space re-entry vehicles, high aspect ratio endurance vehicles, and lightweight highly flexible structures are typical candidates.

   To obtain such data, extensive use of research aircraft, flight recorders, lidar/radar, in situ, and remote sensing devices may all have to be used.

RECOMMENDED ACTION:

On-going research and development funding should be provided to support acquisition of required data and to update existing data bases. Inherent in this recommendation may be the need to reassess the inter-related criterion/design aspects of the gust analysis process. A start would be to complete reduction/evaluation/incorporation of existing measured data for large transports (i.e., Norman Crabill work, B-57B gust gradient data, etc.).

RESPONSIBLE AGENCIES:

The driving force for this probably must come from the licensing agencies and user community, basically, FAA, DoD, and NASA. NASA is the logical candidate to coordinate the concerns of all three.

PRIORITY: High

ISSUE:

Avoidance and Awareness: How Can Aircraft Crews be Provided with Sufficient Information to Basically Avoid Turbulence or Make Decisions Based on Knowledge of a Potential Adverse Level of Turbulence?

DISCUSSION:

Satisfactory structural strength in itself is not sufficient. Aircraft/passenger can still be lost/injured due to upsets and loss of control. Operational rules and restrictions are major factors in reducing encroachment into turbulence. But an additional aid would be reliable avoidance and awareness capabilities.

Avoidance, as used here, implies in-flight detection followed by corrective actions to bypass turbulence. Awareness implies some optional decision-making process based upon assessment of the degree of adversity. Awareness could range from "don't," "go ahead, but it is rough," "no problem, it's mild" signals to true definition of intensity profiles allowing pilot to react (i.e., slow down, speed up, etc.).

Devices, techniques, and procedures with these capabilities appear to be available with a somewhat qualified satisfaction level.

Design processes for current and next-generation aircraft are basically satisfactory (with the exception of highly exotic aircraft). Therefore, for existing fleets and near-term production, avoidance and awareness may be most vital.

RECOMMENDED ACTION:

Provide funding to expand research, development, and validation procedures in this area.

RESPONSIBLE AGENCIES: Private industry, NASA, FAA

PRIORITY: High

ISSUE:

What Effect Has Turbulence on Active Controls, Relaxed Stability, and Flight Controls?

DISCUSSION:

The effects of control surfaces employed for purposes of load alleviation or for primary maneuver and control purposes are becoming more prevalent (i.e., L-1011-3ACS, X-29). Historical data bases used in FAR-ASD-53 probably do not reflect such phenomena. Past accounting for systems such as yaw damper has been included by obtaining exceedance curve separately for with and without yaw damping. Results are then combined to reflect rational off/on percentages. The effects of the multi-surface control systems on aircraft response to turbulence penetrations are either unknown or not yet fully determined (i.e., there is some indication that such systems may alleviate gust loading).

RECOMMENDED ACTION:

Provide on-going funding to investigate, measure, and/or provide research activities in this area.

RESPONSIBLE AGENCIES: DoD, NASA

PRIORITY: Low

ISSUE:

What is the Present Status of Turbulence on Criteria, Modeling, Design, and Operation Integration?

DISCUSSION:

The basis for current gust loads criteria, modeling, and basic design analysis procedures should be reviewed. If sufficient evidence is uncovered, consideration should be given to renegotiating criteria, or altering design procedures. Possiblity of agency/manufacturer/user agreement on standardization should be considered.

Omission or oversights should be accounted for as part of an overall integrated approach. For example, helicopter criteria is not defined, operational usage considerations are not fully accounted. Basic methodology and approach need to be reviewed and reassessed in light of recent work.

RECOMMENDED ACTION:

A start may be to revisit TARC 78-55 (Transportation Airworthiness Recommendation Committee met in Washington, D.C., May 25, 1978) to reassess its pluses and minuses. Consideration of John Houbolt's approach, as presented at the workshop and included as a paper in the workshop proceedings, should be reviewed. Impact of turbulence prediction techniques and airline meteorology predictions should be included. Evaluate and include as appropriate available recent gust data.

RESPONSIBLE AGENCY: NASA

PRIORITY: Medium

COMMITTEE: OPERATIONS

CHAIRMAN: John J. Pappas

MEMBERS: James C. McLean, Jr.
W. Dale Meyer
Douglas J. Miller
Creighton Pendarvis
Michael A. Tomlinson
J. Allen Zak

ISSUE:

Measurement of CAT with Doppler Radar

DISCUSSION:

Atmospheric turbulence is known to be associated with spatial and temporal fluctuations of temperature and velocity. However, there is evidence that turbulence is not the only atmospheric process which can cause these fluctuations. For example, observations suggest these fluctuations may also be caused by non-turbulent internal atmospheric gravity waves. Research is required to develop signal analysis techniques which can distinguish between fluctuations associated with atmospheric turbulence and those associated with non-turbulent atmospheric accelerations.

RECOMMENDED ACTION:

OFCM should be asked to sponsor the subject research. The NEXRAD Special Projects Office should be asked to comment on issue.

RESPONSIBLE AGENCIES: OFCM, FAA, DoD, NOAA

PRIORITY: High

ISSUE:

State of Understanding of Atmospheric Turbulence

DISCUSSION:

An effort should be undertaken to document the state of the science in understanding atmospheric turbulence phenomena, including the frequency of occurrence and duration of significant (greater than "moderate") turbulence events. The effort should also define the current state of the understanding of the spatial and temporal distribution of these turbulence events.

RECOMMENDED ACTION:

OFCM should be asked to sponsor this effort.

RESPONSIBLE AGENCY: OFCM

PRIORITY: High

ISSUE:

Joint Research for Improved Techniques in Turbulence

DISCUSSION:

Areas which deserve increased attention include: Aircraft-mounted turbulence measuring/warning equipment and ground-based equipment; test techniques on operational aircraft; multiple approaches to turbulence avoidance (i.e., passive infrared (IR) sensors, Doppler radar, lidar--high altitude and very high altitude); and finally, better pilot education and awareness of turbulence avoidance techniques.

Concerning on-board turbulence avoidance systems, present systems under development can only look straight ahead. Future systems need to be able to scan in horizontal and vertical mode (to give the pilot knowledge as to whether he/she should climb, descend, or turn in order to avoid or miss the most intense turbulence). Military aviation has a need for better turbulence avoidance in areas such as low-level helicopter operations, wind conditions for airdrops, and large aircraft low-altitude operations.

RECOMMENDED ACTION:

Convince air carriers that on-board turbulence avoidance equipment has a potential for lowering their liability insurance rates, improvement of passenger comfort, as well as reducing structural stresses which will increase the service life of their aircraft.

RESPONSIBLE AGENCIES: NASA, FAA, DoD

PRIORITY: High -- On-Going

ISSUE:

Numerical Models and Space Observational Data for High-Altitude Turbulence for Orbital Insertion and Transatmospheric Vehicle Operations

DISCUSSION:

Data collection efforts and models are just now beginning to focus on this turbulence problem.

RECOMMENDED ACTION:

Support further research, data collection, and model development in high-altitude turbulence characterization.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: Medium

ISSUE:

Realistic Numerical Models to Characterize Turbulence in the Lowest 1000 ft (305 m) of the Atmosphere for Flight Simulator Use

DISCUSSION:

Turbulence in this context includes wind shear produced by downbursts, fronts, sea breezes, and other local scale phenomena.

Observational data bases are not available to represent the low-level wind structure. Doppler radar has difficulty due to ground clutter. Instrumented towers are typically not high enough, not closely spaced, and infrequently capture important events. It is understood that there is a concomitant need for flight simulators capable of fully utilizing detailed three-dimensional inputs to produce realistic instruments and motion responses for aircrew training. Although microbursts are frequently singled out as the only real hazard to aviation, turbulence and wind shear produced from any mechanism can be catastrophic when combined with other problems such as heavy rain or equipment malfunctions in this critical region of flight.

RECOMMENDED ACTION:

Sponsor the continued development of high-resolution models capable of depicting three-dimensional turbulent wind fields.

RESPONSIBLE AGENCIES: FAA, NASA, OFCM

PRIORITY: Very High

ISSUE:

Affordability or Practicality of Present Atmospheric Prediction Models Capable of Resolving the Higher Frequency Turbulence Components for Real-Time Operational Environments

DISCUSSION:

Existing models with fine resolution time and space scales as well as sophisticated treatment of diffusion fluxes, friction, and so forth need large research-oriented computers and long running times to produce prognostic output even for limited areas.

RECOMMENDED ACTION:

Support efforts to scale down models by focusing on pieces of the turbulence problem. For example, a model might be specifically tuned to treat mountain waves, convection, or Kelvin Helmholtz waves.

RESPONSIBLE AGENCIES: OFCM, NASA

PRIORITY: Medium

ISSUE:

Improvements in Turbulence Forecasts Using Existing or Foreseeable Models to Gain Outputs Better Oriented to Provide Turbulence Information

DISCUSSION:

Existing synoptic scale models provide wind, temperature, and moisture fields for spacing larger than most turbulence events. Can they provide valid fields at higher resolutions? Can the existing fields be used to infer higher resolution turbulence values? Can mesoscale models be run using synoptic scale model outputs and/or post-model-run observations to provide mesoscale turbulence information?

RECOMMENDED ACTION:

These questions should be addressed and, if feasible, improved mesoscale information should be developed for operational use.

RESPONSIBLE AGENCIES: NWS, DoD (FNOC, AFGWC)

PRIORITY: Medium -- Medium to Long Range

ISSUE:

Scope and Nature of the Turbulence Problem for Aircraft Operations

DISCUSSION:

There is a need for a clear definition of what is the operational objective of understanding turbulence. Questions of cost and cost/benefit must have answers that explain why turbulence is a problem and not just a phenomena.

RECOMMENDED ACTION:

Define the turbulence problem for aviation operations.

RESPONSIBLE AGENCIES: FAA, DoD, NTSB

PRIORITY: High -- Short Term

ISSUE:

The Meaning of Terminology Used to Describe Turbulence for Researchers, Forecasters, Pilots, and Passengers

DISCUSSION:

Turbulence intensity terms and reports are subjective and, to a large extent, aircraft and/or pilot dependent. This means that controllers, flight service specialists, and forecasters must interpret and evaluate reports. Reports which may appear to say the same thing may be interpreted differently by each person receiving them and may have meant something different to each person providing them.

RECOMMENDED ACTION:

Turbulence intensity terms and reports should be standardized and "objectivized" or quantified.

RESPONSIBLE AGENCY: OFCM

PRIORITY: High -- Short Term

ISSUE:

Current Techniques for Predicting En-Route Turbulence and Terminal Area Wind Variations Including Turbulence and Shear

DISCUSSION:

While the operational impacts of turbulence may be significant, particularly for DoD, the number of fatalities associated with en route turbulence is small and the cost of injuries is perceived as relatively small. The forecasts provided by the existing system are perceived as needing improvement but the point at which the cost/benefit ratio becomes too large is thought to be close. An effort to evaluate the existing prediction techniques would provide an opportunity to re-evaluate the turbulence hazard and determine the current cost/benefit ratio, as well as the state of available observational data. This should include operational evaluations of newer techniques which might otherwise have too small a set of verification data.

On the other hand, the number of low-level turbulence and wind shear fatalities is relatively large as are the attendant liability and legal costs. The nature of the objectives and techniques for forecasting these conditions is fundamentally different from those associated with turbulence in the en route environment. These techniques also need evaluation for appropriateness and effectiveness.

RECOMMENDED ACTION:

The appropriateness and operational effectiveness of existing forecast techniques should be evaluated with the objective of quantifying the hazard's significance and identifying the most effective forecast techniques and any deficiencies in the current data used as a basis for these techniques.

RESPONSIBLE AGENCY: OFCM

PRIORITY: High -- Short Term

ISSUE:

Resolution of the Numerous Turbulence Forecasting Techniques and Rules of Thumb into a Set of Validated, Standard Techniques

DISCUSSION:

There are many subjective and objective turbulence forecasting techniques and rules which are based on data as old as 35 years and as new as GOES moisture channel data. There has been little organized effort to evaluate and validate or discard these rules and techniques. The result is a lack of standardized turbulence forecasts, contradictory forecasts, and an uneven level of forecast quality.

RECOMMENDED ACTION:

The body of turbulence forecast techniques and rules should be reviewed and evaluated. Validated ones should be published and their use encouraged.

RESPONSIBLE AGENCIES: OFCM, NWS, DoD

PRIORITY: High -- Medium Term

COMMITTEE: REMOTE SENSING

CHAIRMAN: Gary P. Ellrod

MEMBERS:
Alan Bohne
Diana Collier
G. David Emmitt
Phil Rogers
James R. Scoggins
Robert W. Smith
Laj Utreja

ISSUE:

What is the Status of Remotely Sensing Turbulence from Ground Stations?

DISCUSSION:

Considerable research has been performed in the quantification of turbulence intensity in regions of precipitation. Methods such as the NEXRAD turbulence algorithm may be used with Doppler radars to identify regions of turbulence in the non-hazardous and hazardous ranges with relatively high probability of detection. The clear-air boundary layer (1-3 km) is routinely observed with Doppler radars to ranges of about 60 km. Again, accuracy of turbulence severity estimates, when compared with in situ aircraft measurements, has been shown to be quite high.

Above the boundary layer, UHF radars may detect layers of CAT to heights of 6-10 km and moderate ranges, perhaps 30-40 km. Wind profilers, which will play an adjunct role with radiosondes, will be able to routinely measure winds in the vicinity of the sensor up to the tropopause.

In summary, in precipitation, radars such as those to be incorporated in the NEXRAD system will routinely measure turbulence severity indices up to 130 km. In clear air, measurements are restricted to 30-40 km.

RECOMMENDED ACTION: None

RESPONSIBLE AGENCY:

PRIORITY:

ISSUE:

What Plans are There for Directly Measuring Turbulence Remotely from Space?

DISCUSSION:

A space-based lidar would be a means of direct clear-air turbulence detection. Current sensors are capable of reasonably accurate measurements of winds and gust velocities, but currently they are technically feasible only for polar and equatorial orbiting satellites. There are plans for putting a lidar profiler on the Space Station or polar platform scheduled to be launched in the 1990's.

RECOMMENDED ACTION:

Continue evaluation and improvement of lidars for eventual use on space platforms.

RESPONSIBLE AGENCY: NASA

PRIORITY: Low

ISSUE:

What is the Status of an On-Board Warning Indicator of Turbulence for Aircraft?

DISCUSSION:

A lead time of 20 to 40 seconds is needed to allow jet aircraft to respond to a warning of impending turbulence in flight. An infrared radiometer now available has a maximum range of 60 km and high accuracy (≈94%) for detecting clear-air turbulence. Current lidar instruments have limited range and would not provide sufficient warning.

The addition of a low-cost Doppler radar or direct readout from ground-based Doppler would be desirable for detection of downbursts on approaches to airports.

RECOMMENDED ACTION:

1. Evaluate existing infrared radiometers as to their usefulness in in-flight CAT detection.

2. Determine feasibility of on-board Doppler radar systems.

RESPONSIBLE AGENCY: FAA

PRIORITY: Medium

ISSUE:

How Can Remote Sensing Data Best be Utilized to Improve the Prediction of Turbulence?

DISCUSSION:

The primary data needed are winds, temperatures, and pressure heights with a higher resolution than that provided by the radiosonde network. Many new sources of remotely sensed data will become routinely available by 1990 (VAS soundings, ASDAR, profilers). Due to the high volume of data, automatic collection and processing will be needed. In order to evaluate improvements in prediction, a high density of verifiable turbulence reports will be needed. Ground-based sensors such as Doppler radar and lidar may contribute in this effort. Even with improvements in the objective forecast of winds, wind shears or turbulence indices, some interpretation and inference will likely be required by meteorologists in the operational environment. Qualitative image features will continue to be useful for short-range turbulence prediction.

RECOMMENDED ACTION:

1. Determine if the addition of aircraft, VAS, or profiler data will lead to improvement of numerical models.

2. Improve the current system of collecting and disseminating standardized aircraft turbulence reports.

3. Refine techniques for detecting and short-range prediction of turbulence using VAS sounding data and multi-spectral imagery.

RESPONSIBLE AGENCIES: NWS(NMC), FAA, NESDIS(SAL)

PRIORITY: High

ISSUE:

How Does Turbulence Impact Space Operations?

DISCUSSION:

Launch pad operations and the launch of a rocket are affected by wind and wind shear. These are normally handled well at the launch site. Any improvement in measuring upper winds and temperatures would benefit this phase.

In the future, satellite recovery vehicles will be required and will probably use the atmosphere between 70 and 120 km to accomplish orbital plane changes. Large amplitude, small-scale fluctuations in density are known to exist, but, at present, we have no real time method to measure in this region.

RECOMMENDED ACTION:

1. Study existing data from past rocket-grenade experiments to understand the problem.

2. Develop a remote sensor capable of measuring density in the 70 to 120 km region.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: Medium

COMMITTEE: SIMULATION

CHAIRMAN: Robert L. Ireland

MEMBERS:
Roland L. Bowles
Sue-li (Kingsley) Chuang
Richard E. Dickson
John Klehr
Burnell T. McKissick
Bill Melvin

The primary thrust of our committee discussions centered around the several reasons for simulation and the resultant types of turbulence models needed. We certainly furthered understanding among the participants, but did not reach any earth-shattering conclusions.

First, we recognized and discussed the requirement for fully researched, state-of-the-art, physically complete turbulence models. It was agreed that such simulations must form the groundwork for any follow-on models of simpler nature, but more importantly, they further the understanding of the phenomenon itself.

The first subset of turbulence models may differ little from the first. These models would be applicable to the design, testing, and certification for airframes and systems. In order to assess the impact of turbulence on the structure, and to guarantee that auto flight systems work well, physically representative models of turbulence must be available. The better these models become through research, the more reliable the results. It is "Mom and apple pie," really.

The committee's point of disagreement was reached regarding turbulence simulation for training purposes. While some participants felt strongly that equally complete models were required, others, myself included [Ireland], are quite certain that such simulations for training need only provide approximate instrument and motion responses. As a compromise, we recommended piloted studies.

The committee also surfaced the question of turbulence versus wind shear. The two may be differentiated by scale length (workshop committee meeting notes) or by pilot response required. The boundary conditions are important. Ultimately both disturbances surround a mean; however, wind shear initiates deviations from the mean for periods of time which require pilot resonse to avoid aircraft upset or ground impact. Once again, the same set of models: research, engineering, and training, is foreseen. The training models may range from the very simple to teach specific pilot techniques, to the complex for demonstration of workload and complications clouding recognition.

ISSUE:

What is a good turbulence model? How is it simulated? Do we need a new standard?

DISCUSSION:

Theoretical model to start Tailor solution to need. For training: If pilot cannot tell the difference, complex model unnecessary. Complex theoretical models necessary for research and testing of auto flight systems.

RECOMMENDED ACTION:

Piloted studies in simulators, compare responses to theoretically accurate models to those with simplified models.

RESPONSIBLE AGENCY: NASA

PRIORITY: High

ISSUE: What is wrong with superimposing linearly?

DISCUSSION:

Have to simulate mechanism that transports energy into the smaller scales. (The real thing is nonlinear.)

RECOMMENDED ACTION:

RESPONSIBLE AGENCY: NASA

PRIORITY: Medium

ISSUE:

Use of turbulence motion simulation: Is it merely an annoyance to the pilot or does it provide a valuable piece of realism?

DISCUSSION:

Melvin: Causes problems for the pilot which are irrelevant to the airplane.

RECOMMENDED ACTION: Piloted study.

RESPONSIBLE AGENCY: NASA

PRIORITY: High

ISSUE: Differentiation of turbulence versus wind shear.

DISCUSSION:

Upset of aircraft? Bowles proposed that wind shear is scale length >5 b or >10 c. Simulate turbulence with zero mean. Depends on effect on vehicle. In general, wind shear may be expected to cause a gross disturbance necessitating corrective action while "turbulence" is of short scale length about a mean--control inputs unnecessary.

RECOMMENDED ACTION:

Need a definition of turbulence versus/or including wind shear. (Is wind shear a subset or a separate entity. Need concensus.)

RESPONSIBLE AGENCY: Can only be addressed by open forum.

PRIORITY: Low

COMMITTEE: MEASURING

CHAIRMAN: Robert A. McClatchey

MEMBERS:
Pat Adamson
L. Jack Ehernberger
George Gal
Robert K. Sleeper
Anthony Smart
Jim Usry

ISSUE:

Instrumentation Needed for Avoiding Turbulence, Wind Shear, and Microbursts

DISCUSSION:

Development of in situ and remote sensors, e.g., Doppler radar, passive radiometry, lidar, other electro-optical sensors and techniques for using data is required.

RECOMMENDED ACTION:

1. Develop small, lightweight instrumentation instrumentation for measuring turbulence to altitudes of 30 km.

2. Test sensors and techniques on aircraft.

RESPONSIBLE AGENCIES: DoD, NASA, USAF

PRIORITY: High

ISSUE:

Adequacy of High-Altitude Turbulence Understanding

DISCUSSION:

The understanding of turbulence to high altitudes (>30 km), effects of turbulence on the shuttle, and aerospace plane was discussed in detail.

RECOMMENDED ACTION:

Develop measurement techniques for altitudes greater than 30 km.

RESPONSIBLE AGENCIES: DoD, NASA

PRIORITY: High

ISSUE:

Measurements for Extending the Turbulence Design Data Base

DISCUSSION:

1. Design of expanded aircraft flight envelopes, new control system design evaluation, and laser communications.
2. Operational implications.

RECOMMENDED ACTION:

Develop and implement techniques to update and extend global turbulence data base.

RESPONSIBLE AGENCIES: NASA, SDIO, USAF

PRIORITY: High

ISSUE:

Verification and Standardization of Turbulence Forecasting Techniques

DISCUSSION:

1. PIREPS are "happen-stance."
2. Need comprehensive measures of forecast method skills.

RECOMMENDED ACTION:

1. Gather selective sets of digital flight recorder data.
2. Analyze and establish a national repository of turbulence data.

RESPONSIBLE AGENCIES: NASA, FAA, DoD, NOAA, NTSB

PRIORITY: High

ISSUE:

Process and Use of Currently Available On-Board Sensor Data to Help Pilots Avoid Turbulence and Wind Shear

DISCUSSION:

Information presently on-board may provide a real-time decision aid for avoiding turbulence.

RECOMMENDED ACTION:

Develop algorithms for processing on-board information.

RESPONSIBLE AGENCIES: FAA, DoD, NASA

PRIORITY: High

ISSUE:

Specifications of Operational Requirements for Turbulence and Wind Shear Warning Techniques

DISCUSSION:

The need for quantitative specifications at all altitudes.

RECOMMENDED ACTION:

The operation community needs to document the requirements, i.e., utility or benefit to them vs. warning skill as a function of intensity, lead time, etc.

RESPONSIBLE AGENCIES: USAF, FAA

PRIORITY: High

ISSUE:

Need for In Situ On-Board Profilers to Measure Temperature, Wind, Turbulence, and Composition

DISCUSSION:

The Measuring Committee did not have a scheduled meeting with the Understanding Committee but feels the above issue should receive immediate action.

RECOMMENDED ACTION:

Assemble a comprehensive sensor system to provide cost-effective flight research of fluid dynamic instabilities in the atmosphere.

RESPONSIBLE AGENCIES: NASA, NOAA, DoD, FAA

PRIORITY: High

ISSUE:

Strategic Defense Initiative Office (SDIO) Turbulence Requirements

DISCUSSION:

The SDIO turbulence research and operational requirements are an important subject area but largely omitted at this workshop.

RECOMMENDED ACTION:

Do not drop from subject list, include in a future workshop.

RESPONSIBLE AGENCY: DoD (SDIO)

PRIORITY: High

COMMITTEE: MODELING

CHAIRMAN: Robert K. Heffley

MEMBERS:
Stephen D. Burk
Warren Campbell
William D. Mark
C. M. Tchen
George Trevino
Morton G. Wurtele

This committee considered a number of modeling-related topics both from a general perspective and with regard to the four interactive group meetings (simulation, design, operations, and remote sensing). The results of our discussions are summarized according to selected issues identified during our individual and interactive group meetings. These results are loosely categorized according to model type or area of interest (i.e., Monte Carlo models, flux models, simulation applications, design applications, operations applications, and remote sensing issues).

The information which is presented is not claimed to be complete nor is it presented in a consistent form. The synopses of issues and discussions were prepared by individual committee members having a close association or strong interest.

One common factor among the various applications and disciplines is that communication between those engaged in model development and those using models is difficult and limited. Perhaps the most effective solution is meetings or workshops such as this. Problems are then quickly detected in articulation of model developers and model users.

A summary of major points is given in Table 1. This is the basis of the oral summary presented on the final day of the workshop.

TABLE 1. Summary of Major Points.

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1. **Monte Carlo Models**

   a) The Dryden form of the turbulence spectrum is still most widely used although rational von Karman forms are readily available.
   b) Non-Gaussian turbulence models are available but are in limited use. Factors which call for implementation of these models are correctness, less regularity to pilot with more "surprise," and more faithful compliance with the nonlinear governing equations.
   c) Coherence and cross-correlation models exist but have not been developed to the point where simulation usefulness is recognized.
   d) Non-stationary models can produce "patchiness" as with non-Gaussian.
   e) Future models in progress will have better correlation between turbulence and shear.

TABLE 1. (continued).

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2. **Models of Turbulence Closure (Flux Models, CFD-Related)**

   a) CFD turbulence models work reasonably well for shear flows but are less effective where there exists buoyancy forces, recirculation zones, rapid accelerations, and large scale turbulence.
   b) Two-equation turbulence models are more general than algebraic models; the higher order models are better than lower order as a general trend.
   c) No clear rational approach to coupling of CFD and Monte Carlo models was indicated but it is attractive to use CFD for mean profiles and Monte Carlo for high frequency.
   d) A group-kinetic approach was presented by C. P. Tchen which transforms the prime equation into a system of macro-equations having the same form as the primitive equations, with added transformation coefficients (eddy viscosity, eddy damping) derived from kinetic theory.

3. **Simulation Applications**

   a) There is a desire for models which are practical and reliable but they should be reasonably correct physically--shear/turbulence interaction is a major area of interest.
   b) Pilot's perception of turbulence features is not well documented but is needed for engineering, modeling, information choices.
   c) A clear consistent handbook or users guide on model implementation is needed.

4. **Design Applications**

   a) There is a need for structural, flight control, flying qualities specification models (specific turbulence ranges of interest span 0.03 to 300 rad/sec).
   b) Despite advanced turbulence models being available, it is difficult to incorporate new models in specs as illustrated in the recent flying qualities (F.Q.) specifications update. That is, even when specifications are updated, it is hard to get new models incorporated (even in background handbook/instruction guidelines which is a highly reasonable document to list new models).
   c) An appropriate rotary wing model is needed. No turbulence model in new F.Q. specifications (MIL-H-8501).
   d) It would be helpful to designers if the characterization of turbulence model is compatible with system response model, especially calculated statistics.

TABLE 1. (concluded).

5. **Operations Applications**

   a) Turbulence prediction models are desired but even if available computation power may be a fundamental limitation--mesoscale models are on threshold of numerical weather prediction (NWP) use.
   b) Improved training simulator "turbulence" models are desired to broaden available simulated conditions, but credibility is essential.
   c) JAWS data are becoming increasingly useful but need to be implemented in training systems. However, it is believed these data do not reflect the most severe conditions.

6. **Remote Sensing Issues**

   a) There is a clear connection of remote sensing with model development activities.
   b) There is a need for better understanding of model requirements and sensing capabilities--clear definition of parameters needed.
   c) There is a data assimilation problem (lots to handle).
   d) Use of turbulence simulation models as a data source for lidar simulation application is a possibility.

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1. Monte Carlo Models

Monte Carlo models, in a variety of forms, are used in flight simulation and aircraft design applications. A key factor setting this class of model apart from the flux models is the relative simplicity and ease of computation of the former.

The main discussion presented is an overview of the status of such models. Special aspects considered are probability density function modeling, anisotropy, and dispersion of passive contaminants. A special issue deserving mention is generation of "simple" functional models based on measured data.

ISSUE:

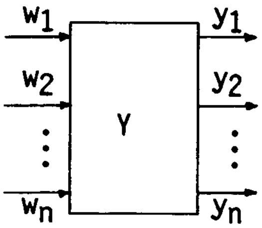
Status of Monte Carlo Models

DISCUSSION:

1. Simple Gaussian Models -- The Dryden model (so called because of the form of the spectrum used in the filter) is well known and has a computationally rational form. Some good rational approximations to von Karman spectra are also available (e.g., Campbell or Boeing model forms).

2. Non-Gaussian Models -- Gaussian models can be modulated or acted on by nonlinear filters to generate non-Gaussian models, which are more representative of atmospheric data.

3. Coherence and cross-correlation models -- Several approaches to incorporate coherence or cross-correlations into the models have been developed. Some have been implemented and others proposed. The general problem of this type is as shown in the figure; given a number, n, of desired outputs with given auto- and cross-correlations, and n input white noise sources, w_i, find the set of filters indicated by "Y". "Y" is the unknown set of filters.



Preferably the box should be composed of rational filters for computational efficiency or the simulation community will probably not use these models.

4. Nonstationary models -- Non-stationary models and non-Gaussian models are similar.

RECOMMENDED ACTION:

1. Investigate the general Monte Carlo (turbulence) simulation problems described above. Look into coupling Monte Carlo techniques with CFD.

2. Investigate the influence of probability density functions (pdf) on aircraft response. This can be done simply using a Monte Carlo simulation model with different pdf's. Feed the simulated "turbulence" into a fixed-stick aircraft model flying a glide slope and study landing footprints.

RESPONSIBLE AGENCY: NASA

PRIORITY: Medium to High

ISSUE:

Modeling Probability Density Function (pdf) of Turbulence, p{u(x)}

DISCUSSION:

1. Variation of pdf with position (i.e., How does it vary from one location to another?).
2. Definite non-Gaussian structure of pdf for both $p\{u(x)\}$ and $p\{u(x), u(x + r)\}$ (Is it necessary to incorporate the effects of skewness?).

RECOMMENDED ACTION:

1. Data to model these characteristics need to be generated.
2. Pursue self-similar model of the form $p\{u(x + \Delta x)\} \approx \eta p\{\xi u(x)\}$ where η and ξ are x-dependent scale factors.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: Medium

ISSUE:

Anisotropy of Turbulence (What is it and what does it mean?)

DISCUSSION:

1. Anisotropy means that the turbulence intensities (and integral scales) are different from one direction to another.
2. Anisotropy is crucial whenever strong shear is present (particularly boundary-layer turbulence).
3. The time decay of "low" Reynolds number anisotropic turbulence is still an unsolved problem.

RECOMMENDED ACTION:

1. Model (at least crudely) anisotropy in wind shear turbulence.
2. Attempt to formulate a "rule-of-thumb" estimate of decay rate.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: Medium

ISSUE:

Dispersion of Passive Contaminants

DISCUSSION:

Both in the earth's planetary boundary layer and in the stratosphere, the Lagrangian problem of passive contaminant dispersion is of great interest. Theoretical models of dispersion have become highly sophisticated, far exceeding the capacity of observational data sets for validation. Model simulations of Eulerian turbulence can, with some additional effort, also simulate dispersion.

RECOMMENDED ACTION:

Modelers should be encouraged to treat turbulence and diffusion as two ways of describing the same phenomena.

RESPONSIBLE AGENCIES: NOAA, NASA

PRIORITY: Low to Medium

ISSUE:

Generation of "Simple" Functional/Probabilistic Models of Measured Turbulence Time Histories

DISCUSSION:

One approach to Monte Carlo model development is to develop the simplest functional/probabilistic models that will represent all obvious features of measured turbulence time histories. For such models to be useful it is necessary to be able to extract model parameters, e.g., standard deviations, integral scales, probability densities, etc. from measured turbulence time histories.

RECOMMENDED ACTION:

The underlying philosophy is simplistic and functional depending, of course, on the projected use. This should be stated in applied research efforts and should be considered in approaching any modeling application.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: Medium

2. Models of Turbulent Closure (Flux Models)

This class of models can be categorized according to the following:

a. Truncation models
b. Constant dissipation models

c. High-order closure (either by mixing length or normality)
d. Kinetic methods (either probability or group-kinetic methods)
e. Numerical simulation models.

A discussion of the status of turbulent closure models is followed by a description of Dr. Tchen's "group-kinetic" modeling, anlaytical foundation of Monin-Obukhov similarity theory, and turbulence parameterization in operational numerical weather prediction.

ISSUE:

Status of Turbulence Closure Models and Coupling of CFD, Engineering Applications, and Monte Carlo Turbulence Simulation

DISCUSSION:

Most turbulence closure models work reasonably well for simple shear flows (i.e., jets, wakes, etc.) but for flows with boundary forces, recirculation zones, or rapid accelerations, they do not work as well. In general, the two-equation models have more generality than algebraic models and higher order models are better than lower order models. Recently, a new turbulence model, the multiple scale model developed by C. P. Tchen (NRC fellow at Marshall Space Flight Center), has had great success in predicting complex flows (i.e., with swirl and associated recirculation), which were previously difficult to predict. This four-equation model shows great promise for a wide variety of problems. One area it cannot handle is flows where regions of countergradient diffusion are present.

Generalizations are being added by Tchen to account for countergradient diffusion. The question of coupling CFD analyses with Monte Carlo simulation is relevant for many applications. At the same time, a rational approach is not clear for doing this. One possibility is to use CFD to predict the mean values of the flow. The calculation can be done with a two-equation turbulence model which provides turbulent kinetic energy and length scale. The problem is with the spectrum. Some approach for computing the spectrum function with the CFD model is also required. With this information, Monte Carlo simulation can be performed and added to the mean wind speeds to give the turbulent fluctuations.

Treatment of boundary conditions is an issue of considerable interest. In the CFD community, boundary condition treatment is controversial. Some believe surface treatment with wall functions is completely unacceptable in complex flows. Others believe it is a necessary evil.

RECOMMENDED ACTION:

Cross coupling of CFD with Monte Carlo simulation should be investigated. Methods for generating spectra, turbulence intensity length scale, etc. should be evaluated. The sources of any such a technique need to be tested. The best hope for conclusive tests is in a controlled laboratory environment.

Comparisons of calculations and "tuning" of models can proceed from an experimental data base.

RESPONSIBLE AGENCIES: NASA, DoD, NCAR, NOAA

Each agency has its own applications and requires its own models. Generality from one application to the next is not guaranteed.

PRIORITY: High!

ISSUE:

Group-Kinetic Method of Modeling Large-Scale Turbulence

DISCUSSION:

Dr. Tchen described a group-kinetic theory which he is developing. With the group-kinetic method, the system of primitive equations (Navier-Stokes equations) that describe the microdynamic state of turbulence are transformed into the equations of evolution in turbulence that are similar to the primitive equations with added terms containing transport coefficients that represent the statistical effects of small-scale turbulence. The transport coefficients are derived analytically by the group-kinetic method and take the form of an eddy viscosity for small-scale transport or of a damping coefficient for large-scale transport. Thus, the outcome of the group-kinetic theory is to transform the primitive equations into a system in the macro-form without escalating a hierarchy. The method is valid for the determination of mean profiles, the probability functions, and the spectral distributions.
A nonlinear dynamical system in the form of a non-homogeneous and nonlinear partial differential equation is transformed into a homogeneous master equation in the t, x, v space. It is decomposed into three transport equations: the macro-group describes the spectral evolution, the micro-group describes the transport properties, and the sub-group describes the relaxation. The memory loss in the relaxation defines the closure. The kinetic equation is derived.

The transport coefficients (eddy viscosity, damping coefficients) are calculated. The equation of spectral flow is obtained, including all the transport functions, i.e., production, coupling, cascades (direct and inverse) and dissipation. The solutions yield the spectral distributions and the probability function.

The group-kinetic theory derives the spectral laws $k^{-5/3}$, k^{-1}, gap, k^{-3} for the spectral density of velocity fluctuations at increasing scales.

By using the Prandtl hypothesis of mixing length, Monin and Obukhov had derived a similarity theory of profiles for mean velocity, temperature, and humidity. The Monin-Obukhov theory cannot determine the universal functions that characterize the neutral, stable, and unstable stratifications. A group-kinetic method of closure could analytically determine these universal functions.

RECOMMENDED ACTION:

Dr. Tchen should pursue the following issues in his current program:

1. The group-kinetic theory should be extended to include the interactions between turbulence and internal gravity wave, Rossby waves with uniform and differential rotation, geostrophic planetary waves, and other large-scale motions, e.g., vortex motions, in order to investigate the coupling and the reverse cascade.
2. In an atmosphere with rain and snow, the coupling between phases of turbulence should be investigated.
3. The method of lidar sensing should be analytically investigated for multi-phases.

RESPONSIBLE AGENCY: NASA

PRIORITY:

The three topics are listed in the order of their priority.

ISSUE:

Turbulence Parameterization in Operational Numerical Weather Prediction (NWP)

DISCUSSION:

Operational numerical weather prediction models have to cover a sizable region of the atmosphere in order to provide useful meteorological forecasts. This necessitates the use of computational grid volumes which are so large that a considerable portion of the atmospheric turbulence is subgrid and must be parameterized. There is a need to improve these parameterizations.

RECOMMENDED ACTION:

Results from finer resolution models can be used to improve parameterizations in the coarser resolution models. Models should be made more flexible to handle remotely sensed data, such as scatterometer measurements of surface stress over the ocean. New modeling approaches to parameterization should be investigated.

RESPONSIBLE AGENCIES: DoD, NOAA, NASA

PRIORITY: Medium

3. Simulation Applications

Simulation is an important use of turbulence models and can span a range of applications. Simulation involves engineering (design and research) and training (airline and military) applications. It was also suggested that there are possibly important non-aviation applications of turbulence simulation, namely, atmospheric circulation (as was suggested by the presentation made by Dr. John Theon of NASA HQ).

ISSUE:

Pragmatic Solution of Turbulence Wind Shear Simulation Using a Linear Combination of Random Turbulence and Deterministic Wind Profile

DISCUSSION:

This is an approach commonly used in engineering simulation applications. Ease of implementation is a major benefit, but some credibility questions persist (as suggested by the Operations Committee). Also, basic incorrectness of probability distribution (due to linear combination) is another negative argument for this approach.

RECOMMENDED ACTION:

Continue to develop physically correct flow models which will provide the potential for better formulation of this modeling technique.

RESPONSIBLE AGENCY: NASA

PRIORITY: High

ISSUE:

Pilot Perception of Simulated Turbulence Effects

DISCUSSION:

This issue is not well documented but is crucial to making engineering tradeoffs between computational complexity and "realism."

Microscale turbulence is important to effects on instruments even though it is beyond the frequency response of aircraft.

A major limitation in "realism" is outside the turbulence or aircraft models, i.e., limited by visual or motion systems.

While a comprehensive turbulence model is theoretically desirable, more pragmatic approaches must be taken because of economics and of the status of existing models.

Realism, *per se*, may not be as important as identifying critical design conditions.

RECOMMENDED ACTION:

Carry out a systematic investigation and determination of effects which can be perceived by a pilot and their relative level of importance for performance of various flight tasks.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: Medium to High

4. Design Applications

One central concern is the use of turbulence models in conjunction with design standards, specifications, and criteria. These include structures, flying qualities, and flight controls.

ISSUE:

Revision of Military Specification (MIL spec) Models

DISCUSSION:

In spite of recent revisions of specifications (flying qualities military standard, MIL-F-8785C), there are not substantial changes from previous models.

Specification handbooks should contain explicit guidance in how to implement, define the parameters, and use the model.

RECOMMENDED ACTION:

Review current MIL spec models for structural, flying qualities, and flight control applications.

RESPONSIBLE AGENCIES: DoD, NASA

PRIORITY: Medium

ISSUE:

Modeling of Deterministic Features such as Wind Shear and Microbursts

DISCUSSION:

Need meaningful statement of turbulence conditions relative to critical design points.

An initial model has been developed by FWG Associates, Inc.

RECOMMENDED ACTION:

Continue development of understanding and models.

RESPONSIBLE AGENCIES: NASA, FAA

PRIORITY: High

ISSUE:

Needs of Rotary Wing Designers/Users

DISCUSSION:

One area lacking guidance is application of turbulence models in design of rotary wing aircraft. Rotor aerodynamics are important in defining modeling forms and may require time-space dependence.

RECOMMENDED ACTION:

Develop suitable models for rotary wing design and simulation.

RESPONSIBLE AGENCIES: Army, NASA

PRIORITY: High in view of near-term LHX (proposed U.S. Army advanced light scout/attack helicopter family) and JVX (joint services advanced vertical lift aircraft (V-22)) design activities.

5. Operations Applications

Three needs expressed by the Operations Committee were:

1. A better three-dimensional turbulence model for general purpose training simulator use,
2. A better low-level (<500 ft) model for training in terminal area operations (especially regarding wind shear), and

3. An improved model for turbulence forecasting.

ISSUE:

Improved Low-Level Models with Emphasis on Training for Wind Shear

DISCUSSION:

1. Presently, most training likely to be with very limited set of profiles (JFK, MSY, DEN).
2. Pilots learn specific wind shear profiles quickly; therefore, a large variety of cases is needed.
3. Lack of credibility is the reason for not employing direct Monte Carlo modeling.

RECOMMENDED ACTION:

Activities such as those being carried out by NASA LaRC, i.e., viable solution with credibility based on physics and computationally manageable, should be supported.

RESPONSIBLE AGENCIES: NASA, DoD

PRIORITY: High

ISSUE:

Improved Three-Dimensional Turbulence Simulation for Training Simulator

DISCUSSION:

1. Need credible, flexible turbulence model for broad flight envelope application.
2. Objective is training.
3. Need more detailed statement of requirements.
4. Need operational definition for modelers (i.e., what elements of turbulence are observable by pilot and reproducible by simulator).
5. This model would blend into low-level model (or be same).

RECOMMENDED ACTION:

Study the necessity of a three-dimensional model for training application.

RESPONSIBLE AGENCIES: FAA, NASA

PRIORITY: Low

ISSUE:

Turbulence Forecasting: Is Improved Numerical Guidance Available or Possible?

DISCUSSION:

Many high-resolution research models currently in existence hold promise for improved turbulence forecasting. Models which simulate individual thunderstorms, mountain-lee waves, etc. on the mesoscale are currently used primarily in research applications. They show many realistic features of the physical processes involved. With anticipated computing power increases and data assimilation increases associated with advances in satellite and other remote sensing techniques, these models should become true numerical weather prediction models in the next decade.

RECOMMENDED ACTION:

Continue to support development of high-resolution research models.

RESPONSIBLE AGENCIES: NOAA, DoD, NASA

PRIORITY: Medium

6. Remote Sensing Issues

Two topics of discussion were explored:

1. Remote sensing requirements for supplying various modeling needs, and
2. How particular models could be used in studying development of remote sensing techniques.

Discussion of the first of these led to the "wind shear" training simulator requirement. This, in turn, led to the solution posed by current use of JAWS data. The second issue centered on the discussion of requirement for models in lidar simulation.

It was again found that clear communication of requirements is needed across disciplines.

ISSUE:

What Modeling Needs are Supported by Remote Sensing Techniques?

DISCUSSION:

1. There is a very broad range of needs spanning "wind shear" to mesoscale.
2. For "wind shear," JAWS data have led to a set of improved models for low-level training simulator applications.
3. Limitations of remote sensing need to be defined and understood by modelers (e.g., resolution of lidar regarding the need to generate simulator wind/turbulence profiles which affects flight path and airspeed).

RECOMMENDED ACTION:

Modelers should establish more direct contact with appropriate individuals in the remote sensing community.

RESPONSIBLE AGENCIES: NOAA, NASA, DoD

PRIORITY: Medium

ISSUE:

What Models/Approaches Might be Available for Lidar Simulation (Connected with Development of Lidar Usage Techniques)?

DISCUSSION:

Use of large eddy simulation models could be used as numerical data source for lidar simulation application.

RECOMMENDED ACTION:

Lidar developers should define needs and present them to the modeling community.

RESPONSIBLE AGENCIES: NOAA, DoD, NASA

PRIORITY: Medium

COMMITTEE: PREDICTING

CHAIRMAN: John L. Keller

MEMBERS:
C. L. Chandler
Dave Forrester
George Modica
Charles H. Sprinkle
Donald Wylie

ISSUE:

Simulation of Turbulence

DISCUSSION:

There were differing opinions as to the importance of simulating CAT. The line-of-flight training (LOFT) approach would seem to require more sophisticated representations of both boundary layer and high-level non-convective turbulence (CAT).

RECOMMENDED ACTION:

The NASA/Ames work using flight recorder data with the equations governing aircraft motion may provide a more realistic representation of individual events. These could be superimposed over the large-scale wind fields associated with CAT outbreaks. It is recommended this work be continued.

RESPONSIBLE AGENCY: NASA

PRIORITY: Very Low

ISSUE:

Need for Ground-Based and Airborne Remote Sensing of Convective and Non-Convective (CAT) Turbulence

DISCUSSION:

Direct sensing of turbulence in the boundary layer seems feasible using ground-based Doppler radar and lidar.

Airborne Doppler lidar data collection efforts for research efforts at the present time. The use of lidar sensors on commerical air carriers at a later time was also discussed.

Use of satellite cloud picture was discussed.

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RECOMMENDED ACTION:

Investigate techniques for possible long-term implementation.

RESPONSIBLE AGENCIES: NASA, FAA

PRIORITY: Low

ISSUE:

Operations: Validation and Standardization of CAT Forecasting Techniques/ Quality of PIREPS

DISCUSSION:

Problems exist for validating both the qualitative techniques currently used by airlines and quantitative numerical techniques under development. Parameterization techniques related to specific turbulence indices could also benefit numerical weather prediction accuracy.

RECOMMENDED ACTION:

1. Use INS-based automatic PIREPS.
2. Evaluate and validate CAT forecast techniques.
3. Standardize forecast techniques (numerical and qualitative).

RESPONSIBLE AGENCIES: NASA, NOAA, DoD

PRIORITY: Medium

ISSUE:

Effects on Aircraft Design

DISCUSSION:

An improvement in turbulence forecasting may lead to an increase in the average life span of the aircraft fleet. Design and forecast validation share a need for the data base.

RECOMMENDED ACTION:

NASA should sponsor a study to determine benefit thresholds of effects on the increased life span of aircraft due to improved clear-air turbulence forecasting methods.

RESPONSIBLE AGENCIES: NASA, FAA

PRIORITY: Medium to High

ISSUE:

Central Automated PIREPS Assimilation Center

DISCUSSION:

There seems to be a unanimous concensus that a need for a reliable turbulence validation data base exists. The development of a quantitative clear-air turbulence (or CAT) index is greatly hindered by the current lack of such information. INS-based automated PIREPS, which are gradually increasing in number, represent a potential resource for providing a quantitative measure of turbulence intensity as well as wind, temperature, and altitude which can be used for improving short-term forecasting at cruising altitude.

RECOMMENDED ACTION:

The Prediction Committee wishes to second the recommendation, which is expected to be made by the FAA's Aviation Weather Task Force, that a centrally located automated PIREPS assimilation center be established within the next several years. This includes the implementation of necessary communications systems and the systematic archiving of these data. The problem of aircraft avoidance of CAT will remain.

RESPONSIBLE AGENCIES: FAA, NOAA, NASA

PRIORITY: Very High

COMMITTEE: UNDERSTANDING

CHAIRMAN: Rodney Wingrove

MEMBERS:
Ray Arritt
Alfred J. Bedard
Coleman D. Donaldson
Jean T. Lee
Peter F. Lester
James K. Luers
Ernest W. Millen
Fred H. Proctor
J. D. A. Walker

ISSUE:

Produce a Better Definition of Atmospheric Turbulence as It Influences Aircraft

DISCUSSION:

There is a need for a better definition of atmospheric turbulence that includes the broad range of atmospheric phenomena encountered by aircraft. Specialists currently have differing perspectives on the nature and effects of turbulence. The definition should include turbulence in the statistical sense as well as organized instabilities.

RECOMMENDED ACTION:

Encourage representatives from several agencies and sectors of the industry to work to develop and to disseminate a standard that clearly encompasses all aspects of aircraft turbulence.

RESPONSIBLE AGENCIES: Multi-Agency (Research Organizations, NASA, FAA, DoD, etc.)

PRIORITY: Medium

ISSUE:

NEXRAD Application to Turbulence Recognition

DISCUSSION:

Questions were asked as to how well does the measured spectrum width/energy dissipation rate represent (indicate) turbulence in convective situations.

RECOMMENDED ACTION:

Education and communication of present information are strongly encouraged. Prior to commissioning the NEXRAD radars, users and operators need to be trained as to the interpretation of the data and the limitations brought about by the sampling mode, the mode in which the radar is operated--the algorithm used and the problem area in very weak reflectivity regions.

RESPONSIBLE AGENCIES: NWS, FAA, USAF Air Weather Service

PRIORITY: High

ISSUE:

Evaluation of Wind Profiler and Thermodynamic Profiler Capabilities for Predicting and Monitoring Atmospheric Turbulence

DISCUSSION:

Recent results indicate that thermodynamic profilers can monitor the fluctuations of constant pressure surfaces and provide data on the amplitude and spectral content. Wind profiling radars have also detected short period fluctuations, and the mean wind fields will be valuable for prediction.

RECOMMENDED ACTION:

Document present state of knowledge on the use of profilers for monitoring turbulence aloft. Encourage NOAA to test collocated wind and thermodynamic profilers. Encourage agencies responsible for prediction and warning to consider how higher time resolution data on mean winds aloft could be incorporated into turbulence prediction models.

RESPONSIBLE AGENCY: NOAA

PRIORITY: Medium

ISSUE:

Standardization of Turbulence Reporting Procedures

DISCUSSION:

There is a need for regular, dependable reporting procedures of turbulence for forecast development and verification, for research and for encouraging more reports for operational purposes.

RECOMMENDED ACTION:

Develop a simple, automated, standard, quantitative turbulence reporting procedure for use by all domestic and international flights.

RESPONSIBLE AGENCIES: FAA, Military

PRIORITY: High

ISSUE:

A More Objective and Accessible Way to Measure G-Forces

DISCUSSION:

On many aircraft (commercial and general aviation) quantitative measurements of g-forces are often not available or of poor quality. There exists no method of providing objective pilot reports quantifying the hazard level encountered in real time.

RECOMMENDED ACTION:

Encourage the development of a simple and low-cost "g" meter, permitting easy visual readout (of max g) and reset capability.

RESPONSIBLE AGENCIES: FAA, NASA, Industry

PRIORITY: Low

ISSUE:

Unsteady Flow Structure

DISCUSSION:

There is a need to understand and categorize the different types of unsteady flow structures that occur in the atmosphere and that the aircraft may encounter.

1. Turbulent boundary layers -- Production in the lower portion of turbulent boundary layers is known to take place through abrupt and intermittent eruptions of fluid from the region near the wall (bursts); the burst is then followed by a rapid inrush of fluid toward the wall (the sweep). Similar phenomena undoubtedly occur in the planetary boundary layer; a rough calculation suggests eruptions for a vertical scale of several hundred feet are possible. This may pose a threat to landing aircraft.

2. Three-dimensional vortex motions are common near airports, e.g., (a) trailing aircraft vortices, (b) vortices created near the ground due to downwash, and (c) structured unsteady vortices shed form topographical features.

3. Convected roll cells and waves are also a feature of atmospheric flows. These convected vorticular disturbances (flow structures) will have an affect on aircraft which might be broadly classified as turbulence. However, although they will contain small-scale background turbulence, they are really organized, defined, and unsteady flow structures. As such structures evolve and are convected, updrafts, downdrafts, and sharp shearing regions will occur. All of these effects pose a potential problem for aircraft but on an intermittent or discrete basis. There is a need to understand and categorize such motions, which may be throught of as structured unsteadiness. How do such vortices evolve with time? What types of flow do they induce as they move (particularly near the ground)? Do they generate more vortices near the ground?

RECOMMENDED ACTION:

1. Efforts are needed relative to detailed flow visualization and/or measurements of unsteady phenomena (not the mean quantities--they are not relevant to these kinds of phenomena).

2. Theoretical calculations of the evolution of three-dimensional vortices and their effects on the flow near the ground plane should be accomplished. Interactions with other vortices should also be investigated.

3. Develop an understanding of the most important types of unsteadiness near airports and/or topographical features.

RESPONSIBLE AGENCIES: NSF, NASA, Research

PRIORITY: Medium

ISSUE:

Characterization of Low-Altitude (Terminal) Turbulence

DISCUSSION:

Standardization of data output becomes important for comparison/education of forecasted data from NEXRAD, TDR, LLWSAS facilities.

RECOMMENDED ACTION:

Education; communication among interested technical communities.

RESPONSIBLE AGENCY: NASA, FAA

PRIORITY: Medium

ISSUE:

Turbulence Data Base

DISCUSSION:

There is a need to update and expand the turbulence data base including both old but unused data and new information such as DFDR and Doppler/lidar outputs. These data are needed for an updated physical description of observed turbulence for better understanding, training, and design as aircraft fly higher and composite constructions become common.

RECOMMENDED ACTION:

Inventory current data bases; expand as needed; analyze; and develop a catalog of turbulence describing each type of turbulence, its frequency content (or discrete structure), its altitude range, its pitch size, and its average duration.

RESPONSIBLE AGENCIES: FAA, NASA

PRIORITY: Medium

ISSUE:

Turbulence Knowledge/Understanding "Gap"

DISCUSSION:

Despite the rapid developments in our understanding of turbulence through 1973 and the steady, albeit, slower developments since that time, it appears that there has developed a knowledge gap between the scientist/researcher and the user. This problem has been exacerbated by the growth in our capabilities to detect turbulence and turbulence-related structures via remote sensing devices (sodar, radar, lidar, etc.). The interpretation and use of these data are not immediately obvious to many users including both operational meteorologists and pilots.

RECOMMENDED ACTION:

Develop a systematic program of information/education to include a comprehensive review of the appropriate literature and the preparation of circulars and manuals. In view of the continued impetus towards the establishment of networks of remote sensors in the near future, continued regular updates in this material is encouraged.

RESPONSIBLE AGENCIES: Multi-Agency

PRIORITY: Medium

CLOSING REMARKS

Walter Frost
FWG Associates, Inc.
Tullahoma, Tennessee

I think the workshop was pretty successful relative to our objectives and goals. We had a very good exchange of information. As usual, you don't always achieve exactly what you hoped and there were a few areas where we fell a little short. First of all, not through a fault of ours, at least not because we didn't try, we did miss our presentation on SDI. That was an area in which I believe a number of you were interested. A definition of what may be some of the anticipated problems relative to disturbances and turbulence in the atmosphere was not discussed in too much detail. We'd hoped to do that.

There was also a gap, and some mentioned it toward the end, relative to the fact that we should have had a presentation on the atmospheric boundary layer. There is a lot of work going on in the atmospheric boundary in terms of turbulence modeling that the diffusion people are doing and we intentionally did not invite a large contingency from diffusion modeling because we felt that would be trying to cover too broad an area. But there is a lot of work on turbulence modeling in terms of the effects of buoyancy on turbulence models and the effects of terrain on turbulence models. One of things I'd hoped might come out of the discussion but I didn't see it in any of the presentations is whether we really need to be able to simulate better terrain effects, stability effects, etc. in the atmospheric boundary layer.

There was no real discussion on aircraft wake turbulence, and that is an area that is being researched in the FAA. Unfortunately, the FAA personnel we invited had no travel funds.

I thought the issue of non-stationary turbulence might have been discussed a lot more than it was. That is one place where we are bogging down in turbulence modeling. We have a lot of turbulence models in terms of isotropic and homogeneous turbulence but, how we model non-stationary turbulence, how do you do ensemble averaging, etc. didn't seem to receive much discussion.

One of the things that came out as a recommendation was that we need to define operational requirements. I had hoped that definition would be a result of this workshop. There are no current reports summarizing these requirements. John Houbolt did it in 1972* and the recommendation is we need to do it again. A similar recommendation was made relative to design: It was to review criteria modeling and design procedures. The workshop in its final documentation might provide some specific recommendations on areas that we needed further data for design, but basically the recommendation is that there needs to be a specific study.

There was a good point made that we really didn't address the non-rotary wing application problem. That wasn't entirely by design either. We had invited people from the rotary wing community who did not come and a number we

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*Houbolt, John C.: Atmospheric Turbulence. AIAA Journal, vol. 11, no. 4, pp. 421-437, April 1973.

asked turned us down. I think most of the rotary wing people I talked to don't think they have a wind problem. Some how or other we have to get the word out to the rotary wing aircraft community that there are wind problems.

Finally, there could have been a little more discussion on joint and integrated programs. We don't have the money for everybody to go out and study their own thing. We had hoped to generate cooperation between the groups who are measuring statistical turbulence parameters for design working with the group who is doing computational fluid mechanics. There was some discussion of this topic.

In general, I think that the recommendations which came out of this workshop were very good and I believe they gave us guidance. The workshop provided a good opportunity to get together and summarize where we are currently. I hope Hal Murrow felt the same. He was one of the leaders in getting this workshop together. John Houbolt, John Theon, Joe Stickle, and Ed Harrison were also very instrumental in this regard. I hope they are happy with what we achieved. I personally feel we had a very effective workshop.

Harold N. Murrow
NASA Langley Research Center
Hampton, Virginia

I don't have much to add. I think Walter Frost summarized it very well. I think we all owe a debt of gratitude to Walter Frost and Dennis Camp for putting together such a group for both the interactive working sessions and the presentations. I thought you might be interested in just where the participants at our workshop came from. I summarized from the attendance list that we had 30 from industry, 10 from universities, 9 from DoD, 5 from NOAA, 17 from NASA, and 3 from other government agencies. As you know, this was an international meeting. We hope that you feel this was as profitable as we think it was.

ATTENDEES

Pat Adamson
Adaptive Instruments Corp.
2450 Central Avenue, Suite H
Boulder, CO 80301
303/443-1319

Dr. Ray Arritt
Dept. of Atmospheric Science
Colorado State University
Ft. Collins, CO 80325
303/491-8293

Dr. Alfred J. Bedard
Environmental Research Laboratories
NOAA/WPL
325 Broadway
Boulder, CO 80303
303/497-6508

Dr. Alan Bohne
Air Force Geophysical Lab/LYR
Hanscom AFB, MA 01731
617/377-4406

Dr. Roland L. Bowles
MS 156A
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3621

Dr. Stephen D. Burk
Naval Environmental Protection Research Facility
US Navy
Monterey, CA 93943-5106
408/646-2856

Dennis W. Camp
FWG Associates, Inc.
Rt. 2, Box 271A
Tullahoma, TN 37388
615/455-1982

Dr. Warren Campbell
The BDM Corporation
2227 Drake Avenue
Huntsville, AL 35805
205/882-7540

C. L. Chandler
Operation Center, Dept. 091
Delta Air Lines
Hartsfield International Airport
Atlanta, GA 30320
404/765-6478

Dr. Sue-li (Kingsley) Chuang
SASC Technologies, Inc.
17 Research Dr.
Hampton, VA 23666
804/865-3621

Diana Collier
Lockheed Calif. Co.
P.O. Box 551
Burbank, CA 91520
818/847-7128

Richard Dickson
AMSMI/RD-SS-SD
Army Missile Command
Redstone Arsenal, AL 35898-5252
205/876-1951

Coleman DuPont Donaldson
Aeronautical Research Associates of Princeton
1800 Old Meadow Rd., #114
McLean, VA 22102
703/734-1930

Ben F. Dotson
MS 3304
Advance Airplane Branch
Boeing Military Aircraft Company
P.O. Box 3707
Seattle, WA 98124
206/241-4435

Earl Dunham
MS 247
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3274

L. Jack Ehernberger
MS OFA
NASA Ames Research Center
Dryden Flight Research Facility
P.O. Box 273
Edwards, CA 93523-5000
805/258-3699

Gary P. Ellrod
Satellite Application Lab.
NOAA NES/DIS
E/RA21:GE
Washington, DC 20233
301/763-8251

G. David Emmitt
Simpson Weather Associates
P.O. Drawer 5508
Charlottesville, VA 22903
804/979-3571

Bruce D. Fisher
MS 247
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3274

Dave Forrester
Special Investigations Branch
Meteorological Office
London Road
Bracknell, Berkshire
England
011-44-0344-420242, x. 2306

Dr. Walter Frost
FWG Associates, Inc.
Rt. 2, Box 271A
Tullahoma, TN 37388
615/455-1982

George Gal
Dept. 97-01/Bldg. 201
Lockheed RDD
3251 Hanover St.
Palo Alto, CA 94306-1187
415/424-2332

William D. Grantham
MS 489
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-2132

Capt. Edward J. Harrison, Jr.
Military Asst. for Environmental Sciences
R&AT/E&LS
Office of the Under Secretary of Defense
The Pentagon
Washington, DC 20301
202/695-9604

George C. (Cliff) Hay
ADL-15
FAA
800 Independence Ave., SW
Washington, DC 20591
202/426-3677

Robert K. Heffley
Technical Director
Manudyne Systems, Inc.
349 First St.
Los Altos, CA 94022
415/949-1747

Richard M. Heimbaugh
McDonnell Douglas Corp.
Douglas Aircraft Co.
Dept. C1, E84
Mail Code 35-05
3855 Lakewood Blvd.
Long Beach, CA 90846
213/593-0563

Dr. John C. Houbolt (Retired NASA Consultant)
MS 246A
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-2037

Robert L. Ireland
United Airlines Flight Center
Stapleton International Airport
Denver, CO 80207
303/398-4553

John L. Keller
Senior Meteorologist
WSI Corporation
41 North Road
Bedford, MA 01730
617/275-5300

John T. Klehr
Link Flight Simulation Division
Singer Co.
Kirkwood Industrial Park
Binghamton, NY 13902
607/772-4695

Dr. V. Klein
George Washington University
JIAFS
Attn: AMB
MS 489
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-4887

Jean T. Lee (Retired)
NOAA/NSSL
1313 Halley Circle
Norman, OK 73069
405/321-8011

Peter F. Lester
Dept. of Meteorology
San Jose State University
San Jose, CA 95192
408/277-2311

James K. Luers
University of Dayton Research Center
College Park Drive
Dayton, OH 45469
513/229-3921

Dr. William D. Mark
Bolt, Beranek, and Newman, Inc.
10 Moulton St.
Cambridge, MA 02238
617/497-3527

Dr. Robert A. McClatchey
Director, Atmospheric Sciences Division
Air Force Geophysics Lab/LY
Hanscom AFB, MA 01731
617/377-2975

Dr. Burnell T. McKissick
MS 156A
NASA Langley Research Center
Hampton, VA 23665-5225

James C. McLean, Jr.
National Transportation Safety Board
800 Independence Ave., SW
Washington, DC 20594
202/382-6679

William W. Melvin
ALPA
1101 West Morton
Denison, TX 75020
214/463-1246

Robert T. Meyer
Stability & Control Group Eng.
Lockheed Georgia Co.
86 S. Cobb Dr.
Marietta, GA 30063
404/424-2866

Dr. W. Dale Meyer
HQ Air Weather Services/DNXS
Scott AFB, IL 62225-5008
618/256-4781

Ernest W. Millen
MS 156A
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3621

Major Douglas Miller
HQ AFISC/SEFB
Norton AFB, CA 92409-7001
714/382-2226

George Modica
Air Force Geophysics Lab/LYP
Hanscom AFB, MA 01731-5000
617/377-2956

Richard N. Moon
Lockheed California Co.
Dept. 76-11, Bldg. 63, Plant A1
P.O. Box 551
Burbank, CA 91503
818/847-1732

Harold N. Murrow
MS 243
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3451

Jerry R. Newsom
MS 243
Head, Aeroservoelasticity Branch, LAD
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3451

Joe J. Nishikawa
MS 08-40
Boeing Commercial Airplane Co.
P.O. Box 3707
Seattle, WA 98124
206/342-4871

David O'Keefe
Project Loads Dept., Bldg. 63, Plant A-1
Lockheed-California Co.
P.O. Box 551
Burbank, CA 91520
818/847-3198

John J. Pappas
Manager Meteorology/Flight Planning
Western Airlines
6060 Avion Drive
Los Angeles, CA 90009
213/646-9267

Creighton Pendarvis
Instructor Pilot, Advanced Aeronautics
SimuFlite Training International
P.O. Box 611011
Dallas/Ft. Worth Airport, TX 75261
214/456-8066/8000 (1-800-527-2463)

Fred H. Proctor
Meso
28 Research Drive
Hampton, VA 23666
804/865-7800

Phil Rogers
Lockheed California Company
P.O. Box 551
Burbank, CA 91503
818/847-4550

Dr. James R. Scoggins
Dept. of Meteorology
Texas A&M University
College Station, TX 77843
409/845-7671

Robert K. Sleeper
MS 243
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-2273

Anthony Smart
Spectron Development Labs., Inc.
3303 Harbor Blvd., G3
Costa Mesa, CA 92626-1579
714/549-8477

Robert Smith
Chief
Night Vision & EO Labs
ASL Ft. Belvoir Met Team
Ft. Belvoir, VA 22060-5677
703/664-1188

Charles H. Sprinkle
Chief, Aviation Services Branch (W/OM13)
NOAA/NWS
8060 - 13th St.
Silver Spring, MD 20910
202/427-7726

Dr. C. M. Tchen, Professor Emeritus
City College of the City University of New York
Dept. of Mechanical Engineering
900 West 190th Street
New York, NY 10040
212/781-4111 (Home)

Dr. John S. Theon
Mail Code EET
NASA HQ
600 Independence Ave., SW
Washington, DC 20546
202/453-1474

Michael Tomlinson
National Weather Service
W/OM13X1
8060 - 13th St.
Silver Spring, MD 20910
301/427-7726

Dr. George Treviño
Dept. of Mechanical Engineering and Engineering Mechanics
Michigan Technological University
Houghton, MI 49931
906/487-2551

Elijah W. Turner
Air Force Flight Dynamics Lab
AFWAL/FIBEB
Wright-Patterson AFB, OH 45433-6553
513/255-6434

Jim Usry
MS 247
NASA Langley Research Center
Hampton, VA 23665-5225
804/865-3274

Dr. Laj Utreja
The BDM Corporation
2227 Drake Avenue
Huntsville, AL 35805
205/882-4970

Harry A. Verstynen
Manager, FAA Langley Development
and Logistics Field Office
MS 250
Langley Research Center
Hampton, VA 23665-5225
804/865-4595

Dr. J. D. A. Walker
Packard Lab #19
Dept. of Mechanical Engineering
Lehigh University
Bethlehem, PA 18015
215/861-3789

Rodney Wingrove
MS 210-9
NASA Ames Research Center
Moffett Field, CA 94035
415/694-5429

Dr. Morton G. Wurtele
Professor, Dept. of Atmospheric Sciences
UCLA
Los Angeles, CA 90024
213/825-1751

Dr. Donald Wylie
Space Science & Engineering Center
University of Wisconsin
1225 West Dayton St.
Madison, WI 53706
608/263-7458

Dr. E. Carson Yates, Jr.
MS 243
NASA Langley Research Center, LAD
Hampton, VA 23665-5225
804/865-3451

Dr. J. Allen Zak
SASC Technologies, Inc.
17 Research Drive
Hampton, VA 23666
804/865-0214

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16. Abstract

This report is a compilation of proceedings of a workshop conducted at the NASA Langley Research Center April 2-4, 1986. The purpose of the workshop was to bring together representatives of various disciplines of aviation, missile, and space programs involved in predicting, measuring, modeling, and understanding processes of atmospheric turbulence, and to assess the status of knowledge and define work needed to satisfy stated requirements. The contents include 14 invited papers that were presented at plenary sessions and summary reports from 8 committees that were formed from all attendees and which met interactively with other committees.

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