A Human Performance Evaluation of Airborne-Detected Windshear Displays

by

Mark T. Salzberger

B.S., Mechanical Engineering
Cornell University, 1985

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE
in Aeronautics and Astronautics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1994

Signature of the Author ______________
Department of Aeronautics and Astronautics
12 May 1994

Certified by ____________________________
Associate Professor R. John Hansman, Jr.
Department of Aeronautics and Astronautics
Thesis Supervisor

Accepted by ____________________________
Professor Harold Y. Wachman
Chairman, Department Graduate Committee

A Human Performance Evaluation of Airborne-Detected Windshear Displays

by

Mark T. Salzberger

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the Degree of Master of Science in Aeronautics and Astronautics

Abstract

Aircrew interface issues concerning displays of hazardous windshear are examined. A part-task simulation is carried out to compare the effectiveness of different cockpit presentations of airborne-measured windshear. Airborne predictive detectors of windshear enable the dissemination of varying levels of information. Three display formats are generated: a multiple intensity level radar mapping, a multilevel, and a single level icon. Different positional and time-varying situations are presented to experienced airline pilots in a Boeing 767 simulator using data from historical microburst events at Orlando and Denver. Associated precipitation reflectivity is included. No critical performance differences were found between display types. A slight performance gain in decision-making ability was noted with pilots using the multilevel icon versus the single level icon. Subjectively, pilots favored the multilevel formats and judged them superior in aiding hazard identification and avoidance over the single iconic display.

Thesis Supervisor: Dr. R. John Hansman, Jr.
Associate Professor of Aeronautics and Astronautics

Acknowledgments

The author would like to thank Professor John Hansman for his guidance, interest, and inspiration in this effort. Additionally, the author is grateful to the members of the Aeronautical Systems Laboratory at MIT who have all volunteered their wisdom and encouragement at one time or another in designing and realizing this simulator experiment. In particular, the contributions of Craig Wanke, Lee Yang, Jim Kuchar, and Dave Rahn were integral to its development. The pilots who volunteered their time and expertise, and those who continue to do so, are worthy of commendation that they will not get as anonymous participants. The understanding and moral support of the NROTC Staff, particularly Lt Chris Waaler, helped make this experiment possible. Finally, the author is especially thankful for the strength and continuous support of his wife Ann and children, Kyle, Cam, and Rory.

Table of Contents

List of Figures

List of Tables

1. Introduction

Despite great advancements in technology, low-level windshear remains a significant threat to commercial aviation. It is a problem that has been researched vigorously from many angles, particularly since the Dallas-Fort Worth crash of Delta 191 in 1985 [Bowles, 1993]. Capable ground-based systems such as the Terminal Doppler Weather Radar (TDWR) have been highly successful at detecting hazardous windshear [Campbell et. al., 1989]. Improved VHF communications and experimental work with new datalink applications have increased the efficiency of alert dissemination [Wanke, 1993].

Recent developments in technology have created forward-look airborne systems capable of detecting windshear and displaying it to the aircrew in real time [Hinton and Oseguera, 1993]. The amount of applicable information readily available to the aircrew using airborne-measuring devices is in most cases significantly greater than that which is communicated to the aircraft from external sources. But, ultimately, the success of any system depends upon the effective communication of the hazard to the aircrew. Is more information necessarily better? Much depends on how it is presented.

Significant research has been done in the field of windshear to examine the issues surrounding detection, integration, and presentation of this data to the aircrew. The Aeronautical Systems Laboratory at the Massachusetts Institute of Technology has been heavily involved in helping to develop guidelines and proposals in the latter two areas [Wanke and Hansman, 1990, 1992, Hansman et. al., 1992, Wanke, 1993]. This thesis is a continuation of that work and seeks to address the possible benefits of certain display designs using airborne-detection equipment.

From their five senses, humans gain 90% of their input from visual sources. Graphical displays best utilize this characteristic without needlessly increasing the high mental workload of today's commercial transport pilots [Wanke and Hansman, 1990]. The proper design of such a graphical display is still open to question. Common sense and equipment capabilities dictate much. Pilot surveys and previous experiments have yielded important information about aircrew desires and tendencies. For standardization, one simple design has been proposed with these ideas in mind. There is still some concern that pilots may not be getting all the information they could use or in the best possible format. This study addresses the issue by comparing three proposed designs across a variety of scenarios.

The main objectives of this study were to:

- Evaluate differences between three proposed graphical windshear alert formats by observing the performance of pilots in a simulation of a variety of scenarios.

- Obtain user information related to the employment of these displays in the form of ratings, preferences, and suggestions.

- Develop possible options and recommendations for the design and use of airborne-measured windshear displays.

2. Background

There have been numerous commercial aviation accidents costing thousands of lives during the last few decades. Of these, the majority can be attributed to pilot error of some sort. Weather-related accidents are the next leading cause and it is low-level windshear that is the major contributor to this genre of accidents. It is unfortunate when human mistakes cost the lives of many but it is, perhaps, even more tragic to know that there were situations where even the most capable pilot could not have changed the outcome of a fateful approach or departure.

Until the advent of major windshear detection systems primarily on the heels of the Dallas-Fort Worth accident, this was the case. After a period of intense development, the field is now burgeoning with proven methods to achieve accuracy, range, and reliability in measuring windshear, and in particular, microbursts. The short-lived, intense, and local nature of a microburst makes the effective translation of a detected threat to the aircrew of critical importance so that appropriate and, sometimes, lifesaving actions may be taken. Airborne-measured windshear methods are now available, allowing access to a large pool of information in a timely manner.

2.1 Windshear and Microbursts

There have been many new developments in the detection of windshear, but the most important factor in safety increases thus far appears to have been the raised level of awareness in the aviation community and the knowledge of what is involved in low-level windshear.

Windshear phenomena generally can be classified into two subdivisions, that of gust fronts and microbursts. The latter begin as pockets of cooler air which form downdrafts leaving the base of cumulus-type clouds. When the downdraft reaches the surface, the descending air spreads out horizontally forming a diverging source whose edges may curl upwards to make tight vortices. Microbursts that have divergences of greater than about 20 kts over a 2.5 nm area are potentially hazardous to aircraft at low level altitude, and low speed or energy state [Merritt, Klingle-Wilson, and Campbell, 1989].

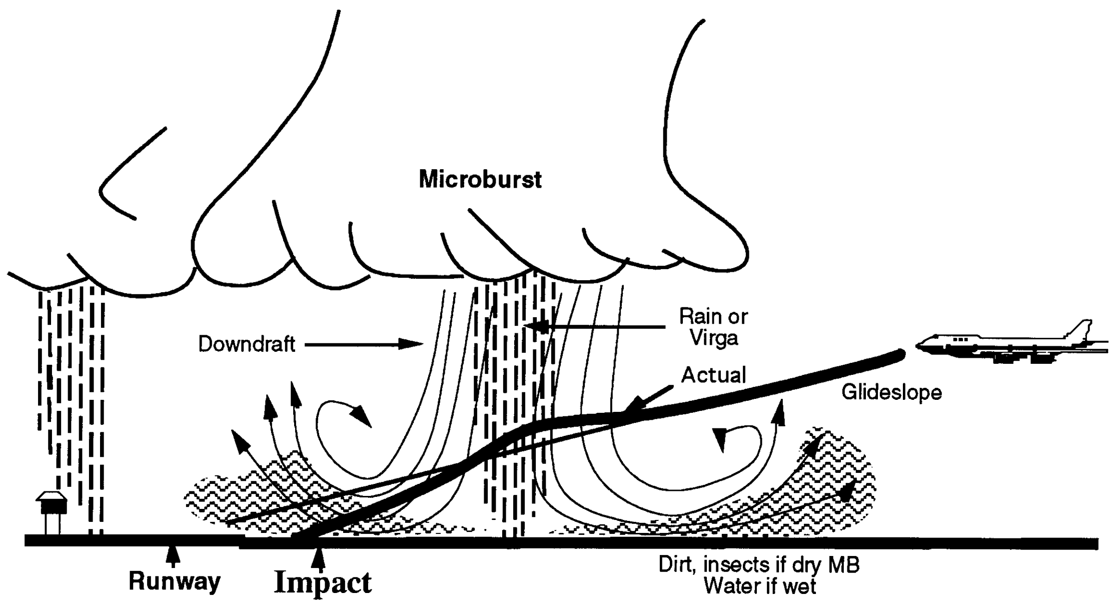


Figure 2.1 The Potential Problem of the Microburst

As depicted in Figure 2.1, the unsuspecting aircraft that encounters a microburst, say on an approach, will first experience a performance increase in the form of a headwind. On an approach this would raise the aircraft above glide slope and/or increase the airspeed necessitating a reduction in power. Upon reaching the central area of the microburst, the decrease in headwind and the main downdraft would impact the aircraft negatively, driving it through the glide slope. Exiting the core the pilot may have increased power but there is a finite time lag due to both recognition and engine spool up. A tailwind begins to build and, if the aircraft does not have sufficient reserve energy, the pilot may not be able to overcome these effects before ground impact.

Microbursts are not easily detected with normal resources. Visual cues such as intense rain or curling dust clouds are available on occasion, but not always noticeable depending upon flight conditions. Frequently, they are accompanied by significant rain or reflectivity ('a wet microburst') but some, more common to the West, have no low-level precipitation ('dry') although virga may be present. The hazardous area of a microburst is generally 0.5 - 2.5 nm in size but groups or lines may form affecting much larger areas. An additional dimension which complicates the detection of microbursts is the time scale over which they grow and decay. Microbursts have been known to increase from a weak downdraft to a strong microburst over the course of one to two minutes [Merritt et. al., 1989]. Their decay is slower and they usually persist for 10-20 minutes. Locating, classifying, and transmitting this information to the pilot is a job that must be done quickly.

2.2 Detection of Windshear

The standard technique for identifying an area of windshear that is still in use today involves at least one aircraft having a notable encounter and the pilot's report (PIREP) of this encounter being used to warn other aircraft. Improvements have been made but the aviation industry is still evolving products to meet the need. Because most small commercial and general aviation aircraft have stricter minimum weather conditions and a lot less people on board, this discussion will deal mostly with transport category aircraft. On board many of these aircraft is a reactive windshear detection system based upon the inertial system which can detect unexpected accelerations. This can be helpful, but its use as an alert is limited due to its post-facto warning.

Ground-based systems such as the Terminal Doppler Weather Radar (TDWR) and the Low-Level Windshear Alert System (LLWAS) have added significantly to the detection capabilities of major airports so equipped. The latter system uses strategically spaced anemometers to detect wind shifts but was designed for large scale phenomena. An LLWAS unit was in place and operating at Dallas-Fort Worth when Delta 191 crashed [Newton, 1989]. It is capable of microburst detection only when specifically adapted and even then it may only be suitable to detect strong microbursts [Wanke and Hansman, 1990]. The TDWR system is reliable (on the order of 85 - 98% depending upon microburst strength) and constantly improving. It is not inexpensive, though, and has been allotted to only 47 airports. For the remaining airports with a need, a modified version of the Airport Surveillance Radar (ASR-9) has shown promise in detecting microbursts. It's vertical fan-shaped radar beam does not have the gain of the TDWR's pencil beam radar, but by using suitable algorithms and numerous sweeps, this can be surmounted [Wanke, 1993, Weber and Noyes, 1989]. Ground-based systems possess some tremendous advantages:

- Equipment power and complexity;
- Time available
- Manpower and expertise
- Knowledge of local weather patterns and recent historical weather

Once this type of information is processed along with applicable pilot reports from the area, the critical step of notifying the aircrews can be accomplished. This can be done via verbal radio contact or datalink systems now in work. The latter method allows for selective notification to those aircraft concerned and can be displayed in graphical as well as textual format.

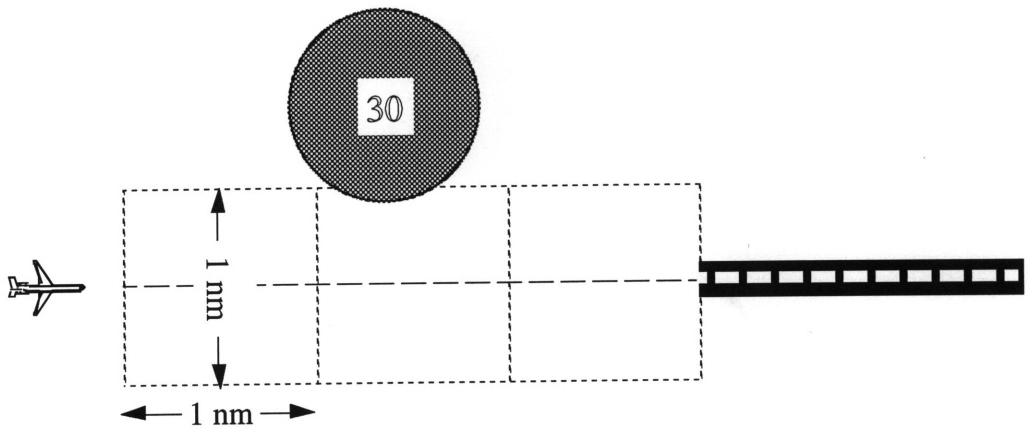


Figure 2.2 A Situational Nuisance Alert: An aircraft on approach will be informed by ATC of a microburst and an expected 30 kt loss of speed, when, in fact, it will encounter little change in performance at all.

The potential for "nuisance alarms" is high and can be as much as one third of all alarms [Wanke, 1993]. Nuisance alarms are alerts about actual microbursts, but their location is such that they have little or no impact on the flight of the aircraft. An alert to aircraft is required if any part of the windshear icon impinges upon an area one-half mile either side of course on the approach and departure ends as in Figure 2.2. The use of graphical icons on Electronic Flight Instrument System (EFIS) capable aircraft enables the aircrew to "see the threat" and evaluate its urgency in the context of their flight.

The recent maturation of airborne detection ability has opened an avenue of great potential. Suitably equipped aircraft would be able to detect microbursts and other windshear on their respective flight paths. The on-board nature of this approach offers many advantages, namely:

- Self-reliance
- A display of hazard commensurate with the aircraft state and abilities
- Availability of pertinent information (e.g. exact location, shape, etc.)
- High update rate

- Aircrew confidence

Sufficient aircrew education and training is required but this is not without precedent (TCAS, for example). Crews are already on step with windshear training and would likely adapt well. This comes with a price -- the equipment itself (reliability and cost) and the quality of output compared to ground-based systems.

The driving force behind this route of microburst detection is the Forward Looking Windshear Detection Working Group. Representatives of the FAA, NASA, and four airline companies worked together with various research organizations and manufacturers to develop certification guidelines. The document is entitled, *Airborne Short and Long Range Windshear Predictive Systems, General Certification and System Level Requirements*, and the current version is Revision 8.0. The document is a working paper and not referenceable at this time. However, the proposed standards therein are the basis upon which certification of at least two companies' products are proceeding. Because predictive airborne detectors are being developed as an improved *alternative* to currently certified reactive windshear detection systems, the requirements are extremely rigorous. As of this writing, neither company has been certified for production although extensive testing has taken place.

The system closest to certification is a Doppler radar design that essentially measures the rate and volume of airflow along a radial from the sensor. This can be seen by radar using the reflectivity of precipitation in the case of a wet microburst, and dust, insects and other particles in the dry case. By using measured air mass dynamics and analytical models, a measure of the hazard level of a particular windfield can be determined. A similar technique is used for Light Detection and Ranging (LIDAR) systems, but is much further from certification. Passive infrared detection systems and millimeter wave radars are also being explored as alternative detection sources.

These sources have their own unique weaknesses and may miss a microburst detection under certain conditions. Doppler radars are vulnerable to dry, low reflectivity microbursts, LIDAR's may miss something under high precipitation conditions, and the infrared requires a set temperature differential that may not be evident at the low altitude elevation sample taken.

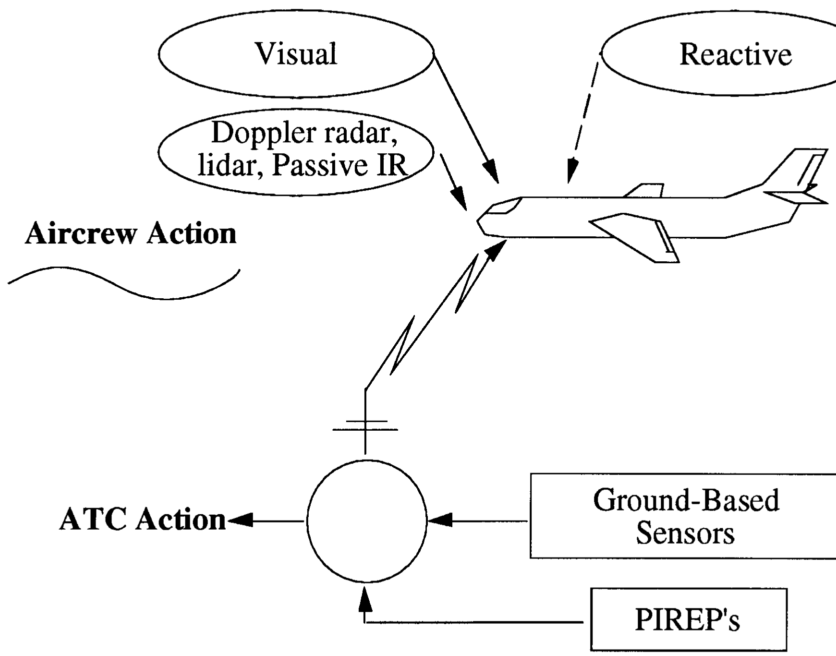


Figure 2.3 Integrated Network for the Detection of Windshear

Airborne detectors need not stand alone, but can aid or be aided by the external sources discussed previously. Surely, the tools are there to build an adequate detection system to cover most situations. In addition to aircrew action, action by ATC is necessary. Approaching aircraft may be rerouted or put into holding. Certain category aircraft may be able to continue while others may not. The integration of ground-based detectors, communications links, and forward looking airborne systems into a successful network is not too far away.

2.3 Quantifying the Hazard

The traditional measure of a windshear hazard's intensity relies on that change in airspeed an aircraft would expect to experience due to the expanding microburst outflow. This divergence as seen in Figure 2.4 is only part of the story since this can be over a large or a small area. The mean shear is determined by taking the maximum divergence (i.e. maximum wind velocities in each direction) divided by the distance between these points. Shear is a significant improvement on divergence as a measure of hazard, and correlates well with actual aircraft dynamics profiles through microbursts [Wanke and Hansman, undated].

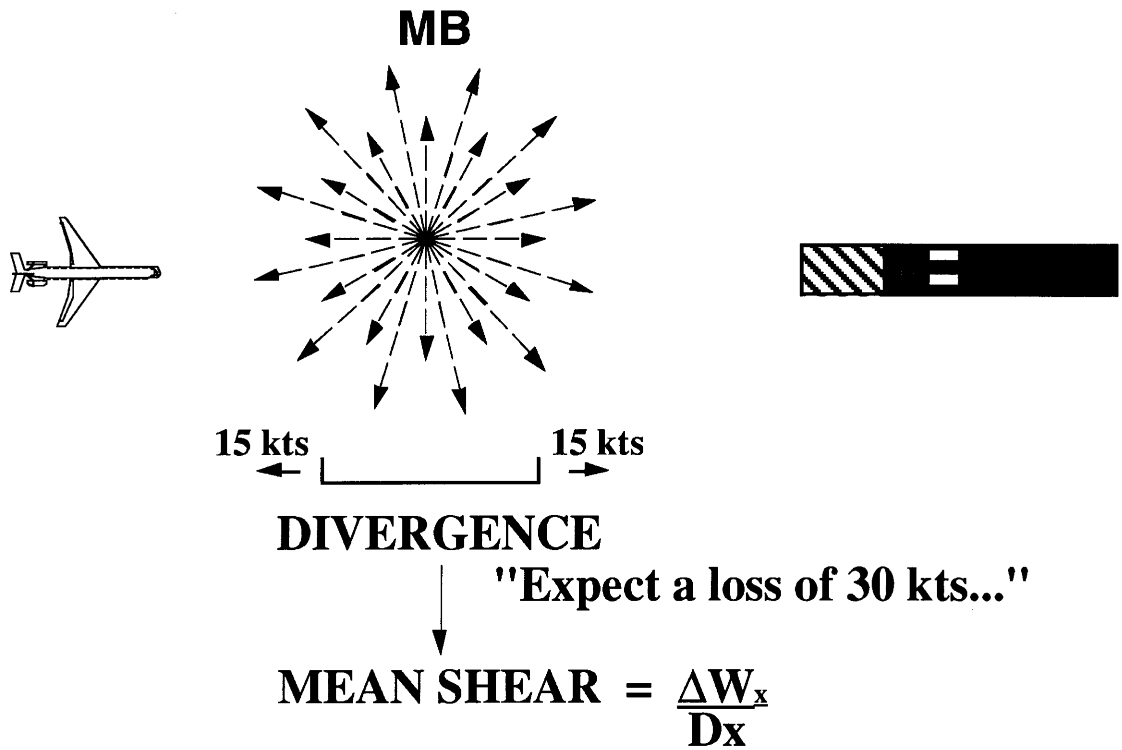


Figure 2.4 Measures of Microburst Intensity -- Divergence and Mean Shear: The maximum points of opposing radial velocity (W_X) form the amount of divergence. This Δ(velocity) over the distance between the points is a measure of mean shear.

A more refined measure, the "F-factor," may be determined using the change in the volumetric outflow rate and the downward flow rate of the microburst [Bowles, 1990]. Based upon standard aircraft dynamics and some assumptions (constant instantaneous aircraft speed, small angle approximations), the potential rate of climb of an aircraft reduces to the product of the excess thrust, less any windfield disturbances, times the aircraft's velocity as in Equation 2.1.

$$\dot{h}_p = V\left(\frac{T-D}{W} - F\right) \qquad (2.1)$$

$\dot{h}_p$ = potential rate of climb

T = Thrust

D = Drag

W = Weight

V = aircraft Velocity

F = F - factor

$\dot{W}_x$ = rate of change of radial Wind velocity along A / C axis (over time), tailwind positive

W_h = vertical Wind velocity, updraft positive where the non-dimensional F-factor is defined as:

$$F \equiv \frac{\dot{W}_x}{g} - \frac{W_h}{V} \qquad (2.2)$$

Equation 2.2 shows that the F-factor takes into account the velocity of the aircraft and the downdraft component in addition to the shear (g is gravitational acceleration). The F-factor, as such, is a measure of the instantaneous loss of available rate-of-climb (or loss of effective thrust-to-weight ratio) due to the immediate windfield. An aircraft with an excess thrust to weight ratio ((T-D)/W) of 0.12 encountering a microburst with a sustained F-factor of 0.15 would be unable to overcome the downward force until it escaped the affected area, or received some "support" from the ground. A typical transport aircraft has an excess thrust-to-weight ratio of 0.10 to 0.18, depending on weight and configuration [Bowles, 1990].

Once again, it is important to consider the time scale involved. An aircraft encountering hazardous windshear for a very short period, and therefore over a short distance, would generally be unaffected on average as with turbulence. In fact, the reactive systems for detection of windshear are not even required to detect hazardous windshear at shear lengths less than 0.21 nm (400 m) [FAA, 1990]. The shear length over which a hazardous level of F-factor must exist to qualify as a hazard is generally regarded to be of the order of 0.54 nm (1 km). The approximation is due to the fact that different algorithms may use varying lengths to achieve the same ends. The detection of windshear with airborne equipment must meet reliability standards in its *ability to detect the shear* in addition to its ability to correctly classify it as a hazard.

The FAA working group's proposed measure of success in this regard is the detection of windshear with F equal to or greater than 0.13 over 0.54 nm (1 km) with a failure rate of less than one in ten thousand. To accomplish this, the detection level must be set lower. The working group has suggested use of F = 0.105 over 0.54 nm (1km) as a detection threshold based on the same reactive windshear alert level [FAR, 1990]. "Long range" predictive windshear detectors must be able to meet this criteria three nautical miles from the aircraft and with a Doppler radar sweep of at least 25 degrees to either side of the nose.

With the single source airborne detector, only the portion of microburst outflow that is moving radially to the sensor is visible. NASA researchers have proposed that the magnitude of the downdraft can be inferred by use of algorithms based on the Oseguera, Bowles model [1988] with modifications by Vicroy [1991]. Inaccuracies from asymmetric microbursts and approximations of the algorithm are still present.

2.4 Display of Hazardous Windshear

2.4.1 Prior Work

A microburst that is detected is only half the battle. The aircrew must take appropriate action in one of two ways:

1. Totally avoid the encounter area.
2. Avoid a low aircraft energy state by initiating a recovery prior to entry into the microburst.

In order to do so, it is important to quickly and effectively communicate the presence of a windshear threat so that evaluation and actions can be implemented. Work done by Hinton and Oseguera [1989, 1993] of NASA Langley points to predictive displays necessarily yielding 20-25 seconds of warning. Pilots with 10 seconds of prior warning were able to recover from test microburst simulations with negligible altitude loss. The alert time includes 5-10 seconds for aircrew recognition and action time

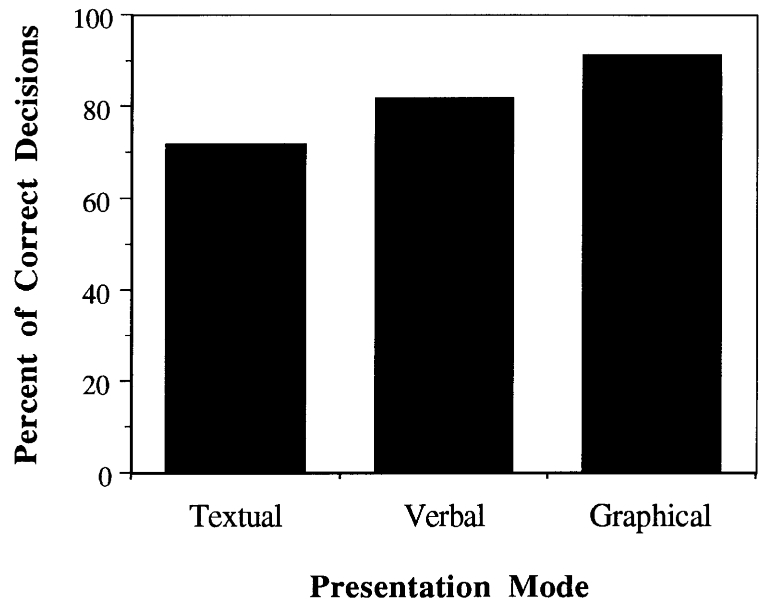


Figure 2.5 Part-Task Simulation Results: Response performance to windshear alerts by mode. Reproduced by permission of the authors [Wanke and Hansman, 1990].

To aid in the process of aircrew recognition a variety of formats have been tested. In tests presupposing ground-based sensors (and therefore larger warning distances), Wanke and Hansman of MIT [1990] were able to conclude that graphical displays were superior to either textual or verbal alert formats. Circular graphical icons were found to decrease the pilot workload, increase performance (see Figure 2.5), and were highly preferred by the pilots over the other formats. Pilots were found to avoid contact with displayed icons by large distances even when at high energy states or the intensity level of the icon was well below hazardous levels.

A survey of pilot opinion on a broad range of windshear topics revealed that pilots were most interested in location of microburst hazards, followed closely by intensity (see Figure 2.6). Microburst size, movement, and intensity trend were of secondary importance. A follow-on study produced subjective evidence that supported the use of multilevel alerts, signified by color differences [Wanke and Hansman, 1992]. Pilots in this study were found to abort their approaches at an average decision distance of 4.26 nm from the hazard.

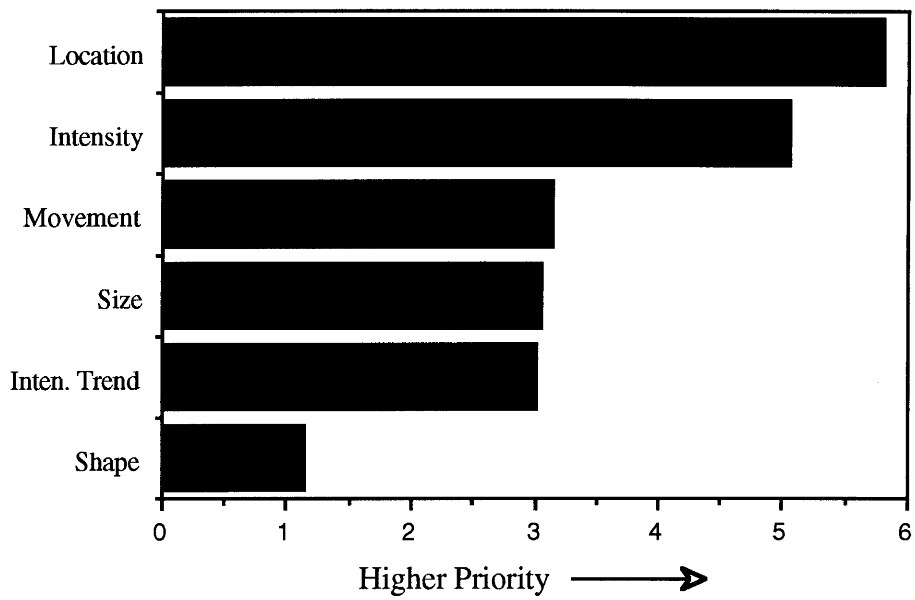


Figure 2.6 Pilot Ranking of Microburst Information by Importance: Reproduced by permission of the authors [Wanke and Hansman, 1990].

A study of windshear alerts by Oseguera and Hinton was done in 1993 using an aural alert alone, a constant color icon, and an icon that changed color in relation to its proximity to the aircraft. Preliminary results indicated that pilots were highly in favor of the two graphical formats. Analytical models of aircraft attempting to turn away from microbursts indicate that turns initiated inside of 1.5 nm yield no performance gains over those that recover straight through them. The pilots in this study also tended to avoid displayed icons even when a straight-ahead missed approach would have maintained as much energy and avoided possible airspace conflicts.

2.4.2 Alerts and Warnings

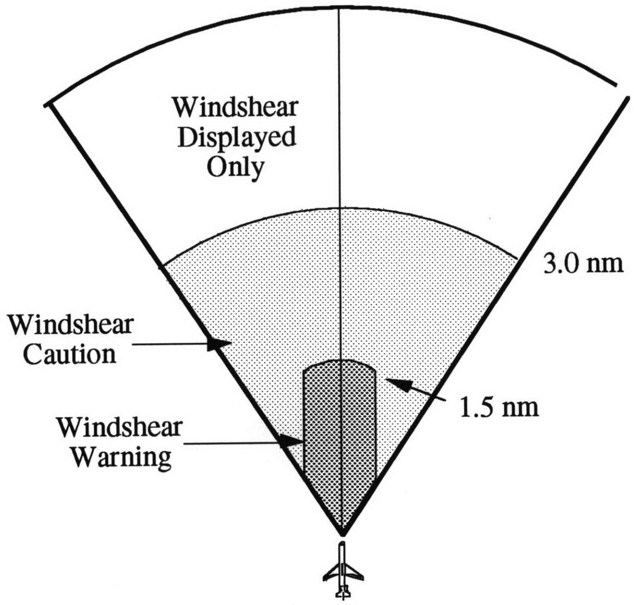


Figure 2.7 Airborne-Detected Windshear Warning and Caution Areas

The 20-25 second predictive warning time naturally sets an approximate boundary for getting the aircrew's attention. At 200 kts or less this is about 1.5 nm which is the proposed distance to execute a windshear warning should the aircraft come that close. A warning corridor 1.5 nm out with lateral distance of 0.25 nm to either side of the aircraft's centerline conservatively takes into account maneuvering and location tolerances [Hinton and Oseguera, 1993]. The forward looking working group proposed an alert or windshear caution be issued when windshear above the hazard level is within 3 nm of the aircraft but outside the warning corridor. Aircrew will then be able to take action, if necessary, before a warning situation is entered. The different areas are depicted in Figure 2.7. To carry out the process of ensuring aircrew attention, the windshear warning consists of a red light on the instrument panel with the words "windshear ahead" displayed and an audible of those words said twice. The windshear caution or alert uses a yellow light with the same words and two "attention" sounds.

2.4.3 General Formats

On those airborne systems that will have displays, certain common characteristics have been proposed by the working group. The area scanned by the Doppler radar is broken down into small sectors or cells by azimuth and radial determined by the resolution characteristics of the radar. Within each cell, a local F-factor is calculated by finding the shear due to velocity differences in adjacent radial cells and applying the NASA algorithm [Vicroy, 1991]. As Figure 2.8 suggests, the average of the F-factors in cells along a radial can then be found to assign a value to that cell in the center, the distance covered by the cells being approximately 0.54 nm (or 1 km). In this way, an F-factor "mapping" or Fmap can be made. Using different threshold values, a contour Fmap can be formed including areas of significant shear below the hazard level and areas of intense hazardous shear above it.

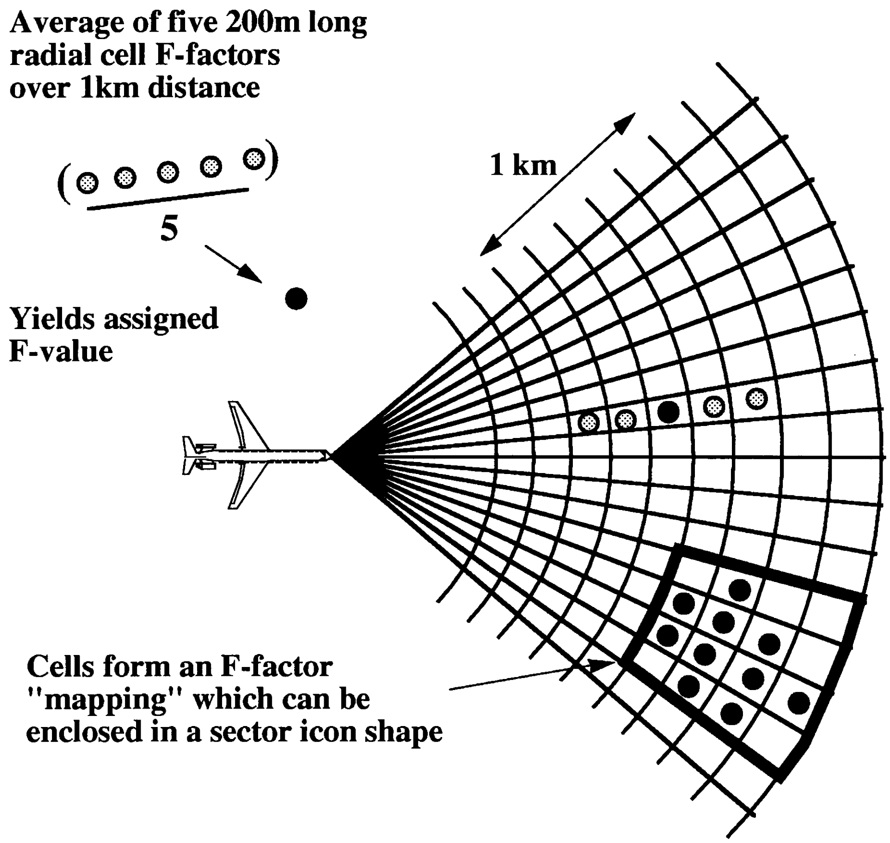


Figure 2.8 Formulation of an F-factor Map and Icon: Dark circles depicted are all cells with an average F-factor value above hazard threshold.

The nature of the airborne radar makes selection of a sector shape an obvious icon choice. A sector encloses all cells above a certain threshold value in an area, encompassing perhaps two or three areas a small distance apart depending upon the algorithm. If the sector covers windshear above the hazard threshold, it is colored with red and black bands for display on either a dedicated, time-share, or overlay on the Electronic Horizontal Situation Indicator (EHSI). An example can be seen in Figure 2.9.

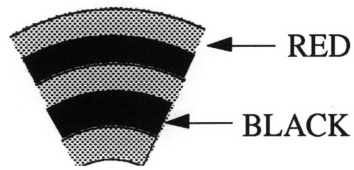


Figure 2.9 Single Intensity Level Sector Icon Above Hazard Threshold: The FAA working group has proposed this format to be used in those windshear detection systems that use graphical displays. Areas below the hazard threshold would not be displayed.

3. Experimental Method

3.1 Overview

In order to most efficiently determine the important differences between display types, a simulator study was chosen. Professional airline pilots currently on active duty were engaged to fly a number of approaches on a part-task simulator using three different graphical displays in successive sets of runs. As an observational study of possible displays and their effects, common but challenging windshear situations were designed to examine pilots' reactions. The approaches included various scenarios in which hazardous windshear often occurred but was not always hazardous to the flight.

The general format of the test involved presenting the pilots with a low-level windshear hazard, specifically, a microburst, on or near the projected flight path. In two of the three scenarios the microbursts were dynamically changing in time. Each pilot was faced with a potentially dangerous situation in which he had a limited amount of time to respond. The ability of the pilot to recognize the location, intensity and associated trends of the microburst impacted his decision about continuation of the approach. The performance of the pilots was gauged by the decisions that were made, the timeliness of those decisions, and, in the case of an aborted approach, their subsequent actions. Subjective results were obtained through interrogation of the pilots after the runs for each type of display were completed and with an overall post flight questionnaire.

3.2 Dependent Measures

There were three primary measures of the effectiveness of the windshear display. The first was the pilot's initial go/no-go decision concerning continuation of the flight. When a missed approach was made, the hazard-to-aircraft distance at which the decision took place was also a measure. A third measure was the closest point of approach (CPA) of the aircraft to the hazard in the course of the abort.

The scenario was designed to differentiate the decision-aiding capabilities of the displays in two ways. The first was to see if confusion or misinterpretation caused a significant number of pilots to get into a dangerous situation, or conversely, avoid an area completely whether or not there was an actual danger. The second aspect, tested in one specific scenario, was meant to examine how well trends in the intensity of a microburst were noticed using the different displays.

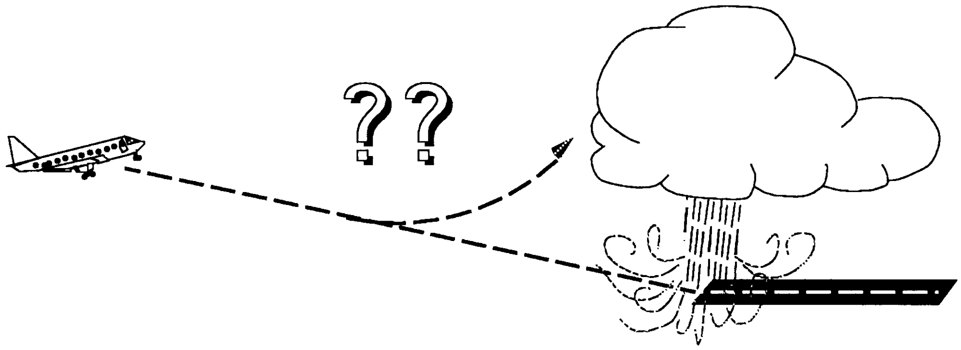


Figure 3.1 Missed Approach Dependent Measure

The distance from the leading edge of the microburst at which a decision to abort the approach occurred was recorded to note differences between displays. In previous studies using ground-based detection alerts at ranges of seven to ten miles or more [Wanke and Hansman, Oseguera], pilots were reluctant to come towards an area of windshear and aborted the approach early on. Generally, with the shorter alert distances of airborne detectors (inside five miles), it was considered better to have made such a decision further out from the windshear hazard, thereby conserving the aircraft's energy, allowing more options, and safer flight.

The measure of closest point of approach relied on the pilot's previously established desire to avoid the windshear area totally [Wanke and Hansman, 1990]. A greater distance between the aircraft and hazard was therefore a measure of how much a certain display may have helped a pilot in achieving that goal, although that may not necessarily be better for safety of flight. Turning within a certain distance (dependent upon microburst strength, configuration, angle of bank, etc. but nominally about 1.5 miles), yields no more benefits in aircraft performance than it would experience on a straight-ahead go-around [Hinton and Oseguera, 1993]. The general impact of an abrupt turn on the ATC pattern and potential obstacles on the new pathway also weigh against it.

Pilots in past studies attempted to acquire larger separation distances the more intense a hazard appeared [Wanke and Hansman, 1992, Oseguera, 1993]. Therefore, it was important to ascertain the pilot's motivating factors in executing a missed approach. Combinations of the variables, if the differences were significant between displays, would reveal more concerning their respective advantages and disadvantages. For instance, a combination of shorter decision distances but larger CPA's would indicate that the pilot had to resort to excessive movement of the aircraft to achieve the desired result.

3.3 Independent Variables

3.3.1 Display Formats and Characteristics

The independent variables consisted of the display formats and the scenarios in which the formats would be seen by the pilots. The three display types tested in this experiment were:

- **Fmap** -- An F-factor mapping using the average F value over a radial distance of 750 meters to depict two levels of intensity.
  (1) $F > 0.105$ RED
  (2) $F > 0.06$ YELLOW - Subordinate to red areas
  An example of the Fmap appears in Figure 3.2. The aircraft is at five miles from touchdown, 140 knots IAS.

- **Single Icon** -- A red and black iconic sector similar to that proposed in the draft document by the FAA Certification Team. The icon encompasses the area of red F-factor, with only a single minimum level of hazard intensity. An example of the Single Icon is seen in Figure 3.3. Identical weather and aircraft conditions as in Figure 3.2.

- **2-Level Icon** (or Multi-Level Icon) -- An iconic display similar to the Single Icon with the addition of a lower level of displayed windshear encompassing that of the yellow area of the Fmap. An example of the 2-Level Icon appears in Figure 3.4 with the same conditions as the other two display figures.

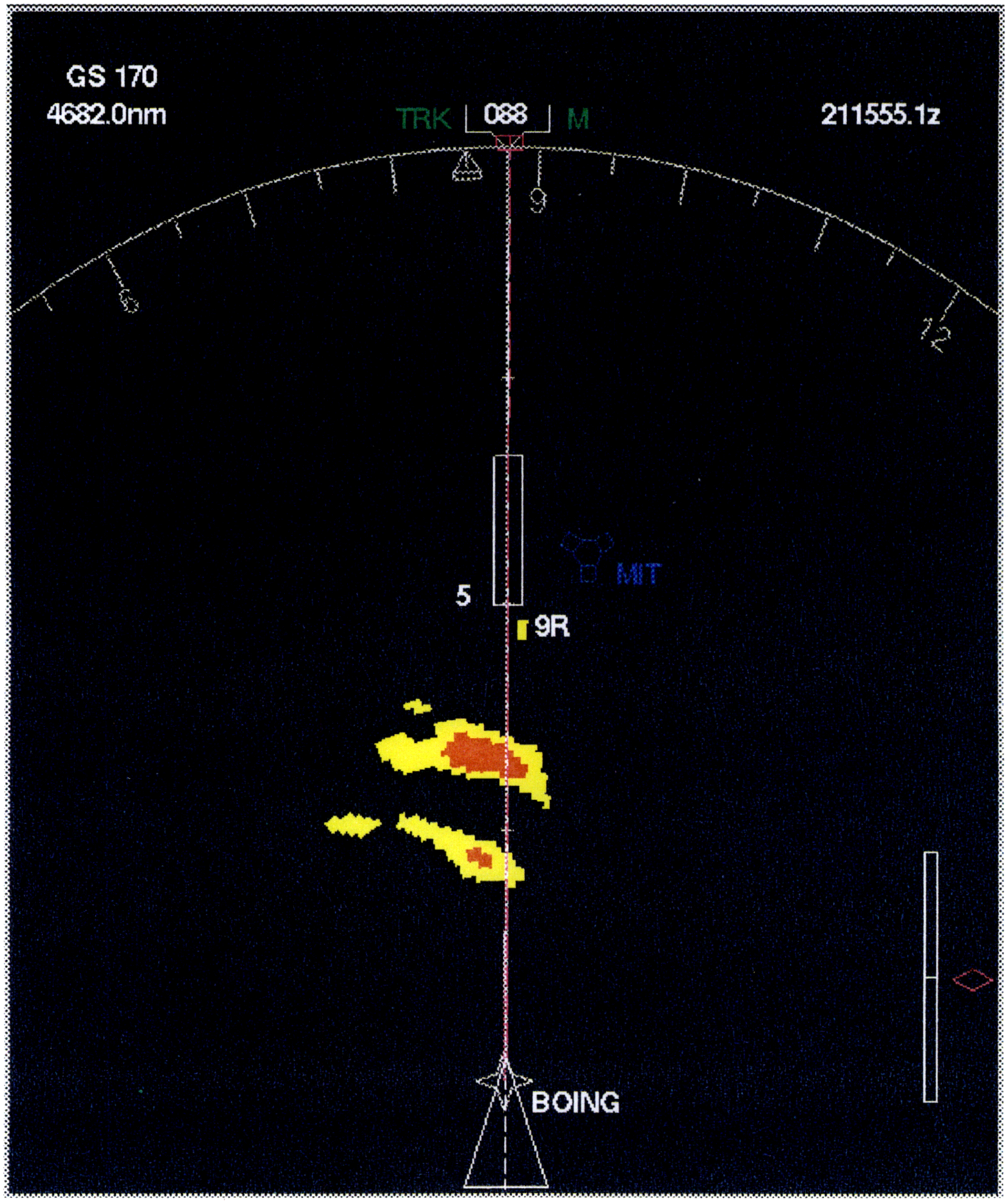


Figure 3.2 Fmap Display: Two levels of windshear intensity according to average F-factor values are displayed. The red portrays F > 0.105, above the FAA hazard criterion. F> 0.06 is also painted.

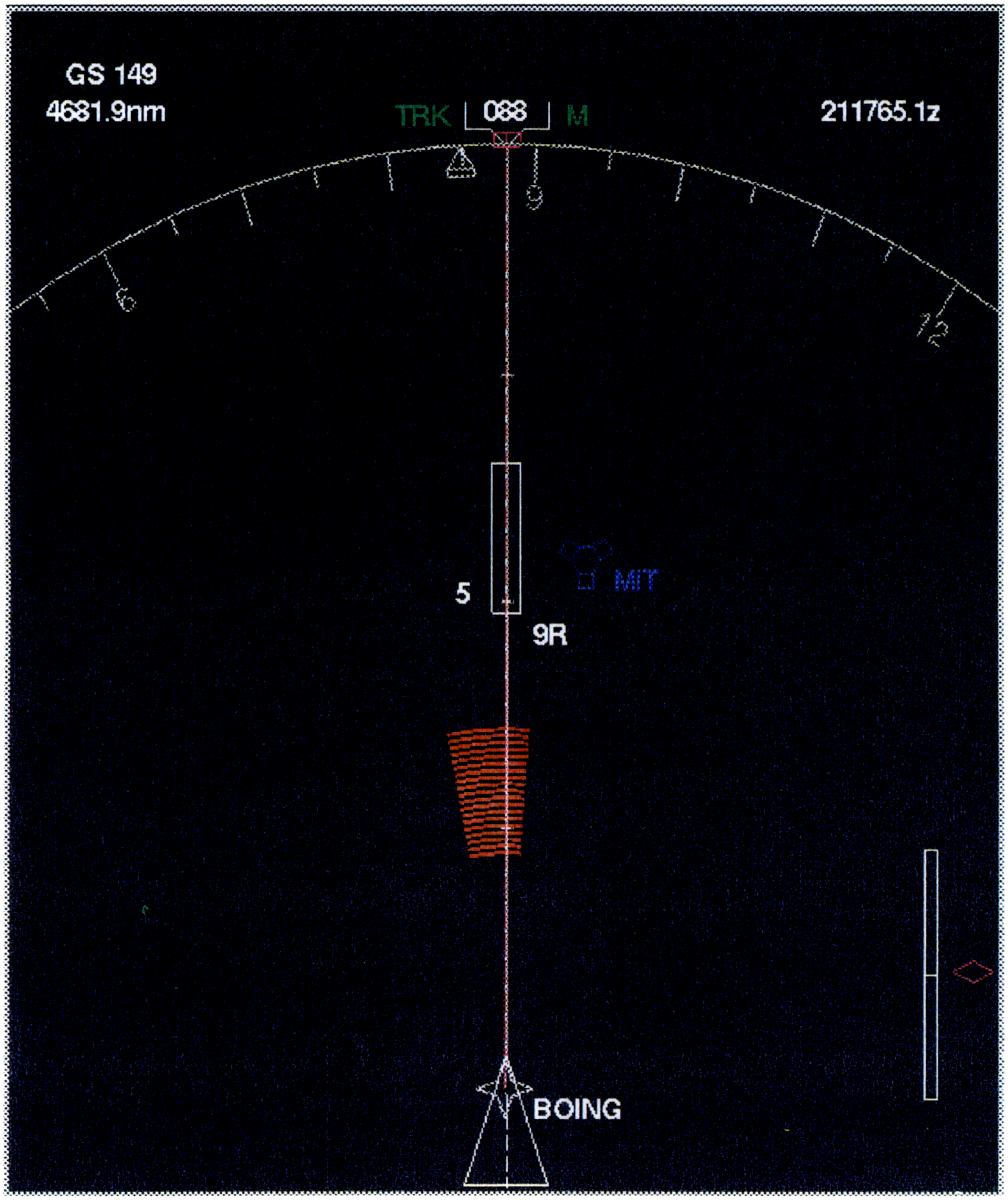


Figure 3.3 Single Icon Display: Hazard level F-factor values contained in iconic sector shapes.

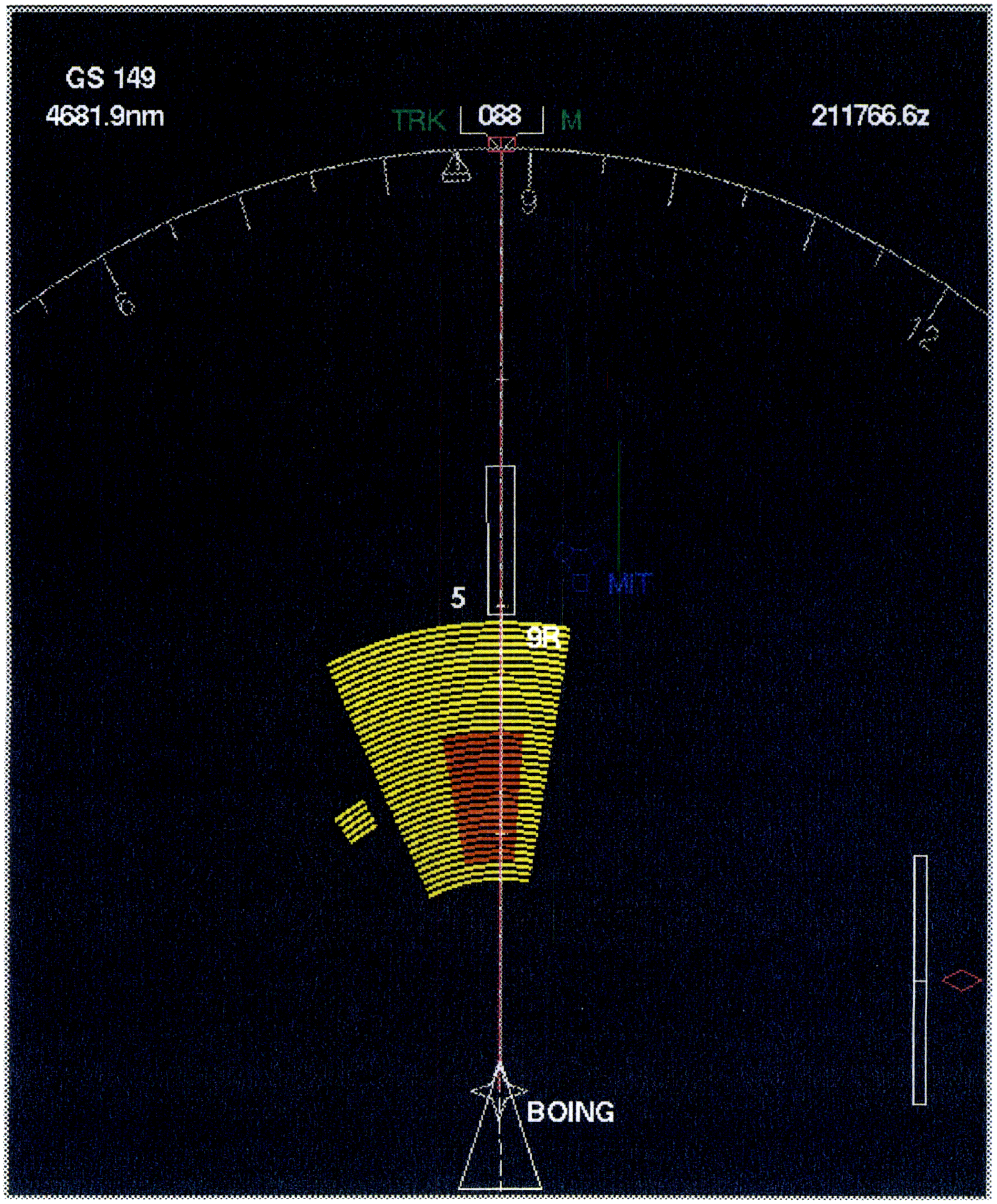


Figure 3.4 2-Level Icon Display: Both the yellow advisory level and red hazard level F-factor values contained in iconic format.

New "long range" airborne windshear detectors are required to detect windshear at a minimum distance of three miles with a view at least 25 degrees to either side. For the simulator, maximum range was set to be under 10 miles with a nominal detection distance of approximately half that depending upon scenario. The radar scan for the simulator was expanded to 90 degrees either side of the nose for clarity with an update rate of one sweep every four seconds.

Resolution of the radar was assumed to be 490 ft (150 m) in range and 1.5 * degrees in azimuth. F-factor was averaged over a radial distance of 0.40 nm (750 m), or five cells, vice 0.54 nm (1 km) to maintain a well-defined microburst for the purposes of this experiment. A larger distance would have put the hazard level (in some time steps) below the threshold if the pilot chose to fly at higher speeds, thereby confounding the data. To avoid noise and unwarranted alerts, individual cells above the threshold average F-factor level that had no similar adjacent cell were disregarded.

The mapping of the average F-factor formed the basis for all three display formats as outlined in Section 2.4.3. The Single Icon format used a sector-shaped area to define the boundaries of the most intense F-factor ($F > 0.105$) both in range and azimuth. If there was overlap between two separate areas of windshear along a radial, both were included in a single icon as seen in Figure 3.5. Although this method was not as accurate in showing location, it was a worthwhile compromise to maintain a less confusing hazard picture, and logical to assume that a radial heading that went through a microburst was not a safe pathway. The same rule held true for the 2-Level Icon algorithm.

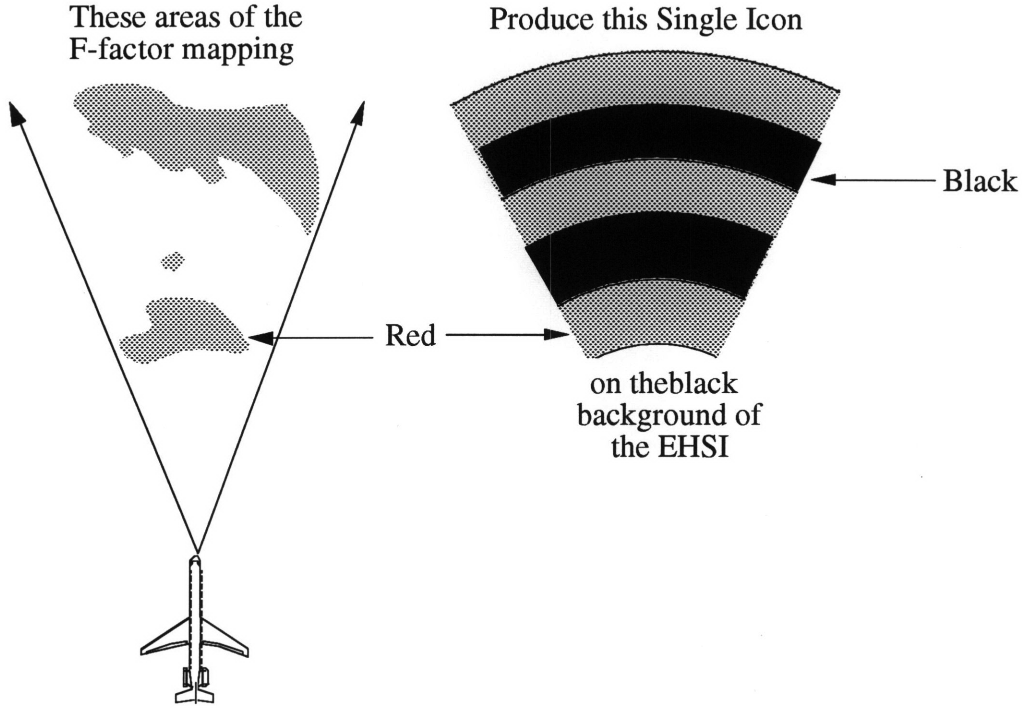


Figure 3.5 Icon Generation Scheme: Areas above the threshold intensity on the Fmap were encapsulated in a single iconic shape unless separated by azimuth along a radial line.

3.3.2 Scenarios

These displays were employed in three scenarios designed to evaluate display performances in a variety of operational situations. (See Figure 3.6)

- **Scenario I** -- Straight-in approach with a building microburst across extended centerline

- **Scenario II** -- Dog-leg or angled approach with a diminishing microburst, allowing a safe landing

- **Scenario III** - Boxed approach with a hazardous static microburst just inside the outer marker on centerline

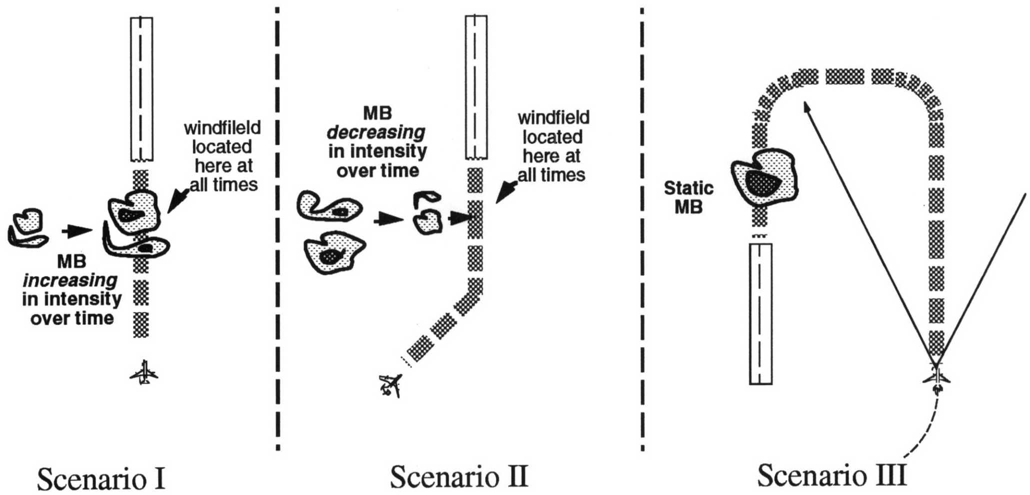


Figure 3.6 Windshear Scenarios

In addition to the three microburst scenarios, a control scenario was included without any windshear activity present. This reduced the pilot's anticipation of windshear and imparted a greater variety to the mix of scenarios.

The scenarios were crafted in an attempt to force the subject into a decision point and to resemble realistic situations in terms of verbal alerts, approach criteria, precipitation and windshear. All of the airports utilized were aliases of actual airports and approach plates. The names and superficial properties were changed to avoid biases and associations that pilots may have had about a particular field (e.g. Denver and dry microbursts). There were 12 separate approaches flown to 12 "different" airports. Of these there were actually four prototype airports, one per scenario. Three versions of each prototype were made, identical in all of the salient features including the aspect angle on the microburst.

Of the situations with windshear displayed, three of the runs depicted a dynamic dry microburst building in intensity, another three had a static microburst with heavy rain and the third consisted of a diminishing dry microburst. Scenarios I and III had hazardous windshear with an expected missed approach at some point. The latter was an obvious and immediate case, while the dynamics of scenario I left room for interpretation during the encounter. Scenario II had a windshear area that decreased in strength until it was ultimately gone by two miles, allowing a safe landing. The remaining three runs had no windshear warnings whatsoever and consisted of approaches similar in nature to that shown in the other three. These were interspersed within each set.

The dry versus wet microbursts differed in that both had reflectivity but the wet microbursts level of return was much more intense. The dry microburst occurred with relatively high cloud ceilings which were simulated in the out-the-window view. The physical make-up of both types were reflected in their respective data, the dry ones generally being tighter in downdraft diameter [Bowles, 1990].

A representative approach plate, accompanying ATIS, and controller communications for each of the scenarios can be found in Appendix A.

Scenario I

In Scenario I ample opportunity to view the developing hazard was afforded the pilot by activating the display with over five nautical miles separation between the aircraft and the microburst. A straight-in approach aided in focusing the pilot's attention. The multiple dry microburst event from Denver was placed between the outer marker and the landing zone as in Figure 3.2. The precipitation display showed a mild return with increasing reflectivity over time.

The initial location of the main hazard was slightly to the left of course, three mile from runway threshold. The aircraft was below the cloud layer and able to see the runway. This made trust of what the display was showing a slight factor. Gradually, the microburst hazard built up across the centerline and eventually another cell appeared at the runway threshold. By then, all pilots were expected to have aborted or made an unrecoverable heading change. A difference in decision distances and any continuations into windshear were the main factors expected in comparing displays.

The ATIS information contained a large temperature - dew point spread and similar ceilings and winds to that reported in Denver that day. A generic announcement stated that, "microburst and low level windshear advisories are in effect." Winds at the runway shifted slightly with the development of the microburst. A wind vector on the EHSI was noticeable inside of 2.5 nm.

Scenario II

Scenario II placed the pilot in the position of choosing between an approach abort or continuation. The same Denver microburst from Scenario I was utilized but in the reverse order with one minute time steps. Additionally, the general weather conditions were less than the actual event to maintain IMC through the encounter. A small microburst was located on centerline just over a mile from the runway threshold. Indications of the microburst appeared three miles in front of the aircraft as it descended below 1500 feet AGL, after the turn to final. The hazard gradually diminished over the next 25 seconds in intensity until it was below both red and yellow F-factor threshold values. The ability of a display to communicate a trend in a timely fashion was the main factor that was contrasted.

A typical ATIS announcement consisted of:

> "...Johnson weather: measured ceiling 700 foot overcast, visibility five miles. A line of thunderstorms exists extending from 20 miles southwest of Brownsville to Corpus Christi, Texas moving east at 15 knots. Microburst and low level windshear advisories are in effect...."

Enroute to the final heading on this angled approach, the pilot was involved in navigating through a line of rainshowers such that there was lessening of anticipation when one more was found close to the final approach fix.

Scenario III

The Orlando event was used as an immediate decision missed approach situation. The aircraft was required to make a rough box pattern to final after departing holding. It was hoped that a difference in displays would be noted in decision distance and commented upon subjectively. This would be due to peripheral advantages and/or the ability to immediately convey the threat. An example of a Scenario III flight route can be seen in Figure 3.7.

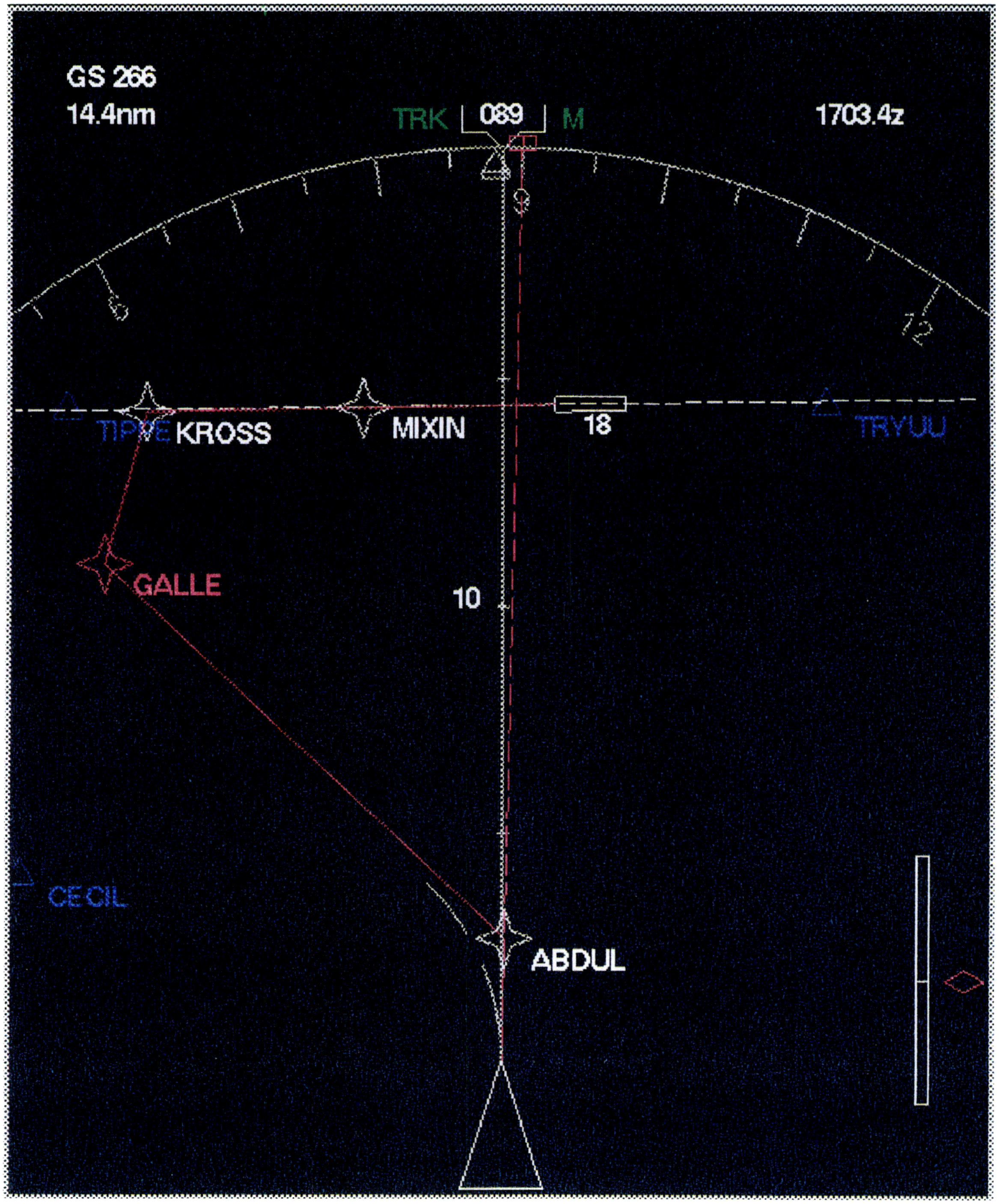


Figure 3.7 Scenario III as Seen from Holding: Vectors were given to place the aircraft on downwind and base leg to intercept a 7-8 nm final. The leading edge of the static microburst was located just inside of MIXIN.

3.3.3 Test Matrix

Table 3.1 Order of Displays by Subject: Each subject had three sets of runs, one for each display type. Within each set were four scenarios for a total of 12 runs.

		SUBJECT #					
S		1	2	3	4	5	6
E	1	Single	Fmap	Single	2-Level	2-Level	Fmap
T	2	2-Level	Single	Fmap	Single	Fmap	2-Level
#	3	Fmap	2-Level	2-Level	Fmap	Single	Single

The three display types were counterbalanced across the four scenarios, requiring six experimental subjects with 12 runs per session. The scenarios and the versions of each scenario were chosen at random without replacement using a table of random numbers and various stocks/futures prices for initial points. The resulting order of displays can be seen in Table 3.1 as well as an example one subject's session in Table 3.2.

Table 3.2 Total Run Order of Subject #1
(Scenario "0" signifies an approach without windshear.)

Display Type	Scenario	Version
Single Icon	I -- Straight-in, Increasing MB	2 -- Anamary Airport
	III -- Boxed approach, Static MB	1 -- Murmanburg Airport
	0 -- No MB	1 -- Billson County Airport (Angled)
	II -- Angled Approach, Decreasing MB	1 -- Johnson Airport
2-Level Icon	I	3
	II	2
	III	3
	0	3
Fmap	0	2
	I	1
	II	3
	III	2

4. Experimental Protocol

4.1 Equipment and Facilities

The design of the experiment centered around use of MIT's Advanced Cockpit Part-Task Simulator. Since the focus of the experiment was on the decision-making process and not on the mechanics of flying (through windshear, for example), the use of a part-task simulator was deemed acceptable. The simulator's modern "glass cockpit" design allowed incorporation of the elements of forward-looking airborne windshear displays into the pilot's instrument panel without deviating from the familiar.

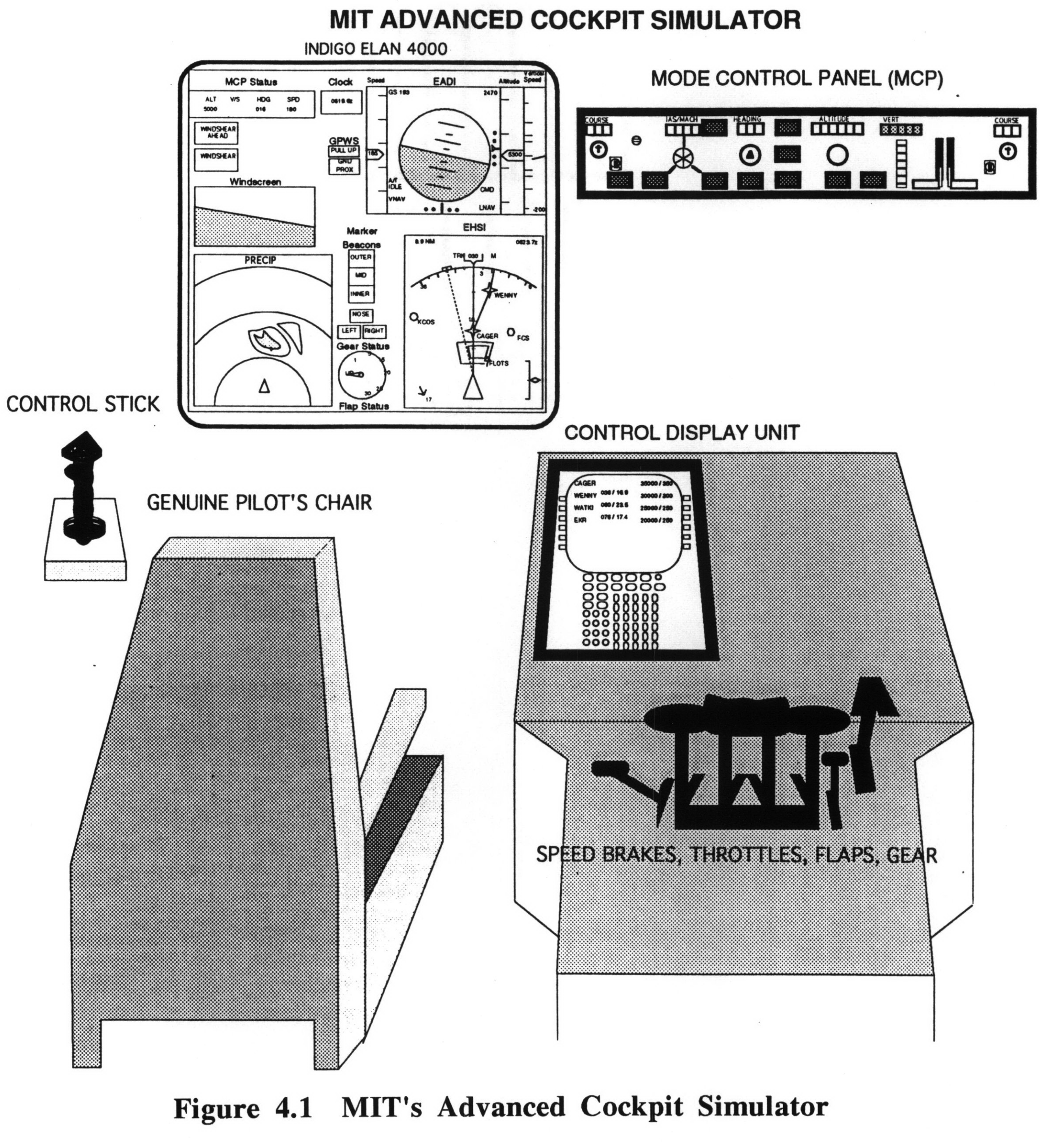


Figure 4.1 MIT's Advanced Cockpit Simulator

The simulator consisted of the flight display of instruments, status and warning lights and the external controls. The external devices available to the pilot included a Boeing 737-400 Mode Control Panel (MCP), flap and gear controls, a navigation control panel and a sidestick for manual flight as shown in Figure 4.1. The bulk of the approach was accomplished using the autopilot through MCP control. Pressing a button on the sidestick disengaged the autopilot and allowed manual flight. The sidestick was employed only in the case of a go-around. The use of the autopilot in the initial phase of the approach assured that all pilots viewed the same weather scenario.

The flight instrumentation depicted an electronic attitude direction indicator with appropriate altitude and airspeed information to serve as a primary flight display (PFD). The windshear information appeared on the electronic horizontal situation indicator (EHSI) with flight path and navigation symbols overlaid. The normal range control selections of 10, 20, 40 nm, etc. were available.

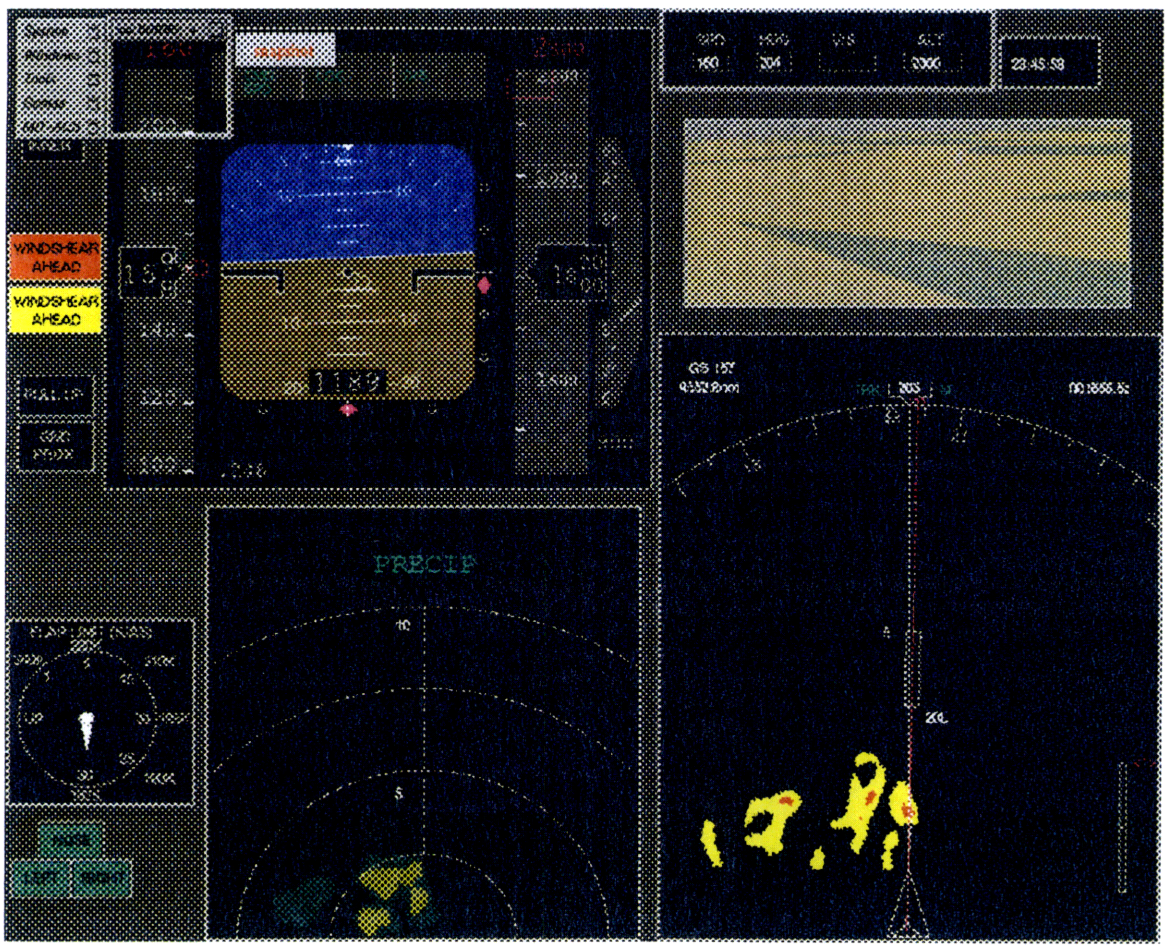


Figure 4.2 Instrument Panel as Depicted on Computer Workstation

The precipitation or weather reflectivity radar display was a separate display to remove confounding factors concerning combined weather and microburst displays and to maintain consistency across pilots of all airframes. This display scope was slaved in range to the EHSI. A wind vector also appeared on the electronic horizontal situation indicator for local wind speeds greater than 15 knots. An out-the-window view was present, essentially affording the assessment of IMC/VMC status and whether the airport was in sight. No visual cues of windshear were available in the visual display. Other necessary elements such as flaps and gear indications, warning lights, etc. were also present (see Figures 4.2 and 4.3).

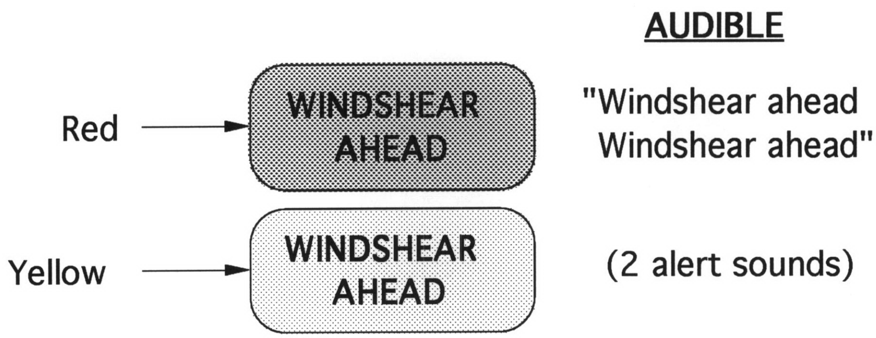


Figure 4.3 Instrument Panel Windshear Warning Lights: Necessary visual and audible alert and warning to call pilot's attention to the windshear situation. Reactive windshear sensors enunciated by voice and light on PFD.

The central control of the simulator resided in software processed by a Silicon Graphics Indigo workstation. This was, in turn, hooked up to a Silicon Graphics IRIS 4D graphics workstation and an IBM 386 to act as the flight management system and to process inputs from external devices. The Indigo performed the bulk of the work by controlling the flight dynamics, displays and the extensive processing of raw weather information. The flexibility of the MIT Advanced Cockpit Simulator due to its "ground-up" software design allowed for numerous configurations changes. Software to calculate, update and realistically present microburst and precipitation information was developed expressly for the purpose of this experiment.**

** The credit for the majority of this work belongs to Craig Wanke, PhD 1993.

4.2 Microburst and Precipitation Data

The windshear scenarios in this experiment incorporated the use of Doppler radar field data and analytical simulation from two historical microburst events**. These data served as a realistic basis for the calculation of F-factor and its subsequent display in the graphical formats tested. Additionally, the actual effects of the windfield on the aircraft could be approximated by inclusion of the appropriate terms in the aircraft dynamics equations. The accompanying reflectivity was also used, lending fidelity to the precipitation radar display as well.

The windfield data from the July 11, 1988 windshear event at Denver-Stapleton Airport was generated through the TASS (Terminal Area Simulation System) of NASA [Proctor, 1987]. Four time steps of this dry multi-microburst event were utilized as a group. The second source of data was from Triple Doppler Radar data recorded by MIT's Lincoln Lab of a July 7, 1990 event in Orlando. A single snapshot of this wet microburst with heavy rainfall was used. In order to be able to process this data as an airborne Doppler radar with its inherent limitations, the vertical component of the microburst windfield was estimated using the Oseguera-Bowles Model [1988] with modifications by Vicroy [1991]. The windfield and reflectivity data were interpolated between time steps and between altitudes to yield estimated values in respect to aircraft time and position. Recent work by Dr. Craig Wanke was central to the integration of all resources.

The time steps from the July 11, 1988 event were two minutes apart. In order to accentuate the dynamics of the microburst, they were used at 30 seconds apart in the case of the building microburst, and one minute apart in the opposite order for a diminishing microburst. Ultimately, the winds were decreased further in the second case since no more time steps were available. This was not a direct replay of recorded events. At any one time, the displays presented actual raw weather data consistent with observed microbursts.

Two sets of precipitation were displayed on the weather display. The first was the actual reflectivity which accompanied the microburst windfield. In addition, secondary non-microburst precipitation cells were included in graphics files modeled on the shapes,

** This was only possible due to the work of several researchers [Proctor, 1987, Oseguera and Bowles, 1988, Vicroy, 1991, Wanke, 1993, Lincoln Lab, MIT] and a powerful computer.

sizes and intensities of the various windfield reflectivities. Combining the two sources reduced a subject's ability to predict the hazardous area a priori and provided practical distractions enroute. An example can be seen in Figures 4.4.

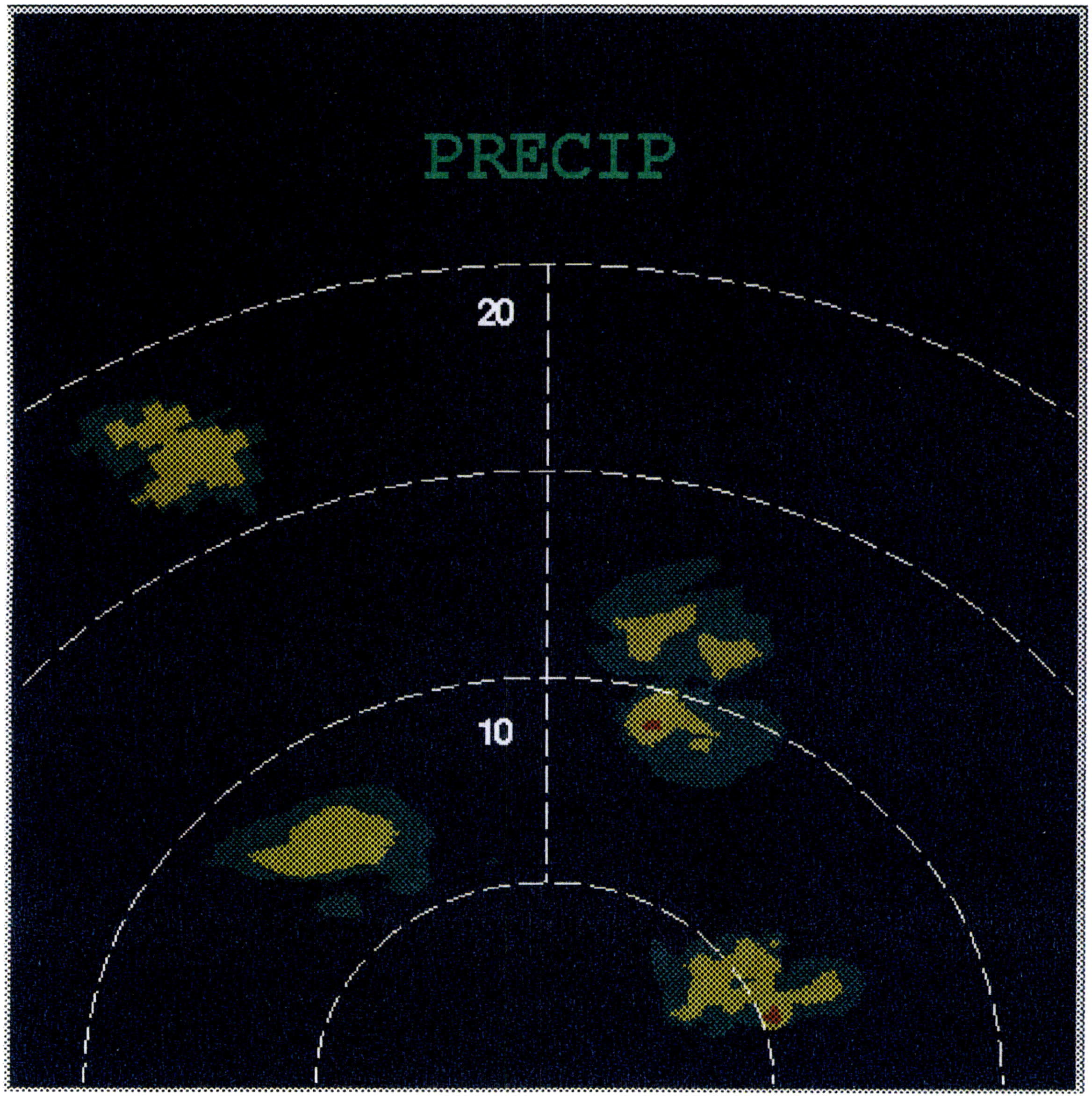


Figure 4.4 Reflectivity from Scenario II: As seen approaching the IAF on a 20 nm display. The return in the upper left is reflectivity from the microburst location.

4.3 Subject Selection

Six volunteer subjects participated in the study during a three week period in March-April 1994. All six were current airline pilots qualified in a variety of aircraft types with an average flight experience of 8500 hours. All had flown the Boeing 757/767 at some point and were using the "glass cockpit" in their current aircraft model. Three other pilots had participated in preliminary runs and evaluations and were similarly qualified. Information on their experience level can be seen in Table 4.1. Four of the six estimated their regular flying duties to include areas known for thunderstorms and windshear more than 10% of the time. All had experienced moderate low level windshear and five had been in a severe low level windshear situation at least once.

Table 4.1 Subject Experience Summary

Average Age	44.6 years old
Average Total Flight Time	8500 hours
Flight Qualification	4 Captains** / 2 First Officers
Number Having Experienced Severe Low Level Windshear	5
Number Having Penetrated a Known Microburst	0

** One captain had been in that status for only four days

4.4 Experimental Procedure

At the beginning of each experimental session, the pilot was given an initial briefing on the characteristics of microbursts and the development of the F-factor as a measure of hazard intensity. The process of determining areas of hazardous windshear and the three different methods of presenting such windshear were outlined. The designated alert areas and required alarms as proposed by the forward looking windshear working group were described (see Section 2.4.2). At this time, the pilot was introduced to the workings of the simulator with an explanation of specific features he may have found different from the actual cockpit. The physical operation of the simulator was described and he was then given two (or more, as required) training approaches to Logan Airport in the different modes of control.

When the subject felt familiar with the system, he was given the four approach plates for the first set of runs and informed of the windshear display format he would be using (see Appendix A for approach plates). A demonstration of the scheduled format was shown to the pilot accompanied by the associated weather, alerts and warnings. The in-situ reactive windshear warning, audible and visual, was also demonstrated. Penetration of windshear in the demonstration flight was done to activate the in-situ warning and to demonstrate the negative effects on an approach. This was repeated as necessary until all the pilot's questions were answered.

The initial aircraft position was 10 nm outside either the initial approach fix (IAF) or the holding fix as dictated by the scenario. The aircraft faced the direction of the airport and the pilot was given an opportunity at the start of each run to familiarize himself with the weather situation and approach path as would be the case on an actual approach. An Airport Terminal Information Service (ATIS) briefing was given and the flight started with the aircraft at altitude, in a clean configuration, 250 kts. Examples of the text of such a message can be found in Section 3.3.2.

All verbal alerts of weather and windshear given by the experimenter acting as an ATC controller were consistent within each scenario and relatively generic. Requests for additional information resulted in similar windshear advisories and an up-to-date weather report as depicted on the precipitation scope.

The pilot executed the final portion of the approach in accordance with the approach procedures, ultimately intercepting the ILS localizer for an autopilot coupled approach. Prior to that point, he was expected to fly according to the filed flight plan unless given vectors or in need of a weather deviation. The preset navigation plan was flown automatically and adjusted through the navigation and mode control panels. The use of the heading select mode was available. Weather deviations and requested turns were allowed outside of the turn to final. If the pilot elected to execute a missed approach he was instructed to do so manually.

After each set of four runs, display ratings were solicited and the next display format was demonstrated. One researcher acted as the controller for the course of the approach. The high workload environment of the approach phase was partially emulated by the lack of a second pilot for communications, etc. and (a MCP speed control that required a little extra effort to adjust due to a slow update rate) or (particular simulator control requirements).

4.5 Data Sources

The actions taken by the pilot during flight were recorded on the simulator while appropriate numerical data was stored in files for analysis. The instrument display was videotaped along with all audibles by the pilot and controller. In order to add insight into the cognitive process behind the results, pilots were asked to articulate what they were thinking throughout the approach as if they were explaining to a new crew member or thinking aloud. Additionally, after each set of four runs, they were given a chance to rate from 1 (Poor) to 4 (Excellent) the display's effectiveness across a number of categories (see Appendix B). At the end of the session the pilots were asked to *rank* the three displays across those same categories, compare them in certain situations, compare them as pairs, and offer suggestions. Three of the comparisons were done on a 17 point scale between each pair of displays. Using the Analytic Hierarchy Process (AHP, see Appendix C), a quantitative preference scale for all three could then be determined from the paired comparisons of the three display types.

5. Experimental Results

Three objective measures were investigated: the missed approach decision, the distance at which such a decision was made, and the closest point of approach to the hazard. The latter two depended upon the pilot executing an abort as was expected in at least six of the runs due to the placement of hazardous windshear. The compiled results of all the runs can be seen in Appendix D.

Subjectively, pilots rated and ranked the display formats over eight categories. They also were asked to compare each pair of displays on a 17 point gradation scale for input to the AHP preference determination. The responses can be found in Appendix C while an overview and discussion of these results follow in Sections 5.5 to 5.6.

5.1 Consideration of Data

The windshear display data associated with Scenario III was not evaluated because all pilots elected to make a missed approach prior to the max range of the sensor. In the case of this Orlando microburst, the extremely heavy precipitation associated with the windfield was enough in itself to enable pilots to make a decision to go missed approach. Since weather could be scanned essentially from holding and at a generally greater distance, the pilots anticipated such a decision without regard to windshear display.

5.2 Missed Approach Decision

Table 5.1 Scenario I Missed Approach Decision and Technique: In this scenario depicting a building hazardous microburst, pilots using all three display formats elected to execute a missed approach on each run. Five of six went straight on the abort using each display.

Sc I	F-Factor Mapping			Single Level Icon			2-Level Icon		
Subj#	Run#	Abort	Strt/Turn	Run#	Abort	Strt/Turn	Run#	Abort	Strt/Turn
1	10	Yes	Straight	1	Yes	Straight	5	Yes	Straight
2	1	Yes	Straight	7	Yes	RT Turn	9	Yes	RT Turn
3	5	Yes	Straight	4	Yes	Straight	9	Yes	Straight
4	9	Yes	Straight	7	Yes	Straight	2	Yes	Straight
5	8	Yes	RT Turn	10	Yes	Straight	1	Yes	Straight
6	1	Yes	Straight	9	Yes	Straight	7	Yes	Straight

Within all the windshear scenarios the possibility for an aborted approach existed. All pilots chose to execute a missed approach in Scenarios I and III where a hazardous microburst either persisted or continued to build on the flight path. Pilots eventually recognized the threat and responded accordingly (see Table 5.1).

Table 5.2 Scenario II Missed Approach Decision and Technique: Not all pilots chose to abort the approach, yet no distinct pattern appears between display formats. The same is true of their windshear avoidance tactics.

Sc II	F-Factor Mapping			Single Level Icon			2-Level Icon		
Subj#	Run#	Appr Abort	Str/Turn	Run#	Appr Abort	Strt/Turn	Run#	Appr Abort	Str/Turn
1	11	Yes	Straight	4	No		6	Yes	Straight
2	3	No		6	Yes	LT Turn	11	No	
3	7	No		1	Yes	Straight	10	No	
4	11	Yes	Straight	8	Yes	Straight	3	Yes	LT Turn
5	5	Yes	RT Turn	11	No		2	Yes	RT Turn
6	3	Yes	LT Turn	11	No		6	No	

Scenario II had a diminishing windfield that could be safely negotiated if the trend was noted. The results shown in Table 5.2 and Figure 5.1 indicate the decision to execute a missed approach in Scenario II was evenly distributed among the pilots and display types. There appeared to be no observed tendency to abort the approach more or less often using a certain display.

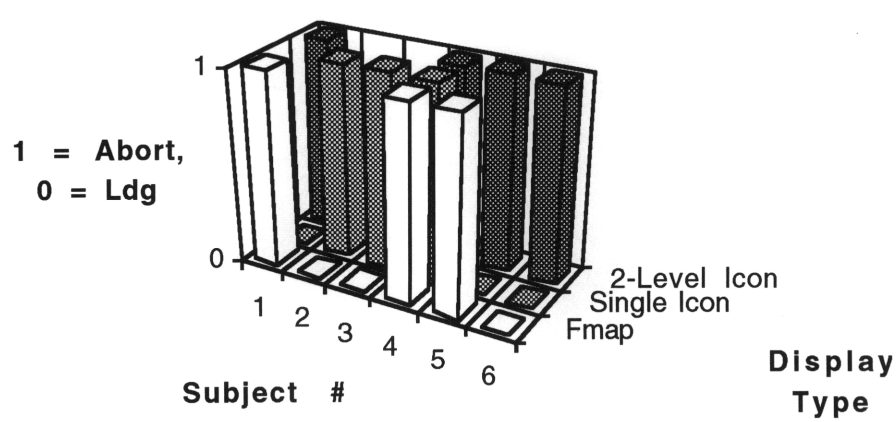


Figure 5.1 Scenario II Missed Approach Decisions

5.3 Missed Approach Strategy / Closest Point of Approach to MB

As shown in Table 5.1, the missed approach strategy used by pilots in Scenario I was primarily a straight-ahead go-around. Five of the six pilots in each display mode went straight off the missed approach. There was no discernible difference between performances of pilots in relation to the windshear display employed.

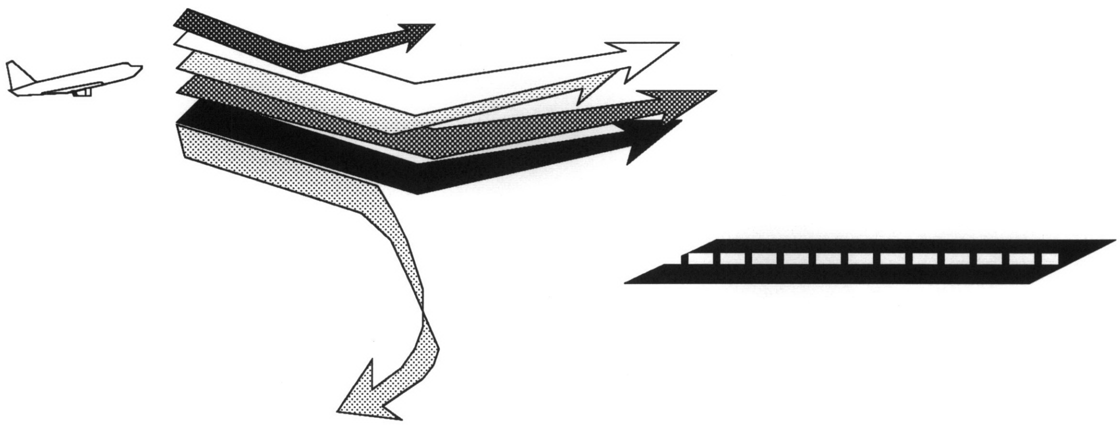


Figure 5.2 Missed Approach Strategy in Scenario I: Five of six pilots went straight on the aborted approach using each of the windshear display modes, only one turned away.

This result is further validated by the lack of a pattern in the case of Scenario II missed approach techniques seen in Table 5.2. Here, pilots in half of the ten missed approaches entered an avoidance turn away from the windshear area. Still, no display had a significantly larger number of turns or straight-ahead aborts than the other two.

The difference in the percentage of missed approach microburst avoidance turns between Scenarios I and II is likely due to the extent of the windshear situation portrayed. The area affected in Scenario I was extensive and eventually covered portions on both sides of the glide path, building from left to right in the main cell. The direction of build up probably accounts for the right turns used despite the location of holding off to the left. The threatening microburst of Scenario II was much more isolated and localized, making a turn to avoid it a relatively simple matter. Pilots who chose the straight-ahead strategy usually executed the airline windshear recommendations in terms of pull-up angle and configuration changes while this was not necessarily true in all the turning cases. Three of the five began the missed approach procedure as in a normal go-around. But, once again, no display-related differences were noted.

5.4 Decision Distance

To evaluate the effectiveness of the candidate windshear displays in regard to decision distance, it was necessary to consider the data generated on two levels. The scored levels of each display were statistically compared to find out what the absolute differences might be between the formats. To complement this approach, a non-parametric analysis of the data was also completed. It is important to remember that decision distances were calculated from the aircraft to the leading edge and not the center of the closest threatening microburst.

5.4.1 Parametric Testing

The variations in hazard criteria and decision-making ability of the individual pilots were taken into account by testing within subjects. In Scenario I all pilots eventually chose to abort the approach. There was, therefore, a full data set for such a test, as seen in Table 5.3.

Table 5.3 Scenario I Abort Decision Distances in Nautical Miles

Subj#	Fmap	Single Icon	2-Level Icon
1	3.0	1.2	2.0
2	1.2	1.3	2.5
3	2.0	1.2	1.3
4	2.1	3.1	0.7
5	1.0	2.0	2.4
6	1.2	1.7	2.2
Ave	**1.75 nm**	**1.75 nm**	**1.85 nm**
Std Dev	**0.76**	**0.73**	**0.71**

Table 5.3 shows the results of an analysis of variance taken within subjects on the data. The negligible F-ratio and the obvious equivalence of means in Table 5.4 and Figure 5.3 indicate that there is no significant difference readily apparent. The P-Value of 0.97 indicates that the probability that the differences could have been due to chance is almost 1.0. In comparing the distances in the table, the data from subject number four seemed out of place and was, perhaps, an outlier. Another ANOVA was performed without subject four but the probability due to chance was still approximately 80% with a slight but insignificant rise in F-Value. The differences between display types in absolute terms were indistinguishable on this level.

Table 5.4 Type III Sums of Squares of Scenario I Decision Distances

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	P-Value
Subject	5	.645	.129		
Display	2	.040	.020	.027	.9736
Display * Subject	10	7.460	.746		

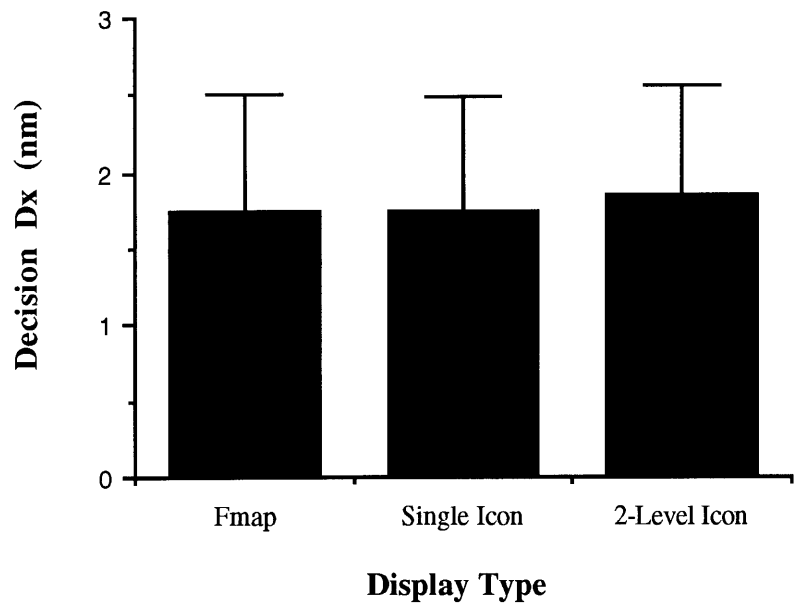


Figure 5.3 Means of Decision Distances in Scenario I

5.4.2 Non-parametric Comparisons

Despite the apparent equivalence of the data among means and variances, it was noticed that there was a relative trend between display types. A nonparametric sign test was conducted on the same data. Comparing the signs of the difference between each pair of results (Fmap-Single Icon, Fmap - 2-Level Icon, 2-Level Icon - Single Icon), enabled distributions to be disregarded. *It was noted that the 2-Level Iconic display produced decision distances for each subject that were greater than that of the Single Icon in five of the six cases* (see Figure 5.4). The result is significant using a non-parametric sign test at approximately the 10% level. Eliminating subject number four here showed all five of the 2-Level Icon approaches being aborted at a greater distance, albeit with a lower sample size. No such significance was found in the other two combinations of displays in regard to decision distance.

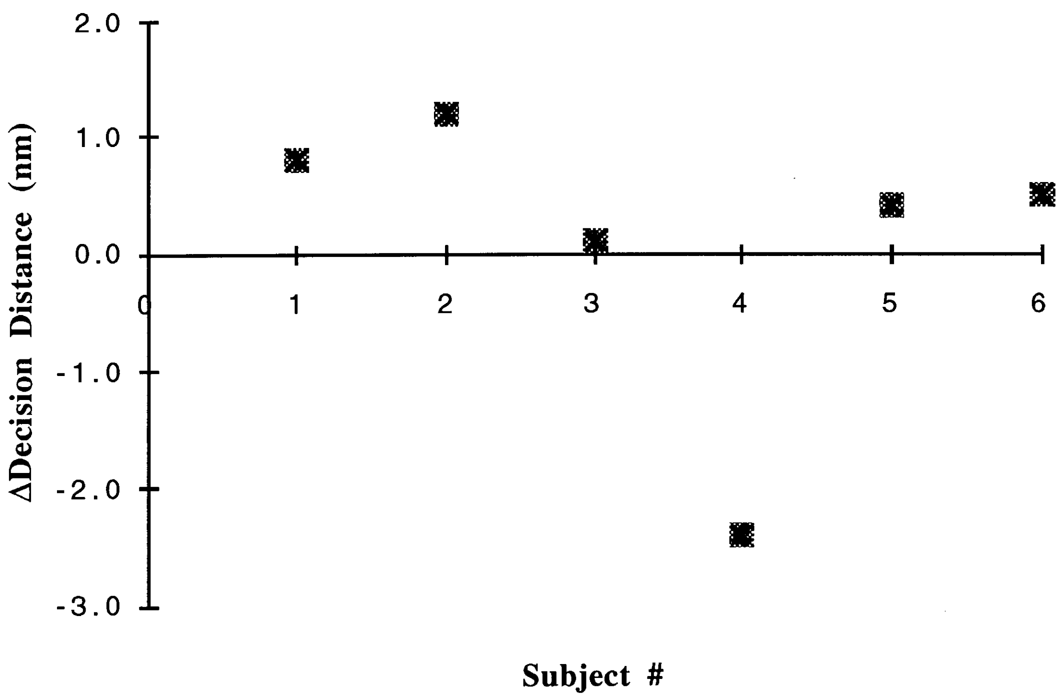


Figure 5.4 Difference in Decision Distances Using 2-Level vs. Single Icon Format by Subject: Subject number four appears to be an outlier.

The nonparametric test method is more robust, although slightly less efficient, for a sample distributed normally. Constricted by the small sample size, another version of this approach, the rank test, was explored including Scenario II decision distances. By taking all the decision distances using the three displays and sorting them into descending order, a nonparametric rank test determined the significance of having a certain number of distances from the 2-Level Icon pool greater than that of the Single Icon. The resulting values reflected sample size.

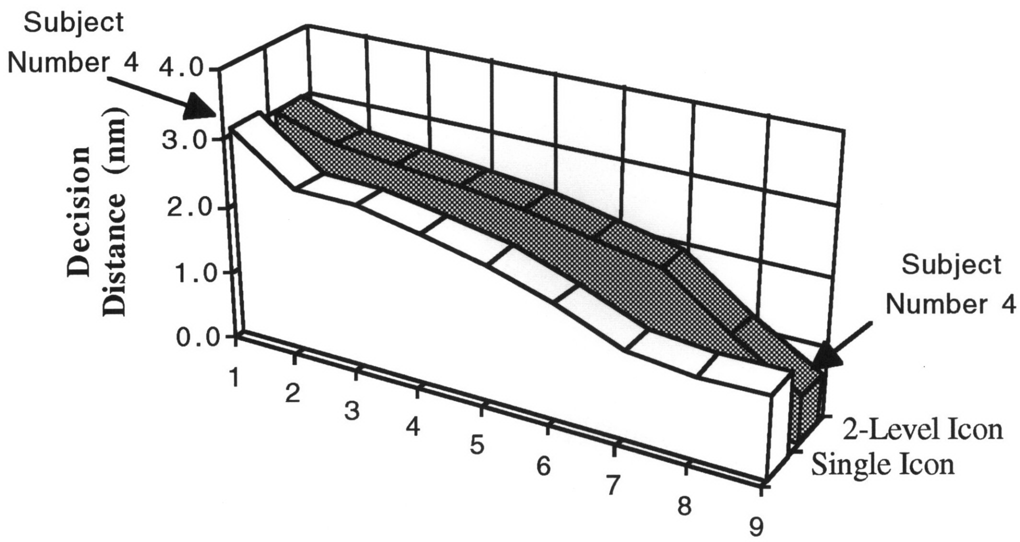


Figure 5.5 Decision Distances of Two Display Types in Scenarios I & II: Seven out of nine 2-Level Icon decision distances are greater than that of the Single Icon. If subject number four is removed as an outlier, the 100% consistency in rank comparison is significant.

The results in Figure 5.5 show seven out of the nine pairs have greater values for the 2-Level Icon than the Single Icon at corresponding rank -- significant at the 10% level. The performance of subject number four occupies both the highest and lowest points indicated overall. These distances are singularly two or more standard deviations away from the remaining mean and median and may be outliers. Eliminating the performance of subject four shows a consistent decision distance gap significant at the 1% level. It would appear that pilots are able to make the decision to abort the approach at an earlier point using the 2-Level display vice the Single Icon. The Fmap, like the 2-Level Icon, showed a similar trend versus the Single Icon but to a less significant degree. No trend was noted between the Fmap and 2-Level Icon.

5.5 Subjective Measures

During the course of the experiment and after completion of all runs, pilots were asked to evaluate what the display in use had been telling them and how did they perceive the windshear depicted in regard to their aircraft state. Pilots rated each display (from 1-POOR to 4-BEST) in eight categories during the sets of approaches and then ranked them

(1, 2, 3 in descending order) after the experiment. In this way, it was hoped to gain a second source of the same information and note trends in preference.

5.5.1 Paired Comparisons of Pilot Rankings

With six pilots, a display may be considered significantly better in one category when at least five of the respondents ranked it higher than the alternative display [Yang, 1992, Hogg and Ledolter, 1992].

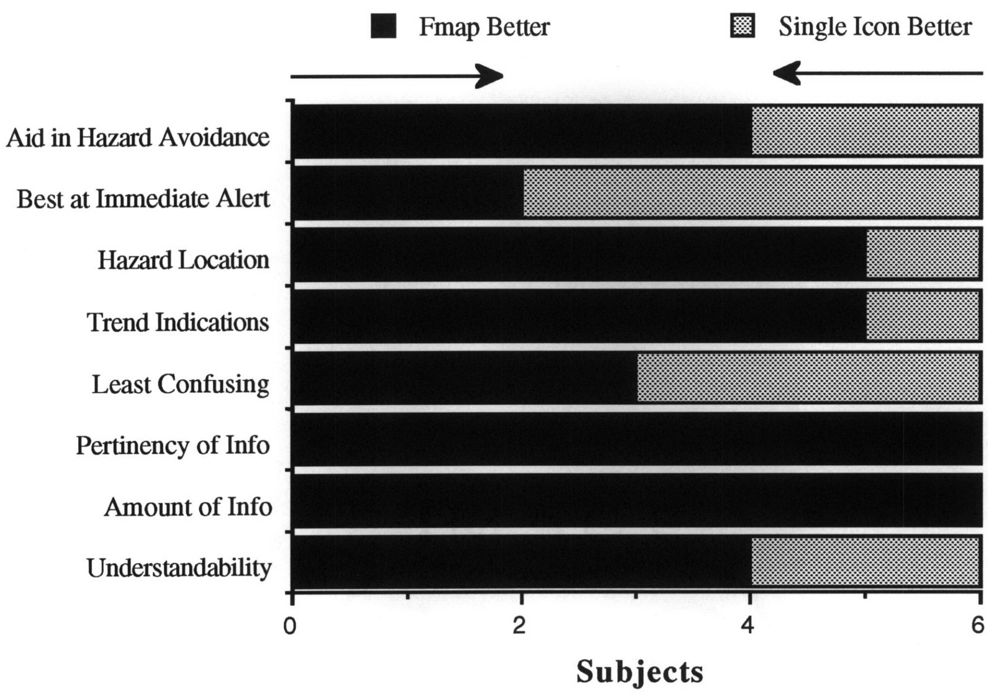


Figure 5.6 Display Traits -- Fmap vs Single Icon: Trend, hazard location and the information rows all seem to favor the use of the Fmap.

As shown in Figure 5.6, the Fmap was highly favored in three important areas: trend, hazard location and pertinent information presented. One pilot stated that, "It gave a broader presentation." Another said the Fmap, "Suggested more of a course of action." The Single Icon did not appear to carry as much credibility and pilots attempted to look for corroborating evidence in the way of glideslope deviations and wind vectors. In the middle of one run a pilot said, "I'm having to look for information..." using the Single Icon.

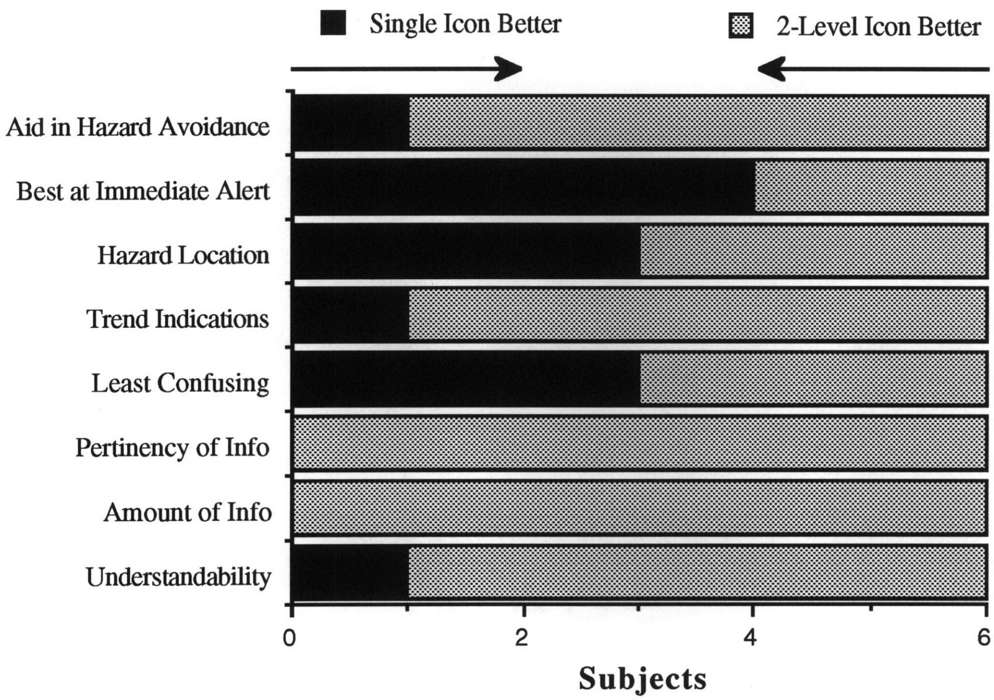


Figure 5.7 Display Traits -- Single Icon vs 2-Level Icon: The 2-Level Icon appears to have the advantage in five of the eight categories, although not in the prime category of hazard location.

The fact that the 2-Level Icon is just a Single Icon with more information appealed to the pilots' general desire to know more (see Figure 5.7). It was significantly better in their eyes particularly because of the "early warning" [yellow area] that something was brewing and the general sense of the extent of the windshear area. Two comments were:

"Gives the pilot a 'heads-up' alert."

"Much more information, but only slightly more confusing [than the Single Icon]."

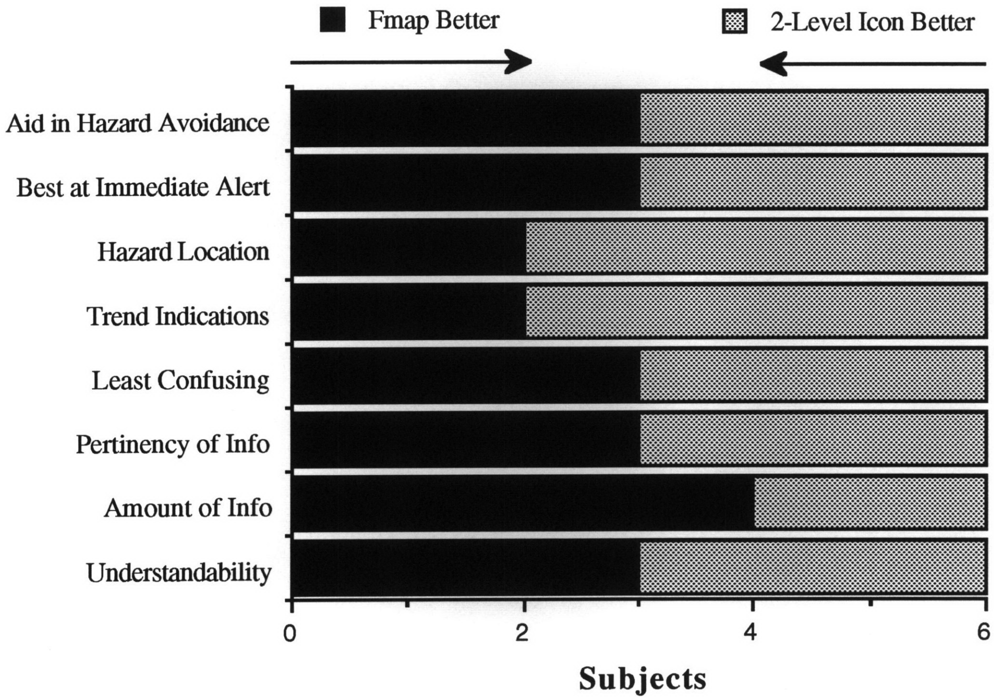


Figure 5.8 Display Traits -- Fmap vs 2-Level Icon: With a fairly even distribution, pilots showed no particular preference between these two displays.

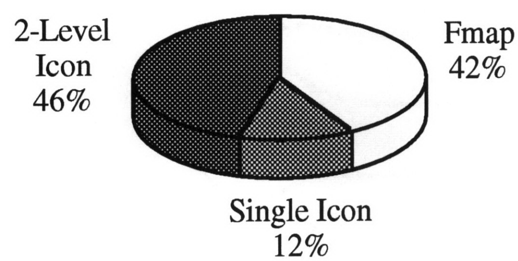
Pilots ranked both the Fmap and the 2-Level Icon higher in significant numbers but were essentially divided when choosing between the two, as illustrated in Figure 5.8. There were advocates on both sides:

> "Fmap gives much more of a feel for where it is specifically located as opposed to just going to run into it."
>
> "Multilevel Icon had the best attributes of both the other systems."

The predominant theme of the responses was that the multilevel formats were superior because they imparted more information sooner to the aircrew. One pilot did remark that, "Maybe the 2-Level Icon was giving you something that you don't need..." but even his scores reflected a preference the 2-Level format. A caveat to this idea is that the pilots were not under a dark night, IMC type workload in the part-task simulator. A more quantitative consideration of the overall preference was completed using the AHP method.

5.5.2 Analytical Hierarchy Process (AHP) Results

The primary advantage of the AHP method is that it can provide meaningful quantitative results using a small sample size. Unlike the simple rankings taken over the categories and then compared as pairs, the AHP method requires a broader scale comparison in pairs to arrive at a summary of the whole system. Subjects rank two displays on a scale that involves relative ratings. These relative ratings are described as "worse," "same," "slightly better," etc. rather than dealing in absolutes such as "bad" or "excellent."



	Ranking
Fmap	0.4216
Single Icon	0.1250
2-Level Icon	0.4539

Figure 5.9 Overall Pilot Preference Determined Through AHP

In this particular case we have only three displays and, therefore, need only three paired rankings. The subject's preference between, say, displays A and B can be thought of as a vector in the two dimensions of AB space. By finding two more such vectors, the three-dimensional summary of these preferences can be determined. The result of the applied AHP is seen in Figure 5.9. The 2-Level Icon and Fmap take the lion's share of the pilots' expressed preference with little difference between them. This compares favorably with the results of the previous section.

5.6 Discussion

5.6.1 Pilot Expectations

Pilots seemed receptive to the explanation of F-factor and the different formats that might be used to display such data. They were genuinely interested in having some form of airborne detector to confirm ground-based sensors or to determine the form and danger level of announced advisories from tower and PIREP's. They did not expect to be the first to discover a microburst, probably due to past experience or the lack thereof .

All pilots tested thought that the ability to display windshear was important and should, if possible, be done in conjunction with the EHSI data without impairing the EHSI-weather combination. They were generally receptive to an iconic overlay or time-sharing scheme, *if the warning was reliable.*

5.6.2 Reflectivity Display Clarity

The pilots were almost unanimous in their praise for the weather radar presented with the one caveat that, "it just wouldn't look that good down low." Aircraft radar images look very similar to the simulated version but require constant adjustment at low altitude to maintain a quality image. In normal approach operations there is not enough time for this fine tuning. Hence, the lack of ground clutter and the perfect "antenna tilt" made the missed approach decision in Scenario III a foregone conclusion without regard to windshear aspects (see Figure 5.10). Typical comments include:

> "As radar deteriorates [at low altitude], the windshear display would come into play."
>
> "Less clear weather radar makes the shear more important."

As an aside, this does point to a realistic workload measurement, the tuning of a mildly unstable radar display, as a sidetask device for future experiments.

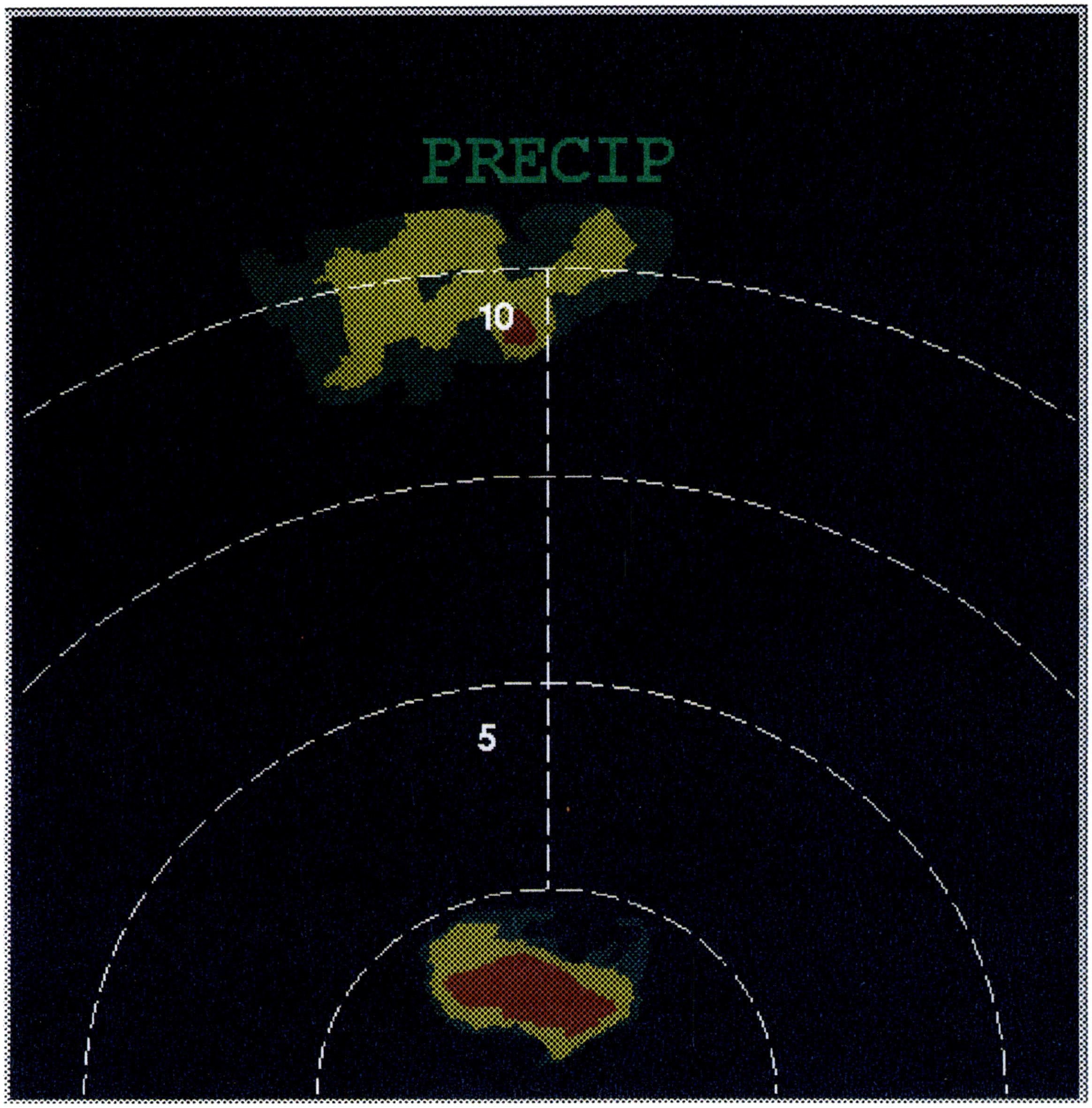


Figure 5.10 Reflectivity from Scenario III: Microburst reflectivity from the July 7, 1990 Orlando microburst (foreground), evidently too intense and too well presented to fly through.

5.6.3 Straight vs. Turning Missed Approaches

Surprisingly, it was found that the majority of pilots who elected to make a missed approach were not turning to avoid the displayed microburst hazard, but rather executed a straight-ahead abort. In past experiments (Wanke and Hansman, 1992, Oseguera and Hinton, 1993), pilots tended to avoid *any* displayed icon although it may not have saved them any energy and could have had dire consequences in the ATC area in regards to other aircraft and terrain.

In addition to the large area of hazardous windshear in Scenario I, the distance at which the hazard first became evident to the pilots may have been a contributing cause in both scenarios. In the Wanke/Hansman [1992] simulation, subjects had a large lead time to view the microburst alert(s) since the alert generated was predicated on ground-based detectors. The mean distance from the microburst at which a *missed approach* occurred was 4.26 nm. In this experiment, hazardous windshear *began to appear* between three and six nautical miles from the aircraft position, resulting in much shorter distances to the microburst at missed approach. Pilots, therefore, may be more inclined to follow the straight out missed approach procedures designed for an aircraft already in windshear.

With an airborne detector-based system, the proposed requirements for long range predictive windshear systems are out to three nautical miles and 25 degrees either side of the nose. The appearance of hazards in the three to six mile range in this experiment were in line with these minimums and the nominal detection distances expected by the manufacturers of such equipment.

5.6.4 Ground-Air Combined Displays

Ground-based windshear detection devices have become more commonplace and sophisticated than the rarities they were a few years ago. The measurements from such a source are likely to be more accurate, highly-processed, and well-studied by ground experts. This alternative resource of information may be datalinked up to aircraft for display. If fusion of the two detection sources is to be easily accomplished, it will have to be along the lines of an iconic format.

5.6.5 Decision Distances and Pilot Motives

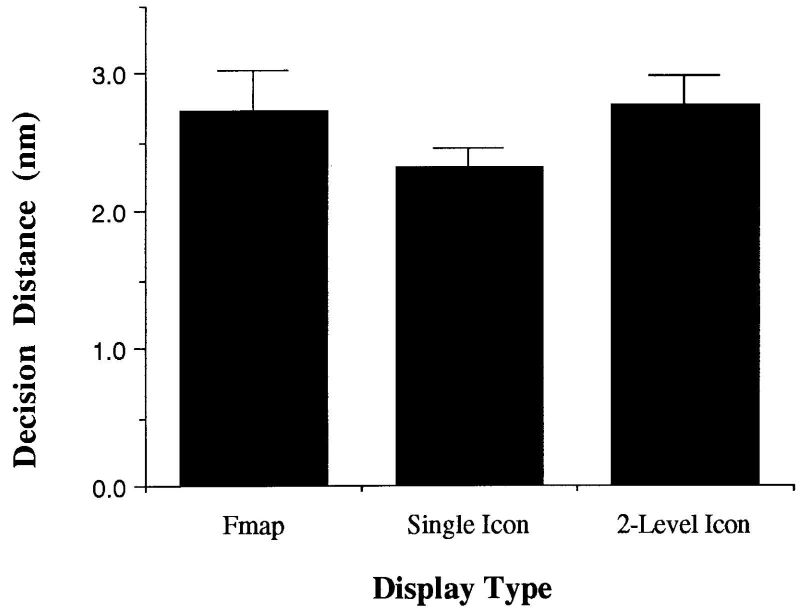


Figure 5.11 Means of Decision Distances in Scenario I

Although this graph is made across all subjects and is based upon a low sample number, 10 missed approaches total, it may be indicative of tendencies seen in the sections prior. The graph of mean decision distances for Scenario II in Figure 5.11 shows the apparent trend of multilevel formats (Fmap and 2-Level Icon) to have pilots make a quicker decision (i.e. at a further distance from microburst). It is also interesting to note that although pilots flew closer in towards the microburst with the Single Icon, they did not see the diminishing trend any better and aborted at the same rate.

In previous experiments pilots were inclined to avoid higher intensity areas by greater distances. If the addition of the yellow alert level was perceived as a more "intense" hazard or just a "bigger" microburst because of its additional area, it is conceivable that pilots would make their decisions or decide to stay further away from the microburst. This interpretation of a *larger* threat is in conflict with the idea of a *quicker assimilation* of the threat. The latter appears to be more likely for a couple reasons. First, if the larger threat hypothesis was true, one would expect to have seen significantly more missed approaches in Scenario II using the multilevel formats than with the Single Icon -- we did not. Second, in accordance with previous experiments and as discussed in Section 5.6.3, a larger threat would likely have resulted in more avoidance turns in Scenarios I and II despite the short warning time. Such a trend was not observed. A majority of pilots stated that the multilevel formats did make them aware of potential problems earlier so that they "could start thinking about them." It is also possible that the multilevel formats yielded better trend information but this advantage was offset by the perception of a larger threat. This would explain the lack of a significant difference in number of aborts in Scenario II. However, the combination of these two characteristics logically would have produced a wide disparity in decision distance in Scenario I. This was not the case, therefore, it appears that multilevel formats simply provide a slight advantage in conveying the windshear threat to the pilot.

5.6.6 Aircraft Velocity and the Hazard Calculation

The fundamental dependence of F-factor upon the aircraft's speed allows the display to directly reflect the amount of hazard *at that instant.* However, as a predictive display of windshear, it can be deceiving during the transitional speed changes of the low-level environment. Aircraft on approach may be better served by a "more predictive" display using a reference speed the aircraft will be slowing to as it nears the runway and its final configuration. An example of this might be use of the "Bug" speed set for approach during descent checks.

5.6.7 Windshear Warning Audible

A number of pilots expressed the opinion that the windshear warning audible was too similar in nature to that of the reactive alert. They believed that a potential source of confusion could be removed by avoiding the use of the word "windshear" in predictive systems, reserving this for the reactive system.

6. Conclusions

A simulation experiment was performed to examine the issues and effects of three airborne-measured windshear display formats on aircrew performance in a number of realistic scenarios.

- Experimental results indicate few clear differences in objective performance improvement between the Fmap, Single Icon, and the 2-Level Icon. All three displays provided equivalent windshear safety margins in the situations presented.

- There were some indications of a slight gain in missed approach decision-making when using the multilevel formats, with a preference for the 2-level icon.

- Subjective results indicate that pilots favor a multilevel format in terms of the ability to convey pertinent information and trends. The Fmap was perceived to be better at showing hazard location while adding another intensity level to the Single Icon was thought to help in hazard avoidance.

- The subject ratings between displays, the unanimous overall preference, and the pilots' evaluations of key traits (Hazard Location, Hazard Avoidance, Trend) all point towards a subjective preference of the multilevel formats.

In summary, although pilots seemed to *like* the multi-level formats better, they didn't appear to *need* it. Performance differences being slight, the currently proposed Single Icon format appears adequate for the display of windshear.

Appendix A

This appendix contains representative documentation of the scenarios developed for the airborne-detected windshear display experiment to include approach plates and ATC controller guidelines. The overall test matrix for the experiment is shown in Table A.1 at the end.

Scenario I -- Version 3

(1_3) STRAIGHT-IN TO A MISSED APPROACH BUILDING MICROBURST CELLS

Airport: Clinton Int'l, Hillary, AK
Approach: ILS Rwy 9R
Initial Posit: 10nm west of WHITE (IAF)
HDG: 088 ALT: 7000' SPD: 250 WIND:

Route: WHITE - INALE - WATER

Missed App: CLIMB straight ahead to 3000', then climbing LEFT turn to 5,000', outbound via MIT VOR r-360 to SLICK and hold.

ATIS: "Clinton International Airport information 'MIKE.' 0220 Zulu. Weather: 7500 scattered, estimated ceiling 12,000 broken, visibility one zero miles. Temperature 74, dew point 54. Wind 270 at 4. Altimeter two niner niner six. Runway 9L inoperative due to construction. Expect ILS approach to runway 9R. Departing runway 9R. Microburst and low level windshear advisories are in effect. All aircraft advise on initial contact you have information 'MIKE.'"

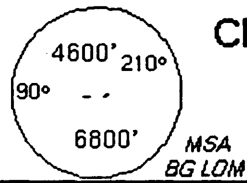
@ Check-in: "________ 123, Little Rock Approach. ILS approach to runway 9R in use. (MIKE is current.) Altimeter two niner niner six. Proceed direct WHITE, descend and maintain 3000. Report established. Call commencing."

@ Established call or at INALE: "Roger. You are cleared for the ILS Approach runway 9R. Contact Eastern Tower on 123.35 and report the outer marker."

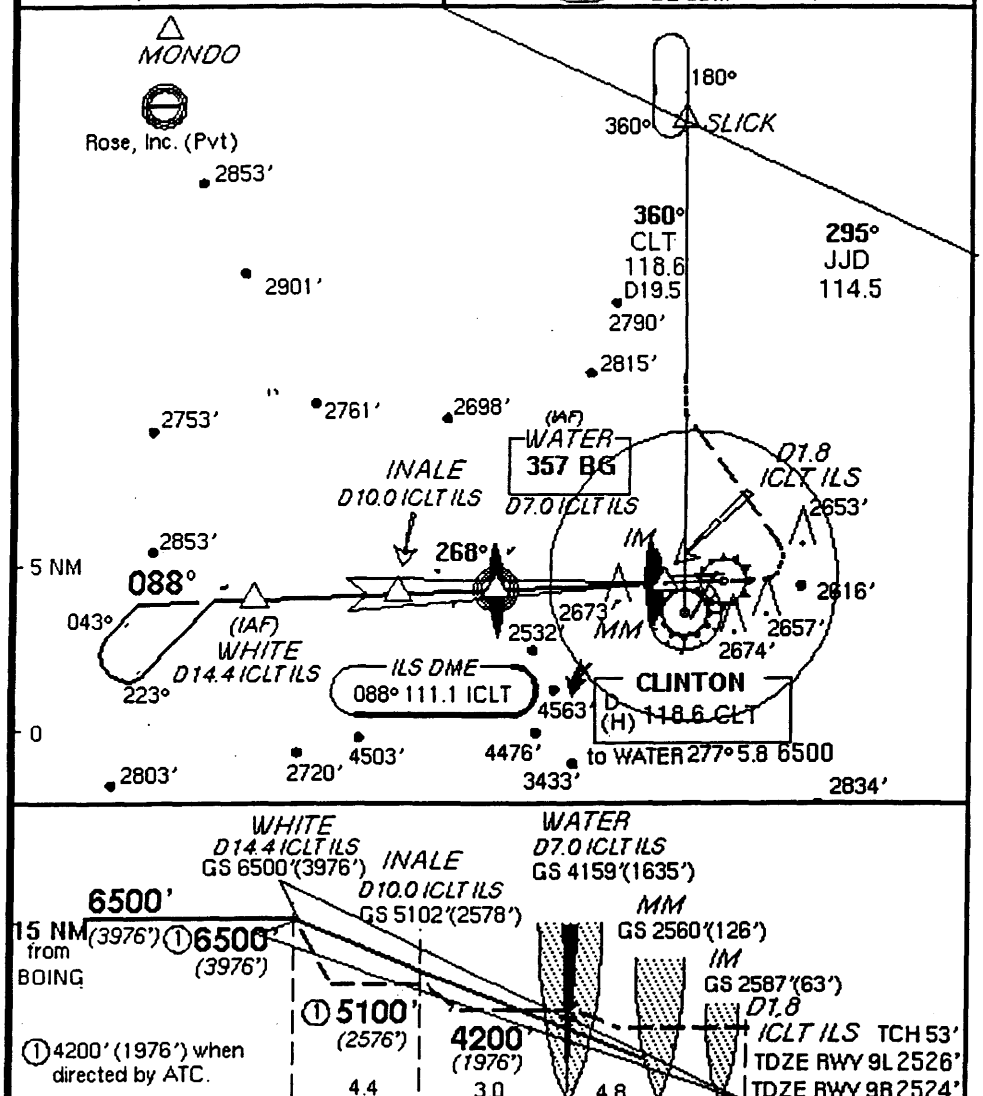
@ Check-in: "_________123, Tower, roger. ILS to runway 9R. Wind 080 at 5. Runway 9R, cleared to land."

ATIS Arrival **119.85**
LITTLE ROCK Approach (R) **128.7**
Clinton Tower Rwy 9R/27L **119.2**
Rwy 9L/27R **119.6**
Ground Rwy 9R/27L **121.8**
Rwy 9L/27R **121.25**

HILLARY, ARK
CLINTON, INTL
ILS Rwy 9R



LOC **111.1 ICLT**
Apt. Elev 2526'



MISSED APPROACH: Climb to 3000' then climbing LEFT turn to 5000' outbound via CLT VOR R-360 to SLICK INT/D15.0 CLT and hold.

STRAIGHT-IN LANDING RWY 9R							SIDESTEP LANDING RWY 9L	
ILS DH 2724' (200')			DH 2774' (250')	LOC (GS out) MDA 2940' (416')			MDA 2940' (425')	
FULL	TDZ or CL out	ALS out	MM out		MM out	ALS out		ALS out
RVR 18 or 1/2	RVR 24 or 1/2	RVR 40 or 3/4	RVR 24 or 1/2	RVR 40 or 3/4		RVR 60 or 1 1/4	RVR 50 or 1	1 1/2

Gnd speed-Kts	70	90	100	120	140	160
GS 3.00°	377	485	538	646	754	861
MAP at D1.8 IANM or WATER to MAP 5.2	4:27	3:28	3:07	2:36	2:14	1:57

Localizer unusable inside runway threshold.

Scenario II -- Version 1

(2_1) DOG-LEG APPROACH
DIMINISHING MICROBURST CELLS

Airport: Johnson Int'l, Brownsville, TX
Approach: ILS Rwy 13L
Initial Posit: 10nm east north of LA SALLE
HDG: 180 ALT: 4000' SPD: 250 WIND:?

Route: LA SALLE - PENTX - MUULE

Missed App: Climb to 500', then climbing LEFT turn to 4000' outbound via JON VOR R-040 to PDK VOR and hold.

ATIS: "This is Johnson International Airport information 'HOTEL,' time recorded, 0240 Zulu. Johnson weather: measured ceiling 700 foot overcast, visibility 5 miles. A line of thunderstorms exists extending from 20 miles southwest of Brownsville to Corpus Christi, Texas moving east at 15 knots. Microburst and low level windshear advisories are in effect.
The temperature is 69, dew point 67; wind 150 at 12, gusts to 21 knots. Altimeter 29.82.
-- Expect vectors to an ILS approach runway 13L. Landing and departing runway 13L.
-- Braking action reported fair to good by a DC-9.
-- Advise on initial contact that you have 'HOTEL.'"

@ Check-in: "Roger __________ Flight 123, Harlegin Approach. Continue direct LA SALLE. Descend and maintain 3000'. Expect clearance on the ILS for 13L at LA SALLE. Altimeter 29.82.

@ LA SALLE: "________ 123, Approach, descend and maintain 3700' until established on the localizer. Cleared ILS approach, runway 13L. Contact Johnson Tower now on 119.8"

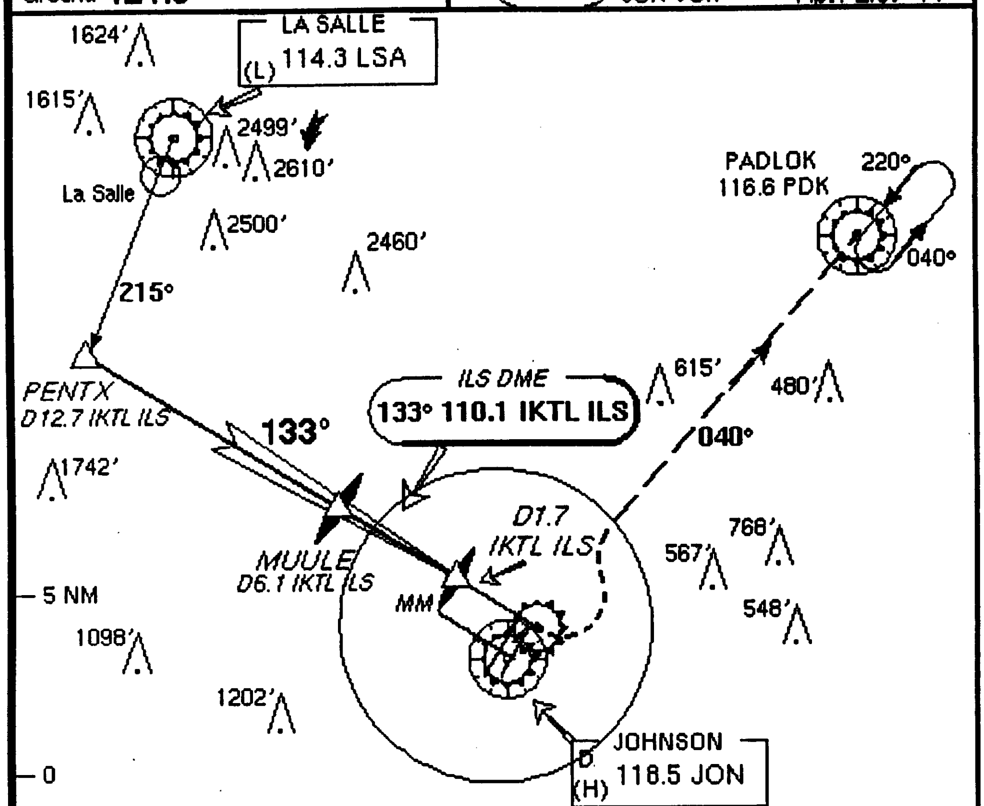
@ 1nm from localizer: "________ 123, continue descent to 2700', report established."

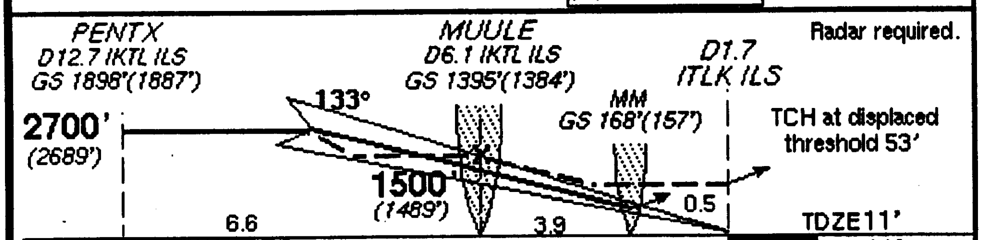
(Expect possible pilot requests to maintain heading, take a vector due to weather -- Clear it accordingly.)

@ Check-in: "_________ 123, Tower, roger. Runway 13L. Last aircraft to land reported braking action good about 10 minutes ago. Report the Outer Marker"

@ MUULE after report: "Roger, ________ 123, wind 100 at 8, gusting to 15. Cleared to land runway 13L."

ATIS Arrival **128.72** (NE) **117.7** (SW) **115.4** HARLEGIN Approach **127.4** JOHNSON Tower **119.1** Ground **121.9**	**BROWNSVILLE, TX** **JOHNSON INTL** **ILS Rwy 13L** *LOC* **110.1 IKTL** *Apt. Elev* 11' 180° 3000' 3600' 270° 090° 1700' *MSA JON VOR*





MISSED APPROACH: Climb to 500' then climbing LEFT turn to 4000' outbound via JON VOR R-040 to PDK VOR and hold.

STRAIGHT-IN LANDING RWY 13L						CIRCLE-TO-LAND
ILS				LOC (GS out)		
DH **211'** *(200')*			*DH* **261'** *(250')*	*MDA* **600'** *(589')*		
FULL	TDZ or CL out	ALS out	MM out		ALS out	*MDA*
RVR **18** or 1/2	RVR **24** or 1/2	RVR **40** or 3/4	RVR **24** or 1/2	RVR **50** or **1**	1 1/2	**600'** *(589')* – 1 1/2

Gnd speed-Kts		*70*	*90*	*100*	*120*	*140*	*160*
GS	3.00°	377	485	538	646	754	861
MAP at D1.7 IKTL ILS or MUULE to MAP	4.4	3:46	2:56	2:38	2:12	1:39	1:53

Scenario III -- Version 1

(3_1) BOXED PATTERN FROM HOLDING SNAPSHOT MICROBURST

Airport: Murmanburg Int'l, Murmanburg, W VA
Approach: ILS Rwy 18
Initial Posit: ABDUL (Holding fix)
HDG: 035 ALT: 7000' SPD: 250 WIND:?

Route: ABDUL - GALLE (IAF) - KROSS - MIXIN

Missed App: CLIMB to 1800', then climbing RT to 4000' out the MMG VOR r-289 to ABDUL (D17.0) and hold as depicted.

ATIS: "This is Murmanburg International Airport information 'ALPHA,' time 0000 Zulu. Murmanburg weather: 1200 foot scattered, measured ceiling 2000 overcast, visibility 4 in rainshowers. Occasional ceiling 1200 foot broken, visibility 2 miles in rain and fog.
The temperature is 69, dew point 67; wind 180 at 11, gusting to 18 knots. Altimeter two niner seven niner. Numerous thundershowers in the vicinity. Microburst and low level windshear advisories are in effect.
-- Expect vectors to an ILS approach runway 18. Landing and departing runway 18.
-- Use caution near Bravo Concourse due to construction.
-- Advise on initial contact that you have 'ALPHA.'"

@ Check-in: "Roger __________ Flight 123, Murmanburg Approach. Continue direct GALLE. At pilot's discretion, descend and maintain 5000'. Altimeter 29.80. Expect ILS approach runway 18.

(Expect pilot to ask for clearance to deviate for weather, vector aircraft heading 040 until clear and then back to Galle to square corner.)

@ 3nm prior to KROSS: "_______ 123, turn right heading 090 to intercept the localizer. Descend to 2800'."

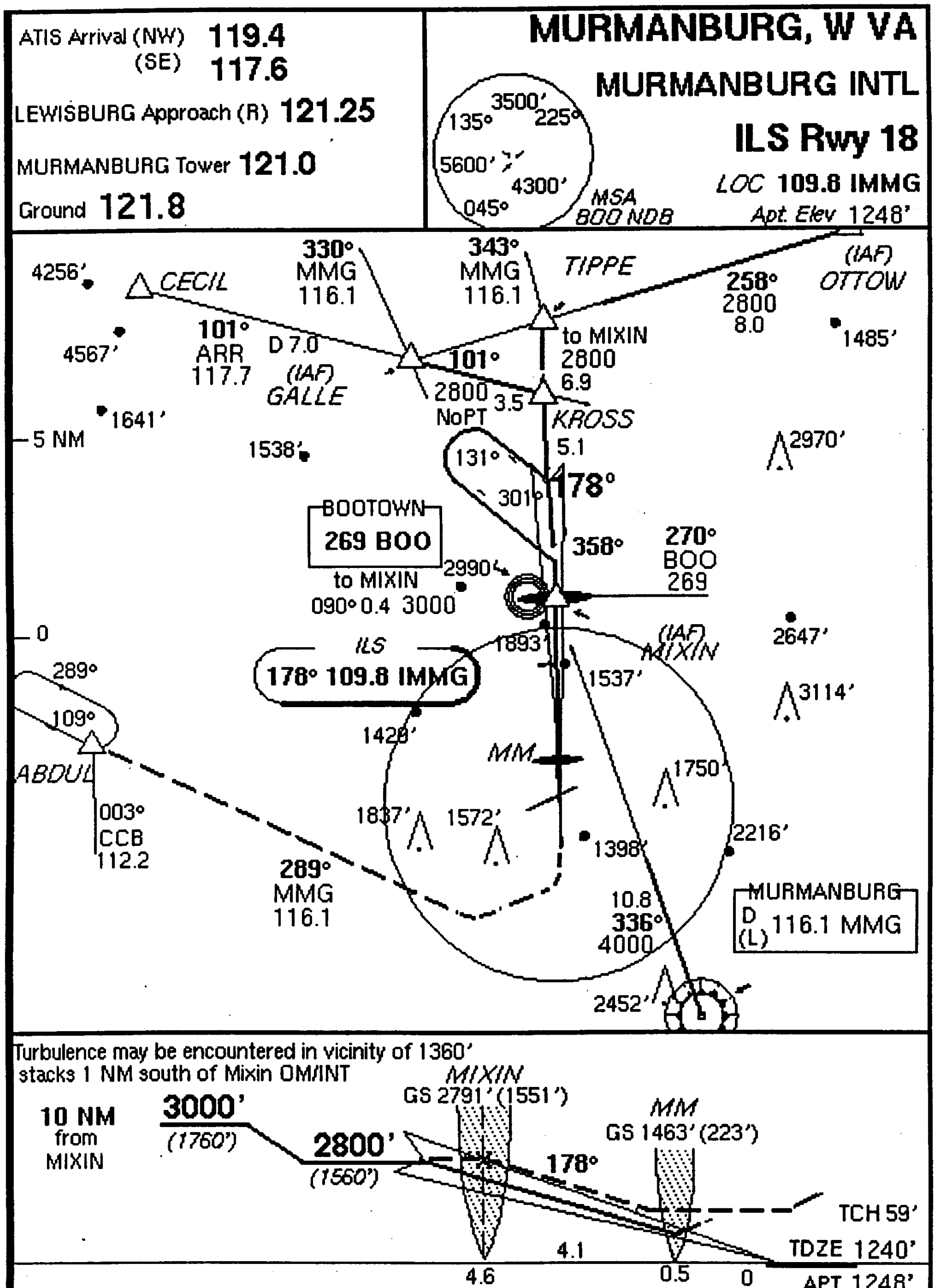
@ 30 seconds later: "________ 123, turn right now heading 160 degrees until established."

@ Established call: "________ 123, Murmanburg Approach, you are cleared ILS approach runway 18.

@ 2nm prior to MIXIN: "_________ 123, switch Murmanburg Tower 121.0."

@ Check-in: "_________ 123, Tower, roger. ILS to runway 18. Braking action reported fair to good. Call MIXIN."

@ MIXIN after report: "Roger, ________ 123, you are cleared to land runway 18. Wind 170 at 10 gusts to 18."



MISSED APPROACH: Climb to 1800', then climbing RIGHT turn to 4000' outbound via MMG VOR R-289 to ABDUL INT/D17.0 and hold.

STRAIGHT-IN LANDING RWY 18						CIRCLE-TO-LAND
ILS			LOC (GS out)			
DH 1440' (200')		DH 1490' (250')	MDA 1800' (560')			
FULL	RAIL or ALS out	MM out		RAIL out	ALS out	MDA
1/2	3/4	1/2	1	1 1/2		1800' (552') – 1 1/2

Gnd speed-Kts	70	90	100	120	140	160
GS 3.00°	377	481	538	646	754	861
MIXIN to MAP 4.6	3:57	3:04	2:46	2:18	1:58	1:44

Table A.1 Overall Test Matrix

RUN	SUBJECT NUMBER					
	1	2	3	4	5	6
1	*S-Icon* 1 2	*Fmap* 1 1	*S-Icon* 2 1	*M-Icon* 0 3	*M-Icon* 1 2	*Fmap* 1 2
2	3 1	3 2	0 3	1 1	2 1	3 3
3	0 1	2 3	3 2	2 2	3 3	2 1
4	2 1	0 2	1 2	3 2	0 1	0 2
5	*M-Icon* 1 3	*S-Icon* 0 3	*Fmap* 1 3	*S-Icon* 3 3	*Fmap* 2 3	*M-Icon* 0 3
6	2 2	2 1	3 1	0 1	3 2	2 3
7	3 3	1 3	2 3	1 2	0 3	1 1
8	0 3	3 1	0 2	2 1	1 1	3 2
9	*Fmap* 0 2	*M-Icon* 1 2	*M-Icon* 1 1	*Fmap* 1 3	*S-Icon* 0 2	*S-Icon* 1 3
10	1 1	0 1	2 2	0 2	1 3	0 1
11	2 3	2 2	0 1	2 3	2 2	2 2
12	3 2	3 3	3 3	3 1	3 1	3 1

DISPLAY TYPE	SCENARIO	VERSION
Fmap	0 -- No microburst	1
Single Level Icon	1 -- Straight-in to MAP	2
2-Level Icon	2 -- Dog-leg, diminishing	3
	3 -- Box-pattern to MAP	

Appendix B Preflight, Inflight, Postflight Questions

Appendix B contains the pre-experiment documentation and post-experiment questionnaire.

INFORMED CONSENT STATEMENT
HAZARDOUS WINDSHEAR DISPLAY STUDY

Research Assistant:
Mark T. Salzberger
MIT Rm. 37-458
77 Massachusetts Ave.
Cambridge, MA 02139

Principal Investigator:
Prof. R. John Hansman
MIT Rm. 33-113
77 Massachusetts Ave.
Cambridge, MA 02139

You may halt the experiment at any time and withdraw from the study for any reason without prejudice. You will remain anonymous in any report which describes this work. If you have any questions concerning the purpose, procedures, or risks associated with this experiment, please ask them.

CONSENT

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the M.I.T. Medical Department, including first aid, emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the Investigator's fault. I also understand that by my participation in this study, I am not waiving any of my legal rights*.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, M.I.T. 253-6787, if I feel I have been treated unfairly as a subject.

I volunteer to participate in this experiment which is to involve using simulated sensor images on a computer screen for a total of 3.0 hours. I understand that I may discontinue my participation at any time. I have been informed as to the nature of this experiment and the risks involved, and agree to participate in the experiment.

____________________ ____________________

Date Signature

* Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.

Background Information

Information concerning your aviation background will help us to more accurately assess some of the variables that affect your preferences for weather and windshear information. *All information you provide will remain completely anonymous.*

Personal Data / Miscellaneous Information

1. Age: __________ Sex: Male ( ) Female ( )

2. How were you *initially* trained to fly? Civil ( ) Military ( )

3. Experience:
   A. Total pilot hours ______________ Position: Capt. 1st Officer

   B. Pilot ratings held:

   Fixed Wing: ATP ( ) Commercial Pilot ( ) F.E. Written ( )

   Rotary Wing: ATP ( ) Commercial Pilot ( ) Other _____________

   C. Types of Aircraft -- Primary______________ Others____________________

   D. Weather radar depictions are displayed on: (circle one)

   The EHSI A separate monitor Both

   C. What percentage of time would you estimate that you have landed/taken off in:

	0-10%	10-25	25-50	>50%
IMC weather (excluding night only)	[ ]	[ ]	[ ]	[ ]
Areas with frequent thunderstorms	[ ]	[ ]	[ ]	[ ]
Areas known for wind shear / microbursts	[ ]	[ ]	[ ]	[ ]

How many times have you encountered	never 0	a few 1 - 5	often 5 - 25	too often > 25
Moderate low level wind shear	[ ]	[ ]	[ ]	[ ]
Severe low level wind shear	[ ]	[ ]	[ ]	[ ]
A known microburst	[ ]	[ ]	[ ]	[ ]

Best story? Please describe the most encounter (i.e. max airspeed loss, altitude loss, location, your altitude/configuration/speed, etc.).

____

____

INFLIGHT QUESTIONS

1. Is the microburst a hazard to your flight?

2. What do you consider the most threatening aspect at this point in time?

POST-SCENARIO QUESTIONS

(after each display set of four approaches)

1. How would you rate the weather as a hazard to your flight prior to any deviations?

2. What made you deviate / go MAP / stay on course?

3. Did the intensity seem to be increasing / staying the same / decreasing?

4. Any remaining questions in your mind using this display?

5. Did you change anything on the approach given the display and, if so, what?

6. Rate from 1 to 4 the effectiveness of each type of graphic format in regards to:

BEST (1 2 3 or 4) WORST

	FMAP	SINGLE ICON	2-LEVEL ICON
Understandability	_______	_______	_______
Amount of information conveyed	_______	_______	_______
Confusion factor	_______	_______	_______
Trend information (intensity, direction of travel)	_______	_______	_______
Location of hazard	_______	_______	_______
General trust	_______	_______	_______

POST-FLIGHT QUESTIONNAIRE

1. How useful was the initial briefing on wind shear procedures?

2. Did you learn anything new from that briefing?_______

   If yes, what stands out most?____

____

   What else should be incorporated into it?__________________________________

3. How desirable is a wind shear display?

4. Rank the graphic formats (1 is best, 3 worst) as to which is best at:

	Fmap	Single Icon	2-Level Icon
Understandability	_______	_______	_______
Amount of information conveyed	_______	_______	_______
Confusion factor	_______	_______	_______
Trend information (intensity, direction of travel)	_______	_______	_______
Location of hazard	_______	_______	_______
General trust	_______	_______	_______

	Fmap	Single Icon	2-Level Icon
Alerting you to the immediate threat	_______	_______	_______
Conveying pertinent information	_______	_______	_______
Aiding in hazard avoidance	_______	_______	_______

5. Which format would you prefer given a:

   90 degree turn to short final. ________________________

   Time critical situation (e.g. at 2nm). ________________________

   Long range warning (e.g. at 8nm). ________________________

6. Which type of format do you prefer overall?________________________

7. Does airborne weather radar need to be on the same display for correlation?

8. Suggestions?:____

Appendix C The AHP Method

Appendix C contains information on the Analytical Hierarchy Process with examples of the three paired comparison sheets.

Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process or AHP was used in this study to produce a subjective ranking of the three windshear display formats. The AHP is able to provide quantitative results with a small number of subjects (in this case six) based on paired comparisons of the displays. Where common statistical methods produce only a relative ranking, the AHP yields a ranking with a measure of the relative "distance" between the subject compared. The AHP was developed by Saaty (1980) and has been used in a wide variety of applications including strategic planning, decision analysis, and engineering design. A short explanation on the applicability and use of AHP can be found in Mitta [1993] and Yang [1994].

With n displays to compare, all possible pairs must be considered. Thus each subject must make $n(n-1)/2$ comparisons. In this case n is three so each subject makes 3(3-1)/2 = 3 paired comparisons.

The result of a set of three comparisons from one subject is placed in a matrix. The three items or displays to be compared are set up as in Figure C.1. Using the comparison sheets, a degree of favorability can be ascertained by assigning the relative ratings a value (refer to the comparison sheets that follow). For instance, "SAME" equates to 1, "SLIGHTLY BETTER" = 3, "BETTER" = 5, and so forth. These are placed into the matrix such that if the row item is ranked higher, say "MUCH BETTER" = 7, a value of 7 is placed in that row at the position corresponding to the column variable with which it was compared. If the column item is given this higher ranking, then the reciprocal (1/7) is placed in this spot. The opposite occurs above the diagonal. Of course the comparison of an item with itself is equal to one, therefore the diagonal is the identity matrix. In the first row of the example, the Fmap is "Much Better" (7) than the Single Icon, and between "Slightly Better" and "Better" over the 2-Level Icon.

	Fmap	Single	2Level
Fmap	1	7	4
Single Icon	1/7	1	1/3
2-Level Icon	1/4	3	1

Figure C.1 Example of AHP Subject Matrix: Compiled from subject's relative ratings of each pair of display types. If the row is dominant, then the corresponding favorable high value is assigned in the appropriate column; the reciprocal is assigned otherwise.

The largest eigenvalue and its associated eigenvector (absolute value) are found through standard mathematical methods for each subject's preference vector. These are *normalized to add up to 1.0.* They are then placed in columns to form an n x N matrix, where N equals the number of subjects. This matrix multiplies a weighted subject vector (N x 1), similarly normalized, to produce a resultant *group preference*, the sum of which totals to 1.0. The "weighted" subject matrix may have equal values for each subject, but it is another tool for classification of how reliable the data from certain subjects may be compared to others. In this case all subjects were weighted equally with a value of 1/6 each.

Table B.1 Windshear Display Experiment AHP Comparison: Subject comparison values and associated eigenvalues and eigenvectors.

SUBJ #1	Single	2-Level	Fmap	Eigen-value	Eigen-vector
Single	1	1/7	1/8		0.0514
2-Level	7	1	1/7	3.3762	0.1965
Fmap	8	7	1		0.7520
#2					
Single	1	1/9	1/6		0.0484
2-Level	9	1	9	3.3674	0.7917
Fmap	6	1/9	1		0.1598
#3					
Single	1	1/5	1/7		0.2331
2-Level	5	1	8	3.2470	0.7125
Fmap	1/7	1/8	1		0.0544
#4					
Single	1	1/5	1/7		0.0647
2-Level	5	1	1/6	3.2400	0.1992
Fmap	7	6	1		0.7360
#5					
Single	1	1/7	1/7		0.0554
2-Level	7	1	1/7	3.4357	0.2027
Fmap	7	7	1		0.7418
#6					
Single	1	1/3	5		0.2969
2-Level	3	1	5	3.1356	0.6175
Fmap	1/5	1/5	1		0.0856

Analytical Hierarchy Process (AHP)

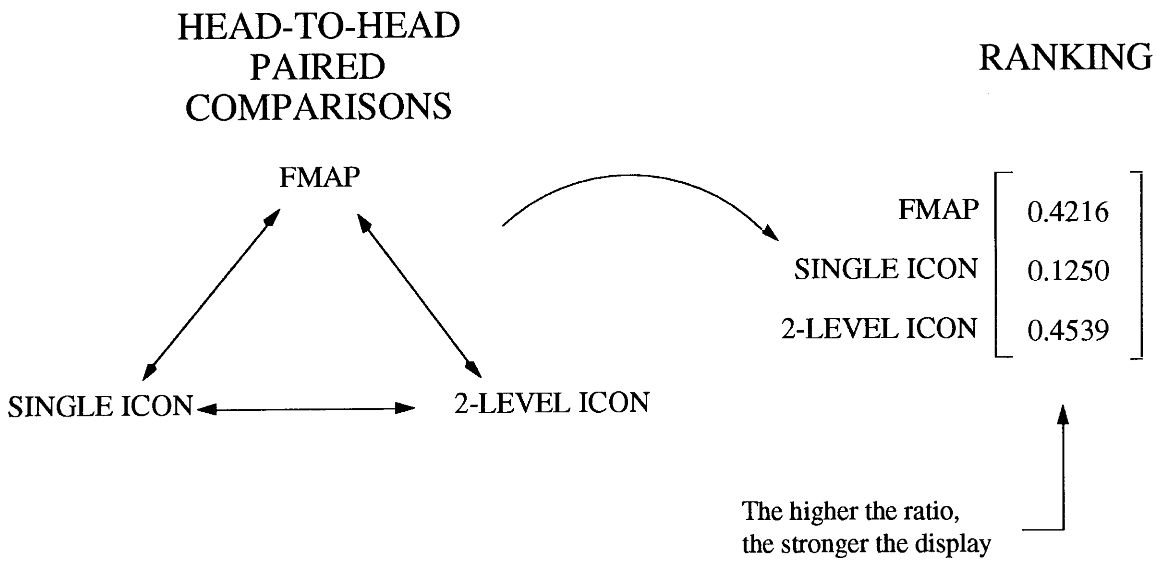


Figure C.2 AHP Comparative Results
(format courtesy of Yang, 1994)

F-MAP vs SINGLE ICON

Which is the “better” display - F-Map or Single Icon?

Use the scale below to indicate the degree in which one display is better than the other.

F-MAP better ← | → SINGLE ICON better

F-MAP																		SINGLE ICON
absolutely better		much better		better		slightly better		same		slightly better		better		much better		absolutely better		

Why? ____

____

____

____

SINGLE vs MULTI-LEVEL ICON

Which is the “better” display - Single or Multi-Level Icon?

Use the scale below to indicate the degree in which one display is better than the other.

SINGLE ICON better ← | → MULTI-LEVEL ICON better

SINGLE ICON																		MULTI-LEVEL ICON
absolutely better		much better		better		slightly better		same		slightly better		better		much better		absolutely better		

Why? ____

____

____

____

MULTI-LEVEL ICON vs F-MAP

Which is the "better" display - Multi-Level Icon or F-Map?

Use the scale below to indicate the degree in which one display is better than the other.

MULTI-LEVEL ICON better ← → F-MAP better

MULTI-LEVEL ICON																		F-MAP
	absolutely better		much better		better		slightly better		same		slightly better		better		much better		absolutely better	

Why? ____

____

____

____

Appendix D Resultant Data

This appendix contains the data compiled from objective and subjective measures used in the windshear display experiment.

Tables D.1 Objective Measures by Subject

Key: Display -- F = Fmap
S = Single Icon
M = 2-Level Icon

Direction -- LT = -1
RT = 1
STR = 0
Applies to Hold Direction & Microburst Side (when present)

SUBJECT #1

Run #	Posit	Display	Scen	Vers	Appr Abort?	Dec Dx (nm)	1st on (nm)	LT STR RT	Hold Dir	MB Side
1	Capt	S	I	2	Y	1.2	5.00	0	- 1	- 1
2	Capt	S	III	1	Y				1	0
3	Capt	S	0	1	N				1	
4	Capt	S	II	1	N		3.08		- 1	0
5	Capt	M	I	3	Y	2.0	5.50	0	- 1	- 1
6	Capt	M	II	2	Y	2.7	2.93	0	- 1	0
7	Capt	M	III	3	Y				1	0
8	Capt	M	0	3	N				- 1	
9	Capt	F	0	2	N				1	
10	Capt	F	I	1	Y	3.0	3.50	0	- 1	- 1
11	Capt	F	II	3	Y	2.8	2.95	0	- 1	0
12	Capt	F	III	2	Y				1	0

SUBJECT #2

Run #	Posit	Display	Scen	Vers	Appr Abort?	Dec Dx (nm)	1st on (nm)	LT STR RT	Hold Dir	MB Side
1	1st Off	F	I	1	Y	1.2	4.76	0	- 1	- 1
2	1st Off	F	III	2	Y				1	0
3	1st Off	F	II	3	N		2.80		- 1	0
4	1st Off	F	0	2	0				1	
5	1st Off	S	0	3	N				- 1	
6	1st Off	S	II	1	Y	2.2	2.80	- 1	- 1	0
7	1st Off	S	I	3	Y	1.3	2.70	1	- 1	- 1
8	1st Off	S	III	1	Y				1	0
9	1st Off	M	I	2	Y	2.5	4.00	1	- 1	- 1
10	1st Off	M	0	1	0				1	
11	1st Off	M	II	2	N		2.80		- 1	0
12	1st Off	M	III	3	Y				1	0

SUBJECT #3

Run #	Posit	Display	Scen	Vers	Appr Abort?	Dec Dx (nm)	1st on (nm)	LT STR RT	Hold Dir	MB Side
1	Capt	S	II	1	Y	2.4	2.93	0	- 1	0
2	Capt	S	0	3	N				- 1	
3	Capt	S	III	2	Y				1	0
4	Capt	S	I	2	Y	1.2	5.00	0	- 1	- 1
5	Capt	F	I	3	Y	2.0	3.92	0	- 1	- 1
6	Capt	F	III	1	Y				1	0
7	Capt	F	II	3	N		2.93	0	- 1	0
8	Capt	F	0	2	N				1	
9	Capt	M	I	1	Y	1.3	2.00	0	- 1	- 1
10	Capt	M	II	2	N		3.08		- 1	0
11	Capt	M	0	1	N				1	
12	Capt	M	III	3	Y				1	0

SUBJECT #4

Run #	Posit	Display	Scen	Vers	Appr Abort?	Dec Dx (nm)	1st on (nm)	LT STR RT	Hold Dir	MB Side
1	Capt	M	0	3	N				-1	
2	Capt	M	I	1	Y	0.7	1.00	0	-1	-1
3	Capt	M	II	2	Y	3.0	3.08	-1	-1	0
4	Capt	M	III	2	Y				1	0
5	Capt	S	III	3	Y				1	0
6	Capt	S	0	1	N				1	
7	Capt	S	I	2	Y	3.1	3.31	0	-1	-1
8	Capt	S	II	1	Y	2.4	2.63	0	-1	0
9	Capt	F	I	3	Y	2.1	5.60	0	-1	-1
10	Capt	F	0	2	N				1	
11	Capt	F	II	3	Y	2.8	2.93	0	-1	0
12	Capt	F	III	1	Y				1	0

SUBJECT #5

Run #	Posit	Display	Scen	Vers	Appr Abort?	Dec Dx (nm)	1st on (nm)	LT STR RT	Hold Dir	MB Side
1	Capt	M	I	2	Y	2.4	4.76	0	-1	-1
2	Capt	M	II	1	Y	2.6	3.01	1	-1	0
3	Capt	M	III	3	Y				1	0
4	Capt	M	0	1	N				1	
5	Capt	F	II	3	Y	3.0	3.08	1	-1	0
6	Capt	F	III	2	Y				1	0
7	Capt	F	0	3	N				-1	
8	Capt	F	I	1	Y	1.0	2.60	1	-1	-1
9	Capt	S	0	2	N				1	
10	Capt	S	I	3	Y	2.0	2.60	0	-1	-1
11	Capt	S	II	2	N		2.93		-1	0
12	Capt	S	III	1	Y				1	0

SUBJECT #6

Run #	Posit	Display	Scen	Vers	Appr Abort?	Dec Dx (nm)	1st on (nm)	LT STR RT	Hold Dir	MB Side
1	1st Off	F	I	2	Y	1.2	5.37	0	- 1	- 1
2	1st Off	F	III	3	Y			0	1	0
3	1st Off	F	II	1	Y	2.3	3.08	- 1	- 1	0
4	1st Off	F	0	2	N				1	
5	1st Off	M	0	3	N				- 1	
6	1st Off	M	II	3	N		2.93		- 1	0
7	1st Off	M	I	1	Y	2.2	3.50	0	- 1	- 1
8	1st Off	M	III	2	Y			- 1	1	0
9	1st Off	S	I	3	Y	1.7	5.29	0	- 1	- 1
10	1st Off	S	0	1	N				1	
11	1st Off	S	II	2	N		3.01		- 1	0
12	1st Off	S	III	1	Y			0	1	0

Table D.2 Subjective Ranking Results by Category

UNDERSTANDABILITY

Subj #	Fmap	Single Icon	2 - Level Icon
1	1st	3rd	2nd
2	2nd	3rd	1st
3	3rd	2nd	1st
4	1st	3rd	2nd
5	1st	3rd	2nd
6	3rd	1st	2nd

HAZARD LOCATION

Subj #	Fmap	Single Icon	2 - Level Icon
1	1st	2nd	3rd
2	2nd	3rd	1st
3	2nd	3rd	1st
4	1st	2nd	3rd
5	3rd	1st	2nd
6	2nd	3rd	1st

AMOUNT OF INFORMATION

Subj #	Fmap	Single Icon	2 - Level Icon
1	1st	3rd	2nd
2	1st	3rd	2nd
3	2nd	3rd	1st
4	1st	3rd	2nd
5	1st	3rd	2nd
6	2nd	3rd	1st

PERTINENT INFORMATION

Subj #	Fmap	Single Icon	2 - Level Icon
1	1st	3rd	2nd
2	2nd	3rd	1st
3	2nd	3rd	1st
4	1st	3rd	2nd
5	1st	3rd	2nd
6	2nd	3rd	1st

LEAST CONFUSING

Subj #	Fmap	Single Icon	2 - Level Icon
1	2nd	1st	3rd
2	2nd	3rd	1st
3	3rd	1st	2nd
4	1st	3rd	2nd
5	1st	3rd	2nd
6	3rd	1st	2nd

AID IN HAZARD AVOIDANCE

Subj #	Fmap	Single Icon	2 - Level Icon
1	1st	3rd	2nd
2	2nd	3rd	1st
3	3rd	2nd	1st
4	1st	2nd	3rd
5	1st	3rd	2nd
6	3rd	2nd	1st

TREND INDICATOR

Subj #	Fmap	Single Icon	2 - Level Icon
1	1st	3rd	2nd
2	2nd	3rd	1st
3	2nd	3rd	1st
4	1st	3rd	2nd
5	3rd	1st	2nd
6	2nd	3rd	1st

References

Bowles, R. L., 1990: "Reducing Windshear Risk Through Airborne Systems Technology." *17th Congress of the International Council on the Aeronautical Sciences*, Stockholm.

Bowles, R. L., 1993: Convening speech, 5th and Final Combined Manufacturers' Windshear Conference, Hampton Roads, VA.

Campbell, S. D., Merrit, M. W., DiStefano, J. T., 1989: "Microburst Recognition Performance of TDWR Operational Testbed." *Preprints, 3rd International Conference on Aviation Weather Systems*, Anaheim, CA.

Federal Aviation Administration, 1990: Technical Standing Order TSO C-117, *Airborne Windshear Warning and Escape Guidance Systems for Transport Airplanes.*

Federal Aviation Rules, 1990: FAR 121.358.

Hansman, R. J., Wanke, C. R., Kuchar, J., Mykityshyn, M. Hahn, E. Midkiff, A., 1992: "Hazard Alerting and Situational Awareness in Advanced Air Transport Cockpits." *Preprint, 18th ICAS Congress*, Beijing, China.

Hogg, R. V., and Ledolter, J., 1992: *Applied Statistics for Engineers and Physical Scientists,* 2nd ed., New York, Macmillan.

Mitta, D. A., 1993: "An Application of the Analytic Hierarchy Process: A Rank-Ordering of Computer Interfaces." *Human Factors*, vol. 35(1).

Newton, D., 1989: "Weather Accident Prevention Using the Tools that We Have," AIAA 89-0707, *27th Aerospace Sciences Meeting*, Reno, NV.

Oseguera, R. M., 1993: Presentation, 5th and Final Combined Manufacturers' Windshear Conference, Hampton Roads, VA.

Oseguera, R. M., 1994: Personal Communication.

Oseguera, R. M., and Bowles, R. L., 1988: "A Simple Analytic 3-Dimensional Downburst Model Based on Boundary Layer Stagnation Flow," NASA Technical Memorandum 100632.

Proctor, F. H., 1987: *The Terminal Area Simulation System - Volume I: Theoretical Formulation; Volume II: Verification Cases*, NASA CR-4046 and CR-4047, DOT/FAA/PM-86/50.

Saaty, T. L., 1990: "How to Make a Decision: The Analytic Hierarchy Process." *European Journal of Operational Research* (Special Issue: Decision Making by the Analytic Hierarchy Process: Theory and Applications), vol. 48(1).

Siegel, A. F., 1990: *Practical Business Statistics,* Boston, Richard D. Irwin, Inc.

Vicroy, D. D., 1991: " A Simple, Analytical, Axisymetric Microburst Model for Downdraft Estimation," NASA Technical Memorandum 104053.

Wanke, C. R., and Hansman, R. J., 1992: "Experimental Evaluation of Candidate Graphical Microburst Alert Displays," AIAA 92-0292.

Wanke, C. R., and Hansman, R. J., undated: "Hazard Assessment and Cockpit Presentation Issues for Microburst and Alerting Systems," Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA.

Wanke, C. R., and Hansman, R. J., 1990: *Operational Cockpit Display of Ground-Measured Hazardous Windshear Information*, SM Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA.

Wanke, C. R., and Hansman, R. J., 1992: *Multidisciplinary Design of an Integrated Microburst Alerting System*, PhD Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA.

Wanke, C. R., 1993: "A Data Fusion Algorithm for Multi-Sensor Microburst Hazard Assessment," *Preprint AIAA Atmospheric Flight Mechanics Conference*, Hilton Head, SC.

Yang, L. C., 1992: "The Treatment of Ties for the Paired Sign Test," Term Project, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA.

Yang, L. C., 1994: *A Human Performance Evaluation of Enhanced Vision Systems for Aircraft Approach and Landing Using Computer Simulated Sensor Imagery*, SM Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA.