Joint Airport Weather Studies(JAWS) Project

John McCarthy
National Center for Atmospheric Research

The Joint Airport Weather Studies (JAWS) Project is a joint program that is funded primarily by the National Science Foundation, which is the parent organization of the National Center for Atmospheric Research (NCAR). It is joint between the University of Chicago and NCAR; and there are three scientists that are the scientific investigators: Ted Fujita, Jim Wilson and myself; the latter two are from NCAR and Ted Fujita is from the University of Chicago. NASA, NOAA, and FAA have also contributed heavily to the project.

The major objectives of the JAWS Project are a fundamental description of the phenomenon, a determination of the hazard potential and a definition of a protection and warning system, all of which are relative to low-level wind shear. The focus of the entire project has been all aspects that we could address of the low-level wind shear phenomenon. The principal focus, however, has been the microburst. The microburst (Figure 1) is fundamentally a rather simple atmospheric flow. It is a downdraft that, upon approaching the surface, spreads out horizontally, producing what is called a diverging radial flow in all directions. Thus, for any direction that an aircraft flies through the microburst, it will first encounter increasing head winds; then the remnants of the downdraft; and then, increasing tail wind (Figure 2).

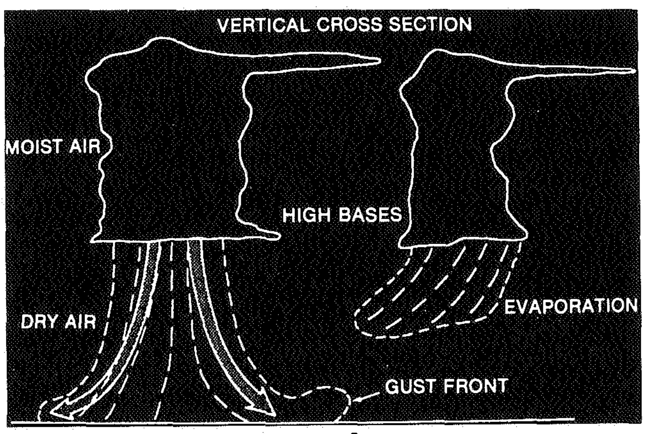

Figure 1.

The microburst feature, no doubt, has been around a long time. It was not identified, however, until the last few years. Probably about 1977, we had our first evidence of the existence of the microburst; but, because it is so small and short-lived, it has been a difficult feature to address scientifically and technologically. The focus of the JAWS Project has been to address that feature.

The location of our experiment was chosen to be the Stapleton International Airport in Denver, Colorado. Figure 3 is a picture of the airport

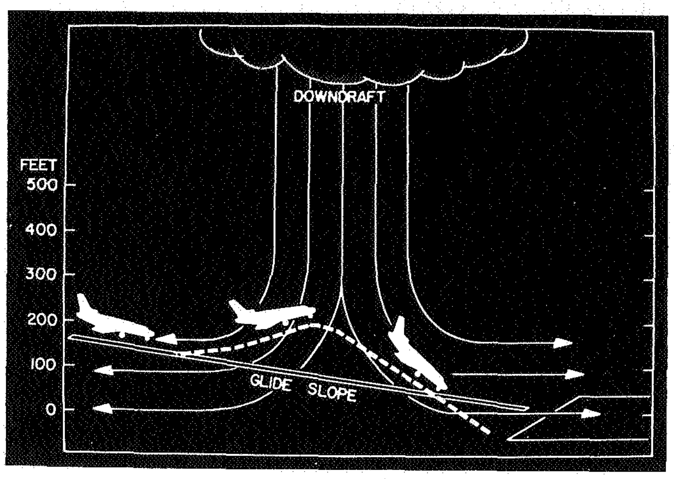

Figure 2.

taken from one of our research aircraft. It should be obvious, from this picture, that we were able to fly very closely around Stapleton Airport in many contexts. I would like to emphasize that the support we obtained from air traffic control to conduct this experiment was phenomenally good.

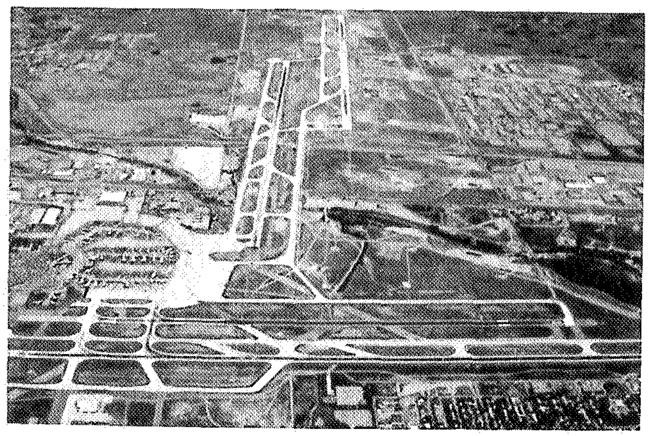

Figure 3.

Many observational tools were used in the experiment, but the principal observational tool was the Doppler radar. Doppler radar is a conventional weather radar with additional hardware that allows us to measure the velocity component of the atmosphere in a radial direction to the radar. It is the key to our observational system.

The blue dots on Figure 4 represent surface measurement systems which measured wind speed and direction, temperature, humidity, pressure and rainfall. Doppler radars were located at each point of the triangle shown in the figure. Basically, the entire area seen in the figure represents our research area, and it covers the northeastern quadrant of Denver.

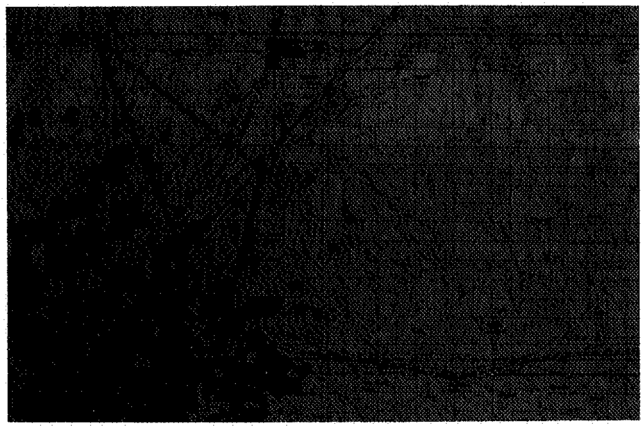

Figure 4.

Figure 5 is simply a summary of what I will cover in this presentation of the JAWS Project: the microburst, a summary of data collection highlights; some impressions on low-level wind shear detection and warning, which is the major focus of our program; some analyses priorities and some recommendations and directions.

The JAWS Project has just ended its field phase. We have lots of data that have not yet been analyzed so that I am presenting impressions, not definitive results. Much analysis is needed to make those results concrete.

1. What is the Joint Airport Weather Studies Project
2. The Microburst
3. A Summary of Data Collection Highlights
4. Preliminary Impressions on Low-level Wind Shear
5. Analysis Priorities
6. Some Recommendations and Directions
7. Discussion

Figure 5. Summary of Presentation

Figure 6 shows the organizations that participated in this project. These were NCAR, the University of Chicago, and the Federal Government agencies shown in Figure 6b. The Universities which participated are shown in Figure 6c. We had a rather broad participation from the university community.

Figure 6d shows a very important and, frankly, a surprise addition to our program. This was the Royal Signals and Radar Establishment and Royal Aircraft Establishment from the United Kingdom. Most of the airborne wind shear detection warning concepts were flown on the aircraft supplied by this group.

The program had three components. Basic studies are ostensibly the National Science Foundation's concentration in the program. What is the microburst? What is its four-dimensional wind structure; the spatial and temporary dimensions? Where did it come from and what are the conditions that set up the existence of a microburst type feature? How long do they last? Why do they die? What is the relationship between small-scale and large-scale? These are very fundamental questions that the program addresses.

(a)
OPERATORS

- The National Center for Atmospheric Research
- The University of Chicago

(b)
FEDERAL GOVERNMENT

- National Science Foundation
- Federal Aviation Administration
- National Aeronautics and Space Administration
  - Marshall Space Flight Center
  - Langley Air Research Center
  - Dryden Flight Research Facility
- National Oceanic and Atmospheric Administration
  - Prototype Regional Observing and Forecasting Service (PROFS)
  - Wave Propagation Laboratory
  - Office of Weather Research and Modification
  - National Weather Service
  - Research Flight Facility
- Transportation Systems Center (Dept. of Transportation)
- Next Generation Radar (Depts. of Commerce, Defense, and Transportation)

(c)
UNIVERSITIES

- University of Chicago
- Massachusetts Institute of Technology
  - Department of Meteorology
  - Lincoln Laboratory
- University of Wyoming
- University of Tennessee Space Institute

(d)
FOREIGN

- Royal Signals and Radar Establishment, United Kingdom
- Royal Aircraft Establishment, United Kingdom

Figure 6. Organizations Participating in JAWS

A second major component of the program is aircraft performance. How do aircraft perform in the face of wind shear? (A lot of work went into this to clarify our thinking before we began the project.) Much of the interface between the atmosphere and aircraft performance was set up in discussions at the workshop on meteorological inputs to aviation systems held annually at the University of Tennessee Space Institute.

It was our intention when we set up the program, to have a very careful examination of flight data recorder from operational air carrier aircraft operating in the JAWS environment. However, we could not obtain the necessary funds. Thus, we did not study operational air carrier aircraft performance in the kind of quantitative detail that we wanted.

A third area of study was made by the Department of Transportation, Transportation Systems Center, on air traffic movements in the weather conditions that we faced in the JAWS Project. This work was done for FAA; it examined how the air carrier, air traffic flow was affected by not only wind shear, but the thunderstorm environment. Some very excellent data were obtained.

An extremely important part of JAWS is the detection and warning aspects. We have three surface sounding-type systems that we examined (or are in the process of examining). The output from the Low-Level Wind Shear Alert System (LLWSAS), which is currently at Stapleton, was recorded. It was through arrangements with FAA that we were able to record the data which, you know, is not normally recorded. The spacing of the LLWSAS between the center field station and the outlying station on the average at Stapleton is about six kilometers, a rather important number to remember; roughly 3.6 miles between the center field and the outlying station.

We had our own PAM (Portable Automated Mesonet) systems located where the blue dots are shown in Figure 4. Spacing between these wind recording stations was about three kilometers. Therefore, we had a system that was about twice as dense as the LLWSAS at the Denver airport.

Finally, we had a pressure jump array system developed by the NOAA Wave Propagation Laboratory, which essentially looks at rapid surface pressure fluctuations as a means of identifying wind shear.

All airborne systems flown were on the Hawker-Siddeley 125 from England; we had a really excellent platform from England. The air speed and ground speed procedure developed by FAA was flown on this aircraft. The aircraft had a forward-looking Doppler lidar that looked out the nose of the aircraft and measured the longitudinal component of wind ahead of the airplane with about six seconds lead time. Finally, it had a Smith's Industry's vertical velocity energy rate system, which is fundamentally an accelerator concept that allows the pilot to understand that he is in a wind shear situation.

A number of Doppler radars were used at the center field of Stapleton Airport looking in all directions. Most of the time they were looking up the approach and departure corridors, measuring the head wind/tail wind component to or from the airport. We also had what I consider the NEXRAD concept. NEXRAD stands for the Next Generation Radar program. It is a joint program between NOAA, FAA and the Department of Defense to Dopplerize the national weather radar system in this country. NEXRAD addresses many applications of Doppler radar in an area-wide mode and it also addresses wind shear explicitly. Finally, at the airport center, we had a NASA Doppler Lidar (Lidar is a laser system as opposed to a pulse microwave radar system), which measures the longitudinal components of the wind.

The Doppler radars in the JAWS Project are located as shown in Figure 4. Figure 7 shows our main radar control center with the front range of Colorado in the background. The interior of our control center is shown in Figure 8. Our entire operation was run from this center. It was a tremendous center. Some of you visited it. It was a very impressive control center where the aircraft and the complete operations were directed.

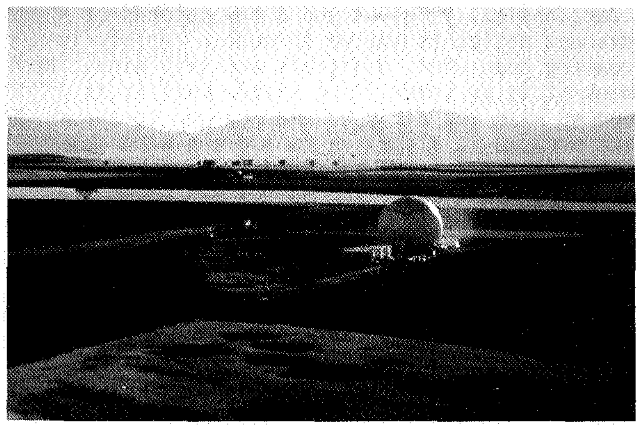

Figure 7.

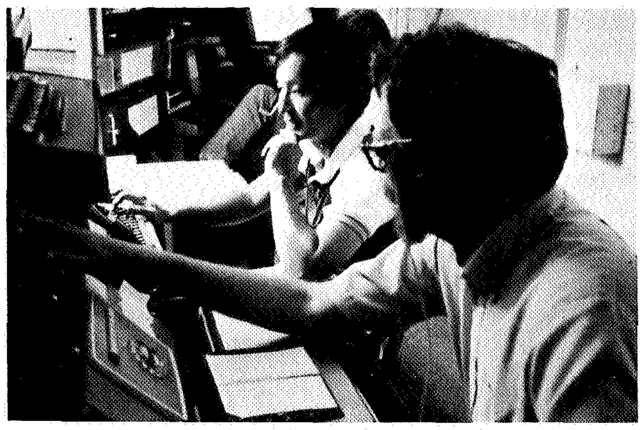

Figure 8.

Figure 9 is a picture of our five centimeter Doppler radar located at Stapleton Airport with another example of one of several thunderstorms and electric storms that occurred in the vicinity of the airport. The terminal building is in the immediate background.

In terms of lidars, we also had the NASA lidar at CP-4 and a NOAA lidar at CP-3. As I mentioned, we also had an airborne lidar on the HS-125. Figure 10 shows the HS-125 with a wind probe on the nose. The lidar looks out ahead of the aircraft at all times and gives you about a four-second lead of what the winds are going

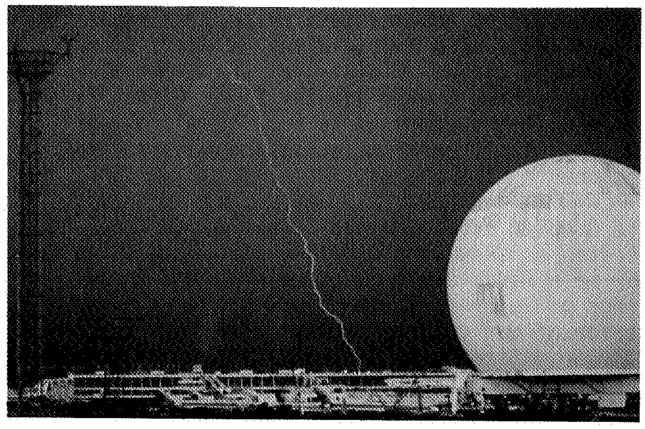

Figure 9.

to be when you get there. The forward-looking lidar, basically, gives you a few seconds of advanced notice as you go through a rapidly increasing head wind, downdraft and tail wind. We think it is an interesting system when it is coupled with the air speed and ground speed concept because it allows us to address wind shear with a slight lead time. Lead time on approach would represent about two-thirds of the spool-up time required if you were to encounter a sudden wind shear. Therefore, it is an exciting system.

In its current configuration, the system does not work on takeoffs. There is no question that it certainly will operate, but I think its usefulness is obviously less on takeoff mode than on landing mode. I think that the airborne systems are basically designed for approach rather than departure. However, there has been quite a bit of discussion about trying to develop a forward-looking Lidar that has scanning capabilities and considerably greater range. It is a concept that we ought to pursue. If you extend the range and give it some scanning capabilities, then it would be a viable system on takeoff as well.

Figure 10.

Lasers are, of course, subject to attenuation, particularly if they are CO_2 lasers and operate in the visible range. It does not penetrate into cloud; but it has a rather excellent ability to penetrate some distance into precipitation, including heavy precipitation. Therefore, I think in the wind shear context, it is really a very viable system. If it is foggy or cloudy, it is not viable; so that is a limitation.

The lidar, like the radar, will work in clear air because, in fact, the air is not clear. There is dust and there are all kinds of scatters out there, particularly at the low levels. If you get up in the high altitude, it doesn't work because the air is clean. However, in the airport environment, there is no problem seeing the wind with a laser.

The HS-125 also had a Smiths Industry system, which is basically an accelerometer system. If you get an upward acceleration difference, it implies a head wind increase, and there is a transition until you get a sudden downward acceleration, which implies a tail wind. It is an inferred system; it is not dissimilar in concept with the Safe Flight type system and I will make some comments on all of these systems a little bit later on.

I have already mentioned the surface observation systems which are portable and automated. NCAR has 27 such stations. A PAM system, located near Stapleton, is shown in Figure 11.

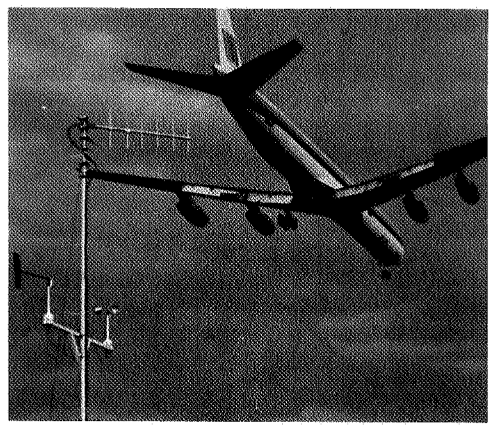

Figure 11.

In terms of aircraft, we had the research King Air from the University of Wyoming; the NCAR Sabreliner; and the NASA B-57, which carried out a gust gradient experiment during JAWS. We also had the NOAA P-3 aircraft primarily to test an airborne Doppler radar. The King Air aircraft is shown in Figure 12. We had very high resolution air motion sensing on it as well as some excellent cloud physics instrumentation to study precipitation; precipitation rates in the downdraft, which are important in the heavy rain kinds of studies as well as in the evolution of the downdraft in precipitation. This is a very important part of the project.

During the project, we had lots of heavy rain. We had a number of cases where the reflectivity values were in excess of 70 DB. Of course, that is probably hail contaminated in terms of the reflectivity. We had many cases of strong wind shear in heavy rain. An important part of that study with the King Air aircraft is that by measuring the precipitation spectrum in great detail, we will be able to determine the negative buoyancy associated with precipitation loading in the precipitation shaft and to understand why the downdraft occurs and why it is so strong.

The NASA B-57 was in the project to study gust gradients. It had a gust probe on each wing tip, and a gust probe on the nose. The gust gradient program is designed to study turbulence and wind shear, not only in the longitudinal sense, as the aircraft flies, but also in the latitudinal cross-spanwise sense. This is a very important basic study.

Figure 12.

The NOAA P-3 had an airborne Doppler radar that got some outstanding results in microbursts. We were able to look down, right down through the center of a microburst on the 29th of June and collect data on the vertical velocity right down to the surface.

Without getting too far into the technical details, I would like to say that one of the things we are trying to do in the JAWS Project is to take Doppler radar from three ground Dopplers. Remember now, that a single Doppler radar gives you only the radial component. So, if we want to reconstruct the three-dimensional wind field, we have to look at it from three different directions. We have rarely had the opportunity to look straight up through a microburst because they are so small and don't last very long. Therefore, we have to infer through the equation of continuity what the vertical velocity structure will be. That is a viable thing to do. However, what we have with the P-3 airborne Doppler is a measure of direct vertical incidence all the way through a microburst. Now we are able to understand the shape function of how the vertical draft converts to a horizontal draft from direct measurement. It is very important, scientifically and technique-wise, to analyze this data set.

I want to now spend a few minutes on describing the microburst. The microburst is a downdraft. We have known about downdrafts for a long time. As a matter of fact, when I was in Washington last week, an employee of NSF told me about a sketch done in about 1650 in England of something that closely resembles a microburst. Thus, people have seen things like microbursts for a long time. It is downdraft in its basic form. When it approaches the ground, it spreads out horizontally. The microburst is defined as a downdraft and outflow, which is no bigger than 4 kilometers or 2.4 miles, horizontally. It is very small, compared to a large supercell, severe thunderstorm. In Denver, we encountered two types...one that was associated with the large thunderstorm, and another that seemed to occur in very benign-looking clouds. These may appear very weakly on our standard weather radar and look benign from a distance; but, in fact, they can produce very strong flows near the surface.

As far as any relationship between the amount of rain that is measured at the surface and the intensity of wind, we think there is no correlation. The reason I say that is because if we have low-level wind shear in a microburst context, it appeared to be just as likely to occur in a little or no-rain situation, as it did in a very heavy rain situation. This suggests that reflectivity measured by ground-based radars, as well as airborne radars, has no correlation between storm intensity and wind shear. This, we believe, is exactly right in the microburst context. The larger and more severe the thunderstorm, the more likely it will be to produce a gust front, which is a large-scale system. However, in terms of the microburst, i.e., the small-scale wind shear event, it appears to us, in a preliminary sense, that it is uncorrelated; a very significant result in our opinion.

Again, referring to Figure 2, why we think a microburst is such an insidious wind shear event is that it is a downdraft and radial outflow. It is very small and rather symmetric; like a jet of water from a hose directed towards the surface of the ground, it spreads out in all directions.

If you fly through a microburst with an airplane, you get the same thing every time, in a conceptual sense. You get a rapidly-increasing head wind, which suddenly changes to a rapidly-increasing tail wind. When you cross through the center, you encounter the remnant of the downdraft.

The problem with the microburst, as we see it, based on some of the aircraft performance studies we have done, is that you get a rapidly-increasing head wind when you first encounter a microburst. This is good news, resulting in increased lift, but decreased airspeed. However, the head wind suddenly changes rapidly to a tail wind, killing the aerodynamic lift.

I believe that approximately 80 percent of the problem with wind shear is loss of lift due to the decaying wind speed horizontal component. The downdraft and what is left of it is certainly not helping the aircraft. It is acting in the wrong direction, downward.

Now, let me contrast the microburst flow from that of a gust front. I think this is very important. Figure 13 is a picture of a gust front. A gust front is produced by a downdraft and outflow, but the outflow has become very large-scale. It may be a front, or like a cold front that stretches out ahead of a thunderstorm for many, many kilometers. Figure 16 is a picture of a cross-section through a gust front. A gust front flows outward from a thunderstorm into quiescent air; thus, cold air flows over the ground while warm moist air flows up into the thunderstorm. The flow is fundamentally a converging phenomenon; that is, cold air is impacting warm air. If you fly through a gust front at low levels, as illustrated in Figure 14, you may have a little lift loss in the warm air accelerating over the cold air; but, as soon as you penetrate the gust front, you get a lift increase because you are entering a rapidly-increasing head wind.

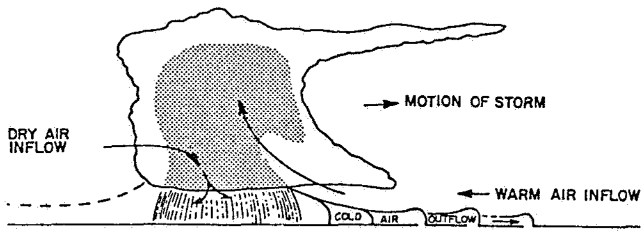

Figure 2.1 Typical thunderstorm cross section (schematic) [22].

Figure 13.

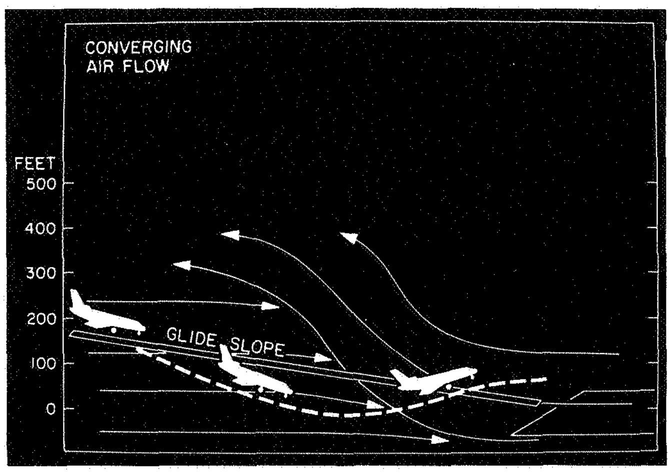

Figure 14.

Penetrating a gust front, in my opinion, is an energy builder for the aircraft, but a microburst is an energy loser. That is, in a diverging outflow (microburst), you tend to lose lift as you penetrate it; but a gust front, in a general sense, is probably an energy gainer.

This is significant because five years ago, we thought the gust front was the name of the game. We thought in the research community that a gust front was the killer in aircraft accidents. We did a lot of work in that area. A lot of work was done at NSSL, and gust fronts were considered to be really a very serious situation. However, it is our opinion in the JAWS Project that the gust front is a larger-scale feature that probably is not the killer in the generic sense. So, we are actually now concentrating on a much smaller scale, that we think is important. I'm not saying, of course, that gust fronts are not an aviation hazard; but there is an evolution in our thinking. We are beginning to believe that the aviation hazard is more associated with a small-scale event than a gust front. I'm not recommending flying through gust fronts. There are some hazardous features in gust fronts. They are turbulent. We think there have been several accidents associated with the turbulence in gust fronts.

Figure 15 is a composite picture of a dry microburst situation over Stapleton Airport. Frequently, a 50-, 60-, 70-knot differential at the surface can occur with this kind of feature. This is an important picture because it shows what a dry microburst can look like. They don't look too serious with the eyeball, but it is a visual clue. Don't fly through virga shafts, i.e., something like that illustrated in the picture at Denver, when you are on immediate approach or takeoff. On one day, we had an 80-knot differential on the north-south runway in Stapleton for this kind of situation (Figure 15); dry, reflectivity values from radar about Level 2. You fly through this situation and get a few drops of rain on the windshield; but you get tremendous wind shears.

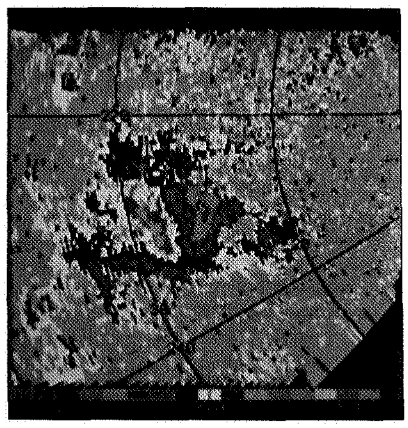

Figure 15.

Figure 16 is a good picture of what a dry microburst looks like from the air. In this picture, a microburst has hit the ground and is spreading out horizontally, creating a ring of dust. The ring goes all the way around the back side, although the picture does not show it terribly well. If you see such a dust ring when you are sitting on the runway or on approach, we recommend that you do not fly through it. It may be a visual clue to a very severe wind shear condition. We don't have a picture of it, but a pilot reported seeing the trees blowing out radially when looking down on approach to

Stapleton. This indicates the wind was blowing out in all directions.

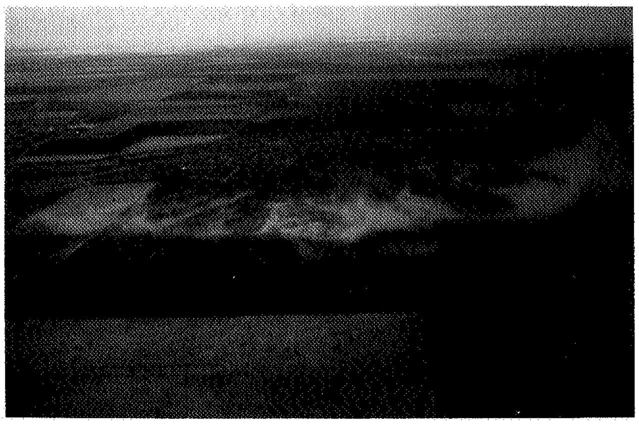

Figure 16.

The important point from this discussion is that there are certain visual clues that are associated with the microburst. We are recommending to FAA that they produce a revised information film to address the visual clues of microbursts, the simulator aspects of microbursts, and finally, the radar aspects of microbursts. These are some of the things we think can help; and one of the first things we can do with JAWS results is to put out a revised information film that gets to the core of the issue and helps raise visual consciousness of the phenomenon.

Now, I would like to show you what a microburst observed during the JAWS Project this summer looks like on Doppler radar. Figure 17 is a photograph of the Doppler radar scope. The radar is located to the right at the point where the horizontal lines converge. The circular lines are spaced at 10 kilometers. The line farthest to the right is 20 kilometers from the radar. Figure 17 is at zero degrees elevation, such that we are looking just above the surface about 28 kilometers away from the radar. The colors represent the magnitude of the Doppler velocities according to the color code given at the bottom of the figure. Only the component of velocity towards or away from the radar is displayed; that is all you can measure with a single Doppler radar. The figure shows a down-

Figure 17.

draft which has reached the surface and has spread out in all directions horizontally, but remember, we can only see the component towards or away from the radar.

The green biological tones represent air moving towards the radar and the browns represent air moving away from the radar. Every color change in the color coding represents 5 knots of increase or decrease in wind speed. Now, consider the evolution of the microburst as a function of time.

Figures 18 a - f are a sequence of pictures of the same microburst as it evolves in time. The time of the first picture, Figure 18a, is 1641 local time, on the 14th of July. At this time, the low-level velocities are benign. Each color change represents 5 knots, so there is 15 knots of velocity represented; no significant microburst features. Figure 18b is two minutes later. We now have the beginning of what we call a diverging outflow, as seen by Doppler radar with air moving away and air moving towards the radar, as indicated by the changing colors. A microburst has hit the ground and has begun to spread out. There are now five (5) different color changes shown on this diverging outflow; five times five is 25 knots...not a particularly serious situation yet. Note the total dimension from maximum head wind to maximum tail wind is slightly less than 2 kilometers. Three minutes later (Figure

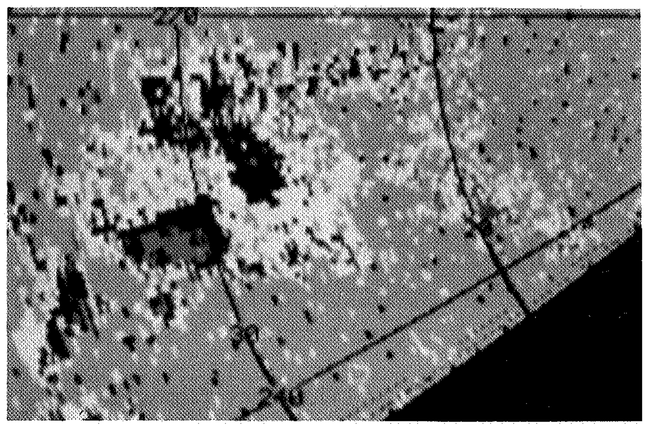

Figure 18a.

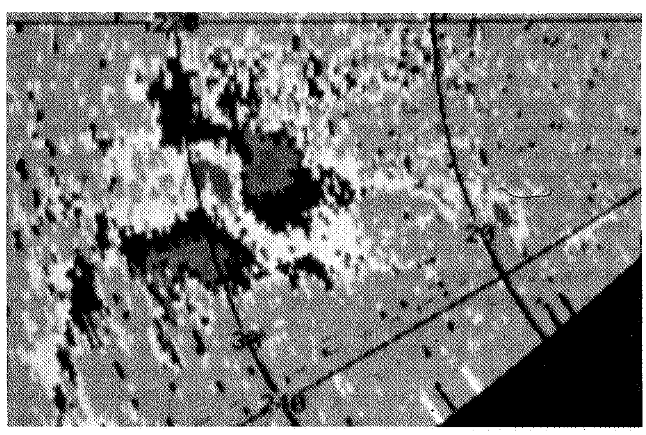

Figure 18b.

18c) there are eight color changes, i.e., 40-knot differential across roughly the same 2 kilometers, a very small feature. The time at the top of the figure is now 1646. Five minutes previously there was nothing in terms of wind shear.

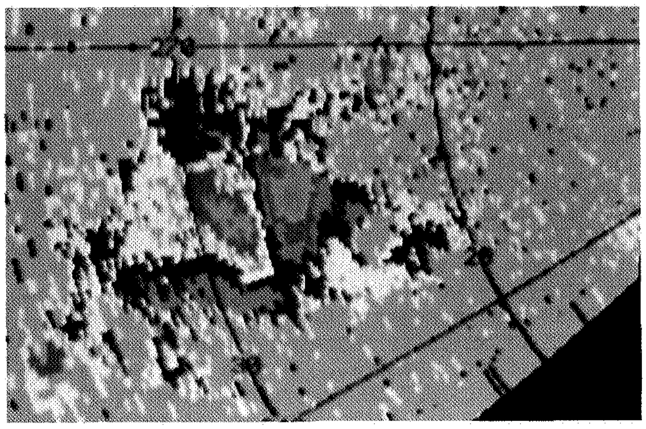

Figure 18c.

Figure 18d is at time 1648; we are now 7 minutes from when there was nothing and we have reached the maximum velocity differential. Eleven different color codes; 55-knot differential. The

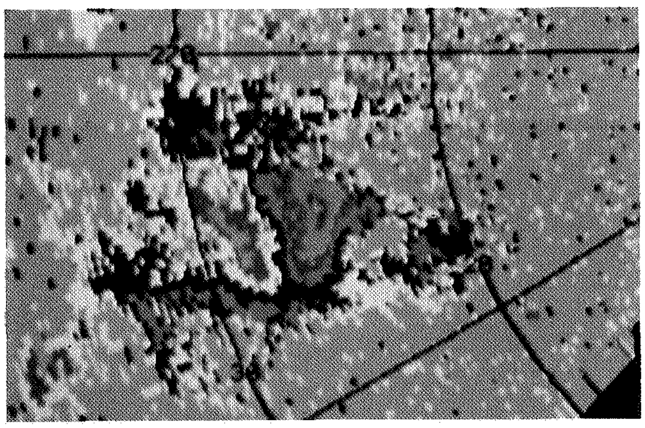

Figure 18d.

feature is about 2-1/2 kilometers from peak to peak. Figure 18e, photographed another 2 minutes later, shows the microburst is falling apart rapidly; it is spread out; the distance between peak velocities is about 5 to 6 kilometers. Figure 18f, the last picture, is 52 past the hour and shows the same kind of wind speed we had in the beginning (Figure 18a). The microburst is gone. The entire evolution of the microburst was about 6 minutes. It never got bigger than about 2-1/2 or 3 kilometers in its most intense form.

At Stapleton, the spacing between the LLWSAS field anemometer and the outlying station anemometer is 6 kilometers. A LLWSAS is not going to see such a small feature.

Commonly, microbursts are 1 to 3 kilometers in maximum dimension, when at their maximum inten-

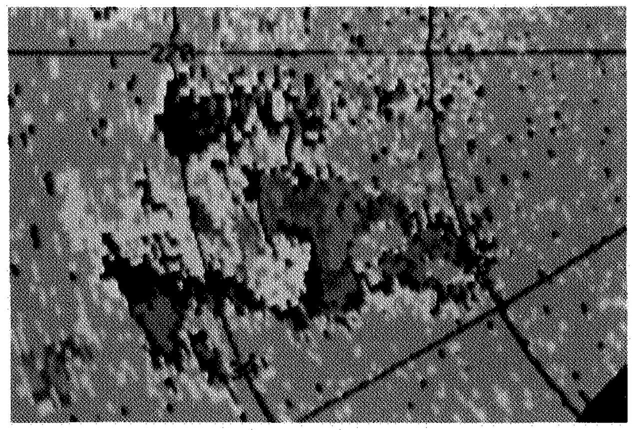

Figure 18e.

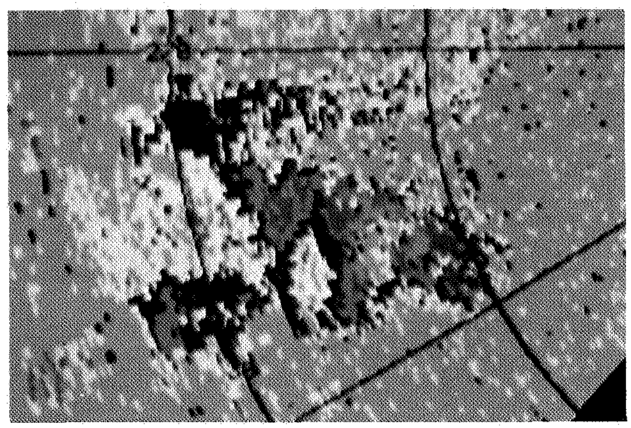

Figure 18f.

sity. When they hit the ground, they accelerate and then die. They are very small and they don't last very long.

We didn't know about microbursts a few years ago. We began to surmise their existence after Eastern 66, Continental 426 and a number of other aircraft accidents; but we didn't have a handle on the short-time scale, the intensity and the small spatial dimension.

If you look at the microburst in the vertical direction at its time of maximum intensity (48 past the hour), it fades fast above 900 feet. At approximately 500 meters above the ground, or at an outer marker height, there is no sign of the microburst on the radar. This is what you would expect because it is a surface feature. It hits the ground and spreads out. It is a downdraft that converts into a horizontal flow close to the ground. (Note: downdrafts are not seen on a single Doppler radar.)

We have just looked at one record of a microburst measured during the JAWS Project. We have an immense amount of other recordings and data as indicated in Figure 19. The JAWS Project consisted of 91 possible operational days (from the 15th of May to the 13th of August). Of that total, we had only 16 days where there was no convective weather.

	Number of Events
Microbursts (<4 km)	62
Microbursts in Good Dual Doppler Coverage	54
Downbursts (>4 km)	14
Virga but No Outflow (null cases)	18
Gust Fronts	35
Mesocyclones	20
Tornadoes	7
Funnel Clouds	2

Figure 19. JAWS Data Collection Highlights

We had expected, when we began the project, to get maybe 25 microbursts this summer. We got 62 microbursts, i.e., diverging outflows less than 4 kilometers in horizontal dimension. Ten or 12 of these microbursts were measured with dual Doppler radars. (Dual Doppler allows us to reconstruct the velocity structure in three dimensions.) We got 54 downbursts in dual Doppler, which are distinguished from microbursts because the outflow is greater than 4 kilometers in extent.

We believe, from the aircraft performance work, that if the outflow region becomes larger than about 4 kilometers, it is probably less likely to be severe in terms of aircraft performance. So, we think that the microburst is the feature of most interest in an aviation context.

Virga is the precipitation coming down towards the ground, but not reaching the ground. What happens to virga is that it evaporates and, of course, in the evaporation process, it cools and causes the downdraft to accelerate. We had 18 cases where we had downdraft air approaching the surface in which it seemed like a microburst may have formed, but need not. Therefore, virga didn't always cause a microburst.

Of the 62 microbursts, about 60 percent occurred in the non-thunderstorm situation; that is, low-level reflectivities, no lightning; not a thunderstorm, by definition. The other 40 percent occurred imbedded in thunderstorms where there were rain, lightning, and all the properties of a thunderstorm. Thus, both types of microbursts were observed.

Data were collected on 35 gust fronts, which is about 10 years of gust front data collected from the National Severe Storms Laboratory (NSSL) in Oklahoma. There was a phenomenal amount of weather this summer.

Twenty mesocyclones, which are the parent circulations of tornadoes, and 7 tornadoes occurred for which we collected data. This was not a JAWS objective, but we couldn't resist working it. Nine hailstorms occurred that dropped hail on the radar, which is a pretty phenomenal statistic considering how close our radars were to one another. Another factor which has a bearing on these discussions is nowcasting applications of Doppler radar. With Doppler radar, we were able to see many features at low levels that allowed us to make a nowcast as to where thunderstorms would form. This is a very exciting use of Doppler radar in the aviation context, and these data were sent to the FAA's Center Weather Service Unit in real-time. The tremendous viability of Doppler radar is thus demonstrated in the aviation system context; not in the wind shear sense, but in using Doppler to identify the formation of hazards for use in changing the airspace flow, etc.

Figure 20 lists detection and warning systems for which I will give you some impressions, and these are only impressions, on what we came up with this summer. The LLWSAS at Stapleton had a spacing that was too large to capture the microburst feature on a regular basis. The LLWSAS did see diverging outflows but only after they became large enough to reach the scale for which the system was capable of responding. The NCAR system, which is on a density twice as great as the LLWSAS, was correspondingly more successful in seeing the microburst because the spacing was 3 kilometers.

- Airborne Systems
  - Airspeed and Groundspeed Procedure
  - Forward-looking LIDAR
  - Vertical Velocity/Energy Rate
- Doppler Radar
  - Airport Approach and Departure Corridors
  - Area-wide NEXRAD Concept
  - Doppler LIDAR at Airport Center
- Surface Sensors
  - Low-level Wind Shear Alert System
  - NCAR Portable Automated Mesonetwork
  - Pressure Jump Array

Figure 20. Detection and Warning

It is a preliminary, but, I think, logical, conclusion that the LLWSAS system in its current dimension is really not addressing the scales of motion which are of concern in the JAWS Project. I think the low-level wind shear alert system was put together at a time when we thought the gust front was the name of the game in terms of the severe hazard. Therefore, I think we need to address making the system better, and you can do that by increasing the number of stations; or, possibly, a number of other things can be done.

We have not yet addressed the pressure jump rate data. At present, I have only the results of verbal conversation with the British HS-125 crew relative to airborne systems. Their comments are, "Very exciting data; the best data we have ever seen in wind shear." The sound quantitative results, however, remain to be seen.

Doppler radar proved to be astoundingly successful in seeing the wind shear, both in dry and wet cases. I think the NEXRAD system, if the radars are placed near the airport, will give very exciting results. It is preliminary, but if you want to cover an airport environment, the Doppler radar does a very fine job. A conventional radar, or a weather channel on the surveillance radars, will not measure wind shear.

Figure 21 lists the analysis priorities. The wind shear profiles used in simulation and manned-flight simulators are not adequate. They do not address the scales of motion that we are looking at in the JAWS Project. The current systems, therefore, do not address worse-case conditions found in the four-dimensional structure of the microburst from the JAWS Project. These data need to be provided to the simulator world, not only for proficiency and training, but in testing of airborne systems. The analyzed data should be added to FAA Circular 120. Analyses of the data is a high priority of the JAWS Project.

- Preparation of High Resolution 4-Dimensional Microburst Profiles for Improved Manned-Flight Simulation
- Establish Microburst Frequency Distribution
- Quantitative Ordering of Detection and Warning Critical Success Ratio
- Training Film for Pilots Describing Microburst Hazard and Providing Visual Clues
- Quantification of Wind Shear Severity Using JAWS Data Set
- Doppler Radar Siting to Establish Suitable Detection Range as a Function of Hazard
- Research Versus Training Simulation Response to Microburst Wind Shear Profiles
- Close Analysis Relationship with United Kingdom Royal Aircraft Establishment
- Development of Prototype Airport Doppler Concept for Wind Shear and Other Terminal Hazard Detection and Warning

Figure 21. Analysis Priorities

We didn't expect to measure enough microbursts to establish a microburst frequency distribution. However, we have enough data from the JAWS Project to do that for Stapleton. What is the frequency distribution? We had lots of microbursts with velocities 50 knots or greater. Why do airplanes not crash all the time? The answer to that, in our opinion, is that the space time window for a microburst is extremely small. You have to encounter it below 500 feet. Moreover, since it is very small in spatial dimension and doesn't last very long, you have to be in the wrong place at the wrong time in order to be in trouble. Thus, even though they are fairly common in summer, the probability of a microburst being over the runway in exact coincidence with an aircraft landing or departure is a very rare event.

All of the detection and warning systems tested will be quantified as to their detection and warning capability. I have given you impressions which we will analyze quantitatively. An updated information film is needed this year and a newly updated film the year after. Pilots and controllers need to view this film to keep the consciousness alive as to how serious a wind shear event is and how to deal with it.

How severe is severe? We have data that we will use in simulator studies, in modeling studies in the analysis phase. The data from JAWS will be used in research simulators such as NASA Ames, NASA Langley, and elsewhere, to measure "How severe is severe?" I think that aircraft are going to fly in wind shear for a long time. We are not going to keep airplanes out of wind shear. Wind shear is all around us all the time. The question is one of accurate and timely detection of wind shear that can cause accidents. We have the data to get to the bottom of that problem, which is what we plan to do.

Doppler radar siting as a function of range needs to be resolved. If the Doppler radar is sited too far away, you cannot see the microburst because when it's right on the surface, it is lost in the earth's curvature. Thus, siting is an important issue relative to NEXRAD.

It is our opinion that the research simulators do a pretty good job of simulating wind shear in the microburst scale, but we're not sure this is the case for training simulators. For reasons which we are not certain of yet, we believe there is a lack of response to the wind shear profile in the training simulator. They either under-damp or over-damp the response to head wind, tail wind, or downdraft on the scale of a few seconds where microbursts wind shear is critical.

Finally, we are going to work closely with the United Kingdom Aircraft Wind Shear Program, and we may be addressing the issue with FAA about the next stage of a prototype system for Doppler radar.

As the final part of this presentation, I am going to give some impressions. Microbursts are common in Denver. We didn't do a research program elsewhere. We did one in Chicago in 1978, and there were quite a few microbursts; but the program was not designed as it was in Denver to adequately address the scale. I think microbursts are rather common. I think if you go east and south from Denver, you are more likely to find microbursts imbedded in thunderstorms and less likely to have the dry microbursts that you have in the west. Wind shear problems in Tucson, El Paso and Denver have been more related to the dry case. If you go east and south, to New York and Philadelphia, you are more likely to encounter the thunderstorm-imbedded microburst.

The question arises as to whether you can apply JAWS results in regions other than Denver. From the fundamental physics perspective, we always worry about that kind of problem. However, from the warning and detection operations point of view, I think the answer is yes. The microburst flowfield which causes accidents will have the same kinematic form near the ground in Florida as it does in Denver.

We have a lot of data on microbursts. We know now that they are small, short-lived and can be intensely lethal. Thus, microburst detection is very important in aviation safety.

The low-level wind shear alert system in its current form, we feel, is inadequate. We have no question that it was a proper decision to install this system. At that time, the gust front was thought to be the culprit, and this system is a great gust front detector.

Our technology and our awareness of the atmosphere has concentrated a lot of attention on the need for new systems and new approaches. A lot of work has been done by FAA. It is outstanding work. For some reason, results of this work were not implemented. We need to think about implementing airborne systems in a more rigorous way. We need to look at Doppler radar and we may be able to address the low-level wind shear alert system problem by increasing the number of anemometer stations.

I am a tremendous proponent of the airborne systems. You cannot have a low-level wind shear alert system or Doppler radar at every airport because the money isn't available. An airborne system goes with the airplane, so that is an obvious advantage. The air speed and ground speed system, I think, is a good system because ground-speed flying makes sense. There is, however, some disadvantages of the ground speed/air speed concept. Eventually, for example, it will encourage you to fly through a wind shear and one of these days you will go into a wind shear that exceeds the capability of the aircraft. So, any system that requires you to enter the wind shear before you can detect it has a problem in concept.

The current airborne systems as they are now construed are useful only on approach; and takeoff accidents are not covered. There is, however, more research that can be done to help improve this part of the situation.

The airport Doppler concept, I think, is a great idea. It costs money. In a warning and detection system, whether it's the Doppler radar or any other system, time is critical. The wind shear signal will live and die in a few minutes. This information must be related to the cockpit immediately. It can be uplinked. The technology exists to uplink the data. Uplink of wind shear information is an issue with which we need to be dealing. Also, the issue of how we decide to fly or not to fly in a certain situation, is a big issue. Thus, there are still many unresolved problems. The JAWS Project has provided a goldmine of data to address the issues. Thus, we believe that we are at the threshold of making a quantum step forward in resolving the wind shear problem.