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MEASUREMENT OF HAZARDOUS WINTER STORM PHENOMENA AT THE PORTLAND OR INTERNATIONAL AIRPORT *

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1. INTRODUCTION

Wind shear and lightning are classically associated with summertime convective weather events at airports east of Reno, NV. However, a recent study concluded that severe wind shear and lightning strike events occasionally occur during winter storms at west coast airports (Evans, et al., 1999). One of the most surprising findings was that the Portland Oregon International Airport (PDX) has operationally significant vertical wind shear and a surprisingly high number of lightning strikes to aircraft within the terminal area during winter storms.

The FAA has for a number of years planned to install an ASR-9 Weather System Processor (WSP) at PDX to provide protection against wind shear from microbursts and gust fronts. However, in view of the findings of the west coast weather study [conducted after the FAA's wind shear deployment study was completed (Rovinsky,1996)[1]], a research program was undertaken to:

- Better understand the phenomenology associated with the Portland winter storms;
- Determine whether the baseline ASR-9 Weather System Processor planned for PDX would adequately address operationally significant wind shear and other safety-related weather phenomena; and
- Identify alternative sensing/data fusion approaches to providing PDX terminal weather decision support if the WSP alone could not adequately provide safety warnings.

In this paper, we provide the initial results on this study. Section 2 provides background on the climatology of concern for winter storms at PDX, the relationship of warnings for vertical wind shear to the current operational horizontal wind shear warnings, and the characteristics of the ASR-9 WSP of particular significance for PDX weather surveillance. Section 3 presents the experimental design used to accomplish the measurements discussed in Section 4. Section 5 summarizes the results of this initial measurement program and makes recommendations for further studies.

2. BACKGROUND

2.1 Climatology

Portland wintertime storm events most often occur when a pacific cold front tracks on shore, providing relatively warm, moist air with strong winds from the south. If this occurs when a cold pool or Arctic air mass has set up in the Columbia River Basin east of the Cascade (see figure1), a strong temperature and pressure gradient will set up between the Basin and coastal region. When this occurs, cold air will be drawn westward through the Columbia River Gorge, and a cold east wind will spill out of its mouth near the Portland airport, which is located on the Columbia River. Winds aloft continue to be influenced by the coastal front in this situation, and as a result a vertical shear zone will set up over the Portland area. This zone can form between 100 and 1000 m and may cause a significant shear zone that impacts aircraft descending or climbing through it.

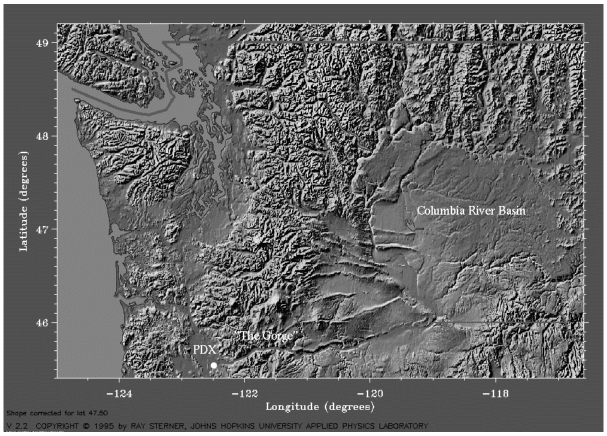

Figure 1. A topographical map of the northwest United States. Note the large Columbia River Basin in which cold air drains out of the Cascades. Also, note the Columbia River Gorge, which is the only "outlet drain" for the Basin. Since the Gorge empties into the Willamette Valley at Portland, strong drainage flows may be anticipated. The velocity of these flows will be increased by two topographical factors: the narrowness of the Gorge near the airport and the vertical drop in elevations through the Gorge.

The winter weather phenomena that are encountered at PDX are well known to western gardeners. The Sunset Western Garden Book (Brenzel, 1999) characterizes the Willamette Valley south of

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[1] It should be noted that the FAA wind shear deployment study only considered protection against microburst and gust front wind shear arising from thunderstorms. No consideration was given to other types of wind shear and terminal weather hazards nor was any attention given to the use of terminal weather sensors to improve aircraft merging and sequencing.

Portland as “a long, mild growing season that is essentially maritime most of the year.” However, the north end of the valley is characterized as:

> “Portland: Mild to Wild. In winter, when cold air builds east of the Cascades, winds can blast through the Columbia Gorge at tree-ripping speed “(emphasis added). “They hit east Portland hard and usually curve south, sometimes icing up trees clear to Milwaukie. If you live in the Portland area east of Interstate 205, plant trees whose limbs bear up well in ice storms …..”

PDX is located just west of Interstate 205 along the Columbia River; hence, it falls in the zone of particularly severe winter weather discussed in the Sunset book.

The detailed characteristics of winter storms which generate aircraft-triggered cloud-to-ground lightning strokes are not well understood. It is known that these storms typically are weakly electrified, with relatively low radar tops compared to summer thunderstorms. However, there have been few if any scientific experiments to determine the special features of these storms.

2.2 Operational Significance of Vertical Wind Shear

Wind shear phenomena have been investigated extensively since the early 1980’s as a result of several major, fatal air carrier accidents and the microburst wind shear research. As a result of this research activity, there now exist both ground-based and airborne wind shear detection systems which issue wind shear alerts when there is a change of headwind greater than 20 knots in a horizontal distance less than 2 nm.

Since commercial air carriers typically land on a 20:1 glide slope, the wind shear alerting criteria could be met either by:

- A horizontal wind change greater than 20 knots in 2 nm, or
- A change of head wind with altitude greater than 20 knots in 600 ft.

The PDX tower has reported (Evans, et al.,1999) that when there are strong east surface winds from the Gorge during winter coastal storms with strong south or west winds aloft, that missed approaches are fairly common. This change in winds can be a problem, particularly when there is aircraft and/or runway icing due to warm rain from the coastal storms falling into cold air at the surface. Note that the aircraft would be landing to the east under these conditions, so the wind shear encountered is an increase in headwind near the surface. Such a head wind increase is of concern because an unwary pilot may land long and have problems stopping on a slippery runway.

The degree to which various current wind shear detection systems actually alert when there is a vertical wind shear depends on the various systems. The airborne wind shear alerting systems that use the instrument navigation system (INS) and airspeed to make a detection will alert on such a vertical wind shear.

For airborne and ground-based radar wind shear alert systems, it is less clear whether the system will alert properly when there is an operationally significant vertical wind shear. One must carefully analyze what range of elevation scanning angles are used by the various systems, the elevation pattern of the antenna (s), and the overall signal processing and alerting logic. Hence, we must review how the ASR-9 WSP operates.

2.3 ASR-9 Weather System Processor (WSP)

The ASR-9 is a multi beam antenna where the two elevation beam patterns are offset up about 3.2 degrees in elevation as shown in figure 2.

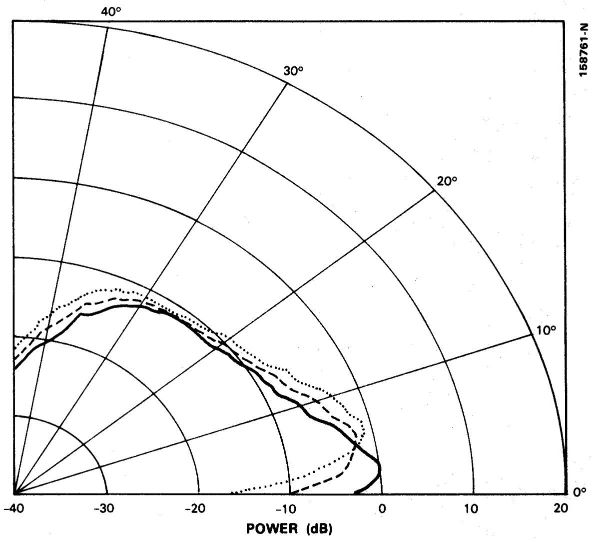

Figure 2. ASR-9 antenna patterns in vertical plane.

The signals received on the two beams are processed separately by the WSP to estimate the mean velocity of the difference spectrum. This is accomplished very efficiently by computing a “conventional” pulse pair estimate for the difference spectrum by using the relationship between correlation function estimates and spectra; that is, the difference autocorrelation function = low beam autocorrelation function – A x high beam autocorrelation function, where A is a constant that attempts to correct for the difference in the two beam patterns at high elevation angles[2] (Weber, 1986).

The reflectivity of the low beam and “difference spectrum” radial velocity are then used by the WSP pattern recognition algorithms to locate microbursts and gust fronts. Since the vertical wind shear corresponds to a head wind change along the glide path that would be similar to that of a gust front, one must carefully consider the gust front detection algorithm of the WSP. This algorithm depends heavily on the spatial pattern and time behavior of the reflectivity data field with some use of the radial velocity information (Delanoy and Troxel, 1993).

Practical experience with the WSP over the past eight years has shown that vertical wind shear typically generates erroneous wind shear detections when the weather radar reflectivity aloft is higher than the surface reflectivity. There is very limited operational experience with vertical wind shear phenomena such as are

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[2] Here, we ignore the clutter filtering applied to the received signals since it is not an important factor in assessing the ability to detect operationally significant vertical wind shear.

believed to occur at Portland (and have also been observed near New York City[3]) since the principal WSP testing has been conducted at locations (e.g., MCO, ABQ, AUS) which typically do not have operationally significant vertical wind shear during precipitation.

3. EXPERIMENT DESIGN

3.1 Radar Data Acquisition

To better understand the phenomology associated with the cold Gorge outflows and the ability of the ASR-9 WSP to provide timely warnings on operationally significant wind shear phenomena, one needs high-resolution (e.g., preferably 100 meter vertical resolution) profiles of the winds and the radar reflectivities. The most appropriate sensor to carry such measurements is a pencil beam Doppler weather radar. The NEXRAD for Portland is located atop a mountain 30 miles to the west, at an altitude of about 1600 feet above airport elevation. Hence, NEXRAD was not a viable source of high-resolution information on the vertical wind shear phenomena (albeit NEXRAD might be useful for studies of storms which create triggered lightning).

Consequently, the Massachusetts Institute of Technology (MIT) Lincoln Laboratory portable C-band Doppler radar was moved from Albuquerque, NM (ABQ) to a site near the runways at PDX. This radar has a 1.5 degree beamwidth and can interleave both in Range Height Indicator (RHI) and Plan Position Indicator (PPI) scans. The RHI scans would be particularly useful for characterizing the wind shear phenomenology in the vertical plane, while the PPI scans would be used to determine the horizontal extent of the wind shear so that it would be possible to determine whether vertical wind shear would be detected as a gust front by the WSP pattern recognition algorithms.

The radar was sited near the center of the PDX airport to view both eastern and western approach and departure paths. Data were collected on 11 storm events over the four-week deployment. During data collection, a meteorologist manually operated the radar to record volume scans. This allowed the meteorologist to adjust radar scans and analyze data in real time to determine the presence and strength of vertical shear. RHI data were used to obtain a vertical profile of both velocity and reflectivity, while volume PPI's were recorded to view the overall wind flow and location of reflectivity.

During events where vertical wind shear was possible, RHI's were taken along the departure and arrival paths as well as into the mouth of the Columbia River Gorge. An aircraft on a 3.0-degree glide slope would need to realize a wind shear of at least 15 meters per second over a 200-meter distance to get a gain or loss value similar to that of a microburst. There were also a few events where atmospheric instability caused vertical storm development. It has been shown that aircraft flying through weakly charged storms could trigger lightning strikes (Evans, et al., 1999). On the fly RHI scans were created to collect data from these cells as well as PPI scan during these types of events.

3.2 Supporting Meteorological Data

Data from surface stations near PDX and in the Columbia River Basin were acquired as well as the soundings from Salem, OR. MDCRS reports from aircraft arriving at and departing from PDX and cloud-to-ground lightning strokes also were obtained and archived.

3.3 Preferred Time Period for Measurements

Portland airport surface data were examined for possible vertical wind shear, or “Gorge” events between December of 1996 and February of 2000. Three criteria were used to determine if an event could be classified as a possible wind shear event. The most important of these criteria would be a strong easterly wind flowing from 70 to 120 degrees recorded at PDX. A peak surface wind gust speed of 22 knots or greater was used as the minimum.

The second criteria required a temperature near freezing at PDX. This would indicate the presence of an arctic air mass east of the gorge as well as a density discontinuity due to the cold dense air over PDX. Lastly, there should be precipitation on the day in question. Precipitation was needed to ensure the presence of Rayleigh scatterers and also indicated the presence of a front or low-pressure system.

There were a total of 10 days during the studied period where all three criteria were met. Of these days, six occurred during January. Surface maps for 00 and 12 Z also were examined for the 10 days where all criteria were met. In each case, strong temperature and pressure gradients occurred between the Columbia River Basin and the Portland area. In addition to the 10 days, there were 36 more days where the wind criteria were met and either the temperature or the precipitation criteria also were met. Of the 46 days with surface weather conditions indicative of Gorge cold outflow-induced wind shear, 20 days occurred in January, 15 days occurred in February, and 11 days occurred in December. We concluded that the highest probability of encountering vertical wind shear caused by a Gorge event would occur between December 20th and February 10th.

4. EXPERIMENTAL RESULTS FROM THE MARCH-APRIL 2000 MEASUREMENTS

4.1 Synoptic Features

The commencement of the radar measurements was delayed several months by various administrative problems (including a long delay in evaluation of whether the radar would pose an airspace obstruction clearance problem when located near the PDX runways). This resulted in the measurements being conducted after the preferred period for “Gorge events.” Additionally, the late winter of 2000 in the Northwest was warmer than the long-term average climatology.

During the four-week deployment, data were collected on nine cold front events and two isolated convection events.The surface winds and temperatures for the observed vertical wind shear events were not as

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[3] Vertical wind changes of 40 knots in 1000 ft. have been observed during winter storms near New York City (S. Gaddy, personal communication, 2000).

indicative of strong wind shear events as many of the events discussed in Section 3.3, and the observed vertical wind shear severity was unlikely to lead to the missed approaches reported by the PDX tower in previous years. The only case to meet two of the three climatological criteria discussed above occurred on March 16th.

4.2 Analysis of the March 16th Event

A cold front pushed on shore during the late night hours of the 15th while a cool, high-pressure system had set up over Idaho and Montana. This set up an easterly flow through the gorge. Surface winds at Portland were easterly throughout the night and into the early morning hours, with speeds ranging between 6 and 16 knots with gusts of up to 22 knots. Winds above 1 km were southwesterly throughout the mission, with maximum wind speeds between 15 and 20 meters per second at around 2 to 3 km. The cold front crossed the Portland runways by 1322 UT, and surface winds quickly switched to northerly. Figures 3 and 4 are examples of RHI data collected at PDX during this case.

The low-level shear feature is evident in figure 3. The light gray area just below 2 km is the zero velocity region (or zero isodop). Winds toward the radar are below this line with winds away from the radar above this region. This illustrates the easterly low-level flow out of the gorge. The three-degree glide slope shows that during this event aircraft approaching or departing PDX would be well below the shear region. Figure 5 is a PPI from the PDX data recorded about 30 minutes before figures 3 and 4. These data supports the vertical wind structure observed in the RHI.

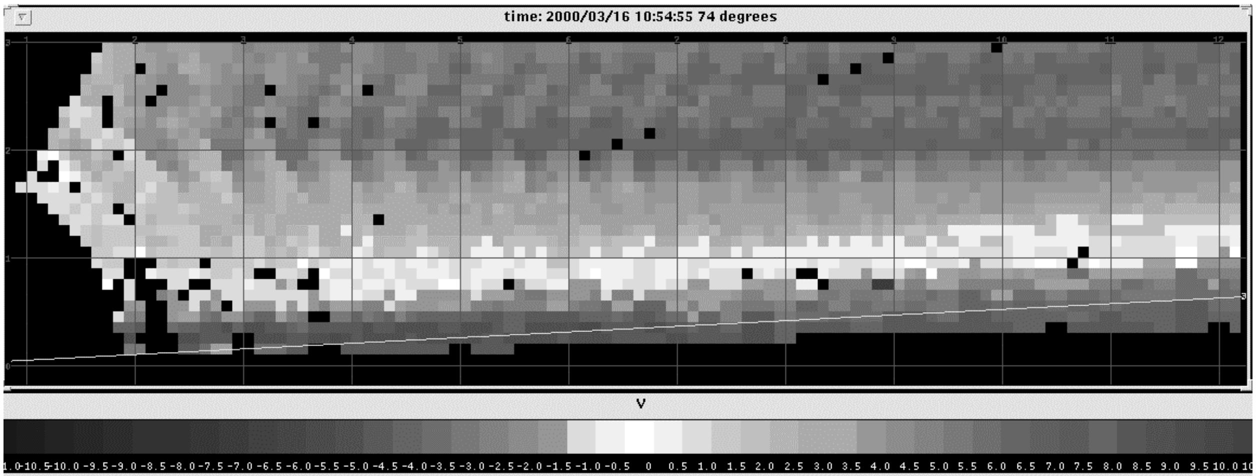

Figure 3. RHI of velocity data along the 74th degree radial from the radar site at 1054 UT. The vertical and horizontal dark lines are 2-km range marks. The line descending from the right to the left shows a 3.0-degree glide slope.

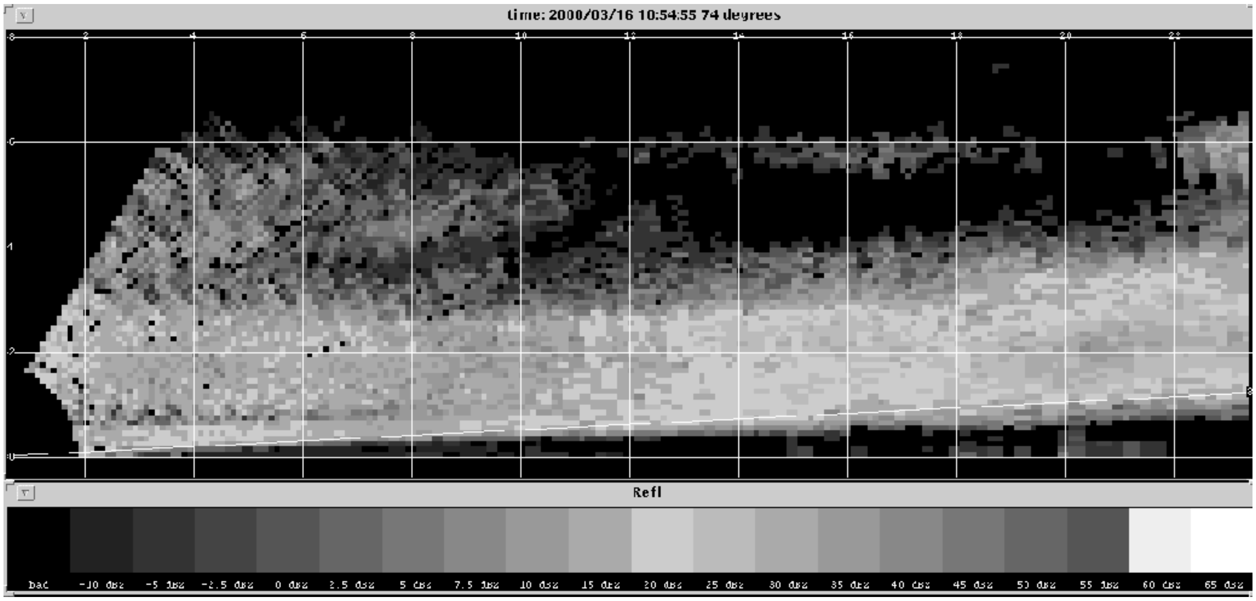

Figure 4. Reflectivity RHI data corresponding to figure 3 RHI velocity data.

Vertical shear values were only around 5 m/s over 200 meters. The shear region also was centered between 800 and 1000 meters (between 2000 and 3000 ft). Therefore, this event was not operationally significant to PDX air traffic. However, with colder and denser air that would flow out of the gorge during the winter months, it would be expected that the shear region would lower.

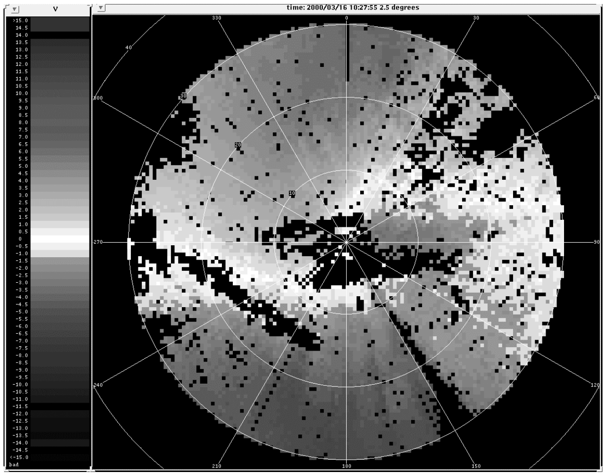

Figure 5. PPI of a 2.5-degree tilt from the March 16th case taken at 1027 UT. In the gray scale, the whites show the near zero velocities while darker shades are inbound velocities, and outbound velocities are lighter. Missing data are due to editing of ground clutter. These data show the east wind at low levels (around 90 degrees) and the winds aloft from the south-southwest (around 200 degrees).

4.3 Convective Weather Events

On the 18th and 19th, data also were collected on isolated storm events caused by unstable air masses behind cold fronts. A few hours after the fronts passed, weakly organized vertical storms developed. These data were collected with the intention of matching the data with any aircraft-triggered lightning strikes. However, there were no reports of triggered strikes during either day.

5. SUMMARY AND CONCLUSIONS

- PDX has unusual, topographically-induced weather hazards (vertical wind shear and icing) during winter storms as well as triggered lightning in weakly convective wintertime weather events. The details of the meteorological phenomena which lead to these weather events are poorly understood, and the nature of these phenomena have not been considered in the FAA wind shear detection system deployment studies.
- To better understand the phenomenology and the degree to which the planned ASR-9 WSP system would provide adequate safety warnings, the MIT Lincoln Laboratory portable C-band radar was deployed to Portland, OR in late winter 1999-2000 to collect data on both vertical wind shear and triggered lightning events.
- Experimental data were recorded on 11 events during a four-week deployment. The majority of the data recorded were in search of vertical wind shear events. However, due to unfortunate administrative delays and a warmer than normal winter, the measurements occurred in a time period which was unfavorable for the generation of operationally significant vertical wind shear events.
- A relatively weak vertical wind shear event was encountered on March 16th. However, the wind shear case observed did not impact air traffic arriving at and departing from PDX. The surface measurements (e.g., surface winds and temperature differential between the Columbia River Basin and PDX) associated with this event are such that we would have expected a relatively weak vertical wind shear.
- Since the surface temperatures were well above freezing at the surface and aloft during the March 16th event, there were no significant changes in the reflectivity structure with altitude that would create performance problems for the ASR-9 WSP algorithms.
- More measurements need to be made to address the objectives of the Portland measurement program. Based on the climatology study reported in Section 3.3, we suggest that measurements should be accomplished in mid winter (e.g., January).

We would note that many of the initial measurement programs to characterize microburst wind shear were inconclusive due to poor understanding of the weather phenomena and/or bad luck in the weather encountered (e.g., the NIMROD program spent much of its time scanning the wrong type of storms, while the first FAA TDWR measurements were conducted during a thunderstorm last summer in Boston). We believe that the methodology utilized in this first effort to understand Portland's unique weather phenomena and its operational consequences are sound and should form the basis for a subsequent measurement program.

It would also be desirable to conduct modeling studies of the wind shear phenomenology for various combinations of coastal storm characteristics and Portland-Columbia River Basin temperature differentials.

Since the key features correspond to large-scale meteorological features, handling the meteorological driving factors should be fairly straightforward. However, the very narrow width of the Gorge may result in a very high spatial resolution over a wide area if a "conventional" approach to direct modeling were to be used. It may be that there is a "composite" modeling approach which could use a fine-scale spatial model for the Gorge and area near the airport, with the Columbia River Basin being handled by an appropriate boundary condition for the east end of the Gorge.

6. REFERENCES

Brenzel, K., Ed., *Sunset Western Garden Book, 6th Edition*, Menlo Park, CA: Sunset Publishing Company, 1999.

Delanoy, R.L. and S.W. Troxel, “Machine Intelligent Gust Front Detection,” Massachusetts Institute of Technology, Lincoln Laboratory, *The Lincoln Laboratory Journal*, Vol. 6, No. 1, 1993, pp. 187-211.

Evans, J.E., T.J. Dasey, D.A. Rhoda, R.E. Cole, R.W. Wilson, E.R. Williams, “Weather Sensing and Data Fusion to Improve Safety and Reduce Delays at Major West Coast Airports,” Massachusetts Institute of Technology, Lincoln Laboratory, Project Report ATC-290, 30 November 1999.

Sterner, R., Johns Hopkins University, Applied Physics Laboratory. Figure 1. Copyright, 1995.

Rovinsky, Robert B., David K. Chin, Ph.D., Mark Kipperman, and Bradley S. Loomis, “FAA Investments in a Budget Constrained Environment: Two Examples of Cost-Benefit Analysis,” *Air Traffic Control Quarterly, Special Issue: Operations Research Applications in ATC*, Volume 4, Number 2, pp. 125-145, 1996.

Weber, M.E., “Assessment of ASR-9 Weather Channel Performance: Analysis and Simulation,” DOT/FAA/RD/PS-88/11, Massachusetts Institute of Technology, Lincoln Laboratory, Project Report ATC-138, 31 July 1986.

Westrick, K.J., C.F. Mass, B A Colle, “The limitations of the WSR-88D Radar Network for Quantitative Precipitation Measurement Over the Coastal Western United States,” Bulletin of the American Meteorological Society, Volume 80, Number 11, pp. 2289-2298, 1999.