Project Report

ATC-290

Weather Sensing and Data Fusion to Improve Safety and Reduce Delays at Major West Coast Airports

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30 November 1999

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Prepared for the Federal Aviation Administration.
Document is available to the public through
the National Technical Information Service,
Springfield, Virginia 22161.

ABSTRACT

The objective of this study was to analyze the weather sensing and data fusion required to improve safety and reduce delays at a number of west coast airports that are not currently scheduled to receive an Integrated Terminal Weather System (ITWS). This report considers the Los Angeles (LAX), San Francisco (SFO), Seattle (SEA) and Portland, OR (PDX) international airports. A number of visits were made to the various ATC facilities to better understand their weather decision support operational needs. Analyses were made of an incident of lightning strikes to two aircraft at SEA in February 1999, and a prototype terminal winds product was developed for LAX that uses profilers as well as plane reports to update the National Weather Service (NWS) Rapid Update Cycle (RUC) winds estimates.

We found that an augmented ITWS could potentially address safety concerns for triggered lightning strikes and vertical wind shear in winter storms at Portland and Seattle. An augmented ITWS terminal winds product (that uses wind profiler data in addition to the current ITWS sensors) could provide very large delay reductions for LAX and SFO during winter storms as a component of a wake vortex advisory system. This augmented product also could provide significant delay reduction benefits at SEA.*

The sensors required to obtain the projected benefits at SFO do not exist currently. Portland may warrant additional sensors to address the vertical wind shear problems, and LAX would require additional sensors for a wake vortex advisory system.

We recommend near-term experimental measurements at PDX to determine the optimum sensor mix and that an operational evaluation of the prototype augmented ITWS terminal winds product be carried out at LAX to determine if the current sensor mix can meet operational needs. Lightning strike data at SEA and PDX should be analyzed to determine if a proposed triggered lightning predictant is accurate.

* The augmented terminal winds product may also be necessary if the planned usage of the Center-TRACON Advisory System (CTAS) is to achieve its full benefit at these airports.

ACKNOWLEDGMENTS

Andy Denneno modified the ITWS terminal winds software to ingest the profiler data from the Los Angeles area to generate the terminal winds grids estimates shown in Section 4. Beth Bouchard generated the plots of lightning data overlaid on NEXt generation weather RADar (NEXRAD) data and plane tracks in Appendix C. Bob Hallowell generated the Terminal Convective Weather Forecasts shown in Section 2 from NEXRAD national mosaic data of 1 June 1999 for the area around Little Rock, AR.

We very much appreciate the interactions with, and input from, the Bay Terminal Radar Approach Center, the Southern California Terminal Radar Approach Center, the Portland Tower/TRACON, and the Seattle Tower/TRACON, the Oakland ARTCC and the Los Angeles ARTCC. Also, the LAX and SFO towers were consulted regarding Wake Vortex. The conclusions expressed in this report are the views of the authors and do not reflect the official position of any of the various FAA facilities interviewed.

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1. INTRODUCTION

The objective of this study was to analyze weather sensing/data fusion required to improve safety and reduce delays at a number of west coast airports that are not currently scheduled to receive an Integrated Terminal Weather System (ITWS). In this study, we place particular emphasis on the needs for improved weather sensing by systems that currently or potentially would be addressed by the Federal Aviation Administration's (FAA's) surveillance/weather Integrated Product Team (IPT) (AND-400).

The principal airports of interest for this initial study were the major west coast airports that did not receive a Terminal Doppler Weather Radar (TDWR) due to low values of the wind shear exposure index

wind shear exposure index = (frequency of thunderstorms) X (operations rate):

- Los Angeles (LAX) [an ASR9 Weather Systems Processor (WSP) site]
- San Francisco (SFO)
- Portland (PDX) (a WSP site)
- Seattle (SEA) (a WSP site)
- Honolulu (HNL) (a WSP site)

Because these airports did not receive a TDWR, currently they are not planned to have an ITWS.

Since the initial ITWS deployment strategy was developed in 1994, it has been learned from operational testing at Dallas-Ft. Worth and New York City that ITWS has substantial capacity enhancement/delay reduction benefits above and beyond the improved wind shear detection and convective weather planning product capabilities that were the principal initial benefits of the ITWS. Furthermore, recent safety incidents in the Pacific Northwest have identified a need for additional weather products that would require ITWS-like data fusion algorithms (i.e., intrinsically multiple-sensor product generation algorithms that could not be generated by a WSP alone).

This study for the major west coast airports is particularly timely due to the increased emphasis on:

(1) Significantly improving aviation safety and

(2) Improving the effective capacity of major airports

in the face of expected increases in operations rates within the National Airspace System (NAS).

For this first phase of the study, the principal operational benefits assessed were improvements in the quality of NAS service (e.g., increased safety, reduced delays, greater airport capacity, more efficient flight operations) that would be obtained by candidate ITWS products, including:

(1) Terminal winds for the identification of dangerous vertical wind shears and improved aircraft merging and sequencing;

(2) Storm products (including storm motion, warnings of high likelihood of triggered lightning and organized precipitation forecasts) for improved operations when heavy precipitation is adversely impacting terminal operations [the organized precipitation forecast is a possible ITWS enhancement under development by the FAA Aviation Weather Research (AWR)];

(3) Predictions of ceiling and visibility for traffic flow management [a possible ITWS enhancement under development by the FAA AWR]; and

(4) Winds, temperature, and turbulence products to support wake vortex reduced separation systems [(such systems are under study by the National Aeronautics and Space Administration (NASA) and the FAA)].

It is important to note that the products described above are generally not provided by the WSP, or the WSP does not provide the full coverage required (e.g., the WSP at LAX does not fully cover the Southern California TRACON).

The approach taken in this study in assessing weather sensing requirements and the associated product generation data fusion algorithms was to consider the following key factors:

(1) Operations rates (current and planned), and

(2) Delays and their causes, including:
- thunderstorms and prefrontal squall lines associated with coastal storms,
- adverse winds leading to difficulties in traffic merging/sequencing,
- low ceiling and/or visibility leading to delays because the scheduled operations exceed the airport capacity;

(3) Potentially unsafe weather conditions such as hazardous wind shear conditions induced by the terminal topography and aircraft-induced lightning strikes;

(4) Deployment plans and the benefits associated with other systems which may need ITWS information (e.g., the Center-TRACON Automation System (CTAS), wake vortex advisory systems, and new concepts for closely spaced parallel approaches);

(5) Characteristics of weather phenomena which are of major concern in providing operational benefits (e.g., spatial extent, variability with space and time);

(6) Performance of currently planned sensors for the various terminal areas at detecting the key phenomena. If deficient, are there cost-effective approaches to meeting the weather sensing needs? and

(7) Adequacy of the initial ITWS data fusion algorithms at addressing site-specific issues.

The remainder of the report proceeds as follows. The next section provides background on the weather phenomena of concern for safety and delays at the major airports under consideration and ITWS capabilities with respect to those phenomena. Section 3 describes the approach taken to resolve these issues. In Section 4, we discuss each of the airports in the context of the above issues. The final Section summarizes the reports for the various airports and makes recommendations for follow-on studies.

One of the major potential improvements in terminal capacity at runway-limited airports would be reduced separations between aircraft when wake vortex separations could be safely reduced due to the weather conditions. The benefits of reducing in-trail separations is discussed in Appendix A, while the benefits of using closely spaced parallel runways in Instrument Meteorological Conditions (IMC) is discussed in Appendix B. The use of closely spaced parallel runways requires understanding of the winds that could blow vortices from one approach path to another approach path.

Appendix C has details on a safety incident analyzed as a part of this study—lightning strikes to two aircraft in Seattle in February 1999. Appendix D provides information on the queueing model used for the bulk of the quantitative benefits estimates in this report. In Appendix E, we apply the model to estimate terminal winds merging and sequencing benefits at LAX, SFO, and SEA.

2. BACKGROUND

In this section, we provide some background information on the ITWS system[1] and on the NAS safety and delay challenges of greatest concern for the airports addressed in this study.

2.1 Safety and Delay Challenges

Table 1 shows the weather phenomena that arise at the various airports, operations rates and delays as summarized in the latest Aviation Capacity Enhancement Plan [Office of System Capacity, 1999]. A major element of adverse weather impacts at these airports is associated with low ceiling/visibility conditions. Figure 1 compares the various causes of low ceiling/visibility conditions at various airports.

Table 1.
Operations, Climatology and Delays for Major Airports

		Climatology			Delays per 1000 Ops	
Airport	FY97 Ops (x 1000)	Tstm Days	Hvy Fog Days	IFR Events*	FY97	FY96
SFO	448	2	17	215	49	56
LAX	780	4	39	95	24	18
SEA	407	7	44	125	7	6
PDX	316	7	34	TBD	3	2
HNL	382	7	0	0	.2	.3
EWR**	469	26	20	101	59	63
LGA**	354	27	14	99	47	42
JFK**	361	25	32	109	18	29
DFW**	903	45	11	64	15	20
MEM**	366	53	11	79	1	1
MCO**	356	80	27	76	4	5
STL**	517	45	11	76	22	32
BOS**	489	19	23	111	24	30
ORD**	893	38	16	101	25	36
ATL**	773	50	30	129	27	27

*Continuous periods (2-hour minimum) of IFR conditions
Tstm = thunderstorm Hvy = heavy
** ITWS systems are planned for these airports

[1] We emphasize ITWS capabilities here because the ITWS provides products that address important West Coast airport unmet needs and because the ITWS is the only FAA terminal weather data fusion system currently in full-scale development. It would be technically possible to reimplement the pertinent ITWS capabilities on other systems (e.g., WSP or a new system, but that hardly seems cost effective).

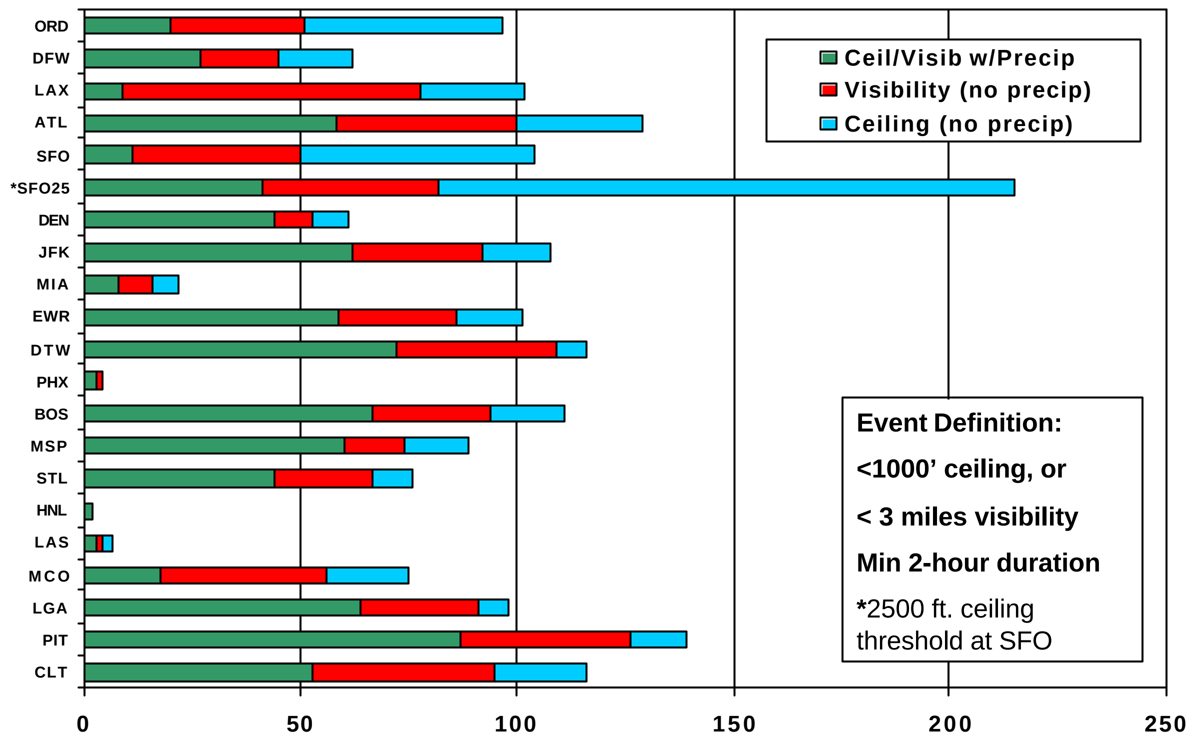

Figure 1. Frequency and distribution of IFR events by cause (Clark, 1995).

2.1.1 Safety Background

For the major airports considered in this study, the principal terminal safety concerns considered were:

(1) Convective wind shear (e.g., microbursts, gust fronts),

(2) Vertical wind shear (e.g., due to rapid changes in the winds as a function of altitude),

(3) Heavy rain (causing loss of lift and/or difficulties in stopping), and

(4) Electrified storms that can create aircraft-triggered lightning strikes within the terminal area.

Below, we discuss each of these safety issues.

2.1.1.1 Convective Wind Shear

Convective wind shear has been addressed in many reports and papers [Fujita, 1985; Klingle-Wilson, 1985; Wolfson, 1988], and was considered in detail in the FAA wind shear detection system deployment studies [e.g., Rovinsky, 1997]. Because no new information on convective wind shear has developed—that would be of significance for the airports of interest here—since the wind shear detection system deployment studies were carried out, we did no further investigation of convective wind shear at these airports.

2.1.1.2 Vertical Wind Shear

Vertical wind shear (e.g., rapid changes in wind as a function of altitude) can be a contributing cause of accidents (e.g., the DC-10 accident at Logan in the 1960s). This is particularly true when there is poor visibility and/or heavy rain on the runway. The coastal storms that frequently impact SEA, PDX and SFO all may have sharp changes with wind as a function of altitude. Portland has special problems due to the local topography, which will be discussed subsequently.

2.1.1.3 Heavy Rain

Heavy rain has been a factor in several recent incidents and accidents (e.g., the 1993 DC-10 incident at DFW which is discussed in (Evans and Ducot, 1994) and the American Airlines accident at Little Rock, AR in June 1999 (Phillips, 1999)). Heavy rain is relatively common during the rain bands associated with Pacific coastal storms in the fall, winter, and spring. It also can occur during the relatively rare convective weather.

An important element of safety with heavy rain is short-term forecasts that can provide guidance to pilots, flight dispatch, and air traffic control on when there will be gaps in the heavy rain, time that can be utilized to land aircraft with a greater safety margin. In the Dallas and Little Rock accidents, it would have been possible to avoid landing in the heavy precipitation had the pilot briefly (e.g., 10-15 minutes) delayed landing.

2.1.1.4 Lightning Strikes to Aircraft

Lightning strikes emerged as a safety issue as a result of our investigation of lightning strikes to two aircraft at Seattle in February 1999 (see Appendix C). Additionally, the Portland tower reported a number of strikes to aircraft in the terminal area in the fall and spring of the past year (See Section 4.4).

The terminal area lightning strikes to aircraft that appear to be triggered by the aircraft themselves are of particular concern since:

(1) There may be minimal or no advance warning provided to pilots, flight dispatch, and/or Air Traffic by the National Lightning Detection Network (NLDN) data, and

(2) The strikes occurred at relatively low altitudes where recovery from the strike must be accomplished more rapidly to ensure safety.

The Pacific Northwest winter storms pose a particular concern because:

(3) The mixed-phase (ice and water) region typically associated with induced lightning can be at relatively low altitudes, thereby subjecting the aircraft to larger electric fields during take off and landing than during summer conditions, and

(4) The storms are less strongly convective so that the electrical fields are not strong enough to create either inter-cloud or cloud-to-ground (CG) lightning unless a triggering mechanism, such as the sharp edge of an antenna, wing, or tail is present.

2.2 Weather Delay Causality and Alleviation

Weather is the main cause of NAS delays [FAA System Capacity Office, 1999]. For the NAS as a whole, convective weather is the principal cause of delays. However, for the west coast airports, low ceiling and visibility and unfavorable winds are the principal causes of delays (see Figure 1).

Low ceiling and visibility and unfavorable winds cause delays by making it impossible to use all of the available runways. In some cases, there is a difference in the number of aircraft landed on a runway per hour during instrument flight rules (IFR) conditions versus the rate during visual flight rules (VFR) conditions that further compounds the delay problems.

There are three basic approaches for reducing these delays:

(1) Use a parallel runway monitoring (PRM) system with a wake vortex encounter avoidance system to permit the use of closely-spaced runways in IFR conditions;

(2) Increase the number of aircraft landed per hour per runway; and

(3) Match the traffic flow to the time varying airport capacity [i.e., traffic flow management (TFM) optimization].

Approach (1) is under consideration for San Francisco as discussed in Section 3 and Appendix B, and would also be appropriate for Seattle. Some key elements of wake vortex encounter avoidance are very high-resolution vertical profiles of winds and temperature/humidity to determine whether wake vortices are not of concern due to advection (i.e., transport by the wind) and/or by dissipation (e.g., by turbulence).

Approach (2) could be achieved by:

- Reducing wake vortex separations on a weather conditional basis, and/or
- Providing controllers with information that enables them to achieve the desired aircraft separations more precisely (e.g., no unnecessary "gaps" between planes), and/or
- Optimum assignment of aircraft to runways.

Reducing wake vortex separations for a single runway on a weather-conditional basis is discussed in Appendix A.

The CTAS is of particular significance since:

- It explicitly addresses delay reduction approaches (2) and (3), and
- The FAA plans to install CTAS at three of the four major West Coast airports (see figure 2), starting with LAX.

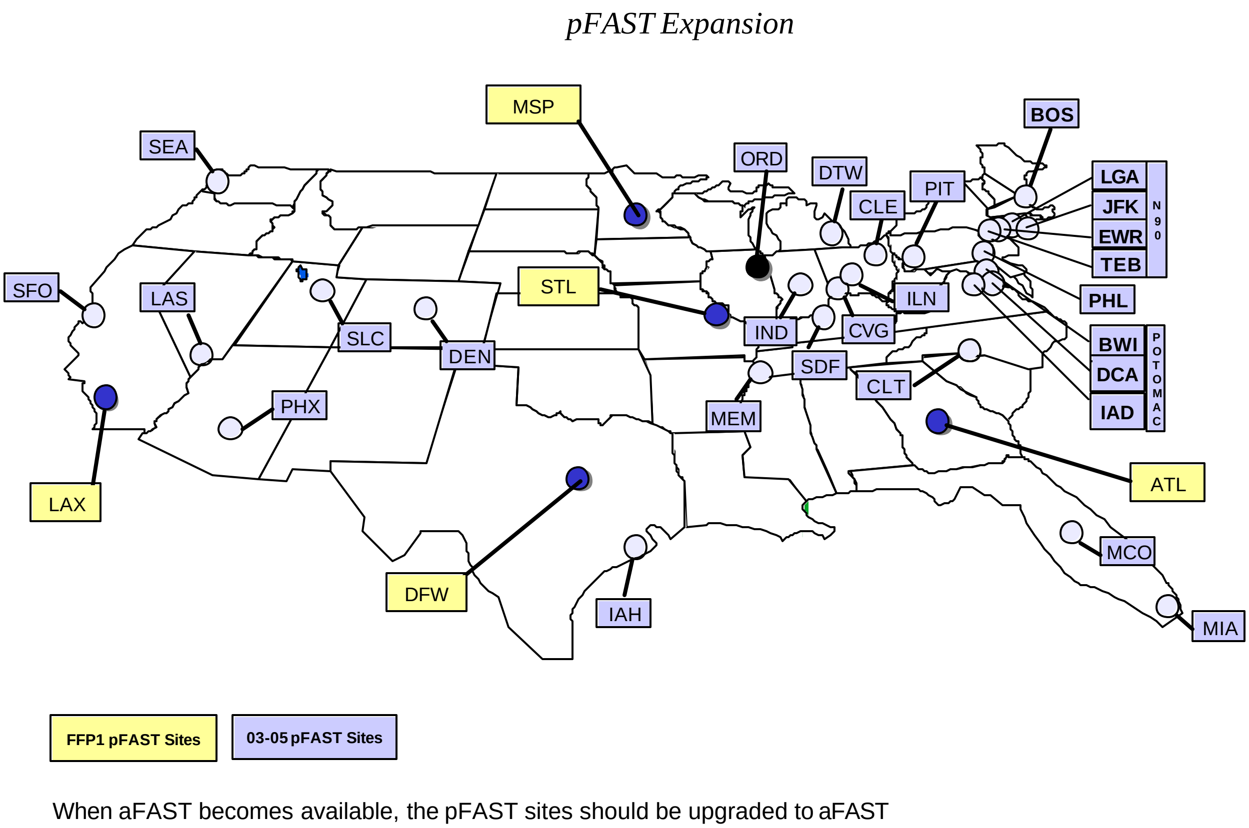

Figure 2. Plans for Terminal CTAS deployment (from RTCA Select Committee on Free Flight Implementation 2003-2005 Capabilities Working Group Status Report of 12 August 1999).

Since the operation of CTAS and the role of high-quality terminal winds information in CTAS operation may not be familiar to many readers, some tutorial discussion is warranted. The CTAS seeks to:

(1) Balance the traffic between the various runways and order the arrivals for a given runway and

(2) Deliver planes to the final approach fix with the desired inter-aircraft spacings, while

(3) Using descent trajectories that are fuel optimal and terminal procedure compliant.

Current testing (Nichol, 1996) is focusing on achieving capabilities (1) and (3), with the major benefit coming from the identification of opportunities to assign a plane from one runway to another runway as the aircraft enter the terminal area (20-30 minutes prior to landing). Figure 3 illustrates a typical example of this at Dallas/Ft. Worth (DFW): there are excess aircraft arriving from the east, so aircraft 3 from the east passes over the airport and is merged into the stream of traffic from the west (aircraft 1, 2, 4 and 5) that will also land on the west side runway.

A CTAS user at a workstation indicates which terminal routes and runways are to be used and can modify the CTAS-computed landing sequences for the various aircraft (that is, the automation software relies on humans to determine which runways and air routes are to be used).

This “passive” Final Approach Spacing Tool (pFAST) mode of CTAS requires the following from the weather information system:

(1) Winds and temperature profiles for use in trajectory synthesis; and

(2) Information for the human user to permit identification of terminal routes and runways which are usable for a prediction period of up to 40 minutes.

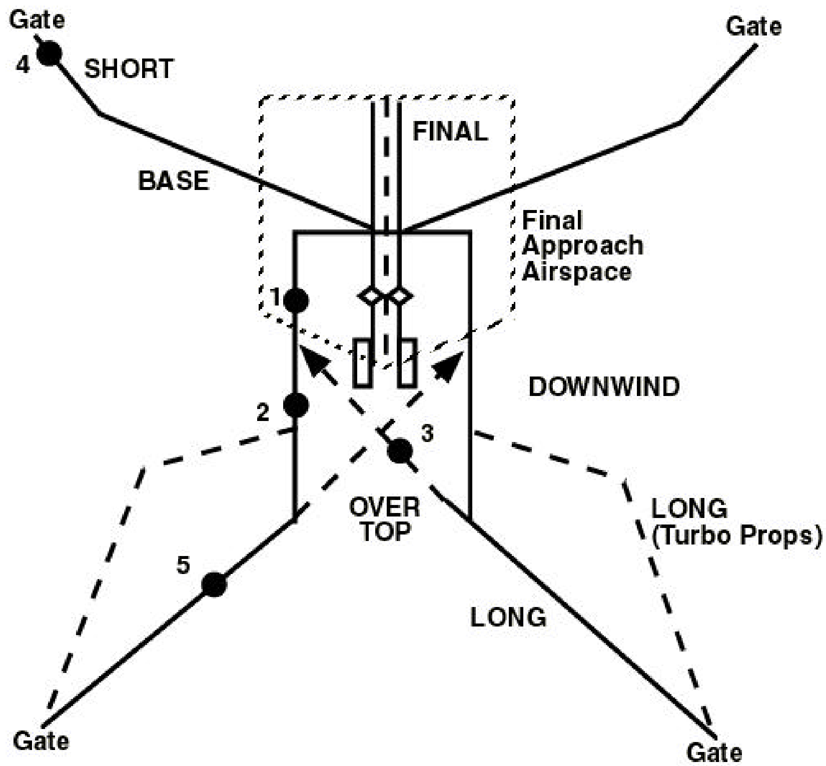

Figure 3. Aircraft being sequenced to left runway are denoted by a numbered ●.

It can be shown that the winds accuracy required to accomplish merging planes of the type shown in figure 3 is approximately 10 knots (Evans, 1997). At airports which do not have an ITWS, CTAS obtains winds information from the National Weather Service Rapid Update Cycle II (RUC II) [(see Sherry, 1999) for information on RUC II technical performance].

The CTAS plans to transition to the “active” FAST (aFAST) mode, wherein the automation system monitors aircraft adherence to the automation plan and provides corrective actions to the controller who then issues advisories to the pilot (Davis, 1994). Active FAST control systems have very different sensitivities to input data (e.g., wind field) errors than do the “passive” FAST (pFAST) mode considered above. For example, the time lags in controller and pilot response can yield major differences in the sensitivity to wind errors with various spatial frequency components. Analysis of this issue is further complicated by the rapidly evolving automation control laws and the lack of validated quantitative models for controller/pilot actions. At this time, there are no quantitative estimates for the winds accuracy to make aFAST operationally viable.

At airports which do not have CTAS, the ITWS terminal winds product has been demonstrated to be operationally useful in allowing ATC to land more aircraft per hour by enabling ATC supervisors to develop and refine optimized aircraft spacings for the terminal area in cases where the winds are different from "nominal" terminal area winds (Cole, et al., 1997).

For purposes of benefits assessments, we have studied the advantages of terminal winds when used by ATC supervisors at an airport which does not have aFAST. This was done because there is no operational experience with aFAST, whereas ITWS terminal winds has been in operational use since 1994.

2.3 Integrated Terminal Weather System (ITWS)

2.3.1 System Architecture

The ITWS integrates information from a variety of data sources as shown in Figure 4. Table 2 shows the ITWS initial operational capability (IOC) products with the products that require a TDWR, indicated by an *, while those that benefit from a TDWR are shown with **. Figure 5 shows the architecture of the computer software used to generate the IOC ITWS products. Details on the algorithms which generate the ITWS products are described in a number of papers [Evans and Ducot, 1994, Cole and Wilson, 1994, Wolfson, et al., 1994, Chornoboy and Matlin, 1994], the ITWS algorithm functional specification (DOT 95/11) and on the Lincoln WWW site (http://WWW.LL.MIT.EDU/AviationWeather/).

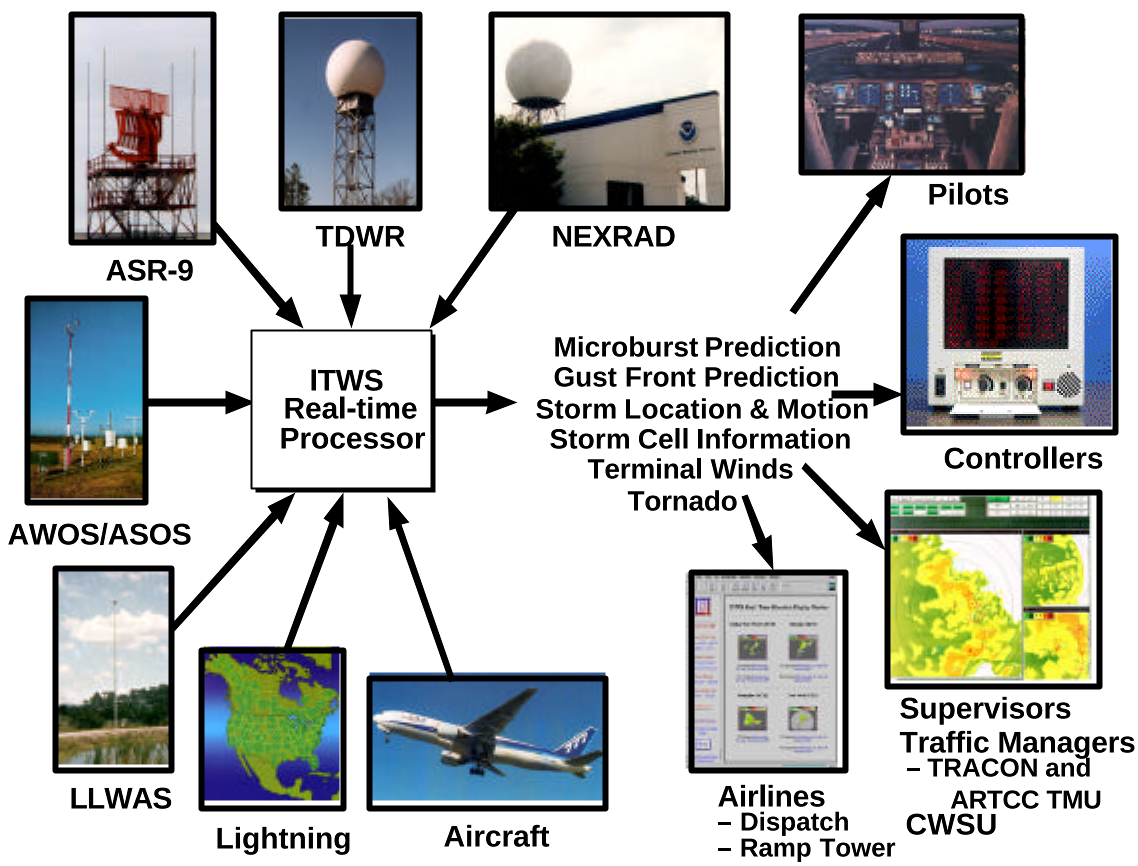

Figure 4. ITWS block diagram.

Table 2.
Initial Operational Capability (IOC) ITWS Products

	ITWS Products	Capability
a)	Wind Shear: 1) Microburst detection/prediction* 2) Gust front detection and forecast* 3) Ribbon display alerts 4) Microburst alert ATIS timer 5) Wind shear alert ATIS timer 6) Gust front impact timer*	Accurate detection/prediction and alerting of microbursts including location, runway impact and intensity; Improved gust front detection and forecasts; Timers to reduce ATC workload (ATIS and Gust front impact);
b)	Gust front wind shift estimate*	Estimate of wind speed and direction 10 minutes behind the gust front;
c)	Precipitation: 1) 5 nautical mile range* 2) TRACON range** 3) 100 nautical mile range 4) 200 nautical mile range	Precipitation intensity, location and extent in 4 ranges; TRACON precipitation with ASR-9 AP removed;
d)	Storm motion and extrapolated position: 1) 5 nautical mile range* 2) TRACON range 3) 100 nautical mile range 4) 200 nautical mile range	Indication of storm speed and direction; Near-term projected storm location, and extent depicted in 4 ranges;
e)	Storm cell information: 1) 5 nautical mile range* 2) TRACON range 3) 100 nautical mile range 4) 200 nautical mile range	Detailed data, on request, indicating storm features including; hail, lightning, mesocyclone and echo tops in 4 ranges;
f)	ASR-9 AP: Precipitation with AP flagged** AP alert	Indication of location and extent of AP in the ASR-9 reflectivity; Alerting to the presence and location of ASR-9 AP;
g)	Tornado: detection alert	Indication of locations on SD in 4 ranges; Alert to the presence of tornadoes within designated distances of each ITWS airport;
h)	Airport lightning warning	Indication of lightning within designated distances of each ITWS airport;
i)	LLWAS winds	Centerfield and runway-specific winds as designated to cover each ITWS airport;
j)	Terminal winds: Gridded wind field** Wind profile**	Profiles of winds for each ITWS airport for designated reference points and altitudes for display; Gridded winds for TATCA;
k)	Runway configuration	Airport configuration (runway configuration).

* require TDWR
** benefit from TDWR data

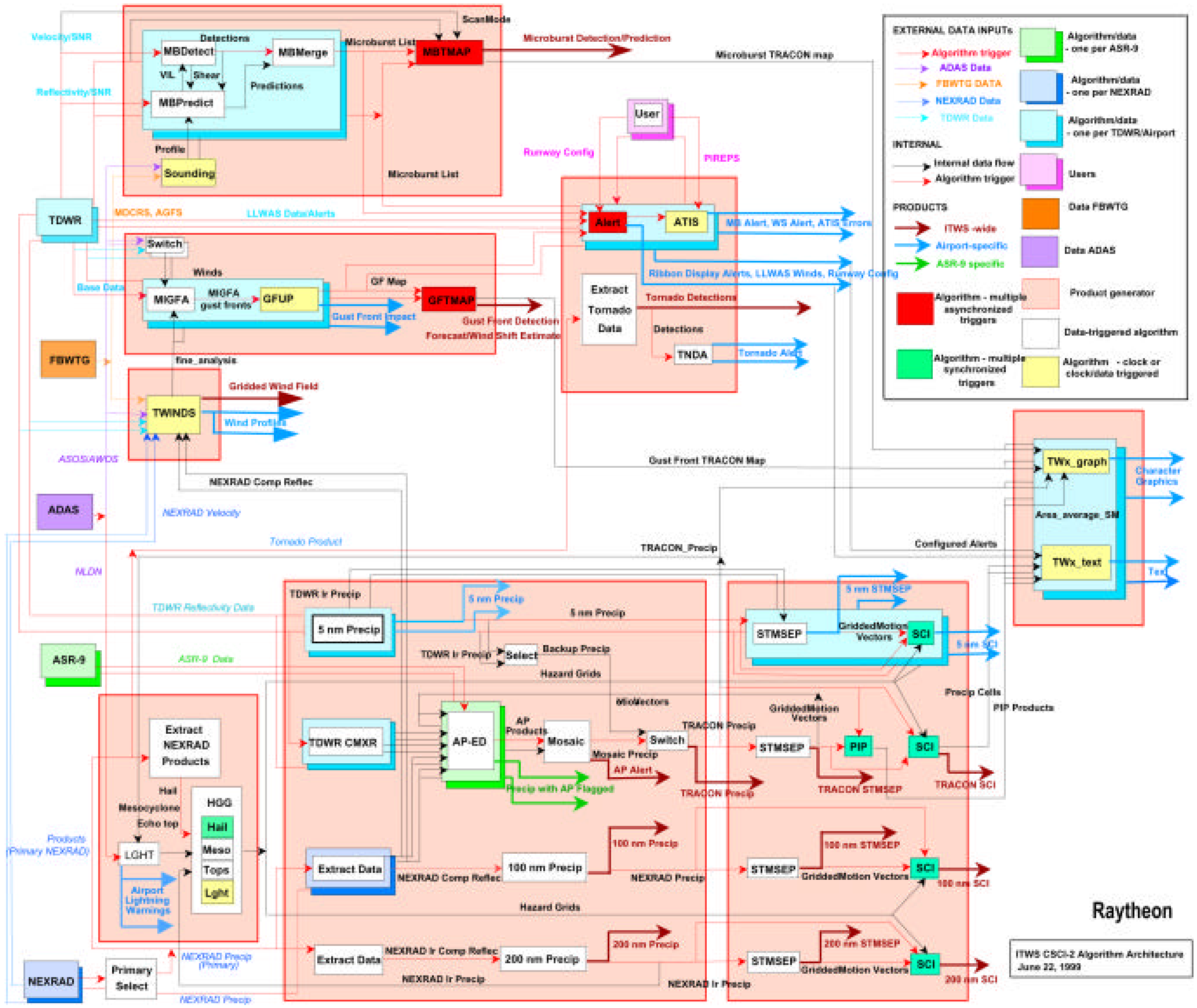

Figure 5. IOC ITWS Computer Software Configuration Item (CSCI) architecture (graphic from Raytheon, Sudbury, MA).

2.3.2 ITWS IOC Safety Benefits

The IOC ITWS products can address several of the west coast airport safety concerns discussed in Section A above:

(1) Vertical wind shear can be determined from the ITWS terminal winds vertical profile near the airport. It should be noted that there is no explicit controller warning for vertical wind shear (e.g., based on the rate of change of horizontal velocity with altitude). Such warnings could be created easily by an algorithm operating on the ITWS terminal wind grid data.

(2) The ITWS precipitation and storm motion/extrapolated position products can provide 10-20 minute warning of the impact of heavy precipitation on the airport runways and other critical locations. The WSP also will provide similar 10-20 minute warnings.

(3) Storms which are creating CG strikes near the airport will cause the ITWS airport lightning warning to trigger and, in the ITWS storm cell information product, they will be shown as storms with lightning.

However, studies of lightning strikes to aircraft (Mazur, 1993) have shown that nearly all lightning strikes to aircraft in Pacific Northwest-type storms arise in cases where there is little or no natural CG lightning. Hence, the IOC ITWS lightning capability will generally be useful only in identifying storms in which an aircraft has triggered a CG strike.

In principle, it would be possible to generate a warning based on the storm vertical structure (especially the mixed-phase region where there is ice and water). There is no current explicit IOC ITWS determination for the altitude of the mixed-phase region in a storm, although this could be created easily from radar data and the sounding profile generated by the microburst prediction module ("sounding" in Figure 3) as discussed in Section 5.

2.3.3 ITWS IOC Delay Reduction Benefits

Table 3 shows the national delay reduction benefits for the IOC ITWS products as estimated based on 1993-1994 testing at Orlando, Dallas and Memphis, together with the latest estimates which include operational experience from 1995 to 1998 (Cole, et al., 1997; Bieringer, et al., 1999). The major delay reduction benefit for the west coast airports that would be generated by the ITWS involve the use of the terminal winds information (either directly via the terminal winds product or as an input to CTAS and wake vortex advisory systems). To give some perspective on the potential magnitude of the benefits, we show in Table 4 the projected ITWS benefits at New York, which is similar to LAX, SFO and SEA in having the bulk of the delays arising from low ceiling and visibility (as opposed to convective weather).

Table 3.
ITWS National Implementation Benefits for Initial Products

User Identified Payoff Area	1994 Yearly Benefit * ($M)	Latest Estimate** ($M/year)
Higher effective airport capacity during thunderstorm	11	18
Anticipated arrival and departure area closure/reopening	81	134
Anticipated runway impacts and shifts	57	94
Better terminal area traffic pattern	5	10
Optimizing traffic flow	62	125
Improved merging and sequencing using terminal winds	-	71
Airline operations optimization (fuel, connections, ramp operation)	19	31
Total	235	483

* Based on 1993-1994 testing at Dallas, Memphis and Orlando
** Includes terminal winds benefits and improved climatological estimates of convective impacts on terminal areas

Table 4.
Projected Annual ITWS Benefits at New York City Airports

Airport	Ops (x 10^3/year)	Delay Reduction (hours/year)		Benefits ($M/year)	
		Thunderstorms	Winds	Total	Airline DOC
Newark	440	1,613	5,116	18.1	9.1
LaGuardia	338	1,299	3,360	12.9	6.9
Kennedy	350	1,233	1,785	8.4	4.7
Total		14,519		39.4	20.7

DOC = direct operating cost.
"Total benefits" includes passenger time per the FAA guidelines

2.4 Additions to the ITWS IOC Product Suite of Special Interest for West Coast Airports

In addition to the IOC products described above, there are two additional candidate products for ITWS that should be considered in a study of sensor data needs for the major west coast/Hawaiian airports. These are the terminal convective weather forecast product and the stratus cloud prediction product.

2.4.1 Terminal Convective Weather Forecast (TCWF) Product

The west coast heavy precipitation events represent a form of organized convection which is typified by precipitation bands and line storms. Determining the motion of large-scale, line-like storms is a long-standing problem in weather radar research. To determine line storm motion correctly, the large-scale "envelope" motion must be found separate from the storm "cell" motion. Conventionally, storms are forecast by extrapolating the motion of individual cells. For very short-term predictions the cell motion is accurate, but for longer-term predictions, the envelope must be tracked. By separating the scales in the original weather radar image and tracking the large scale and small scale components separately, the motions of the envelope (large scale) and cells (small scale) can be determined [(Wolfson, 1999), (http://WWW.LL.MIT.EDU/AviationWeather/)].

The Terminal Convective Weather Forecast (TCWF) product has been used successfully in operations at Dallas and Orlando in 1998-1999 (Hallowell, et al., 1999) and applied to data from the Little Rock, AR accident. Figure 6 shows the NEXRAD precipitation products for Little Rock prior to and just after the accident in June 1999. Figure 7 shows the pixel by pixel scoring of the 30 minute TCWF product for the case shown in Figure 6 where green indicates regions where heavy precipitation (NWS VIP level 3 or higher) was correctly forecast, red indicates areas where heavy precipitation occurred that was not forecast (i.e., misses), and blue indicates regions where forecast heavy precipitation did not materialize (i.e., false alarms).[2] Comparison of the TCWF product predictions with the NEXRAD data at the forecast times found that the product did an excellent job of anticipating the start and stop of heavy precipitation on the Little Rock airport.

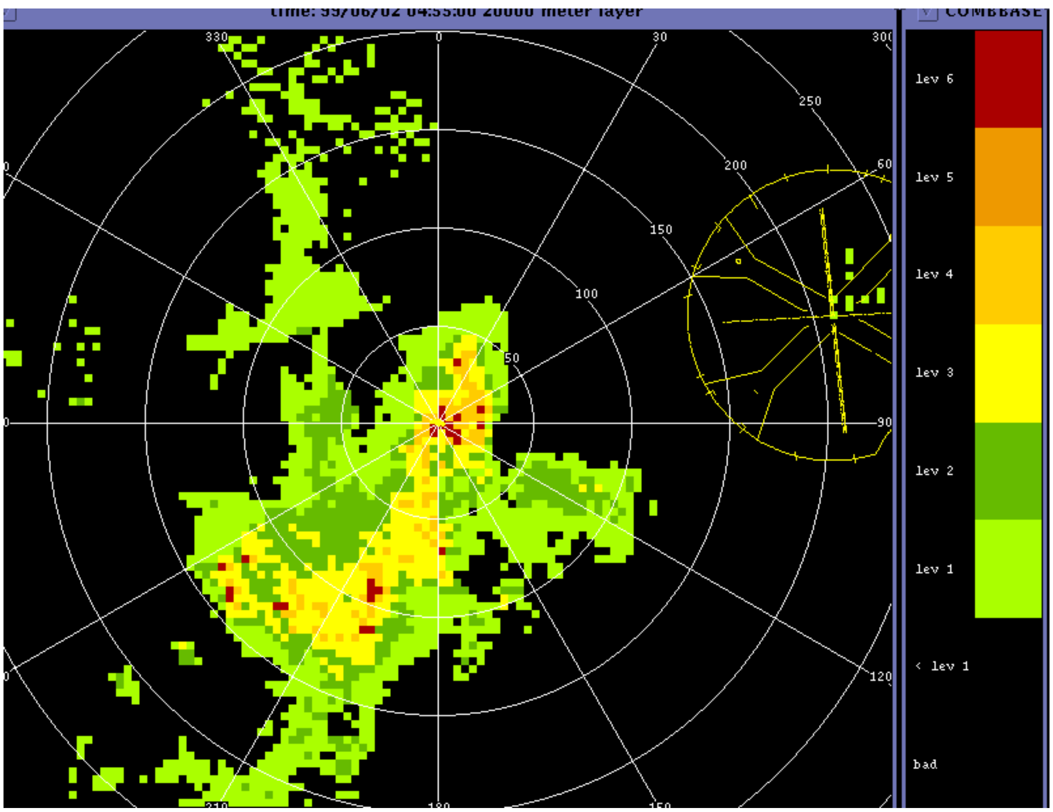

Figure 6. Reflectivity at Little Rock before accident.

[2] The TCWF scoring methodology is described in (Hallowell, 1999).

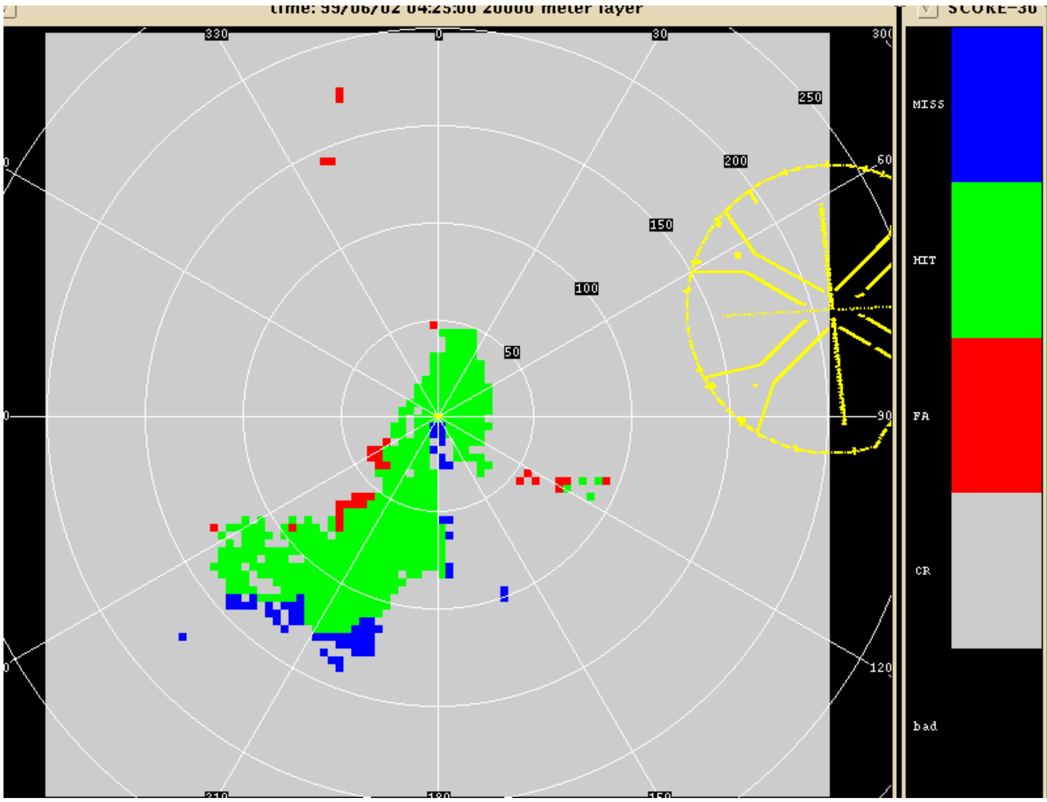

Figure 7. Scoring of 30 min TCWF at Little Rock.

Since such heavy precipitation is both a safety concern and significantly reduces ceiling/visibility, being able to correctly forecast the impacts 30-60 minutes in advance provides both safety and delay reduction benefits.

2.4.2 Marine Stratus Cloud Prediction

Marine stratus clouds are a major cause of low ceiling and visibility at San Francisco, Seattle, and Los Angeles that results in delay programs. Figure 8 shows the mechanism by which these marine stratus clouds occur in San Francisco. Similar mechanisms operate in Los Angeles and Seattle.

The failure to forecast the times of onset and burn-off of marine stratus accurately results in significant costs to the NAS. Traffic Management Unit (TMU) delay program decisions, based on current forecast capabilities, frequently err in both directions: holding patterns result from failure to impose or maintain a needed program, and unnecessary delays result from failure to cancel an unneeded program (Wilson and Clark, 1999).

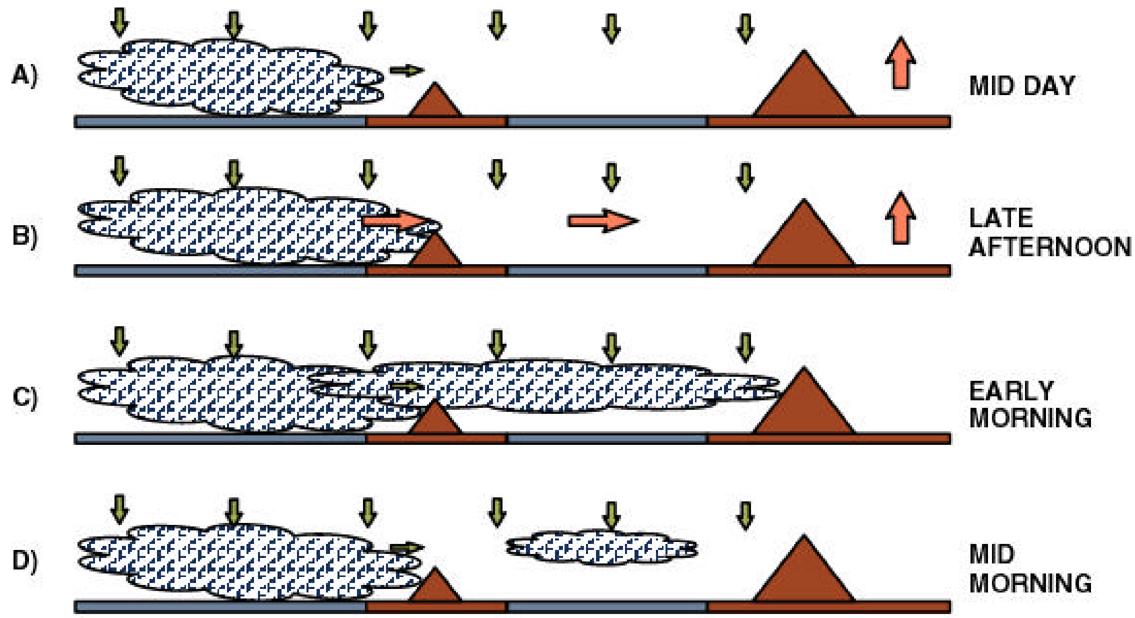

Figure 8. Marine Stratus Cloud.

Figure 9 shows key meteorological parameters that need to be measured to predict dissipation of the coastal stratus. At this point, neither is there an operational weather sensor system to accomplish many of these measurements nor is there an operational data fusion system that would execute the data fusion algorithms to predict marine stratus onset and dissipation.

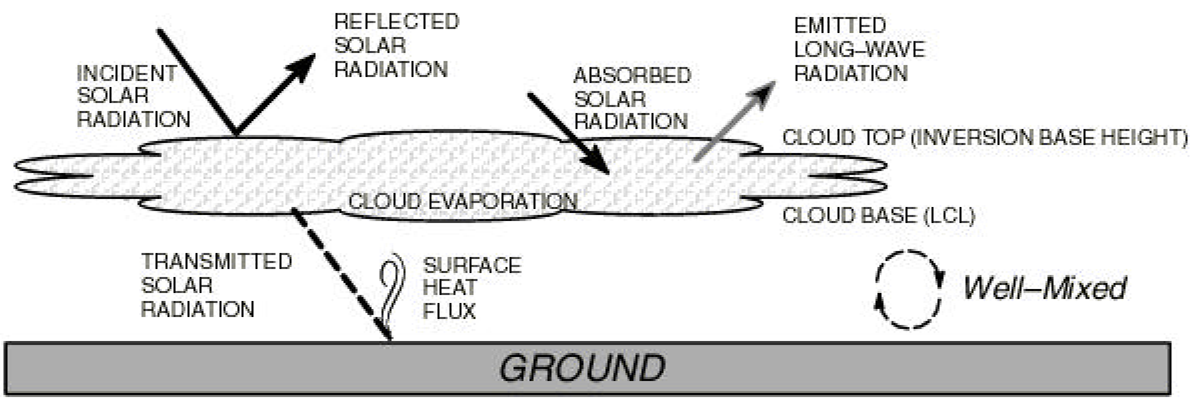

Figure 9. Key meteorological parameters for coastal stratus prediction.

Extending the ITWS to ingest data from additional sensors seems cost effective, as ITWS already has access to key information (e.g., RUC data, plane reports, NEXRAD data) and has certain internal products (e.g., sounding, terminal winds) that would be useful to a stratus cloud prediction algorithm.

3. APPROACH TAKEN

Figure 10 shows the methodology for the study. Information on current operations rates and delays was obtained from the FAA. The 1997 FAA Aviation Capacity Enhancement (ACE) Plan was used to determine planned airport changes. The expected traffic loads were determined from the 1998 Official Airline Guide (OAG).

The principal mechanism for obtaining information on delay causality, terminal-specific weather phenomena, capabilities of the current weather sensors, and terminal operational constraints was visits and phone calls to the various ATC facilities. Multiple trips were made to the Southern California TRACON and the San Francisco terminal radar facility. A single trip each was made to the Seattle TRACON, to the planned North California TRACON, to the Oakland and to the Los Angeles ARTCC facilities. Detailed phone discussions were held with the Portland TRACON.

The ATC and Center Weather Service Unit meteorologist data on weather characteristics were complemented with climatological data for the various airports. The calculations made for terminal winds and wake vortex benefits use the queueing model developed by Lincoln for the IOC ITWS benefits studies, and subsequently used for Dallas and New York terminal winds studies. This model and its validation are described in Appendix D.

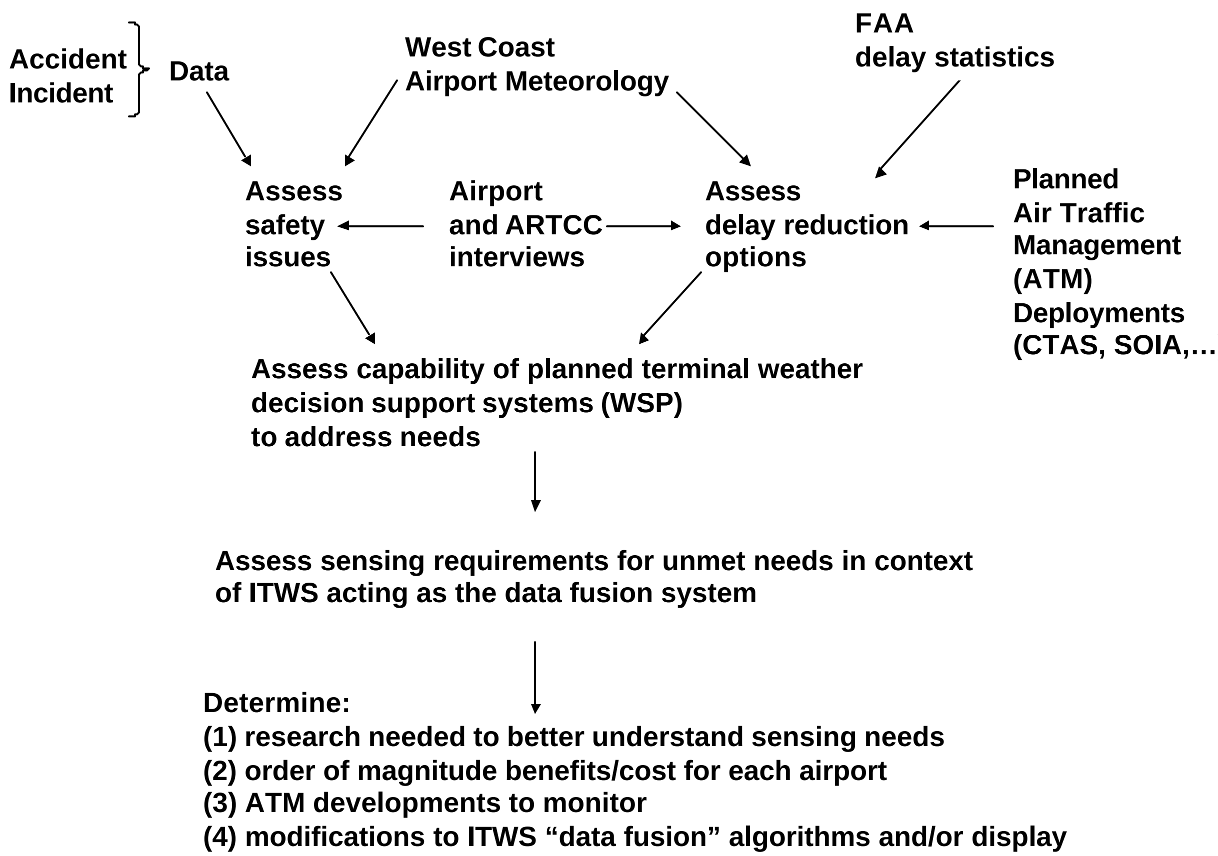

Figure 10. Methodology for study.

4. SPECIFIC AIRPORT RESULTS

4.1 San Francisco (SFO)

Given the very high rate of delays at SFO in Table 1, SFO would appear to be a good candidate for the products provided by ITWS. However, it turns out that IOC ITWS alone cannot make a major reduction in the summer delays due to the inability to fully use the runways when the stratus cloud is present. Rather, one would need enhanced weather sensing and additional surveillance systems as well as an augmented ITWS.

Figure 11 shows the runway configuration at San Francisco International Airport. The normal operation is landing to the northwest on runways 28L and 28R while running departures to the north-northeast on 01L and 01R. When in this normal mode, aircraft arriving at SFO are merged together in the approach zone approximately 5-15 miles to the east-southeast of the airport. Due to the mountainous terrain to the east and west, this merger occurs at an altitude of approximately 3500 feet. Under visual approaches, aircraft are allowed to merge in pairs and make simultaneous parallel approaches on runways 28L and 28R. Under these conditions, the airport operates at an arrival rate of approximately 50-55 planes per hour. When other runway configurations are used, arrival rates can drop to as low as 25 per hour. Table 5 shows the SFO arrival rates used by the FAA Command Center.

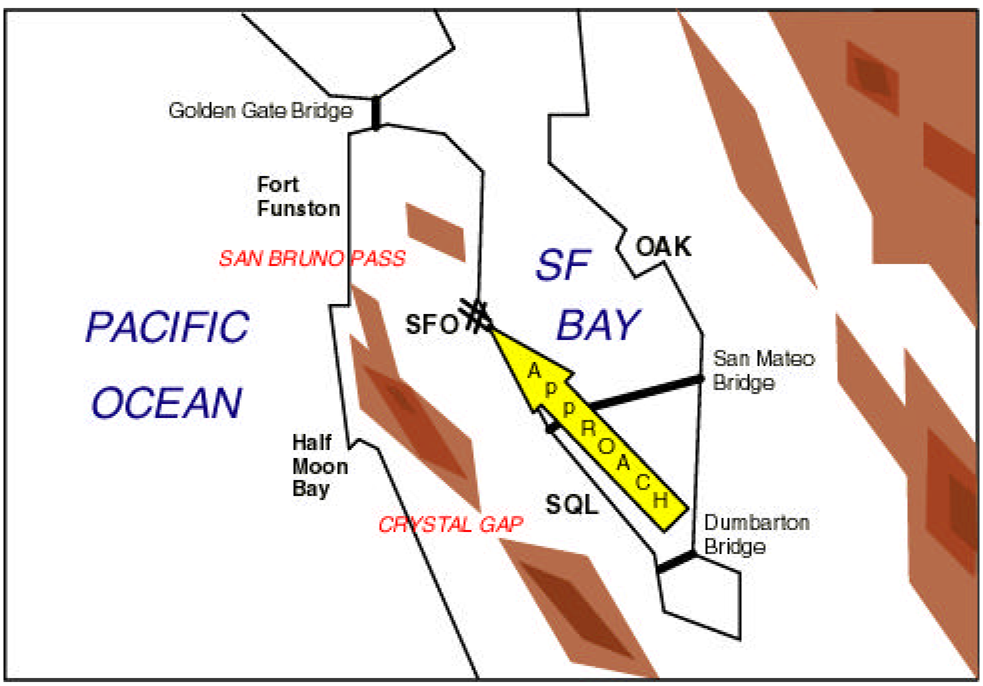

Figure 11. Runway configuration at San Francisco International Airport (SFO).

Table 5.
San Francisco Arrival Rates for Various Runway and Ceiling/Visibility Conditions

San Francisco Arrival Rates (aircraft per hour)					
Land	**Depart**	**IFR**	**VFR**	**Visual Approaches (VAPS)**	**Notes**
28L 28R	1L 1R	30	45	60 during daylight hours.50 during non-daylight hours.	Minimum ceiling for VAPS 3000-3500
28L 28R	28L 28R	30	45	45	Minimum ceiling for VAPS 3000 to 3500
28L or 28R	1L 1R	30	N/A	30	Minimum ceiling for VAPS 3000 to 3500
28L 28R	1L or 1R	30	45	45	Minimum ceiling for VAPS 3000 to 3500
1L 1R	1L 1R	30	N/A	30	
19L 19R	10L 19R	27-30	N/A	45	Minimum ceiling for VAPS 4000
19L 19R	19L 19R	25-30	N/A	42	Minimum ceiling for VAPS 4000
19L or 19R	10L 10R	27-30	N/A	30	Minimum ceiling for VAPS 4000
19L 19R	10L or 10R	27-30	N/A	45	Minimum ceiling for VAPS 4000
10L 10R	10L 10R	27-30	N/A	37	
Any Single Runway		27	N/A	27	

Source: FAA Command Center (F. Terrell), 1999.

When aircraft are not able to see one another in this merger zone due to low ceilings or poor visibility, the approaching aircraft must be staggered to provide the equivalent of a single runway stream. This reduces the capacity to 30-35 planes per hour. The typical weekday demand for arrivals (Figure 12) shows the impact of the capacity loss when the airport cannot operate with VFR. The morning "push" that begins shortly before 10:00 AM local time and lasts until 1:00 PM cannot be accommodated, as there is an excess of approximately 15 planes per hour. This excess is managed by delay programs. As a consequence of the large number of IFR events which occur in the morning (see Figure 13), SFO often has the greatest number of delay programs of any airport in the NAS.

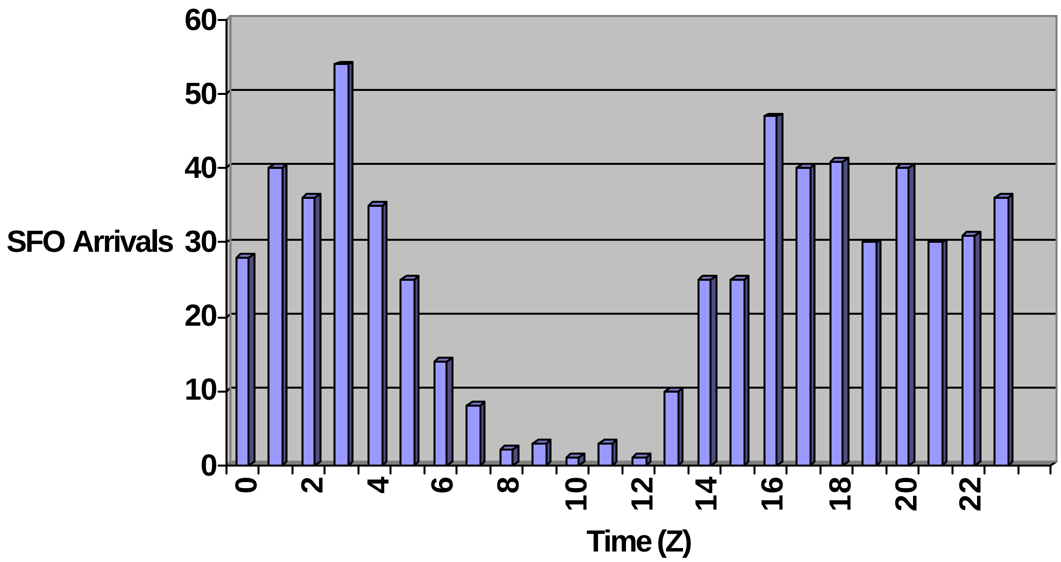

Figure 12. Typical weekday arrival demand in one-hour intervals at San Francisco.

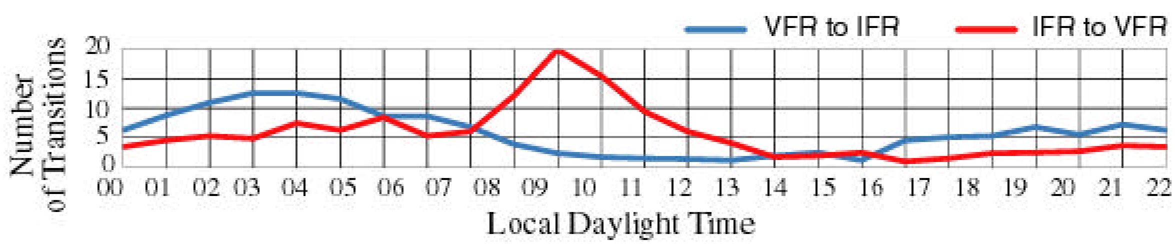

Figure 13. Diurnal distrubution of frequency of transition from VFR to IFR at SFO, and vice versa, from May through September. IFR conditions are defined as presence of cloud ceiling height of less than 2000 feet.

The key SFO factors assumed for this study can be summarized as follows:

Capacity: landing to northwest (NW) with visual approaches = 52 arrivals per hour

Landing to southeast (SE) with visual approaches = 45 arrivals per hour

IFR=33 arrivals per hour

Operation: May-Oct: NW 100%; Nov-Apr: NW 80%; SE 20%

The visual approach and IFR capacities used here are slightly different from those in Table 5 based on discussions with the SFO TRACON.

Weather problems:

May-Oct: Marine stratus 100 days possible late burnoff

20 days possible early onset (see Figure 13)

Airmass convection over mountains is frequent in late spring and early summer but does not cause delays unless it blocks Air Route Traffic Control Center (ARTCC) routes (approx. 10 days/year)

Nov-Apr: Winter storm prefrontal bands

Vertical wind shear & reduced visibility in rain bands

~50 events in a wet year

~7 events in a dry year

Current "operational" weather sensors

NEXRAD south of San Jose in the mountains with a radar phase center altitude of 3600 feet. Lowest tilt covers about 4000 feet above SFO airport surface.

AWOS at San Mateo Bridge

Unique ATC features

The Northern California TRACON (NoCal TRACON) is currently being formed. This will be located at Sacramento. A potentially important issue is the display system design for the TMU—if ITWS is to be deployed eventually at the NoCal TRACON, it would be very helpful to reserve display space now.

A number of additional weather sensors are available in the SFO area as a result of the AWR stratus cloud burnoff prediction project. Figure 14 shows all of the ground sensors used for the stratus project.

The weather sensors currently deployed at SFO for stratus cloud prediction include a number of sensors not currently accessed or utilized by ITWS including:

- Wind profilers
- Pyrometer
- GOES satellite data

The GOES satellite data ingest would be the most challenging addition to ITWS due to the data volume. It should be noted that use of GOES data will probably be an ITWS enhancement eventually for convective weather forecasting at the current ITWS sites.

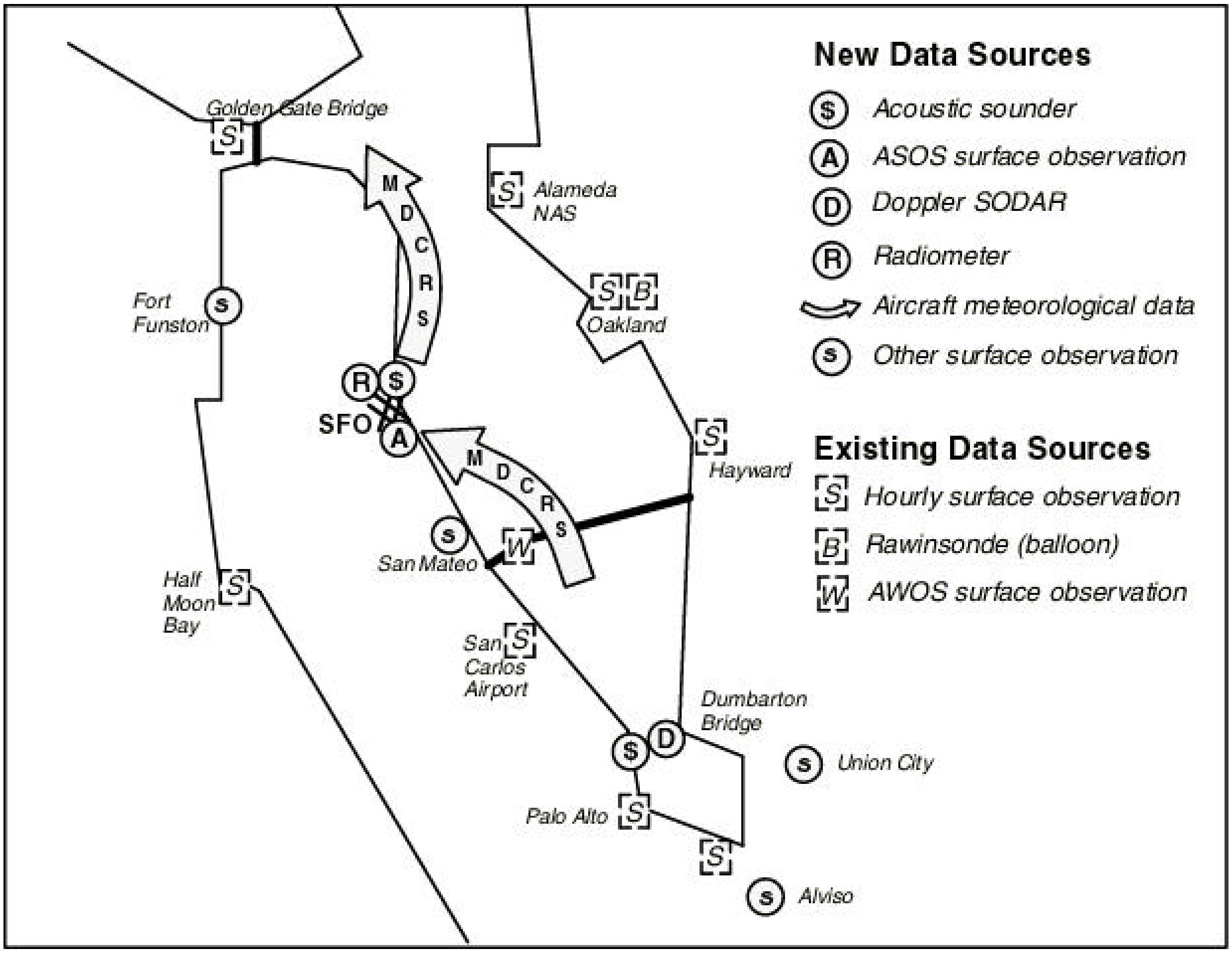

Figure 14. Locations of data sources in San Francisco Bay area.

4.1.1 ITWS Terminal Winds

4.1.1.1 IOC Terminal Winds for Improved Aircraft Merging and Sequencing

A number of discussions were held with the SFO TRACON on the value of the ITWS terminal winds product to assist aircraft merging and sequencing so that a higher arrival runway capacity would be achieved. They felt it would not be very beneficial during the May-October time period when the marine stratus clouds are present since the winds during such situations do not change very quickly, and typically are the same from day-to-day. In such familiar conditions, the SFO TRACON controllers can achieve near optimum performance in aircraft merging and sequencing without better winds information.

By contrast, during winter storms when the airport is in the unfamiliar southeast configuration and the winds vary rapidly vertically and in time, the ITWS terminal winds could provide a benefit. However, the local users were reluctant to provide quantitative estimates of the possible improvement in terms of additional aircraft landed per hour relative to the current capability. Based on the ITWS Dallas experience, we believe that the TRACON could land about two additional planes per hour during the winter storms. Table 6 summarizes the expected benefits using the queueing model of Appendix D.

Table 6.
Projected SFO Delay Reduction During Winter Storms due to Improved Merging and Sequencing of Aircraft

Delays for a Single All-Day IFR Operation with Landing to Southeast in Adverse Winds

Assumed Capacity (a/c per hr)	Max Delay (min)	Hours of Delay		Cost of Delay	
		Direct	Indirect	Airline ($M)	Total ($M)
33 (w/o ITWS)	105	492	394	1.2	3.0
35 (w ITWS)	53	255	204	0.8	1.7
Delay Reduction (per event)	52	237	190	0.4	1.3
Savings for 15 events		6405 hrs delay		$ 6.0 M	$ 19.5 M

Notes:
1. The computed delays assume no flights were cancelled. The delays are such that cancellations would probably have occurred in the afternoon and evening (see Appendix E for the delay as a function of time of day). However, it is likely that the costs of the cancellations (certainly for the passengers) would be higher than the costs shown above for the delays
2. The number of events per year can vary significantly from year to year (the TRACON estimated 7 to 50 storms per year).

4.1.1.2 Enhanced ITWS Terminal Winds to Support Closely Spaced Approaches During IFR Conditions

Figure 15 shows two approaches to increasing the SFO airport capacity during IFR conditions when runways 28L and 28R are used for arrivals. United Airlines is planning to purchase a Parallel Runway Monitor (PRM) system for SFO that would enable the Simultaneous Operation with Independent Approaches (SOIA) approach to be accomplished. Appendix B discusses the SOIA system. The Paired Approach system would require airborne precise position monitoring by the aircraft [e.g., by Automatic Dependent Surveillance-Broadcast (ADS-B)] and special cockpit displays). Thus, in both closely spaced approach schemes, there is a need for accurate information on winds as a function of altitude along the portions of the approach where the two aircraft are in close proximity.

Estimation of the benefits of SOIA at SFO is currently being made by United Airlines. In lieu of available benefit figures, a simple queuing model analysis was performed of arrival SFO traffic and weather conditions that should provide a sense for the range of benefits from SOIA. In this model, the arrival runways are treated as a simple queue, with input to the queue dictated by aircraft arriving for landing at the airport and output of the queue dictated by the airport arrival capacity. The aircraft arrival rate, on an hourly basis, was extracted from 1998 OAG data. The airport capacity was chosen based on the weather conditions. The queuing model was run through nine years of hourly surface observations at SFO and a running total queue delay was computed, with and without a SOIA system. The model estimated that SOIA would save 11,224 hours of arrival aircraft delay per year, resulting in the dollar and capacity benefits shown in Table 7. A more detailed analysis of the model is given in Appendix B.

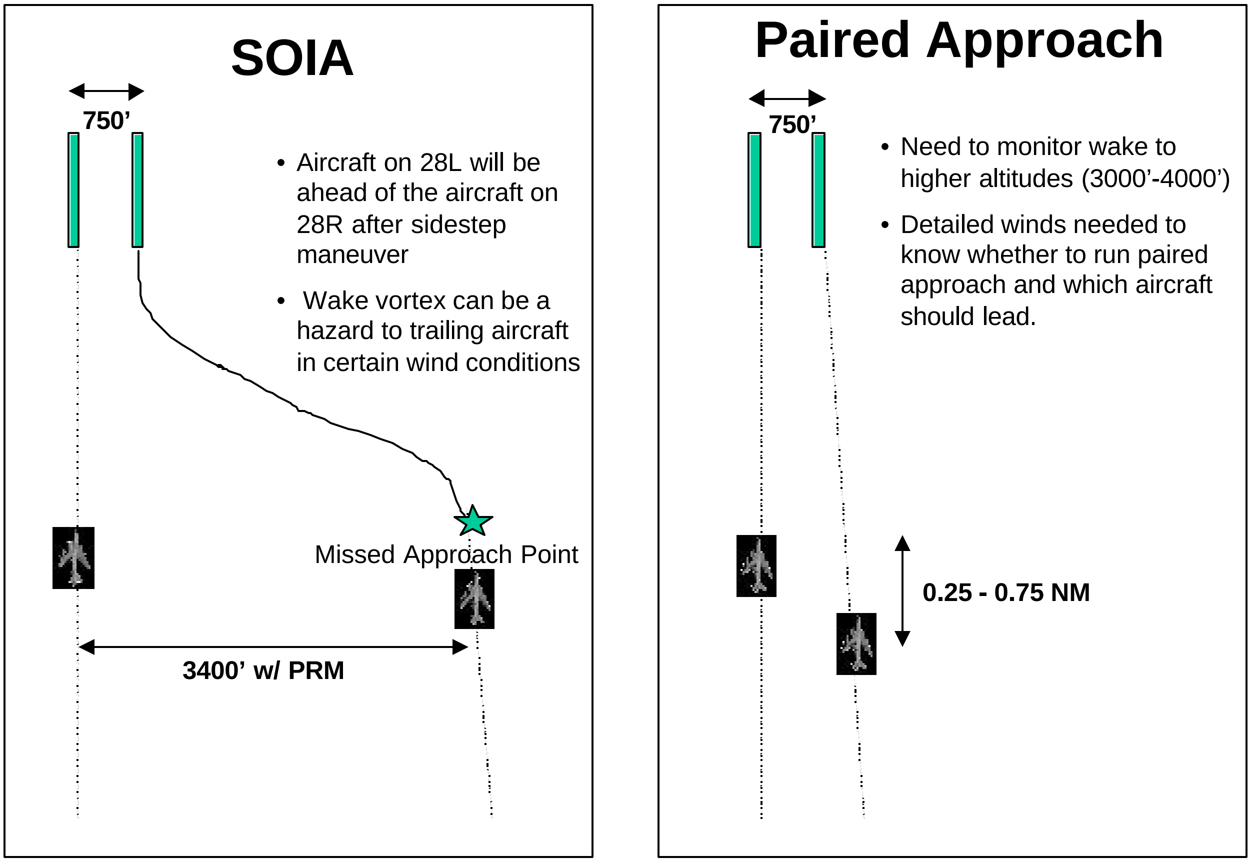

Figure 15. SFO parallel approach (Figure from T.J. Dasey, 23 June 1999 briefing to AND 400).

Table 7.
Summary of the Estimated benefits of a SOIA System at SFO
(see Appendix B for details)

Metric	Benefit
Airline Direct Operating Cost	**$42.2 M/year**
Passenger Time	**$35.9 M/year**
Arrival Capacity	**Average 4.3% increase**

4.1.1.3 Wind Sensors to Support the Generation of ITWS Terminal Winds

From the discussion above, high-quality terminal winds would clearly be very beneficial at SFO. Providing the detailed winds information with an SFO ITWS using the current wind sensors will be difficult because there is no TDWR in the area and the NEXRAD is well to the south of SFO atop a mountain (so it has visibility of storms at sea). As a result of the radar altitude, the distance from SFO and very unfavorable viewing angle geometry, the NEXRAD does not effectively measure the winds along the approach path in the region of concern. As a result, an SFO ITWS would be estimating winds only from NWS numerical models, aircraft and surface observations. This sensor configuration would probably not be adequate unless the aircraft observations of the winds at SFO were improved significantly in terms of vertical resolution and frequency of reports.

A volume scanned pencil beam radar (e.g., a TDWR) located at Oakland airport would do a very good job of estimating winds in the region of interest as well as being of use during winter storms. Unfortunately, the FAA does not have a TDWR which is immediately available for this location. A commercial off-the-shelf (COTS) pencil beam radar (e.g., commercial 2-degree beamwidth radars) would probably suffice for this application (since low-altitude wind shear is not the principal concern). The overall availability could be relatively low (e.g., 99 percent) for this application since the data is not critical for safety in the same sense as data for low-altitude wind shear protection. However, the FAA surveillance and weather IPT has no current convenient mechanism for purchasing and operating such a system.

A more likely prospect might be for an SFO ITWS to obtain data from several (at least two) low-altitude wind profilers located on or near the approach path. An acoustical profiler already operates in the area as a result of the FAA AWR-funded marine stratus cloud prediction project. However, the acoustical profiler has not proven satisfactory in the Dallas wake vortex experiments due to interference from local noise sources (e.g., trucks and aircraft). Rather, we would recommend a COTS UHF vertical profiler (typical cost is $250K).

The software to accomplish such merging has been developed from the terminal winds code and was applied to estimate the terminal winds at LAX (see next section). A modified version of the Lincoln prototype ITWS terminal winds algorithm software that uses profiler data has been developed. The software costs to modify a production ITWS to ingest the profiler data have not been determined but should be relatively low.

4.1.2 Ceiling and Visibility Prediction at SFO

4.1.2.1 <u>Stratus Burnoff Prediction</u>

The previously mentioned report on the San Francisco marine stratus prediction project summarizes the utility of the ITWS for improved ceiling forecasts at SFO and the sensors currently deployed at SFO to provide algorithm data. Given the in-depth studies in that report (and the report references), we did not address stratus burnoff prediction in this study.

4.1.2.2 <u>VFR to IFR Transitions in Winter Storms</u>

The closely parallel approach schemes described above apply only when SFO is in its normal landing configuration and would provide no benefits during winter storms when IFR landings occur to the southeast. The rather large delays that occur during such IFR conditions show that the TMU will need to anticipate the IFR/VFR transitions if delays are to be minimized. The ITWS terminal convective weather forecast may be useful in this respect. However, the product performance on such storms and the relationship of the storm reflectivities to ceiling/visibility have not been investigated experimentally.

4.2 Los Angeles (LAX) International Airport

The Southern California (SoCal) TRACON had very strong Air Traffic user interest in an ITWS to improve operations at Los Angeles airport (LAX). Figure 16 shows the LAX airport layout. Arrivals occur on the outer runways with departures from the inner runways.

Key elements of LAX for purposes of this study can be summarized as follows:

Capacity:

Landing to west VFR: 84 arrivals per hour

Landing to east VFR: 76 arrivals per hour

IFR: 60 arrivals per hour

Operations:

May-Oct: West 100%; Nov-Apr: West 80%; East 20% (storms)

Weather problems:

May-Oct:

Marine stratus clouds and/or haze causing IFR operations (see Figure 1)

Airmass convection over mountains when there is still snow cover and/or high soil moisture-frequency TBD

Nov-Apr:

Coastal storm prefrontal bands

Vertical wind shear and reduced visibility in rain bands

15-20 days per year of "east" IFR operations

Unique ATC system features:

The Southern California TRACON was formed from four TRACONs a few years ago. The TRACON covers a huge area and has more traffic than the ARTCC. Vertical coverage is up to 17K feet.

Automation systems:

LAX is a near term CTAS airport.

Weather sensors:

There are four NEXRAD sites with some coverage of the SoCal TRACON, all in mountains not near LAX; lowest scan covers above 3000 feet near LAX. The closest NEXRAD is at Pt. Mugu (a range of about 80 km) at an altitude of approximately 2600 feet.

Five wind profilers in Los Angeles area for air quality studies.

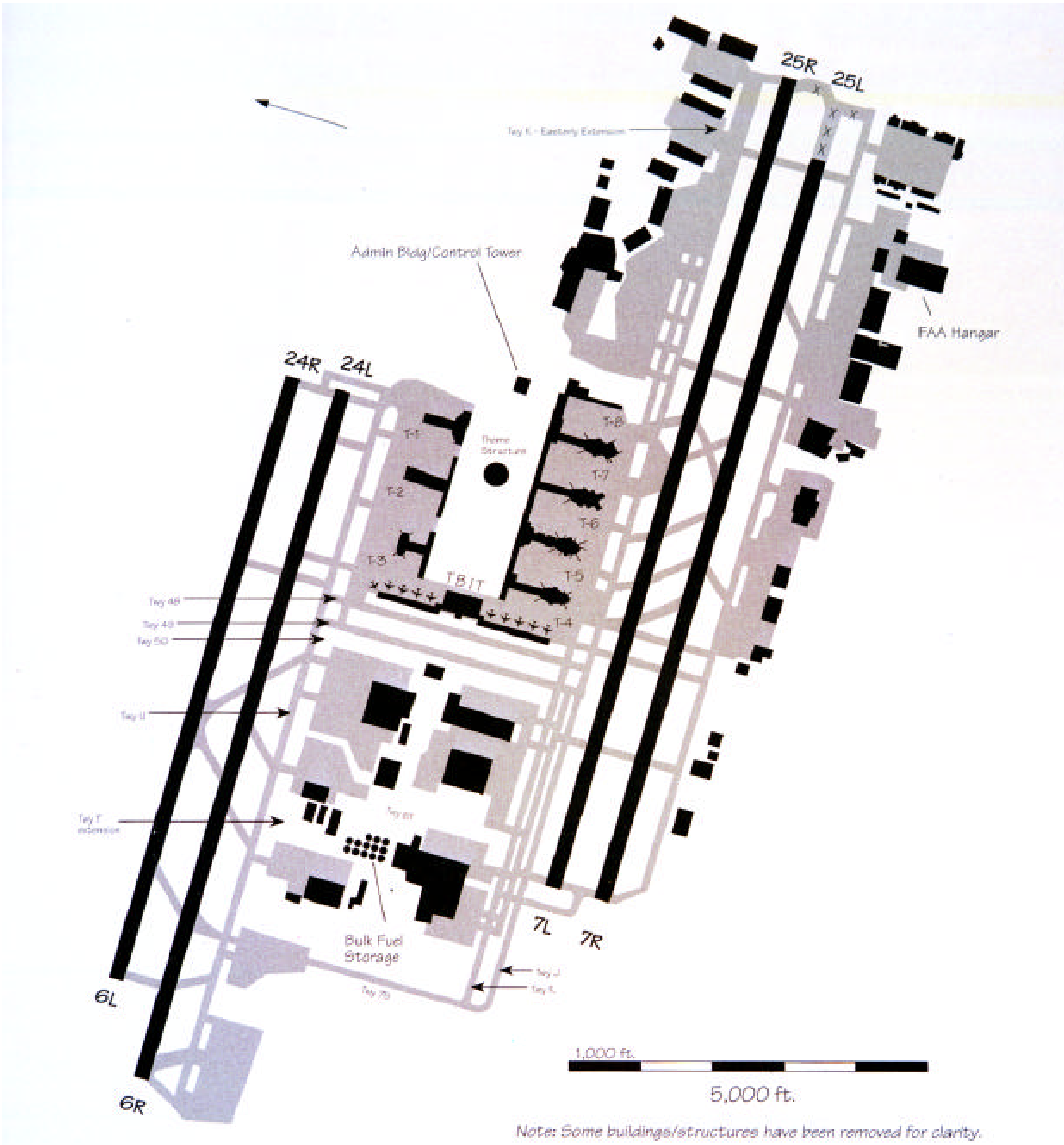

Figure 16. LAX Airport Layout (from US DOT FAA "1994 Aviation Capacity Enhancement (ACE) Plan," DOT/FAA/ASC-94-1, Appendix E-25).

4.2.1 ITWS Terminal Winds

4.2.1.1 Improved Aircraft Merging and Sequencing

Terminal winds (especially in the context of CTAS) represent a significant potential benefit at Los Angeles given their problems with merging and sequencing when planes must land to the east during winter storms and when there are unusual vertical wind shears in fair weather operations landing to the west. Discussions with the TMU personnel suggested that an additional three to five aircraft per hour might be landed during adverse wind with landing to the east during the 15-20 days per year that east IFR conditions occur. Table 8 shows the projected benefits from the ITWS terminal winds for these occasions.

Table 8.
Projected LAX Delay Reduction During Winter Storms
Due to Improved Merging and Sequencing of Aircraft
Delays for a single all day IFR operation with landing to east in adverse winds (from Appendix E)

Assumed Capacity (a/c per hr)	Max Delay (min)	Hours of Delay		Cost of Delay	
		Direct	Indirect	Airline ($M)	Total ($M)
59 (w/o ITWS)	40	311	248	1.0	2.2
63 (w ITWS)	20	110	88	0.4	0.8
Reduction (per event)	20	200	160	0.6	1.4
Savings for 15 events		5,400 hrs delay		$ 9.0 M	$ 21.0 M

Without a TDWR, the most attractive prospect for winds sensing at LAX to support aircraft merging and sequencing is the Pt. Mugu NEXRAD, a combination of aircraft reports and use of the many wind profilers in the LAX basin. As a part of this study, we worked with NOAA's Forecast Systems Laboratory (FSL) to develop Internet access to data from the five wind profilers in the Los Angeles area. Software was developed to access the FSL data from Lincoln Laboratory, and the algorithms developed by Lincoln for the ITWS terminal winds algorithm were modified to utilize the profiler data.

Figures 17 and 18 show the gridded winds estimates at 4500 and 9000 feet, respectively, using only the profilers, MDCRS plane reports, and the RUC. Table 9 shows a candidate ATC display for the winds developed from discussions with the SoCal TRACON. It is not clear whether the accuracy of these winds will fully meet the user needs such that the benefits shown in Table 8 can be realized. Also, we believe that the format for display of the winds data could be significantly improved through interactions with operational users. We strongly recommend a limited operational evaluation of the accuracy of the LAX winds product during a winter storm season.

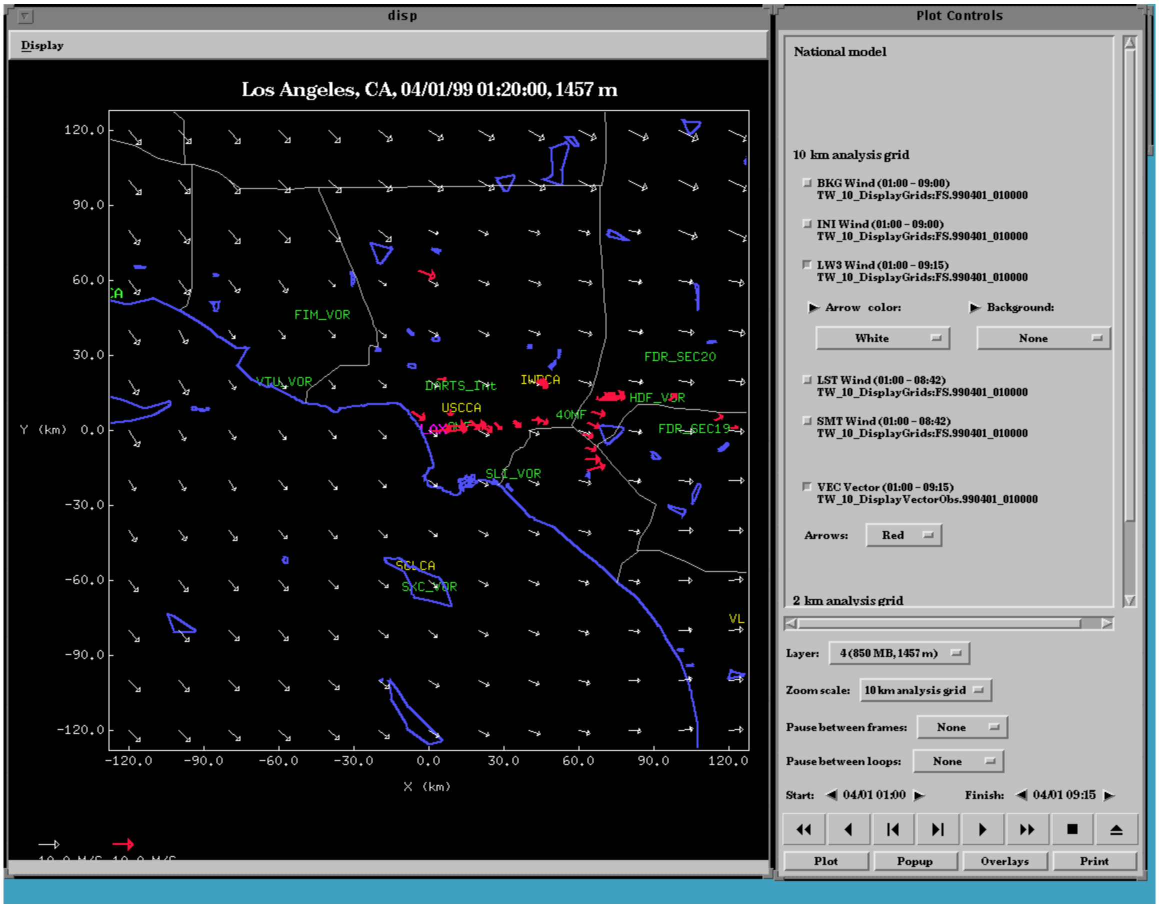

Figure 17. LAX Terminal Winds at 4500 ft. The white arrows are the horizontal gridded wind estimates on a 10 km grid. The yellow text indicates the locations of wind profilers, the red arrows indicate MDCRS reports from a 30-minute period. The length of arrows at the bottom left indicate a 10 m/s wind velocity. The green text indicates ATC fixes for the SoCal TRACON.

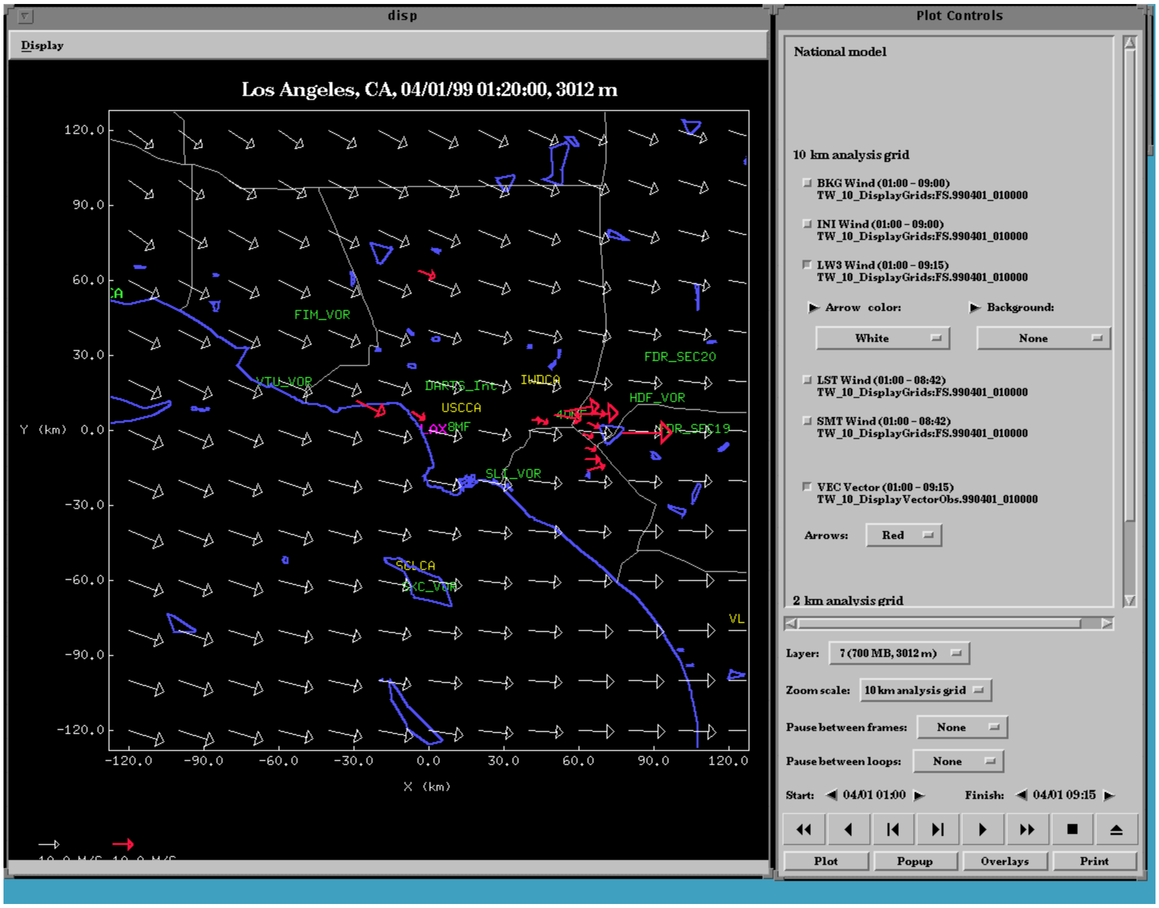

Figure 18. LAX terminal winds at 9000 ft. The white arrows are the horizontal gridded wind estimates on a 10 km grid. The yellow text indicates the locations of wind profilers, the red arrows indicate MDCRS reports from a 30-minute period. The length of arrows at the bottom left indicate a 10 m/s wind velocity. The green text indicates ATC fixes for the SoCal TRACON.

Table 9.
LAX Terminal Winds as it Might be Displayed on an IOC ITWS Situation Display

LAX TERMWINDS
(ALT DIR SPD)

FIMVOR	DARTS INTER.	FEEDER, SECT20
120 290 46	060 320 13	240 260 62
		230 270 59
		220 270 58
		210 270 57
		200 280 57
		190 280 56
		180 280 54
		170 280 54

8MF LAX	VTU VOR	40MF LAX
030 320 12 1	10 280 41	120 280 46
090 280 27		

SLI VOR	HDF VOR	FEEDER, SECT19
070 300 17	160 280 55	240 260 61
	120 280 46	230 260 58
		220 270 56
		210 270 55
		200 270 54
		190 280 54
		180 280 54
		170 280 54

SXC VOR
110 280 45

4.2.1.2 Wake Vortex Advisory Systems

A departure wake vortex system at LAX (see Appendix A) would have major benefits. This would require high-resolution winds information (see Table A-1). The WSP MIGFA will do a good job of detecting gust fronts during the approximate four days a year that there is convective weather near LAX. However, it is much less likely that the WSP will be able to detect non-convective gust fronts (e.g., sea breeze fronts and/or the Santa Ana fronts). Detection of these would probably best be done with a pencil beam radar (e.g., a TDWR or a COTS radar sited in the LAX basin inland from LAX or at the east end of LAX).

4.2.2 Storm Motion Planning

The WSP at LAX will probably meet the TRACON needs for short-term storm motion information near LAX. However, storm motion information over the mountains to the east of LAX would have to be provided by ITWS algorithms operating on NEXRAD data. The potential benefit of this information was not assessed.

4.2.3 Ceiling and Visibility Prediction

4.2.3.1 Stratus and Haze Forecasting

The LAX Air Traffic personnel emphasized the need for improved marine stratus and haze forecasting at LAX—LAX has more IFR operations per year than does O'Hare. The technology being developed and sensors being used at SFO should be applicable to LAX. We have not made quantitative estimates of the benefits of improved stratus and haze forecasting at LAX.

4.2.3.2 VFR to IFR Transitions in Winter Storms

The delays that occur during such IFR conditions (see Appendix D) show that if the TMU can anticipate the VFR/IFR transitions in winter storms well enough to match the traffic flow, there could be a significant reduction in delays. The terminal convective weather forecast discussed in Section 2 may be useful in this respect. However, the product performance on such storms and the relationship of the storm reflectivities to ceiling/visibility at LAX have not been investigated experimentally.

4.3 Seattle (SEA) International Airport

Seattle International Airport (SEA) had strong Air Traffic user interest in an ITWS. Figure 19 shows the SEA current and planned airport layout.

Key elements of SEA for purposes of this study are as follows:

Capacity:

VFR: 52 arrivals per hour; IFR: 32 arrivals per hour

Operation: North 80%; South: 20%; little effect on capacity

Weather Problems:

May-Oct: Marine Stratus & Fog, possible late burnoff

Nov-Apr: Winter Storms; Prefrontal bands

Mixed phase conditions at low altitude which may promote lighting strikes to aircraft

Vertical wind shear and reduced visibility in rain bands

Planned airport changes:

An additional runway 2500 feet from the existing runway pair is under construction and will be completed in 2004. This will require a PRM if independent parallel arrivals are to be accomplished.

Weather sensing:

- NEXRAD approximately 50 miles north of SEA
- Vertical profiler 20 miles north of SEA
- WSP at airport.

4.3.1 Avoidance of Triggered Lightning Strikes at Low Altitude

As discussed in Appendix C, Seattle has a propensity for triggered lightning strikes at low altitudes due to the nature of the convective weather that occurs in winter storms. Providing effective warning on such storms would require ITWS since both thermodynamic profiles and the vertical development of storm reflectivity are required. The sensor data to generate such a product is available at Seattle.

4.3.2 Storm Motion Information for Heavy Rain Avoidance and Route Planning

The WSP at SEA should do a good job of providing short term (i.e., 0-20 min) precipitation locations and storm motion estimates for Air Traffic use. The TCWF product operating on the NEXRAD data could be of help to the SEA traffic management unit and airline dispatch at anticipating heavy rain impacts from storm frontal bands.

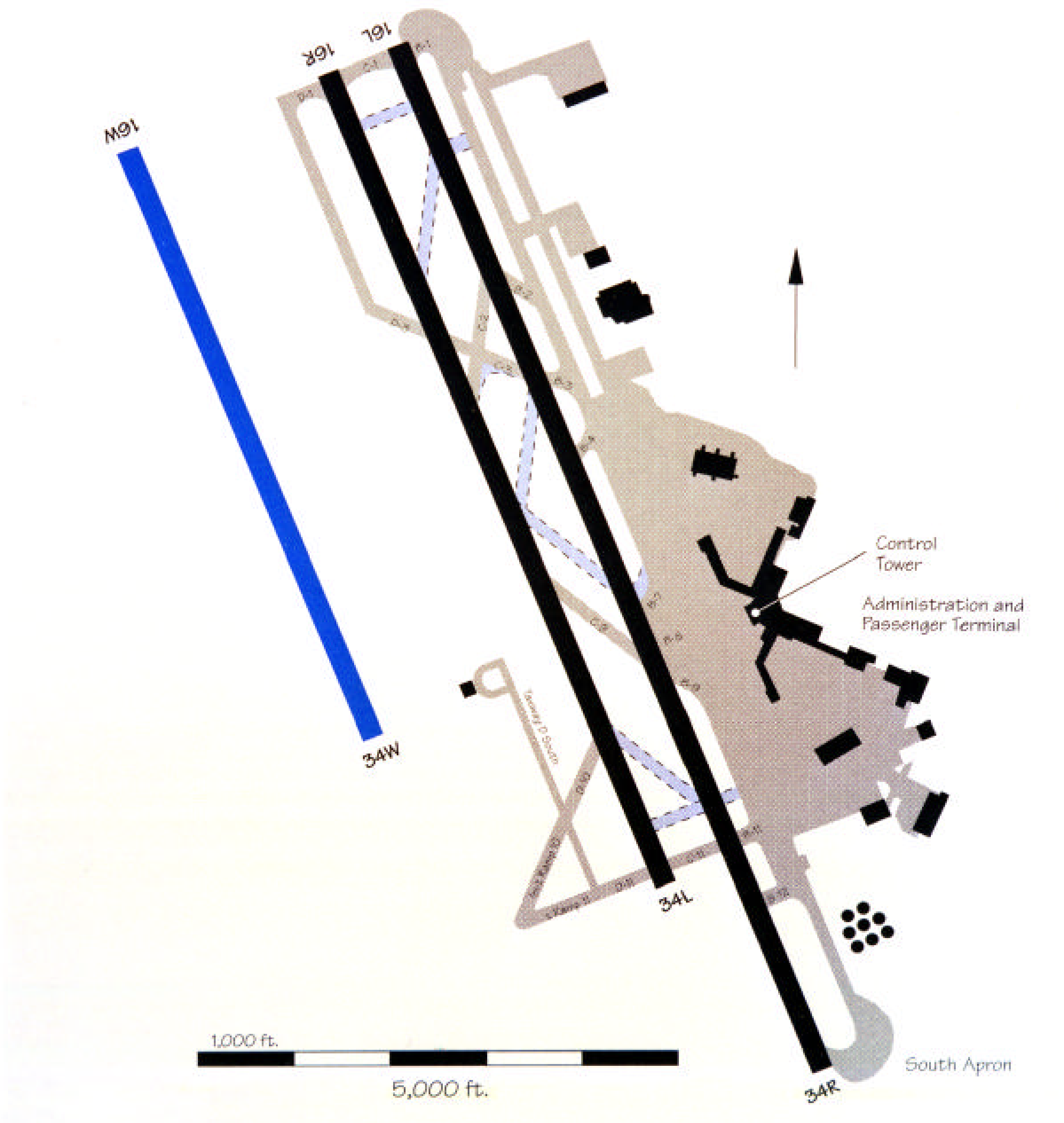

Figure 19. SEA Airport Layout. Blue indicates runway under construction. (from US DOT FAA "1998 Aviation Capacity Enhancement (ACE) CD-ROM and Airport Database")

4.3.3 Terminal Winds

4.3.3.1 IOC ITWS Terminal Winds for Improved Merging and Sequencing

There is a need for the ITWS terminal winds product at SEA during the winter storms with the current runway configuration since as many as 41 arrivals are scheduled for certain hours during the day, whereas the IFR capacity is 32/hr. When the bands of precipitation move across the airport and the approach corridor, there are significant changes in the winds which cause major difficulties in merging and sequencing planes. The rapid variation in the winds (20-30 min.) results in the NWS RUC data being very inaccurate. Based on the ITWS Dallas experience, we believe that the TRACON could land about an additional two planes per hour during the winter storms. Table 10 summarizes the expected benefits at SEA using the queueing model of Appendix E.

Table 10.
Projected SEA Delay Reduction During Winter Storms due to Improved Merging and Sequencing of Aircraft

Delays for a single all day IFR operation with landing to south in adverse winds					
		Hours of Delay		Cost of Delay	
Assumed Capacity (a/c per hr)	Max Delay (min)	Direct	Indirect	Airline ($ M)	Total ($ M)
33 (w/o ITWS)	18	47	37	0.17	0.33
35 (w ITWS)	12	19	15	0.07	0.14
Delay reduction (per event)	6	28	22	0.10	0.39
Savings for 35 events per year		1750 hrs delay		$ 3.5 M	$ 13.7 M

We emphasize that the delay calculations shown in Table 8 assume the current airport runway configuration. However, if the PRM can be used at SEA successfully and the scheduled arrivals stay less than about 65 per hour, then there will be quite limited delay reduction benefits from the terminal winds product at SEA.

The most attractive sensors to provide input for the terminal winds product at SEA would be Doppler weather radar data and the vertical profiler. The Seattle NEXRAD is on an island, 50 miles north, with a good viewing angle to measure the north-south component of the winds. However, the radar scans a bit high (low scan at 2000 feet) and has coarse vertical resolution (3000 feet) due to the long range (100 km) from the airport. The 900 MHz profiler near the NWS offices by Lake Washington has excellent vertical resolution (50 m). However, the NWS has stated that the local topography and meteorology is such that winds at the airport can differ substantially from winds near the NWS office.

Here again, a pencil beam Doppler radar sited at the airport could be very beneficial at providing improved wind estimates during these storms.

4.3.3.2 Terminal Winds for a Wake Vortex Advisory System

Seattle is also a candidate for both the SOIA/paired approach system and the departure wake vortex product discussed in Appendix B. The rapid variation of the winds when winter storms occur would require a high-quality ITWS terminal winds product if the departure system were to be used during winter storms. A profiler near or at the airport should suffice as a data source for the departure wake vortex product.

4.3.4 Ceiling Visibility Prediction

4.3.4.1 Stratus Cloud/Fog Prediction

Both coastal stratus clouds and fog are frequent at Seattle. However, it is not clear that the sensors used in the SFO stratus prediction project will suffice for Seattle. We did not carry out a detailed study of this issue in this phase of the study because the new runway with a PRM would probably eliminate most of the benefits from improved stratus prediction.

4.3.4.2 VFR to IFR Transitions in Winter Storms

The delays that occur during such IFR conditions (see Appendix D) show that if the TMU can anticipate the VFR/IFR transitions in winter storms well enough to match the traffic flow, there could be a reduction in delays with the current runway configuration. The terminal convective weather forecast discussed in Section 2 may be useful in this respect. However, the product performance on such storms and the relationship of the storm reflectivities to ceiling/visibility at SEA have not been investigated experimentally.

4.4 Portland, Oregon (PDX) International Airport

Portland International Airport had strong Air Traffic user interest in an ITWS. Figure 20 shows the geometry of PDX in relation to the Columbia River gorge and the city of Portland.

Figure 20. Geometry of Portland, OR International Airport (PDX) (grey area near center).

Portland suffers significant weather-related delays in the winter due to adverse winds and icing (especially freezing rain). The local topography around the airport (near the Columbia River Gorge) causes wind shear and icing during winter storms. Cold air to the east of Portland pours out of the Gorge at low altitudes, causing decoupling of the winds aloft from the surface winds, with the result being very sharp vertical wind shears and a potential for freezing rain. In a winter storm, surface winds may be from the south, with the winds aloft strong from the east.

The cold air at the surface can create freezing rain when the relatively warm rain from coastal storms falls into the cold air. Due to the topography, the region of freezing rain can be very localized (e.g., it is not uncommon for there to be freezing rain at the airport but not in the city, which is approximately 30 miles away).

Since the winter storms in Portland are similar aloft to those in Seattle, it is not surprising that lightning strikes to aircraft in the terminal area are a safety concern.

The PDX TRACON has indicated that a number of lightning strikes to aircraft occurred in the terminal area between October 1998 and June 1999:

(a) Arriving aircraft on 10/4/98, 4/8/99 (2 aircraft on this date), 4/26/99 and 5/8/99

(b) Departing aircraft on 2/7/99

Thunderstorms do occur within the TRACON due to the mountains east of the airport [5000-foot peaks within 15 miles; Mt. Hood (peak altitude of 11,000 feet) is 25 miles east of the airport]. Flight deviations just after departure to avoid cells are a safety concern that occurs quite frequently according to the PDX facility logs.

The NEXRAD for Portland is approximately 30 miles from the airport atop a small mountain (elevation 1700 feet). As a consequence, the NEXRAD antenna scans about 1700 feet above the airport (elevation 30 feet). There will be a WSP at the airport.

4.4.1 Wind Shear

The Portland terminal facility has not observed microbursts in connection with the convective weather. If they do occur in convective weather, the current WSP algorithms will be effective. However, the WSP will not be useful for the winter-storm-induced vertical shear.

Given the topography-induced variability in winds and the nature of the west coast prefrontal storms (see the Seattle discussion above), the ITWS terminal winds product would need Doppler weather radar information to provide an operationally effective product. However, NEXRAD data alone may not be adequate to characterize the low-altitude vertical wind shear due to the elevation of the antenna.

Measurements from a research pencil beam Doppler radar sited at or near the PDX airport surface are needed to better understand the nature of the vertical wind shear that arises so that an appropriate sensor configuration can be determined. The principal candidates for sensing are a pencil beam Doppler radar sited at the airport and a profiler sited between the airport and the Columbia River gorge.

4.4.2 Avoidance of Triggered Lightning Strikes at Low Altitude

Since the winter storms at Portland have many similarities to those at Seattle, triggered lightning strikes at low altitudes are a concern. Providing effective warning on such storms would require ITWS since both thermodynamic profiles and information on the vertical development of storm reflectivity are required. The sensor data to generate such a product is available at Portland.

4.4.3 Storm Motion Information for Heavy Rain Avoidance and Route Planning

The WSP at PDX should do a good job of providing short term (i.e., 0-20 min) precipitation locations and storm motion estimates for Air Traffic use. The enhanced ITWS organized storm extrapolation product operating on the NEXRAD data could be of help to the PDX traffic management unit and airline dispatch at anticipating heavy rain impacts from storm frontal bands.

4.4.4 Estimates of the Hazard Region and Time Evolution of Freezing Rain

Freezing rain is both a safety concern and a major cause of delays at PDX. Better forecasts of freezing rain would clearly facilitate traffic flow management and safety. It should be possible to do a good job of forecasting the freezing rain by use of the NEXRAD data together with surface observations, plane data, and NWS forecast models. An ITWS would be an appropriate vehicle to accomplish this by using the ITWS storm extrapolation position algorithms operating on the NEXRAD data. The WSP would not be as useful in this application since it observes both precipitation reaching the surface and precipitation aloft (including the melting layer).

4.5 Honolulu (HNL) International Airport

We conducted a cursory study of HNL which has very low delays now, but is expected to experience major delays if the operations rates postulated by the ACE plan occur. The principal benefit would appear to be terminal winds when the airport is in an east flow. The potential benefits of this would have to be addressed in the next phase of the study

5. SUMMARY AND RECOMMENDATIONS FOR FUTURE STUDIES

5.1 Summary

All four of the airports studied in some depth (SFO, LAX, SEA and PDX) have aspects of their operations which would significantly benefit from weather products which could be produced by an augmented ITWS. Table 11 summarizes these benefits. The projected delay reduction per year at LAX, SFO, and SEA is many times greater than the marginal cost of an additional ITWS (approximately $500 K with hardware costs of about $150 K, and $350 K for site-specific engineering and installation).[3]

Table 11.
Projected Benefits of an Augmented ITWS for Major West Coast Airports

Airport	Safety Improvements				Delay Benefit (per year)	
	Triggered Lightning Warning	Heavy Rain Impact Warning	Vertical Wind Shear Warning	Aircraft Merging/ Sequencing	Closely Spaced Dual Parallel Approaches	Departure Wake Vortex Service
LAX	No	No	No	Yes ($21 M)	No	Yes ($12 M)
SFO	No	No	No	Yes ($20 M)	Yes ($65 M)*	No
PDX	Yes	Yes	Yes	No	No	No
SEA	Yes	Yes	No	Yes ($13 M)**	Yes	Yes

<u>NOTES</u>:
*ITWS is necessary to achieve this, but other systems (e.g., a PRM) are also required
** if closely spaced dual approaches can be accomplished for the planned new runway at SEA, this benefit would go away.

Perhaps the greatest near-term benefit for the initial capability ITWS would arise at LAX due to the problems with aircraft merging and sequencing when there are adverse winds aloft. As a part of this study, we demonstrated that an LAX terminal winds product could be created using current weather sensors in the Los Angeles area. However, this product needs to be evaluated operationally by the SoCal TRACON in winter storms to determine if it is sufficiently accurate. This evaluation could be accomplished quite economically by:

(1) Creating a real-time version of the current off-line LAX winds estimation software,

[3] These cost estimates were derived from the current prices (with university discounts) of the likely ITWS hardware and Lincoln estimates of the level of effort for site-specific installation based on experience with the Lincoln ITWS prototypes. In addition to these costs, one must also consider the non-recurring costs to modify the ITWS to access and utilize additional data sources (especially the vertical profilers) as well as the cost for the additional sensors. The augmented terminal winds software treats profiler data as point measurements (similar to aircraft reports) at a number of altitudes above the profiler. Hence, the only additional software required is profiler data ingest software which was 200 lines of C code in the implementation developed as a part of this study. We estimate the implementation cost for this software to be less than $40K.

(2) Processing the profiler and aircraft data in real time in Lexington, and

(3) Transferring the resulting winds product to the SoCal TRACON by Internet.

San Francisco and Seattle may obtain significant benefits from the ITWS terminal winds product during winter storms. However, there is a need at both of those airports for a pencil beam Doppler weather radar (e.g., TDWR or COTS) or a wind profiler sited near the airport to resolve the wind features of concern.

The greatest improvements in the quality of service provided at LAX and SFO would arise from wake vortex separation related systems (a departure system at LAX and closely spaced staggered approaches at SFO). In both cases, there would be a need for much better horizontal and vertical resolution of the winds near the airport than can be provided by the existing NEXRAD radars. In both cases, a pencil beam Doppler weather radar (e.g., TDWR or a COTS system), or a wind profiler sited nearer the airport, is needed to resolve the wind features of concern for wake vortex advection and dissipation.

Portland was one of the major surprises in the study. The winter storm problems at Portland are quite different from the meteorology at the current ITWS prototype sites and warrant much more detailed meteorological and operational analysis than could be accomplished in this first phase of the study. The WSP planned for PDX is not likely to be effective in addressing the winter storm wind shear problems at Portland.

The investigation of triggered lightning strikes to aircraft at low altitudes at Seattle and Portland was another significant result of this study. As a result of analyzing two lightning strikes to aircraft at SEA in February 1999 and discussing the results with experts on atmospheric electricity and convective weather in the Pacific Northwest, we have concluded that there is a safety concern at these airports which might be addressed by a straightforward addition to the IOC ITWS storm product suite.

5.2 Recommendations

We recommend the following:

(a) Experimental observations of the winter weather phenomena (especially vertical wind shear) should be accomplished at Portland during the 1999-2000 winter storm season. Key issues to be resolved include (1) the ability of the Portland NEXRAD to sense key wind features, (2) which alternative sensors (e.g., a pencil beam weather radar or a profiler) are needed, and (3) a better understanding of the operational Air Traffic decision making associated with the winter storms. Progress in the FAA Aviation Weather Research program should be reviewed to determine whether the technology is sufficiently mature to warrant a winter prototype freezing rain short-term prediction experiment in the 2000-2001 time frame at Portland.

(b) An operational evaluation of the LAX terminal winds product using aircraft reports, the Pt. Mugu NEXRAD VAD product, and profilers near LAX as the principal local sensors be carried out in 1999-2000 to determine if an operationally useful capability is available with these sources alone. The high-delay benefits projected for this product in winter storms would make the deployment of an augmented production ITWS highly cost beneficial if the quality of the terminal winds product is high enough to improve the Air Traffic merging and sequencing of aircraft. There may also be substantive benefits at times in fair weather as well. We also note that such a terminal winds product will significantly improve the CTAS performance at LAX in winter storms.

(c) Progress in the development of a departure wake vortex monitor and the closely staggered approaches at San Francisco should be monitored closely to determine whether either or both of these approaches will create a near-term need for high-resolution vertical wind data to predict wake vortex behavior. There is also a very high benefit of the ITWS terminal winds product at SFO during IFR conditions in winter storms when the aircraft must land to the southeast. The staggered approach schemes currently under investigation at SFO will not address the capacity deficit which arises when there are IFR conditions and the aircraft are landing to the south.

(d) Discussions should be held with the Honolulu terminal facility and en route center on the weather-related safety and delay issues associated with HNL. If the only problem is wind shear and storm movements associated with convective weather, the WSP planned for HNL should suffice.

(e) Our preliminary estimates of the IOC terminal winds product benefits for LAX, SFO, and SEA are based on several assumptions on adverse weather frequency and the duration of events. These could be refined by analysis of station observations and tower logs.

(f) Research needs to be carried out on the feasibility of generating warnings for triggered lightning strikes in the terminal area from Pacific Northwest storms. Thermodynamic soundings should be used to identify the freezing level heights. Given these heights, three-dimensional reflectivity data could be used to produce two-dimensional maps of the integrated condensate above the freezing level (a quantity know as VIF, a derivative of the better known VIL, vertically integrated liquid water, and a well recognized signature for electrification). Threshold values for VIF could be selected to cordon off hazardous regions.

The proposed product could be evaluated using lightning strike data sets of the type described in Appendix C. [NEXRAD base data can be obtained from the National Climatic Data Center (NCDC) and soundings can be created from archived aircraft reports and RUC.] However, a mechanism is needed for retaining HOST and ARTS data tapes following lightning strikes to aircraft.

It should be noted that triggered lightning prediction has considerable scientific uncertainties. Predicting triggered lightning for rocket launches at the Kennedy Space Center has proven quite difficult. Currently, the presence of any cloud aloft is viewed as a potential source of triggered lightning for rockets at the Kennedy Space Center. However, the conductive nature of rocket exhaust extending to the ground is quite different from the aircraft situation. Hence, we feel that the VIF approach may be feasible for aircraft triggered lightning prediction whereas it is not for rockets.

(g) Freezing rain needs to be investigated as a potential terminal area hazard at SEA and PDX.

APPENDIX A
REDUCED IN-TRAIL SEPARATIONS FOR APPROACHES TO A RUNWAY THROUGH A WAKE VORTEX ADVISORY SYSTEM

An adaptive wake vortex spacing system will require weather information as detailed in Table A-1. In each weather variable of interest, there are multiple sensing options that will probably provide the necessary information for a wake vortex spacing system. Since most of the airports that would receive a wake vortex advisory system also will be equipped with an ITWS, it is logical to conclude that the most cost-effective provider of weather information at those airports will be ITWS. It may then be cost inefficient to design specialized solutions for the West Coast airports that use, for example, an ASR9-WSP to provide the precipitation, storm motion, and gust front information. Given that a wake vortex system will require a long-range (1-2 km) Doppler sensor to detect the wakes, it is reasonable to expect that this sensor can also provide high-resolution wind information to the system. A data fusion algorithm that uses Terminal Winds technology will be necessary to provide the most comprehensive wind information to the wake vortex system. It is possible that other special purpose weather sensors will need to be added for a wake vortex spacing system, but the exact sensor mix that will be required is subject to current research as part of the NASA wake vortex research program.

**Table A-1.
Weather Information Needed by Wake Vortex Spacing Systems and the Potential Systems for Providing that Information.**

Weather Information	Candidate Sensors/Algorithms
Profile of mean wind and wind variability in 10 miles around airport from surface to ~1000 m AGL.	Remote wind sensor (Doppler lidars used for wake detection). High vertical resolution ITWS Terminal Winds (includes additional surface anemometer and wind profiling instruments).
Notification of impending wind shifts	ITWS MIGFA. ASR9-WSP MIGFA. NEXRAD MIGFA.
Notification of impending convection	ITWS Storm Extrapolated Position (SEP). ASR9-WSP Precipitation and Storm Motion. NEXRAD Precipitation and Storm Motion.
Atmospheric turbulence profile from surface to TBD m AGL	Surface anemometers. High update rate remote wind sensors (Doppler lidars used for wake detection).
Temperature profile from surface to TBD m AGL	ITWS Sounding. RASS + surface observations.

The benefits for future adaptive wake vortex separation systems are clearly largest at capacity-constrained airports, with a significant fraction of B757 and heavier aircraft operations. These criteria are met by both SFO and LAX, but the SFO intersecting runways limit the benefits of a reduction in in-trail separation.

LAX has two sets of parallel runways. Each pair is separated by about 700 feet, and the distance between the two pairs of parallels is at least 4500 feet. With very few exceptions they operate in a west configuration, landing on the outer runways (25L and 24R) and departing on the inner runways (25R and 24L). During busy arrivals periods, all four runways may be used for arrivals, but noise constraints generally prevent them from using the outer runways for departures.

LAX presents a most appealing site for implementation of both arrival and departure wake monitoring systems (see Table A-2). Air traffic is generally unable to separate air traffic so that the heavy aircraft use a different runway from small aircraft, which would minimize the wake constraints. The airport has a significant percentage of both heavy and small aircraft so that larger separations between aircraft are often required. LAX tower personal identified the two largest constraints on traffic flow at LAX as noise abatement procedures and wake vortex constraints.

Table A-2.
Summary of the Benefits of a Wake Vortex Departure Monitor for LAX.

Metric	Benefit
Airline Direct Operating Cost	$7.0M/year
Passenger Time	$4.9M/year
Departure Capacity	8.3% increase

The benefits for a wake vortex arrival system have not been as well quantified. A recent study (Dasey and Hinton, 1999) was conducted of the frequency of weather conditions which are conducive to a high-benefit application of a wake vortex arrival system. In this study it was estimated that about 18 percent of LAX operating time had weather conditions appropriate for high benefits from a wake vortex arrival system. This is the highest proportion of time for any of the large U.S. capacity-limited airports, primarily because of reduced visibility in haze.

The LAX wake departure system benefits at LAX were examined in more detail. Data on existing taxi-out delay at LAX was gathered from the Airline Service Quality Performance (ASQP) system, which provides actual versus scheduled times for departure time, wheels-up time, wheels-down time, and arrival time. Commuter and international flights are not included in the database. The analysis was conducted on ASQP data from all of 1996.

Figure A-1 shows the distribution of taxi-out times at LAX. For every departure, the time between leaving the gate and arriving at the end of the departure queue cannot be reduced by a wake departure system. Also, the time from when the aircraft is cleared for departure and the wheels are up must similarly be discounted. Using Figure A-1 and analyzing the distribution by time of day, an attempt was made to determine the average time that an aircraft would take to depart in the absence of a queue of aircraft ahead of it. For LAX, this was estimated at five minutes.

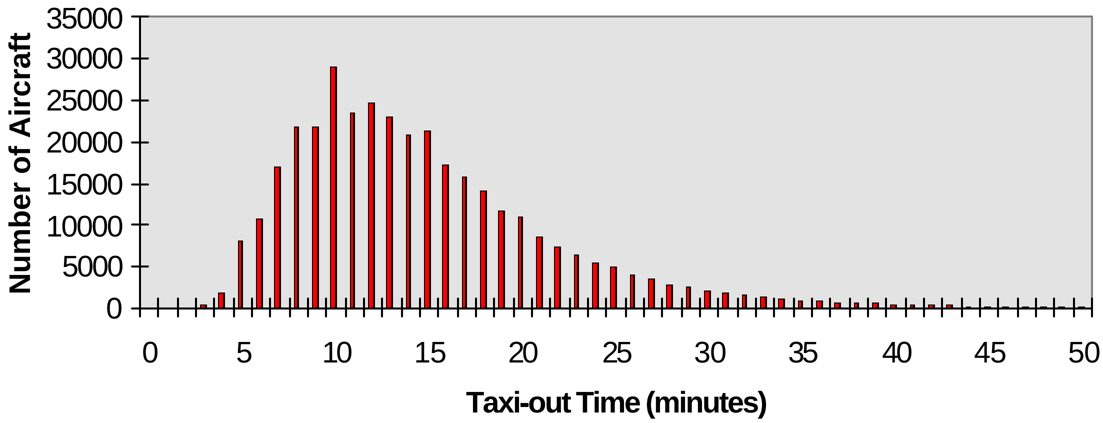

Figure A-1. Distribution of taxi-out times at LAX during 1996.

The ASQP database for LAX contains 45,858 combined hours of taxi-out time. Since this does not include commuter or international flights, the delay hours were extrapolated upward. The percent commuter and international is estimated at 30 percent (from Southern California TRACON), leading to an estimate of 45,858/0.7 = 65,512 hours of total taxi-out time for LAX. Subtracting five minutes for each aircraft gives 50,552 hours of time waiting in a departure queue.

The strategy employed is to assume that the likelihood of a given leader-follower pair is related solely to the likelihood of each weight category. That is, the likelihood that any particular aircraft waiting in a departure queue is waiting behind an aircraft in a particular weight category is just the prevalence of that category in the traffic mix. Table A-3 shows the separations as a function of the aircraft sizes. The traffic mix at LAX was taken to be 20 percent small; 52 percent large; 10 percent B757; and 18 percent heavy aircraft, as provided by the Southern California TRACON.

Table A-3.
Wake Vortex Departure Separation Criteria.
These criteria are used if the facility decides to use this separation matrix in lieu of a two-minute wait behind a B757 or heavy.

Follow/Lead	Small	Large	B757	Heavy
Small	3	3	5	6
Large/B757	3	3	4	5
Heavy	3	3	4	4

What we would like to know is how much each leader/follower pair contributes to the delay. This is computed as

$$T_{LF} = \frac{P_L P_F S_{LF}}{\sum_a \sum_b P_a P_b S_{ab}} \qquad \textbf{(A-1)}$$

where T_{LF} is the fractions of departure queue time that is consumed because of an aircraft in weight category F following an aircraft in weight category L. P_L and P_S are the probabilities of the leader and follower categories at LAX, respectively, and S_{LF} is the required spacing between category L and F aircraft, taken from Table A-3. The result of this calculation is shown in Table A-4. Only the time spent behind a B757 or a heavy (38 percent of the time) can be reduced, since it is assumed that the three-mile separations in Table A-3 are constrained by factors other than wake vortices (e.g., runway occupancy times, radar separation minima) and cannot be reduced.

The fraction of operating time where it could be expected that separations could be reduced due to wake demise was estimated using operational data collected during the late 1970s and early 1980s by the Volpe Transportation Systems Center (Hallock, 1997). They collected the most comprehensive data set available on take-off wake vortices, measuring and analyzing over 30,000 departures from O'Hare International Airport (ORD). The criteria used in this benefit assessment are taken from this vortex data collection from plots of the probability of a vortex living to various ages. Each vortex is this study is assumed to be an L1011.

Table A-4.
Fraction of Departure Queue Time at LAX That is Spent Waiting for Each Possible Leader/Follower Combination (TLF).

Follow/Lead	Small	Large	B757	Heavy
Small	0.03	0.09	0.03	0.06
Large/B757	0.11	0.28	0.07	0.16
Heavy	0.03	0.08	0.02	0.04

Table A-5.
Fraction of Time that a Vortex is Clear of the Departure Corridor for Various Time Periods (Hallock, 1997) and the Delay Savings Found by Applying Equation 2.

Time (s)	Fraction of time L1011 vortex decays (P_c)	Delay Savings (hours), B
< 60	0.6	2551.4
60 – 70	0.2	566.6
70 – 80	0.13	183.8
90 – 100	0.04	28.3
100 – 110	0.02	0.0
Total	**0.99**	**3330.1**

The delay time saved for each leader/follower pair (B_{LF}) by being able to reduce the wake separations to each of these time intervals c was computed as

$$B_{LF}(c) = P_c\left[\frac{tS_{LF} - c}{tS_{LF}}\right]T_{LF}\left(D_{total} - N\overline{T_{taxi}}\right) \quad \textbf{(A-2)}$$

which is basically the probability (P_c) that the vortex transported or decayed in the time period c multiplied by the fraction of time saved over the existing spacings S (where τ is the time it takes for the aircraft to travel one mile, and is assumed to be 20 seconds), multiplied by the fraction of time T_{LF} taken by this pairing, times the total taxi time (D_{total}), minus the taxi-time the aircraft are not in the departure queue (T_{taxi} = five minutes, N = number of aircraft). The delay savings, along with the vortex lifetime criteria used in this calculation, are shown in Table A-5.

Airline Operating Costs

The 3330.1 hour departure queue delay savings represents a 7.3 percent decrease in that delay. According to a FAA LAX Airport Capacity Plan (LAX Airport Capacity Plan Enhancement, 1991), the average airline operating cost (fuel, crew, maintenance) for LAX is $2,100 per hour. This results in estimated savings of $7.0M/year in airline operating costs. The maximum benefit that a wake vortex departure system could provide, assuming that any separation times over one minute could be reduced to one minute all of the time, is a 15 percent reduction in taxi-out time and a $14.7M/year savings in airline operating costs.

Passenger Time

For departure queue waits greater than 15 minutes (selected because of its relevance to air traffic on-time statistics), it is assumed passenger time then becomes a factor. This study uses a downstream delay multiplier that is due to the passenger time for the aircraft being late for its next flight. The delay savings for the taxi-times greater than 15 minutes is 1522.7 hours, over half of the total departure queue delay savings. The downstream multiplier was determined in a study of downstream delay with ASQP data (Boswell and Evans, 1997), and is taken to be 0.8 times the original delay. That is to say, that for delays greater than 15 minutes there are typically 0.8 minutes of downstream delay for every minute of primary delay. The number of passengers per plane was assumed to be on average 40 people (computed by taking the ratio of the number of emplanements to number of operations at LAX in 1996). The value of a passenger hour is taken as $45 per hour (FAA Cost, Benefit and Risk Assessment Guidelines, 1996). The passenger delay is then computed to be

1.8 * 1522.7 hours * $45/hour * 40 passengers = $4.9M/year.

Increase in Runway Capacity

The current runway departure capacity can be estimated by finding the average time interval behind a departure. This is computed by summing up the probability of each leader/follower pair ($P_L P_F$) divided by the time interval required (S_{LF}*20 seconds/mile), and is 51.7 aircraft/hour/runway for the current separations. Using the criteria in Table A-5 results in an increase to 56.0 aircraft/hour/runway, an increase in the departure capacity of 8.3 percent.

These computed benefits make some simplifying assumptions that should be mentioned. One assumption is that the taxi-out time is either waiting in a departure queue or taxiing to the queue. This is generally true for LAX, which normally uses one runway on each side of the airport for landing and one on each side for takeoff. However, some small fraction of this time is spent waiting for an incoming arrival that is using the same runway. A quantifiable means of estimating this influence was not available but should be investigated as a refinement to this analysis. There are other simplifications in this analysis that could counteract these influences and increase the benefits. By using the ASQP taxi-out delays, all delays are assumed to be from aircraft waiting in a runway queue. In reality, much of the delay is probably spent waiting at the gate for times where the taxi-out delay is extensive. In addition, some arrival delay may be experienced during periods where the facility is concentrating on getting departures out.

APPENDIX B
SFO SIMULTANEOUS OPERATION
WITH INDEPENDENT APPROACH (SOIA) BENEFITS

The arrival capacity of SFO is highly dependent on the weather conditions, as is shown in Table B-1. In periods where the demand for the runways exceeds the arrival capacity, delay is accumulated by the aircraft that cannot be serviced. The airport can be thought of as a simple queue, with the input rate determined by the number of aircraft requiring landing, and the output rate fixed by the current airport capacity. The queue model described in Appendix D has the advantage of simple properties that make it computationally efficient, and it has been validated against available delay data .

Table B-1.
Assumed Capacity of SFO in Various Ceiling and Visibility Conditions with and Without a SOIA System (from Discussions with SFO ATC).

Ceiling (ft.)	Visibility (miles)	Capacity without SOIA (aircraft/hr)	Capacity with SOIA (aircraft/hr)
100 - 1900	0.25 - 5	30	30
1900 - 3000	5 - 7	30	60
3000 - 4500	5 - 7	45	60
> 4500	> 7	60	60

The queuing model was used to estimate the effect of a SOIA system on delay reduction and capacity enhancement at SFO. The hourly arrival demand rate was taken from the OAG (Official Airline Guide) for a day during the summer of 1998 and was shown in Figure 9. Hourly surface observations for the continuous time period from 1984 through 1992 were fed into the queuing model, and a capacity was selected from Table B-1 based on the hourly ceilings and visibilities. It was not considered important that the weather did not correspond exactly with 1998 schedule. The nine-year surface observation record represents a good climatological representation, and the assumption of fair weather traffic demand means that SFO is isolated from other airport weather woes and is a worst-case demand.[4]

Aircraft demand and capacity rates were assumed to be uniform distributions within each hour period (a 60 aircraft/hour demand is delivered to the queue as one aircraft per minute). The model was for the airport capacities with SOIA and without SOIA (Table B-1) and the results were compared. Without SOIA the model indicated the delay as 34,927 hours/year, and with SOIA as 23,703 hours/year, for a savings of 11,224 hours/year. Similar direct operating cost data for SFO as was presented in Appendix A for LAX was not available, so the LAX figure of $2,100/hour cost for fuel, crew, and maintenance was used. Using a downstream delay multiplier of 1.8 (Boswell, 1987), the total direct operating cost savings are 11,224 * $2,100 * 1.8 = $42.2 M/year. Passenger time costs were considered only for delays that exceeded 15 minutes.

4 Although it can be argued that reducing demand based on the weather implies flight cancellations and diversions, these are probably at least as expensive as the incurred delay of continuing the flight.

The model indicated that passenger time delay was reduced 11,077 hours. Assuming 40 passengers at $45/hour gives a total passenger time savings of 11,077 * 40 * $45 * 1.8 = $35.9 M/year. The model runs showed the average capacity of the airport was raised 4.3 percent from 52.19 aircraft/hour to 54.46 aircraft/hour.

APPENDIX C
LIGHTNING STRIKES TO AIRCRAFT IN TERMINAL AREA

Two commercial aircraft were hit by lightning near the Seattle-Tacoma International Airport (SEA) on February 28, 1999. The first, NWA946, was a DC10 bound for Seattle from Honolulu. The aircraft was struck by lightning at about 1147 UT while on final approach for SEA. The lightning strike reportedly "took out" one of the DC-10's engines and the pilots asked for emergency vehicles to stand-by on the ground when it landed. As far as we know, the plane landed without incident and there were no injuries.

The second aircraft, ASA110, (unknown type and origin) was the first plane in line behind NWA946. ASA110 broke off its approach to SEA (possibly as a result of the emergency on NWA946) and turned left—apparently into a storm. The aircraft completed a single loop and landed at SEA. ASA110 was reportedly struck by lightning at 1257 UT. According to informal communication with Alaska Airlines, the lightning strike did not result in any significant damage.

Infrared satellite imagery (Figure C-1) shows cloud bands along the west coast of the United States that were associated with an occluded cold front in conjunction with an off-shore upper level low.

Figures C-2 and C-3 show precipitation data from the Weather Services Incorporated (WSI) NEXRAD mosaic along with flight track data from the Airport Surveillance Radar near the airport. The WSI images show widespread NWS level 1 precipitation, with regions of embedded levels 3 and 4 in western Washington state. In the time period leading up to the lightning strikes, the weather became organized into a long north-south oriented line of storms which had rapid development of cells within the overall envelope. One region of precipitation southwest of the airport changed from level 1 precipitation to a level 3 and 4 thunderstorm in about 15 minutes and moved northeastward across the airport. The level 3 precipitation appeared to reach the airport at roughly 1230 UT and appeared to clear the airport at roughly 1300 UT. There were several regions of level 4 and 5 precipitation inside the level 3 at various times in the lifetime of the storm.

For several reasons, it is impossible to use the WSI data to say exactly what level of precipitation was encountered by the aircraft. First, the data are two-dimensional and the aircrafts' flight paths are three-dimensional. Second, the data are mosaicked from multiple NEXRADs, and the mosaic is issued only every five minutes.

We obtained a NEXRAD base data tape from the NEXRAD nearest to SEA but were unable to reconstruct the three-dimensional storm structure at the time of the incident due to a gap in the recorded data at the time of the incidents. We will order a copy of the tape from the NCDC and analyze it in the next phase of the study.

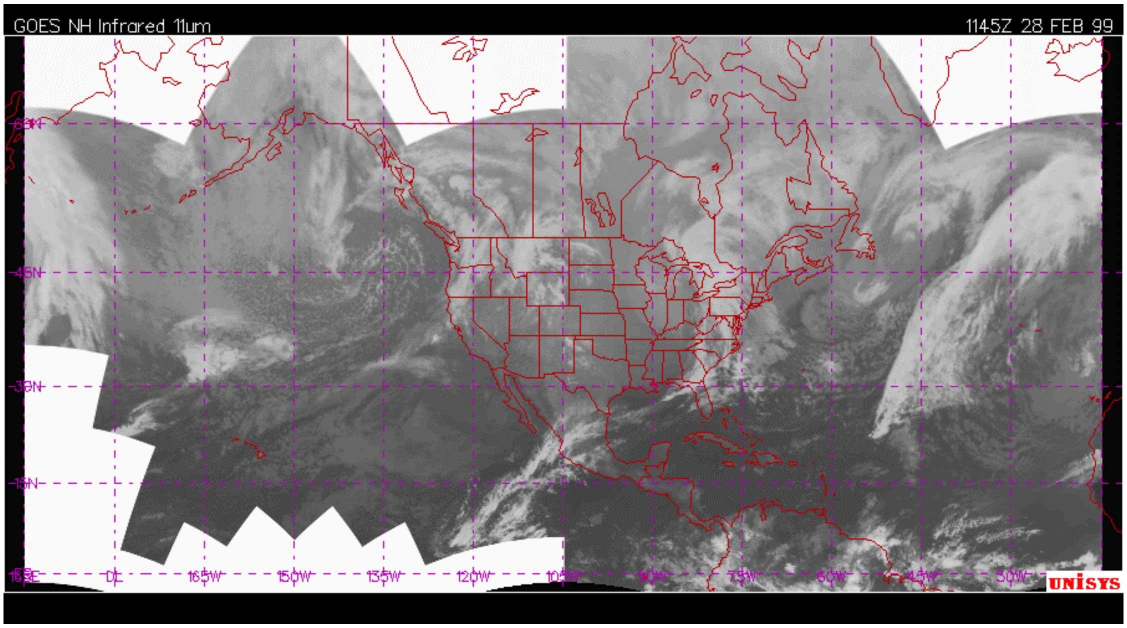

Figure C-1. Infrared satellite Image from 12Z.

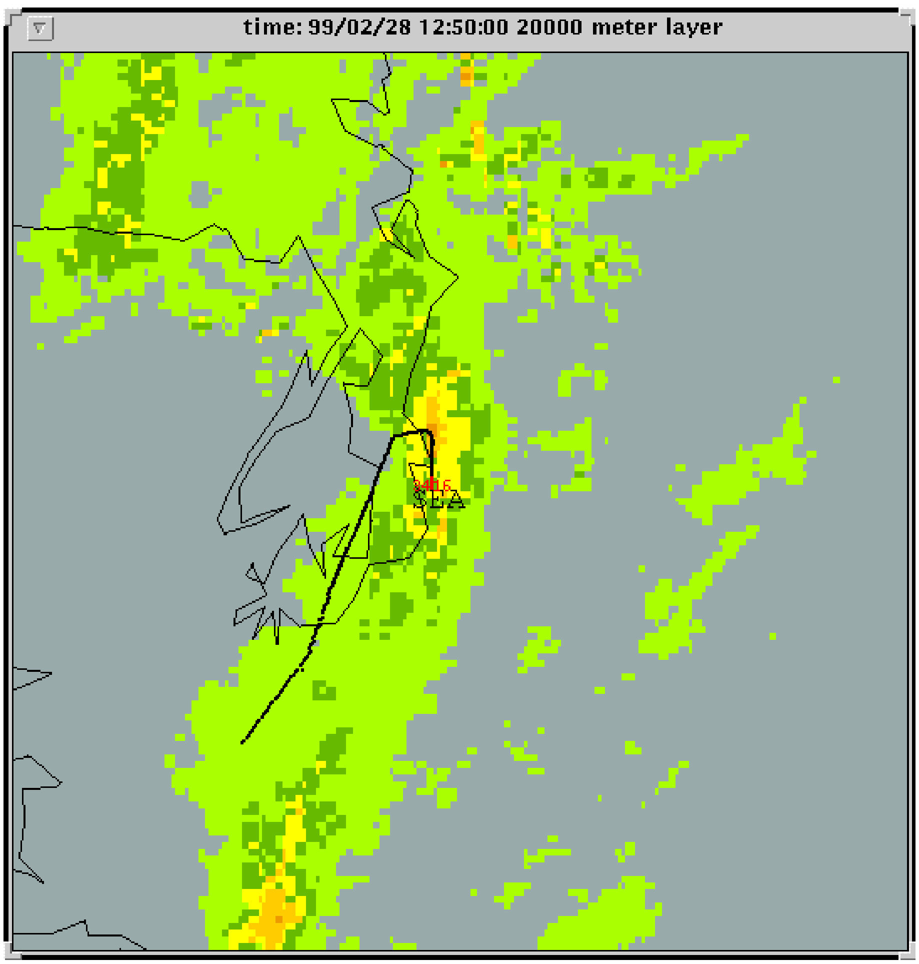

Figure C-2. Track of Flight NWA946. The SEATAC airport is labeled with the letters "SEA" and the red portion of the track indicates the position of the aircraft at the time of the lightning strike.

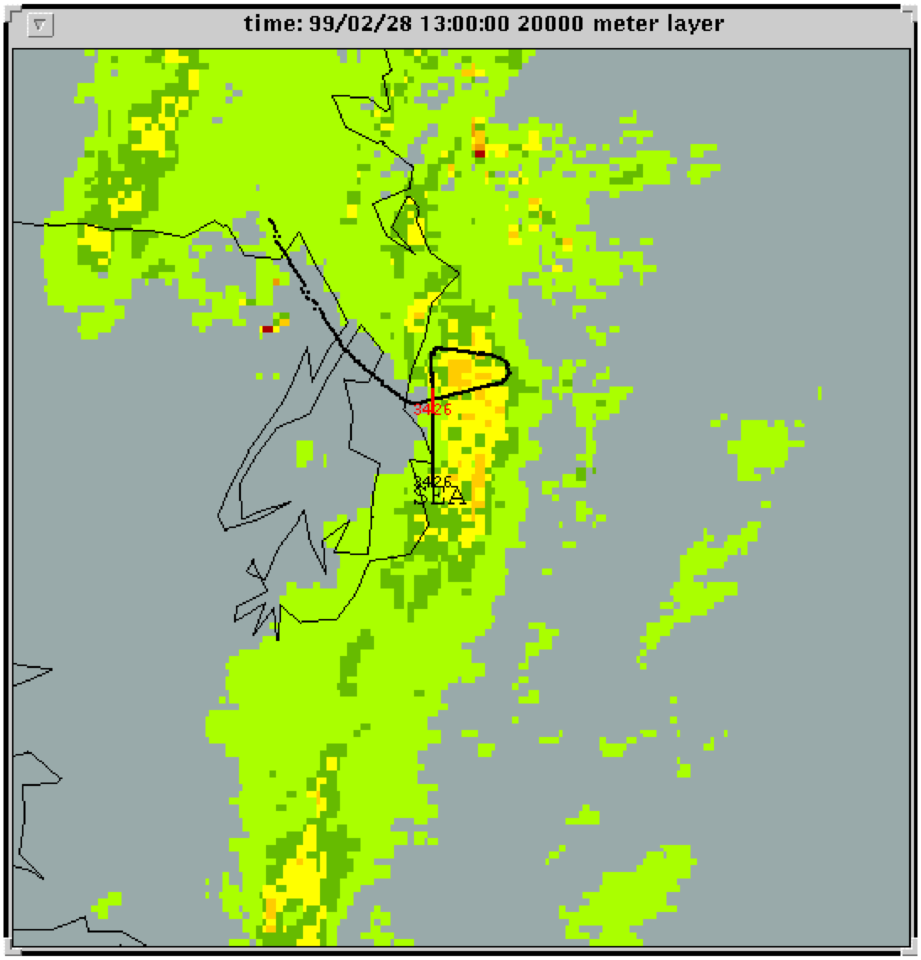

Figure C-3. Track of Flight ASA110. The SEATAC airport is labeled with the letters "SEA" and the red portion of the track indicates the position of the aircraft at the time of the lightning strike.

The National Lightning Detection Network (NLDN) recorded only three cloud-to-ground lightning strikes in the vicinity of the airport during the time period in question. None of those strikes corresponded to the locations of the two aircraft in question, so it seems unlikely that the planes were struck by cloud-to-ground lightning. Previous work (Mazur, 1993) on lightning strikes to aircraft have shown that the majority of such strikes are intracloud discharges. Intra-cloud and cloud-to-cloud lightning flashes are not recorded by any sensor system in the Seattle area. Although the latter lightning types are generally more prevalent than CG lightning, it is impossible to say whether the two aircraft initiated lightning discharges or whether they intercepted discharges that would have occurred regardless of the presence of the plane. Previous studies (Mazur, 1984; 1993) indicate that more than 90 percent of lightning strikes to aircraft are initiated by the aircraft itself.

It is interesting to note that in a recent study of thunderstorm penetrations and deviations by commercial aircraft in the Dallas-Fort Worth area that hundreds of aircraft were observed penetrating late spring and summer thunderstorms, and to the best of the authors' knowledge, none of the aircraft experienced significant lightning strikes (Rhoda and Pawlak, 1999).

One possible difference between the Dallas penetrations and this Seattle incident is the altitude, where water would begin to freeze in the atmosphere. In the summertime in Dallas, the freezing level would typically occur at an altitude higher than the top of the TRACON airspace, which is typically 10,000 to 12,000 feet MSL. The skew-T plot from the nearest weather balloon (Figure C-4) indicates that the freezing level during this winter storm was at 850mb or roughly 5000 feet MSL.

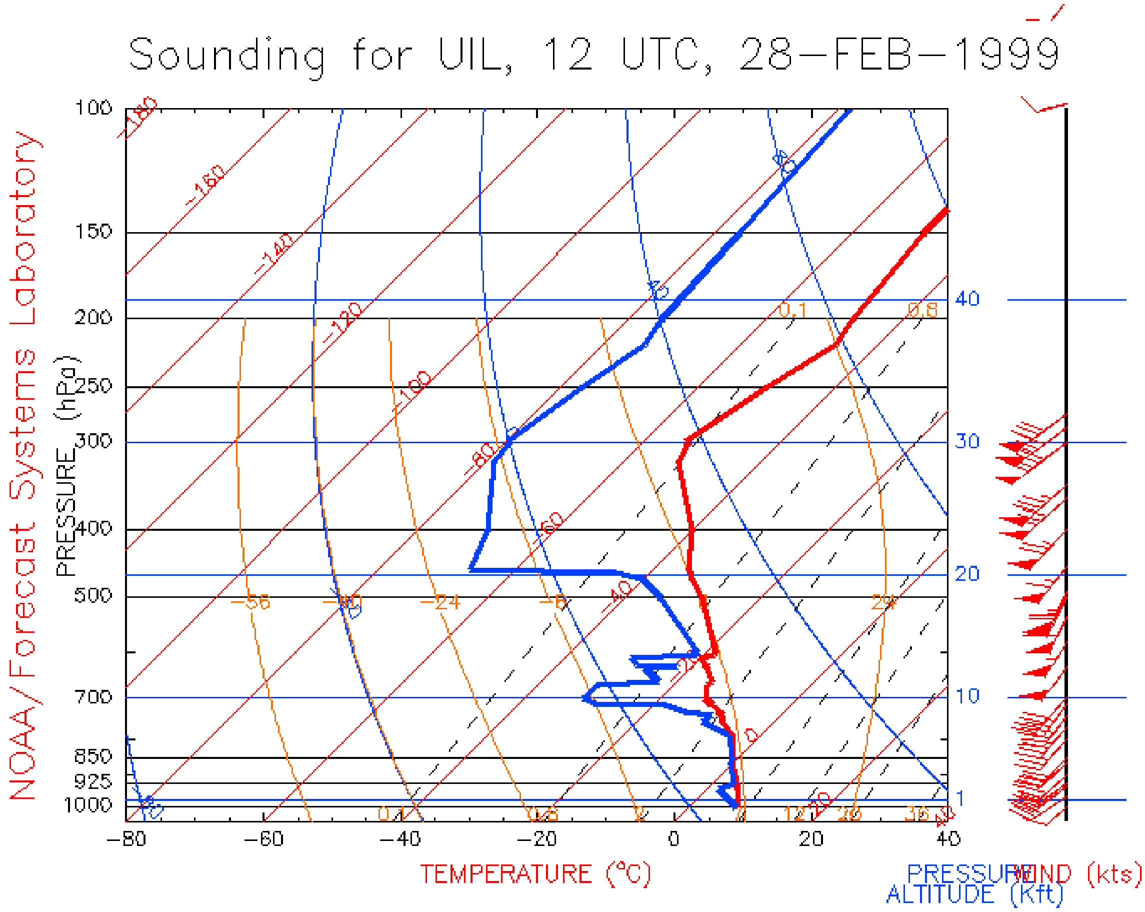

Figure C-4. Rawinsonde from Quillayute, WA at 12Z on February 28, 1999.

Seattle is not the only west coast airport concerned with lightning strikes. The Portland, OR tower has documented five strikes to aircraft in their terminal area over the past year (see Section 4.4.).

To better understand why the Northwest appears to have a much higher incidence of such lightning strikes at low altitude, we conducted a review of the literature in this area. The results of this review are as described below.

Statistics on aircraft lightning strikes gathered over several years in the 1970s and early 1980s show that 87 percent of the aircraft were struck at altitudes below 16 Kft, with 96 percent of aircraft reporting their location "in cloud" (not below cloud base) when struck by lightning (Plumer, 1985). Williams (1985) shows that "spontaneous" cloud-to-ground (CG) strikes are very infrequent (less than one per 10 min) in storms with cloud tops less than 5 km (16.4 Kft).

Plumer, et al., (1985) show that 43 percent of the aircraft lightning strikes occurred in storms with cloud tops 15 Kft and below. (He also showed that aircraft were struck mostly in springtime storms, leading to the conclusion that aircraft were effectively avoiding well-defined, tall, highly electrified summer thunderstorms.) Typically, only 40 percent of pilots observed any other lightning activity at the time they were hit, suggesting that possibly 60 percent of the lightning strikes could have been triggered by the aircraft itself in marginally electrified clouds that were not producing any natural lightning. In studies of lightning strikes to aircraft (Mazur, 1984; 1993), it was found that the plane frequently initiated the discharge.

The electrification of storms is closely coupled to the vertical air motions and associated microphysical conditions which define the convective stage of the storm. Laboratory studies, field measurements and numerical models are all consistent with the widely accepted hypothesis that charge separation during the active phase of storms occurs through a non-inductive, ice-ice interaction that occurs within specific temperature ($T < -10^{o}C$) and liquid water content ($0.1\ gm/m^3 < L < 5\ gm/m^3$) regimes. A sustained and vigorous updraft is required to generate the necessary values of L and the charge carrying hydrometeors at altitudes with environmental temperatures of $-10^{o}C$ and below. Owing to the different terminal fall speeds of the more massive negatively charged hydrometeors and the ice crystals/snowflakes to which positive charge is transferred, the updraft also plays a crucial role in the macroscopic separation of electric charge in a thundercloud.

As a result of this charging process, active thunderstorms exhibit a bipolar charge distribution with negative charge distributed near and below the mid-level ice-ice interaction region, topped by positive charge in the upper cloud (Figure C-5(a)). Initial lightning activity typically commences several minutes after moderate intensity (>35 dBz) radar echoes form in the mixed-phase region of the cloud; these are almost invariably intracloud (IC) discharges between the mid-level negative and upper positive regions of the thundercloud dipole. Relative to subsequent CG flashes, the IC lightning is characterized by higher occurrence frequencies and smaller energy dissipation (i.e., charge transfer) per flash. IC lightning rates may vary from a few per minute in small, air-mass thunderstorms to more than one per second in severe thunderstorms.

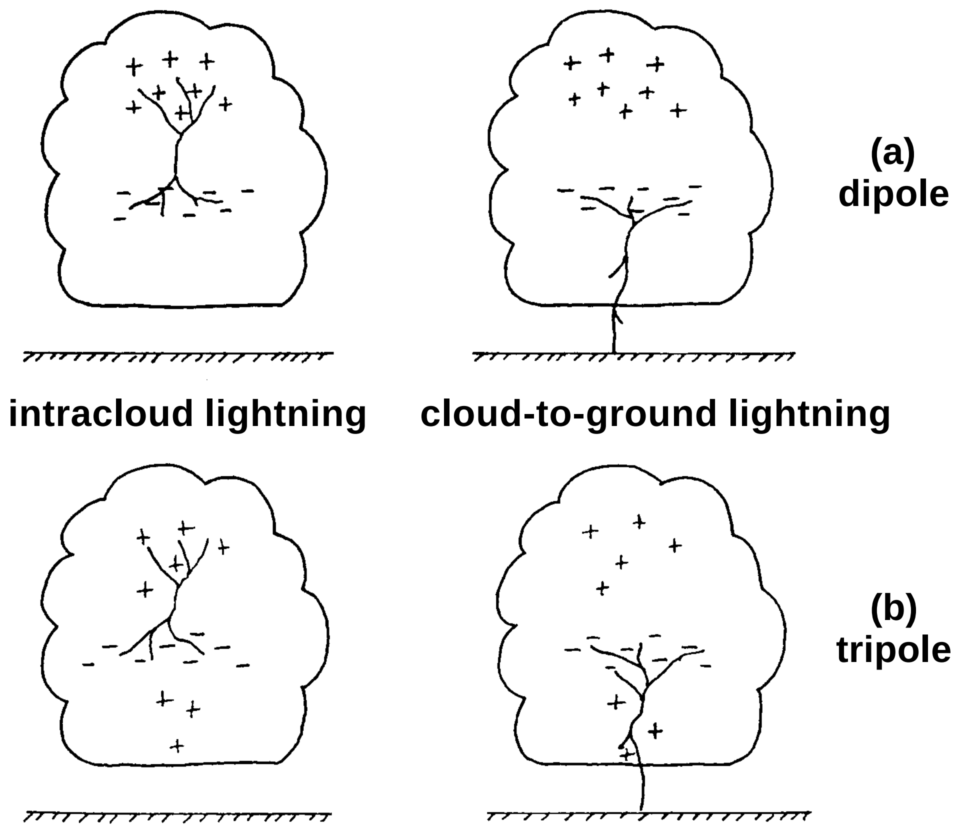

Figure C-5. Depiction of intracloud and cloud-to-ground lightning in prototype electrostatic structures: (a) dipole and (b) tripole (from Williams, et al., 1998).

Ground (CG) flashes are normally not manifest until the thunderstorm reaches its "mature" phase, characterized by significant, descending precipitation accumulations and downdrafts in some portions of the cloud. Laboratory experiments indicate that the sign of charge transfer in ice-ice interactions reverses at temperatures near and above freezing; thus graupel particles descending through the lower portions of the cloud may acquire positive charge. Intensification of electrostatic fields in the lower portion of the resulting tripolar thunderstorm charge distribution (Figure C-5(b)) may be the impetus for the onset of CG lightnings.

Applying the discussion above to the case of the Pacific Northwest winter storms, we observe that the mixed-phase region that typically is associated with induced lightning is at a much lower altitude (5000 feet) than at Dallas, thereby subjecting the aircraft to larger electric fields during take-off and landing than during summer conditions. Since these Northwest winter storms are less strongly convective than Dallas storms, the electrical fields are not strong enough to create either inter-cloud or cloud-to-ground lightning unless a triggering mechanism such as the sharp edge of an antenna or wing or tail is present.

Our analysis above of the differences in the lightning strikes to aircraft in the Pacific Northwest versus those in Dallas largely coincide with key findings in (Mazur, 1993) where he states:

(1) "The majority of reported strikes to civil aircraft and space vehicles in the U.S. occurred in marginally electrified and mixed-phase clouds."

(2) "In Japan, the majority of reported strikes occurred in winter storms."

(3) "Marginally electrified and mixed-phase clouds do not produce natural lightning," and

(4) "The probability of triggered lightning is very low when the rate of natural lightning is high and vice versa."

The Japanese experience would appear to be quite applicable to the Pacific Northwest.

Mazur also recommends a focused research programs on lightning strikes in winter storms because:

(1) The in-flight research programs to date focused only on summer thunderstorms, and

(2) Although the physics of strike initiation in winter thunderstorms, stratiform, and mixed-phase storms should be the same as in summer thunderstorms, there is no scientific data on electric discharges in these winter storms to verify this hypothesis.

APPENDIX D
QUEUEING MODEL FOR CAPACITY CONSTRAINED AIRPORTS

1. Introduction

A queueing model has been developed which can be used as a tool to estimate the benefits of:

(1) Greater effective capacity with ITWS and wake vortex advisory systems during a weather event, and

(2) The benefits associated with better forecasting of the start and top of the event.

The model requires only two inputs—a time profile of scheduled arrival demand[5] and a time profile of effective airport arrival capacity. Each profile extends over a period of time encompassing a weather event—a period where the effective airport arrival capacity may dip below the scheduled arrival demand.

Section 1 describes the model for the initial delay to a flight. This is a simple extension of the classical queueing model to consider the case where the server capacity makes a step change at various points in time. The basic idea is as follows:

[5] Or, scheduled departure demand can be used if one is studying departure delay reduction.

(1) A queue of planes builds up if the demand is greater than the server capacity, with the queue size at a given time representing the time integral of the time series (demand minus server capacity), and

(2) If the server capacity is constant at some value, C, an aircraft scheduled to arrive at time t will be delayed by an amount Q(t)/C, where Q(t) is the queue length at time t.

To illustrate, if there are 10 people in front of you at the supermarket line (i.e., Q(t) = 10) and the checker handles one person per minute (i.e., C = 1/min), you will have a 10-minute delay. The complication that arises in practice is that the effective airport capacity may change during the period in which an aircraft is waiting in the queue.

This model has been validated by comparison of the initial delay model with closed form expressions (described below in Section 2) and by ASQP data from a thunderstorm incident at Atlanta Hartsfield International Airport (ATL) (Section 3). We see in Section 3 that reasonably good agreement is obtained for both the hourly delays and the total accumulated delay of the ATL case.

In Appendix E, we use this model to estimate the benefits of the ITWS terminal winds product for LAX, SFO and SEA. Downstream delays are estimated using the approach described in (Boswell and Evans, 1997).

2. Description of the Basic Model for Initial Delay to a flight

(a) Model Mathematics for Initial Delay caused by the Weather

This section describes a simple queueing model used to estimate the delays as a function of desired aircraft arrivals and effective airport capacity. The planned arrival rate [A(t) in equations below] and the effective capacity C(t) both can change with time.

The queue of planes waiting to land, Q(t), is given by an integral

$$Q(t) = ? [A(x) - C(x)]\, dx \qquad \textbf{(D-1)}$$

The limits of the integral are from the start time to time t. We assume in equation (D-1) that Q(t) is nonnegative for all times from 0 to t.

To compute the delays due to the queue, we assume that the planes in a queue are handled in the order of the scheduled arrival time and that the event starts at time t = 0. An elementary result of queueing theory is that the delay D(t) for the next plane in the queue (assuming first come, first served) is the solution to the integral equation:

$$Q(t) = ? C(x)\, dx \qquad \textbf{(D-2)}$$

The limits of the integral in equation D-2 are from t to t+D(t).

The number of aircraft arriving between t and t + dt is simply

$$dN(t\,) = A(t)\, dt \qquad \textbf{(D-3)}$$

The accumulated direct delay for all the aircraft is then simply:

$$\text{direct delay} = ? D(x)\, dN(x) = ? D(x)\, A(x)\, dx \qquad \textbf{(D-4)}$$

The above equations are captured in the computational algorithm that will be described subsequently. However, providing a simple example at this point will be instructive in understanding the nature of the overall model.

(b) A Simple Example

We consider here a simple case where the capacity at the start of the event is C_{ifr} which then changes to capacity C_{vfr} when the weather impacting event ends at time T. Throughout the period, the arrival demand is constant at A with $C_{ifr} < A < C_{vfr}$.

From equation (D-1), we find that for t < T,

$$Q(t) = (A - C_{ifr})\, t \qquad \textbf{(D-5)}$$

i.e., the queue builds up linearly with time. Since C (t) is now constant in equation (D-2) we find that

$$Q(t) = C_{ifr} [t + D(t) - t] = C_{ifr} D(t) \qquad \textbf{(D-6)}$$

so that

$$D(t) = Q(t) / C_{ifr} \qquad \textbf{(D-7)}$$

Substituting equation (7) into equation (4), we find that the accumulated direct delay at time T is

$$? D(t) d N (t) = [(A - C_{ifr})/C_{ifr}] ? x A dx = [A (A-C_{ifr}) / C_{ifr}] T^2 /2 \qquad \textbf{(D-8)}$$

Note that the accumulated delay is quadratic in both the arrival rate and the time duration of the event. This is a significant result since it tells us that:

(1) Busy airports (a large A) are much more important than quieter airports even though both may be affected similarly by IFR weather, and

(2) Any traffic flow decision making which has the effect of increasing T can sharply increase the accumulated delay. We have argued earlier if the traffic management system put ground holds into effect early into a event and are not relaxed until the event ends, then the transit time for the ground hold aircraft to the terminal is equivalent to increasing the effective duration of the event. If the event duration is two hours and the transit time is one hour, then equation (D-8) suggests that the accumulated delay up to time T would more than double (2^2=4, 3^2=9).

Now suppose that at time T, the capacity increases to C_{vfr}. For aircraft whose arrival time plus delay are greater than T, i.e.,

$$t + D(t) > T \qquad \textbf{(D-9)}$$

it can be shown by substituting into equation (D-4) that for t < T, the delay is the solution to the equation

$$Q(t) = C_{ifr} (T - t) + C_{vfr} [t + D (t) - T] \qquad \textbf{(D-10)}$$

which is given by

$$D(t) = T - t + [Q(t) - C_{ifr} (T-t)] / C_{vfr} \qquad \textbf{(D-11)}$$

For t > T, the delay is given by equation (D-7) with C_{vfr} in place of C_{ifr} .

(c) Computational Algorithm Used

The computations of the key results (queue length and delay as a function of time, and accumulated delay) are carried out by straightforward numerical integration using a spreadsheet. The principal challenge in solving the general equations [equations (D-1) - (D-4)] was to solve the integral equation (D-3). By adding the constant term

? C(x) dx to both sides of (D-3), we obtain:

$$Q(t) + ?\, C(t)\, dt = ?\, C(t)\, dt \qquad \textbf{(D-12)}$$

which seems to be no improvement.

However, it turns out that this can be solved simply with an Excel spreadsheet by creating a column which is the running sum of the capacities as a function of time and using an intrinsic Excel lookup function. Basically, one adds the queue length at time t [Q(t)] to the integrated capacity at time t

$$CSUM(t) = ?\, C(x)\, dx \qquad \textbf{(D-13)}$$

and then determines the time Y at which

$$CSUM(Y) = Q(t) + CSUM(t).$$

The delay is then given by

$$D(t) = Y - t \qquad \textbf{(D-14)}$$

with appropriate corrections for the case where Q(t) + CSUM(t) is between the lookup table values.

3. Model Validation

(a) Simple Model Results

The simple delay model described earlier [equations (D-5)-(D-11)] permits comparison of the analytical results with the numerical results. This has been done and exact numerical equivalence achieved.

(b) Validation by comparison with measured delays

Data reported in the Airline System Quality Performance (ASQP) guide provides delays for individual flights as well as the scheduled arrival times for each of the flights. Data from a thunderstorm event at Atlanta Hartsfield International Airport (ATL) on 4/27/94 was used to construct a demand and capacity rate profile for which the computed delays could be compared to the actual delays. Table D-1 shows the basic data used to construct the scenario.

We assumed that the ASQP scheduled arrivals represent the demand from 1600 to 0100, with the ASQP actual arrivals representing the effective airport capacity for all times except 0100, which was assumed to be 53 (the effective capacity in the preceding hour). Figure D-1 shows the model results for this scenario while Figure D-2 compares the actual and computed delays.

We see that the trend of computed delays agree well on an hour-by-hour basis with the actual delays, but there are obvious small underestimates at 2100 followed by overestimates at 2200 and 2300. Recall that the model assumes that the aircraft were landed in the order that they were scheduled. If this was not the case, we would expect that some time periods might show shorter actual delays than the computed delay, with other periods showing longer actual delays than the computed delay. However, the overall accumulated delays should be similar.

The accumulated delay (i.e., the sum of the product # a/c scheduled to land in a given hour x average delay in that hour) was 312 hours which is within five percent of the ASQP accumulated delay of 325 hours. We regard this as excellent agreement given the very coarse capacity model time resolution used in a period where there were very large hour-to-hour changes in the effective capacity.

Table D-1.
Data Used to Construct ATL Delay Scenario

Time (LST	Scheduled Arrivals	Actual Arrivals
1600	61	53
1700	35	33
1800	41	48
1900	34	12
2000	38	33
2100	34	19
2200	36	16
2300	34	24
0000	28	53
100	5	53

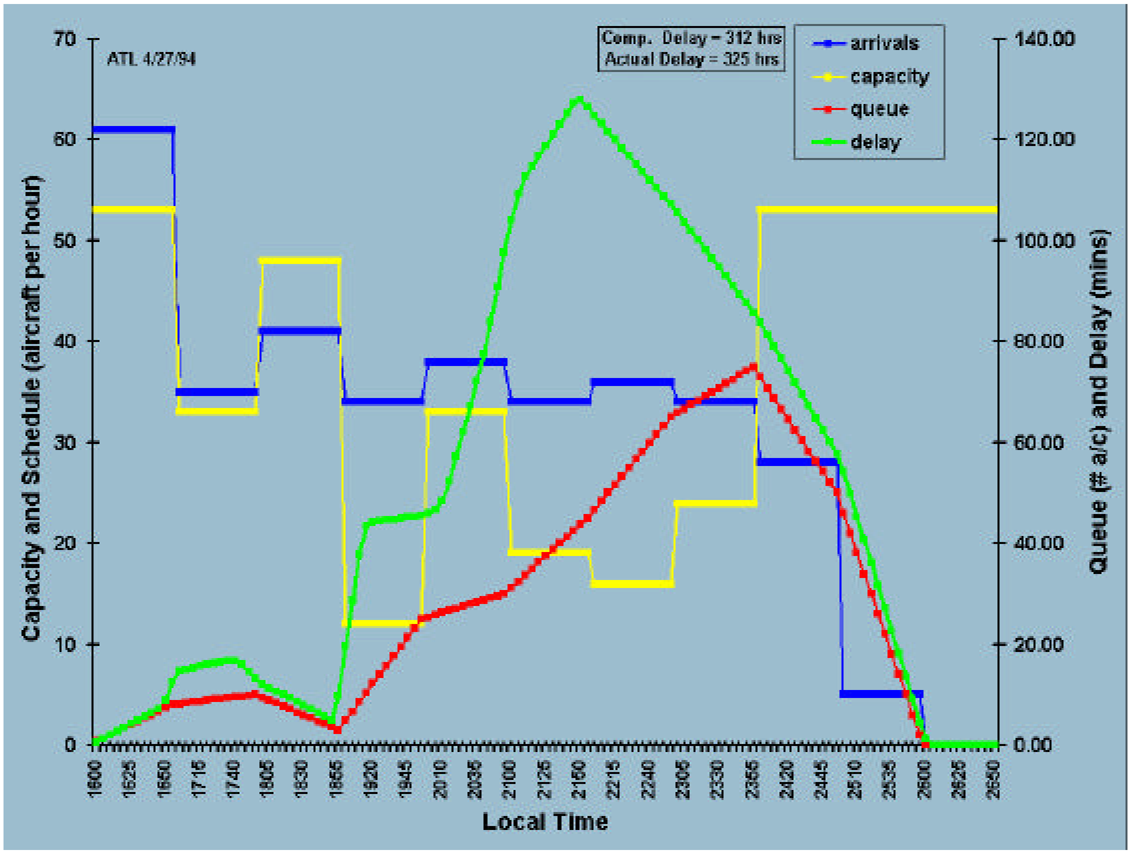

Figure D-1. Computed Delays for Atlanta ASQP data of 4/27/94.

Figure D-2. Comparison of computed delays with measured delays for ATL ASQP data of 4/27/94.

APPENDIX E
APPLICATION OF QUEUEING MODEL
TO ESTIMATING TERMINAL WINDS BENEFITS

In this appendix, we show results of applying the queue delay model to estimating the benefits of the ITWS terminal winds product at LAX, SFO, and SEA. Figures E-1 and E-2 show the results of computations for LAX using the nominal IFR capacity of 59 aircraft per hour. We see from Figure E-1 that there 11 one-hour periods that the OAG schedule exceeds 59 aircraft per hour. The greatest queue length and delays occur in the evening rush period. If ITWS can permit the controllers to land two more aircraft per hour per runway, we see that there are now seven one-hour periods where the schedule exceeds the capacity and that the maximum delays are now reduced to about 20 minutes versus the 40-minute maximum delays of Figure E-1. This case illustrates the tremendous leverage from landing a few more aircraft per hour in reducing delays at airports such as LAX.

Figures E-3 and E-4 shows similar calculations for SFO. Figure E-3 shows the queue and delays to flights with a "favorable" IFR capacity[6] of 31 aircraft per hour. Figure E-4 shows the queue and delays assuming that the ITWS permits two more aircraft per hour to land during IFR conditions. We see that there are 9 one-hour periods in which the schedule exceeds the capacity. However, at SFO, the peak excess demand is a much greater fraction of the IFR capacity than was the case at LAX. Although the queue sizes at SFO are comparable to those at LAX, the much lower IFR capacity means that the plane delays are much greater (delays exceeding 100 minutes in Figure E-3). Computations were also done for SFO assuming that the effective IFR capacity is 33 aircraft per hour, which could be increased to 35 aircraft per hour using ITWS. The delay reductions for that scenario were quite similar to those for the scenarios of figures E-3 and E-4. We assumed the higher nominal IFR capacity.

Figures E-5 and E-6 show similar calculations for SEA. At SEA, the schedule exceeds the IFR capacity for 5 one-hour periods per day. However, in contrast to SFO and LAX, the schedule in between these periods of excess demand is well below capacity. Consequently, the queue built up in the morning excess demand period completely disappears before the evening period of excess demand. This is to be contrasted with SFO and LAX without ITWS (figures E-1 and E-3) in which the queue that builds up in the late morning lasts all day. As a result, the delays at SEA are much less than at SFO and LAX. The percentage reduction in maximum delays at SEA if the ITWS terminal winds can permit Air Traffic to land two more aircraft per hour per runway is comparable to the percentage reduction at LAX and SFO, but the overall level of delays is much less.

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[6] The FAA Command Center "nominal" SFO IFR capacity for landing on runways 28L and 28R and departing on runways 1L and 1R is 30 aircraft per hour. However, there is considerable variance in actual performance.

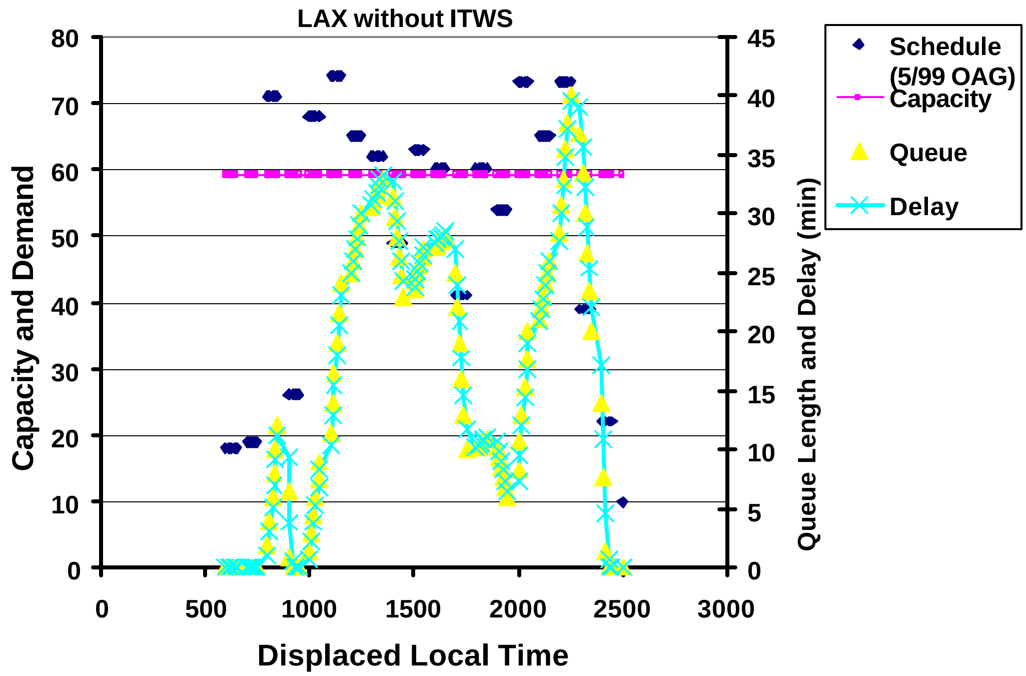

Figure E-1. LAX delays landing 59 aircraft per hour.

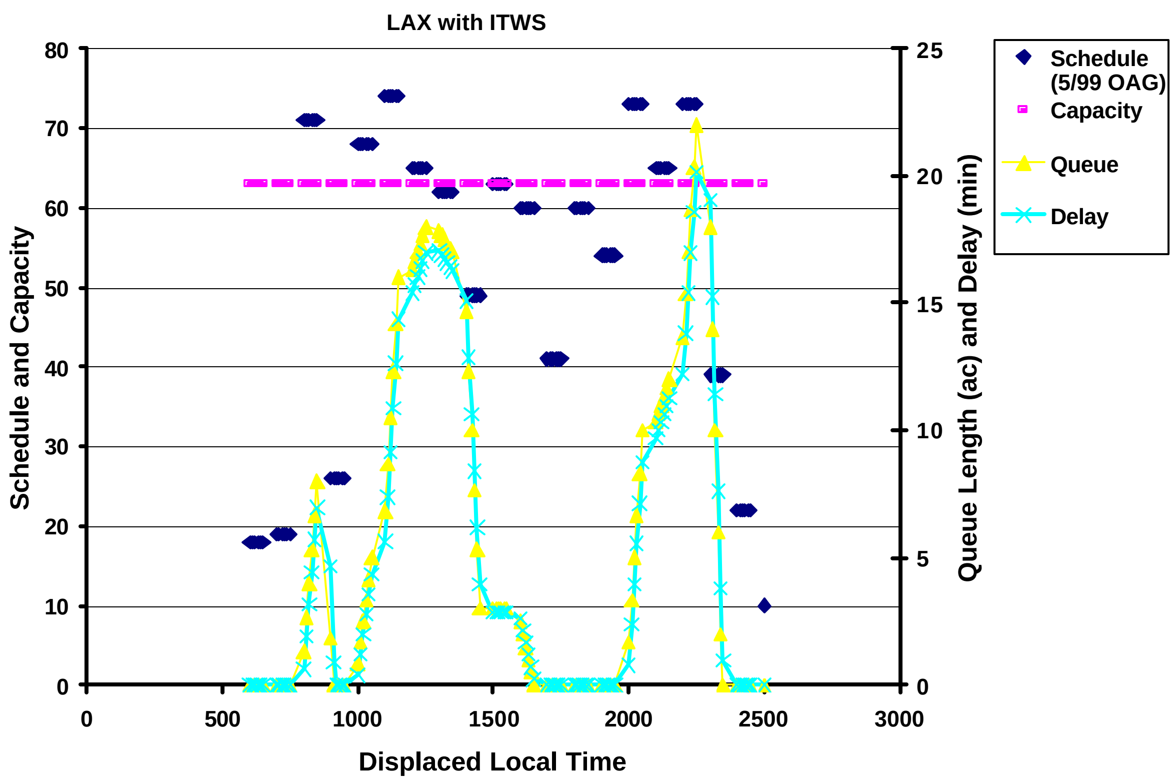

Figure E-2. LAX delays assuming ITWS terminal winds permits landing 63 aircraft per hour.

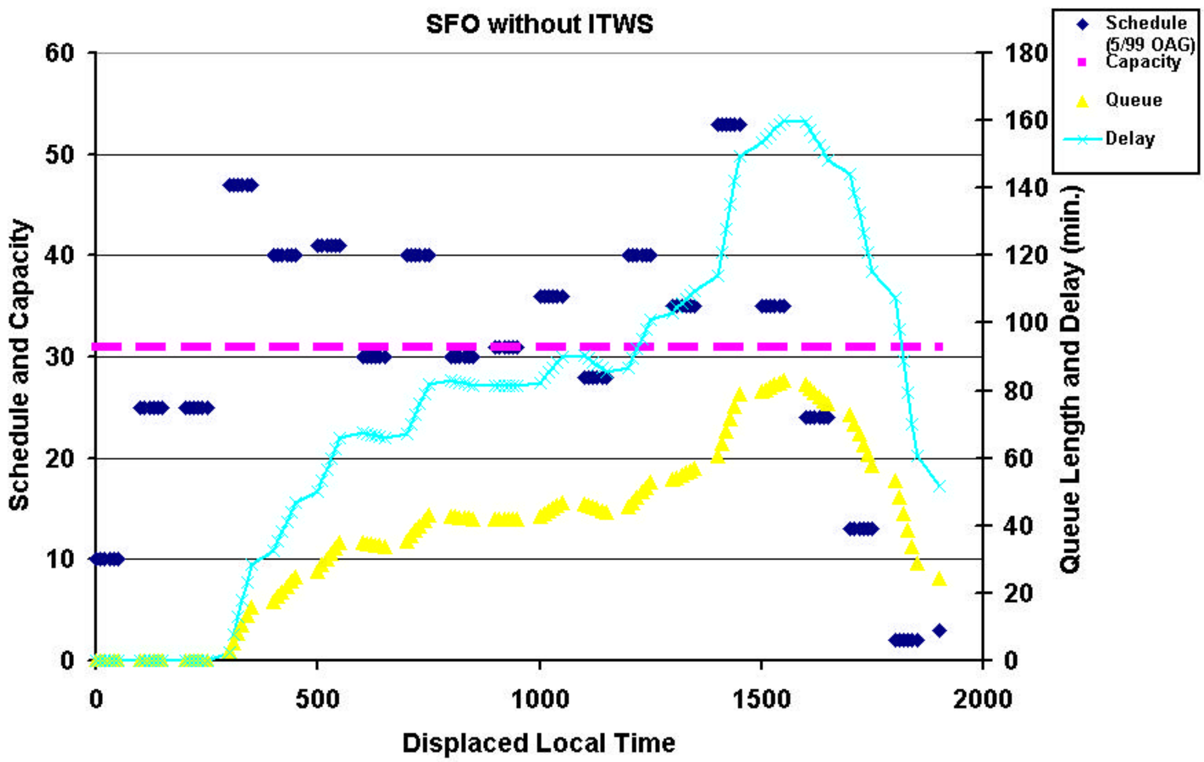

Figure E-3. SFO delays assuming landing 31 aircraft per hour.

Figure E-4. SFO delays assuming that ITWS permits landing 33 aircraft per hour.

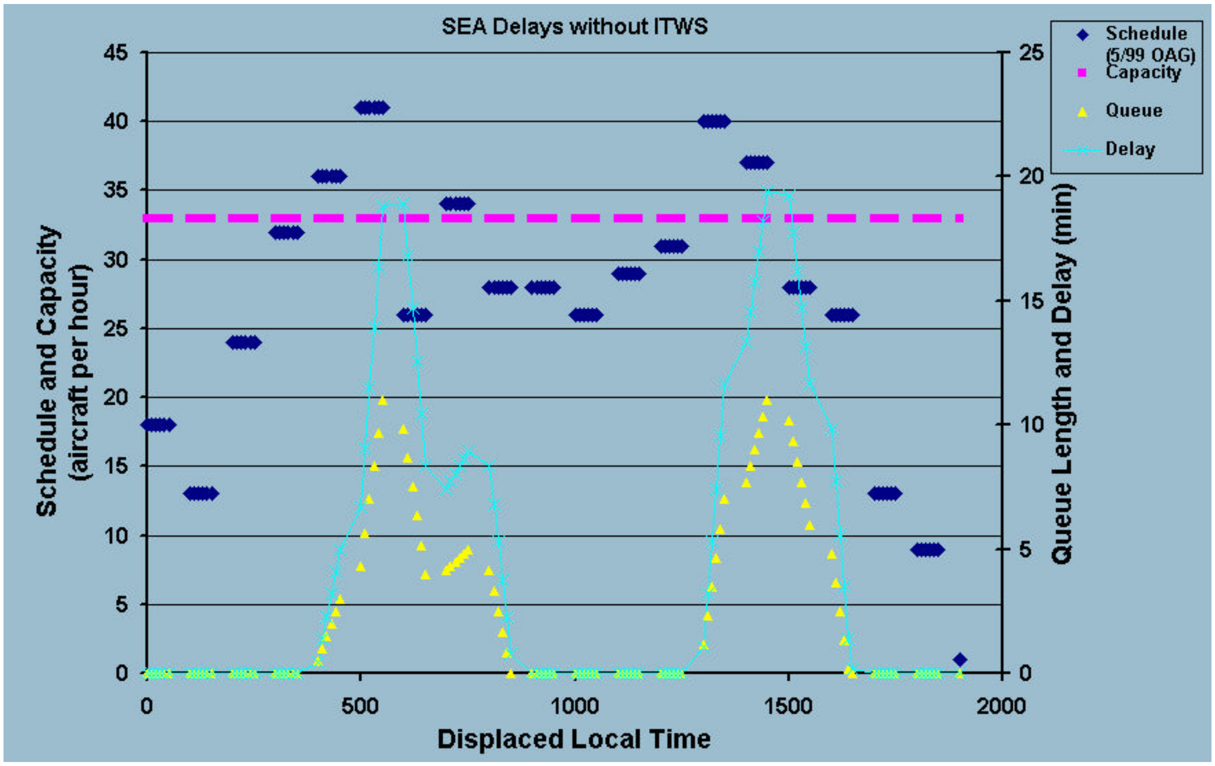

Figure E-5. SEA delays assuming landing 33 aircraft per hour.

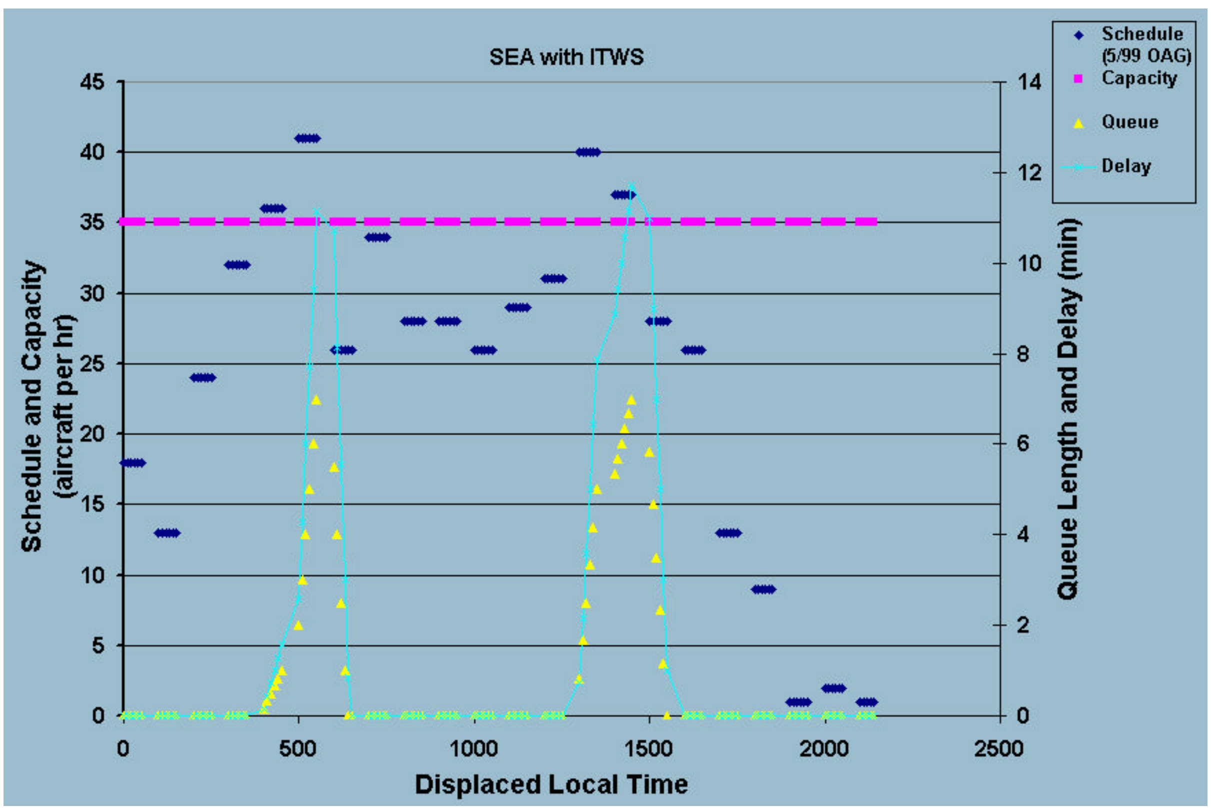

Figure E-6. SEA delays assuming that ITWS permits landing 35 aircraft per hour.

The estimates of delay reduction in hours of delay were converted to airline direct operating cost (DOC) benefits as follows, using the following "fleet average" costs:

- Airborne delay cost = $48/minute
- Taxi delay cost = $30/minute
- Gate delay cost = $15/minute = downstream delay cost (i.e., a flight flying the current flight segment in the scheduled amount of time, but running late due to an earlier weather delay that day).

The improved aircraft merging/sequencing benefit arises in cases where the airport capacity is reduced to less than the scheduled arrival rate due to a mixture of adverse winds (typically, significant vertical wind shear) and IFR conditions. Since the weather situations modeled arise from large Pacific storms, the weather impacts are well understood so that the bulk of the delays should be taken on the ground.

Downstream delays were considered to have the same DOC cost as gate delays.

For the wake vortex related benefits, a lumped value of $1000 per hour of delay (i.e., the delay savings was not separated into airborne, taxi, and gate delays.)

The passenger time was estimated to cost $2000 per hour (per the FAA guidelines for the 1994 ITWS cost benefits study) for all cases.

GLOSSARY

aFAST	"active" Final Approach Spacing Tool
ACE	Aviation Capacity Enhancement
ARTCC	Air Route Traffic Control Center
ASQP	Airline Service Quality Performance
CG	Cloud-to-Ground
COTS	Commercial Off-The Shelf
CSCI	Computer Software Configuration Item
CTAS	Center-TRACON Advisory System
DOC	Direct Operating Cost
FAA	Federal Aviation Administration
FAST	Final Approach Spacing Tool
HNL	Honolulu International Airport
IC	Intracloud
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IOC	Initial Operational Capability
IPT	Integrated Product Team
ITWS	Integrated Terminal Weather System
LAX	Los Angeles International Airport
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NEXRAD	NEXt generation weather RADar
NLDN	National Lightning Detection Network
NoCal	Northern California
NWS	National Weather Service
OAG	Official Airline Guide
pFAST	"passive" Final Approach Spacing Tool
PDX	Portland International Airport
PRM	Parallel Runway Monitoring
RUC	Rapid Update Cycle
SEA	Seattle International Airport
SEP	Storm Extrapolated Position
SFO	San Francisco International Airport
SOIA	Simultaneous Operation with Independent Approach
TCWF	Terminal Convective Weather Forecast
TDWR	Terminal Doppler Weather Radar
TFM	Traffic Flow Management
TMU	Traffic Management Unit
VFR	Visual Flight Rules
VIF	Vertically Integrated water above the freezing level
VIL	Vertically Integrated Liquid water
WSP	Weather Systems Processor

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