1.3 **MEETING FAA'S THUNDERSTORM FORECASTING REQUIREMENTS - CENTRALIZED VS. DISTRIBUTED PROCESSING**

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1. INTRODUCTION

In a January 2004 speech, Transportation Secretary Norman Mineta related both good and bad news regarding the state of aviation and air travel. The good news—passengers are filling commercial airliner seats and air traffic is rapidly approaching pre-September 11, 2001 levels. The bad news—the National Airspace System (NAS) is again beginning to show signs of stress in terms of having the airspace capacity to meet that demand. The Secretary described ongoing infrastructure improvements for aviation (e.g., additional runways and air traffic control facilities and systems, and more weather radars). However, despite these improvements weather will continue to impact NAS operations, restricting the use of available jet routes and reducing the throughput (approaches and departures) at NAS pacing airports where 80%-90% of system delays are encountered.

The primary causes of NAS delays have varied from year to year, however weather has consistently accounted for a large majority of those delays. According to the Aviation Capacity Enhancement Plan for 2002, which is based on Operations Network (OPSNET) data, weather-related delays have averaged 70%. During the last five years unacceptably high levels of air traffic delays have occurred during the summer months (Figure 1.) and have caught the attention of the media. And while flight over-scheduling was a contributing factor in several instances, thunderstorm activity continues to have a major impact on NAS efficiency, affecting jet routes and NAS pacing airports.

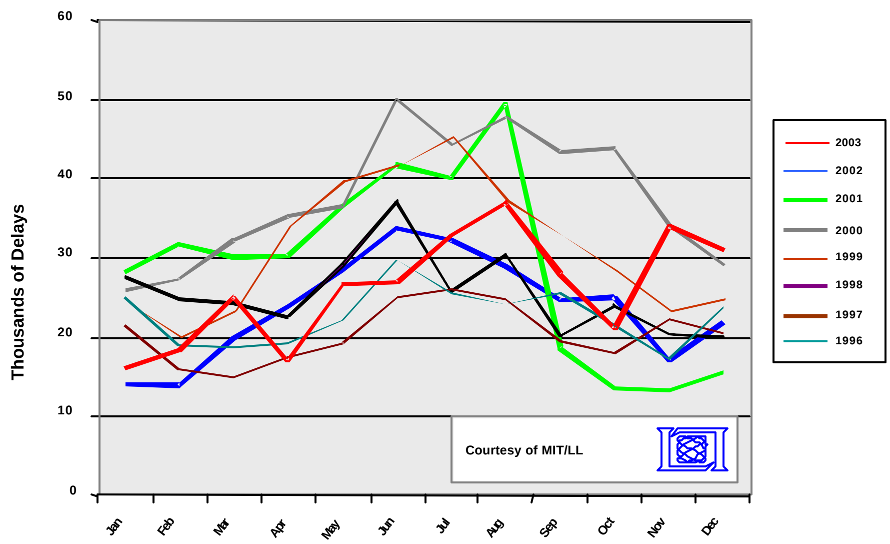

Figure 1 Trends in Aviation Delays

Thunderstorms pose the most significant impact on NAS capacity by reducing system efficiency. Evidence of this can be seen in Figure 1 where from 1996 through 2003, commercial airline delays peaked during the summer months of each year when thunderstorm activity is most prevalent.

As a result, the FAA sponsored aviation weather research, using government and academic laboratories, to focus on developing an improved thunderstorm forecasting capability. Several products have matured out of this research with one product, the Collaborative Convective Forecast Product (CCFP), used today for traffic flow planning purposes in a collaborative effort involving the FAA and the airlines. Other products are in various phases of testing or operational evaluation. In most instances, each product was generated separately, even though they all provide a forecast of thunderstorm activity. These products range in area coverage from the airport or terminal area to products that cover a large area and are regional or national in

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scope. The decision facing the FAA is whether a single product, more correctly an algorithm, can provide a thunderstorm forecasting capability to meet all NAS requirements—terminal, regional, and national—for both tactical and strategic applications.

2. BACKGROUND

NAS users currently see depictions of precipitation intensity from weather radars from which they infer the location of thunderstorm activity. Though ground lightning strike data are currently available and an excellent surrogate for detecting thunderstorm activity, there are some inherent drawbacks. It is not always available and positional information can be a few minutes late given the time to collect, process, and disseminate data from the vendor-operated NLDN (National Lightning Detection Network). Additional time is required for the subsequent correlation into individual automated surface observing systems (ASOS or AWOS). Furthermore, ground lightning strikes occur late in the thunderstorm lifecycle during the dissipation phase. Intra-/inter-cloud lightning activity occurs earlier in the lifecycle and could provide more lead-time of intensifying activity. However, "cloud lightning" data are presently not available from the NLDN. Therefore, additional delays are realized in reporting the existence of hazardous thunderstorm activity.

Studies conducted by the Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL) and the FAA reveal that approximately 40% of all weather-related delays are due to thunderstorms. Users and service providers related that convective weather, particularly line storms, caused the most consistent problems for managing air traffic. Post event analyses of air traffic delays during thunderstorm events reveal that 35% to 45% of these delays are likely avoidable if accurate and reliable forecasts are available to FAA TM specialists for in-flight routing/re-routing purposes, as well as for use at NAS pacing airports. Providing accurate and reliable thunderstorm forecast products to TM specialists and airline dispatchers enables them to collaboratively decide on how best to route/reroute air traffic around areas (both en route and terminal) where convective activity is predicted. Thus with products like the CCFP, the impact of thunderstorms on NAS operations can be mitigated.

Thunderstorm forecast products in support of aviation have been available for some time from National Weather Service (NWS) meteorologists. These advisories include Convective and International SIGMETs (Significant Meteorological information) from the Aviation Weather Center (AWC) in Kansas City, MO, the Center Weather Advisory and the Meteorological Impact Statement from the Center Weather Service Units (CWSU), as well as Terminal Aerodrome Forecasts from Weather Forecast Offices. Other available AWC products relating forecasts of thunderstorm activity include Area Forecasts and significant weather prognosis charts. These products are effective in indicating areas of expected thunderstorm activity to traffic managers and dispatchers. However, being generally text-based or a non-digital graphic, they cannot be easily integrated onto TM displays or into Air Traffic Management Decision Support Systems (ATM/DSS). The prerequisite for current and forecast thunderstorm products used by operational decision makers in the modernized NAS is that they must be in a gridded, digital format easily integrated onto air traffic displays and automatically integrated into ATM/DSS.

Furthermore, FAA service providers (i.e., air traffic control and traffic management specialists) require weather information that is more tactical in nature, requires no meteorological expertise to interpret (or use), and unambiguously conveys the extent of the areas impacted by hazardous thunderstorms. In fact, what non-meteorologist NAS users really need is <u>the forecast impact of the thunderstorms on NAS operations</u> to include the following:

- Jet route constraints (when will they be closed, available, or partially available)
- The altitude of the cloud tops (for over-the-top routing)
- Accurate timing on when thunderstorms (and associated gust fronts) approach/depart NAS pacing airports (to optimize runway usage during wind shifts and mitigate reduced aircraft acceptance-/takeoff-rates during passage)

Recognizing this, the FAA and NWS began working nearly a decade ago to develop forecast products for thunderstorms (and other hazards as well). Under the auspices of the FAA's Aviation Weather Research Program (AWRP), several initiatives were undertaken to develop thunderstorm-forecasting capabilities for the en route as well as for terminal operations. Emerging first was the en route forecast product—the Collaborative Convective Forecast Product (CCFP). Somewhat later, the National Convective Weather Forecast (NCWF) followed.

The CCFP graphically depicts thunderstorm activity forecasts on a CONUS-scale map and has served as the basis for strategic traffic flow planning for several years. During the convective season [April to September], it is used several times daily as the basis for collaborative decision-making between FAA traffic managers and airline dispatchers to plan and coordinate a system-wide approach for mitigating the impact of thunderstorm activity on NAS operations. This collaboration also involves the AWC and CWSU meteorologists and assists the AWC meteorologist in deciding on the final forecast product content and depiction of the location and intensity of the activity to avoid. The CCFP is a manually generated graphic of convective area forecasts for 2-, 4-and 6-hour predictions that is updated every 4 hours. Each convection area for a given forecast time has specified probabilities of convection, percent area coverage, growth/dissipation rates, and storm-top categories.

The NCWF assists dispatchers and traffic managers more in tactical planning and can potentially minimize schedule and flight disruptions with its one-hour national convective forecast with updates that are automatically generated every five minutes. The FAA with the support of the MITRE Corporation's Center for Advanced Aviation System Development is working to incorporate the NCWF into the Collaborative Routing Coordination Tool used to determine if proposed rerouting actions will result in overloaded sectors. The NCWF depicts the extrapolated position of the convective hazard and shows forecasting skill with long-lived mature convective systems. The NCWF product, however, does not forecast the initiation, growth, and decay of thunderstorms. Additional FAA research is ongoing to add the forecast of storm growth and decay to the next version, the NCWF-II (a 2-hour forecast). The CCFP and NCWF products are transmitted to FAA service provider displays via WARP. This enables TM specialists at the ARTCC to assess the impact of predicted thunderstorm locations on traffic flow routing and collaborate mitigation efforts with TM at the FAA Air Traffic Control System Command Center (ATCSCC) and airline dispatchers. Dispatchers access these products via the Internet at the AWC website.

With respect to impacts at airports, it has been known for some time that air traffic delays impacting the NAS are often due to thunderstorm activity occurring at the busiest airports. Pacing airports are often airline "hubs" with many multi-leg flights passing through them to other destinations. Delays due to thunderstorm activity at these hubs can cascade "downstream" to other airports—a "ripple effect"—that extends well beyond the impacted airport to other regions of the NAS. Accordingly, AWRP efforts also produced a convective forecast capability for these airports.

NAS delays reached historically high levels in 1999 and 2000 due to thunderstorm activity that occurred at the busiest NAS airports. Thirty-five of these airports are identified in the FAA Operational Evolution Plan (OEP), which indicates that 80% - 90% of NAS delays are attributed to these airports. The OEP also points out that eight of these 35 airports—Atlanta Hartsfield-Jackson; Boston Logan; Chicago O'Hare; John F. Kennedy, LaGuardia, and Newark Liberty International in the New York area; Philadelphia International; and San Francisco International—have the highest delay rates in the U.S. and are designated as "pacing" airports.

Developed to ameliorate the impact of thunderstorm activity at these airports, the terminal Convective Weather Forecast (CWF) emerged from the AWRP for implementation on the ITWS (Integrated Terminal Weather System). ITWS greatly extends the capability to automatically identify and provide short-term forecasts of significant weather (i.e., microburst, wind shear and gust fronts), which impacts 46 of the busiest NAS airports. The CWF enhances ITWS' convective forecasting capability enabling it to provide accurate forecasts of thunderstorm activity further in time (from 30 minutes out to 60 minutes in ten-minute increments) of storm growth/decay and motion.

When ITWS began deployment in 2002, however, it was fielded without the CWF capability for several reasons. The FAA did not want to delay the ITWS deployment by waiting for the software development to integrate the CWF. Also, significant benefits were obtainable from ITWS' inherent capabilities (e.g., microburst and wind shear prediction (safety); gust front detection and prediction (capacity) for runway optimization; and Terminal Winds for terminal automaton systems (capacity)) to warrant deployment without the CWF.

Recently, the FAA re-examined the issue of adding the CWF algorithm to the ITWS. With studies showing the potential of the CWF capability to mitigate thunderstorm-related delays, it was decided to incorporate the CWF into those ITWS production systems not yet deployed and to retrofit it onto those that were. However, by this time the FAA acquisition funding-approval process to add the CWF was impacted by a budget shortfall for FY05. As a result, the CWF will be implemented [on ITWS] beginning in 2006, but available funding only allows for fielding 22 of the 34 ITWS systems. Funds for fielding the remaining 12 systems will be sought at a later time given it is still cost beneficial to do so.

Another AWRP effort to develop regional thunderstorm forecast capability that is tailored to address line thunderstorms that impact the air route corridor extending from Chicago eastward to Washington, DC, and up into New England has shown promise. In this corridor, the jet routes are constrained by their proximity to each other. When line thunderstorms move through, or even worse overlay these routes they play havoc with traffic flow management. This forecasting capability is called the Regional Convective Weather Forecast (RCWF) algorithm and is hosted on the Corridor Integrated Weather System (CIWS) prototype.

While the NCWF and CCFP are certainly applicable for regional use, the highly congested airspace in a corridor requires both accurate and reliable high-resolution detection of the current convective situation, as well as forecasts to safely improve the flow of air traffic during thunderstorm events. Operated by MIT/LL, the RCWF currently provides a NEXRAD VIL-based, high-resolution (2-km) mosaic of precipitation intensity out to two hours in 15-minute increments with storm growth/decay. Skill scores (current forecasting performance) for each forecast increment are also displayed. Other products from CIWS include an Airport Surveillance Radar (ASR-9) precipitation mosaic (1-km), an Echo Top mosaic (2-km) with altitude labels (for over-the-top routing), Storm motion (vectors and extrapolated positions), and ground lightning strikes. These products are displayed to TM specialists at key ARTCCs (Chicago, Indianapolis, Cleveland, Washington, DC, New York, and Boston), the ATCSCC, and major terminals in New York, Chicago, Detroit, Pittsburgh, Cleveland, and Cincinnati. Airline dispatchers access these products via a special network that pulls them from a MIT/LL website via the Internet.

CIWS is able to generate the above products by using data from both terminal and en route weather radars. The rapid update rate of the ASR-9 weather channel (30 seconds) is used to detect and monitor rapidly growing cells, while NEXRAD data provides information on large-scale 3-dimensional storm structure and boundary layer winds. Lightning data and GOES satellite imagery are integrated with the radar data. In the future, weather information from the Terminal Doppler Weather Radar will likely be added as well as data from Canadian radars to cover more northern re-routing options.

Coincident with the AWRP efforts to develop improved forecast capability for thunderstorm activity, an FAA effort to determine operational decision maker requirements was underway. A Weather Integrated Requirements Team (IRT) of personnel from the FAA (including union representatives for controllers and flight service specialists) and the NWS determined the various types of decisions that were made by NAS operational decision makers—pilots, air traffic controllers, traffic managers, dispatchers, and flight service specialists—in the course of their duties. Next, they examined which weather events influenced (or impacted) those decisions. And lastly, they determined what were the gaps (or shortfalls) in weather information that was available to these decision makers.

The efforts of this team and subsequent analysis led to the first FAA domain-level mission need statement (MNS), Aviation Weather MNS #339. Using a portfolio management toolset to make the "business case", the various weather phenomena (i.e., thunderstorms, non-convective turbulence, airport winds, etc.), for which 'gaps' existed were sorted into Investment Packages and evaluated for 'cost vs. mitigation.' MNS #339 was approved in June 2002, and thunderstorm was the top priority Investment Package. It validated existing thunderstorm shortfalls and the need for improving:

- The detection of attributes (e.g., hail, tornados, etc.)
- Prediction (accuracy, resolution, and storm direction/movement)
- Dissemination of products to NAS users to help mitigate impacts to capacity as well as safety

Subsequent requirements activity leveraged off of the efforts of the weather IRT and MNS #339 and led to the thunderstorm initial Requirements Document (iRD). This NAS-wide iRD, for the first time listed performance requirements for thunderstorm products or information (i.e., type of products to be provided, update frequency, horizontal resolution, accuracy, etc.). The iRD has been completed and is awaiting signature.

Other weather-related requirements activities include a recently completed Weather Functional Analysis that examined the functions that operational decision makers perform in the course of their duties. This functional analysis was conducted to document existing weather requirements and to also determine any requirements that may not have surfaced previously. Also, a Weather Concept of Operations was developed that delineated how operational decision makers would use various weather products under different scenarios, and the products each would need. System engineering led both of these efforts and the resultant reports are currently out for agency review. As a result of these activities, the FAA is reevaluating the weather architecture to determine convective forecasting solutions that are not domain specific, but optimized for NAS-wide use.

3. CENTRALIZED VS. DISTRIBUTED PROCESSING CONSIDERATIONS

The issue before the FAA is that given these various thunderstorm forecast products in different phases of development—the CCFP, the NCWF, the CWF [on ITWS], and the CIWS prototype capability—what course of action should be pursued in fielding a forecasting capability, centralized or distributed processing? The answer to this question has to first take into account several factors.

First, let's examine the requirement(s) before discussing the "solution". With respect to the terminal requirement, it was mentioned earlier that the FAA decided to field the one-hour CWF product on ITWS [at the busiest NAS airports] in order to mitigate terminal delays that "ripple out" to the rest of the NAS. So part of the "solution" has already been determined. However, this solution was based on a business case to reduce operating costs as well as provide additional benefits. Keep in mind, however, that the terminal CWF product only provides a one-hour forecast.

In addition to the longer forecasts required by traffic flow managers (4-8 hours), longer forecasts times (2-4 hours) are likely needed for controllers in the larger TRACONs (terminal radar approach control). Although not yet validated, informal discussions with TM at the New York TRACON indicate that in some instances, even longer forecast times (>4 hours) are required. They stated the need to know by 10 AM EST each day if thunderstorm activity will impact the New York area that afternoon. The reason for this six-to-eight hour notice is that a ground-hold program must be initiated by then to preclude aircraft taking off from west coast airports that are bound for the New York area. So the need for a terminal thunderstorm forecast beyond one hour exists, and in some instances [large TRACONs], beyond four hours.

For CONUS and regional (corridor) applications, forecasts further out (two-to-four hours) are also needed. The Thunderstorm iRD calls for forecasts out to eight hours for Traffic managers, who routinely need to know the predicted location of thunderstorm activity out to four hours. But to have utility, these forecasts must be accurate and sufficiently reliable to enable TM specialists to plan and coordinate an avoidance strategy with the airlines to mitigate the impact of thunderstorms on NAS capacity. Accurate means that the thunderstorm product feature (precipitation intensity or cell location in this case) must actually be within a certain distance (e.g., 1-km, 4-km, etc.) of where it is depicted. Reliable means to what degree of confidence—60%, 70%, etc.—the feature is actually located where it is depicted.

Also, with respect to requirements in the Thunderstorm iRD, it must be recognized that the "shall statements" in this iRD are an "initial" estimate of performance requirements and have to undergo additional analysis for validation from an operational perspective in accordance with existing procedures. Also, the previous paragraph percentages of reliability were discussed in the context of confidence of the forecast. Those percentages must also undergo an operational validation to ascertain that given a level of confidence in the thunderstorm forecast, how does a specific accuracy influence the TM decision. In a similar vein, scientific meteorological analysis needs to be conducted to determine not only when the performance requirement can be met, but also what the cost would be of doing so. Then, any tradeoffs between the costs to meet that requirement versus the benefit of having it available can be worked out. In other words, it may be cost prohibitive to provide an accuracy of 0.25-km for detecting a cell while an accuracy of 1-km would be both cost effective and meet the user's actual need. The point being is that many of the Thunderstorm iRD requirements require additional analyses before being finalized and implemented.

Looking at the existing thunderstorm forecast capabilities of the NAS - the NCWF and the CIWS capability both provide the graphical format that is needed, the areal coverage, and the resolution. The CIWS prototype has several advantages: it forecasts further out in time (two hours), provides a skill score for each forecast increment (every 15 minutes) of the VIL precipitation mosaic, and has demonstrated success to TM who have viewed the products in TRACONs, ARTCCs, and at the ATCSCC.

One of the primary reasons for considering Centralized Processing (in general) results from the Target System Description (TSD). This is a snapshot of NAS capabilities (or services) that the FAA believes it can reasonably deliver in the middle of the next decade in response to the RTCA NAS Concept of Operations (CONOPS) and Vision for the Future of Aviation (2002). One of the overarching themes of the TSD is consolidation of functionality to eliminate unnecessary redundancy, thereby reducing the number of systems and related lifecycle costs. An example would include consolidating information from various sources onto a single workstation (eliminating multiple single-purpose displays or monitors). Or more to the point, consolidating numerous weather-processing systems into a single system (or at least fewer systems).

In the TSD weather architecture, by the year 2017 a single weather processor emerges, called the General Weather Processor (GWP). The GWP subsumes the functionality of WARP Replacement (WARP-R), CIWS, and the weather functionality of OASIS (flight services automation system). This would require that the GWP integrate all sensor data and source data from within and outside of the FAA (e.g., NWS, DoD) for processing to generate a myriad of products for different users across all of the NAS. One system that <u>would not</u> be fully consolidated, however, would be the ITWS, as it provides a safety-related product that warrants it remaining in place. The ITWS is fielded with an algorithm that <u>forecasts the likelihood of a wind shear or microburst event before TDWR detects it</u>. This provides an additional 60-90 seconds of warning to the controller for collaboration with the pilot in helping the pilot determine whether a landing or takeoff should be continued or not. The final decision resides with the pilot after receiving the weather advisory of the hazard from the controller. Also, though ITWS would remain at the terminal, the GWP would provide it with longer-term thunderstorm forecasts (beyond what the terminal CWF provides).

One of the main considerations for not having all the ITWS functionality 'centralized' to a remote site has to do with product latency. As was discussed in the preceding paragraph, Low-level wind shear or microburst events are thunderstorm attributes that pose a significant safety hazard in the terminal environment and warrant immediate notification (weather advisory) to controllers. The FAA fielded three different systems at (or near) approximately 120 airports that are susceptible to wind shear or microburst. Designed solely for this purpose, the TDWR, the ASR-WSP, and the LLWAS provide automatic alerts of wind shear or microburst detection to traffic controllers, who relay these alerts as weather advisories to pilots in departing/approaching aircraft. Attempts to centralize the functionality of these 120+ systems into a single site in order to generate such detections, alerts, and weather advisories remotely must first consider the following:

- Not only would it require transmitting individual sensor data to a distant point for processing, but would also require sending the alert back along the reverse path while meeting stringent latency requirements
- The communications costs associated with constantly transmitting base radar data from two different networks of Doppler radars consisting of 45 TDWRs and 34 ASR-9s, plus wind data from 40 LLWAS to a remote site for wind shear or microburst processing are high

In the foreseeable future, communications improvements may make it technically feasible to accomplish both the detection of wind shear and microbursts as well as alerting controllers remotely while meeting latency requirements. However, various risk factors associated with missed radar data, missed or late alerts, etc., would require careful evaluation before centralizing wind shear and microbursts processing, especially where safety is concerned.

4. SUMMARY

Notwithstanding the FAA budget environment in the next 10 to 15 years, a transition to a Centralized Processing for forecasting thunderstorms (and other products) exemplifies sound system engineering. First, it supports one of the main goals of the NAS weather architecture—to engender common situational awareness of thunderstorm activity for NAS operational decision makers, thereby facilitating the collaborative decision making process to mitigate capacity constraints that thunderstorm activity imposes on the NAS. A single application (or algorithm) providing thunderstorm forecast products throughout the NAS goes a long way in accomplishing this. If NAS users receive forecasts, either from different systems or from a vendor, the depiction of thunderstorm activity that each views could be somewhat different and hinder the collaborative process.

Furthermore, the capability for Centralized Processing of thunderstorm forecasting doesn't have to wait until the TSD timeframe and the GWP. If the WARP-R is fielded by the end of this decade and has the capability to host the CIWS thunderstorm forecasting capability, it may be possible to begin the transition to a consolidated forecasting capability by 2010 or so. During this "pre-GWP" era, the WARP-R would use its existing dissemination capability to provide the thunderstorm forecasts tailored for specific users (e.g., TM, controllers, and automation systems) within the ARTCC, as well as tailored forecasts to various users in other facilities (e.g., small Towers, flight service stations, etc.).

The main difference between WARP-R and the GWP is that the vast majority of weather sensor/source data would come directly to the GWP for processing and tailored product generation of forecasts for other weather phenomena including non-convective turbulence, in-flight icing, etc., that previously came from multiple sources.

The NAS will be best served by a combination of Centralized and Distributed Processing capability for thunderstorm forecasting. Regardless of future communications technology improvements such as bandwidth manager, compression techniques, "intelligent routers", etc., the detection and <u>forecasting</u> of thunderstorm attributes relating directly to safety such as wind shear/microbursts should continue to be performed locally (Distributed Processing). In addition, ITWS should continue to provide its own tactical thunderstorm forecast (likely out to two hours by this time) with the GWP providing longer forecasts as needed.

5. ACRONYMS

ARTCC = Air Route Traffic Control Center
ASOS = Automated Surfaced Observing System
ASR-9 = Airport Surveillance Radar Model 9
ASR-WSP = Airport Surveillance Radar-Weather System Processor
ATCSCC = Air Traffic Control System Command Center
ATM/DSS = Air Traffic Management Decision Support Systems
AWC = Aviation Weather Center (Kansas City, MO)
AWOS = Automated Weather Observing System
AWRP = Aviation Weather Research Program
CCFP = Collaborative Convective Forecast Product
CIWS = Corridor Integrated Weather System
CONOPS = Concept of Operations
CONUS = Continental (or Contiguous) U. S.
CWF = Convective Weather Forecast
CWSU = Center Weather Service Unit
DoD = Department of Defense
FAA = Federal Aviation Administration
GOES = Geostationary Operational Environmental Satellite
GWP = General Weather Processor
IRD = Initial Requirements Document
IRT = Integrated Requirements Team
ITWS = Integrated Terminal Weather System
LLWAS = Low Level Wind shear Alert System
MIT/LL = Massachusetts Institute of Technology/Lincoln Laboratory
MNS = Mission Need Statement
NAS = National Airspace System
NCWF = National Convective Weather Forecast
NEXRAD = Next Generation Weather Radar
NLDN = National Lightning Detection Network
NWS = National Weather Service
OASIS = Operational and Supportability Implementation System
OEP = FAA Operational Evolution Plan
OPSNET = Operations Network
RCWF = Regional Convective Weather Forecast

SIGMET = Significant Meteorological Advisory
TCWF = Terminal Convective Weather Forecast
TDWR = Terminal Doppler Weather Radar
TM = Traffic Management
TSD = Target System Description
TRACON = Terminal Radar Approach Control
VIL = Vertically Integrated Liquid
WARP = Weather and Radar Processor
WARP-R = WARP Replacement

6. REFERENCES

FAA 2002 Capacity Enhancement Plan, page 15, FAA Washington, DC

OPSNET is an FAA delay reporting system derived from observations by FAA personnel

CIWS, ITWS, and TCWF information obtained from the MIT/LL personnel, their website, and FAA Product Teams (MIT/LL Lexington, MA)

Aviation Weather Mission Need Statement (#339), Thunderstorm Investment Package (approved by the FAA's Joint Resources Council in June 2002)

RTCA NAS CONOPS and Vision for the Future of Aviation (December 2002), RTCA Washington DC