NEW STRATEGIES AND INSTRUMENTS FOR ENHANCEMENT OF AVIATION SAFETY

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ABSTRACT

Aviation safety against weather hazards is considered. The major effects of atmospheric convection and precipitation on aviation are summarized. Recent findings on weather effects and their influence on concepts and systems for air safety enhancement are brought out. The role of the modern high-performance radars as primary aviation weather sensors is established. Doppler weather radars are discussed, including original and extended roles of the NEXRAD. Possible performance enhancement through multiparameter observation using frequency and/or polarization diversity is discussed. Accuracy and resolution considerations for single radar observations are brought out and possible backup data sources for regions of poor coverage are mentioned. The particular case of small/medium airport coverage is discussed. The role of simpler and less expensive instruments such as profilers is put in perspective.

INTRODUCTION

Recent research and analysis of aircraft accident data have revealed that weather plays a far greater role in aviation safety (or lack of it) than has been hitherto believed. With this realization, considerable attention and resources are being devoted to research and instrumentation to minimize weather hazards to aviation. This has been reflected in the importance given to procedures and measures for weather effect alleviation in the U.S. National Airspace Plan of 1981. This paper reviews the recent insight gained into the role of weather processes on air safety and discusses some current ideas and plans to enhance the safety of aviation against weather hazards.

Weather phenomena of interest to aviation are of four major types: (1) convective phenomena including wind shear and turbulence (2) hydrometeorological phenomena including heavy rain and hail (3) icing and (4) low visibility. This paper concerns only the first two categories, which may be served by a common type of instrumentation such as radars. The problems associated with icing and low visibility are monitored and countered by a different class of instrumentation and strategies.

Aviation is influenced in a variety of adverse ways by weather phenomena. In extreme cases weather factors may induce, or at least be a strong cause of, air crashes. According to one survey [1], there have been as many as eleven fatal weather-related accidents involving U.S. air carriers alone between 1962 and 1984. In 1985, which was a particularly bad year for aviation with about 2,000 airline fatalities globally, a high proportion of accidents were due largely to weather.

While fatal accidents, especially those involving civilian airliners, are highly visible inviting a lot of attention (and litigation), weather influences airline operations in more subtle but profound ways. One significant effect is on airline schedules. An early study [2] based on a large number (31,672) of flight delays revealed that over 85% of delays that are 30 minutes or longer were weather-related.

Aircraft accidents, incidents and delays due to weather ultimately show up in the operating economy of airlines. Apart from direct loss of aircraft and increase in cost of insurance, litigation and compensation, there is loss of revenue due to reduced number of operations and loss of passenger confidence, and increase in operating expenses due to inflight holding of aircraft caused by adverse weather conditions at airports which may make landing operations unsafe and/or slow.

While the causative factors in most of these cases are natural and cannot be regulated in any significant way, prior information regarding the existence and intensity of aviation-significant weather phenomena can help minimize fatalities and cut losses by proper evasive action.

AVIATION-SIGNIFICANT WEATHER FACTORS

Weather phenomena of interest to aviation have various origins. However, it appears that the most frequent weather hazards are related to thunderstorms. Out of the eleven fatal weather-related air carrier accidents in the U.S. during 1962-84, as many as nine have been reported to have occurred in the area of thunderstorm rain [1]. However, phenomena not directly linked to (or, at least, not in the immediate thunderstorm precipitation zone) are also known to possess considerable degrees of hazard potential for aviation.

A thunderstorm is a composite phenomenon involving many separate effects which may or may not have significant spatial overlap. Considerable insight has now been gained into the effects, detection and estimation of weather factors associated with thunderstorms as well as those that are not.

Wind Shear

Among convective atmospheric phenomena, perhaps the best known, and now most feared, is wind shear. Wind shear is a spatial or temporal gradient in wind speed or direction. Varying degrees of wind shear are widespread in the atmosphere, especially at low levels due to the boundary layer effect. However, wind shear of certain types is potentially hazardous to aircraft during terminal maneuvers, during which aircraft are particularly vulnerable because of low margins of time, airspeed and altitude to effect a recovery.

A common source of relatively strong wind shear is the gust front. It is the leading edge of rain-cooled air, first flowing downward and then outward from the center of thunderstorms, and usually generates both horizontal and vertical shear. A front, characterized by a spatial scale of 10 to 50 km [3], can travel tens of kilometers from its generating storm and yet retain strong enough wind shear to seriously affect flight. Gust fronts often contain rain and/or dust, but frequently they occur in clear air. Clear air gust fronts are more hazardous, since they are invisible and less detectable by radar.

Strong wind shear may also be caused by "downbursts" [4,5] which are shafts of fast-descending air that cause strong localized surface winds on being deflected by the ground. This phenomenon is the subject of intense study, and is dealt with in more detail later.

Other significant sources of wind shear are the passage of cold or warm fronts, low level jet streams and topographical factors.

Although wind shear occurring at low levels are considered more hazardous, shear at higher altitudes can often cause very uncomfortable flights, though aircraft can usually recover from the flight perturbations induced by such shear. In mature thunderstorms, updraft and downdraft exist side by side and would buffet an aircraft passing from one region to another. Strong windspeed gradients also occur within the divergence at the top of thunderstorms. The height of thunderstorms, typically over 25,000 ft but possibly as high as over 65,000 ft, covers the flight altitudes of most types of aircraft.

In recent years, the phenomenon of wind shear has been a subject of considerable study, both by itself and in relation to aviation. A large body of literature is available on the subject, including useful summaries, e.g. [6-8].

Turbulence

Turbulence is caused by air pockets of different spatial scales moving randomly. An aircraft moving through such a medium encounters random fluctuations in the vector wind speed at relatively high frequencies.

Turbulence causes rough rides, causing passenger discomfort. However, in severe cases, turbulence may endanger flight by inducing high levels of dynamic stress or awkward body attitudes [9], by impairing control action, by causing erratic engine combustion resulting in reduced/variable thrust, and by forcing pilots to get into zones with other hazards.

Precipitation

Precipitation may be rain or hail. Light or moderate rain does not have much direct effect on flight, but may still endanger safety (for visual flying) by way of reduced visibility. Heavy rain, however, not only causes extremely poor visibility, but can directly affect flight adversely when ingested into jet engines where it causes poor combustion and reduced thrust [10,11].

Hail may occur as high as 45,000 ft, and thus may endanger flight at all levels. Hail damage to aircraft occurs through impact on critical parts such as airfoil leading edges, windshields, radomes and jet engine compressor blades. Hail may also lead to extinction in jet engines [11].

Downbursts

Downbursts are a major source of wind shear, as mentioned above. However, downbursts, defined as strong downdrafts which induce outbursts of damaging winds on or near the ground, have been studied in their own right in quite some detail in recent years, and merit some special discussion.

Depending on its size, a downburst may be classified as a microburst or a macroburst [12]. A microburst is a small downburst with damaging outburst winds extending only 4 km or less in horizontal dimension; larger downbursts are called macrobursts. Even a microburst could induce wind speeds as high as 75 m/sec and an intense macroburst, which often causes widespread, tornado-like damage, can induce damaging winds lasting 5 to 30 minutes and reaching speeds as high as 60 m/sec.

Although macrobursts are larger and may be more fierce than microbursts, the latter have drawn more attention in the recent past in the context of air safety. Because of its small size and short life (less than 10 minutes), a microburst often escapes detection by ground-based anemometers and even non-Doppler radars. A very small microburst could cause serious difficulties on one runway while other runways are untouched [12]. Also, because of the smaller spatial scale of a microburst, it can generate a higher wind shear level (which is a rate of change of wind speed) than larger phenomena.

Following the understanding of microbursts generated during the past decade, their involvement in air accidents/incidents has been well investigated [12,13]. An analysis of twentyseven wind shear related aircraft accidents/incidents between 1964 and 1982 listed in a comprehensive study by the National Academy of Sciences [14] has revealed that eight of them were caused by microbursts, with a suggestion that upto five more may have been related to microbursts.

Because of the importance of understanding microbursts to aviation safety, dedicated studies have been made to investigate down bursts with emphasis on microbursts. Two major U.S. programs along this line are the NIMROD started in 1978 and the JAWS started in 1982. These programs involved observation by multiple Doppler weather radars, surface instrumentations and aircraft missions for measurements and photography.

A large body of results have been generated by these programs, as reported in the project reports and other publications, e.g. [15,16]. During NIMROD, it was found that not all microbursts occur in severe thunderstorms; some are associated with relatively weak echoes without thunder. Such microbursts would be difficult to detect by conventional sensors.

Detailed studies during the experimental programs have shown that microburst occurrences are poorly correlated to possible indicative parameters such as winds aloft or temperature anomalies. Hence, prediction of microbursts based on upper-air and surface observations has not been considered practicable [12]. In the absence of such predictive capability, air safety against downbursts in the near future must depend heavily on the real-time observation of such phenomena. In view of the small spatial and temporal extent of microbursts, and the absence of strong radar echoes in all cases, it would be necessary to sense the wind speeds with high spatial and temporal resolution to be able to observe microbursts with the degree of confidence and agility necessary for aviation operations.

CURRENT INSTRUMENTATION

The Federal Aviation Administration (FAA) and the National Weather Service (NWS) provide aviation weather information. The Airforce Weather Service (AWS) also provides certain information. The instrumentation that is currently operational for the detection of atmospheric convection and precipitation include surface stations, weather radars and geostationary satellites providing cloud cover photographs.

These types of instruments observe different aspects of weather processes over different spatial and temporal scales and the combined information from all these sources provides the overall weather scenario globally as well as areawise. However, it has now been realized that the dimensionality of the information, spatial resolution and update rates currently available are not adequate for a highly dynamic operation such as aviation.

One of the major limitations of the current weather information system is its high dependence on surface instrumentation. Surface sensing of precipitation is accurate and is adequate for a variety of general weather applications. However, the nature and intensity of precipitation at ground level is often quite different from those at altitudes (e.g. within thunderstorms) which are of interest to aviation.

Another drawback of surface instrumentation (as of any in-situ instrumentation) is its sparse coverage. The grid size of surface stations, which is usually several tens of kilometers, results in information that is too coarse for aviation application.

Much of the problems of coverage and resolution in relation to precipitation is alleviated by the current weather radars, such as the famous WSR-57. They do provide a picture of precipitation echo intensities over an area of a few hundred kilometers diameter with a range resolution of a few hundred meters. However, a number of limitations still remain. Among them are:

1. The echo intensities only roughly correspond to actual precipitation intensities. In spite of decades of research into radar rainfall estimation and calibration, the quantitative estimates of rainfall (especially localized rainfall rates) from radar data are often in error by significant factors.

2. The nature of precipitation can be inferred only from the echo intensity. For example, very heavy echo reflectivities are associated with the presence of hail. However, this serves only as a gross indicator, leading to either non-detection of hail or excessive

false alarms. For aviation, the former could be damaging and the latter would result in frequent detours, resulting in extra delays and expenses.

3. Conventional weather radars have only one scan level. Thus, reflectivity mapping is only along the elevation angle of the scan. Close to the radar, only low-level precipitation is sensed. Far away, because of the relatively broad beam, altitude resolution of precipitation is lost. The intensity map is, thus, not truly three-dimensional.

4. The major limitation of the conventional weather radar is that it provides only the reflectivity map, which is associated with the precipitation field around the radar. It does not provide any explicit data about the motion of air masses, which is of prime importance for aviation.

Current sensing of air motion is also largely in-situ and surface based. Anemometers are the primary sensors, used either singly or in arrays. A system specially intended for the monitoring of airport wind shear is the Low-Level Wind Shear Alert System (LLWSAS) [17]. A center-field anemometer (located close to the centroid of the runways in an airport) of propeller or vane type, along with five more similar outlying sensors, constitutes the array. The outlying sensors are positioned in the vicinity of the approach paths for individual runways. The anemometers are mounted on masts at heights between four and twenty meters above ground (depending on obstructions) and hence essentially sense surface-level air currents.

The data from anemometers are processed together by a central microcomputer. Velocity readings are sampled at intervals of ten seconds and the readings of each outer sensor is compared with the two-minute averaged data of the center sensor. An alert signal is provided when a speed difference equal to or more than fifteen knots is registered between an outlying anemometer and the central one.

The LLWSAS has generally been considered a useful system, but questions have remained regarding certain details of its design and operation. Some major limitations of the system have also been clear.

The primary drawback is that the sensing of wind speeds, and therefore wind shear, is done only at the ground level. Wind shear at altitude and along the flight paths of aircraft can be quite different both by nature and in severity. Close to the ground, the vertical component of wind speed is nearly zero. Phenomena such as microbursts and macrobursts can be detected only through the horizontal wind that they cause at the ground level. Thus, a mere thresholding of speed variations across the LLWSAS array is a poor indicator of the damage potential of different classes of shear-causing phenomena, especially at a different spatial location such along the actual flight paths.

Further, the LLWSAS will respond to all phenomena causing wind velocity variations within and in the area of the anemometer array. The nature of data processing in the system does not produce any useful information about the nature, location and severity (except in a threshold sense) of the causative phenomena. In such circumstances, the primary utility of the LLWSAS has been to provide a warning of a reasonable probability of wind shear related danger in an airport area, based on which either the airport or certain of its runways may decide to suspend operation.

Another limitations of the LLWSAS are lack of predictive capability. To be detected, a wind shear must already be in the area of the runways. Approaching aircraft may be unaware of its existence because of delays in its detection, interpretation and communication. In connection with the Pan Am Clipper 759 accident at New Orleans on 9 July 1982 (attributed to a microburst on the east side of the airport [12]), it has been concluded that the wind shear which affected the aircraft's takeoff was not detected by the LLWSAS until after the takeoff began [18].

In summary, the current instrumentation for weather monitoring lacks the spatial and temporal fineness and coverage required for a dynamic operation such as aviation. Also, aviation weather surveillance and dissemination is overwhelmingly human-based, requiring a large measure of subjective interpretation. With discrete measurement devices such as surface stations and anemometers, only a general picture of the weather pattern over a large area emerges and deduction of hazard potential at small localized regions such as individual airports requires human judgment. Even where more detailed pictures such as those from non-Doppler radars are available, inference regarding the presence of damaging phenomena such as tornadoes, microbursts, gust fronts etc. is only associative (i.e. these are suspected from certain characteristic shapes within the PPI reflectivity display). The same is also true of using the satellite pictures which do not directly sense the local phenomena of interest to aviation. Interpretation of satellite imagery such as cloud cover pictures requires a high level of human judgment and yields limited quantitative information.

A successful aviation weather monitoring system must evaluate hazard potentials of different phenomena in near-real time. To that end, hazard inducing parameters must be sensed quantitatively with adequate sensitivity, coverage, resolution and agility. Also, smart processing algorithms must be devised that can draw inferences as far as possible automatically in order to cut down delays associated with large-scale human intervention. A new breed of instruments and concepts are being developed which promise to possess such characteristics. The Doppler weather radar, notably the NEXRAD, augmented by devices to make multiparameter measurements, promises to be the lead instrument in enhancing the quality of aviation weather nowcasting, but there are other important developments along this direction. Some of these are discussed in the following paragraphs.

NEXRAD ROLE IN AVIATION SAFETY

As discussed already, the current weather radars, which are non-Doppler, do not provide any direct indication or estimation of the strength of atmospheric convective processes. Those instruments that provide a direct measure of wind speeds, such as anemometers and the LLWSAS array, lack coverage and resolution. The Doppler weather radar has been found to be a powerful instrument that overcomes both these types of shortcomings.

The principles, capabilities and operational aspects of Doppler weather radars are now well documented, e.g. [19,20]. Based on the experience gained from a number of research radars of this type, the NEXRAD system has been designed and a network of such radars will be operational in the U.S. in the near future. This chain is expected to play a key role in improving the quality of weather data for aviation, as envisaged in the National Airspace Plan of 1981.

NEXRAD: Original Aims

The NEXRAD was initially conceived as a tool for detecting severe storms; its specifications have been evolved [21] with this in mind. Its system aspects relevant to general weather observation as well as aviation-related weather monitoring have been discussed in some detail, e.g. in [22-25]. In summary, it is an S-band (2.7-3.0 GHz) radar with a beamwidth of the order of a degree and a peak power of the order of a megawatt. Reflectivities are measured upto 460 km and Doppler velocities and their spectral widths are measured upto 230 km. A striking technical feature of the radar is its high effective receiver dynamic range of 93 dB, which facilitates the quantitative detection severe as well as weak phenomena.

In addition to the measurement of reflectivitiy, which is a measure of the precipitation intensity in individual resolution cells, Doppler weather radars, including NEXRAD, provide two other important measurements. These are the mean radial (or Doppler) velocity of scatterers within the resolution volume, and the Doppler spectrum width, which indicates the differential motion of the scatterers (due to shear and turbulence) in the volume. These two parameters are direct indicators of convective motion in the atmosphere and hence are of immense importance to aviation.

In NEXRAD's role as an advanced nowcasting tool for severe weather, the simultaneous real-time display of reflectivities, mean radial speeds and spectrum widths will alert the operators and air traffic controllers regarding the presence, severity and spatial location (in 3-D) of dangerous rain/hail, winds and turbulence. This information will be used to issue traffic control and advisory instructions to pilots.

NEXRAD: Extended Functions

Since NEXRAD is configured as a multiservice sensor, certain optimization can be done to its locational and operational parameters to further enhance its role in aviation. Many such studies have been carried out, e.g. with reference to scanning strategies and data update rates [26], and siting aspects [27].

Through extensive research and refinement of techniques, it has now been realized that the fine quality of data generated by NEXRAD can be used for more sophisticated processing and complex inferences than mere detection of severe storms. Accordingly, the role of the system in aviation may be significantly more extended than originally envisaged.

A direct mapping of the three parameters (reflectivity, radial velocity and Doppler spectrum width) in PPI displays or in a memory array provides a detailed and quantitative 3-D picture of a large volume of space in terms of precipitative as well as convective phenomena. Because of the availability of such detailed multimoment data with a high dynamic range, it is possible to even recognize organized phenomena such as gust fronts, downdrafts, vortices, cyclones, etc which have characteristic signatures in one or more parameter fields. The most useful field in this connection is the mean radial velocity map. If sufficient intelligence is built into the radar data processor, such recognition process can even be automatic, and several research groups have evolved computer programs for this purpose, e.g [28-30]. The introduction of artificial intelligence concepts into this area will further enhance the power of such programs.

One area where such recognition capability would be very useful for air navigation is in detecting dangerous wind shear. The efficacy of the NEXRAD class of radars in detecting fine-scale but potentially hazardous phenomena such as tornadoes and microbursts is now established. Extensive work has been carried out at NOAA's National Severe Storms Laboratory on the detection of tornadoes by Doppler radars, and a series of experimental programs --NIMROD, JAWS and CLAWS -- in the Denver area have established the detectability of microbursts by such radars. Doppler radars may provide a few minutes of advance warning to aircraft regarding low level wind shears; even such very short term forecasting could be crucial to aircraft survival in the highly dynamic environment of terminal areas [25].

In addition to enhanced safety, the availability of real-time wind-shift information can also result in improved airline economy by letting air traffic controllers more effectively manage and plan for runway changes necessary as a consequence of the wind shifts after their passage through the airport area. An estimate by the Transportation Systems Center in Boston has indicated that such information in the control tower (at Stapleton airport) resulted in fuel savings of approximately $375,000 during the 45-day period of the CLAWS experiment [25].

Based on such immensely encouraging results recently obtained, proving the additional power of the NEXRAD class of radars, FAA has now established a national Terminal Doppler Weather Radar (TDWR) program which envisages the installation of Doppler radars at some one hundred major airports in the U.S. [25]

MULTIPARAMETER RADAR OBSERVATIONS

In addition to enhancing NEXRAD functions through more advanced radar data processing, it is possible to effect improvements by incorporating extra hardware features. NEXRAD can take some of these improvements on an optional or add-on basis without much modifications to the system. The most important improvement is the addition of polarization diversity capability.

The principle and advantages of polarization diversity in radar measurements have been well studied, e.g. [31]. The technique provides either for the variation of the polarization of one or both of the transmitted and received signals, or provides for dual-channel reception of orthogonally polarized waves. In the context of precipitation, the polarization characteristics of the received echo signals in different channels are related to the mean values and distributions of size, shape and spatial orientation of the particles in the radar resolution cell and to their phase state (i.e. solid, liquid or mixture).

The radar polarimetric techniques, which permit the measurement of additional target echo characteristics, have considerably enhanced the capacity of weather radars to observe microphysical processes in the atmosphere. However, from the point of view of aviation, the most significant information provided by polarization diversity radars relates to the identification and classification of hydrometeors, particularly hail [32-36] which is hazardous for aircraft. Dual polarization measurements also enhance the accuracy of estimation of rainfall rates [37].

Another multiparameter technique to enhance the observation capabilities of weather radars is the dual-frequency technique [38] in which radar observations are made at two different wavelengths, typically 10 and 3 cm. In relation to aviation, this technique can also be used to detect large hail in severe storms [39]. If a choice has to be made between dual-polarization or dual-frequency facilities, the former is considered simpler and yet more powerful than the latter for estimation of rainfall as well as for discriminating between rain and hail [23]. But the provision of both polarimetric as well as dual-frequency capability in addition to Doppler measurements results in a comprehensive multiparameter observation capability which would make a weather radar a really powerful tool in aviation weather monitoring. However, because of cost and complexity considerations, such extended multiparameter radars are not likely to be adopted in the near-future for dedicated aviation weather applications, except on an experimental basis.

OTHER INSTRUMENTATION

Because of a match between the requirements of aviation weather surveillance and the capabilities of modern weather radars, such radars will be the prime instruments in the aviation weather field in the foreseeable future. However, there will be room for other additional instrumentation in a supplementary role.

Since radar data are obtained in a radar-centered form, the accuracy and resolution of data are highest in a volume close to the radar; farther away, the quality of data degrades. Thus, to get the best performance for aviation applications, where operations in the terminal areas are the most critical, the radars must be located in the vicinity of airports. Obviously, only the relatively large and busy airports will justify the cost of a dedicated modern weather radar. At small and medium airports far from the larger ones, the radar data quality will be poor or, perhaps, nonexistant. There is thus need for simpler and less expensive devices for such airports. Further, even at large airports with Doppler radars, such simpler devices provide a degree of redundancy to allow minimal operation in the event of failure of the radar.

One relatively simple device for remotely sensing winds aloft is the Doppler wind profiler. Although it works on the same principle as a Doppler radar, it performs only one function using a small upward-looking antenna with limited scanning options. These features make the system inexpensive. The profiler measures the horizontal winds from ground upto several kilometers, and in this sense overcomes a major limitation of the LLWSAS. This device is likely to be used at more and more airports for sensing wind shear.

SUMMARY

Viewed against the background of the increasing realization of the importance of timely and high-quality weather information in the safety, economy and schedule-keeping of modern aviation operations, this paper has attempted to summarize the current experience and prospects for the near future. A series of recent developments both in understanding the characteristics of aviation-significant phenomena and in the evolution of a variety of modern powerful sensors and strategies hold the promise that the operational aspects of aviation weather monitoring will undergo a quantum jump in quality and efficacy in the years ahead.

A major shift in the attitude to aviation weather has been to move away from near-total dependence on general weather forecasts and toward accurate, agile and detailed nowcasting and short-period forecasting. As it has been realized that the major threat to aviation comes from localized, mobile and short-lived phenomena, emphasis has been laid on the development of instrumentation and information systems dedicated to aviation, and the generation and processing of data that match aviation operations in spatial and temporal scales.

The future plans of the National Weather Service are built around the NEXRAD, the Geostationary Operational Environmental Satellite (GOES) systems, the Automated Surface Observing Systems (ASOS), the Automated Weather Information Processing Systems (AWIPS) and profiling systems including the Doppler profilers. However, because of a match between the spatial and temporal scales of weather data required for aviation and those supplied by the modern weather radar systems, such radars (most notably the NEXRAD) have emerged as the primary sensors as far as aviation weather is concerned. The current strategy is therefore to build more measurement capabilities (such as multiparameter observation) into such radars, and also to incorporate increasing levels of intelligence in the radar data processors to reduce dependence on human intervention and its attendant delays. With primary aviation weather observational data coming in from high-performance radars, global data from general weather networks and additional local data from simple in-situ instruments and profilers will provide an integrated and comprehensive information system which holds the potential of greatly enhancing aviation safety in the coming years.

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