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**AERONAUTICAL METEOROLOGY**

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## **1. Introduction**

The effect of weather on aviation started being felt from the day on 17 December 1903 when the first successful flights of an engine-powered aircraft were terminated because a gust of wind overturned and damaged the aircraft. It was soon realized that meteorological information was vital to ensure flight safety. As commercial air transport capacity and aircraft technology improved, the frequency of flights increased. The cost of fuel and airport services increased dramatically over the years and this has been compounded by acute international air transport competition. A lot of efforts have also been directed over the recent years to improve the efficiency of flight operations and minimize flight delays due to adverse weather so as to keep the costs of flying at a reasonable level.

A number of significant advances in technology have been made in the recent years in the provision of aeronautical meteorological services. These include the implementation of the satellite based World Area Forecast System (WAFS), which provides en-route meteorological support to international air navigation, and development of sophisticated low-level windshear detection technologies, which provide timely warnings of hazardous windshear events and short-range forecasts of local meteorological conditions in the vicinity of the terminal area. The WAFS will be discussed in Section 2. New techniques in the detection and warning of hazardous low-level windshear, including the Low Level Windshear Alert System (LLWAS) and the Terminal Doppler Weather Radar (TDWR) will be given in Section 3.

## **2. The World Area Forecast System**

### **2.1 Overview**

The World Area Forecast System (WAFS) is a satellite-based broadcast system established by the International Civil Aviation Organization (ICAO) with assistance of the World Meteorological Organization (WMO) to provide meteorologists and airline operators with standardized and high quality forecasts of meteorological elements and phenomena for flight planning. The system could also be extended to include traffic of the WMO Global Telecommunication System (GTS) to satisfy non-aeronautical requirements.

The system is implemented by two World Area Forecast Centres (WAFCs) at Washington, D.C., U.S.A., and London, U.K., with satellite broadcast of products via the International Satellite Communication System (ISCS) and Satellite Distribution System for WAFS Products (SADIS) respectively. These two systems disseminate WAFS products to users in the following regions:

ISCS - Americas, the north Atlantic region, the south-west Pacific and eastern Asia

SADIS - Europe, Africa, the Middle East and Western Asia

Part of Asia (approximately from 105° E to 140° E) is served by both systems - ISCS coverage provided by the Intelsat 177° W satellite positioned over the Pacific Ocean and SADIS coverage provided by the Intelsat 60° E satellite positioned over the Indian Ocean.

## **2.2 System Characteristics**

The ISCS is managed by the U.S. National Weather Service (NWS) through a contract with MCI Telecommunications Incorporated for the space segment. MCI provides the satellite communications segment and satellite receiving terminals. In the Pacific Ocean Region, WAFS data is sent from WAFC Washington via redundant links at 56 kilobytes per second to the uplink facilities at Yaocolt, Washington. The data is then transmitted up to the Intelsat satellite and broadcast to authorized users within the satellite "footprint". The outbound data rate is 38.4 kilobytes per second and data is transmitted in an X.25 protocol format to the satellite. The communications protocol over the satellite is a Hughes Communications proprietary satellite protocol.

Reception of the satellite broadcast is based on the Very Small Aperture Terminal (VSAT) technology which is a cost-effective method to deliver data to a large number of users. At each user site, VSAT equipment with a 2.4 m diameter antenna, radio receiver, indoor controller, X.25 packet assembler / disassembler interface, and a user workstation are required to receive and process the satellite broadcast. The output from the VSAT equipment at the user site is the same X.25 protocol used at WAFC Washington. As proprietary protocols are used, the receiving equipment must be purchased from MCI and access to the broadcast is controlled.

The SADIS is managed by the U.K. Meteorological Office through a contract with Matra Marconi Space and Mercury Communications for the space segment. WAFS data is sent from WAFC London via the Meteorological Office message switch in Bracknell into redundant links at 64 kilobytes per second to the uplink facilities at Whitehill, north of Oxford. The data is then transmitted up to the Intelsat satellite and broadcast to authorized users within the satellite "footprint". Similar to the ISCS, the standard X.25 protocol is used in the data transmission and VSAT equipment is required for the reception of the broadcast at the user site. The VSAT equipment can be purchased directly from Matra Marconi Space with WAFC London acting as a contact point.

Authorization for access to each WAFS broadcast is given by the Meteorological Authority of each Contracting State which will notify ICAO and, for the purpose of efficiency, also the Provider State for the broadcast concerned (i.e. the U.S. NWS for ISCS and U.K. Civil Aviation Authority for SADIS). Where the satellite broadcast also includes a sub-system of the WMO GTS, the WMO Member State concerned determines the users authorized to receive basic synoptic data and analyses via the satellite broadcast and notifies ICAO through WMO.

Various software packages are commercially available to process, store and display the X.25 WAFS data stream output from the VSAT equipment on the user workstation. A Personal Computer MS-DOS based software called PC-GRIDDS (PC-Gridded Interactive Display and Diagnostic System) is also available free of charge from the U.S. NWS through WMO for real-time manipulation and display of the GRIB coded data.

### **2.3 WAFS Products**

Three types of WAFS products are disseminated by the WAFCs - Gridded Binary (GRIB) coded data, digital T4 coded facsimile charts and operational meteorological (OPMET) alphanumeric messages.

The GRIB coded data consist of global upper wind and temperature data generated by global numerical weather prediction models of the WAFCs based on the  $1.25^\circ \times 1.25^\circ$  latitude/longitude "thinned" horizontal grid at the standard flight levels: FL 050, 100, 180, 240, 300, 340, 390 and 450 (850, 700, 500, 400, 300, 250, 200 and 150 hPa). The data also include information on the tropopause (height and temperature) and maximum wind (speed, direction and height). The data can be transformed by software into interpolated upper winds and temperatures at a regular latitude/longitude output grid selected by the user. Each data set covers forecasts valid for 12, 18, 24 and 30 hours after the time of the synoptic data on which they are based and is broadcast once every 12 hours based on the 0000 and 1200 UTC synoptic data. In addition, this "required" data broadcast from either WAFc may be followed by a second broadcast of supplementary fields to satisfy a variety of other aviation forecasting needs. Apart from printing the required upper wind and temperature charts by the users, the GRIB coded data may also be used to initialize numerical weather prediction models and provide lateral boundary conditions for running limited area models.

The facsimile charts consist of flight documentation charts for the appropriate chart areas defined in the ICAO regional air navigation plans. The digital coded data are presented in T4 facsimile code and provide both the gridded upper-air wind and temperature forecasts at selected flight levels (FL 50, 100, 180, 240, 300, 340, 390 and 450 and for special flights FL 530 and 600) and significant weather (SIGWX) forecasts prepared by the WAFCs and, as an interim arrangement, by the Regional Area Forecast Centres (RAFCs). The upper-air wind and temperature charts are created from the  $1.25^\circ \times 1.25^\circ$  latitude/ longitude resolution GRIB data, but for clarity is presented on a lower resolution of  $2.5^\circ \times 5^\circ$  latitude/longitude grid. The SIGWX charts are provided over the same areas of coverage as those used for upper-air wind and

temperature forecasts. Some of the charts are produced from computer graphics products and others from hand-drawn products. The SIGWX forecasts are for layers between specified flight levels. The layers are FL 250 to 400 (high level), and FL 100 to 250 (medium level) for limited geographical areas as determined by regional air navigation agreement, and FL 450 to 600 for special high level flights if so determined by regional air navigation agreement. The facsimile charts are issued twice daily with validity times 0000, 0600, 1200 and 1800 UTC.

The OPMET alphanumeric messages comprise aerodrome forecasts (TAFs), routine aviation weather reports (METARs), special air reports from aircraft (Special AIREPs), and en-route hazardous weather warnings (SIGMETs) including volcanic ash and tropical cyclone advisory messages. Different from the OPMET messages exchanged on the Aeronautical Fixed Telecommunications Network (AFTN) which is a point-to-point network, each OPMET message broadcast by the WAFS is stripped of its AFTN message envelope. The WMO abbreviated heading is used to identify the information being broadcast.

The information broadcast on the WAFS is disseminated as soon as it becomes available at the uplink. Therefore the system is not operated with a strict timetable. However, there is a general schedule for the transmission of the various products to ensure that the information is received in a timely manner.

## **2.4 Role of National Meteorological Services**

With the full implementation of the WAFS, national meteorological services are expected to be relieved of some of their work associated with the provision of en-route meteorological support to international air navigation. Following full implementation of the WAFS, the main emphasis of national meteorological services in the future is expected to concentrate on improving local services to aviation. In particular, the traditional role of reporting and forecasting weather at aerodromes, undertaking area meteorological watch for warning of hazardous weather both en-route and in the vicinity of aerodromes as well as the provision of low level SIGWX charts (below FL 100) should be continued and strengthened by national meteorological services. The tasks of observers and forecasters are expected to be facilitated by the use of a new generation of observing systems and high resolution numerical prediction models which will particularly monitor and help provide advice on current and expected weather hazards at aerodromes and their vicinity. New technologies in the detection and warning of low-level windshear hazards at aerodromes and their vicinity will be discussed in the next section.

## **3. Windshear Detection Technologies**

### **3.1 Overview**

Windshear is the variation of wind speed or wind direction in space. When an aircraft encounters increasing head wind or decreasing tail wind, it will gain lift and tend to rise above the intended flight path. On the other hand, when an aircraft encounters decreasing head

wind or increasing tail wind, it will lose lift and tend to sink below the intended flight path. When windshear occurs at low altitude near the approach and departure zones, it may cause difficulties in the control of the aircraft leading to possible premature landing, overshooting of the runway or failed take-off if the pilot does not intervene appropriately.

Windshear occasionally occurs in association with convective storms and other weather phenomena. Significant low-level windshear often accompanies gust fronts originating from convective storms. A gust front is the leading edge of the cold air from a convective storm down draught which reaches the ground and spreads out in all directions, undercutting the surrounding warmer air. At the gust front, the wind converges. The most severe low-level windshear is associated with microbursts which also originate from convective storms. A microburst is characterized by a very narrow (typically less than 4 km) and intense down flow of cold air. The cold air when impacting on the ground spreads out and produces strongly divergent winds. An aircraft flying across the microburst will first encounter a strong head wind (hence increased lift), then a strong down draught at the core of the microburst, and then a strong tail wind (hence decreased lift). Unless the pilot intervenes appropriately, the aircraft will deviate significantly from the intended flight path. Apart from convective storms, hills also disrupt the flow of air across them. Airports located in hilly areas may also be affected on occasions by windshear caused by the adjacent hills.

During the past two decades, various operational systems have been developed to detect and measure low-level windshear. These include the anemometer-based Low Level Windshear Alert System (LLWAS) and the Terminal Doppler Weather Radar (TDWR) developed and being used operationally in the U.S.A. Other detection equipment, including wind profilers and Doppler lidars, have also been applied in this area and demonstrated good potential to be deployed for operational detection of low-level windshear or enhancement of existing systems in the future.

### **3.2 Low Level Windshear Alert System (LLWAS)**

The Low Level Windshear Alert System (LLWAS) was first developed in the mid-seventies in the U.S.A. for detection of frontal windshear. The algorithm of this original LLWAS was based on the idea that if a central sensor (centrefield) is taken as the reference, then the passage of a front can be detected by placing boundary sensors around the perimeter of the airport and looking for differences between any of the boundary sensor winds and the centrefield winds. The original LLWAS was designed to have six sensors, including the centrefield sensor. Each of the boundary sensors is placed 3 to 5 km from centrefield. The algorithm compares the 2-minute running average wind at centrefield and the 30-second average wind at each boundary sensor. If the magnitude of this vector difference exceeds 15 knots, then a windshear alert is declared. The alert message is a statement that there is windshear at the outlying sensor and a reading of the winds at that sensor and at the centrefield (e.g. Wind Shear Alert, NE sensor winds: 330 at 25, CF winds: 160 at 30).

Fifteen years of operation in a variety of meteorological environments in the U.S. has revealed that the LLWAS can be improved in many ways. The original LLWAS algorithm is appropriate for the detection of frontal shear, but it does not always work for subscale shears. In particular, since the sensors are so widely spaced, microbursts can fall between the sensors and remain unobserved. Furthermore, the original LLWAS only alerts the presence of windshear in the vicinity of the sensors without an accurate depiction of the windshear location relative to the runway and the associated intensity.

To ensure reliable detection of microbursts, enhancement of the original LLWAS was developed and extensively tested in the late eighties. With an increase in the density of wind sensors, the enhanced LLWAS is able to provide reliable microburst and windshear alerts with minimal false alerts. It also provides the wind speed loss/gain and location (relative to each affected runway) estimates for inclusion in the alert message.

The generation of windshear alerts is based on estimations of the divergence of the horizontal wind field. An alert is issued only when there is a persistent large divergence value; large positive values indicating a microburst and large negative values indicating a gust front. An alert is issued only if there is a measured head wind loss or gain along the runway in excess of 15 knots. Divergence estimates are computed by first order numerical differentiation.

Subscale meteorological variations in the wind field can cause the data to fluctuate with magnitude approximately proportional to the speed of the winds. The random fluctuations from several sensors can combine so that the measured winds appear to have a significant divergence or convergence even when the actual wind field is nearly divergence free. Digital filters are used to smooth the time series of data from each sensor, reducing the magnitude of the data errors. A check is made to determine that the divergence estimate from a triangle or edge is persistent before an alert is issued so as to minimize false alerts but at the same time ensuring that the alerts are issued in a timely manner in view of the short life cycle of windshear events.

Persistent divergence leads to one of the two alert messages: Microburst Alert (MBA) if the divergence is very strong, or Windshear Alert with Loss (WSA/L) if the divergence is a little weaker. The decision of which alert is to be issued is based on the magnitude of the head wind loss estimates. Two loss estimates are computed. The first is an estimate of the head wind loss through a symmetric microburst model based on the intensity of the divergence and the geometry of the edge or triangle on which the divergence estimate is computed. This estimation is valid only for microburst related windshear and is designed to be an unbiased estimate of the microburst intensity. If this estimate exceeds 30 knots, then a Microburst Alert is issued for each affected runway. The second is an estimate of the runway-oriented loss based on differences of the sensor wind components in the runway direction; for each runway, the runway oriented wind components are compared for all pairs of sensors which are near the runway and whose distance along the runway is between 1 and 5 km. If the microburst loss estimate is below 30 knots, then a Windshear Alert is issued for each affected runway where the runway-oriented loss exceeds 15 knots. The location of the shear is determined by the location of the persistent divergence along the runway corridor.

Persistent convergence, say associated with a gust front, leads to a Windshear Alert with Gain (WSA/G). Runway-oriented gain is estimated by sensor-to-sensor comparison similar to the computation of runway-oriented loss. A Windshear Alert is issued for each affected runway where the runway-oriented gain estimate exceeds 15 knots.

The enhanced LLWAS has been proven to be a cost effective system which provides timely and accurate detection of microburst and low-level windshear in the immediate vicinity of the airport. Although many of the original LLWAS sites will be decommissioned after deployment of the more sophisticated Terminal Doppler Weather Radar (TDWR), the remaining LLWAS's at 39 U.S. airports will be upgraded to incorporate the enhanced features. Nine U.S. airports which need maximum protection against microburst and low-level windshear hazards will be equipped with integrated TDWR/LLWAS systems.

### **3.3 Terminal Doppler Weather Radar (TDWR)**

Although the enhanced LLWAS can provide timely and accurate detection of microburst and low-level windshear in the immediate vicinity of the airport, its geographical coverage is limited by the extent of the ground-based wind sensors. Doppler weather radars, on the other hand, can produce detailed, three-dimensional depiction of the changing structure of convective storms from which microbursts are generated. After recognizing the microburst as a significant hazard, a series of field experiments sponsored by the U.S. Federal Aviation Administration (FAA) were carried out in the early and mid-eighties to determine the frequency, radar detectability and key characteristics of microbursts. Based on the results of these experiments, the Terminal Doppler Weather Radar (TDWR) was developed jointly by several research institutes, including the MIT/Lincoln Laboratory, National Severe Storms Laboratory and National Centre for Atmospheric Research, and the first system was commissioned in 1994. A total of 45 systems will be deployed by the U.S. FAA at major U.S. airports. The Hong Kong Observatory has also acquired and installed one enhanced system for the new airport at Chek Lap Kok in Hong Kong.

The mission of the TDWR is the detection and warning in real time of microbursts, other low-level windshear activity and gust fronts in and near the approach and departure zones, and provision of precipitation maps within the total area of coverage. Since the microburst and windshear warnings have to be presented as quickly as possible to air traffic controllers for alerting pilots of aircraft landing at or taking off from the airport, the data processing, weather detection and warning algorithms are fully automated, without the necessity for interpretation by meteorologically trained personnel.

The TDWR is designed to operate in a high clutter environment normally present in the vicinity of airports. It makes use of a highly stable klystron-based transmitter giving 55 dB of suppression for stationary targets, augmented by clutter residue editing maps using indexed beams, and point target removal algorithms. To minimize clutter, the C-band radar system has a beamwidth of 0.55 degree at the half power points, with excellent side lobe performance. To

attain a high system availability level, redundant transmitters, receiver/exciter and signal processing channels are implemented on the radar system.

After collection of the clutter filtered zeroth and first moment data from the pulse pair signal processor, the radar product generation processor converts these data into radar base data upon which a number of data conditioning functions are performed. These processing functions include the identification of clutter residue, point targets and range obscured sample volumes, signal-to-noise thresholding and velocity de-aliasing. After the base data have been conditioned to remove data contamination and radar ambiguities, they are processed by several weather detection and warning algorithms to generate alphanumeric, alarm and graphical products for the end users. Based on pattern recognition approach, these algorithms perform microburst detection, gust front detection and wind shift prediction, and provide concise information on precipitation distribution.

During times when prevailing weather conditions are conducive to an increased likelihood of windshear activity which may affect airport operations, system operations will be automatically switched from the normal monitor mode to the hazardous weather mode. In the hazardous weather mode, the radar spends more time to scan the approach and departure zones, and as a result features a reduced detection time for hazardous windshear near the airport. Microburst and windshear warnings are updated once every minute in this mode.

As soon as the processing of radar base data and application of weather detection and warning algorithms are completed, products, system status and alarms are automatically generated and distributed through redundant communication links from the TDWR station to the airport for distribution to various displays for attention of air traffic controllers. Alphanumeric messages that provide warnings of microburst and windshear activity over the approach and departure zones in a standardized format similar to that for the enhanced LLWAS are presented on the Alphanumeric Alarm Displays (AADs). The simple and concise message format allows direct relay of the warnings by air traffic controllers to pilots. A graphical summary of the various TDWR products, including the locations and strength of microburst and windshear events, gust front locations and forecast movement, wind shift predictions and precipitation map, is provided on the Graphical Situation Displays (GSDs). Through the forecast of gust front induced wind shifts at the airport and depiction of precipitation intensity, the GSD helps air traffic control supervisors to improve the management of air traffic in the terminal area. In addition, the weather and warning products will be routinely archived on cartridge tapes for use in accident investigations and for meteorological research. A Base Data Display (BDD) provides the capability of displaying radar base data, including reflectivity, velocity and spectrum width in real time. Apart from serving as a useful tool for TDWR maintenance and calibration purposes, it can also provide useful information for use by aviation forecasters.

The TDWR station is designed to be an unmanned installation. Provisions are therefore made for remote control and monitoring of the system through a maintenance data terminal. On this terminal, system status and performance parameters can be monitored and various commands including changing scan mode, reconfiguring equipment and changing site adaptation data may be executed. In addition, a number of station building services signals



including intrusion alarm, fire alarm, air-conditioner status and engine generator status can be remotely monitored.

The TDWR is designed to achieve a high probability of detection (POD) and low false alarm rate (FAR) for microburst related windshear. The performance goal is a POD of 90% and an FAR of 10%. A series of field experiments was carried out in the late-eighties in the U.S. over regions with different climatological characteristics to assess the performance of a prototype TDWR system. Results indicated that detection was very reliable for the strongest windshear events, with overall microburst detection probability meeting the performance goal. The false alarm rate was also well within the requirement.

To ensure that the TDWR algorithms perform well under different environments, it is essential to carry out initial system optimization by tuning various system parameters. Special emphasis should be put on clutter mitigation and, in the case of a coastal environment, minimizing the impact of marine vessels and sea clutter. This may require changes of the scan strategy, clutter filtering, clutter residue editing and polygon definition, and point target filter adaptation data. It is also important to continue to monitor the system performance under different meteorological conditions over a long period taking into account of possible seasonal variations.

### **3.4 Other Windshear Detection Equipment**

Continuous measurement of the three components of the wind up to the tropopause can be made using vertically pointing VHF/UHF Doppler radars which are commonly known as wind profilers. Of the two types, the UHF wind profiler is better suited for measuring winds in the boundary layer in near real-time and could provide profiles of wind in the vicinity of the aerodrome with a frequency of up to once per ten minutes. Profilers are the subject of considerable research interest as their potential to augment and possibly replace the existing upper air sounding network at a reduced recurrent cost, while at the same time producing more frequent and higher resolution wind profiles, could revolutionize mesoscale forecasting.

The Doppler method is primarily used for measuring wind velocities with VHF/UHF radars. This method uses two or more narrow beams pointing in different directions. By measuring the Doppler frequency of Bragg scatter echoes, the wind velocity vector can be determined. Complex autocovariance or spectral analysis, and further digital signal processing yields the radial velocities in different beam pointing directions. These line-of-sight velocities are then used to calculate the three orthogonal wind components.

Wind profilers would be particularly useful for detecting and monitoring non-transitory windshear such as that associated with low-level jet streams and disturbed atmospheric flow due to terrain effect. Sophisticated algorithms have also been developed recently to estimate wind parameters (e.g. wind vector, windshear and turbulence) at approximately one to two minute update rate. With such high data update rate, detection of terrain induced windshear with fast changing wind fields by wind profilers has become possible. However, data quality

control measures which are required to eliminate outliers, remove precipitation effects, mitigate clutter contamination and remove velocity folding have yet to be developed for reliable winds estimation.

Pulsed Doppler lidars also hold great promise for real-time detection of low-level windshear in clear-air conditions. LIDAR is an acronym formed in the same manner as radar standing for LIght Detection And Ranging. Fundamentally, lidars are similar to radars in that electromagnetic energy is transmitted into the atmosphere, where it scatters from atmospheric constituents and is collected at a receiver. Information on an abundance of atmospheric properties, including winds and turbulence, can be obtained. Doppler lidars operate analogously to Doppler radars in that winds can be measured from the Doppler shift of radiation backscattered from atmospheric particles, small aerosols in the lidar case.

These devices produce very accurate radial wind measurements in optically clear-air, without many of the artifacts associated with traditional microwave radars. The transverse pulse volume width is extremely narrow even at large distances (typically a few metres at ranges of 10-20 km), which helps to minimize contamination due to clutter. Sidelobe problems seen with wide beam microwave radars are essentially non-existent with lidars. The range resolution of Doppler lidars (ranges from 5 to 300 m) is generally quite adequate for the calculation of radial windshear on the scales of importance to aircraft. Field experiments have also been carried out in the U.S.A. to develop a measurement system of wake vortices using Continuous Wave Doppler lidars. However, reliable windshear detection algorithms have yet to be developed and it may still be several years away before a hardened and reliable lidar is commercially available for operational use.