

# Chapter II.2

## Understanding Aviation Meteorology and Weather Hazards with Ground-Based Observations

### Improving Aircraft Safety in Terminal Area

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#### 1 Introduction

Weather hazards have a significant negative impact on aircraft safety. Based on recent surveys, 20–30% of worldwide air accidents are due to adverse weather conditions. In Europe, as much as 22% of air traffic delays are due to bad weather. The problem is that the latest trends estimate that air traffic will increase by a factor of three within the next 20 years. If the accident rates stay the same, the number of accidents will be increasing significantly and this is considered unacceptable by airline and aircraft companies and government agencies. To mitigate these risks, several actions have been taken in the world.

In Europe, the FLYSAFE consortium is developing a mock-up of a system to uplink, in real-time, weather information in the cockpit and to the air traffic controllers (Pradier-Vabre et al., 2008). In FLYSAFE and in other projects, weather systems are being developed to identify weather hazards using weather data fusion. These systems are trying to combine weather data from different sources and instruments, such as ground-based and space-based observation platforms in combination with meteorological numerical models.

#### 2 Main Weather Hazards for Aviation

There are several weather hazards that are dangerous for aviation. Because of the different scales involved in weather phenomena, the hazards have not the same impact if the aircrafts encounter them En-Route (regional and global scales) or in the airport terminal area (local scale). Furthermore, some phenomena are only present

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either at local scale or at high altitude when the aircraft is En-Route. Consequently, the main weather hazards can be tentatively classified as follows:

1. Airports terminal area: local airport weather
  - Wake vortex
  - Thunderstorms: microbursts, hail, wind shear
  - Icing (waiting aircraft stacks)
  - Low ceilings and visibility
2. En-Route: regional and global scales weather
  - Thunderstorms (hail, turbulence)
  - Clear air turbulence (CAT)
  - Icing (regional flights at lower altitudes)

To assess, identify, and predict these weather hazards, observations are needed from different instruments and sources.

### **3 The Needs of Ground-Based Remote Sensing Observations to Support Aviation Activities**

Now, let us focus on the local airport terminal area weather hazards. In this section, we will review weather data that are available for this scale.

The main sources of weather observations at the airport are from the standard meteorological observation system. These provide data appropriate for synoptic scale weather systems, e.g., at the scale of standard high and low pressure weather systems:

1. METAR which gives surface data (temperature, altimeter setting, humidity, winds), cloud types and bases, as well as significant weather such as precipitation, thunderstorms
  - Data taken at 30-min-to-1-h interval.
2. Radiosoundings, which gives a vertical profile of temperature, humidity, and winds
  - Data taken at 12-h interval.

The limitation of these instruments is mainly that the data frequency is quite low and that they are point data. Other types of observation systems have greater data frequencies, such as space-based satellites, which are remote sensing observation systems.

These space-based satellites can be categorized into two main families, respectively, geostationary and polar-orbiting. The geostationary satellites have the following main characteristics and limitations:

- Orbit at 35,000 km altitude
- Limited spatial resolution: 1–6 km
- Typical temporal resolution is 15 min
- Information is limited in the vertical

The polar-orbiting satellites have the following ones:

- Orbit at 700–800 km altitude
- Very high spatial resolution: 250 to 5,000 m
- Limited temporal resolution: 2 passes per day
- Information is also limited in the vertical

One of the main advantages of most of these remote sensing instruments is that their measurements are quasi-continuous. The space-based instruments have the advantage of covering a large part of the Earth, at the expense of either low spatial resolution or temporal resolution.

For local scale weather needs at the airport terminal scale, specific ground-based instruments can be more appropriate. Some are sensor based, such as meteorological towers, which have instruments at different heights and taking measurements at very high temporal resolution, e.g., at each second. However, these instruments also have the following problem: they give only point data and their vertical resolution is quite limited. Other instruments, which are rather based on remote sensing technology, are:

- 1D and 3D weather radars (several band frequencies)
- Vertical wind profilers (several band frequencies)
- Radio acoustic sounding system (RASS)
- Lidar
- Sodar
- Radiometer
- Ceilometer

## **4 Applications of Ground-Based Remote Sensing Instruments to Aviation**

In the previous section, several weather observing instruments that can be used to mitigate weather hazards were briefly introduced. One conclusion that can be set is that the standard meteorological observation system is not always suitable because of limited time and spatial scales, as well as limited 3D coverage. On the other hand, ground-based remote sensing systems are helpful to provide additional weather

information. However, remote sensing data are often difficult to use directly: data post-processing and/or data fusion is needed. In the next sections, practical applications on how remote sensing-based instruments can be used to mitigate aircraft delays and accidents are described.

#### ***4.1 San Francisco Marine Stratus Initiative: Burn-off Forecasts***

In the United States, low ceilings and visibility are responsible for 35% of all weather-related accidents in the US civil aviation sector. They are also a major cause of flight delays. To mitigate these problems, a project to develop an integrated automated system was initiated by the MIT/LL. The first US airport test site that has been chosen was San Francisco: this became the San Francisco Marine Stratus Initiative (Wilson, 2004). The objective of the project was to develop accurate forecasts of the time that Marine Stratus will clear in the approach to San Francisco Airport (SFO). The integrated system that has been developed was for direct use by forecasters. The display integrated all the weather data available in the airport area along with a consensus forecast of the burn-off time using several numerical meteorological models:

- Statistical model
- 1D column model
- Boundary layer model

The instruments available were high temporal resolution surface data, sodar and ceilometer, infrared satellite data, and radiometers. An array of ground-based instruments were deployed in the San Francisco Bay Area, especially at SFO and San Carlos (Fig. II.2.1).

The sodar provides the boundary layer inversion height using acoustic backscatter. It uses the fact that at the top of stratus clouds, there is a sharp temperature inversion that gives high backscatter energy picked up by the sodar (Fig. II.2.2).

The ceilometer provides the cloud bases of stratus clouds using the reflectivity of very small water droplets.

The data of these two instruments can thus be used in combination with surface and radiosounding data along with a 1D column numerical model to provide burn-off stratus forecasts. The observation data are used to build a vertical profile of temperature and humidity to initialize properly the column model (Fig. II.2.3).

In summary, a fully integrated system approach has been used in this project: it shows the potential of direct and indirect uses of ground-based remote sensing data. The system combined the use of sodar and ceilometer data along with numerical modeling and an array of ground-based observations. The important aspect was also that an integrated display was designed for use directly by forecasters and air traffic controllers.

The technology of this system has been transferred in 2004 to the US National Weather Service (NWS) and it is now running operationally: a great success!

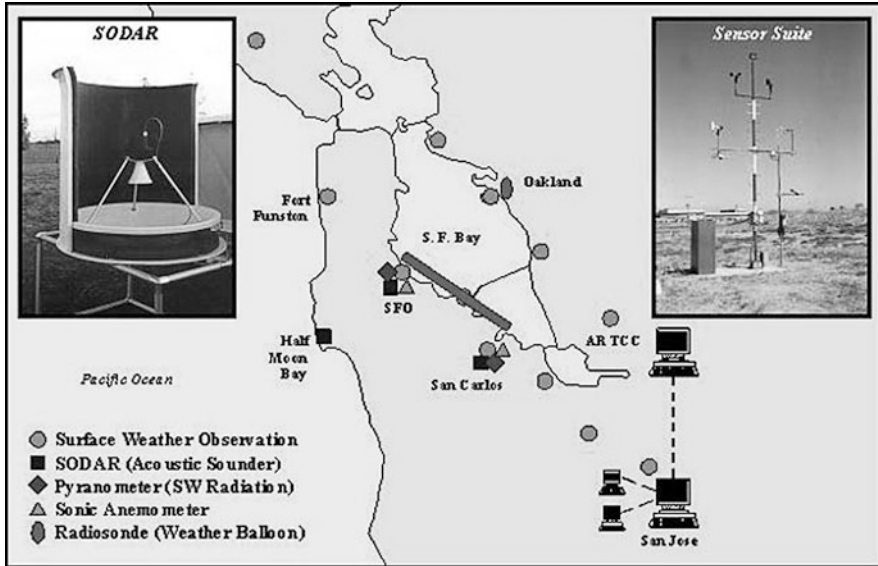


Fig. II.2.1 Array of ground-based instruments in the San Francisco Bay Area for the San Francisco marine stratus initiative

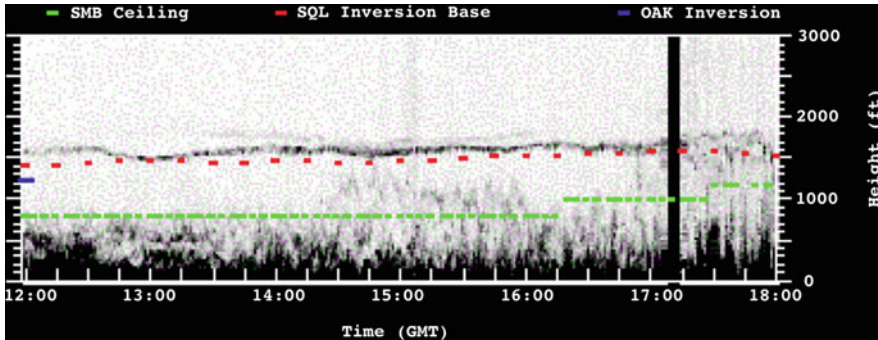


Fig. II.2.2 Sodar estimation of the boundary layer inversion height using acoustic backscatter

### 4.2 Terminal Ceiling and Visibility in the Northeastern United States

The success of the SFO Marine Stratus Initiative has led to a project follow-up: the Terminal Ceiling and Visibility Product Development Team in the NorthEastern (NE) United States (Clark, 2006). The main problem of this project is that Instruments-Flight-Rules conditions are quite frequent in the NE US during winter (November through April). These conditions are generally the consequence of transient synoptic scale situations, combined with high traffic. The physical phenomena responsible for these conditions are quite various.

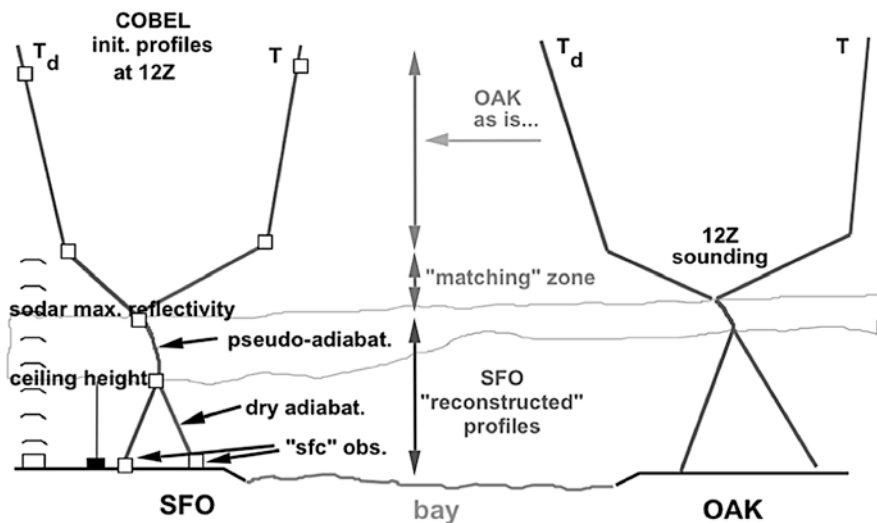


Fig. II.2.3 Reconstruction of a vertical profile of temperature and humidity using information from a numerical column model and observations (figure courtesy of Robert Tardif)

The project objective was to identify independent forecast technologies that are able to give some skill to forecast these IFR conditions, in a terminal-centric approach in high impacted terminals. The project focused on tactical scale forecasts (0–3 h), which involve tracking and trending techniques, using high-resolution observations.

Some techniques were developed to use 3D ground-based radar to detect low visibilities. This technique involved correlating reflectivity and surface-based observations, along with cell tracking (Fig. II.2.4). The calibration of such a technique

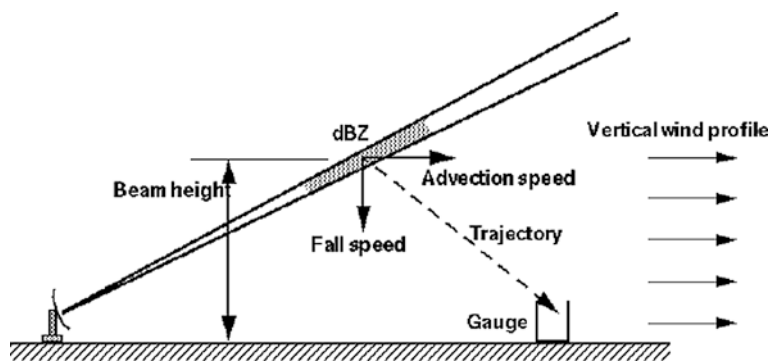


Fig. II.2.4 Particle trajectory for wind profile with no wind shear (Dixon et al., 2005). Technique used to detect low visibilities

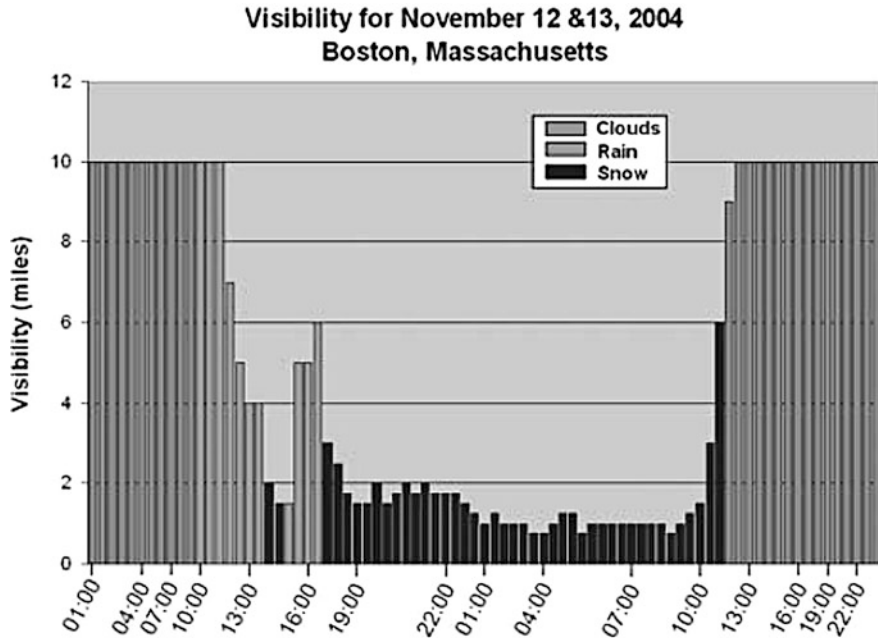


Fig. II.2.5 Variation in observed surface visibilities during transition from rain to snow during winter event at Boston Logan International Airport (Clark, 2006)

(radar-visibility relationship) showed to be quite tricky, because visibilities are quite dependent on precipitation type (snow/rain) (Fig. II.2.5). The results showed that forecasting low visibilities is a non-trivial task, and data fusion techniques must be used to improve the accuracy of the methodologies, such as using wind profiler, sodar, and lidar information combined with 3D ground-based radar data.

### 4.3 Aircraft In-Flight Icing

Another meteorological condition that can be quite hazardous for aircraft is in-flight icing, especially for regional flights. It causes reduced lift, raise stall speed, imbalance, and increased fuel consumption. In the United States, there were almost 600 accidents in the last 20 years related to in-flight icing. This phenomenon is caused by supercooled water droplets. The main problems are that it cannot be measured by remote sensing and that it is very difficult to predict (fast transient phenomena).

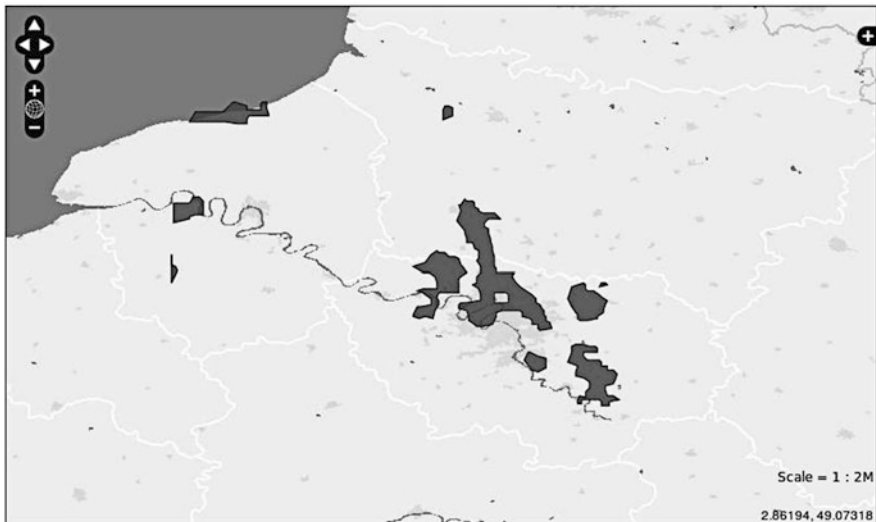
One of the techniques that can be used to infer in-flight icing regions is to identify the melting layer (0°C altitude) along with temperature and humidity. However, in some conditions, there is no melting layer while there is some icing, such as in deep convection and supercooled rain.

Another information that can be used to identify icing regions (and determine its intensity) is precipitation occurrence, which causes aerosol scavenging and an increase in supercooled water potential. In fact, when there are fewer aerosols, especially the ones that act as ice nuclei, the water vapor is forced to condense as water and cannot freeze because there are not enough ice nuclei. It has been shown that precipitation scavenging dominates the aerosol removal process: it is as high as 80%.

Other promising methodologies to diagnose in-flight icing involve a data fusion process. The idea is to combine the information from different data sources according to their potential to detect icing-related features. Such a system was developed at Météo-France, called SIGMA (Le Bot, 2004). Its first version used data from numerical models (temperature, humidity), satellite infrared temperature, along with ground-based weather radar reflectivity (precipitation occurrence). This type of diagnostic system can be run in near-real time, providing diagnostics of aircraft icing potential (Fig. II.2.6).

This type of system can also be extended to provide forecasts using one of the following techniques:

- Extrapolating radar and satellite data (experimental) and perform data fusion with temperature and humidity fields from numerical model forecasts.
- Use a numerical model approach only, without using any remote sensing data, such as in the CIP algorithm from NCAR (Bernstein et al., 2005).



**Fig. II.2.6** Severe icing risk diagnosed using data fusion techniques. Figure is showing severe icing risk objects around Charles-de-Gaulle Paris Terminal approach (figure courtesy of Sébastien Geindre, Météo-France)



### 4.4 3D Wind Field Nowcasting

The 3D wind structure is very important to aviation safety and performance. This is why a good knowledge of the current and future wind field is crucial for aircraft activities. In the terminal airport area, the wind can threaten aircrafts when there is low-level wind shear and turbulence, wave vortex, or convective cells.

In the terminal airport area, there are several ground-based remote sensing instruments that can be used to measure the wind structure. One of these instruments is the ground-based weather radar. This can be achieved using either a network of Doppler radars (at least three) or a bistatic network. A bistatic network was built in Montreal, Canada, using the McGill Weather Doppler Radar (Protat and Zawadzki, 1999). There were two bistatic receivers installed at proper locations to provide good coverage over the Dorval Airport (Fig. II.2.7).

The three radial wind measurements can then be combined using a variational data assimilation approach to compute a 3D wind field. This methodology has also been extended to perform thermodynamic retrievals of pressure and temperature perturbations.

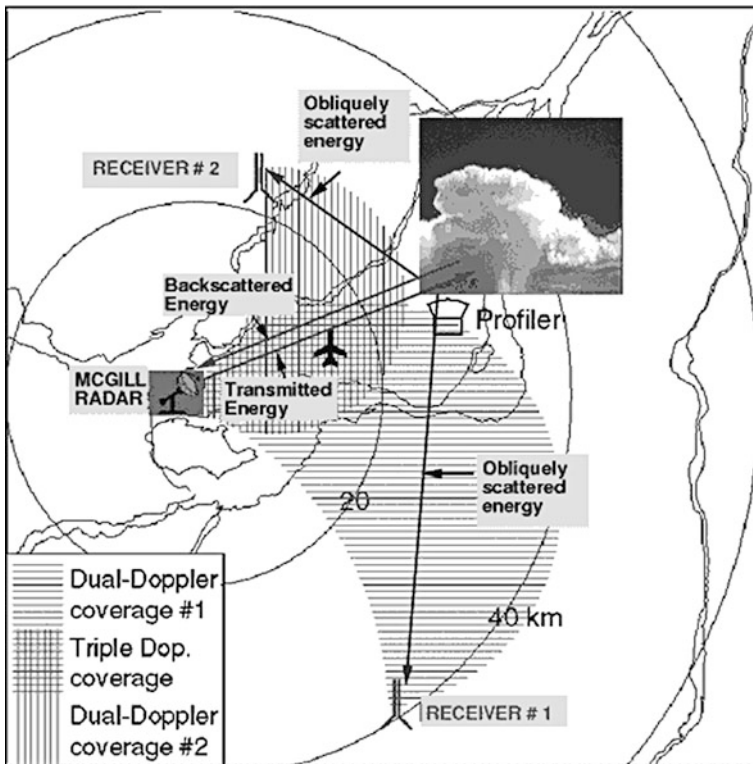


Fig. II.2.7 Schematic of the bistatic radar network at McGill Radar in Montreal, Canada (figure from McGill Radar Observatory website <http://www.radar.mcgill.ca/science/ex-instrument/ex-bistatic.html>)

**Fig. II.2.8** Instruments deployed during the wake vortex project in Memphis, 1994 (Dasey et al., 1997)

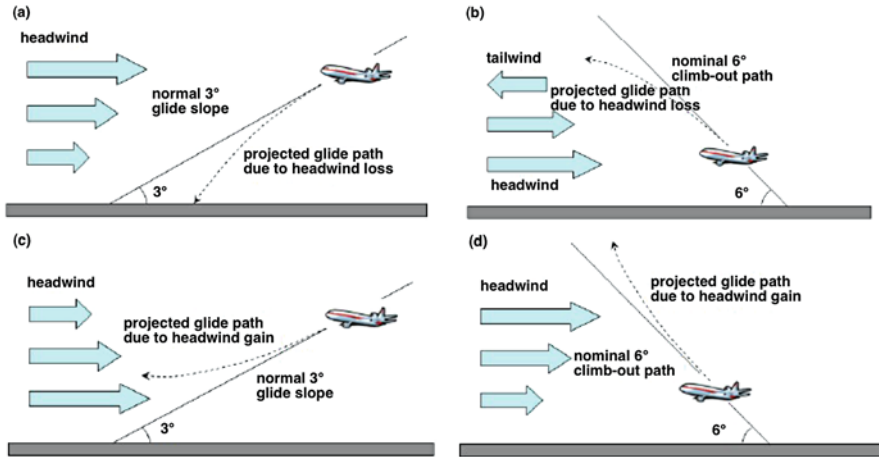


Smaller scale weather phenomena, like wake vortex, can be very dangerous for aircraft and can cause accidents. They limit airport capacity because these vortices take time to dissipate or be advected away from the runway, thus imposing a minimum aircraft separation. However, these vortices are sensible to atmospheric conditions such as crosswinds and atmosphere stability, which can cause them to take a longer or a shorter time to dissipate. So, in theory, it would be possible for aircrafts to have a shorter separation between them to increase airport capacity if we can measure or calculate the time it takes for the wake vortex to dissipate or be advected away.

One of the methodologies used is to install a ground-based remote sensing LIDAR network around the airport, such as in the WAKENET Europe project (Paris CDG, Frankfurt, London Heathrow) (Gerz et al., 2005) or Memphis in 1994 (Dasey et al., 1997) (see Fig. II.2.8) or Dallas in 2000 (Dasey et al., 1998). Lidar, along with other instruments, can be used to measure horizontal winds that can be used to determine a wake avoidance strategy to reduce aircraft spacing.

#### ***4.5 Low-Level Wind Shear and Turbulence***

Important problems can arise from another type of 3D wind level structures, such as turbulence and low-level wind shear. Turbulence can cause many problems to crew and passengers, while low-level wind shear can cause crashes as it



**Fig. II.2.9** Vertical wind shear: problems for aircraft (figure courtesy of Hong-Kong Weather Service)

produces trajectory differences compared to calculated trajectory. Low-level wind shear can be caused, among others, by lee-side mountain peaks, updrafts near coasts (sea breeze), thunderstorm gust fronts and microbursts, and low-level jet streams (Fig. II.2.9).

To mitigate the risks caused by these phenomena, a system based on ground-based weather radar has been designed: the terminal Doppler weather radar (TDWR). It can detect wind shear and also microbursts. This system is designed specially for terminal area in a high-clutter environment and it includes sophisticated clean-up algorithms to eliminate clutter and small moving targets such as insects, birds, and other aircrafts. The wavelength used is 5 cm. For the vertical wind profile, sodar, lidar, and vertical wind profiler can also be used. The TDWR has a major problem though it cannot be used when there is no precipitation. Thus, to complement the TDWR, a system using one or several lidars has been successfully operated using a wavelength of 2 μm. The lidar operates better in rain-free (or fine rain) conditions. An integrated system was developed by the Hong-Kong Weather Service for windshear and turbulence alerts over various runway corridors at Hong-Kong International Airports (HKIA) (Tsui et al., 2000).

### 4.6 Thunderstorm Avoidance

One of the main weather hazards are thunderstorms. These storms are often accompanied by almost all of the aircraft weather hazards, such as severe icing and turbulence, hail, low ceiling and visibility, microburst and downburst, wind shear, strong surface winds, heavy rain, and lightning. Identification and spotting of

these storms almost always involve the use of ground weather radars. Many algorithms have been developed to detect hail, heavy rain (reflectivity), and outflow (Doppler radial winds and reflectivity). Nowcasting thunderstorm movements are also very important: several cell-tracking algorithms have been developed using ground weather radar data, which are usually based on reflectivity thresholds and time cross-correlation. More sophisticated cell-tracking techniques have also been developed, such as the MAPLE McGill Radar system (Turner et. al., 2004).

## 5 Conclusion

Weather hazards have a significant negative impact on aircraft safety. The use of ground-based remote sensing instruments can help to mitigate these hazards by observing the weather phenomena associated with these hazards. By using data fusion from several instruments or algorithms, it is possible to better identify and nowcast them to improve airport terminal area security. Several important application projects have been pursued in the last decade to tackle with these problems, and the use of ground-based remote sensing instruments was almost always included. Among many projects, the San Francisco Marine Stratus Initiative, the Terminal Ceiling and Visibility project, and the FLYSAFE project were briefly discussed. These extensive projects showed that it is possible to develop algorithm that post-process and merge data from different sources, especially from quasi-continuous data sources such as remote sensing instruments. By combining data from different instruments, one can capitalize on strengths of each of these instruments to overcome their individual defaults. Results have shown that ground-based remote sensing instruments are useful to improve security in airports terminal area.

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