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LIDAR Windshear Alerting System

at the Hong Kong International Airport –

An Application of Information and Communication Technologies

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LIDAR WINDSHEAR ALERTING SYSTEM AT THE HONG KONG INTERNATIONAL AIRPORT - AN APPLICATION OF INFORMATION AND COMMUNICATION TECHNOLOGIES

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Abstract

Windshear could be hazardous to the landing/departing aircraft. At the Hong Kong International Airport (HKIA), the majority of windshear occurs in clear-air, non-rainy situation, in which the conventional microwave radar may not perform well. In order to detect windshear in this kind of weather condition, Doppler LIDAR (Light Detection And Ranging) systems have been introduced to HKIA since 2002. This is the first time that LIDAR technology is used in aviation weather alerting in an operational environment. Moreover, a sophisticated algorithm has been developed by the Hong Kong Observatory (HKO) to automatically detect windshear based on the LIDAR measurements. The LIDAR windshear alerts are also uplinked to the aircraft through satellite communication. These two developments are the first in the world. This paper discusses the application of information and communication technologies, viz. the LIDAR, the windshear algorithm and the satellite uplinking of windshear alerts to the aircraft, in the assurance of aviation safety.

Keywords

windshear, LIDAR, LIDAR Windshear Alerting System (LIWAS), uplinking

1. Introduction

Windshear refers to a sustained change in the wind direction and/or speed, resulting in a change in the headwind or tailwind encountered by an aircraft. The change normally lasts more than a few seconds as experienced by the aircraft. With a decrease of headwind/increase of tailwind, there may be a decrease in lift, which may cause the aircraft to go below the intended flight path. Conversely, an increased lift may cause the aircraft to fly above the intended flight path. Significant windshear at low levels on approach and departure zones may cause difficulty in control, thus requiring timely and appropriate corrective actions of the pilots to ensure aircraft safety. An introduction of windshear and its characteristics at HKIA could be found in HKO, IFALPA and GAPAN (2010).

Based on pilot reports, the majority of windshear at HKIA (about 90%) occurs in clear-air, non-rainy

weather condition, in which the conventional microwave radar may not work well due to the lack of rain droplets in reflecting the microwave. In order to observe the wind in the airport area in this kind of weather condition, HKO introduced Doppler LIDAR to HKIA, the first application of LIDAR for aviation weather alerting in an operational environment. The LIDAR provides an overview of the wind distribution around the airport for reference by the aviation weather forecasters.

The next step would be automatic alerting of windshear based on LIDAR data. In this regard, a new scan strategy of the LIDAR, namely, the glide-path scan, has been invented to focus on the wind variation along the flight path of the aircraft. A sophisticated, scientific algorithm has also been developed to detect windshear automatically based on the data collected by the glide-path scan. Moreover, runway-specific LIDAR has been deployed so that one LIDAR is dedicated to serve a particular runway in order to maximize the data collection frequency. Apart from voice communication to the pilots, the LIDAR windshear alerts are also uplinked automatically through satellite communication. All these developments of the LIDAR Windshear Alerting System (LIWAS) are the first in the world.

This paper uses LIWAS as an example to illustrate the application of information and communication technologies in the assurance of aviation safety. This paper is organized as follows. Section 2 provides some background information about windshear at HKIA. Section 3 describes the LIDAR used for windshear alerting in Hong Kong. The glide-path scan, LIWAS and windshear alerting uplinking are presented in Section 4. An example of the application of LIWAS in capturing windshear is shown in Section 5. Future developments of windshear and turbulence alerting service are described in Section 6. Conclusions of this paper are drawn in Section 7.

2. Windshear at HKIA

Low-level windshear could be hazardous to the landing/departing aircraft at the airport. It refers to sustained wind change occurring below 1600 feet or within 3 nautical miles from the runway end. In aviation meteorology, significant windshear is a

headwind change of 15 knots or more occurring over a distance between around 400 m and several kilometres. The latter (the maximum spatial scale of significant windshear) is taken as 4 km in the case of microburst. At HKIA, about 1 in 500 aircraft reports the encountering of significant windshear.

The majority of the pilot windshear reports at HKIA (about 70%) are related to terrain-disrupted airflow disturbances. The airport in Hong Kong is situated in an area of complex terrain (Figure 1). To its south is the mountainous Lantau Island with peaks rising to about 1000 m above mean sea level with valleys as low as 400 m in between. It is surrounded by seas on the other three sides. When winds from the east through southwest climb over the terrain of Lantau Island, airflow disruptions may appear at the glide paths of HKIA (Figure 2). This situation occurs in the east to southeasterly flow in the spring in stable boundary layer, strong southwest monsoon in the summer, and high winds crossing the mountains in association with tropical cyclones.

The next common type of low-level windshear at HKIA (about 20%) is sea breeze (Figure 3). It occurs in the winter to spring when westerly sea breeze sets in over the airport against the prevailing easterly wind. When the aircraft lands at HKIA from the west, it may experience sudden increase of headwind as it flies through the sea breeze front. Under the southwest monsoonal weather in the summer, sea breeze may appear as easterly wind over the seas to the east of the airport. The remaining windshear events (about 10% of the pilot reports) occur in convective weather such as gust front and microburst, and low-level jets in winter time.

3. LIDAR

In order to detect low-level windshear, a suite of meteorological instruments (Figure 1) has been operated by HKO inside and around the airport. Since the opening of HKIA at mid-1998, a dense network of surface anemometers has been set up. It has undergone continuous expansion in the last 10 years or so, and now includes ground-based anemometers at the peaks and valleys of Lantau Island as well as weather buoys over the waters around the airport. A Terminal Doppler Weather Radar (TDWR) has also been operated for detecting gust fronts and microbursts using sophisticated algorithms. A number of radar wind profilers have been working near the flight paths to the east and west of the airport as well as on an island upstream of Lantau Island (for east to southeasterly flow) to monitor the vertical wind profiles within the boundary layer of the atmosphere. Furthermore, a microwave radiometer is recently introduced to HKIA to measure the low-level temperature and humidity changes in association with

cross-mountain airflow. Among all the meteorological instruments working at HKIA, Doppler LIDAR systems make the most direct measurements of the winds to be encountered by the landing/departing aircraft because they scan right along the glide paths.

Since the majority of low-level windshear at HKIA (terrain-disrupted airflow and sea breeze) occurs in non rainy condition, Doppler LIDAR (Figure 4) is very suitable for the detection of such wind changes at the airport. The first LIDAR at HKIA was installed in mid-2002 at the rooftop of Air Traffic Control Complex (ATCX) near the centre of the airport in order to have a good view over all the arrival runway corridors. It is still working at the airport and, to the knowledge of the author, this is the Doppler LIDAR with the longest record of continuous operation for aviation weather alerting purpose.

One special aspect of the operation of a LIDAR at the airport is the laser safety concern. Through theoretical calculations, the LIDAR at HKIA is confirmed to be eye-safe when it is scanning. When the laser beam is stationary, it may affect the aided eyes, e.g. as seen through binoculars. As such, a number of laser safety measures have been implemented, such as sector blanking and safety interlock. Since the operation of the LIDAR system at HKIA in 2002, there is no report of health issue related to the laser beam.

The LIDAR technology is well suited for detecting terrain-induced windshear at HKIA as it possesses the following characteristics:

- (a) Measurement capability – the presence of abundant aerosols in the airport area and the drying up of the air after climbing over the mountains provide a suitable environmental condition for wind measurements by the LIDAR;
- (b) Scanning flexibility – compared to a conventional microwave radar, the LIDAR has a smaller scanner (which is functionally equivalent to the antenna of the weather radar) which allows more flexibility in designing the scan strategy. This enables more precise depiction of the complicated, three-dimensional flow structure in terrain-induced disturbances, particularly along the glide paths;
- (c) High spatial resolution – with a range resolution of about 100 m, the LIDAR is able to resolve windshear, which has an internationally recognized length scale between 400 m and 4 km;
- (d) Ease of deployment – the LIDAR system is a compact instrument which can be housed in a rectangular fibre-glass equipment shelter with a length of 2-3 m on each side. It is therefore much easier to deploy a LIDAR system in the airport environment compared with a radar with ~8 m

radius antenna dish. Moreover, unlike the weather radar, it is not an active source of electromagnetic radiation in the frequency range for air navigation signals, and thus interference with other systems at the airport is of lesser concern.

With no prior application of LIDAR in windshear alerting in an operational environment, the HKO developed an algorithm for automatic alerting of windshear. The single LIDAR already demonstrated the usefulness of monitoring low-level windshear and providing timely alerts to the pilots. However, when it was required to measure the winds over the eight runway corridors of HKIA, the data update frequency at a particular corridor may not be fast enough at times to capture the terrain-induced airflow disturbances, which are highly transient and sporadic in nature. As such, it was planned to set up runway-specific LIDAR. The north runway LIDAR of HKIA was installed in late 2006. In the spring of the following year, the LIDAR originally deployed at the rooftop of ATCX was moved to the south runway. The dual LIDAR operation mode, the so-called dual LIWAS has been in use since then.

4. Glide-path scan and LIWAS

With high spatial resolution (100 m) and fast data updates (~1-2 minutes), the LIDAR is able to reveal many salient features of terrain-induced airflow disturbances. In many cases observed by the LIDAR, and also confirmed by aircraft data, such disturbances are generally small-sized, with horizontal length-scale of several hundred metres or less. Such a case occurred on 30 August 2004 (Figure 5). On that day, an area of low pressure over southwestern part of China brought strong southerly winds to Hong Kong. As shown from the 1-degree elevation conical scans of the LIDAR, there were areas of reverse flow to the west of HKIA as embedded in the background southerly wind, generated from disruption of the southerly airflow by the hills on Lantau Island.

Advected by the strong background wind, these airflow disturbances only affect a particular runway corridor intermittently due to their small size and high advection speed across the corridor. For example, an airflow disturbance with horizontal size of 600 m advected by a wind of 15 m/s would only intersect the flight path in 40 seconds. Furthermore, as shown in Figure 5, the life cycle of these small-scale terrain-induced disturbances – emergence from the terrain, advection across the runway corridors, and dissipation could be typically a few minutes. For an aircraft on approach (with typical speed of 75 m/s) traversing these small-scale features, the change in headwind would only last 10 seconds or less.

Due to the above characteristics of terrain-induced airflow disturbances, the windshear experienced by aircraft is transient and sporadic. It is common for an aircraft to encounter significant windshear but with the preceding and the following aircraft reporting no windshear or events of different impact (e.g. headwind loss versus headwind gain). A successful windshear warning service provided by the LIDAR would therefore require the following:

- (a) general overview of the winds in the airport area, whereby the weather forecaster could monitor the presence of windshear and issue/cancel the windshear warning for Air Traffic Control (ATC) and pilots. This is achieved through the conventional conical and vertical scans of the LIDAR; and
- (b) zoom-in of the wind fluctuations along the individual glide paths, whereby automatic windshear alerts could be issued on a minute-to-minute basis for relay to aircraft. This is achieved by a new kind of scan strategy devised by HKO to measure the winds along the glide paths – the glide-path scan.

With the deployment of the runway-specific LIDARs, the laser beam from each LIDAR system is well aligned with the orientation of the respective runway. The radial wind velocity measured by the LIDAR along the glide paths could be used to represent the headwind to be encountered by the aircraft. Significant changes of the headwind profile measured by the LIDAR are detected automatically by LIWAS for the issuance of low-level windshear alerts to pilots via the ATC.

In order to measure the winds along the glide paths, HKO invents the glide-path scan, a special scanning strategy of the LIDAR. This kind of scan involves the orchestrated motion of the elevation and azimuthal motors of the LIDAR scanner to collect the wind data along the glide paths, which are slanted straight lines in the sky. A schematic diagram of the glide-path scan is given in Figure 6. The glide-path scan is different from the convectional scans of LIDAR and weather radar, which only involve either elevation motion (vertical scan) or azimuthal motion (surveillance/conical scan). The glide-path for an arrival runway corridor is taken to be a straight line with 3-degree elevation from the horizon starting at the end of the respective runway, whereas the one for a departure runway corridor is taken to be a line with 6-degree elevation starting from the middle of the runway. If the angle between the laser beam and the runway orientation is greater than 30 degrees, the radial velocity measured by the LIDAR is not regarded as having good representation of the headwind to be encountered by the aircraft and it would not be included in the construction of the headwind profile.

With the deployment of the runway-specific LIDAR, the revisit time of the laser beam over a particular runway corridor is in the order of 1 to 2 minutes.

A significant wind change in the headwind profile is called a windshear ramp. In general, a headwind profile contains more than one windshear ramp. The detected ramps are prioritized according to the severity factor S :

$$S = \left(\frac{dV}{dt}\right) \left(\frac{\Delta V}{V_{app}}\right)^2 = \left(\frac{\Delta V}{H^{1/3}}\right)^3 / V_{app}. \quad (1)$$

The primary parameter turned out to be the normalized windshear value $\Delta V/H^{1/3}$ (WOODFIELD and WOODS, 1983).

LIWAS generates a windshear alert automatically when a windshear ramp with ΔV exceeding the alert threshold is detected. The LIWAS alert is ingested into the Windshear and Turbulence Warning System (WTWS) operated by HKO to provide windshear alerts to ATC for relay via voice communications to the pilots. WTWS also integrates alerts from the other windshear detection systems/algorithms, including alerts from the Terminal Doppler Weather Radar (TDWR) and alerts generated by an anemometer-based windshear algorithm developed by HKO. The integration is carried out based on an alert prioritization scheme which considers the significance of the event and credibility of the respective system issuing the alert. After the integration, one single windshear alert will be generated for each runway corridor.

To further enhance flight safety and to complement the voice communication, windshear alerts from LIWAS are uplinked to the cockpit in the standard ARINC 623 "Terminal Weather Information for Pilots (TWIP)" format on a semi-operational trial basis to the aircraft of Northwest Airlines (NWA). To minimize the number of messages uplinked and pilot's workload in receiving frequent updates, alerts from TDWR and LIWAS are first consolidated based on a priority scheme. This is to ensure that the TWIP message represents the most severe hazard impacting the airport at the time. Categorization of the resulting windshear alert into three levels (viz. SIG WINDSHEAR for windshear with magnitude ≥ 15 knots but less than 30 knots, SEV WINDSHEAR for windshear with magnitude ≥ 30 knots and MICROBURST, in increasing order of priority) and coasting of the final message (i.e. the TWIP message will be kept for a period of 10 minutes unless the latest one has a higher priority than the message issued, and in which case, the latest TWIP message will be issued immediately) are introduced. The pilots of NWA find that the uplinked windshear alerts are useful for the operation of the aircraft.

5. Example of application

In general, LIWAS captures about 75 – 80% of the pilot windshear reports. An example showing the performance of LIWAS is discussed here. This case occurs in the early morning of 5 March 2009 and is typical for terrain-induced airflow disturbances at HKIA. From the LIDAR's velocity imagery (Figure 7), east to southeasterly airflow prevails in the airport area. However, there are blobs of reverse flow, each having a size of several hundred metres, appearing to the west of the airport, probably arising from the disruption of cross-mountain airflow by Lantau terrain. An aircraft landing at the south runway of HKIA from the west had to conduct missed approach due to significant windshear. The headwind measured onboard of the aircraft is shown in Figure 8, and significant changes of the headwind could be seen. Such wind changes are also successfully captured by the LIDAR data (Figure 9). In fact, multiple windshear ramps with both headwind gains and losses have been detected by the LIDAR, and timely windshear alerts have been issued and relayed to the pilot.

6. Future developments

Works are going on at HKO to develop turbulence detection algorithm based on the LIDAR data. It has been shown that calculation of eddy dissipation rate (EDR) from LIDAR's radial velocity data could capture the mechanical turbulence at HKIA in association with cross-mountain airflow (Chan, 2009). However, such EDR computation, based on the so-called "structure function approach", requires quite a lot of computing resources in order to implement the algorithm in real time. An alternative is to use the spectrum width data from the LIDAR. To this end, it has been planned to upgrade the signal processors of the LIDAR systems at HKIA in order to obtain high quality spectrum width data for EDR computation.

Apart from turbulence associated with mountains, the effect of buildings at the airport on the low-level winds is also of great concern at HKIA. A preliminary field study was carried out in the summer of 2009 to use a short-range, high resolution LIDAR (with a spatial resolution of 30 m) for detecting wind fluctuations associated with a building along a glide path of HKIA (Chan, 2010). This kind of LIDAR provides radial velocity map, 2D wind field as well as EDR distribution. Further study would be conducted to find out how to use this LIDAR to issue low-level wind alerts.

The windshear algorithms developed so far at HKIA are mainly based on pilot reports, which are prone to subjective perception of the wind changes by the pilots.

An objective windshear/turbulence database is being built up by processing Quick Access Recorder (QAR) data of the transport category commercial jets using a sophisticated aerodynamic model of the aircraft (Haverdings and Chan, 2009). The meteorological measuring system of a fixed-wing aircraft of the Government Flying Service in Hong Kong has also been upgraded to conduct windshear and turbulence research flights.

7. Conclusions

The first operational LIDAR-based windshear alerting system has been developed in Hong Kong to provide real-time alerts for all the arriving and departing aircraft at HKIA. It is based on a specially-devised scanning strategy of the LIDAR, namely, the glide-path scan to measure the headwind profile to be encountered by the aircraft. Significant wind changes in the headwind profile are detected automatically for issuing windshear alerts to the pilots. The algorithm captures about 80% of the pilot windshear reports.

Apart from windshear and turbulence, meteorological studies in other areas have also carried out by HKO in order to enhance the provision of aviation weather services. For instance, works are on-going about the nowcasting of lightning and short-term forecasting of thunderstorms at the Pearl River Delta area because intense convective weather could have significant impact on the operation of the aircraft. Collaborative studies with other meteorological institutes around the world are also being conducted to improve the provision of weather forecasts for the terminal area.

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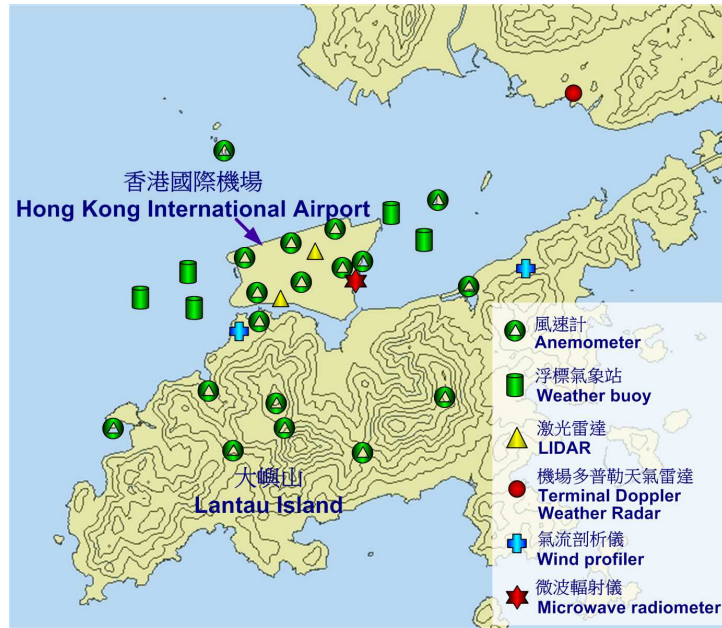


Figure 1 Meteorological instruments installed inside and around HKIA for the monitoring of low-level windshear.

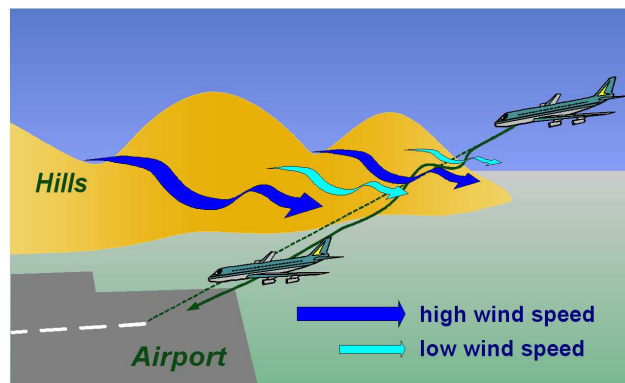


Figure 2 Schematic diagram of terrain-induced windshear.

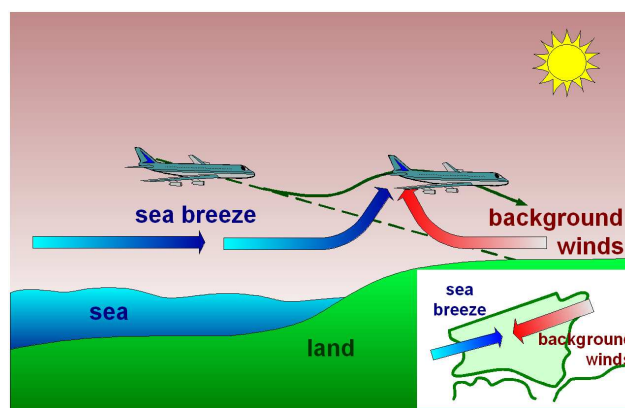


Figure 3 Schematic diagram of windshear arising from sea breeze.



Figure 4 The south runway LIDAR operating at HKIA.

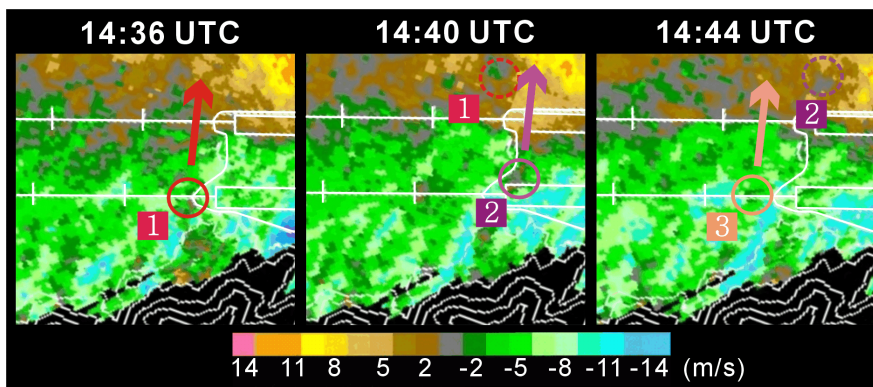


Figure 5 1-degree conical scans of the LIDAR on 30 August 2004. The cool/warm colours represent winds towards/away from the LIDAR (see scale at the bottom). The arrows indicate the movement of the windshear features marked by circles within the subsequent 4 minutes.

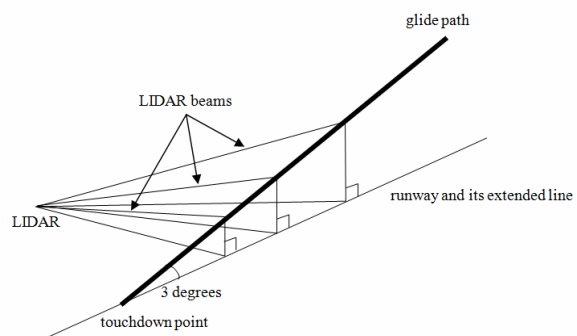
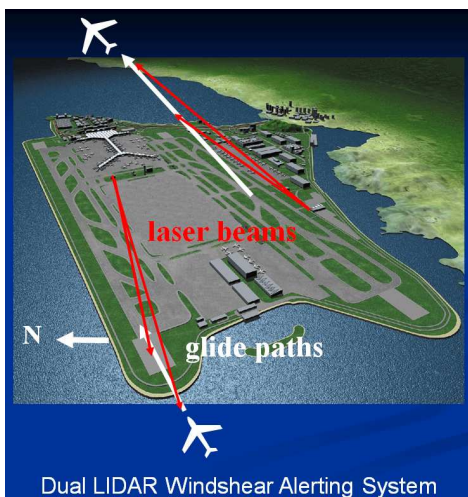


Figure 6 Schematic diagrams of glide-path scans of the two LIDARs.

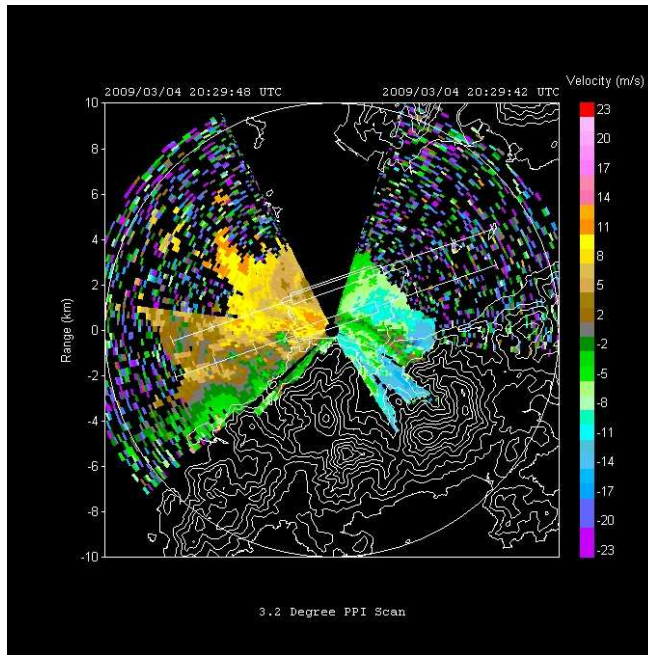


Figure 7 3.2-degree velocity imagery from the south runway LIDAR in the morning of 5 March 2009. Blobs of reverse flow (coloured in green) could be seen to the west of HKIA.

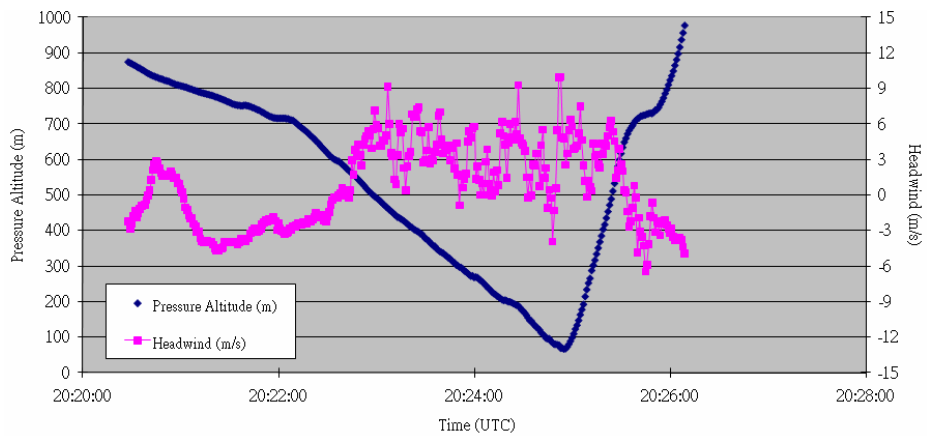


Figure 8 Headwind and pressure altitude measured at an aircraft which conducted missed approach due to significant windshear in the morning of 5 March 2009.

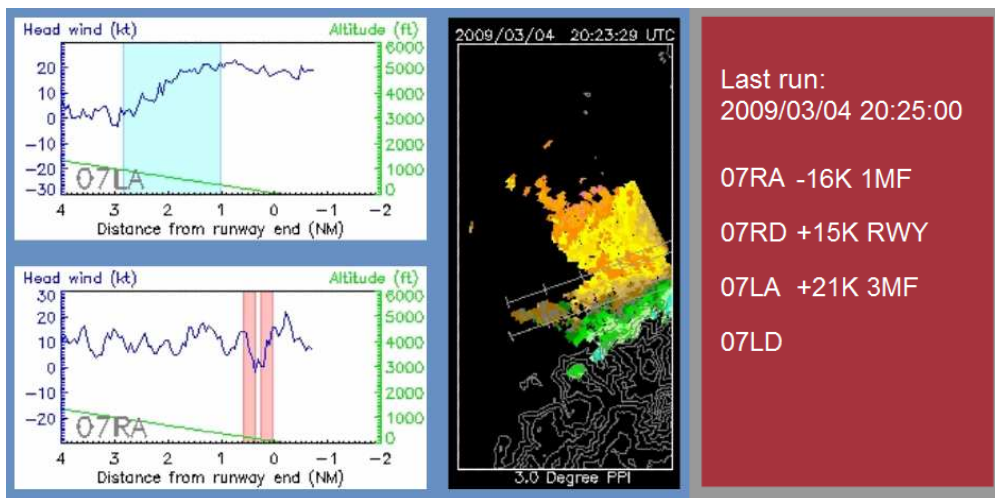


Figure 9 Headwind profile measured by the south runway LIDAR over the runway corridor 07RA (arrival at the south runway of HKIA from the west), with the significant windshear ramps highlighted in red.