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Application of brightness temperature data from a ground-based microwave radiometer to issue low-level windshear alert over Hong Kong International Airport

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सार – हांग कांग अंतर्राष्ट्रीय हवाई अड्डे पर निचले स्तर के पवन अपरूपण की सूचना देने में माइक्रोवेव रेडियोमीटर के उपयोग की चर्चा चॉन और ली (2011) के शोध पत्र में की गई है। इस शोध पत्र में हांग कांग में प्रयोग किए जा रहे माइक्रोवेव रेडियोमीटर के सभी 14 चैनलों को ध्यान में रख कर पूर्ववर्ती कार्य को आगे बढ़ाया गया है और समय श्रृंखलाओं के स्व सहबंध नामक प्रसरण के अलावा रेडियोमीटर के तापमान की चमक में उतार चढ़ाव के अन्य प्रॉक्सी का पता लगाने का प्रयास किया गया है। ऐसा पाया गया है कि इस क्षेत्र में 57 से 58 गीगा हट्र्ज की आवृत्तियों वाले ऑक्सीजन चैनल्स निचले स्तर के पवन अपरूपण को ग्रहण करने में सबसे अच्छा परिणाम देते हैं संभवतः इसलिए कि उनके प्रभाव क्षेत्र पवन अपरूपण रिपोर्टों (500 मी. अथवा 1600 फीट के नीचे) की ऊँचाईयों के निकट होते हैं और पवन अपरूपण से अभिप्रेरित भू–भाग से लगे होने के कारण तापमान में उतार चढ़ाव आता है जो निचले स्तर के पवन अपरूपण का मुख्य कारण वसंत ऋतु में (इस शोध पत्र के जाँच की अवधि) होती है। लाइट डिटैक्शन एण्ड रेजिंग (LIDAR) प्रणाली अथवा पवन अपरूपण एवं विक्षोभ चेतावनी प्रणाली (WTWS) के साथ रेडियोमीटर आधारित पवन अपरूपण चेतावनियों को मिलाकर वसंत ऋतु के समय सबसे अधिक उपयोग में लाए जाने वाले डिपार्चर रनवे कॉरीडोर में 95% के निकट पायलट पवन अपरूपण रिपोर्ट का हिट रेट प्राप्त करना और 20% से कम की चेतावनी की अवधि प्राप्त करना संभव है जो हांग कांग एअरपोर्ट की संपूर्ण पवन अपरूपण चेतावनी सेवा के तुल्य है। दो विचारधाराओं जैसेः (*i*) प्रसरण और (*ii*) तापमानों की चमक का स्व सहबंध गुणांक में से रेडियोमीटर के तापमान की चमक की प्रसरण उच्च हिट रेट के साथ थोड़ा बेहतर परिणाम देता है।

ABSTRACT. The use of the microwave radiometer in the alerting of low-level windshear at the Hong Kong International Airport has been discussed in Chan and Lee (2011). This paper extends the previous work by considering all the 14 channels of the microwave radiometer in use in Hong Kong and trying out other proxies of the fluctuations of the brightness temperature of the radiometer apart from variance, namely, auto-correlation of the time series. It turns out that the oxygen channels with frequencies in the region of 57 to 58 GHz perform the best in the capturing of the low-level windshear, probably because their effective ranges are close to the heights of the windshear reports (below 500 m, or 1600 feet) and there are temperature fluctuations associated with terrain-induced windshear, the main cause of low-level windshear in the spring time (the period under investigation in this study). By combining the radiometer-based windshear alerts with those from the Light Detection And Ranging (LIDAR) systems or the Windshear and Turbulence Warning System (WTWS), it is possible to achieve a hit rate of pilot windshear reports close to 95% and an alert duration less than 20% over the most used departure runway corridor in the spring time, which are comparable with the overall windshear alerting service at the Hong Kong airport. Among the two approaches, *viz*., (i) variance and (ii) auto correlation coefficient of the brightness temperatures, the variance of brightness temperature of the radiometer performs slightly better with a higher hit rate.

Key words – Low level wind shear (LLWS), Brightness temperature, Microwave radiometer, Hong Kong.

1. Introduction

Ground-based, multiple-channel microwave radiometers provide continuous measurements of the tropospheric temperature and humidity profiles. They have been used in a wide variety of applications, such as monitoring of intense convective weather, cloud observations, nowcasting of gust, etc. Some of the applications have been described in Chan (2009), Chan & Lee (2011) and Chan & Hon (2011). In the nowcasting of intense convective weather, instability indices of the atmosphere are calculated based on the temperature and humidity profiles as provided by the radiometer. The temporal evolution of the radiometer-based instability indices is then compared with the development of lightning strokes within a certain distance from the radiometer to see the correlation between the two. In particular, in Chan and Lee (2011), some preliminary results are presented in the use of the raw brightness temperature data from a radiometer in the monitoring of low-level windshear at the Hong Kong International Airport (HKIA). They are based on one frequency channel of the radiometer only to see if there is any correlation between the fluctuation of the brightness temperature and the occurrence of windshear at the airport.

Low-level windshear refers to sudden changes of the wind speed and/or wind direction along the glide path of the aircraft, within 3 nautical miles from the runway end. Such windshear could change the lift of the aircraft significantly and is thus hazardous to the operation of the aircraft. Traditionally, windshear is monitored by wind measurements, such as ground-based anemometer data or line-of-sight velocity provided by remote-sensing instruments like Doppler Light Detection And Ranging (LIDAR) system and Terminal Doppler Weather Radar (TDWR). However, there are some limitations with such wind data. For the ground-based anemometers, wind measurements are available near the ground only, and they may not be representative of the wind situation along the glide path of the aircraft. Remote-sensing instruments could be used to measure the winds along the flight path, but the data availability may be limited by the atmospheric condition. For example, in case of LIDAR, wind data may not be available when the laser beam is attenuated rapidly in low cloud base. For TDWR, when the atmosphere is relatively dry, there may not be sufficient water droplets and/or humidity discontinuity in the air to give good quality radar returns.

An alternative approach is to use fluctuations of the temperature as an indication of the airflow disturbances. In fact, at HKIA, the majority of low-level windshear (about 70% of the pilot windshear reports) is related to the disruption of the prevailing airflow by the complex terrain, including the mountainous Lantau Island to the south of the airport. Radiometer may have limitation in the sampling volume in the zenith mode because it measures the temperature data in the air column aloft the instrument only. But the effective range of a measurement channel could cover a height range of several hundred metres (Table 1), and thus the radiometer may give an indication of the degree of airflow disruption within the atmospheric boundary layer by measuring the associated variation of the atmospheric temperature.

In Chan and Lee (2011), the potential application of a microwave radiometer in monitoring low-level windshear is studied by considering a particular oxygen channel only. The present paper looks at this application

TABLE 1

Weighting functions for the oxygen line complex channels (derived from Rose and Czekala, 2008)

Channel frequency (GHz)	Height at which the normalized difference weighting functions attains maximum (m)
58.0	400
57.3	450
56.66	500
54.94	900
53.86	1400
52.28	2100
51.26	2300

in more detail. In particular, the following issues would be addressed:

(*i*) All the channels of a microwave radiometer would be considered in order to determine the best-performing channel in capturing the pilot windshear reports;

(*ii*) Apart from standard deviation of the brightness temperature at two consecutive moments, other proxies of wind fluctuations based on the temperature fluctuations would be tried out in order to optimize the performance of applying brightness temperatures in the capturing of low-level windshear.

2. A review of windshear alerting service

The overall windshear alerting service at HKIA consists of two parts, namely, machine-generated windshear alerts and subjective windshear warnings issued by the aviation weather forecasters. For the former, the alerts are issued by the Windshear and Turbulence Warning System (WTWS), in which the LIDAR-based windshear alerts form a major part. The LIDAR-based windshear alerting system is also called GLYGA (glide-path scan windshear alert generation algorithm). They are briefly described below.

2.1. *GLYGA*

GLYGA makes use of the glide-path scans in constructing the headwind profiles to be encountered by the aircraft. Glide-path scan is a special scanning strategy in which both the azimuthal and the elevation motors of the LIDAR's scanner move at the same time so that the laser beam slides along the glide paths of all the runway corridors of HKIA. The wind data so collected along the glide path itself are used to construct the headwind profile. GLYGA then makes use of a special algorithm to automatically detect abrupt changes of the headwind, based on which windshear alerts are generated. Technical

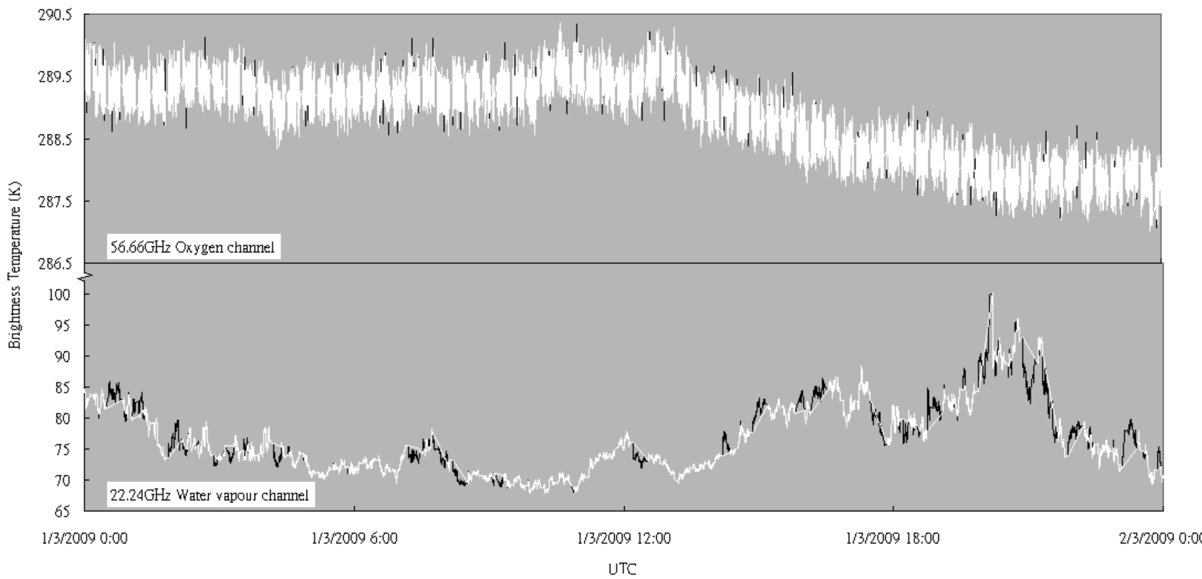


Fig. 1. Sample time series of the brightness temperature from an oxygen channel (upper) and a water vapour channel (lower). The raw brightness temperatures are shown in black, and the quality-controlled values are shown in white. The effective height of the oxygen channel considered here is several hundred metres (in the order of 400 m) above ground

details of GLYGA could be found in Shun and Chan (2008).

2.2. *WTWS*

WTWS integrates windshear alerts from a number of windshear alerting algorithms to produce the final, single alert for each of the 8 runway corridors of HKIA. Runway-specific alerts are generated, namely, the arrival and the departure corridors of the same runway can have different alerts. The windshear algorithms under consideration include GLYGA, anemometer-based algorithms, as well as windshear alerts from the TDWR. An alert prioritization scheme has been agreed and regularly reviewed with the aviation stakeholders for implementation of WTWS. It is described in HKO, IFALPA and GAPAN (2010). WTWS provides windshear alert every 10 seconds.

2.3. *Subjective warning*

Apart from the machine-generated windshear alerts (provided by WTWS), the windshear alerting service also requires human issuance of windshear warnings. The aviation weather forecaster would inspect the available meteorological information, such as the vertical temperature profile, winds measured by the network of ground-based anemometers near HKIA, as well as conical scans of LIDAR systems and the TDWR to assess the chance of occurrence of windshear. The warnings are supposed to cover relatively long term windshear occurrence, instead of the second by second fluctuations of windshear occurrence (which are covered by WTWS). As such, they are normally issued for at least half an hour. However, because of the transient and sporadic nature of terrain-induced windshear and/or no report from the Pilots on active wind shear or otherwise presumably due to oversight or pre-occupations, there may be null windshear reports at times when windshear warnings are in force. As a result, windshear warnings may result in higher false alarm rate of windshear alerting service occasionally. The best approach to the service is the full automation of the alerting service, *i.e.*, all the windshear information to be generated by machines, without the need of human-issued warnings.

3. Instrument

A ground-based microwave radiometer (model: RPG HATPRO from Radiometer Physics) was permanently introduced to Hong Kong in February 2008. It consists of 14 channels, namely, 7 oxygen channels (with frequencies 51.26, 52.28, 53.86, 54.94, 56.66, 57.30 and 58.00 GHz) and 7 water vapour channels (with frequencies 22.24, 23.04, 23.84, 25.44, 26.24, 27.84 and 31.40 GHz). In the present configuration, it mostly scans in "zenith mode", with brightness temperatures obtained in each second or so. In the "zenith mode", the elevation angle is 79.8 degrees with respect to the horizon instead of 90 degrees in order to avoid solar interference effect in the summer. The "zenith mode" gives all the quantities, namely, temperature profile, humidity profile, integrated water vapour (IWV), liquid water path (LWP) and cloud-base height (in combination with the data from an infrared radiometer).

4. Quality control of brightness temperature data

Before the brightness temperature data could be used for the various applications, they have to be processed through quality control algorithms. It is because these raw measurements are subject to various sources of noise, such as the noise of the instrument due to occasional interference by the equipment in the region (*e.g.*, radars and radio links at the airport) and temporary water accumulation on the radome in rain, and the brightness temperatures are obtained with rather weak signals from the radiations of the oxygen and water vapour in the atmosphere, particularly for those frequencies with effective heights higher up in the troposphere.

The quality control procedure aims at removing "spikes" in the time series of the brightness temperature. For this purpose, the brightness temperature at a particular time is compared with those in the previous two time instances (brightness temperatures are normally available every 2-3 seconds) and used only if the difference from the previous two time instances is less than a threshold. After tuning, this threshold is found to be about 0.6 degrees K.

The time series of brightness temperature for a sample oxygen channel and a sample water vapour channel are shown in Fig. 1, before and after the quality control. The channel under consideration is 56.66 GHz, with an effective height of several hundred metres above ground. It could be seen that in general there are more rapid fluctuations in the water vapour channel. The quality control threshold may need to be fine-turned in future studies for such channels.

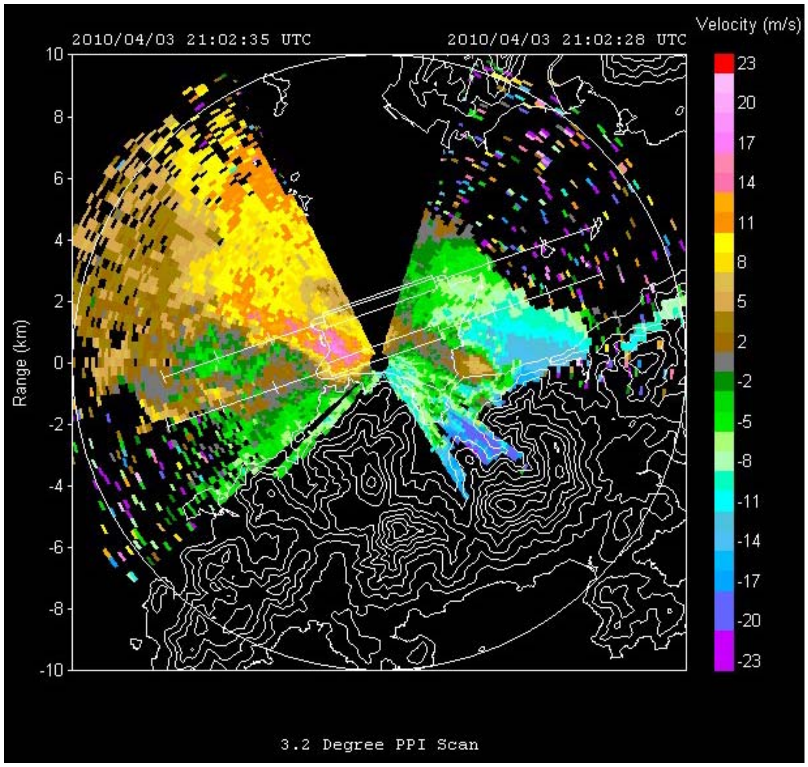
5. Use of variance of brightness temperature in capturing low level windshear

With the quality-controlled brightness temperature data, the variance of the brightness temperature is calculated with the aim of capturing low level windshear. It is postulated that when rapid wind fluctuations occur in terrain-induced windshear condition at HKIA, there may be simultaneous variations in the temperature and humidity of the troposphere so that the low-level windshear reports from the pilots may be compared with the variance of the brightness temperature.

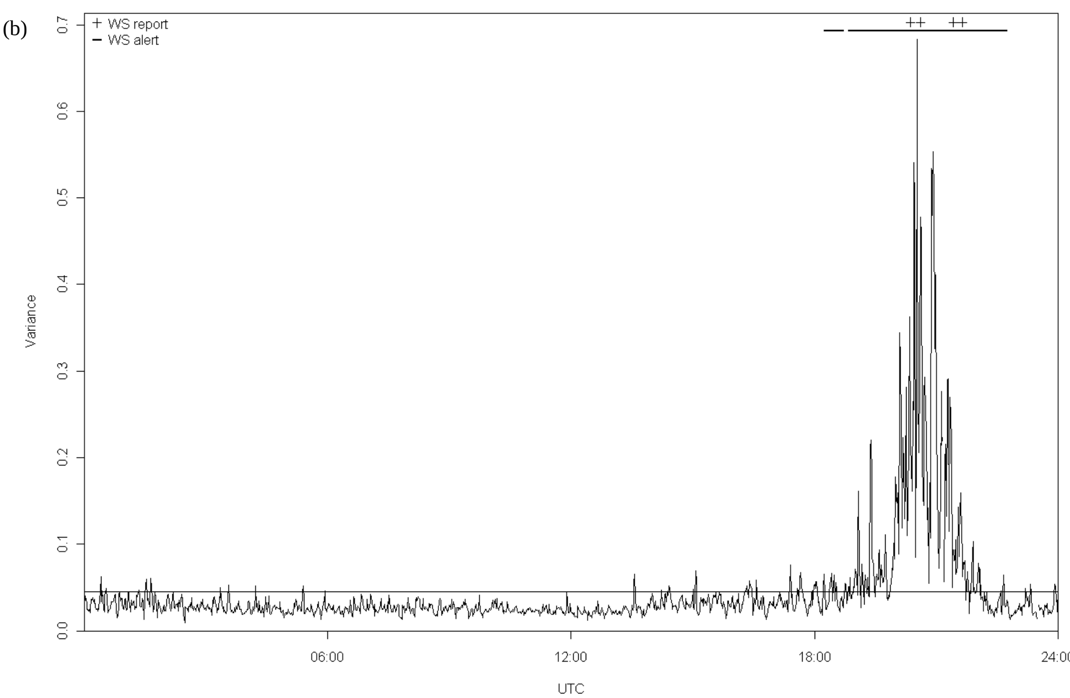
The use of brightness temperature variance in capturing windshear has been discussed in Chan and Lee (2011). At that time, due to computational constraint, variance (or standard deviation) is calculated every 10 minutes, and it is based on the quality-controlled brightness temperature within that period. The calculation method has been revised in the present study. First of all, the variance is updated more frequently, namely, every minute. In order to collect enough data samples in the calculation of variance (brightness temperature data are updated about every second), the variance is computed based on the data in the last 3 minutes. That is to say, variance is computed for the previous 3 minutes' data and the computed variance is updated every minute. The variance has been computed for all the 7 oxygen channels and the 7 water vapour channels. As such, at the end of every minute, there would be 60 values of 3-minute variance in the past hour, and selection is made out of these 60 values in order to maximize the capturing of low-level windshear reports from the pilots. Through tuning with respect to the reports, it turns out to be the most skillful in capturing the windshear by considering the 20th largest value of the variance among the 60 values in the past hour. This is generally in line with the selection of the 2nd largest value of the variance based on the 6 values in the past hour in the study of Chan and Lee (2011). The physical significance of the choice is that the low level windshear, especially for terrain-induced windshear, is transient and sporadic in nature, and the pilot may not experience the maximum of the wind fluctuation (and the associated temperature fluctuation). Moreover, the pilot is busy in the landing process of the aircraft, and the reported timing of encountering the low level windshear may not be accurate. As such, though it would be more physically meaningful to compare the maximum of the brightness temperature variance concurrently with the reported windshear by the pilot, there are many practical constraints so that these two pieces of information are not perfectly correlated with each other. Based on such considerations, empirical tuning in the use of the brightness temperature variance is tried out, and the 20th largest value is somewhere in between the maximum value and the medium value, and may be more representative of the windshear condition actually encountered by the pilot.

As a demonstration of the concept, the variance of the brightness temperature is calculated for an episode of low-level windshear at HKIA on 3 April 2010. From the velocity imagery of the LIDAR system, strong east to southeasterly winds prevailed in the airport area on that day [Fig. 2(a)]. There was an extensive area of reverse flow [coloured brown in Fig. 2(a)] over the southeastern part of the airport, in association with the wake of the mountains on Lantau Island. Aircraft departing from the south runway of HKIA to the east might encounter significant windshear due to the terrain-disrupted airflow. There were four pilot reports of significant windshear between 1800 UTC, 3 April and 0000 UTC, 4 April, as

(a)



(b)



Figs. 2(a&b). (a) The radial velocity imagery of the south runway LIDAR for the case of terrain-induced windshear on 3 April 2010. (b) Time series of the variance of the brightness temperature at 57.3 GHz with the times of the pilot windshear reports shown in crosses. The effective height of 57.3 GHz is about several hundred metres (in the order of 400 m) above ground, which closely corresponds to the height of reporting of low-level windshear by the pilots

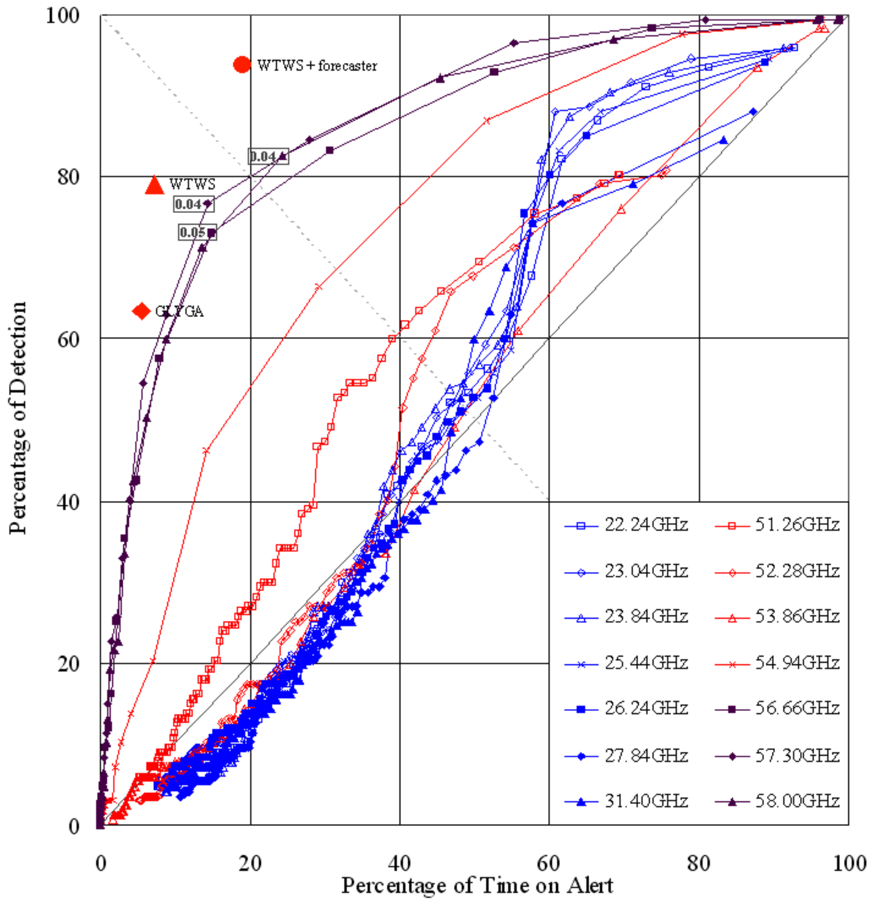


Fig. 3. The ROC curves of all the frequency channels of the microwave radiometer at HKIA. The variance of two successive data points in each curve differs by 0.005. It ranges from 0.005 to 0.5 from right to left with 100 data points. The performances of GLYGA, WTWS and overall windshear alerting service (WTWS + forecaster) are also shown

indicated in crosses in chart in Fig. 2(b). The 20th largest variance value in the past hour has been calculated based on the brightness temperature of 57.3 GHz, and the time series is shown in Fig. 2(b) as well. It could be seen that the windshear reported by pilots occurred mostly in the period when the variance of brightness temperature was higher.

To study the variance rule more systematically, the pilot windshear reports in the spring time of 2009 to 2010 (*viz*., January to April) are considered. There are altogether 167 pilot reports for aircraft departing from the south runway of HKIA to the east. The performance of the variance rule is studied by balancing between the hit rate of pilot windshear report (*i.e.*, the percentage of the reports that are successfully captured by the rule) and the alert duration as percentage of time (*i.e.*, the total alert duration divided by the total period under study, expressed as a percentage). The best performing rule would have a relative operating characteristics (ROC) curve getting close to the upper left corner of the ROC diagram, *i.e.*, with high hit rate, and a short alert duration. The ROC curve for each frequency channel is determined by varying the alerting threshold for the variance. The curves of all the 14 channels of the microwave radiometer under study are shown in Fig. 3. The following features are observed:

(*i*) Among the oxygen channels, the three channels with the lowest effective heights, namely, 56.66, 57.3 and 58 GHz have the best performance. The performance could be close to that of the LIDAR-based windshear alerting rule (namely, GLYGA) and the overall windshear alerting service at HKIA (*i.e.*, combining all the windshear alerts from the Windshear and Turbulence Alerting System, WTWS, and subjective windshear warnings issued by the aviation weather forecasters);

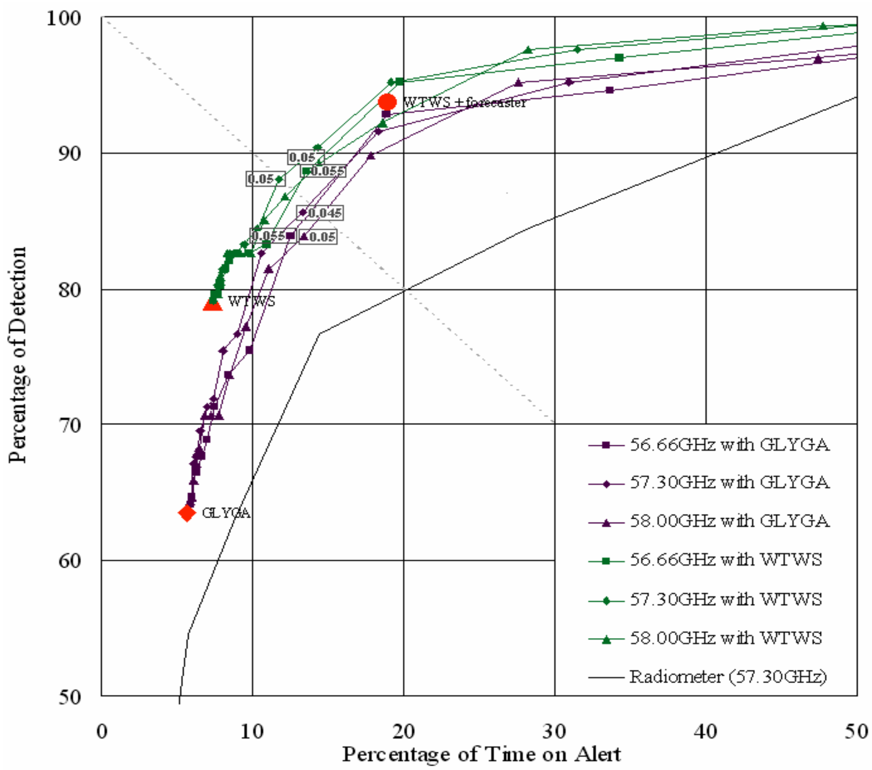


Fig. 4. The ROC curves by combining variance-based alerts of three oxygen channels (56.66 GHz, 57.3 GHz and 58.0 GHZ) with GLYGA alerts, and by combining them with WTWS alerts. The variance of two successive data points in each curve differs by 0.005. It ranges from 0.035 to 0.1 from right to left in 20 data points

(*ii*) In general, the water vapour channels do not show much skill in capturing the low-level windshear. This may be due to the larger fluctuations of the brightness temperatures (as could be seen from Fig. 1). The quality-control algorithm of the brightness temperature data may need to be enhanced.

As in Chan and Lee (2011), an attempt has been made by combining variance rule with GLYGA, and variance rule with WTWS, to see if there is any performance improvement in the overall windshear alerting service, so that the windshear alerts could be issued automatically in the future without the need of issuing subjective windshear warnings by human forecasters. The resulting ROC curves could be found in Fig. 4. It could be seen that, by combining variance rule with WTWS, it is possible to outperform the overall windshear alerting service. The hit rate could reach 95% with an alert duration less than 20% of the time. Such automatic windshear alerting rules could have the potential for operational use, without the need of any subjective windshear warnings.

From Fig. 4, the best-performing frequency channel is 57.3 GHz (by combination with GLYGA alerts) with the threshold 0.045 because the intersection between the ROC curve and the diagonal of the ROC diagram is the closest to the upper left corner of the diagram. As given in Table 2, the variance-rule itself has a hit rate of 62.87%; together with WTWS, the hit rate could increase to 88.62%.

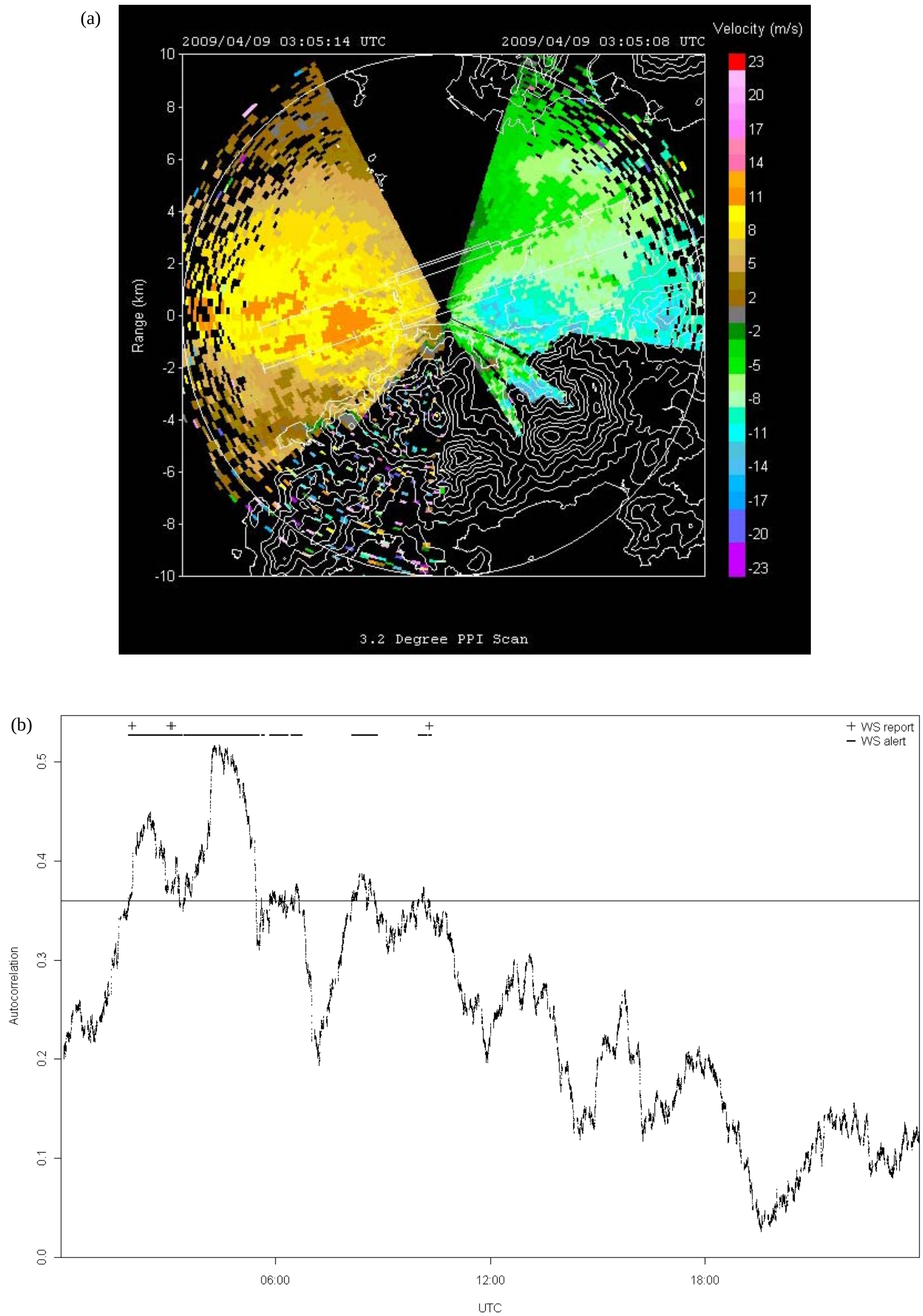
6. Autocorrelation

Autocorrelation has been demonstrated to be a candidate of early-warning signal on phenomenon arising from many complex systems (Biggs *et al*., 2009, Scheffer *et al*., 2009). In addition to variance rule, the capability of autocorrelation on windshear alerting is investigated in the present study. Physically, autocorrelation is a measure of the fluctuations of a quantity. At times of low-level windshear, the wind and the temperature may vary significantly, especially for terrain-induced windshear, and it would be difficult for the pilot to distinguish between windshear and turbulence under such conditions. As such, autocorrelation is tried out in detecting low-level windshear.

To analyze the dataset, the time series of quality-controlled brightness temperature of each frequency

(a)

(b)



Figs. 5(a&b). (a) The radial velocity imagery of the south runway LIDAR for the windshear case on 4 April 2009. (b) Time series of the auto-correlation values for this case, with the pilot windshear reports indicated by crosses. There are two overlapping crosses (two windshear reports) at about 0400 UTC. The horizontal line is a proposed threshold for detecting low level windshear based on autocorrelation method. There are no pilot reports between 0400 and 0500 UTC when the autocorrelation coefficient value is high, probably because it is the busy time of the airport and the air traffic control is too busy to collect reports

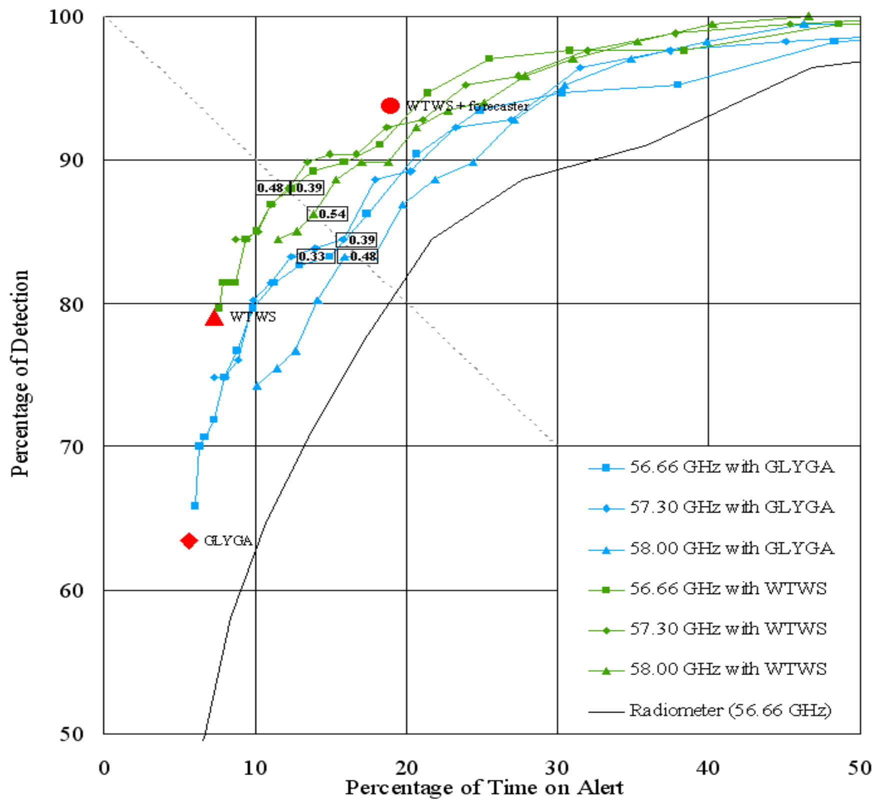


Fig. 6. Same as Fig. 4 but considering the windshear alerts based on the auto-correlation of three oxygen channels of the radiometer. The auto-correlation of two successive data points in each curve differs by 0.03. It ranges from 0.15 to 0.6 from right to left

TABLE 2

The number of pilot windshear reports captured by the two approaches of using the brightness temperature data from the radiometer, namely, variance and auto-correlation, based on the most optimum threshold values. They are indicated by "radiometer only" if the reports are only captured by the radiometer-based rules. Those captured by both WTWS alerts and radiometer-based alerts are indicated under "both". Those captured by WTWS only are shown as "WTWS only". The final column refers to the number of pilot reports that are missed by both WTWS and radiometer-based alerts. With the variance method, the radiometer could capture more windshear reports and thus a smaller amount of pilot reports are captured by the WTWS alone (43). On the other hand, with the autocorrelation method, the radiometer capture less amount of pilot reports, and as such there would be more reports captured by the WTWS alone (50)

	Radiometer only	Both	WTWS only	Missed
Variance	27	78	43	19
Autocorrelation	26	71	50	20

channel is considered. It is detrended by subtracting a Gaussian kernel smoothing function (Nadaraya-Watson kernel regression estimate) from the time series. Lag-1 autocorrelations within a sliding window are calculated from the detrended time series.

In the calculation of autocorrelation, there are two empirical parameters, namely, the bandwidth of the data selected for applying the detrending, and the window size of the data selected for calculating the Lag-1 autocorrelation. Different settings of these two parameters have been tried out for maximizing the performance of the autocorrelation in capturing significant windshear in the ROC diagram. After experimentation, bandwidth = 100 and window size = 1000 (between 2000 and 3000 seconds) yields the best performance, and the corresponding results are presented in this paper. The selected window size is generally consistent with similar consideration of the variance rule in the data sampling period, namely, brightness temperatures in the last hour or so (3600 seconds) are involved.

An example of the time series of autocorrelation is shown in Fig. 5(b). The oxygen channel of 56.66 GHz is used. The case under consideration is the daytime of 4 April, 2009. On that day, from the velocity imagery of the LIDAR [Fig. 5(a)], fresh east to southeasterly winds prevailed in the airport area. There were four pilot reports of significant windshear for aircraft departing from the south runway to the east. It could be seen that the reports all occurred at times when the autocorrelation reached larger value. As such, there appears to be some skills in autocorrelation in capturing the windshear.

The use of autocorrelation is studied more systematically by considering the ROC curves of all those oxygen channels that have been demonstrated to have skills in the variance rule, namely, 56.66, 57.3 and 58 GHz. The alerts from the autocorrelation rule are combined with those from GLYGA and WTWS, with the resultant ROC curves shown in Fig. 6. It could be seen that the skills levels of the combined levels are comparable with those obtained by combining variance rule and WTWS/GLYGA. The best performing rule is the use of 56.66 GHz with an autocorrelation threshold of 0.39. With that combination, from Table 2, the autocorrelation rule has a hit rate of 58.08%; together with WTWS, the hit rate increase to 88.02%. Either the use of variance rule or autocorrelation rule is found to improve the windshear alerting for the departing aircraft from the south runway to the east. By combining with the alerts from WTWS, the alerting skill may even outperform that of the overall windshear alerting service.

As the study is based on limited dataset only, *i.e*., the spring time of two years, in order to study the possibility of issuing automatic windshear alerts without any subjective windshear warnings, more data would be used in future studies to establish the skill levels of the radiometer-based rules.

7. Conclusions

The use of the raw brightness temperature measurements of a ground-based microwave radiometer in the alerting of low-level windshear at an operational airport is studied in this paper. This extends the previous work of Chan and Lee (2011) by considering all the 14 channels of the radiometer in use at HKIA. Two approaches are considered, namely, the variance of brightness temperature, and the auto-correlation in the time series of the brightness temperature. It turns out that both methods show skills in the capturing of the low-level windshear based on the data of two years. For instance, by combining the windshear alerts from the variance of brightness temperature of selected channels and those of GLYGA, it is possible to achieve POD of nearly 95% and the alert duration less than 20%, which are comparable with the performance of the overall windshear alerting service at HKIA. Similar results are obtained by combining the WTWS alerts with those from the auto-correlation of the time series of the brightness temperatures of selected channels. In general, the oxygen channels in the region of 57 to 58 GHz perform the best in the capturing of windshear, probably because their effective ranges are comparable with the heights of the windshear reports (below 500 m, or 1600 feet).

It may be noted that as the present results are based on the data of two years only, more data in the coming spring-times would be used to assess the long-term performance of the brightness-temperature-based windshear rules as introduced in this paper.

References

Biggs, R., Carpenter, S. R. and Brock, W. A., 2009, "Turning back from the brink: Detecting an impending regime shift in time to avert it." *Proceedings of the National Academy of Sciences of the United States of America*, **106**, 3, 826-831.

Chan, P. W., 2009, "Performance and application of a multi-wavelength, ground-based microwave radiometer in intense convective weather", *Meteorologische Zeitschrift*, **18**, 253-265.

Chan, P. W. and Hon, K. K., 2011, "Application of ground-based, multi-channel microwave radiometer in the nowcasting of intense convective weather through instability indices of the atmosphere", *Meteorologische Zeitschrift*, **20**, 431-440

Chan, P. W. and Lee, Y. F., 2011, "Application of a ground-based, multi-channel microwave radiometer to the alerting of low-level windshear at an airport", *Meteorologische Zeitschrift*, **20**, 423-429

HKO, IFALPA and GAPAN, 2010, "Windshear and turbulence in Hong Kong – information for pilots", Hong Kong Observatory, International Federation of Air Line Pilots' Associations (IFALPA) and The Guild of Air Pilots and Air Navigators (GAPAN), 36 pages.

Rose, Th. and Czekala, H., 2008, "RPG-HATPRO, RPG-TEMPRO, RPG-HUMPRO, RPG-LHUMPRO, RPG-LHATPRO Humidity and Temperature Profilers Operating Manual", Radiometer Physics Gmbh.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., Van Nes, E. H., Rietkerk, M. and Sugihara, G., 2009, "Early-warning signals for critical transitions". *Nature*, **461**, 53-59.

Shun, C. M. and Chan, P. W., 2008, "Applications of an infrared Doppler Lidar in detection of wind shear", *J. Atmos. Oceanic Technol.*, **25**, 637-655.