J13.1

DEVELOPMENT OF AN AVIATION UNUSAUAL WEATHER NOW-CASTING SYSTEM BASED ON AIRCRAFT AUTOMATIC DEPENDENT SURVEILLANCE-BROADCAST (ADS-B) DATA

Wen-Yao Ting*, Shau-Shiun Jan*
National Cheng Kung University, Tainan 70101, Taiwan

1. INTRODUCTION

The current aviation weather information system is ground oriented, and according to the demand of aviation meteorology, the aviation personnel most concern about is the layers between 2,000 feet to 4,000 feet in altitude. Importantly, pilots need weather anomaly information for approaching and landing at an airport. Therefore, a pilot oriented aviation weather system is essential within airport vicinity. The proposed approach in this paper is to add vertical profile to the current aviation weather information, and the added information source is efficient in the sense of cost and performance. We thus developed a method of deriving meteorological information, like wind vector and temperature, from the ADS-B Mode-S ES signals [1] to now-casting weather anomaly information on the flight path. The attractive part of this 1090 MHz ADS-B Mode-S ES approach is the use of the current or planned infrastructures. In this paper, In order to determine possible turbulence position and the wind shear type, the wind profiles and Richardson number profiles are established on the route of the approaching/departure flight path. The Kalman filter is applied to estimate the wind profile with the ADS-B observation data to offer now-casting entire wind velocity information on the trajectory of aircraft. We then obtain temperature and pressure data from ADS-B to calculate Richardson number profiles with the constructed wind profiles. Finally, the three-dimensional unusual weather could be detected by analyzing the Richardson number profiles. In addition, the principal component analysis (PCA) is utilized to assess the results. The eigenvectors of the first principal component and the first principal component scores derived from PCA is the leading method to analyze observation data. Through PCA the three-dimension weather information provide more definite unusual weather information to the aviation personnel. In order to validate the now-casting, two pilot repots with weather anomalies are discussed in this paper.

The rest of this paper is organized as follows. Section II introduces how to use ADS-B data to construct three-dimensional wind profile. In Section III the unusual weather now-cast on flight paths are discussed. Section IV presents the results using two pilot report cases. Finally, Section V summarizes this paper and provides recommendations for future work.

2. THREE-DIMENSIONAL WIND PROFILES

In order to establish high-resolution and real-time wind profiles on the flight path as well as to overcome the possible discontinuity of weather observation data, we use the Kalman filter with the actual ADS-B observation data to obtain the enhanced prediction result along the flight path of interest [2][4].

2.1 *ADS-B Data*

The 1090 MHz ADS-B Mode-S ES transponder is standard equipment on almost all commercial aircraft, and ADS-B data can provide real-time data with update rate (1 Hz typical) which is higher than that of the traditional aviation weather observation data. Therefore, the meteorology data decoded from ADS-B signal would be close to the real atmospheric condition and thus it is suitable to analyze the rapid changes in the aviation weather system. The observation data, namely wind velocity, temperature and pressure, are required to establish wind profiles and Richardson number profiles, and these data can be obtained from the ADS-B Mode-S ES Downlink Format (DF) 17, 20 and 21 data. The decoded true airspeed and ground speed are utilized to derive the wind velocity [1]. In addition, temperature can be calculated from the true airspeed and the decoded Mach number (M) as depicted in Eq. 1, where T is temperature in Kelvin (K), R_d is the gas constant of dry air, $\vec{V}_{air}$ is the true airspeed, and $\gamma = c_p / c_v$ is the ratio of the specific heats [7].

$$T = \frac{1}{\gamma R_d} \frac{\vec{V}_{air}^2}{M^2} \qquad \textbf{(1)}$$

2.2 *Kalman filter*

In the Kalman filter model, the wind speed initial state is generated by the wind profile power law as shown in Eq. 2 and the initial state of the corresponding wind direction is obtained by the sounding data. These two initial states are taken as the first predictions of the wind speed profile and the wind direction profile. Because the resolution of the wind profile is 50 feet, the initial state is therefore interpolated to obtain 200 initial states from ground to altitude of 10,000 feet.

$$u = u_r \left(\frac{z}{z_r} \right)^{\alpha} \qquad \textbf{(2)}$$

Where u is the wind speed at the height of z and it depends on the wind speed u_r at the reference height of z_r. The exponent α is an empirically derived coefficient and has a value approximately 0.143 [3][8].

In this Kalman filter model, the state estimation and covariance update only if the new observation data is received from ADS-B date. Therefore, the received data of wind velocity, altitude and position are put into the measurement equation as well as stored in the observation-matrix and then to calculate the horizontal distance between the trajectories. These observation data are kept according to the altitude where the data is received at and then these observation data are utilized to revise the prediction. Thus the update would not change predictions of other layers at which no new observation data is received [4]. By doing so, a high-resolution real-time wind information can be provided on the approaching and departure flight paths of interest. Importantly, the resulting wind profiles can be used to detect the unusual weather information via the calculation of the corresponding Richardson numbers that are discussed in the next section.

3. UNUSUAL WEATHER NOW-CASTING

3.1 *Richardson number profile*

In this work the Richardson number profiles are utilized to now-cast the unusual weather on the flight path. To establish Richardson number profile on the flight path of interest, the wind profiles and the potential temperature profiles are needed. The wind profiles are established by the Kalman filter model described in the previous section and the potential temperature profile can be derived from Eq. 4 below. The Richardson number R_i is defined as [5]:

$$R_i = \frac{\frac{g}{\theta}\frac{\partial \theta}{\partial z}}{\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]} = \frac{\text{buoyancy term}}{\text{wind shear term}} \quad \textbf{(3)}$$

$$\theta = T\left(\frac{P_0}{P}\right)^k \quad \textbf{(4)}$$

As shown in Eq. 3, the Richardson number is regarded as the ratio of the buoyancy term and the wind shear term. The buoyancy term is composed by the gradient of the potential temperature, and the wind shear term is the combination of the gradients of the u-component and v-component winds. According to the definition of the Richardson number, when the wind shear term in Eq. 4 is four times larger than the buoyancy term, that is, R_i is smaller than the critical Richardson number R_c (i.e., 0.25), then it indicates that this atmosphere condition is favorable for the occurrence of turbulence [5]. Furthermore, if R_i is negative value, then the thermodynamic instability plays an important role. In other words, the turbulence might be induced because of the weather systems passing through**.** On the u-component wind gradient and the v-component wind gradient, the vertical wind gradient need to be smoothed because of the rapid fluctuation [5]. Moreover, the potential temperature profiles are also smoothed to reduce the observation noise from ADS-B. In this paper we use two examples to demonstrate the proposed scheme including one normal weather case and one disturbed weather case. According to Figure 1, the radar echoes showed that there was no weather system near Taoyuan International Airport (RCTP) area (the red circle). The Richardson number profiles are expected to be larger than R_c (i.e., 0.25). As shown in Figure 2, the resulting Richardson number profile at 2,000 to 4,000 feet reveals that most of the R_i at different altitude layers are larger than 0.25. Figure 3 shows a disturbed weather case, and as shown in Figure 4, most of the resulting Richardson numbers are as expected less than 0.25 (R_c). Additionally, for flight level between 2,000 to 2,400 feet, the resulting Richardson numbers are negative values. This feature is mainly due to the thermodynamic instability.

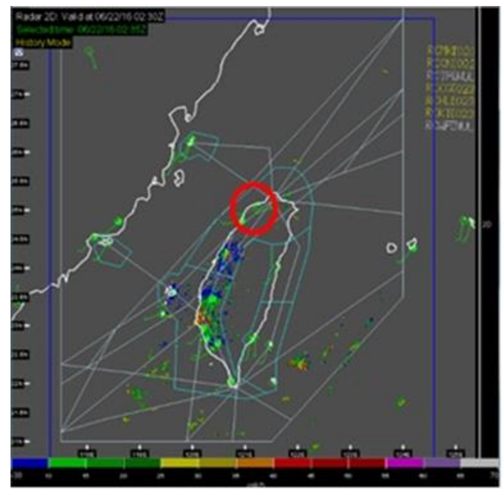

Figure 1. Radar echoes at 02:35 UTC on 2016/06/22

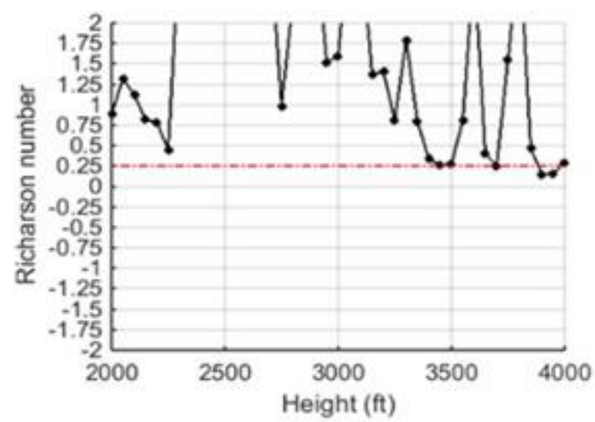

Figure 2. Richardson number profile at 02:35 UTC on 2016/06/22

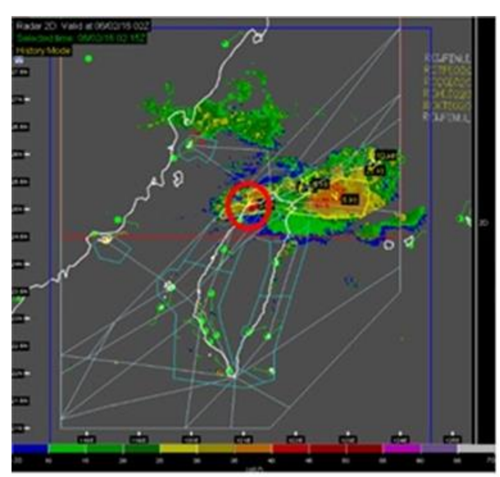

Figure 3. Radar echoes at 02:15 UTC on 2016/06/02

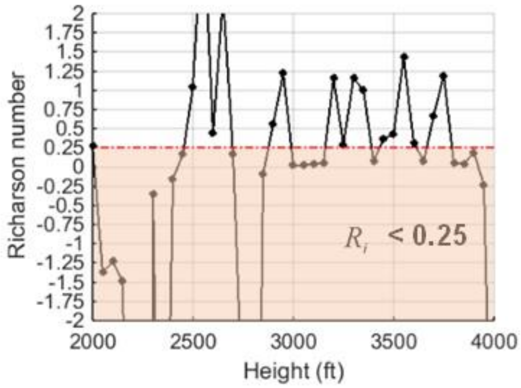

Figure 4. Richardson number profile at 02:15 UTC on 2016/06/02

3.2 *Principal Component Analysis*

According to the equation of Richardson number (Eq. 3), the index is influenced by the gradient of potential temperature and the gradients of wind on u-component and v-component winds. To figure out which component is the main influence to the turbulence index, we use the principal component analysis (PCA) to analyze the above three parameters in the cases with pilot reports of the onset of turbulence on flight paths as shown in the next section. Furthermore, the PCA results provide the more definite weather anomaly information, the position of unusual weather system, by calculating the eigenvectors and the principal component scores of the observation covariance matrix. The eigenvectors and the principal component scores are used to study the wind shear type and the turbulence position. Because the statistical data indicated that the first principal component has already reveal over 50% of the original data [6], we therefore focuses only on the first principal component for the following pilot report case analyses.

4. RESULTS

In order to verify that our proposed scheme could be utilized in real world situations. Two real cases of turbulences that were included in the pilot reports are studied [9~10]. One flight was in the procedure of approaching an airport and encountered turbulence at 1,200 feet. Another flight was over the departure runway and pilot reported turbulence between 4,000 feet to 8000 feet. In these two cases, the ADS-B data is collected for one hour including the occurrence's time and the data at altitude below 10,000 feet.

4.1 *Case 1 --- 12 January 2016, on departure path*

UACI31 RCTP 121557
ARS CAL5848 N2505 E12114 FL040 TO FL080 OBS AT 1520Z MOD TURB=

According to the above pilot report, one aircraft departed from Taoyuan International Airport (RCTP) and pilot reported the moderate turbulence between 4,000 feet to 8,000 feet at 15:20 UTC on 12 January 2016 [10]. We calculate the Richardson number profiles from 15:00 UTC to 16:00 UTC and output Richardson number profile result every five minutes. As shown in Figure 5, the Richardson numbers at most of layers between 4,000 feet to 8,000 feet at 15:15 UTC are smaller than 0.25 and larger than 0.

Comparing the Richardson number profiles at the time before (Figure 5, 15:15 UTC) and as the turbulence announced (Figure 6, 15:20 UTC), the atmosphere condition from 4,000 feet to 8,000 feet in Figure 6 became more unstable than that of Figure 5. Consequently, the Richardson number profile result is consistent with the pilot report.

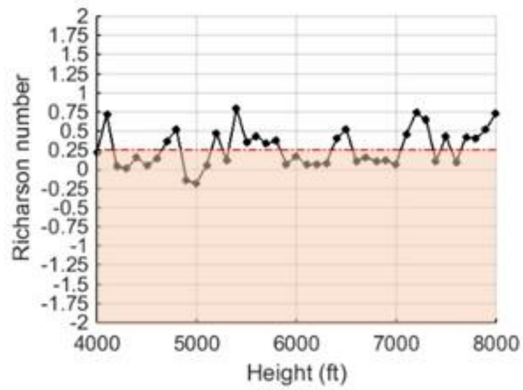

Figure 5. Richardson number profile at 15:15 UTC on 2016/01/12

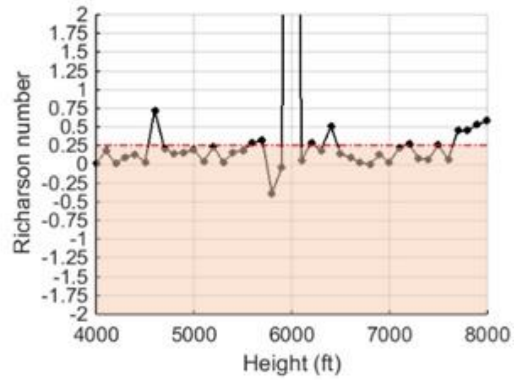

Figure 6. Richardson number profile at 15:20 UTC on 2016/01/12

According to the PCA result, the eigenvector of the gradient of u-component wind, v-component wind and the potential temperature are 0.938377, 0.344143 and -0.031860, respectively, and the weighting of the u-component wind gradient is larger than other variables. Furthermore, as the original data is used to calculate the first principal component scores. Figure 7 shows that the scores at 4,000 feet and 5,000 feet are larger than that at different altitudes. Base on this analysis, the proposed system would announce that the atmosphere is unstable at the altitude of 4,000 to 5,000 feet and pilots would be advised about the wind shear on west and east direction.

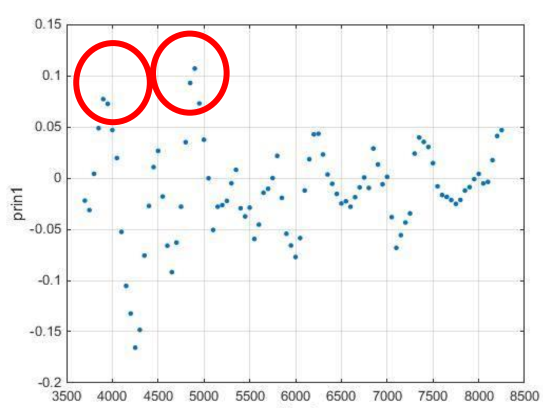

Figure 7. Principal components scores 2016/01/12

4.2 *Case 2 --- 17 October 2015, on glide path*

UACI31 RCTP 170837
ARS CRK252 N2505 E12114 FL012 OBS AT 0603Z MOD TURB=

The second case was that an aircraft landed at Taoyuan International Airport (RCTP) and pilot reported moderate turbulence at 06:03 UTC on 17 October 2015 at height of 1200 feet [9]. Similar to the previous case, the Richardson number profiles are considered at five minutes earlier and at the turbulence time. Because the turbulence was reported at 1,200 feet, the analysis focuses on 1000 feet to 5000 feet in altitude.

From the Richardson number profiles at 05:55 UTC (Figure 8) and 06:00 UTC (Figure 9), the Richardson number at the altitude about 1200 feet are smaller than 0.25 and negative. Therefore, the environment is classified as the thermodynamic instability, so the turbulence type would be the thermodynamic instability. According to the PCA result, the eigenvector of the three variables, namely the gradient of u-component wind, the v-component wind and the potential temperature are 0.653221, 0.757043 and 0.013738, respectively. The weighting of v-component wind is larger than that of the others. Moreover, in Figure 10 the principal component scores are obvious at 1,200 feet and 5,000 feet. Thus, the environment is unstable at 1200 feet and 5000 feet and the v-direction wind shear is distinct. The now-casting results of Richardson number and PCA are consistent with the pilot report.

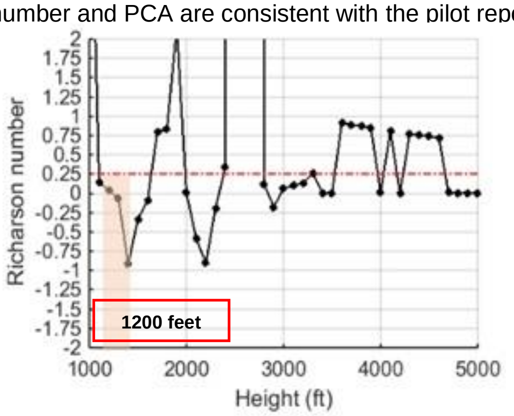

Figure 8. Richardson number profile at 05:55 UTC on 2015/10/17

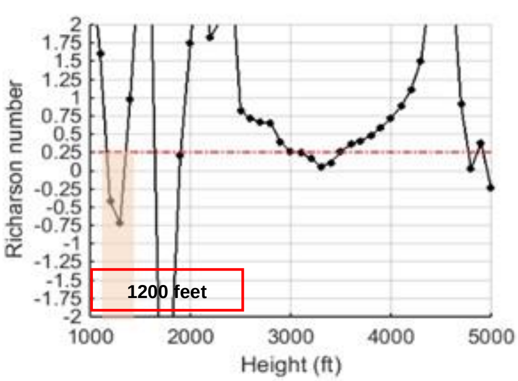

Figure 9. Richardson number profile at 06:00 UTC on 2015/10/17

* *Corresponding author address:* No.1, University Road, Tainan City, Taiwan, Institute of Civil Aviation, NCKU; e-mail: adsl5643@gmail.com; ssjan@mail.ncku.edu.tw

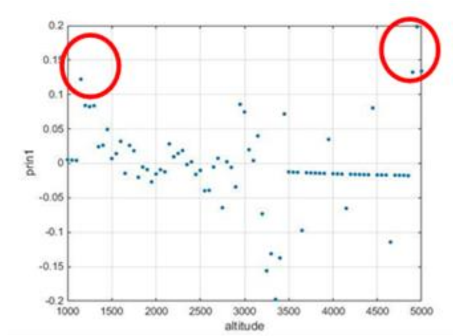

Figure 10. Principal components scores 2015/10/17

5. CONCLUSIONS

We proposed an aviation unusual weather detection scheme for aircraft using the data from its1090 MHz Mode-S ES transponder, and as shown in the results the weather profile obtained from our proposed system is more similar to the actual weather condition close to aircraft than the traditional ground-oriented weather information. According to the results of two pilot report cases, the Richardson number profiles calculated from ADS-B data were consistent with both pilot reports. As a result, the use of the ADS-B data with the traditional meteorology algorithm can enhance the aviation weather system.

Our next step will investigate the processes to make the ADS-B weather observation data, such as temperature and wind direction, more accurate in order to find the possible dominant factors to the unusual weather types for aviation.

7. REFERENCE

[1] Hao-Wei Peng, 2016: Development of a three-dimensional aviation unusual weather detection system based on the use of ADS-B 1090MHz data. S. S. J.

[2] S. de Haan, 2011: High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar., JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116.

[3] Zoumakis, N. M., 1990: Methodology for Bulk Approximation of the Wind Profile Power-Law Exponent Under Stable tratification. K. A. G., Boundary-Layer Meteorology, Vol. 55, Nos. 1–2, pp. 199–203.

[4] P. M. A. de Jong,: Wind-Profile Estimation Using Airborne Sensors. J. J. van der Laan, A. C. in 't Veld, M. M. van Paassen, M. Mulder.

[5] Chan, P. W.: Determination of Richardson number profile from remote sensing data and its aviation application.

[6] Subhash S., 1996: Applied Multivariate Techniques, 62-92, pp.

[7] S. de Haan, 2011: High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar., JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116.

[8] Technical note, 1979: A theoretical variation of the wind profile power-law exponent as a function of surface roughness and stability., Atmospheric Environment, Vol. 13 pp. 191-194.

[9] Pilot report, 2015/10/17: http://aoaws.caa.gov.tw/wmds/content/aoaws_chinese/wmds.html

[10] Pilot report, 2016/01/12: http://aoaws.caa.gov.tw/wmds/content/aoaws_chinese/wmds.html