

Obtaining Meteorological Data from Aircraft with Mode-S Radars

Marko Hrastovec
Slovenia Control, Ltd.

Franc Solina
University of Ljubljana

INTRODUCTION

The main sources of meteorological data at high altitudes are radiosondes and Aircraft Meteorological Data Relay (AMDAR) data [1]. Mode-select (Mode-S) radars are capable of getting similar readings from aircraft as AMDAR; however, this source of meteorological data has not been used systematically so far. In this article, we analyze the meteorological data obtained by means of Mode-S radars and propose how this data can be used. The first prerequisite for acquiring meteorological data with radars is the necessary aircraft on-board sensors that can measure the meteorological data. Next, the aircraft transponder has to fetch the data from the sensors and report them. Mode-S radar configuration further determines whether the radar will request meteorological data from the aircraft. In our experiments, described later, approximately only 6% of responses from aircraft included meteorological information required by the radar. Still, the amount of data collected by means of Mode-S radars is much larger and much cheaper to obtain in comparison with radiosondes. We expect that in the future this percentage of successful responses from aircraft will grow with the modernization of airliner fleets because newer aircraft are better equipped with meteorological sensors.

In this article we analyze the quality of meteorological data collected with Mode-S radars. During a 5-month period we collected meteorological data with a Mode-S radar and compared it with corresponding radiosonde measurements. We developed a method for gathering the data from Mode-S radars and generate atmosphere profiles for wind and temperature. Air traffic control uses upper wind tables

generated by numerical weather prediction (NWP) models for flight path calculations. The profiles that we generate from Mode-S radar data can be a relatively good substitute for these tables.

A recent study by Strajnar [2] shows that both Mode-S wind and Mode-S temperature are of sufficient accuracy for use in meteorology. De Haan and Stoffelen [3] also used a type of Mode-S data as input to a NWP model to compute 1-hour wind and temperature predictions. Since they could not access the actual Mode-S weather data from the aircraft, they computed Mode-S data indirectly from the flight characteristics of aircraft. Wind, for example, is computed from the difference between airspeed and groundspeed. They reported that when such indirectly derived Mode-S data are used as inputs to the NWP model, in addition to the usual input, the difference between the computed predicted winds and the actual winds is 5% smaller than when the NWP model prediction is computed without Mode-S data. One can assume that by using actual Mode-S weather data that is sent from the aircraft instead of indirectly derived Mode-S data, the predictions would be even more accurate.

ACQUIRING ATMOSPHERIC METEOROLOGICAL DATA

NWP models for calculating and predicting weather depend heavily on dense and reliable atmospheric data. The main data sources for these models are still radiosondes. Meteorological readings from aircraft that are not participating in AMDAR are lost. Using Mode-S radars opens up an alternative path to get these readings from aircraft sensors. This requires minimal additional expense, since the necessary infrastructure for collecting and transmitting meteorological data is already in place. We just need to use it. Meteorological data collected from aircraft can reduce costs by exploiting a cheap source of data. They can also contribute to improved weather forecast accuracy with higher density of measurements. In a study on Tropospheric Airborne Meteorological Data Reporting [4], a strong business case for equipping aircraft to send weather data is identified based on the positive impact of this new system on the aviation sector.

Authors' current address: M. Hrastovec, Slovenia Control, Ltd., Zgorjnj Brnik 130n, 4210 Brnik-Aerodrom, Slovenia, (E-mail: marko.hrastovec@sloveniacontrol.si). F. Solina, Faculty of Computer and Information Science, University of Ljubljana, Tržaska cesta 25, 1000 Ljubljana, Slovenia, (E-mail: franc.solina@fri.uni-lj.si). Manuscript received April 3, 2012, revised October 9, 2012, and April 11, 2012, and ready for publication April 15, 2013. Review handled by D. Crouse.
0885/8985/13/\$26.00 © 2013 IEEE



RADIOSONDES

Radiosondes are deployed with weather balloons once or twice a day. The sensors mounted in a radiosonde are calibrated prior to the launch, and they return measurements every second via a radio link. It takes approximately an hour and a half for a radiosonde to reach its maximum height. At a 1-second reporting rate we get around 5000 measurements from each radiosonde.

Radiosonde measurements are, in this context, the most accurate since their sensors are calibrated before launching. They have served as a reliable upper atmosphere data source for many years. Therefore, radiosondes can serve as references for comparison with readings from the sensors mounted on aircraft.

AMDAR

The AMDAR project began in 1970s. The purpose of the project is to get automatic meteorological data reporting from aircraft. AMDAR uses very high frequency radio equipment or the Aircraft Communications Addressing and Reporting System to transfer the meteorological data to data centers. The data are then used in meteorological centers as inputs to NWP models. The quality of data is constantly monitored, and aircraft with bad data are notified to recalibrate or repair their sensors. AMDAR recommends a smoothing method for relayed data, but standards vary widely among avionics manufacturers.

According to AMDAR [5], the cost of a vertical profile made from aircraft-derived data is just 1% of the cost of radiosonde data. Unfortunately, only a few airline companies have joined AMDAR. In the European part of AMDAR project, for example, only around 400 aircraft participate. In contrast, using ground-based Mode-S radars, all aircraft appropriately equipped could contribute meteorological data, not just the ones that joined the AMDAR project.

RADARS

The primary function of radars is to locate aircraft. Altitude reported to radar is measured with a pressure sensor and

is a good indicator of the static air pressure. It is calculated from the measured static air pressure with the International Civil Aviation Organization standard atmosphere model [6]. The exact position and altitude are important information required primarily for air traffic control—and in our case for meteorological data. On every turn of the radar, aircraft are located and interrogated for data. In ideal conditions we get new data on every turn of the radar. Due to physical limitations such as obstacles, reflections, and garbling, data can be lost. Generally, we can expect a valid aircraft response on almost every turn.

Mode-S radars are a modern generation of secondary radars that are able to request additional data from aircraft with Mode-S capable transponders. Mode-S radars can fetch 56-bit Comm-B Data Selector (BDS) registers [7]. There are over 40 possible BDS registers that can report valuable data to the ground. Two of the registers: BDS code (4,4) and BDS code (4,5) are designed to hold meteorological data. BDS code (4,4), which is called the meteorological routine air report, holds the following values in its 56 bits: wind speed, wind direction, static air temperature, turbulence, and humidity. BDS code (4,5), which is called the meteorological hazard report, is composed of the following hazard report values: turbulence, wind shear, microburst, icing, and wake vortex.

The radar fetches data from all aircraft that are able to respond. However, there is no mechanism in place to notify airlines to calibrate their sensors. Often air companies are not even aware that their aircraft are sending meteorological data via Mode-S radars to flight control centers. The only way to get rid of erroneous readings is therefore to identify them and eliminate them. The quantity of data obtained via Mode-S radars is so large in comparison to radiosondes or even AMDAR that the faulty readings can be identified as outliers rather easily if they represent a minority of all available data.

NUMERICAL WEATHER PREDICTION MODELS AND FORECASTS

Although forecast data from NWP models are not strictly measurements, we mention them in this section because

we use them as references to evaluate our error elimination method described in the section on exclusion criteria. To use radiosonde data for that purpose would not be sensible because radiosondes are deployed only in the morning, whereas NWP forecasts are issued every 12 hours and include predictions for the whole day. Each forecast includes predictions for 3-hour intervals (typically for 00:00 UTC, 03:00 UTC, 06:00 UTC, 09:00 UTC, etc.).

We used in particular the NWP upper wind tables, which are issued for aviation purposes. The upper wind table consists of values for temperature and wind at predefined flight levels. For instance, in Ljubljana, Slovenia, upper wind tables include altitudes from 2000 to 38000 feet in 1000-ft intervals. For air traffic control it is important to know when an aircraft is going to reach a certain navigation point. If weather conditions (especially wind) are ignored, these calculations would not be precise enough. We show in the “Generation of Upper Wind Tables” section how similar reports could be produced with the help of data collected by aircraft via Mode-S radars and compare them with NWP reports.

COMPARISON OF ACQUIRED DATA

The World Meteorological Organization (WMO) defines the required accuracy for upper-air measurements [8]. Table 1 shows how accurate the results are for the altitudes at which aircraft are also reporting. To be able to calculate predictions accurately enough, NWP models need to get the data with required accuracy. Our goal is to show that Mode-S data complies with these requirements.

Table 2 shows the output resolution of each measurement method and its accuracy. Temperature measurements from radiosondes are usually more accurate than those from aircraft. At low wind speeds, vector errors can lead to larger errors in wind direction. Thus, an indication for wind error combines wind speed and wind direction as a vector error. Table 2 shows that wind measurements from aircraft are not compliant with WMO accuracy requirements.

In this article we show that with averaging and error elimination we can improve the quality of results to be compliant with WMO accuracy requirements.

EVALUATION OF ACQUIRED DATA

In our experiment we collected meteorological data with the Mode-S radar stationed at the Ljubljana Jože Pučnik Airport. The radar’s range is 200 nautical miles. The experiment lasted five months, starting on 1.3.2011 and ending on 31.7.2011. The period selected for the study includes a stable weather period, as well as turbulent months during the summer. We selected a period with low traffic intensity at the beginning and a change to the summer season with peak air traffic. The radar was configured to interrogate for registers BDS code (4,4) and BDS code (4,5). A little over 6% of all detected aircraft returned at least one meteorological datum.

Table 1.

Accuracy Requirements (Standard Error) for Upper-Air Measurements for Synoptic Meteorology, Interpreted for Conventional Upper-Air and Wind Measurements	
Variable	Accuracy Requirement
Pressure	1–2 hPa near 100 hPa
Temperature	0.5 K
Relative humidity	5%
Wind direction	5° for less than 15 m/s
	2.5° at higher speeds
Wind speed	1 m/s

The sets of returned data were different. All combinations of responses are possible. Some aircraft return only temperature, some return only wind, others return all of the above. These configurations depend on the meteorological sensors that are available on board and the configuration and capabilities of the transponder. Aircraft are measuring most of the data, but the sensors are often not connected to the transponder bus to provide the data or the transponder is not configured for data transmission to the radar. Table 3 shows the relationships among all data collected and the share of types of meteorological data acquired from the radar in the 5-month period that we analyzed. For similar airspace, the AMDAR system receives on the average about 200 measurements daily, or 30000 measurements in a 5-month period. This means that for the airspace within which we performed our experiment, the amount of AMDAR data represents less than 1% of collected Mode-S meteorological data.

As shown in Table 3, aircraft are not yet equipped with humidity sensors. AMDAR reports that only a small number of aircraft in the project is equipped with humidity sensors for test and evaluation purposes. In the future, we hope that aircraft will also report humidity through transponders. The necessary space is already reserved in BDS registers. Unfortunately, we have not been able to record a single instance of a meteorological hazard report. This suggests that aircraft do not return these reports.

It is possible to estimate wind and temperature from other data available via Mode-S radars. Similarly, although aircraft on-board equipment calculates wind, it can be calculated also from the relation between airspeed, which is reported via Mode-S, and groundspeed, which is measured with radar [9], [10]. Temperature can also be deducted from true airspeed and Mach number [10]. We decided to use only aircraft-reported meteorological data from the BDS code (4,4) register and not to calculate them from other sources.

Table 2.

Measurement Accuracy						
	Output Resolution			Accuracy		
	Radiosonde	AMDAR	Mode-S	Radiosonde	AMDAR	Mode-S
Longitude, latitude	0.01 m	1 min (~1 NM)	1/128 NM	10 m	5 NM	2.5 NM
Time	1 s	1 min	1/128 s	1 s	1 s	0.1 s
Pressure altitude	0.1 hPa	10 ft	100 ft	1 hPa	100 ft	100 ft
Temperature	0.1 K	0.1 K	0.25 K	0.5 K	0.5 K	0.5 K
Wind direction	40.1°	1°	180/256°	2°	4-6 kt ^a	4-6 kt ^a
Wind speed	0.01 m/s	1 kt	1 kt	1.15 m/s	4-6 kt ^a	4-6 kt ^a
Humidity	1%	1%		5%	5%	

^a Vector error.

NM, nautical mile (1852 m); **ft**, (~27 ft/hPa); **kt**, knot (~0.5 m/s).

Table 3.

Amount of Data Collected in a 5-Month Period (March 1–July 31, 2011) by a Single Mode-S Radar Used in Our Analysis		
	Measurements	Percentage
All readings	116975815	100.00
Flight level (transponder)	113734684	97.23
Average static pressure	1533037	1.31
Static air temperature	7271912	6.22
Wind speed and direction	5948169	5.08
Humidity	0	0.00

COMPARISON WITH RADIOSONDE DATA

The first part of our experiment was to evaluate the meteorological data acquired from the aircraft. The reference for evaluating the quality of the Mode-S–obtained readings was the radiosonde data. Figure 1 shows how the data were compared.

Aircraft sensors measure the data all the times (sa_{raw}). These data are encoded by a transponder and sent to radar (sa_{radar}). Radar receives the meteorological data and adds attributes such as aircraft position and a time stamp. Radar encodes the data in an All Purpose Structured Eurocontrol Surveillance Information Exchange (ASTERIX) message and sends it over the line to air traffic control ($m_{asterix}$).

On the other side, radiosonde sensors are also measuring the meteorological data (sr_{raw}) with meteorological sensors and position the data with a global positioning system. The data are encoded as a radio signal (sr_{radio}) and sent to the meteorological agency to be decoded and stored with an added time stamp ($m_{radiosonde}$).

When we have measurements from both sources, we can compare them. The criteria for finding the data suitable for comparison are described in the next section.

CRITERIA FOR METEOROLOGICAL DATA COMPARISON

Several studies that evaluated the quality of meteorological data from aircraft in comparison to radiosondes have been published [11]–[13]. These comparisons of aircraft and radiosonde data developed some quality criteria that we used also in this study. Usually, only aircraft data collected no more than 150 km away from a radiosonde and no more than 90 minutes before or after the radiosonde measurements are used for comparison [13].

In addition to these criteria, it is also important to know whether aircraft data are reliable. The AMDAR project defines conditions for when to trust wind measurements. If an aircraft is performing a maneuver, wind measurements are

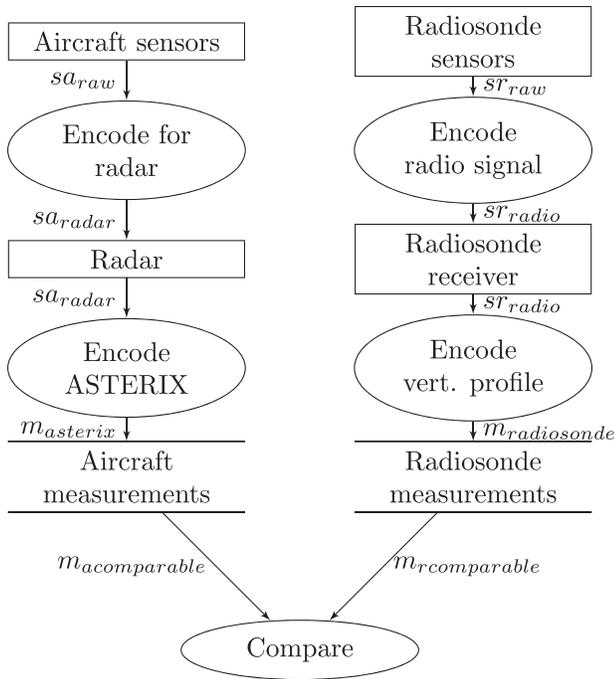


Figure 1. Evaluation of meteorological data acquired from aircraft.

not accurate and are excluded. If the roll angle is bigger than 5°, the wind measurements are not used. Pitch angle is also taken into account. If both pitch angle and roll angle are bigger than 3°, the data are also not used [1].

During our experiment we collected, with the help of the selected Mode-S radar, all available data from the aircraft. From the meteorological agency we obtained the corresponding radiosonde measurements for the same period. In the first phase we compared the collected data with radiosonde measurements as a reliable source. In this part of our investigation we have shown that the data from aircraft is similar to radiosondes data and therefore could be used for various purposes.

Figure 2a shows radiosondes trajectories. It can be seen that all were deployed from the same spot and that wind carried them in different directions. Trajectories of aircraft that contributed meteorological data for comparison with radiosondes are presented in Figure 2b. Many more aircraft were flying in the same airspace during our experiment, but only data from aircraft that fulfilled the following conditions were included in the comparison with radiosonde data:

- ▶ The aircraft measurement needed to be taken less than 150 km from the radiosonde.
- ▶ When taken, it needed to be within ±90 minutes of radiosonde measurement.
- ▶ The pressure (altitude) measured had to be within ±1 hPa radiosonde pressure.
- ▶ For wind the roll angle was taken into account, as stated earlier in the AMDAR conditions.

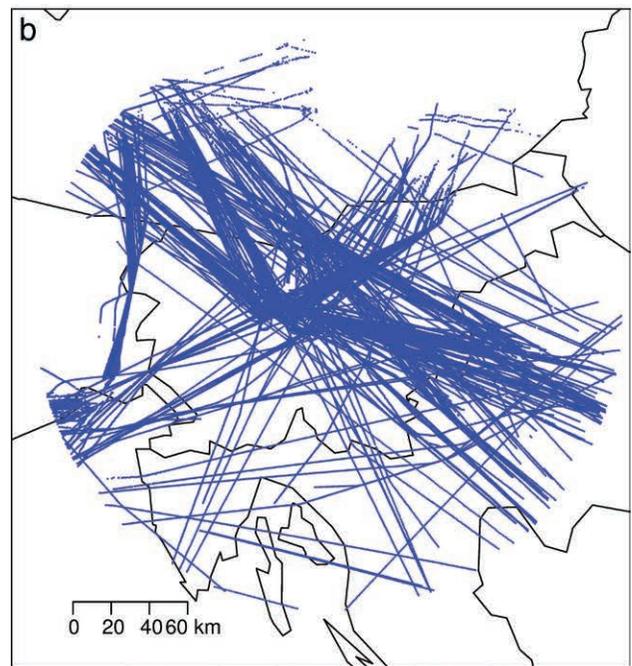
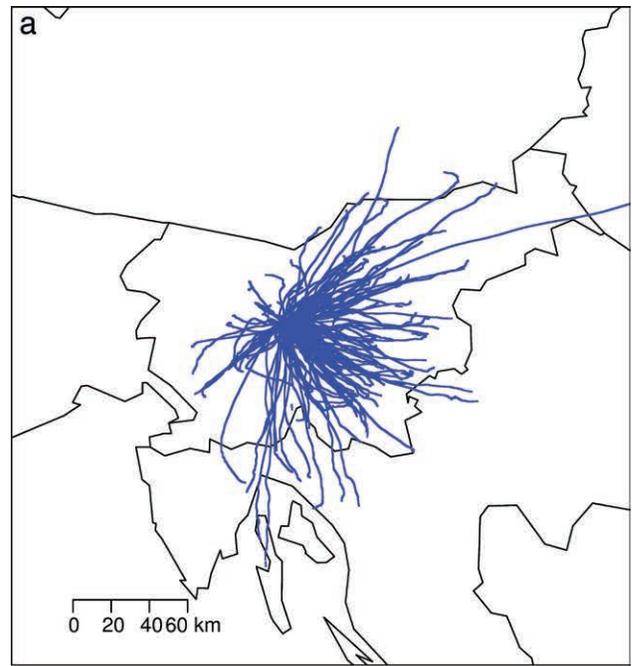


Figure 2. Comparable meteorological data collected over Slovenia during a 5-month experiment.

Using the preceding selection criteria, out of all measurements collected in the 5-month period (Table 3), we found a limited number of combinations of radiosonde and aircraft measurements that we were then able to compare (Table 4). A similar study [13] reports 4440 matched data in a 2-month period.

We evaluated how distance, altitude, and time difference influence the meteorological data collected on aircraft in comparison with radiosondes. All measurements from aircraft were

used in this analysis, although it is clear that some of them are faulty. These faulty measurements can be seen in Figures 3–11 as data point outliers. At this stage we want to show the quality and quantity of data. We show that the average is acceptable but that many errors need to be corrected. In the section on the Kalman filter we show how such faulty measurements can be discarded and more accurate results can be obtained.

The charts in the following subsections show the comparison just described. There are three types of charts in each figure. The chart on the left shows the actual compared values, presented as dots. The chart in the center shows the average differences, grouped into approximately 30 classes, and a linear regression line to indicate the trend. The chart on the right presents the standard deviation and a trend line of grouped measurements in dependency to the chosen attribute.

Temperature

The comparison of temperatures in Figures 3–5 shows the differences between aircraft and radiosondes measurements. Three groups of charts show how these differences are affected by lateral distance (Figure 3), altitude (static pressure) (Figure 4), and time offset (Figure 5). The figures show that aircraft measurements are a little warmer than radiosonde sensors because differences are always shifted above 0 K. A similar temperature bias was observed by Ballisha and

Table 4.

Amount of Aircraft Data Comparable to Data from a Radiosonde and Used in Further Analysis	
	Comparable Combinations
Temperature	1 004 019
Wind speed and wind direction	768 557

Kumarb [11]. As seen in Figure 3, the uncertainty of aircraft measurements grows with distance from the radiosonde. The same applies for temperature difference according to altitude in Figure 4. For temperature differences between aircraft and radiosondes related to the time of the measurement (Figure 5), the trends are not so obvious and it seems that the influence is the least significant.

Wind Speed

The wind speed difference between readings from aircraft and radiosondes in Figures 6–8 shows that values from aircraft are a little lower than values from radiosondes. The average difference is around 3 m/s. Figure 6 shows that the differences increase with distance. Figure 7 shows that at low altitudes, the

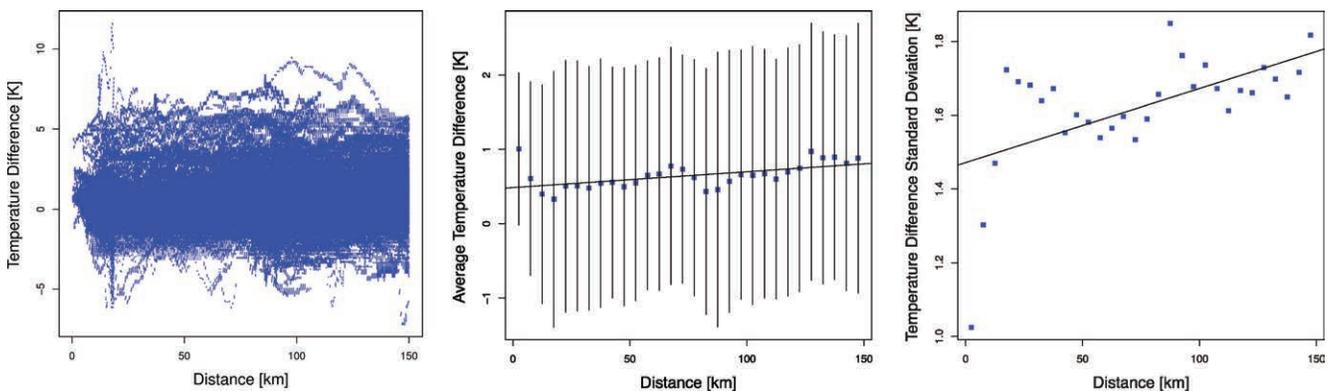


Figure 3. Temperature difference dependency on distance from radiosonde.

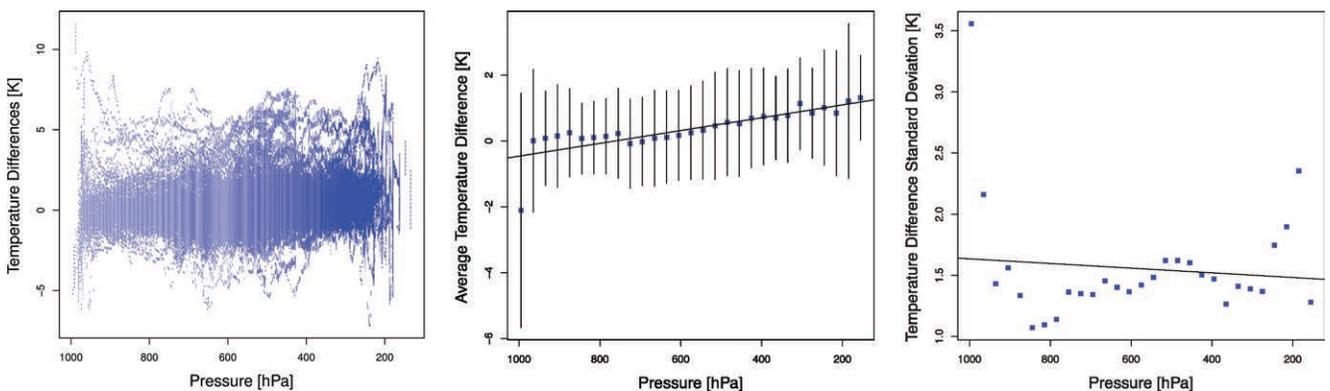


Figure 4. Temperature difference dependency on same pressure (altitude) with radiosonde.

measurements from aircraft are more reliable. However, at higher altitudes with stronger winds, the relative error is even lower. Time is again seen as the least significant factor (Figure 8).

Wind Direction

As expected, the wind direction comparison in Figures 9–11 shows the largest deviations in measurements. However, the average difference is still low. Local wind conditions are notable at lower altitudes where winds are more unstable. The distance chart in Figure 9 shows that the measurements

taken closest to the radiosonde have the largest deviations. This is probably because the closest measurements are taken at low altitudes, since the airport and the radiosonde launching site are not far apart (~20 km). Unfortunately, we cannot avoid the influence of altitude and distance. Figure 10 shows that winds at low altitudes are more unstable. They are also weaker and harder to measure accurately. Figure 11 shows that in this case, time also plays a significant role. Measurements from aircraft taken more than 1 hour later than from radiosonde show a lot of different values. A radiosonde is deployed early in the morning. During the night, before

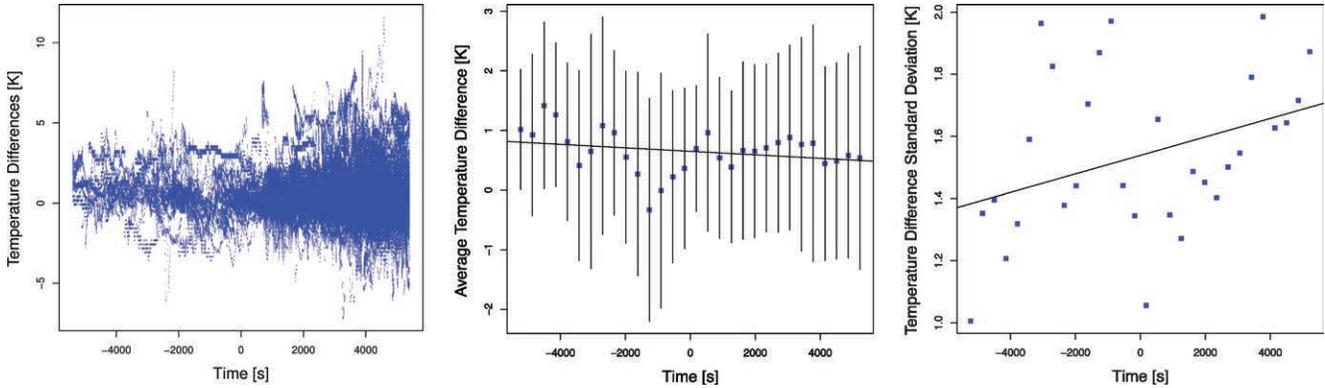


Figure 5. Temperature difference dependency on time offset from radiosonde.

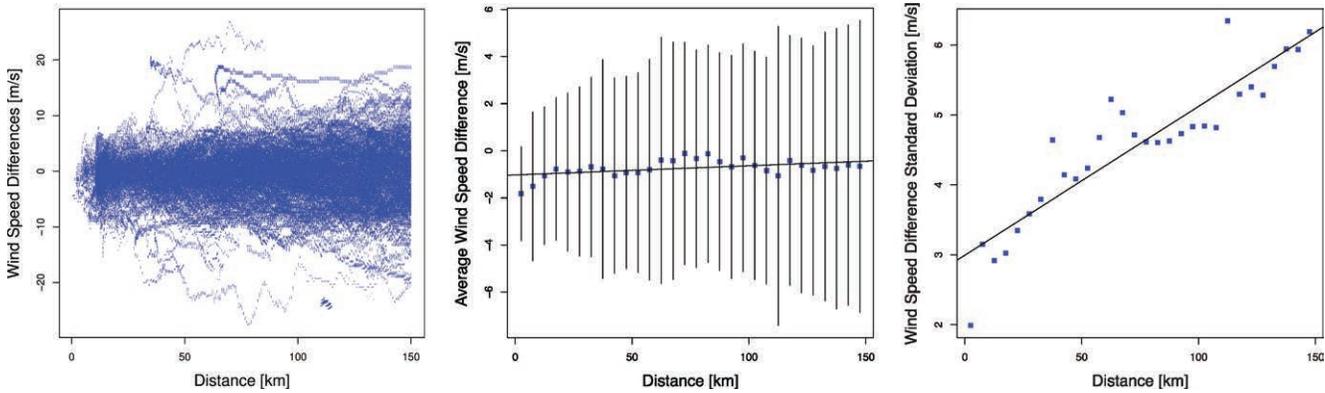


Figure 6. Wind speed difference dependency on distance from radiosonde.

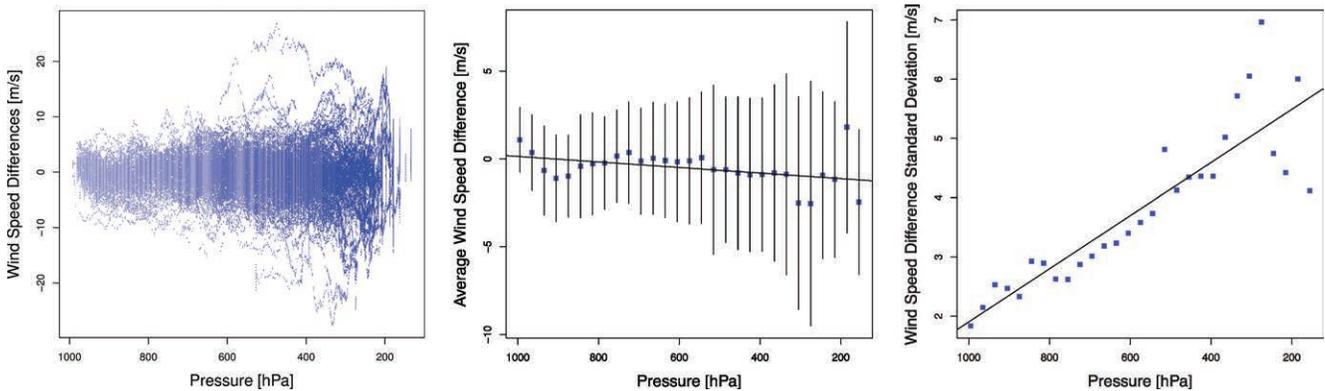


Figure 7. Wind speed difference dependency on same pressure (altitude) with radiosonde.

radiosonde deployment, the air traffic level is low and it is composed mainly of overflights. In the hours after the radiosonde deployment, the activity in the airport rises significantly and there are a lot of departures. At that time dawn also breaks and wind direction changes are more common.

GENERATION OF UPPER WIND TABLES

There are many possible applications for the use of meteorological data acquired from aircraft by means of Mode-S radars. The most important application for air traffic control is genera-

tion of upper wind tables and temperatures, which are normally provided by NWP systems. Figure 12 shows the standard process of generating upper wind tables from radiosonde measurements with the help of NWP models and the generation of upper wind tables from Mode-S radar meteorological data.

We decided to generate upper wind tables from our data ($m_{asterix}$). Air traffic control uses upper wind tables (UWT_{meteo}) operationally for calculating times that aircraft need to fly from one point to another. Winds influence these times considerably. Incorrect or missing upper wind values require manual interventions and corrections of aircraft's flight

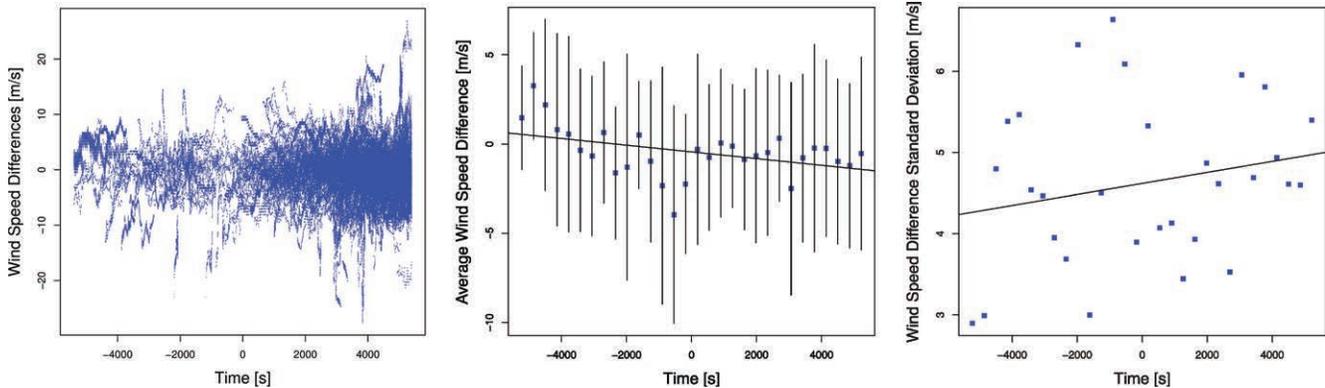


Figure 8. Wind speed difference dependency on time offset from radiosonde.

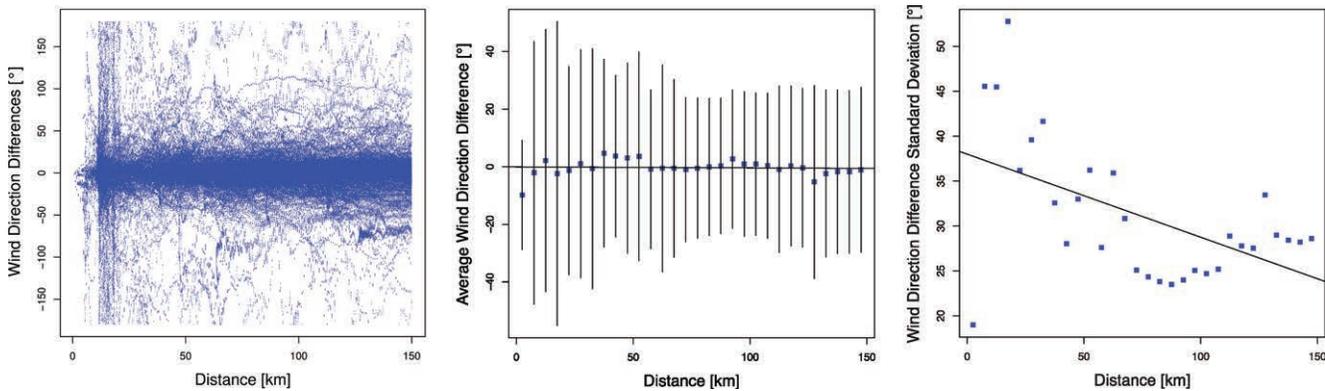


Figure 9. Wind direction difference dependency on distance from radiosonde.

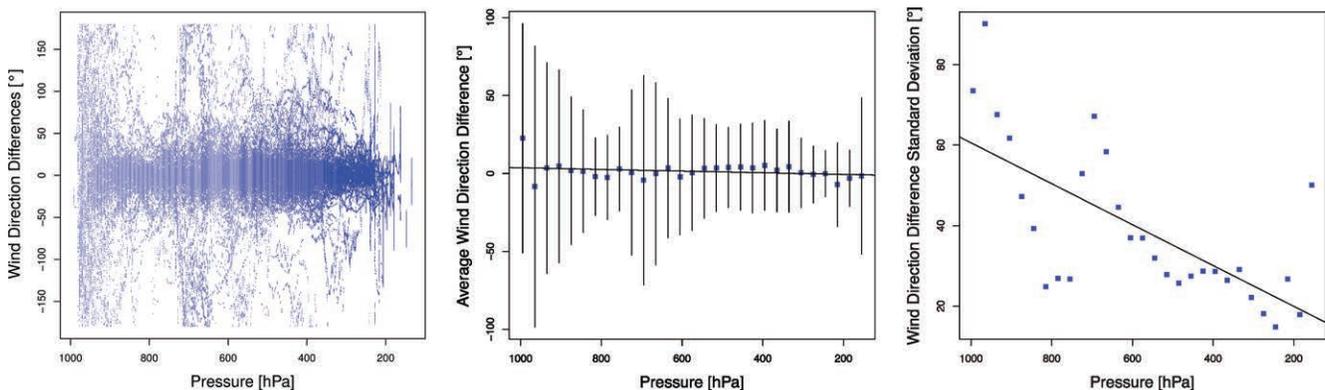


Figure 10. Wind direction difference dependency on same pressure (altitude) with radiosonde.

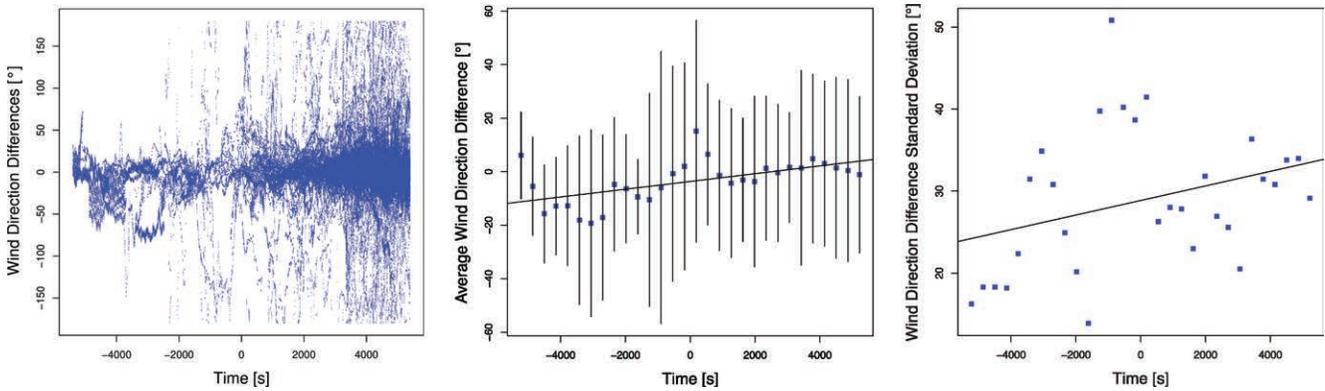


Figure 11. Wind direction difference dependency on time offset from radiosonde.

times. That brings additional workload to air traffic controllers. Upper wind tables (UWT_{meteo}) are normally provided by environmental services from their NWP models. We argue that if the NWP-generated upper wind tables are not available, we can generate them (UWT_{ATC}) from the large amount of meteorological data that we are getting from the aircraft. Before using Mode-S meteorological data, we need to filter out faulty values that are not used ($m_{filtered}$). The criteria for filtering are described in the section on exclusion criteria.

Even if the generated upper wind tables are not as accurate as those calculated from weather prediction models, they are better than having no tables, since the calculation of aircraft flight duration times is still more accurate than if no upper wind data are available. A smaller number of manual corrections also means a lower workload for air traffic controllers.

In Slovenia Control the meteorological data from radars has been collected continuously from June 2009. Upper wind tables (UWT_{ATC}) have also been generated since then, but so far they have not been used operationally.

The problem that we had to address is how to smooth the collected Mode-S meteorological data and eliminate measurement errors. Due to its efficiency, the Kalman filter was chosen for this task. After we generated upper wind tables from aircraft data, we compared them to upper wind tables from NWP models, as explained later.

KALMAN FILTER

The Kalman filter is a mathematical method developed in 1960 by R. E. Kalman [14]. This method effectively smoothes data by taking into account measurement errors and converges to the right value quickly. In that way we can make a good estimation of the measurements with effective error correction. It is an iterative method that does not store values from previous iterations. The important feature of the Kalman filter is that the number of measurements does not influence the complexity or require more resources. The filter adjusts the error covariance matrix, which is an estimate how close the Kalman filter has come to the real state of the system observed at every step.

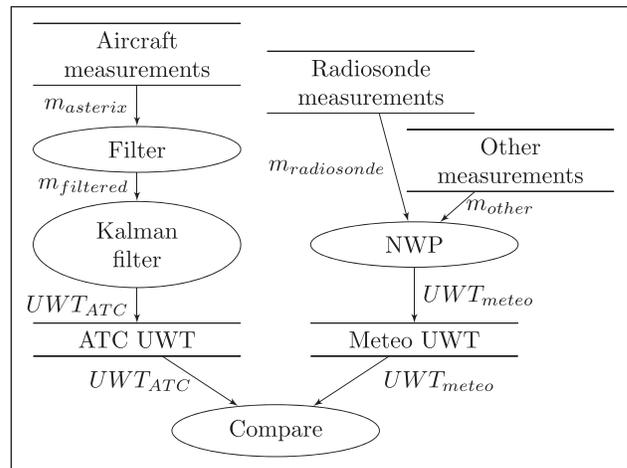


Figure 12. Generation and comparison of upper wind tables (UWT). ATC, air traffic control.

The algorithm in the Kalman filter tries to get the best values from the process being observed. It uses two groups of calculations. The first group is called time update, and it predicts the observed value. The second group contains measurement update equations. These equations use the latest measurement to correct the estimate. Every cycle of the Kalman filter gives the best approximation and prediction according to the last measurement.

Kalman Filter Simplifications

Our problem allows the following simplifications of the general Kalman filter:

- ▶ The Kalman filter uses vectors and matrices to calculate the parameters of a system. We used one-dimensional separate filters for temperature and wind speed. In that way the equations are simpler. For wind direction we used a two-dimensional vector, described in the next section.
- ▶ Since the system that we observed did not use controlling mechanisms, the part for calculation of control values was left out.

- ▶ The Kalman filter uses a conversion matrix to calculate the observed value from the measured one. Since in our case the measured and observed values are the same, there is no need for a conversion matrix.
- ▶ Because the measured and observed values are the same, we also do not need the conversion back from the estimated value to the expected measurement.

The simplified equations for time update are then as follows. The Kalman filter prediction is just a copy of the value estimate \hat{x}_k^- and error covariance P_k^- from previous step $k-1$, as shown in Equations 1 and 2:

$$\hat{x}_k^- = \hat{x}_{k-1} \quad (1)$$

$$P_k^- = P_{k-1} \quad (2)$$

For the measurement update step, we use the following. We get the new value estimate \hat{x}_k from previous estimate \hat{x}_k^- , and the trust in the new measurement z_k is based on previous ones reflected in Kalman gain K_k (Equation 4). Kalman gain K_k determines how much we expect to trust the next measurement. It is calculated from the error covariance P_k^- and measurement covariance R (Equation 3). At the end, we calculate the new error covariance P_k for the next step in Equation 5.

$$K_k = \frac{P_k^-}{P_k^- + R} \quad (3)$$

$$\hat{x}_k = \hat{x}_k^- + K_k(z_k - \hat{x}_k^-) \quad (4)$$

$$P_k = (1 - K_k)P_k^- \quad (5)$$

Parameters and Settings

To get the best results from the Kalman filter, it needs to be parameterized and the start values should be selected properly. We decided to take the first measurement x_0 for the starting value. P_0 determines the uncertainty of the first value. If we can assume that the value for x_0 is correct and without errors, we could set P_0 to 0. Since we know that is not the case, we must choose something different. We usually set P_0 to 1, or to the identity matrix in the case of a multidimensional filter.

The efficiency of the Kalman filter can be increased with the correct setting of the covariance matrix R . Matrix R influences the filter's trust in measurements. With well-tuned covariances, the values converge quickly to the right value. If uncertainty in R is set too large, the filter does not trust the measurements enough and it converges to the right values too slowly. If the uncertainty is set too small, every error out of threshold influences the calculated value and it jumps instead of converging. Since we had enough measurements to accurately calculate the standard deviation for every class of data, we could calculate the covariance matrices accurately.

In the case of one-dimensional filters, covariance is simply the standard deviation. We used it for temperature and wind

speed. For wind direction we had to use a covariance matrix R . The reason for that is the discontinuity in the encoding of wind direction values. If we encode wind directions from 0° to 360° , we have a problem with calculating wind directions around 0° , since some measurement may return 359° and the next measurement may return 1° . The numerical average in this case would be 180° , which is wrong. Therefore, wind directions were converted to Cartesian coordinates, and $\sin \alpha$ and $\cos \alpha$ were used for calculations since they are continuous. Vector z_k in this case has two values:

$$z_k = x_k = \begin{bmatrix} \sin \alpha \\ \cos \alpha \end{bmatrix} \quad (6)$$

The Kalman filter calculates vector x_k in step k . To get the wind direction value we simply need to convert it back to polar coordinates, where length ρ is not important (Equation 7). If we used ρ we could put the wind speed in the same Kalman filter, but we chose to smooth wind speed with a separate filter.

$$\alpha = \text{atan2}(x_{k_0}, x_{k_1}) \quad (7)$$

Exclusion Criteria

Some sensors on aircraft are not calibrated and are returning biased measurements. All measurements from such sensors present values that are constantly shifting the final Kalman filter value from the correct value in the same direction. Uncalibrated sensors cannot contribute to the correctness of the value, and their measurements must be discarded. We developed a method to automatically exclude measurements from such sensors.

Weather forecasts split the airspace into horizontal slices and provide wind and temperature values for every slice. Our method uses one Kalman filter for each horizontal slice. All measurements from a particular slice that satisfy a given data criteria contribute to the Kalman filter. At the end of a measuring period we have Kalman filter values for each horizontal slice in which aircraft were reporting.

The method for automatic exclusion uses the Kalman filter again—this time for a different purpose. The filter measures the bias that each sensor is producing in relation to all other measurements. This means that the value that the filter is smoothing is the difference between aircraft measurements and the Kalman filter values to which all aircraft are contributing. If the difference shows a constant deviation, the measurements from this sensor are not used any more. Since the Kalman filter does not remember any previous measurements, we do not correct any previous values after a faulty sensor is recognized. We let the filter converge to a more accurate value when faulty inputs do not contribute any more. It is clear that we need at least three aircraft contributing to the value to be able to exclude a faulty one. If we have only two aircraft, we cannot determine which one is accurate and the Kalman value is somewhere in the middle.

We need to determine a threshold to point out biased measurements. For that we used the following method. We have standard deviations for all values measured. We use them primarily to parameterize the Kalman filter, as described in the preceding section. We decided to consider a measurement to be faulty if it was off for more than twice the standard deviation.

The values and methods that we used to exclude faulty measurements were chosen after some testing. For another radar and environment they should be reevaluated. The exclusion of measurements presents a constant dilemma. Stricter criteria exclude more measurements, and results are based on less data. More relaxed criteria allow more data to be included and let more errors in.

We followed also the AMDAR criteria (as explained earlier) to exclude measurements from aircraft in maneuvers. The only AMDAR criterion that we did not follow was the pitch angle. The pitch angle is not directly reported from aircraft and therefore should have been calculated. The pitch angle could only be calculated from two consecutive positions and the altitude change between them. Since the radar is not considered accurate enough to determine horizontal position change in relation to altitude change, the calculated pitch angle would not be accurate enough; therefore, we ignored it.

For lateral distance we used the same range as for radiosonde comparison—150 km. We generated upper wind tables for the same navigational points that are used for aircraft trajectories calculations and for which NWP values are available. Therefore, flights more than 150 km from those points were filtered out.

Comparison of Generated Values with Values from the Meteorological Forecasts

After applying the Kalman filter to the meteorological data collected by Mode-S radars from aircraft, we compared them to the NWP values provided by the meteorological agency (Figure 12). The overall accuracy of the output of the Kalman filter in comparison to the meteorological forecast on all altitudes is presented in Table 5. The calculated profiles could be safely used for air traffic control in case of a forecast outage. The generated wind values would provide more accurate data than using outdated data or even nothing.

The difference between NWP values and values generated from aircraft’s sensors can result from measurement inaccuracy, misprediction of NWP, or locally bounded atmosphere anomalies reflected in the measured data. NWP calculates values for altitudes directly above the selected navigation point. However, weather on the edge of contributing area (as explained in the section on exclusion criteria) can be quite different.

It is difficult to determine which factor contributes more to the deviations. More measurements could provide finer-grained input data to the NWP model but could also contribute more errors. Therefore, the use of these data requires special attention, good error elimination, and carefully selected data criteria.

One possible way of filtering and error elimination was shown here, but there is still room for improvements. For in-

Table 5.

Average Difference between Data Generated from Meteorological Data Collected from Aircraft and Data from NWP Models		
	Difference Δ	Standard Deviation σ
Temperature	0.4 K	2.1 K
Wind speed	0.3 m/s	5.6 m/s
Wind direction	0°	41°

stance, we identified an aircraft reporting 114°C at an altitude of 43000 feet. Since there were no other aircraft at that altitude around that time, the Kalman filter reported it as a valid temperature. On another occasion, snow precipitation was forecasted but we had rain instead. The comparison showed that the air was much warmer, which resulted in wrong weather prediction. So our generated tables were better.

Charts in Figure 13 present the differences from Table 5 in a more detailed view by altitudes. Dots in the temperature charts indicate that there is no notable correlation between temperature error and altitude.

Wind speeds at higher levels have larger uncertainty. However, average wind speeds at lower altitudes are around three times lower than those at higher altitudes. Therefore, even if the absolute difference in wind speed rises with altitude, it declines relative to the values being measured. The wind direction measurements in the right column of Figure 13 confirm that wind measurements at high altitudes are more precise. That was expected, because higher winds are known to be more stable and uninfluenced by local terrain characteristics.

The problem with the upper wind tables that we generated are holes in data where aircraft are not flying. For air traffic control this is acceptable, because data are usually not needed on missing altitudes. These gaps are more problematic for meteorological use. We measured data in a low-traffic and in a high-traffic period. We sliced the vertical profile into 45 horizontal slices from flight level 10 to 450, representing 1000 up to 45000 feet in standard atmosphere. On average, the temperature was measured in 19 out of 45 horizontal slices, leaving 26 slices empty. The wind speed was calculated in 13 horizontal slices and the wind direction was calculated in 23 slices on average. This shows that there were quite large gaps in the data. Usually, the most valuable values for lower altitudes were present.

OTHER APPLICATIONS OF METEOROLOGICAL DATA OBTAINED BY MODE-S RADARS

Generation of upper wind tables is just one example of using meteorological data obtained from aircraft by means of Mode-S radars. We believe that this data source has a lot of potential for other applications as well.

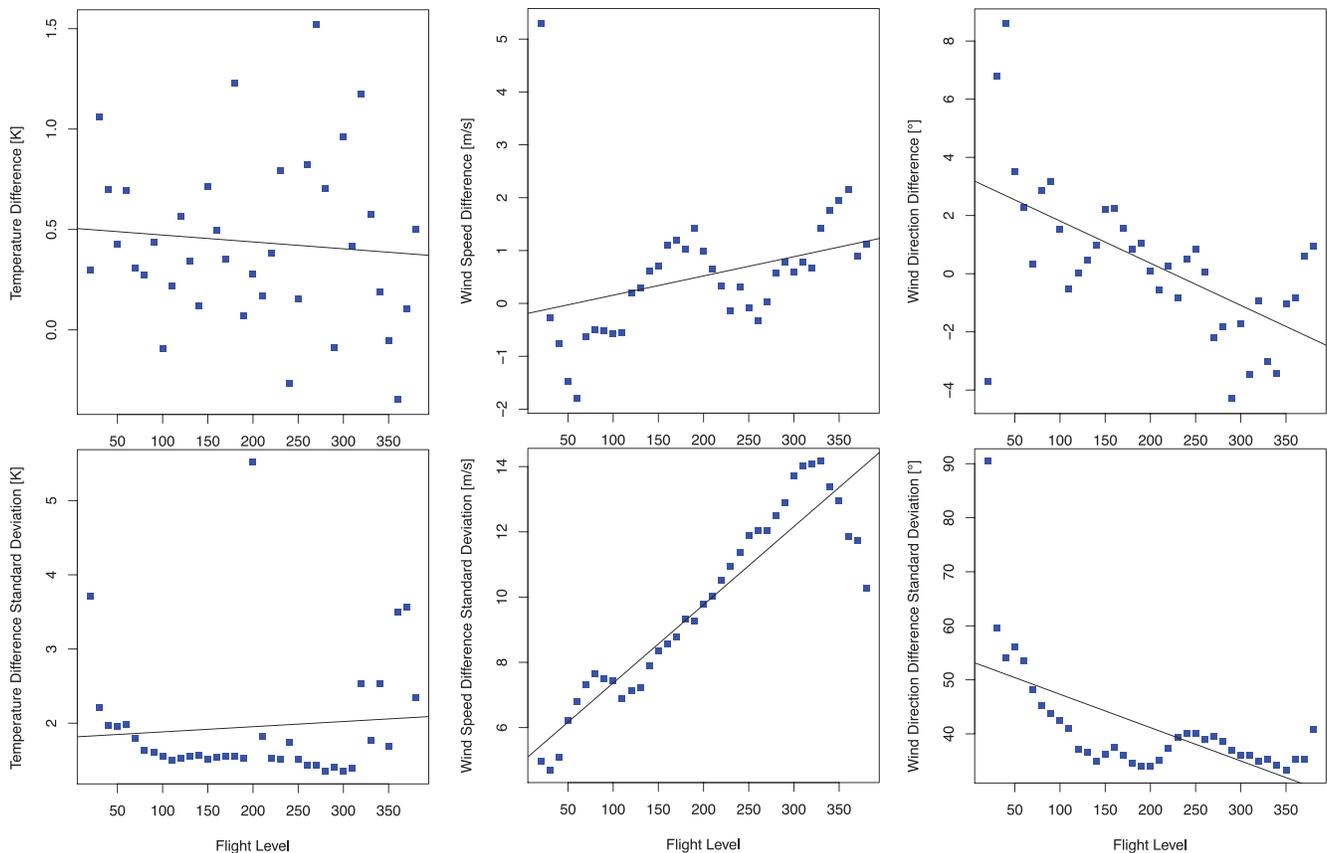


Figure 13.

Differences between Kalman filter-generated meteorological values from aircraft data and values from NWP.

RADIOSONDE EMULATION

Another possible application of meteorological data collected by Mode-S radars is radiosonde emulation. It is similar to upper wind table calculation. The difference is in the altitude classes. For radiosonde emulation we split the atmosphere into smaller altitude slices divided by pressure layers. We calculate the Kalman filter values for each slice and provide smoothed values for it. Unfortunately, we do not get readings of vertical winds and humidity, which are provided by radiosonde sensors; however, the emulated measurements can be obtained more cheaply and more frequently.

In Slovenia Control we have been producing these radiosonde emulation tables in parallel with upper wind tables since June 2009. They are still not used operationally.

SENDING DATA TO AMDAR

Meteorological data collected by Mode-S radars could serve as input to the AMDAR project. The values can be fed into AMDAR in the same way as from aircraft data are sent directly via data links to AMDAR. In this way, the existing AMDAR infrastructure could be used as it is being used today. Software similar to that used in aircraft to send the data to AMDAR could be used in radar ground stations instead to relay the meteorological data received by radar to AMDAR. In that case the smoothing of data and the frequency of re-

ports could be effectively emulated on relaying stations, inducing minimal changes on AMDAR receiving algorithms.

The AMDAR project is limited to aircraft from companies that have joined the project and are sending data voluntarily. When radar interrogates for meteorological data, the aircraft return the data if they have the equipment to measure it and if they are configured to return the measurements via transponder to the radar. In this way AMDAR could receive data from more aircraft. There are more than 200 Mode-S radars installed in Europe. We do not have information on how many of them could spare some registers for meteorological purposes. However, we believe that even with a small number of radars, we could get a lot of measurements and good coverage over all of Europe.

These two paths for meteorological data complement each other. AMDAR gets data from areas where radar coverage is not available, and radars can get data from more aircraft, providing a larger number of measurements.

USING DATA DIRECTLY IN NUMERICAL METEOROLOGICAL MODELS

Meteorological data originating from the Mode-S radars at the Ljubljana Jože Pučnik Airport has been sent to the Slovenian meteorological agency since 2011 for use in NWP models. NWP models are still not optimized for such large quantities of data and for such high frequency in comparison to ra-

diasonde measurements, which are done only once per day. The focus therefore is on how to efficiently use the new data source in NWP models to get better weather forecasts. This project is on its way but is beyond the scope of this article.

CONCLUSIONS

We have evaluated the meteorological data acquired from aircraft via Mode-S radars. Radiosonde measurements served as a reference for this evaluation.

We developed a smoothing and error elimination method for meteorological data obtained via Mode-S radars that is based on the Kalman filter. The analysis shows that data acquired in this way comply with WMO standards. The upper wind tables generated are within WMO requirements when compared with the upper wind tables from NWP models. The acquisition of this meteorological data is cheaper than other ways of getting atmospheric measurements. There are more than 200 Mode-S radars installed in Europe; however, not all ground radars can be configured to interrogate aircraft for atmospheric data. Where this is possible it would be sensible to start collecting meteorological data and sending it to meteorological agencies, where they could serve as inputs into NWP models. More data means more accuracy in NWP models. More data also requires more computing power, but nowadays this is not a big problem. Meteorological data from aircraft relayed by Mode-S radars has been collected in Slovenia Control since June 2009. The generation of upper wind tables from this data has started. Since 2011 these meteorological data have been forwarded to the Slovenian meteorological agency, where the task of using them in NWP models is under way.

We have shown that meteorological data collected by Mode-S radars could be used for aircraft trajectory calculations. Accurate trajectory calculations are becoming increasingly important with changes in European airspace driven by the Single European Sky Air Traffic Management Research project [15]. ♦

ACKNOWLEDGMENT

We thank Benedikt Strajnar and the Slovenian Environment Agency for help in providing meteorological data from radiosondes for the purpose of this article.

REFERENCES

- [1] World Meteorological Organization. *Aircraft Meteorological Data Relay (AMDAR) Reference Manual*. Geneva, Switzerland: Secretariat of the World Meteorological Organization, 2003.
- [2] Strajnar, B. Validation of mode-S meteorological routine air report aircraft observations. *Journal of Geophysical Research: Atmospheres*, Vol. 117, D23 (2012). [Online]. Available: <http://dx.doi.org/10.1029/2012JD018315>.
- [3] de Haan, S., and Stoffelen, A. Assimilation of high-resolution mode-S wind and temperature observations in a regional NWP model for nowcasting applications. *Weather and Forecasting*, Vol. 27 (2012), 918–937.
- [4] Kauffmann, P., Ozan, E., and Sireli, Y. Feasibility of TAMDAR: an aircraft-based weather data collection system. *Journal of Air Transport Management*, Vol. 10, 3 (2004), 207–215. [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0969699703000899>.
- [5] World Meteorological Organization Aircraft Meteorological Data Relay Panel. *Aircraft Meteorological Data Relay: The International AMDAR Program*. Geneva, Switzerland: AMDAR Panel Flyer, World Meteorological Organization, 2007. [Online]. Available: <http://www.wmo.int/pages/prog/www/GOS/ABO/AMDAR/publications/Final%20Production%20AMDAR%20Flyer.pdf>.
- [6] International Civil Aviation Organization. *Manual of the ICAO Standard Atmosphere: extended to 80 kilometres (262 500 feet)*, (1993) ISBN: 92-9194-004-6 *Doc. 7488* (3rd ed.). Montreal, Quebec: ICAO, 1993.
- [7] International Civil Aviation Organization. *Aeronautical Telecommunications Annex 10* (1st ed.). Montreal, Quebec: ICAO, July 1995.
- [8] World Meteorological Organization. *Guide to Meteorological Instruments and Methods of Observation*. (7th ed.). Geneva, Switzerland: WMO, 2008.
- [9] Lefas, C. C. Real-time wind estimation and tracking with transponder downlinked airspeed and heading data. *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-23, 2 (Mar. 1987), 169–174.
- [10] de Haan S. High-resolution wind and temperature observations from aircraft tracked by mode-S air traffic control radar. *Journal of Geophysical Research*, Vol. 116, D10111 (2011). [Online]. Available: <http://www.agu.org/pubs/crossref/2011/2010JD015264.shtml>.
- [11] Ballisha, B. A., and Kumarb, V. K. Systematic differences in aircraft and radiosonde temperatures. *Bulletin of the American Meteorological Society*, Vol. 89, 11 (Nov. 2008), 1689–1707.
- [12] Drüe, C., Frey, W., Hoff, A., and Hauf, T. Aircraft type-specific errors in AMDAR weather reports from commercial aircraft. *The Quarterly Journal of the Royal Meteorological Society*, Vol. 134, 630 (2008), 229–239.
- [13] B. Schwartz and S. G. Benjamin. A comparison of temperature and wind measurements from ACARS-equipped aircraft and rawinsondes. *Weather and Forecasting*, Vol. 10, 3 (Sept. 1995), 528–544.
- [14] Kalman, R. A new approach to linear filtering and prediction problems. *Transaction of the ASME—Journal of Basic Engineering*, Vol. 82, Series D (Mar. 1960), 35–45.
- [15] EuroControl. Single European sky ATM research programme, <http://www.eurocontrol.int/content/sesar-and-research> Mar. 2012, last access March 2012.