Royal Netherlands
Meteorological Institute
Ministry of Infrastructure and the
Environment

Aircraft as a meteorological sensor

Using Mode-S Enhanced Surveillance data to derive upper air wind and temperature information

Photo cover:
A KLM Airbus A330-200 lands at Amsterdam Airport Schiphol in The Netherlands. Increased aircraft movements will result in a greater number of meteorological observations.

Aircraft as a meteorological sensor

Using Mode-S Enhanced Surveillance data to derive upper air wind and temperature information

Assimilation of Mode-S EHS derived observations in rapid update cycles of numerical weather prediction models will result in better nowcasts of wind information for the meteorological and air traffic management community.

Jan Sondij MBA

Dr. Siebren de Haan

Figure 1: The take off of a Boeing 777-200ER of KLM at Amsterdam Airport Schiphol in The Netherlands. It is from aircraft like these that meteorological observations as wind and temperature are being derived.

BDS Register	**Basic DAP Set** (if track Angle Rate is available)	**Alternative DAP Set** (if Track Angle Rate is not available)
BDS 4,0	Selected Altitude	Selected Altitude
BDS 5,0	Roll Angle	Roll Angle
	Track Angle Rate	
	True Track Angle	True Track Angle
	Ground Speed	Ground Speed
		True Airspeed (provided if Track Angle Rate is not available)
BDS 6,0	Magnetic Heading	Magnetic Heading
	Indicated Airspeed (IAS) / Mach no. (Note: IAS and Mach no. are considered as 1 DAP (even if technically they are 2 separate ARINC labels). If the aircraft can provide both, it must do so).	Indicated Airspeed (IAS) / Mach no. (Note: IAS and Mach no. are considered as 1 DAP (even if technically they are 2 separate ARINC labels). If the aircraft can provide both, it must do so).
	Vertical Rate (Barometric rate of climb/descend or baro inertial)	Vertical Rate (Barometric rate of climb/descend or baro inertial)

Table 1: Mode-S EHS downlink aircraft parameters (DAPs). Fixed wing aircraft that can provide the list of 8 DAPs displayed in this table are considered to be Mode-S EHS capable. Where the parameter 'Track Angle Rate' cannot be provided 'True Air Speed' should be used instead. Source website EUROCONTROL.

Introduction

Upper air atmospheric wind and temperature information is crucial for numerical weather prediction and nowcasting. The current observation systems which are exploited to collect this information are radiosonde, wind profilers, Doppler radar, satellites, and aircraft via the AMDAR program of the World Meteorological Organization (WMO). A novel method to measure wind and temperature is related to tracking and ranging by an enhanced surveillance (EHS) Air Traffic Control (ATC) radar. This EHS radar interrogates in a selective mode (Mode-S) all aircraft in sight on which the aircraft replies with a message containing for example magnetic heading, airspeed and Mach number. From this information wind and temperature can be inferred.

Origin of the initiative

The Royal Netherlands Meteorological Institute (KNMI) started research on utilizing Mode-S EHS data on request of Air Traffic Control The Netherlands (LVNL) in 2008. The objective was to develop and implement a system to provide nowcast and forecast of wind, temperature and air-density data in a 4D grid covering an area with a radius of about 250 NM around Schiphol, from sea-level to FL450. The prime use of this service will be the trajectory prediction function for arrival management of LVNL. A second goal is the provision of meteorological data to airlines and other users in the air traffic management domain. LVNL provided KNMI with a 10 minute update of the Mode-S EHS data containing the downlink aircraft parameters (DAPs) of the BDS registers 4.0, 5.0 and 6.0, see table 1.

The use of ADS-C data - another opportunity to collect meteorological observations

KLM aircraft transmit messages at standard positions or intervals or on request of the KLM dispatch department. These are called Automatic Dependent Surveillance Contract messages (ADS-C) and are different from AMDAR and Mode-S EHS but contain the same type of information. Based on a global set of 76 days of ADS-C messages from KLM a KDC study has been performed in 2011. It showed that around 23 % of the 71.832 messages contained meteorological information. The direct and derived wind observations are of good quality compared to ECWMF data and Mode-S EHS derived observations. The ADS-C temperature observations are of better quality than Mode-S EHS. The Mode-S EHS derived wind information is available with a temporal resolution of 4 seconds, while ADS-C reports are less frequent. Because of this difference in temporal resolution profile information of ADS-C in this data set is limited. Improving the vertical resolution of wind and temperature observations can be achieved by requesting more reports for ascending and descending aircraft, but will result in increased data communication costs.

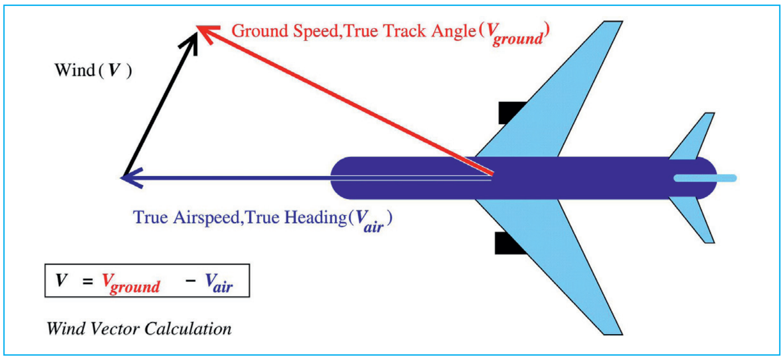

Figure 2: Schematic representation of wind derivation from aircraft flight information. The wind vector (black) is deduced from the difference between the ground track vector (red) and the orientation (heading) and speed of the aircraft relative to the air (dark blue). The ground track vector is constructed by ground speed and true track angle. Note that both heading and ground track angle are defined with respect to true north.

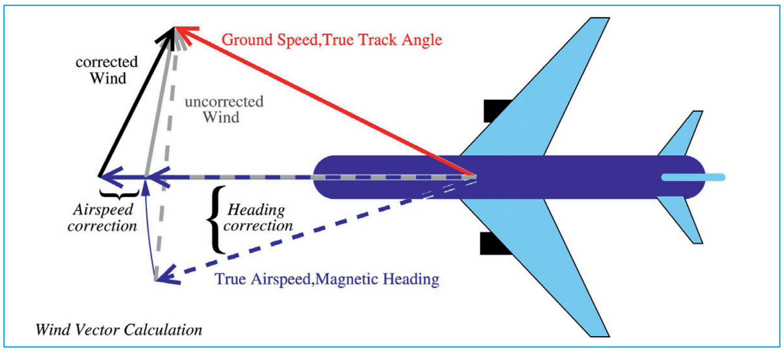

Figure 3: Schematic representation of used heading and airspeed corrections to derive high quality wind estimate from aircraft flight information. The dashed white-blue vector (uncorrected vector) is constructed using aircraft downlink information of magnetic heading and true airspeed (see figure 2). The dashed grey-blue vector is the result when the proper heading correction is applied to correct for heading offsets and to convert to true heading. The solid blue vector denotes the air vector after heading and airspeed correction. In black is the resulting wind after corrections and in grey are the intermediate wind estimates without any corrections visualized as dashed grey, and solid grey with only heading correction applied. The ground track is assumed to be correct.

Derivation process and corrections developed

Since meteorological information is not directly measured in this way, preprocessing is necessary to obtain atmospheric information with adequate quality. Temperature is deduced from the Mach number and airspeed, see separate box. The wind vector is deduced from the difference between the ground track vector and the orientation and speed of the aircraft relative to the air, as is sketched in an idealized setting in figure 2. The ground track is observed accurately but the aircraft orientation contains systematic errors and preprocessing steps for heading and airspeed are essential (figure 3).

Since the magnetic heading is reported a correction to true north is necessary. It is very likely that (slightly) outdated magnetic variance tables are used in aircraft and thus an additional correction might be needed. Research also showed that aircraft have specific and time dependent heading offsets. The true north heading is obtained by a correction of the reported magnetic heading for each individual aircraft and taking into account a latitude and longitude dependent correction based on magnetic variance model as defined using the International Geomagnetic Reference Field by Maus and Macmillan. In order to determine the heading correction two methods have been developed. The first takes into account the heading of the aircraft when it (just) has landed on the runway. When on the runway with a significant speed the heading of an aircraft and the runway should match. The limitation of this method is that heading correction can only be applied for aircraft regularly landing at Amsterdam Airport Schiphol. The second method is by using external wind information and calculating backwards what the heading (and airspeed) of the aircraft should have been assuming that the external wind

Temperature derivation and correction

Mode-S EHS temperature is derived using the measurements of the downlinked Mach number and airspeed. The airspeed is not observed by the aircraft, but derived from the measured Mach-number (using a pitot-probe) and temperature (using a sensor), because the Mach-number is the quotient between the airspeed and the speed of sound. The latter is dependent on the temperature. We use the following equation to determine the temperature (T) from the Mach-number (M) and airspeed (V_{air}),

$$T = Constant * (V_{air}/M)^2.$$

Investigation on temperature differences between numerical weather prediction temperature and Mode-S EHS temperatures revealed aircraft, flight phase (ascending, level flight or descending) and time dependent signals. Therefore, for each aircraft, flight phase and time, a temperature correction is applied to the Mode-S EHS derived temperature which resulted in a decrease of the standard deviation by 50%.

factor is perfect. Wind information from a numerical weather prediction model is used as external source. The heading correction is calculated and used after 40 days with at least 15 days of observations from a specific aircraft. The advantage of this method is that observations are also derived from aircraft that cross the Amsterdam Flight Information Region at cruise level. A dynamic database has been constructed that determines the heading correction using both methods for each individual aircraft every day.

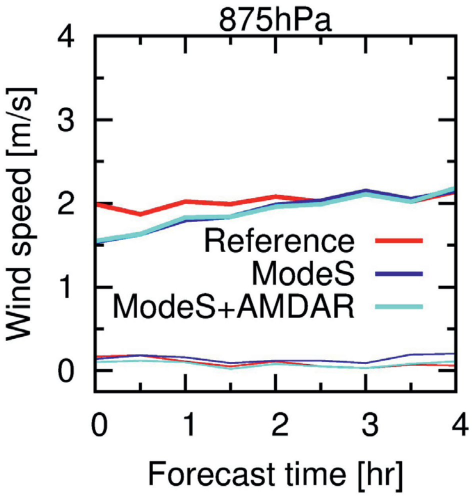

Figure 4: Impact of the assimilation of Mode-S EHS derived wind and temperature information in a Rapid Update Cycle (RUC) Numerical Weather Prediction (NWP) model (HIRLAM) on 850hPa wind forecast. Mode-S EHS wind speed observations are compared to wind speed forecasts at different forecast times for three assimilation trials: reference, Mode-S EHS only, Mode-S EHS and AMDAR. The mean difference (bottom lines) and the standard deviation of the mean differences (top lines) are shown. The statistics of the reference run (no additional information assimilated) is shown in red. The blue lines show the bias and standard deviation when Mode-S EHS derived information is assimilated and the cyan lines show the statistics when additionally AMDAR wind information is assimilated. The impact of only Mode-S EHS information is visible up to 2,5 hours into the forecast, while adding AMDAR extends the impact to nearly 4 hours into the forecast. At the time of the assimilation only the Mode-S EHS data of Schiphol Airport was available. Recent assimilation trials with expanded Mode-S EHS geographical coverage and altered observation error structures of the NWP do show an impact up to 15 hours into the forecast.

Quality of the derived meteorological observations

The developed corrections were applied on a four and half year Mode-S EHS data set and the resulting wind and temperature observations were compared to the ECMWF operational model data.
The Mode-S EHS derived wind direction has a standard deviation between 15 and 20 degrees. The introduction of airspeed correction resulted in an improved wind observation with a reduction of 5 % in wind speed error in the flight direction of the aircraft. By applying the airspeed correction, the wind speed bias is almost zero in this direction, while the heading correction reduces bias and standard deviation in the transversal direction. The improvement in the standard deviation of the wind observation in the north-south and east-west component is respectively 5% and 2%. Comparing co-located AMDAR and Mode-S EHS derived wind observations showed that the standard deviation of Mode-S EHS of 2 m/s is equal to AMDAR above 800 hPa. Below 800 hPa the standard deviation of AMDAR increases from 2 m/s to 2,5 m/s at the surface, while the Mode-S EHS derived wind standard deviation is constant and equal to 2 m/s.
The corrected temperature observations showed an almost zero bias and an improvement of the temperature standard deviation by 50 % above 750 hPa. The temperature observations from AMDAR have a clear better standard deviation of 1 K, although the quality of the Mode-S EHS derived and AMDAR temperature observations at 200 hPa are almost similar. Overall, the quality of the Mode-S EHS derived temperature is clearly less than the AMDAR temperature.

Assimilation in a numerical weather model

Upper air observations, especially wind observations, are important for short-range weather forecasting of extreme weather and for meeting new requirements in aviation meteorology. The impact of timely, high spatial and temporal resolution Mode-S EHS derived observations is assessed on the nowcasting time scale in the HIRLAM NWP by performing experiments without and with the new data. An hourly assimilation cycle is applied to exploit the high resolution (in space and time) of the new observations.
Verification of the forecasts with independent Mode-S EHS aircraft observations shows clear analysis and short-range impact, see figure 4.
The HIRLAM background error and Mode-S EHS observation error statistics were not modified in this

experiment to cope with the large observation densities. Research is ongoing to compute background error correlation structure based on the actual weather observation and by doing so increasing the added value of the new observations for improved weather forecasts.

Benefits for ATM and meteorological community

The future ATM system is developing towards performance based navigation as laid down in the ICAO Global Air Navigation Plan and the associated ICAO Aviation System Block Upgrades (ASBU). Important elements of this evolution, also described in the European ATM Master Plan, are the introduction of concepts such as 4D Trajectory Management, Arrival Managers (AMAN), Departure Managers (DMAN) and Continuous Descent Operations (CDO). An important enabler for these concepts is the availability of accurate and high quality wind nowcast and forecast information. It is envisaged that aircraft could downlink accurate wind information directly as a source for deriving these accurate forecasts. Until this will be implemented, deriving meteorological observations from e.g. Mode-S EHS data and to assimilate these into numerical weather models is an essential component in providing the ATM community with the accurate wind information they require.

KNMI will make available the derived meteorological data from Mode-S EHS sources to the global meteorological community free of charge in line with the WMO practice of sharing information between national meteorological services. Terms and conditions for the use of this information apply, including the disclaimer to not use the data for any commercial purpose.

Limitations

Using the aircraft as a sensor implies that observations are available only at those locations where aircraft are operating. Furthermore, it is essential that ATC interrogates aircraft to provide the EHS BDS registers 4.0, 5.0 and 6.0, and that aircraft are capable to respond to this interrogation. For this reason there are for example no Mode-S EHS data available over the oceans. In these regions other methods of collecting observations can be used like AMDAR or ADS-C, see separate box. And finally, that the meteorological community is able to retrieve the EHS information either directly via ATC or by using a public ADS-B Mode-S EHS receiver, see separate box.

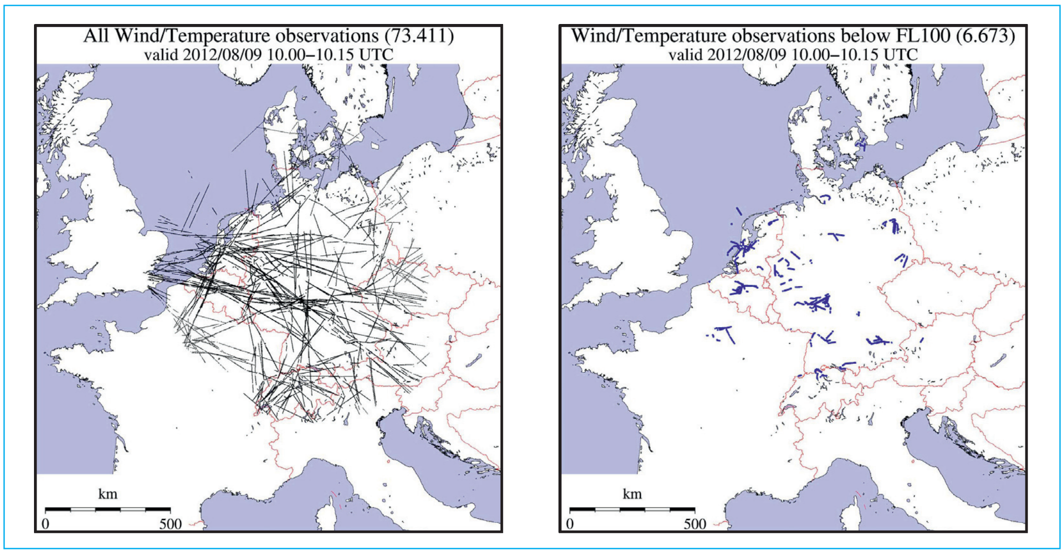

Figure 5: Current coverage of Mode-S EHS derived and quality controlled Wind and Temperature observations available at KNMI. The example shows 15 minutes of observations for a day in August 2012 over Western Europe, source MUAC in ASTERIX Cat 48 format, processed by KNMI. The left panel shows all derived observations, the right panel the derived observations below Flight Level 100. In total there were almost 4 times as many (258.940) BDS 4.0, 5.0 and 6.0 observations available in this time period. The reason that less derived observations are available is the fact that at that time heading correction was only available for aircraft regularly arriving and departing at Amsterdam Airport Schiphol. The number of derived observations will increase when the new correction method based on external sources of wind information will become operational.

Collecting Mode-S EHS data with a commercial off the shelf ADS-B receiver

In cases where ATC is not able or willing to provide Mode-S EHS data a good alternative is the installation of a local receiver. A trial, performed by KNMI in 2012, using a commercial off the shelf ADS-B receiver has shown that Mode-S EHS data can be received, see figure 6. The parameters contain information which can be used to derive upper air wind and temperature observations. The quality of the derived meteorological information is slightly worse than the meteorological data derived from the Mode-S EHS data received from ATC The Netherlands (LVNL). Derived wind speed and direction are within meteorological requirements. Air temperature derived from Mode-S EHS data collected via the ADS-B receiver is not compliant to these requirements. The volume of the derived meteorological information is a fraction, about 8%, of the Mode-S EHS data flow in use by LVNL. As at present the rapid update cycle of the numerical weather prediction model HIRLAM of KNMI uses about 2 % of the available Mode-S EHS data it is expected that the same relevant information for assimilation in HIRLAM can be received through a local ADS-B receiver. The costs of the local installation are in the order of 1.000 Euro. For reasons of coverage, amount and quality of the data, as well as cost efficiency, the reception of Mode-S EHS data directly from ATC is preferred by KNMI.

Figure 6: Data acquisition PC and Mode-S Beast (left) and GP1090 antenna on the roof of the KNMI premises (right).

Next steps and foreseen developments

Currently EHS designated airspace is notified by the Civil Aviation Authorities of Germany, United Kingdom, France, Belgium and The Netherlands. Within this airspace Mode-S EHS data is available in all countries except for France, where data is expected to be available in 2014. It is planned to expand the current geographical coverage of the observations, see figure 5, by exploiting the Mode-S EHS data of France and United Kingdom. The area can be further enlarged over the European area when more States are implementing Mode-S EHS.

A way forward to improve the quality of the temperature observations is the interrogation of BDS register 4.4 which contains a direct temperature read out of the aircraft and is of similar quality as AMDAR. A dialogue with ATC organizations is ongoing to explore opportunities in this regard.

Research on the assimilation of Mode-S EHS derived wind and temperature observations in the non-hydrostatic weather model AROME/HARMONIE is part of the Single European Sky ATM Research (SESAR) program.

As part of sub work package 11.2 Meteorological Services KNMI and MeteoFrance will provide improved wind forecasts based on Mode-S EHS derived observations for validation and verification test bed exercises.

Acknowledgements

The authors wish to express their gratitude for the partial funding of the research by The Knowledge Development Center Mainport Schiphol (KDC), as well as for the support, resources and Mode-S EHS and ADS-C data provided by Air Traffic Control The Netherlands (LVNL), KLM (Royal Dutch Airline), the Boeing Company and the Maastricht Upper Area Control Centre (MUAC) of EUROCONTROL.

About the authors

Jan Sondij, MBA is a senior advisor aviation meteorology and Mode-S EHS program manager, and Dr. Siebren de Haan is a senior scientist in meteorological observations and has the scientific lead of the Mode-S EHS research, both at the Royal Netherlands Meteorological Institute (KNMI).

More detailed information on the Mode-S EHS program of KNMI can be found at mode-s.knmi.nl

This brochure is published by:

Royal Netherlands Meteorological Institute

P.O. Box 201 | 3730 AE De Bilt | The Netherlands
T +31 (0) 30 220 69 11 | www.knmi.nl