# Operational use of Aircraft Derived Data for meteorology and other applications

**Conference Paper** · October 2018



**6 authors**, including:

Paul M.A. de Jong
Koninklijk Nederlands Meteorologisch Instituut


Siebren De Haan
Koninklijk Nederlands Meteorologisch Instituut


Jan Sondij


Michal Koutek
Koninklijk Nederlands Meteorologisch Instituut

# OPERATIONAL USE OF AIRCRAFT DERIVED DATA FOR METEOROLOGICAL AND OTHER APPLICATIONS

Paul M.A. de Jong, Siebren de Haan, Jan Sondij, Michal Koutek, Anika Hoekstra and Jantine Bokhorst

Royal Netherlands Meteorological Institute (KNMI)

P.O. Box 201, 3730 AE De Bilt, The Netherlands

E-mail: jong@knmi.nl

**ABSTRACT**

Nowadays, thousands of aircraft equipped with different sensors roar our skies. These sensors measure various meteorological properties to deduce the aircraft's state vector. For Air Traffic Management (ATM) purposes, parts of the aircraft state vector are broadcast to the ground – through several different techniques – and can in the case of Mode-S EHS and ADS-B data, be freely received by a receiver or through Air Traffic Control's radar installation. Once received, these parameters can be used **to derive** the sensed meteorological properties, such as wind speed, wind direction and temperature, at the location of the interrogation. To make full use of the shear amount of aircraft data that is available, the European Meteorological Aircraft Derived Data Center (EMADDC) is being established to receive, process - including quality control - and distribute the derived wind and temperature data. The quality controlled derived data is assimilated (semi-) operational in several Numerical Weather Prediction (NWP) models in Europe and results in an improved quality of NWP forecasts for up to 15 hours. Currently, data is not derived in real-time but at 15 minutes interval. Future updates are foreseen to get closer to real-time and to use the data in Rapid Update Cycles of NWP. Also the coverage is foreseen to expand to a large part of Europe. Improved wind forecasts are enablers for ATM applications such as Time Based Separation and Continuous Descent Operations. Other non-aviation foreseen uses are improved weather forecasting and for example climate monitoring (re-analysis, in-situ observations). The current status and foreseen improvements of EMADDC are presented.

## *1. Introduction*

Over the last decades, both in Europe and the United States, research programs as Single European Sky Air Traffic Management Research (SESAR) and NextGen, respectively, have driven the development of new surveillance techniques for Air Traffic Management. New surveillance technologies, such as Secondary Surveillance Systems (SSR) Mode Select (Mode-S), a successor to Mode-A/C, and Automatic Dependent Surveillance (ADS) Broadcast and Contract have added more information to be shared between aircraft and ground station.

Modern aircraft carry several sensors to determine their speed relative to air, altitude and other parameters. Using a combination of these parameters, aircraft also determine wind speed and direction that it experiences and display this to the pilot for situational awareness.

The aircraft transponder broadcasts basic flight information to the ground and additional and upon request only, several other parameters. For Mode-S Enhanced Surveillance (EHS), the ATC ground-radar interrogates all aircraft within range in selective mode (Mode-S) in which the aircraft responds with information on e.g. heading, airspeed, Mach number and ground track which can be used to derive wind speed, wind direction and temperature [1] [2] [3].

The start of the Mode-S EHS research was initiated by a request from LVNL (Netherlands ATC) in 2007 to assist in deriving wind information form surveillance data as discrepancies and unexpected outcomes were observed. KNMI investigated and developed over time several routines to improve the quality of the derived wind and temperature observations.

This paper highlights the various aspects that are required to come from a research idea to an operational application that continuously provides quality controlled derived upper air observations. First the current status of EMADDC is described, then the derivation process is explained, and use cases are provided. Finally, the different aspects to realize the EMADDC application are described, followed by conclusions.

## *2. European Meteorological Aircraft Derived Data Center (EMADDC)*

For over a decade, KNMI has been investigating the use of aircraft radar surveillance data as a means of collecting meteorological upper air observations [2] [3] [4]. After several studies and use cases of aircraft derived data, and based on an initial business case, KNMI made the decision to go from a scientific research project to an operational application. This resulted in the establishment of the European Meteorological Aircraft Derived Data Center (EMADDC) project as part of the European SESAR Deployment. The objective of EMADDC is to obtain as many near real time quality controlled meteorological upper air observations (wind and temperature) for Europe at large for as little cost as possible. This is achieved by implementing an operational service for collecting, processing and disseminating Mode-S EHS derived, quality controlled meteorological data.

The SESAR Deployment project runs until the end of 2020 and is led by KNMI, the Royal Netherlands Meteorological Institute. The Met Office (United Kingdom) is cooperating and contributor to the EMADDC project. It is anticipated that EMADDC will be part of the EUMETNET Aircraft Based Observation (E-ABO) program as of 2021.

### 2.1 Aircraft Derived Data (ADD) collection methods

Although several technologies are available to retrieve aircraft data [5], this paper focuses on Mode-S EHS surveillance data. Other surveillance technologies that can be used to derive or obtain meteorological data are briefly described.

The Mode-S technology also defines the Mode-S Meteorological Routine Air Report (MRAR) in BDS register 4.4 [6]. This register provides direct measurement of wind speed, direction and temperature. The register also allows for transmission of sensed turbulence and humidity, however, in practice, these parameters are not relayed as most aircraft do not carry sensors for these parameters. Also, Mode-S MRAR is not mandatory and only few aircraft (less than 5%) fill this register (with wind speed and wind direction) which in most cases is not interrogated by ATC radar at all.

A second technology is Automatic Dependent Surveillance – Broadcast (ADS-B) which uses the Mode-S Extended Squitter (ES) 1090 MHz data-link to transmit position and velocity data to ATC and other aircraft. The data is used onboard aircraft to provide situational awareness and used by onboard Traffic Avoidance (TA) systems. ADS-B contains BDS 0.E to 0.9 messages to provide additional positional (altitude) information that can be used for deriving temperature through an altitude layer [7].

The third technology works per contract basis and is thus not freely broadcasted or received. This technology is named Automatic Dependent Surveillance – Contract (ADS-C) and ADS-C messages are generated by contract request only, hence its name. The contract request can be a query to report a set of parameters repeatedly at certain intervals. The basic data contains the same data as ADS-B, but additional data can be requested, such as direct measurements of meteorological data (wind speed, wind direction, temperature, turbulence and humidity (if available)), or derived [8].

Mode-S EHS surveillance data can be collected from local ATC organizations. Alternatively, Mode-S EHS ADS-B receivers can be deployed locally when data delivery from ATC is not possible [9]. In this case the ADS-B data is used to identify the location of the aircraft. An overview of the two methods to collect Mode-S EHS data is given in Figure 1.

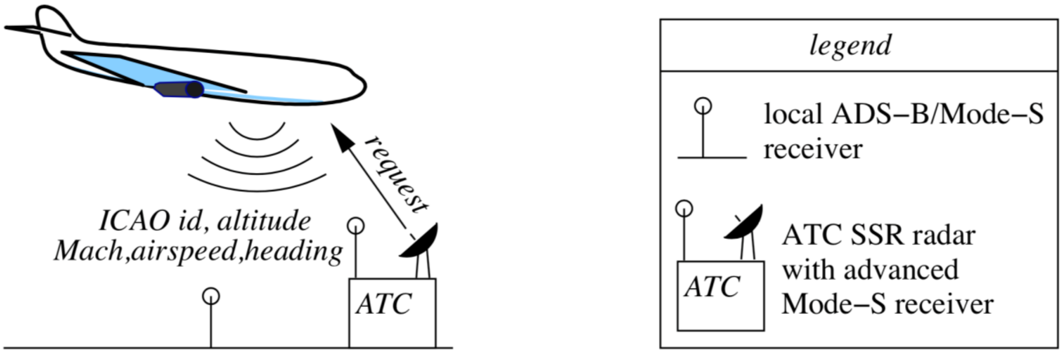


**Figure 1: The two methods of receiving Mode-S EHS data on interrogation of ATC.**

Note that a prerequisite is that ATC or military radar interrogates aircraft for the Mode-S EHS registers (BDS 4.0, BDS 5.0 and BDS 6.0), which is not always the case. Furthermore, the interval at which the interrogation occurs varies, and hence the time resolution of received data depends per country and even per radar installation.

## 2.2. The derivation process explained

The derivation of wind speed and direction from Mode-S EHS surveillance data resolves around the following principle: wind affects the aircraft track over ground and thus by calculating the difference between the expected flight path and the actual (ground) track, an estimate of the wind can be derived;

$$\vec{V}_w = \vec{V}_g - \vec{V}_a \#(1)$$

In which $\vec{V}_w$ is the wind vector, $\vec{V}_g$ is the ground vector and $\vec{V}_a$ the true airspeed respectively. This is shown graphically in Figure 2.

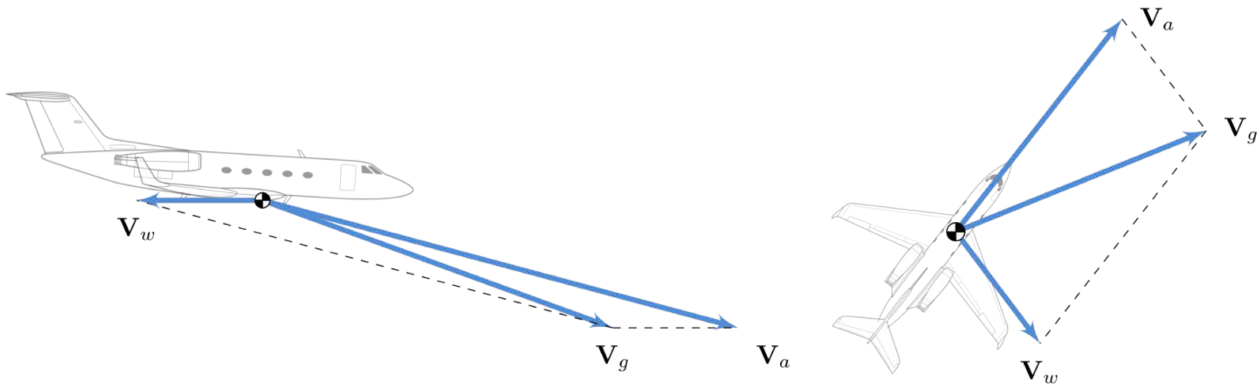


**Figure 2: Geometry of an aircraft's path with respect to air and ground.**

The ground speed is measured horizontally over ground, and hence, parallel to the horizon. A vertical component of ground speed is not received and for meteorological purposes, the horizontal component of wind is of interest mainly. This results in the following equations when decomposing the wind equation 1 in North and East direction on the horizontal plane;

$$\mathrm{V}_{\mathrm{w}_x} = V_g \cos \chi_t - V_a \cos \chi_a \#(2)$$

$$\mathrm{V}_{\mathrm{w}_y} = V_g \sin \chi_t - V_a \sin \chi_a \#(3)$$

In these equations, $\chi_t$ and $\chi_a$ are (true) track angle and (true) heading angle (with respect to air stream) respectively.

The state parameters provided by aircraft can also be used to derive temperature using Mach number $M$, speed of sound $c$ and true airspeed $V_a$;

$$M = \frac{V_a}{c} = \frac{V_a}{\sqrt{\gamma R\, T}} \#(4)$$

$$T = \frac{1}{\gamma R} \left(\frac{V_a}{M}\right)^2 \#(5)$$

In these equations, $\gamma$ is the ratio of specify heats and $R$ is the universal gas constant which both are constants.

The received interrogations require quality-control to disqualify fault parameters. This could occur due to transmission errors but also due to mechanical or physical errors which need to be filtered out in order to obtain sufficient quality of the parameters.

Using the equations above on quality-controlled data without applying corrections, the wind east-west component typically contains a bias close to zero while the north-south component contains a slightly larger bias [3]. Standard deviations of the error, when comparing to ECMWF NWP data, depend on altitude and typically range than 2.0 m/s to 3.5 m/s. Note that these values consists of observation error and model error. By applying various corrections, discussed later in this paper, the standard deviation with respect to NWP is reduced significantly to values below 3.0 m/s, while slightly improving the bias as well [3]. Absolute wind error estimates, based on triple collocation, show values of 1.5 to 2.0 m/s [4].

For derived temperature data, the corrections mainly improve the bias present in the temperature observations to values better than AMDAR observations [3]. The standard deviation (with respect to NWP), however, is only improved at higher altitudes but is larger than 2.5 K at lower altitudes near the surface [3]

## *3 Use cases*

There are many use cases for the enormous amount of quality controlled upper air observations for the MUAC area that is now available and will expand geographically in the near future. The data set can for example be used for verification or validation of other observations or for climate monitoring. The observations can also be used for assimilation in NWP, operational use in the weather room, or in ATM concepts, and these are explained in some more detail in this section.

### 3.1 Assimilation into Numerical Weather Prediction (NWP)

In 2010, a first experiment [10] investigated the impact of assimilating aircraft derived upper air observations into HIRLAM [11]. The impact was assessed by performing NWP experiments with and without the derived observations in the HIRLAM NWP model. The model was configured to be close to the settings, boundaries and inputs used operationally at KNMI at the time and data was assimilated using 3DVAR.

The experiment was carried out in the winter with varying weather and therefore the impact statistics vary over time, but generally show a beneficial impact in the most variable (and uncertain) weather. When the Mode-S EHS observations, limited to the Netherlands, were complemented with more globally available Aircraft Meteorological DAta Relay (AMDAR) observations, the synergy of the two variants of observations became clear and improved impact even further. Interestingly, the impact of AMDAR observations alone was negligible. This is a clear indication that the availability of more airport surveillance radar aircraft observations would further improve the analyses and forecasts in our area of interest. Largest impact is seen in the first hours and up to 15 hours of a forecast, hence derived data could be of particular use in nowcasting.

Meanwhile, on an experimental basis, aircraft derived data has been assimilated in experimental versions of KNMI’s Harmonie Mesoscale-NWP to investigate effects on newer versions of the operational NWP. Within the next year, work will start in applying 4D-VAR to assimilation of aircraft derived data to further investigate potential benefit of this assimilation system on the forecast impact.

Similar studies showing positive impact have been performed in several other countries (e.g. United Kingdom, Germany and Slovenia). [6] [12]

### 3.2 Vertical Profiles of Temperature and Wind

The aircraft derived data is also used by meteorologists in KNMI’s weather room. By collecting all quality controlled and corrected observations within a 50 x 50 km area around an airport, a vertical altitude profile is constructed for that airport for wind speed, wind direction and temperature. These profiles are visualized and displayed to the meteorologist on duty. A sample profile is shown in Figure 3.

Besides an overall vertical profile of temperature, wind speed and wind direction are displayed on the left. A zoomed-in figure is displayed for the lower altitudes containing numerical values for the wind speed and direction. This zoomed-in figure increases visibility and provides a higher resolution in the lower area of the atmosphere. The resulting freezing level ($T = 0°K$) is also depicted in the figure.

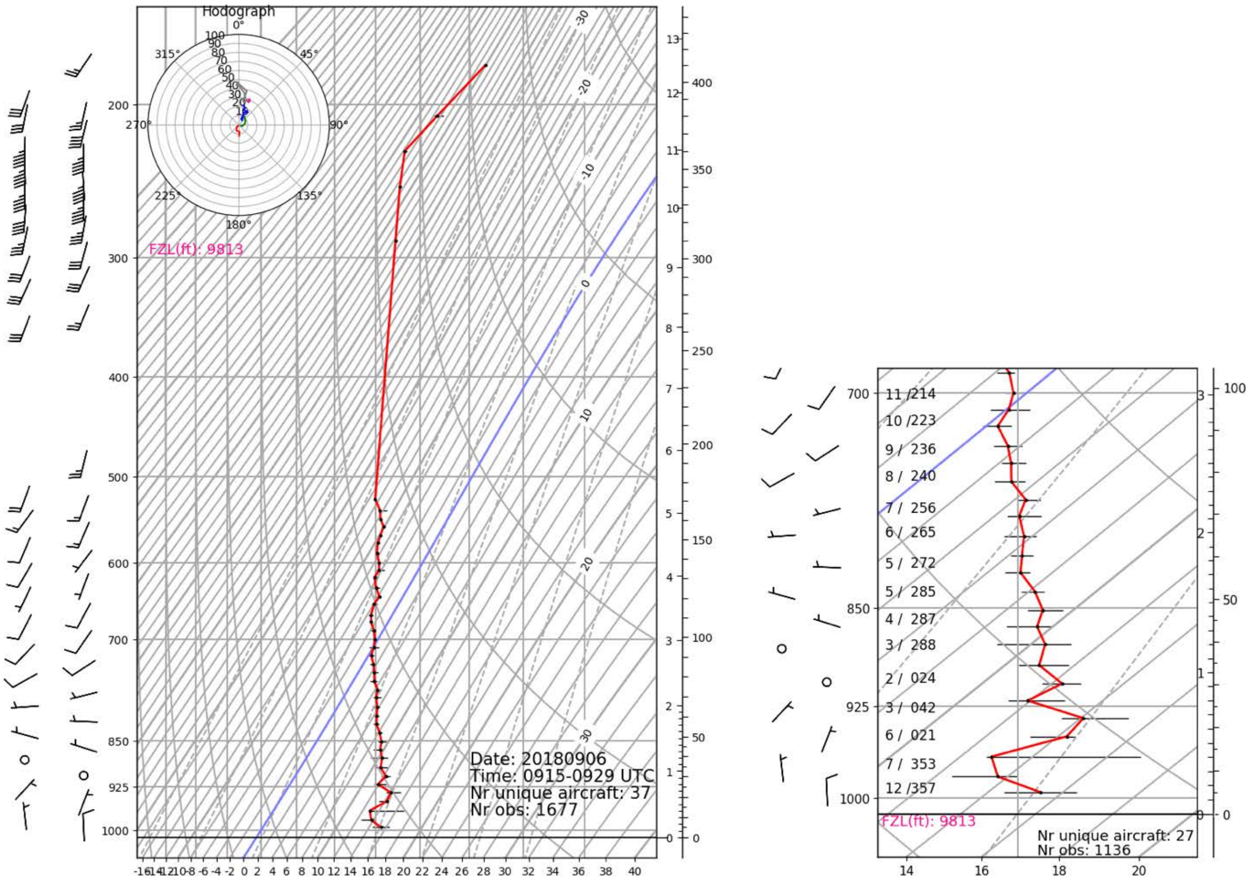


**Figure 3: Vertical profile of wind speed, wind direction and temperature based on 15 minutes of Mode-S EHS data at 6 September 2018.**

This profile is generated based on all data points of a processed file. Since currently data from MUAC is received at 15-minute batches, a profile is constructed using data within that 15-minute timeframe and thus four profiles are constructed per hour. This is a significant improvement over the hourly AMDAR profiles for Schiphol Airport that are currently in use. The profiles show median temperature for an altitude interval and also show the number of observations and unique aircraft. When an altitude interval contains less than 10 observations, the error bars are shown in red to indicate a lesser quality for temperature. Unpublished research has shown that the quality of the temperature profiles from aircraft derived data are of similar quality or better than AMDAR profiles when a minimum of 10 temperature observations are available for an altitude interval.

## 3.3 Air Traffic Management concepts

The derived upper air information (wind and temperature) is of high temporal and spatial resolution and particularly of interest to the aviation domain and ATM concepts like 4D trajectories [13]. Since wind speed and direction affect the movement of aircraft to a great extent [14] and determine the time (the fourth component of the trajectory) an aircraft passes a certain waypoint, high quality wind forecast information supports an aircraft in meeting time requirements along its trajectory. Since both an airborne aircraft, and ATC on ground perform trajectory predictions, both airlines and ATC will benefit from improved wind forecasts. KNMI provides improved wind forecasts to LVNL (Netherlands ATC) and MUAC for research and validation purposes. Apart from improved forecasts the derived observations itself can be used by ATM when applying for example Time Based Separation concepts.

## *4 The EMADDC Application*

A small and dedicated KNMI team has been created to develop, implement and maintain EMADDC. For several elements this is done in cooperation with the UK Met Office. This section describes several aspects of EMADDC in some more detail.

EMADDC version 1.0 will become operational before the end of 2018 and is now running in a semi-operational mode. The outcome of version 1.0 is verified with the outcome of the prior developed scientific version. Version 1.0 is in essence similar as the scientific version, however the software has been rewritten in line with KNMI policies, is stored in version control, and uses a phased approach of testing and deployment on a DTAP street (Development, Testing, Acceptance and Production). The hardware runs on a government data center (Equinix) in Amsterdam and not at KNMI at De Bilt.

EMADDC version 2.0 is planned for 2019. This version will include additional functionality to deal with different data type inputs and to allow near real time processing. It will also include a location (longitude and latitude) dependent magnetic deviation correction. The architecture of the system will very likely be changed in order to cope with many data streams (scalable) and will most likely use a database for processing - instead of a file query system – and for archiving. An analysis is being performed to select the most appropriate and future proof software and coding tools, considering KNMI data science policies.

### 4.1 Current and foreseen coverage area

The current area of coverage is The Netherlands, Belgium, Luxemburg and the most part of Germany as shown in Figure 4 below. The surveillance data is being provided by the Maastricht Upper Area Control Centre (MUAC) of EUROCONTROL based on an NDA.

The data is received in 15-minute batches which during the day contain roughly 200.000 interrogations per batch. During the night, these number decrease drastically due to the lower number of active flights to below 18.000 interrogations. On a daily basis in total more than 10 million 'raw'' interrogations are available. Out of the 200.000 raw observations per 15 minutes during day time, roughly 50.000 quality-controlled observations can be obtained, aggregating to more than 3 million observations per day.

Besides the MUAC data set, experimental data is currently received from Danish ATC and from a local Mode-S EHS ADS-B receiver in France and Ireland. In the near future, data from multiple local Mode-S EHS ADS-B receivers within United Kingdom and Ireland is expected as well. Negotiations are started with for example Austria, Switzerland, Czech Republic and Slovenia and it is expected to expand the coverage significantly in 2019.

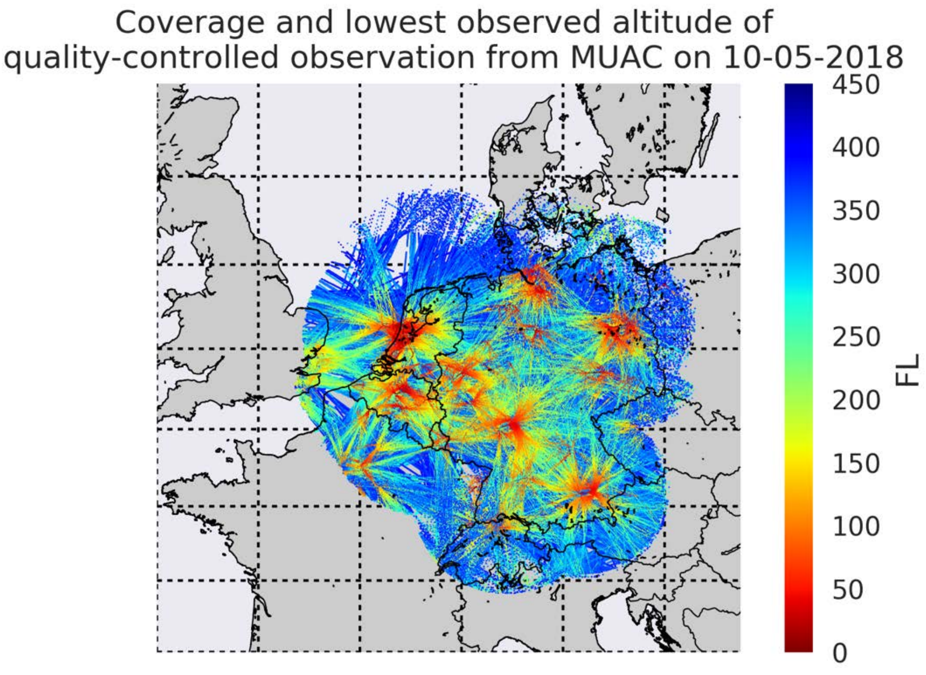


**Figure 4: Geographical coverage and overview of lowest observed quality-controlled Mode-S EHS interrogations from MUAC on 05-10-2018.**

## 4.2 Input and output data types

Surveillance data containing Mode-S EHS data is provided in all-purpose structured EUROCONTROL surveillance information exchange (ASTERIX) data format. ASTERIX was designed for exchanging surveillance-related information for communication media with limited bandwidth. This is why it follows rules that enable it to transmit all the information needed, with the smallest data load possible. EMADDC 1.0 uses ASTERIX CAT048 and CAT062. Mode-S EHS data is also provided by other partners like LVNL in the ASCII format.

The data is provided by using the File Transfer Protocol (FTP) and KNMI retrieves the data. Under investigation is the opportunity to use the NewPENS network that is currently being rolled out in Europe [15]. It could improve the coverage and timeliness of surveillance data if EMADDC could use this network to receive surveillance data from all over Europe.

The processed data results in quality controlled upper air observations of wind speed, wind direction and temperature for the MUAC area. The data is available in ASCII, NetCDF and BUFR WMO(7). Using BUFR posed a challenge as no data identity for Mode-S EHS or other aircraft derived observations is available. For this reason, EMADDC is in the process of proposing a new identity in support of aircraft derived data. [5]

## 4.3 Software application

The EMADDC processing software contains several methods to improve the quality of derived data. A first step is quality control to disqualify observations that do not match quality criteria. Secondly, several corrections are applied to further improve the quality in terms of accuracy and precision.

### 4.3.1 Quality Control

Due to both mechanical and aerodynamic behavior of the aircraft but also possible errors in data transmission, a number of verification steps are performed to control the quality of the raw data. When an aircraft is turning, the flow around the aircraft is disturbed, resulting in erroneous measurements in the pitot-tubes which result in equation 1 to be invalid. Therefore, observations in which the aircraft exceeds a threshold bank angle are discarded. Furthermore, lower and upper limits are set for certain parameters to assure physical sanity. Finally, since often an observation is received by multiple radars due to overlapping, a simple timing check is performed to disqualify duplicate observations.

### 4.3.2 Corrections

The heading value received from aircraft in Mode-S EHS interrogations are defined with respect to magnetic north. Aircraft however, do not sense this parameter directly but in turn measure heading with respect to true north and use lookup tables to obtain a value with respect to magnetic north. KNMI found that the error in wind resulted from the use of different lookup tables by individual aircraft. Tables could potentially also be outdated and therefore a reasonable conversion from received magnetic heading to true north heading as required in Equations 2 and 3 is not possible. To overcome this issue, and to improve the quality of the derived wind information, a heading correction method was developed.

To resolve this issue, the correction method applied uses the fact that aircraft land on a runway with a fixed magnetic heading. The offset between the reported magnetic heading upon touchdown and rollout of an aircraft and the actual runway heading, can be used to derive a correction term [2]. An initial version of the processing software used the runways of Schiphol to determine heading correction terms.

This method has proven to work well but suffers from one great disadvantage being the requirement that an aircraft lands (at Schiphol) and data at runway level is available. Although the requirement for Schiphol could theoretically be lifted by implementing similar logic for other airports, this is labor intensive, not very efficient and requires data when the aircraft is no longer airborne which is not available everywhere depending on the contract with ATC and location of radars or receivers.

For this reason, a novel method [3] was developed that uses NWP forecast data as an external source for the heading. Instead of using externally gathered magnetic heading observations, an inverse approach is applied. External wind information is used to calculate the heading (and airspeed) of the aircraft assuming the external wind information is perfect. A daily average of the previous heading errors is compared to a running mean of the last 40 days to obtain new correction values for each individual aircraft for the current day. This method can be applied to all observations that pass quality control and for which an external wind NWP information is available increasing the amount of derived observations significantly.

To improve temperature and airspeed, a similar correction method using NWP data is used as well [3]. For temperature, the correction is flight phase dependent (climb, cruise or descent) while for airspeed the correction is airspeed dependent.

Graphically the correction terms can be seen in Figure 5. First, the true airspeed is corrected using the heading correction $\chi_{cor}$. This results in a new true airspeed, $\tilde{V}_{a_{cor}}$, in the correct direction but with incorrect magnitude. Adding the true airspeed correction yields the corrected true airspeed with combined with the ground speed yields the wind vector $V_w$ which differs from the uncorrected wind vector $\tilde{V}_w$ .

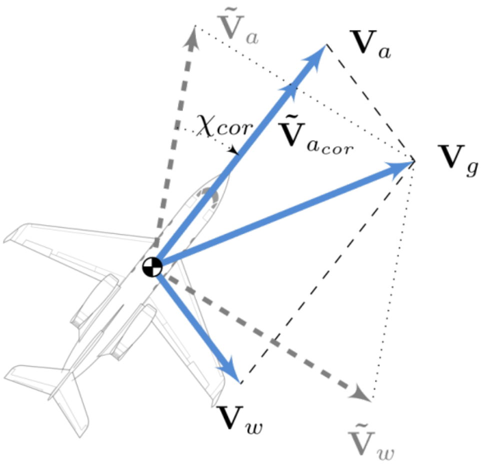


**Figure 5: Graphical overview of the different corrections to improve wind vector quality.**

### 4.3.3 Validation

In order to use the aircraft derived data, it is required to prove that the quality of derived data is sufficient for its applications. Several experiments have been carried out to validate the derived values which in turn resulted in several new correction methods to further improve the quality [1].

Since the true value of wind and temperature at the location of an aircraft is unknown, collocation with radar, sodar and NWP data was used to compare wind speed and direction [4]. The investigation showed that Mode-S EHS wind contains an observation error of approx. 1.40 m/s in zonal direction and 1.45 in meridional direction with an uncertainty of about 0.1 m/s.

To estimate the quality of derived temperature, collocation of observations over a 4-and-a-half-year period with data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and AMDAR observations was performed [3]. This experiment showed that the observed temperature error for corrected Mode-S EHS derived temperature was slightly better than AMDAR temperature observations. However, the uncertainty of an observation deteriorates for lower altitudes in the case of Mode-S EHS observations due to the low resolution of airspeed and Mach number that become more apparent at lower speeds and hence lower altitudes of a standard deviation of up to 2.5 K for temperature at near surface level. [16]

## 4.4 Operational system

Over the last few years the processing has run on a scientific basis. Also, the current operational agreements with data suppliers do not contain a specific service level. Such, outages of data have occurred, although not very frequent. As EMADDC will become operational the agreements will be updated to achieve improved continuity of input data streams.

EMADDC software runs on four different machines, using the DTAP (development, testing, acceptance and production) approach. The first two machines are used by developers and scientists for development and software testing. The third machine is used operationally for acceptance testing of new software versions and input data and to run the operational software as an additional backup and the fourth machine runs the operational software. This set-up allows for a phased approach and stable testing of new software versions and new data inputs without interruptions to users of the data.

Currently, the operational machines are being integrated into KNMI's 24/7 process chain management monitoring department. It is expected to be fully operational, including 24/7 monitoring before the end of 2018. This includes the development of tools that support automatic monitoring in case a system or machine fails. Alerts are presented to the process operator when data is not received for quite some time and in case processing fails. The corrections process, which calculates individual aircraft corrections, is also monitored and can be verified in case the amount of processed data is not as expected.

Actual monitoring of each individual derived observation is not possible manually due to the shear amount of observations easily exceeding 50.000 in a 15-minute batch. For this reason, a monitoring system has to be developed that provides, for example bias and standard deviation statistics with respect to an NWP forecast. If these statistics deviate from a running average, this could indicate a processing problem which requires manual investigation. It will require significant development to find solutions for the continuous monitoring of the quality of derived observations.

## 4.5 Future steps

It is expected that EMADDC 2.0 will increase its coverage to the United Kingdom and Central and Northern Europe in the coming year. Negotiations with MUAC are ongoing to increase the update frequency of the surveillance data and have more guarantees for non-interrupted data provision in order to improve the continuity and availability of EMADDC output.

The heading correction process currently uses Schiphol as a reference for magnetic declination [3] which is valid for the MUAC area currently being processed. The magnetic declination varies depending on position on the Earth's and changes over time. The correction routine for EMADDC 2.0 needs to be updated to account for the anticipated larger coverage area. This means that individual aircraft corrections will also depend on the position (longitude and latitude) of an aircraft to properly account for the changing magnetic deviation throughout Europe.

The EMADDC 2.0 software will no longer store the processed data in fixed data formats. Instead, it is foreseen that an online database will be used to store raw surveillance data aggregated with processed observations and quality control flags. New tools will allow easy extraction of different parameters in a format of choice. This online approach is in line with KNMI's digital strategy for the future which is a prerequisite when developing software at KNMI.

The new version will be developed based on new insights, functionalities and KNMI digital strategy. The tools, languages and libraries (currently a mix of C, Fortran and scripting) to be used will be selected based on functional needs, architecture and KNMI digital strategy. This includes the use, where possible, of freely available open-source software and tools.

The software will be adapted to allow for adding new types of data, for example ADS-C meteorological observations from airlines are of high quality [8] and could be used to improve corrections and/or aggregate the output data.

A specific work package of EMADCC is for KNMI and UK Met Office to develop a standalone local Mode-S EHS ADS-B receiver. This receiver can be used by national meteorological services to collect surveillance data if for some reason the data cannot be provided by Air Traffic Control. The receivers are cost effective and can be easy installed and configured to receive Mode-S EHS interrogations and ADS-B messages. The software will allow for easy uploading to EMADDC software for further processing and dissemination.

Use cases will be performed in more detail. For example, to identify the added value of EMADDC upper air observations for the HARMONIE NWP of KNMI, and impact using 4DVAR assimilation.

Finally, a new EMADDC website is under construction to replace the current mode-s.knmi.nl website. The website is to inform stakeholders about the possibilities, status and benefits of using aircraft derived data like Mode-S EHS. The website will also contain information for stakeholders on how to cooperate in the program and share surveillance data with EMADDC.

## *5 Conclusions*

Upper air observations that are derived from Mode-S EHS data in Europe have proven to be of benefit to the meteorological and aeronautical community. Research and development are ongoing to improve the quality of the derived data. But the huge temporal and spatial resolution of the data itself is already of great benefit to NWP and other applications. The process to transfer from a scientific research project towards an operational 24x7 monitored application like EMADDC is complex. This paper described the various aspects that have to be considered when developing and implementing an operational center like EMADDC and sketches the foreseen future steps.

## *Acknowledgements*

Suppliers of surveillance data: MUAC, LVNL and KLM.
The UK Met Office as contributor to the EMADDC project.
EMADDC is co-financed by the Connecting Europe Facility of the European Union.

## *References*

[1] S. de Haan, “Quality assessment of high resolution wind and temperature observation from ModeS,” KNMI, De Bilt, 2010.

[2] S. de Haan, “High-resolution wind and temperature observations from aircraft tracked by Mode-S air traffic control radar,” *Journal of Geophysical Research,* vol. 116, no. D10111, 2011.

[3] S. de Haan, “An improved correction method for high quality wind and temperature observations dervied from Mode-S EHS,” KNMI, De Bilt, 2013.

[4] S. de Haan, “Estimates of Mode-S EHS aircraft-dervied wind observatio errors using triplle collocation,” *Atmospheric Measurement Techniques,* vol. 9, pp. 4141-4150, 2016.

[5] EUMETNET E-ADD Feasability Study Expert Team, “Final report of the EUMETNET ADD FS ET on the feasibility to initiate a new EuMETNET activity for aircraft derived observations under the EUMETNET observation program,” KNMI, De Bilt, 2017.

[6] B. Strajnar, N. Žagar and L. Berre, “Impact of new aircraft observations Mode-S MRAR in a mesoscale NWP model,” *J. Geophys. Res. Atmos.,,* vol. 120, p. 3920–3938, 2015.

[7] E. Stone and M. Kitchen, “Introducing and approach for extracting temperature from aircraft GNSS and pressure altitude reports in ADS-B messages,” *Journal of Atmospheric and Oceanic Technology,* vol. 32, no. 4, p. 736–743, April 2015.

[8] S. de Haan, L. J. Bailey and J. E. Können, “Quality assessment of Automatic Dependent Surveillance Contract (ADS-C) wind and tempreature observations from commercial aircraft,” *Atmospheric Measurement Techniques,* vol. 6, pp. 199-206, 2013.

[9] S. de Haan, J. Sondij and M. de Haij, “The use of a commercial ADS-B receiver to derive upper air wind and temperature observations from Mode-S EHS information in The Netherlands,” KNMI, De Bilt, 2013.

[10] S. de Haan and A. C. M. Stoffelen, “Assimilation of High-Resolution Mode-S Wind and Temperature Observations in a Regional NWP model,” *Weather and Forecasting,* vol. 27, pp. 918-937, 2012.

[11] P. Undén, L. Rontu, H. Järvinen, P. Lynch, J. Calvo, G. Cats, J. Curxart, K. Eerola, C. Fortelius, J. Garcia-Moya, C. Jones, G. Lenderlink, A. McDonald, R. McGrath, B. Navascues, N. Nielsen, V. Odegaard, E. Rodriguez and M. Rummukainen, “HIRLAM-5 scientific documentation,” HIRLAM-project, Norrkoping, 2002.

[12] H. Lange and T. Janjić, “Assimilation of Mode-S EHS Aircraft Observations in COSMO-KENDA,” *Monthly Weather Review,* vol. 144, pp. 1697-1711, 2016.

[13] SESAR, “European ATM Master Plan,” EUROCONTROL, Brussels, 2012.

[14] P. M. A. de Jong, J. J. van der Laan, A. C. in 't Veld, M. M. van Paassen and M. Mulder,

"Wind-Profile Estimation Using Airborne Sensors," *Journal of Aircraft,* vol. 51, no. 6, pp. 1852-1863, 2014.

[15] EUROCONTROL, "New pan-European Network Service (NewPENS)," 2018. [Online]. Available: https://www.eurocontrol.int/new-pens. [Accessed September 2018].

[16] E. K. Stone, "A comparison of Mode-S Enhanced Surveillance observations with other in situ aircraft observations," *Q J R Meteorol Soc,* vol. 144, no. 712, p. 695–700, 2018.