

EUMETNET Aircraft Derived Data Feasibility 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.

Prepared by EUMETNET ADD FS ET

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Version 1.0



A KLM Airbus A330-200 takes off at Amsterdam Airport Schiphol in The Netherlands. It is from aircraft like these that meteorological observations as wind and temperature are being derived.

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1 Introduction

The main objective of the EUMETNET Aircraft Derived Data (ADD) Feasibility Study is to study the feasibility of operational collection of ADD data for meteorological purposes. The study was triggered by various initiatives employed by Members to obtain and derive meteorological observations from aircraft data. Programs as Single European Sky (SES) and NextGen (Next Generation Air Transportation system – US FAA) are the main drivers for more and new aircraft data to become available.

New air traffic control surveillance technology like ADS-B and Mode-S are designed to help modernize the air transportation system. They provide foundational technology for improvements related to the Single European Sky Air Traffic Management Research program (SESAR), aiming to support a larger volume of airplanes more efficiently. The European Community (EU) and EUROCONTROL are the founding members of SESAR.

The changing environment, as this study will show, offers great potential to either obtain or derive wind direction, wind speed and temperature observations in numbers unprecedented in the European region. These observations in itself can be useful to aviation stakeholders and for the overall meteorological community. Furthermore, assimilating these additional observations in numerical weather prediction models enables rapidly updated short-range weather forecasts with improved quality and this is beneficial to both the meteorological community as a whole, and the aviation domain for operational and planning purposes. This will improve meteorological services for aviation including updates to aircraft in flight. As such one could argue that this is a classic example of a win-win situation for all parties involved.

Similarly, the way in which meteorological information is derived from aircraft derived data can be seen as a ‘big data’ case, and offers great potential when made available to users in Europe in line with open data policies based on the European legislation on re-use of public sector information.

In the end one of the objectives of the meteorological community is to obtain as many high quality meteorological observations for as little costs as possible, while maintaining the productive cooperation with the airlines developed through E-AMDAR which allows for improved sensors on aircraft. As such the Expert Team does propose to start a separate EUMETNET activity under the observations program to operationally process aircraft derived data and disseminate this data as part of the European Meteorological Infrastructure (EMI) to all European stakeholders.

Having that said, as always the devil is in the detail. This study describes in more detail the various types and sub-types of ADD data, and the various ways and methods for obtaining and processing the data. A proposal for EUMETNET PFAC and STAC is included to start with the preparations of a pre-operational service.

September 28th, the EUMETNET ADD FS ET

2 Executive summary

One of the objectives of the meteorological community is to obtain as many high quality meteorological observations for as little costs as possible. New air traffic control surveillance technologies present opportunities to obtain or derive wind direction, wind speed and temperature from aircraft derived data (ADD). A feasibility study is performed to identify the opportunities and added value for EUMETNET to implement an operational ADD data processing center.

The following ADD data types and sub-types have been identified and studied for potential meteorological use. Each data type has its own characteristics with consequential pros and cons.

| Type | Sub-type | Direct meteorological information | Derived meteorological information | Remarks |
|---|--------------------------|-----------------------------------|------------------------------------|---|
| Automatic Dependent Surveillance (ADS) | ADS-B | ✗ | ✓ | - Only wind - Small number - Poor quality |
| | ADS-B ES | ✗ | ✓ | - Small number - Poor quality |
| | ADS-C | ✓ | ✓ | - Only small portion of messages - Good quality - Data only via ATC or airlines - Data communication costs |
| Secondary Surveillance Radar (SSR) Mode-S | Mode-S ELS | ✗ | ✗ | - |
| | Mode-S EHS | ✗ | ✓ | - Specific dynamic aircraft corrections and quality control required - Good quality wind - Lower quality of temperature - Exceptionally large amounts of observations - Data distribution costs still to be negotiated with ATM community |
| | Mode-S MRAR | ✓ | ✗ | - Small number - Good quality |
| | Mode-S MET Hazard Report | ✗ | ✗ | - |
| E-AMDAR (for comparison) | E-AMDAR | ✓ | ✗ | - Requires on-board AMDAR software - Contract with airlines - Data communication costs - Good quality |

With the exception of ADS-C and E-AMDAR data all sub-data types can be collected via local ADS-B/Mode-S receivers. For Mode-S data types an interrogation of an authorized body (Air Traffic Control - ATC) is a precondition. As already existing Air Traffic Management infrastructure is utilized there are no data communication costs involved. ADD data can be provided by ATC for free or for distribution costs. In situations where ATC is reluctant to provide the ADD data or asks excessive fees the meteorological community can deploy local receivers.

ADS-C and E-AMDAR data need to be provided by ATC or airlines, and cannot be intercepted with local receivers. These ADD data have a global coverage, as opposed to Mode-S data, and involve data communication costs.

The expected future volume of the various ADD sub-types in Europe, and thus the potential, has been analyzed in detail. The European region is almost entirely covered with secondary surveillance radar systems, and Mode-S ELS and Mode-S EHS use the same ground based surveillance infrastructure. At the moment many of the radars are interrogating Mode-S ELS only. This offers an enormous future potential for Mode-S EHS interrogation by ATC organizations. However, updating from ELS to EHS radar interrogation is not trivial for ATC with regard to bandwidth of radar data communication and network capacity issues.

Based upon EU regulations a significant number of aircraft are Mode-S EHS compliant and this number will further increase for all aircraft (maximum take-off mass exceeding 5.700 kg or maximum true airspeed capability greater than 250 knots) in the near future (2020).

Secondary Surveillance Radar capability requesting Mode-S EHS data is already available and operational in United Kingdom, The Netherlands, Belgium, Germany, Czech Republic, Slovenia and soon to be in France. Based on EU regulations it is expected that SSR capability will be expanded towards Italy, Austria, Hungary and Romania before 2020. Whether all the radars will interrogate Mode-S EHS is uncertain.

Interrogation by these radars results for the Maastricht Upper Area Control Centre (MUAC) area alone in more than 20 million 'raw' Mode-S EHS reports per day. After quality control and corrections more than 3,5 million derived observations of wind direction, wind speed and temperature are available daily for use in meteorological applications. These numbers can be further increased by improvements of the derivation process and by increasing the numbers of ATC radars interrogating the Mode-S EHS registers. The latency of the observations is depending on the data source, local NMHS receiver versus ATC data stream, and varies from near real time to 20 or 30 minutes.

To interrogate Mode-S MRAR, ATC must further upgrade the SSR to request an additional data register. High quality wind and temperature observations are available from a small fraction of all aircraft, depending on the type of aircraft transponder. Interrogation of Mode-S MRAR is currently implemented and operational in Czech Republic and Slovenia.

The expert team proposes to EUMETNET, based on the evidence in this study, to implement an operational ADD data processing center that focuses primarily on Mode-S EHS and MRAR data in Europe. As a second step the potential of ADS-C data can be exploited using currently available, and as such paid for, global data and possibly extend that in the future towards e.g. data sparse regions.

Due to the quantity of data, the different processing compared to E-AMDAR, the different ways of dissemination, the study shows that the E-AMDAR processing is not convenient for ADD data.

Although it may be obvious it is important to realize that aircraft observations are only available in areas and regions where aircraft are flying, and that significant differences in volume do exist between e.g. day and night time. Similar differences exist e.g. with regard to the vertical distribution of the aircraft observations, in general more observations are available on cruise altitude and less at lower levels.

With regard to the operational processing a central processing facility is proposed. This centre can perform central processing and corrections, including the operation of the dynamic aircraft database with individual heading and temperature corrections. Additional local processing is foreseen for situations where data provision is time critical, and one of these centres could act as a back-up for the central processing facility.

With a new method obtaining aircraft observations of an appropriate quality and quantity it may be feasible to reduce the number of AMDAR observations in regions where aircraft observations are available. This will require coordination between the ADD activity and E-AMDAR. If feasible there may be an opportunity to direct the saved funding into other geographical areas or into the humidity measurement program. Before ADD processing becomes operational some actions should be conducted to understand the impact of the new observations on the E-AMDAR program.

End-users and customers of the meteorological observations obtained or derived from ADD data are aviation stakeholders and the meteorological community at large. This includes commercial and non-commercial organizations and the general public. The data provision can be seen as part of the European Meteorological Infrastructure and is offered to these users as official duty or 'open data' in line with EU regulations on the re-use of public sector information.

The calibrated and quality controlled observation data can be centrally provided via the ADD data processing center in BUFR, netCDF and ASCII. There would be no license costs involved, and open data would be provided with little guarantees for data availability and so on. A more operational service could be provided at a small distribution fee, and as such financing the internal handling costs.

This would create a level playing field for other parties, commercial and non-commercial, aviation and non-aviation, to make best use of these observations and as such provide the highest added value for the European community. More analysis and work on IPR issues, data collection and data provision of ADD data has to be carried out by the meteorological community, and coordinated with legal experts, regulators, airlines, air traffic organizations and airports.

2.1 Business requirements & justifications.

Using already existing ground and air-borne infrastructure offers an enormous potential to acquire millions of meteorological observations per day for a large part of West and Central Europe.

2.2 Financials.

2.2.1 Costs

The investment to obtain and derive meteorological observations can be categorized as follows:

- Initial set-up of operational aircraft derived data processing center, including algorithms for processing and quality control, dynamic aircraft correction database, data storage, and data dissemination.
- Initial set-up of legal conditions, standard contracts for data collection and data provision, in line with EU regulations on re-use of public sector information.
- Coordination with air traffic control organizations, airlines, aircraft and engine manufactures, airports, radar tracking organizations and regulators on data provision and distribution conditions.
- Exploitation costs for maintaining and operating the EUMETNET ADD data processing center.
- Further development of the program to explore new opportunities of ADD data, e.g. ADS-C with global geographical coverage potential, to increase the geographical coverage of ADD data (Mode-S EHS and MRAR), and explore opportunities for added value utilizing the meteorological observations.
- Deployment of local ADS-B/Mode-S receivers in parts of Europe, if needed, including the necessary infrastructure to maintain and operate these receivers operationally.

- Further action research to investigate current and future potential of collecting and using ADD data for meteorological purposes.

A first and rough estimation provided by KNMI is that the center can be operated for the first five years with approximately 2,5 fte per year, including set-up, operational processing, coordination with aviation stakeholders, and improvements to the program. The annual costs for data communication, processing and storage is estimated at € 100.000. Not included are the cost for ADS-B/Mode-S receivers that are operated locally. This would lead to an annual program cost of € 500.000. The expectation is that after five years the center can be operated with 1,5 fte.

As stated this is a rough estimate and costs could be reduced via in-kind contributions from members, or through delaying e.g. the investigation on opportunities other than Mode-S EHS and MRAR data. At the same time there may exist opportunities to receive co-funding, e.g. via SESAR 2020 (development) or SESAR deployment.

2.2.2 In kind costs for the National Meteorological Services

A number of activities that have been identified in the study could be contributed as in kind costs.

- The Mode-S EHS and MRAR data collection process requires coordination with Air Traffic Organizations, and in some cases with airports. This could be facilitated by the national air navigation service provider for meteorology, which in several countries is part of the ATC.
- The provision of ADD data collection and distribution to the centralized processing center in situations where ADD data is provided locally to the National Meteorological Hydrological Service.
- A number of opportunities for improvements to the number of derived observations, the quality control process, and the added value have been identified. Operational studies could be performed by the National Meteorological Hydrological Services.
- The national deployment of local ADS-B/Mode-S receivers in the vicinity of ATC Secondary Surveillance Radar for ADD reception. If this is due to reluctance of ATC to provide the ADD data it could be considered to integrate these costs in the EUMETNET ADD activity.
- The deployment and internal use of the obtained and derived meteorological observations in the National Meteorological Hydrological Service.

2.3 Risk & Issues.

Issues

- Data collection of Mode-S EHS and MRAR data via ATC offers great potential for one-stop-shop data collection, and reduces the number of access points. KNMI for example receives data from 20 radars from Maastricht Upper Area Control Centre, and some aspects of quality control are organized for by ATC.
- Pros and cons of the ADD data provided by ATC and or airlines versus local reception using ADS-B/Mode-S receivers need to be further investigated.
- There are no EU regulations on Mode-S MRAR and only very few secondary surveillance radars interrogate the BDS 4.4 register (MRAR). The number of Mode-S MRAR equipped aircraft is slightly decreasing and can therefore not be considered as a fully reliable and stable data type.

- Coordination with ATC on the possible interrogation of BDS register 4.4, Mode-S MRAR, is required in order to use the potential of MRAR data, being the better quality temperature than from Mode-S EHS derived temperature.
- Coordination with airlines and transponder manufactures on the potential use of Mode-S MRAR and request to update responders with BDS 4.4 data.
- More analysis and work on IPR issues, data collection, and data licensing aspects of ADD data has to be carried out by the meteorological community, and coordinated with legal experts, regulators, airlines, air traffic organizations and airports.
- The abundance from Mode-S EHS derived temperature potentially outweigh their reduced precision individually with regard to AMDAR, and should be checked in the next phase.
- It should be noticed that the airspace in Europe has extremely dense air traffic and specific ground surveillance infrastructure. As such the potential for the use of ADD data is not representative for other parts in the world.
- More analysis on the various data types for processing and distribution is advised.
- The derivation of meteorological observations from Mode-S EHS data requires quality control of the Mode-S EHS data, conversion of magnetic heading to true heading, and specific aircraft corrections for heading and temperature. For this process a dynamic database, updated daily, of individual aircraft heading and temperature corrections is required.
- Although widely available ADS-B and ADS-B ES data offer limited opportunities for acquiring meteorological observations. The ADS-B position data however is imperative for the decoding of Mode-S EHS and MRAR data received by local receivers.

Risks

- If observations over Europe are shifting from E-AMDAR towards other ADD types there is a risk that current E-AMDAR airlines may step out of the E-AMDAR program. E-AMDAR is important for global coverage of observations, and it is important and useful to have redundant systems for operations. Also, E-AMDAR temperature have a higher quality, and the E-AMDAR program offers the availability of additional metrics such as turbulence, icing, water vapour, etc.
- An impact study to identify the impact of replacing E-AMDAR with derived observations from Mode-S EHS has to be carried out. The quality of the derived temperature from Mode-S EHS is worse than the quality of the E-AMDAR temperature. Additional study on improvements of the quality of the derivation process, and optimal use in NWP assimilation, is required.
- ATC organizations and airlines not willing to share their ADD data, or require significant financial compensation for providing the data. This can be mitigated by installing and maintaining local receivers but as such results in additional infrastructure costs for the meteorological community. Another mitigation is to lobby within EU and SESAR and to coordinate with regulators, national administrations, air traffic organizations, airports and airlines on the potential use of the data for aviation in order to create a playing field in which sharing this data with the meteorological community is seen as natural.
- ATC organizations or airlines do not comply with the envisaged dissemination of obtained and derived meteorological information in line with EU regulation on re-use of public sector information. This could be mitigated by lobbying or installing and maintaining local receivers but as such results in additional infrastructure costs for the meteorological community.

- Including the new EUMETNET ADD activity in the current E-AMDAR program. The nature of both programs is different, although the same object for deriving data, in casu an aircraft, is used. Where E-AMDAR is a mature program and software is installed on aircraft, is E-ADD a pioneering development program investigating options and methods and looking for new opportunities. The volume and data processing differs significantly from that of E-AMDAR, as well as the data update frequency and proposed 'open data' distribution. E-ADD is a development program that coordinates with different stakeholders than just airlines. The chance of losing the current flexibility is seen as a risk.

2.4 Benefits

A number of benefits are identified in this report. The direct result will be the availability of significant numbers of meteorological information, in casu wind direction, wind speed and temperature, in West and Central Europe. A significant amount of these observations will be from relatively low levels over land, where satellite radiances are difficult to use. Today it is mainly radiosonde, E-AMDAR data, and wind profiler data that provide such measurements.

As such there are no direct financial benefits, although there are opportunities to optimize between the E-AMDAR and E-ADD activities. The main benefit lies in the added value of huge numbers of timely and good quality upper air observations for the aviation and meteorological community.

- Approximately 5 million quality controlled Mode-S EHS meteorological observations of wind direction, wind speed and temperature for West and Central Europe per day. The quality of the wind observations is good and similar to E-AMDAR. The temperature is of lower quality than E-AMDAR. The expectation is that the geographical coverage will expand toward a large part of Europe before 2020, and as such the number of observations will increase in time.
- Approximately 200.000 high quality Mode-S MRAR meteorological observations per day in Central Europe, which can be extended in case of interrogation by more SSR radars and further support for BDS 4.4. on board the aircraft.
- The observations are useful for the aviation community for current and future Air Traffic Management concepts, both as observations and as enabler to provide better nowcasts from rapid update cycle numerical weather prediction modelling, that use these observations for assimilation.
- The observations and nowcasts, especially the wind data, are useful for the aviation community for improved trajectory prediction, both for air-borne and ground based systems.
- Derived aircraft heading corrections, and possible slide slip angle, being an outcome of the derivation process, may be beneficial for the aviation community.
- The observations and nowcasts are useful for aviation meteorologists in their daily operation providing aviation service provision including advice to aviation stake holders.
- The observations are useful for the meteorological community for various reasons:
 - General forecasting improvements related to low winds and convection, including precipitation, and freezing rain.
 - Input to Numerical Weather Prediction modelling for both hydrostatic and non-hydrostatic models with high horizontal resolution.
 - Climate monitoring with regard to temperature trends, where the good coverage near the tropopause is a main asset.

- In re-analyses and in improving the preparation of boundary conditions for climate models, and the physics of climate models. In particular due to their high timeliness, resolving the diurnal cycle.

2.5 Conclusions and recommendations to STAC and PFAC

The outcome of the EUMETNET Aircraft Derived Feasibility Study is laid out in this report.

PFAC and STAC are recommended to initiate the foundation of an operational centralized service for obtaining and deriving meteorological observations from aircraft derived data in Europe as a separate activity under the EUMETNET Observations program. The E-ADD function should focus primarily on Mode-S EHS and MRAR data in Europe. Next the potential of ADS-C data could be exploited using currently available, and as such paid for, global data and possibly extend that in the future towards data sparse regions.

3 Global overview / synopsis

Aircraft related weather information has proven to be a valuable source for (numerical) weather forecasting in both the public domain as well as the aviation domain. Aircraft data is also of significant value to climate research where it is used for both climate monitoring and for initiating and validating climate models. The data is also used by operational forecasters to validate model output and forecasts and for advisory services to aeronautical stakeholders. The EUMETNET programme E-AMDAR supplies an operational service to, amongst others, evenly distribute the AMDAR observations over the European area.

Recently, work has been conducted investigating novel methods of deriving and gathering meteorological data from aircraft using different methods than AMDAR. This work shows significant potential to supplement existing observations systems.

This report of the EUMETNET ADD Feasibility Study Expert Team provides an overview of the current and future aircraft related methods of deriving meteorological information measured by (commercial) aircraft.

In the following chapter we describe the meteorological content and methods of extracting for basically three different methods relating to:

1. Automatic Dependent Surveillance;
2. Secondary Surveillance Radar or Mode-S; and
3. E-AMDAR.

The current and future status of these three methods (and their sub methods) are presented in the following chapters.

While the [WMO AMDAR Observing System](#) is the chief source of [aircraft-based observations on the GTS](#), other aircraft-based observations are derived from several sources including:

1. Under regulations and cooperative arrangements with ICAO, data from Pilot REports (PIREP) and AIRcraft REports (AIREP) are available on the GTS for utilisation by data users.
2. AMDAR-like data can also be derived from commercially operated observing systems, such as the Panasonic Avionics Corp. [TAMDAR system](#) and the FLYHT Aerospace Solutions [AFIRS system](#). These may be available on the GTS, depending on the arrangements between the contracting NMHS and the vendor for the purchase of the data.

These types of observations are not addressed in this report. More information on these aircraft-based observations data sources is available from the WMO website under the [Data area](#).

This report is set-up as follows. In Chapter 4 a description of all ADD types are given, together with meteorological value. Chapter 5 describes the current and future availability of the different types and sub-types of aircraft derived data as identified in the previous chapter. Chapter 6 describes the (proposed) method of processing of each specific ADD type in detail. Chapter 7 describes the various used data formats for exchanging ADD data and the obtained or derived meteorological information from ADD data and identifies a number of potential users. The expected added value of ADD is described in chapter 8 and a roadmap for implementation is given in chapter 9. A survey of (near) future developments with respect to ADD is presented in chapter 10. Chapter 11 sums up all characteristics of ADD types and related meteorological information. Chapter 12 contains a list of acronyms and the

references can be found in chapter 13. Finally, this report contains four appendices: an ADD BUFR description; a questionnaire for national ATC and airlines; a list with “loose ends” ; and, a list with E-ADD ET FS members, of which the Members are also shown in figure 1.

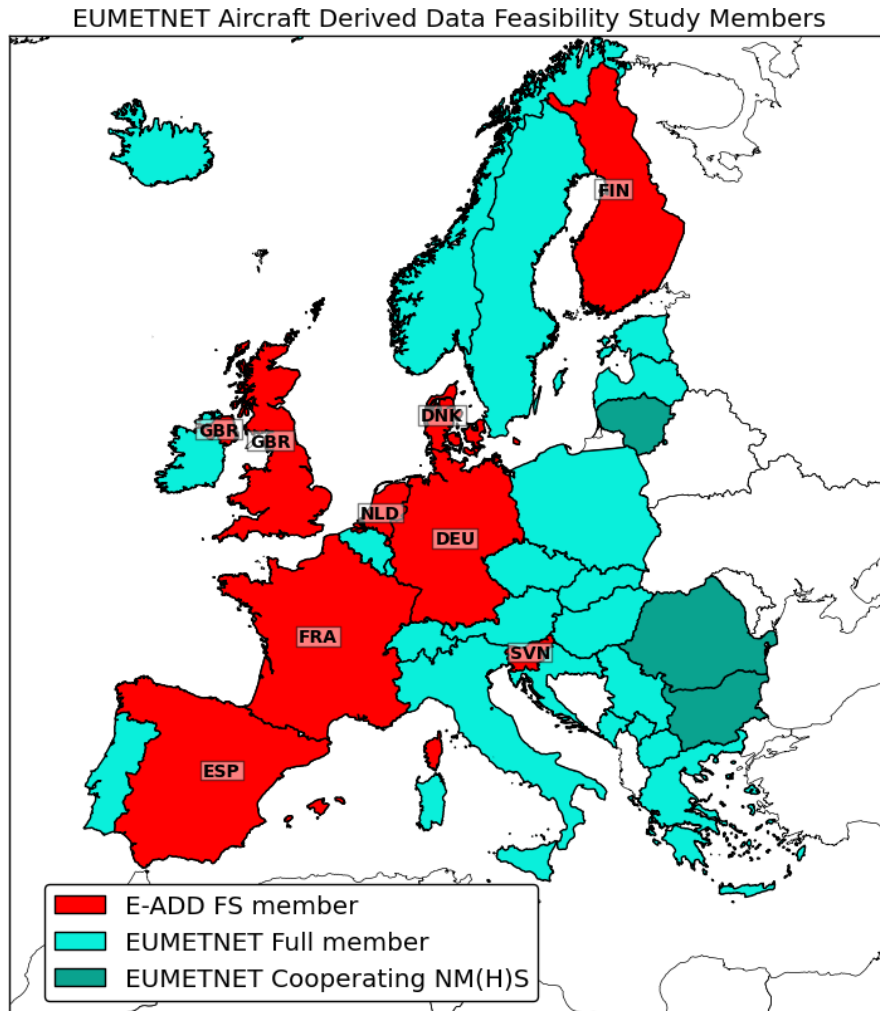


Figure 1: Overview of EUMETNET Members and cooperating NM(H)Ss and the Members of the EUMETNET Aircraft Derived Data Feasibility Study Expert Team (EUMETNET ADD FS ET)

4 Description of ADD data types and characteristics

This chapter identifies and describes three different types of aircraft derived data:

- Automatic Dependent Surveillance (ADS);
- Secondary Surveillance Radar (SSR) Mode-S; and
- E-AMDAR (for comparison).

For each type, including the various sub-types, the available data variables are identified and the opportunities to collect meteorological observations, in casu wind direction, wind speed and temperature, are being described. In some cases meteorological information is directly available within the aircraft derived data. In other cases meteorological observations are not available, or can be derived from other variables.

This derivation process is described in some detail, including the necessary quality control and aircraft specific corrections. For each sub-type the quality of the meteorological observations is provided, as well as a conclusion about the usefulness of the aircraft derived data type for meteorological purposes.

4.1 Automatic Dependent Surveillance (ADS)

The definition of Automatic Dependent Surveillance according to ICAO is:

“A surveillance technique in which aircraft automatically provide, via a data link, data derived from on-board navigation and position-fixing systems, including aircraft identification, four-dimensional position, and additional data as appropriate.” (ICAO Circular 256-AN/152)

ADS is highly dependent on accurate airborne positioning systems and requires additional special aircraft systems (Global Navigation Satellite System - GNSS) which can measure the ADS position and height of the aircraft.

ADS includes the following sub-types or services:

- ADS-A - Automatic Dependent Surveillance Addressed (also called ADS-C);
- ADS-B - Automatic Dependent Surveillance Broadcast; and
- ADS-C - Automatic Dependent Surveillance Contract (called ADS-A).

4.1.1 ADS-Addressed (ADS-A) / ADS-Contract (ADS-C)

Automatic Dependent Surveillance-Contract (ADS-C) is defined as a means for surveillance by which the terms of an ADS-C agreement will be exchanged between the ground system and the aircraft using a datalink. The messages are used for air traffic control, ADS-C is primarily designed for oceanic control, and the airline dispatch organization. These messages are also referred to as ADS-A.

Specification under which conditions ADS contracts would be initiated and what data would be contained depends on the service. ADS contracts can be established using the FANS 1/A service or the Aeronautical Telecommunication Network (ATN) B1.

FANS 1/A¹ uses the Aircraft Communications Addressing and Reporting System (ACARS) as datalink while ATN B1 uses the VHF Data Link Mode 2 (VDL2) where the latter datalink does not support ADS-C yet. The transfer of data via these datalink is carried out by a commercial service provider and is associated with costs for airlines.

ADS-C is conceptually capable of three types of message contracts:

1. A periodic contract (normal and emergency) in which certain information is requested to be sent at a specified rate;
2. An event contract in which certain information is requested at the occurrence of a specified event (or sequence of events);
3. A demand contract in which a one-time polling of the aircraft for specific information is requested.

In summary, ADS-C messages are transmitted at standard positions or intervals or on request of the dispatch department of an airline or ATC, see Figure 2. All ADS-C communications are point-to-point communications between the ground and systems on the aircraft.

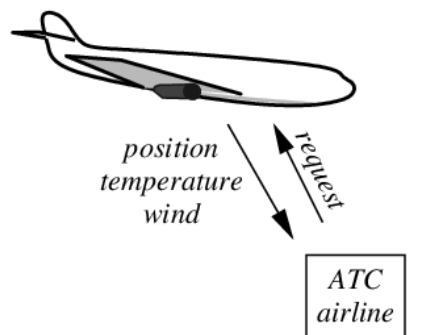


Figure 2: Schematic data flow of ADS-C

There is a wide variety of data items available through ADS-C. This makes it possible to downlink for example aircraft state information, aircraft intent information and meteorological information. The information can be used, for instance, to verify the aircraft information with the ground systems information to detect discrepancies between Air Traffic Control (ATC) ground systems and Flight Management System (FMS). The exchange of state and intent information can also be used to enhance

¹ FANS 1 is used by Boeing, FANS A is used by Airbus Industries

ATC radar trackers and planning tools. In particular, intent information may enhance the predictability of the operation and is a key ingredient to future Trajectory Based Operations.

The information transmitted from the aircraft to the ground systems (ICAO, Doc4444) contains position, and can contain, amongst others, temperature and wind, see Table 1.

Table 1 ADS-C variables

| Message | Contents |
|---|---|
| Basic ADS | Latitude, Longitude, Altitude, Time, Figure of merit |
| Ground vector track, | Ground speed, Rate of climb or descent |
| Air vector | Heading, Mach or IAS, Rate of climb or descent |
| Projected profile next way-point | Estimated altitude at next way-point, Estimated time at next way-point, (Next + 1) way-point, Estimated altitude at (next + 1) way-point |
| Meteorological information | Wind speed, Wind direction, Temperature, Turbulence (if available), Humidity (if available) |
| Short-term intent | Latitude at projected intent point, Longitude at projected intent point, Altitude at projected intent point, Time of projection |
| Extended projected profile (in response to an interrogation from the ground system) | Next way-point, Estimated altitude at next way-point, Estimated time at next way-point, (Next + 1) way-point |

A KNMI study (De Haan et al, 2013) showed that circa 25% of ADS-C data received from KLM contained meteorological information. The quality of the information, in casu wind direction, wind speed and temperature, is good, see Table 2, and is similar to the quality of AMDAR observations. Note that included in this 25% is also derived wind information, using ground track vector and air vector, when direct wind information is not available. This is not further discussed in this document.

Table 2 : Quality of meteorological parameters from ADS-C

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|-------------------|---------|-------------------------|
| Wind speed | Yes | selected aircraft | Good | 2-2.5 m/s |
| Wind direction | Yes | selected aircraft | Good | 10-15 degrees |
| Temperature | Yes | selected aircraft | Good | 1 K |

Conclusion: only a small portion of the ADS-C messages contain meteorological information, in casu wind direction, wind speed and temperature. The quality of the obtained meteorological information is good and comparable to the quality of AMDAR data. Reception of the data requires cooperation with either ATC, airlines, aircraft and engine manufacturers, and involves data communication costs.

4.1.2 ADS-Broadcast (ADS-B)

Automatic Dependent Surveillance – Broadcast (ADS–B) is a cooperative surveillance technology in which an aircraft determines its position via satellite navigation and periodically broadcasts it, enabling it to be tracked. The information can be received by air traffic control ground stations as a replacement for secondary radar. It can also be received by other aircraft to provide situational awareness and allow self-separation.

ADS–B is "automatic" in that it requires no pilot or external input. It is "dependent" in that it depends on data from the aircraft's navigation system.

ADS-B provides many benefits to both pilots and air traffic control that improve both the safety and efficiency of flight. One of the foreseen solutions is that aircraft equipped with universal access transceiver (UAT) ADS-B In technology will be able to receive weather reports, and weather radar through flight information service-broadcast (FIS-B).

ADS-B data are routinely broadcast by commercial aircraft. There is no triggering required like e.g. interrogation from air traffic control radar, see Figure 3. This data source is the most basic described in this document. The data are used by ATM as a secondary source of aircraft position information.

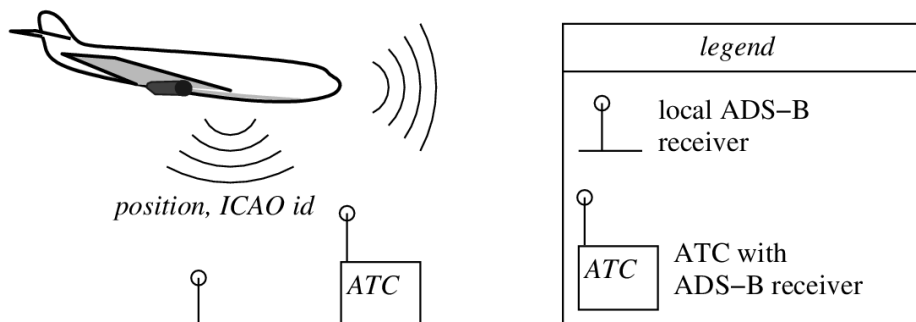


Figure 3: Schematic data flow of ADS-B

The available parameters of ADS-B are described in Table 3, and are limited in number. Meteorological information is not directly available in the ADS-B data. Although the data is easily and widely available it is of little use for meteorological purposes.

There are opportunities to derive meteorological information from the ADS-B data. It should be possible to calculate an estimate of the wind acting on aircraft during controlled turns during manoeuvring. The ground track would need to be found from the aircraft 2D location. There is currently no published work on applying this method to this data type although it is similar to that introduced by De Leeghe (2013). As the data resolution is lower than ADS-B ES (extended squitter, see next paragraph) and the availability is lower than ADS-B ES it is unlikely that the quality would be high enough to be worthwhile.

It should be noted that the stated resolution is as defined in the broadcast standards [ICAO 2012]. Therefore there may be additional loss of precision from decoding/storing the data and uncertainties in the instruments used to measure the quantities.

Table 3 ADS-B variables.

| Data type | Resolution | Unit |
|-----------|------------|------|
|-----------|------------|------|

| | | |
|---------------------------------|------------|-----------------|
| 24-bit ICAO aircraft address; | - | - |
| aircraft 2D position; | ~5 | m (CPR encoded) |
| aircraft vertical position; | 100 | ft |
| aircraft altitude; | 100 | ft |
| aircraft identity; | - | - |
| aircraft intent; | Boolean | True/False |
| aircraft ground velocity; | $\sqrt{2}$ | knot |
| aircraft vertical acceleration; | 64 | ft/min |

Although there is no meteorological information in ADS-B the quality of the meteorological parameters are shown in Table 4 for consistency reasons.

Table 4 : Quality of meteorological parameters from ADS-B

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|--------------|---------|-------------------------|
| Wind speed | No | All aircraft | - | - |
| Wind direction | No | All aircraft | - | - |
| Temperature | No | All aircraft | - | - |

Conclusion: ADS-B data does not contain meteorological information. Although the data is easily and widely available it is of little use for meteorological purposes. There may be theoretical opportunities to derive wind data but this is expected to be of poor quality. The amount of derived wind observations will also be low as derivation is only possible during controlled turns of aircraft when manoeuvring. Reception of the data is possible with a local ADS-B receiver and does not involve data communication costs.

4.1.3 ADS-Broadcast Extended Squitter (ADS-B ES)

ADS-B extended Squitter contains significantly more information than the above ADS-B, although it's use case is very similar. ADS-B ES data are routinely broadcast by commercial aircraft. There is no triggering required like e.g. interrogation from an air traffic control radar, see Figure 4.

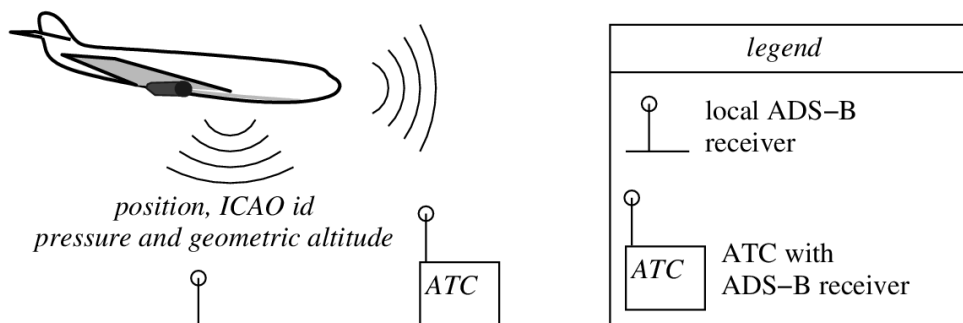


Figure 4: Schematic data flow of ADS-B ES

It is a periodic message that provides position, velocity, time, and, in the future, intent, for available parameters see table 5. Meteorological information is not directly available in the ADS-B data. Although the data is easily available it is of little use for meteorological purposes.

The additional information of ES allows for a better understanding of the quality of the data available as well as more and ‘better’ data. This data allows for the derivation of wind information for aircraft conducting controlled turns. The initial work indicates that this data is not of a high quality (De Leege, 2013) and is only capable of working in areas where aircraft are manoeuvring.

It is also possible to derive temperatures from this method. Two methods have been proposed for finding temperatures, a method proposed by De Leege (2013) requires fitting a polynomial using the pressure and GNSS altitude information to find a temperature, the initial analysis of this provides errors of 2-5K.

The second method proposed by Stone and Kitchen (2015) uses descending or ascending to find an average layer temperature, when the layer thickness is set to be 2000 m an error of below 1 K can be achieved. The layer temperatures can only be derived where aircraft are taking off or landing.

In most circumstances where Mode-S EHS data is available a better average temperature can be found by averaging the individual derived temperatures (Stone and Kitchen, 2015). These methods for deriving temperatures may be of use for operational forecasting where the data is to be presented to people.

The data is widely available as no ground systems are required. It may be useful in regions where Mode-S EHS will not be available. Where Mode-S EHS is possible it is likely to be a better use of resources to lobby for that rather than develop ADS-B ES systems.

For NWP data assimilation it is more likely that using the pressure and GNSS altitudes will be of greater value. This has not been investigated and is likely to have a significantly smaller impact than Mode-S EHS or Mode-S MRAR data.

It should be noted that the stated resolution is as defined in the broadcast standards [ICAO 2012]. Therefore there may be additional loss of precision from decoding/storing the data and uncertainties in the instruments used to measure the quantities.

Table 5 ADS-B ES variables.

| Data type | BDS² | Resolution | Unit |
|--|------------------------|-------------------|-----------------|
| 24-bit ICAO aircraft address; | 3 | - | - |
| aircraft identification; | | - | - |
| Mode A code; | | - | - |
| special position indication (SPI); | | - | - |
| emergency status (general emergency, no communications, unlawful interf.); | | - | - |
| ADS-B version number (equal to 2); | | - | - |
| ADS-B emitter category; | 0,8 | - | 8char |
| geodetic horizontal position (WGS84) latitude and | 0,5 | ~5 | m (CPR encoded) |

² BDS stands for Comm-B Data Selector

³ Grey cells indicate “not relevant” for the specific column and/or for meteorological purposes

| | | | |
|---|-----|-----------|--------|
| longitude; | | | |
| geodetic horizontal position quality indicators; | | | |
| pressure altitude; | 0,5 | 25 or 100 | ft |
| geometric altitude (WGS84), as a difference to pressure altitude; | 0,9 | 25 | ft |
| geometric vertical accuracy (GVA); | | | |
| velocity over ground (airborne or ground); | 0,9 | 2 | kt |
| velocity quality indicator; | | | |
| coded aircraft length and width; | | | |
| global navigation satellite system (GNSS) antenna offset; | | | |
| vertical rate: barometric vertical rate; | 0,9 | 64 | ft/min |
| MCP/FCU selected altitude | | 16 | Ft |
| barometric pressure setting (minus 800 hectoPascals); | | 0.1 | hPa |
| ACAS active resolution advisories when the aircraft is equipped with TCAS II. | | | |

Although there is no meteorological information in ADS-B ES the quality of the meteorological parameters are shown in table 6 for consistency reasons.

Table 6 : Quality of meteorological parameters from ADS-B ES

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|--------------|---------|-------------------------|
| Wind speed | No | All aircraft | - | - |
| Wind direction | No | All aircraft | - | - |
| Temperature | No | All aircraft | - | - |

Conclusion: ADS-B ES data does not contain meteorological information. Although the data is easily available it is of little use for meteorological purposes. There are opportunities to derive temperature and wind data but this is either of low quality or averaged over a significant layer of atmosphere. There may be value in assimilating GNSS and pressure altitude data. Reception of the data is possible with a local ADS-B receiver and does not involve data communication costs.

4.2 Secondary Surveillance Radar (SSR) Mode-S

Whilst traditional Secondary Surveillance Radar (SSR) stations interrogate all aircraft within their range, Mode-S (Select) establishes selective and addressed interrogations with aircraft within its coverage. Such selective interrogation improves the quality and integrity of the detection, identification and altitude reporting. These improvements translate into benefits in terms of safety, capacity and efficiency benefits which are key to supporting the future of the high-traffic density airspace of Europe.

In Europe, SSR Mode S is being implemented in two stages: Mode S Elementary Surveillance (ELS) and Mode S Enhanced Surveillance (EHS).

Mode-S includes several sub-types or services, and only the following are described in this report:

- Mode-S ELS – Mode Select Elementary Surveillance;
- Mode-S EHS – Mode Select Enhanced Surveillance;
- Mode-S MRAR – Mode Select Meteorological Routine Air Report; and

- Mode-S BDS 4.5 – Mode Select Meteorological Hazard Report.

4.2.1 Mode-S ELS

Mode-S ELS data requires a selective interrogation from an air traffic control radar, see Figure 5. The response of the aircraft can be received using a local ADS-B/Mode-S receiver.

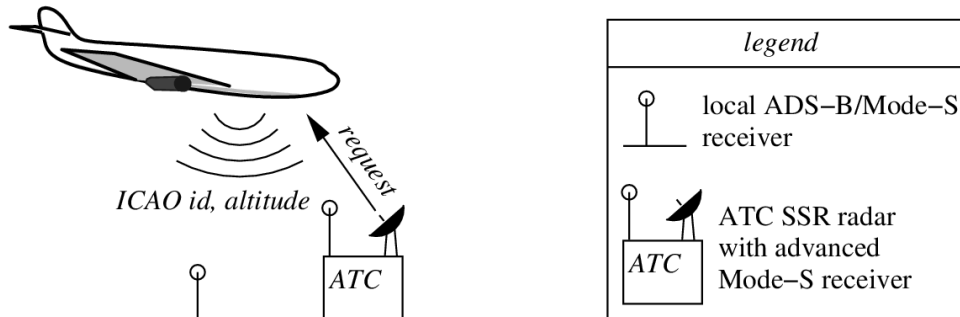


Figure 5: Schematic data flow of Mode-S ELS

Aircraft compliant with Mode S ELS provide the following functionality, which is also referred to as "Basic Functionality", see Table 7.

Table 7 : Mode-S ELS variables

| Data type | Resolution | Unit |
|-------------------|------------|-------------------------|
| Aircraft Identity | - | - |
| Altitude | 25ft | ft |
| Flight status | - | (airborne/on the ground |

Mode-S ELS information does not contain any meteorological related parameters. There are no opportunities to derive meteorological information either.

Conclusion: Mode-S ELS data does not contain meteorological information. Although the data is easily available it is of no direct use for meteorological purposes. Reception of the data is possible with a local ADS-B/Mode-S receiver and does not involve data communication costs.

4.2.2 Mode-S EHS (registers 4.0, 5.0, 6.0)

Mode-S EHS data requires active interrogation from an air traffic control radar. The interrogation can only be done by an authorized body e.g. air traffic control, and the response of the aircraft can be received using a local ADS-B/Mode-S receiver, see Figure 6.

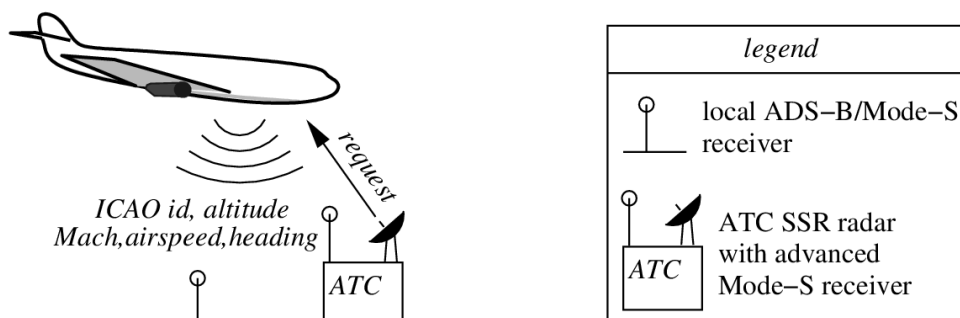


Figure 6: Schematic data flow of Mode-S EHS. The methods of data collection are discussed in section .

The frequency of interrogation is purpose dependent; for approach purposes generally an update frequency of around 4 to 8 seconds is applied (dependent on the radar and the amount of traffic), for area-control purposes a frequency of circa 20 seconds is more general.

Aircraft compliant with Mode S EHS provide basic functionality features of Elementary Surveillance plus eight downlinked aircraft parameters (DAPs). The parameters can be provided via a basic DAP set or via an alternative DAP set, see Table 8. In this report the definition Mode-S EHS is used for data that contains the BDS registers 4.0, 5.0 and 6.0.

Table 8: 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: EUROCONTROL.

| 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) |

The available parameters of Mode-S EHS data are described in Table 9. Mode-S EHS information does not contain meteorological parameters, so wind and temperature are not directly available. There are opportunities to derive meteorological information from the Mode-S EHS data. Temperature can be inferred from the Mach number and the airspeed, while wind is derived from the difference between the movement of the aircraft relative to the ground (track angle and speed) and the air (airspeed and heading). This is explained in more detail below.

Table 9 Mode-S EHS variables

| Data type | BDS | Resolution | Unit |
|--|-----|---------------------|---------|
| Mode-A slant position (range) ⁴ | | 1/256 | Nm |
| Mode-A slant position (azimuth) ⁵ | | 360/2 ¹⁶ | Degrees |

⁴ Measured by ATC

| | | | |
|--|-----|-----------|--------------------|
| Position from ADS-B ⁶ | - | ~5 | M |
| MCP/FCU selected altitude; | 4,0 | 16 | Feet |
| roll angle; | 5,0 | 45/512 | Degrees |
| true track angle; | 5,0 | 90/512 | Degrees |
| ground speed; | 5,0 | 2 | Knots |
| magnetic heading; | 6,0 | 90/512 | Degrees |
| indicated airspeed (IAS) | 6,0 | 1 | Knots |
| Mach number (iso. IAS); | 6,0 | 2.048/512 | [-] |
| vertical rate (barometric or baro-inertial); | 6,0 | 32 | Feet per minute |
| barometric pressure setting (minus 800 hPa); | 6,0 | 0.1 | Millibar |
| track angle rate (TAR) | 6,0 | 8/256 | Degrees per second |
| true airspeed (iso. TAR) | 6,0 | 2 | Knots |

Derivation process and corrections as developed by KNMI

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 shown in an idealized setting in Figure 7.

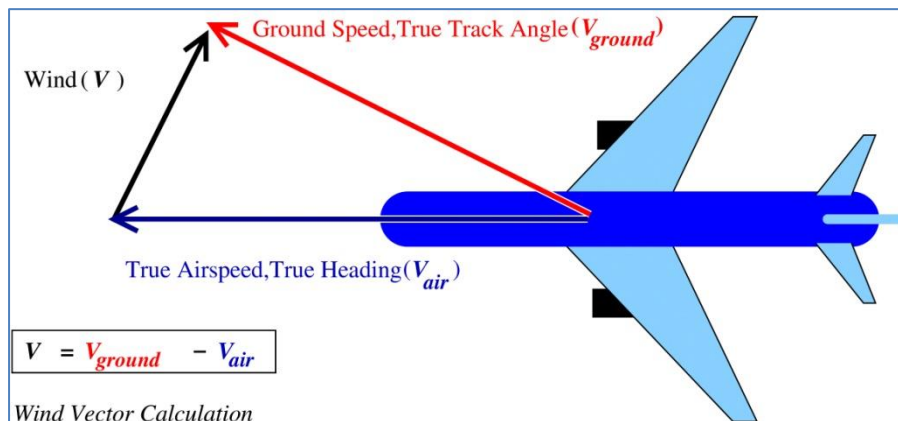


Figure 7 : Schematic representation of wind derivation from aircraft flight information. The wind vector (black) is deduced from the difference between the ground track vector (red) and the orientation (heading) and speed of the aircraft relative to the air (dark blue). The ground track vector is constructed by ground speed and true track angle. Note that both heading and ground track angle are defined with respect to true north.

The ground track is observed accurately but the aircraft orientation contains systematic errors, and preprocessing steps for heading and airspeed are essential, see Figure 8. 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 therefore an additional correction might be needed.

⁵ The accuracy of the position (latitude/longitude) depends on the range to the radar of the target; at 200Nm the position is accurate up to 1km

⁶ Using a local ADS-B receiver, in fact this information is not available in the Mode-S EHS data itself as the content of the ADS-B data is used

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 aircraft and takes into account a latitude and longitude dependent correction based on a magnetic variance model as defined using Maus and Macmillan (2005) International Geomagnetic Reference Field.

Two methods have been developed to determine the heading correction. The first takes into account the heading of the aircraft immediately after it has landed on the runway. When on the runway at a significant speed the heading of an aircraft and the runway should match. The limitation of this method is that the heading correction can only be applied for aircraft regularly landing at Schiphol. The second method uses external wind information from NWP and calculating backwards what the heading (and airspeed) of the aircraft should have been, assuming that the external wind factor is perfect. The heading correction is calculated and used after 30 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 every aircraft, every day. The differences between NWP derived corrections and landing corrections is within the reported resolution of heading and are in general equal, apart from possible angle of side slip of the individual aircraft.

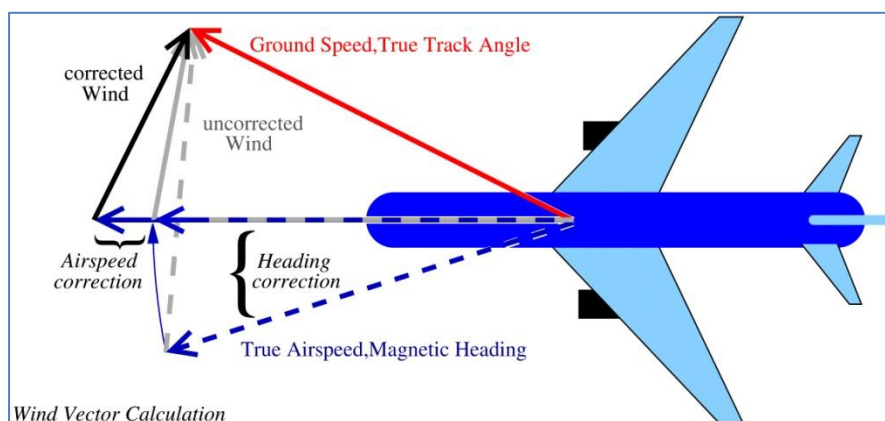


Figure 8 : Schematic representation of used heading and airspeed corrections to derive high quality wind estimate from aircraft flight information. The dashed white-blue vector (uncorrected vector) is constructed using aircraft downlink information of magnetic heading and true airspeed (see Figure 7). The dashed grey-blue vector is the result of the proper heading correction being 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 - in dashed gray without any corrections and solid grey with only heading correction applied. The ground track is assumed to be correct.

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.

Investigation on temperature differences between numerical weather prediction temperatures 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%.

Note that for the derivation of the meteorological parameters only the BDS registers 5.0 and 6.0 of the Mode-S EHS data are required.

More detail on the derivation of meteorological observations from Mode-S EHS data can be found in the following publications (De Haan, 2010, 2011, 2013).

Quality of the derived meteorological observations

The developed corrections and quality control were applied on a 4.5-year Mode-S EHS data set, and the resulting wind and temperature observations were compared with the ECMWF operational model data which has a resolution of 16 km (changed from 25 km to 16 km due to model change in January 2010).

The Mode-S EHS derived wind direction has a standard deviation between 15° and 20°. 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 transverse 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 800hPa. Below 800hPa the standard deviation of AMDAR increases from 2m/s to 2.5m/s at the surface, while the Mode-S derived wind standard deviation is constant and equal to 2m/s.

The corrected temperature observations showed an almost zero bias and an improvement of the temperature standard deviation by 50% above 750hPa. The temperature observations from AMDAR have a clear better standard deviation of 1K, although the quality of the Mode-S EHS derived and AMDAR temperature observations at 200hPa are almost similar. Overall the quality of the Mode-S EHS derived temperature is clearly less than the AMDAR temperature.

In summary, after quality control and individual aircraft corrections the quality of the derived wind direction and wind speed is good, see Table 10, and is similar to the quality of AMDAR observations. The quality of the derived temperature is less than the AMDAR temperature.

Table 10 : Quality of derived meteorological parameters from Mode-S EHS after quality control and corrections

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|--------------|----------|-------------------------|
| Wind speed | Derived | All aircraft | Good | 2-2.5 m/s |
| Wind direction | Derived | All aircraft | Good | 10-15 degrees |
| Temperature | Derived | All aircraft | Moderate | 2K |

Conclusion: Mode-S EHS data does not contain meteorological information. It is possible to derive meteorological information, in casu wind direction, wind speed and temperature. This requires quality control of the Mode-S EHS data, conversion of magnetic heading to true heading, and specific aircraft corrections for heading and temperature. For this process a dynamic database, updated daily, of individual aircraft heading and temperature corrections is required. The derived wind observations are of good quality and of similar quality as the AMDAR wind observations. The derived temperature observations are of lower quality than the quality of AMDAR temperature observations. Reception of the data is possible with a local ADS-B/Mode-S receiver and does not involve data communication costs.

Additional information on runway heading correction, derivation of side slip angle

Mode-S EHS data allows for the access to the aircraft heading as well as the true airspeed (TAS). By use of the background fields of the numerical forecast models it is possible to derive the wind error with respect to the aircraft's coordinate system. The aircraft's heading information is generated as values referring to magnetic north. The calculation back to the true heading with respect to the geographic north depends on the use of the lookup table having been implemented individually on each aircraft or series of aircraft. The distribution process of Mode S EHS allows for a direct true heading calibration of each aircraft. In contrast to AMDAR the distribution of data is not stopped after the touch down. Hence, the heading value can be directly compared with the landing direction of the corresponding runway. The resulting difference value to the indicated heading can be applied to get a clean result for the true heading. The wind data calculated by use of this new value finally allows for the analysis of possibly systematic components of the wind error. The error components can be divided into the one longitudinal and the one lateral to the heading. The longitudinal gives information about an error in the magnitude of the true airspeed. The lateral one gives information about an unwanted angle of sideslip.

In short, the correction using the model gives the heading deviation caused by a systematic side slip angle, while correction using runway gives the heading correction for the use of an eventually erroneous magnetic deviation, and the final benefit is side slip detection. In case of a systematic behaviour in the aircraft's sideslip, this will be of interest not only for the weather services but considerably more for the airline getting the possibility to improve the economics of their flight operation. The use of Mode-S EHS and the background of the weather service's numerical model references could evolve into a tool for each airline to optimize the aerodynamic performance of their aircraft. However, planned research on the current data sets by KNMI and DWD has to provide an answer to the feasibility of calculating side slip angle, and the consecutive question if, and how many, aircraft are having a systematic slide slip angle.

4.2.3 Mode-S MRAR (register 4.4)

Mode-S Meteorological Routine Air Report (MRAR) data are transmitted through active interrogation of register BDS 4.4 by a Mode-S radar. The frequency of interrogation is generally every 4 seconds but can depend on the application.

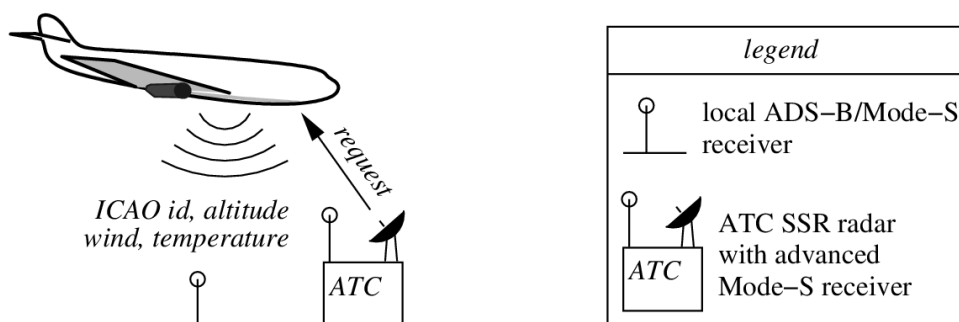


Figure 9: Schematic data flow of Mode-S MRAR

Mode-S MRAR data contains wind and temperature observations that are measured/calculated by the aircraft, see Table 11. Humidity and turbulence are included as available parameters but are in reality not filled with information in the European region, and as such have not been further looked into.

Table 11 Mode-S MRAR variables.

| Data type | Resolution | Unit |
|--|---------------------|---------------------------|
| Mode-A slant position (range) ⁷ | 1/256 | Nm |
| Mode-A slant position (azimuth) | 360/2 ¹⁶ | Degrees |
| Position from ADS-B | ~5 | m |
| wind speed | 1 | Knot |
| Wind direction | 180/256 | Degrees |
| Static air temperature | 0.25 | °C |
| Average static pressure | 1 | hPa |
| Turbulence | 4 levels | nil/light/moderate/severe |
| Humidity | 100/64 | % |

The quality of Mode-S MRAR wind and temperature is comparable to the quality of AMDAR at least on aircraft equipped with AMDAR (Strajnar, 2012), see Table 12. The quality depends on aircraft type: it is generally good on commercial passenger aircraft while biased temperatures were observed on small business/private aircraft (Strajnar et al., 2015).

Table 12 : Quality of meteorological parameters from Mode-S MRAR

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|--------------|---------|-------------------------|
| Wind speed | Yes | 10% aircraft | Good | 2-2.5 m/s |
| Wind direction | Yes | 10% aircraft | Good | 10-15 degrees |
| Temperature | Yes | 10% aircraft | Good | 1K |

Note that the average static pressure is not a requirement of ICAO Annex 3 and is rarely available in the MRAR message. However the pressure can be computed at any time from flight level information.

Conclusion: Mode-S MRAR data does contain meteorological information, in casu wind direction, wind speed and temperature. The quality of the observations are good and similar to the quality of AMDAR observations. Reception of the data is possible with a local ADS-B/Mode-S receiver and does not involve data communication costs.

4.2.4 Mode-S Met. Hazard Report (register 4.5)

A specific Mode-S register BDS 4.5 is called Met. Hazard Report, and the variables are described in Table 13. Although this register is currently not populated with data by any known transponder type, it remains a possible way to exchange hazard reports. This could replace the current voice communication between pilots and air traffic control to report turbulence. Register BDS 4.5 is generally not

⁷ Identical as, and explained in more detail in, Table 9.

requested/available from Mode-S radars. The content of this data needs to be evaluated when this data source becomes available.

Table 13 Mode-S meteorological Hazard Report variables.

| Data type | Resolution | Unit |
|-------------------------|------------|---------|
| Turbulence | 16 | Feet |
| wind shear | 45/512 | Degrees |
| microburst | 90/512 | Degrees |
| ground speed | 2 | Knots |
| Icing | 90/512 | Degrees |
| wake vortex | 1 | Knots |
| static air temperature | 0.25 | ° C |
| average static pressure | 1 | hPa |
| radio height | 16 | Feet |

Although the Mode-S Met. Hazard Report is not available the quality of the meteorological parameters, which is unknown, are shown in Table 14 for consistency reasons.

Table 14 : Quality of meteorological parameters from Mode-S Met. Hazard Report

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|----------|---------|-------------------------|
| Wind speed | Yes | No | unknown | Unknown |
| Wind direction | Yes | No | Unknown | Unknown |
| Temperature | Yes | No | unknown | Unknown |

Conclusion: currently the Mode-S meteorological hazard report is not being interrogated. It is very likely that aircraft transponders are not capable to provide this information at this time. As such the report is not available for meteorological purposes.

4.2.5 Mode-S data collection

There are currently two known ways in which Mode-S data can be collected for meteorological use.

The first method utilizes data being provided by ATM, in this case the data is collected and decoded using the already available ATC infrastructure. This has been shown to work for both Mode-S EHS and MRAR data. The data will normally be encoded in an ASTERIX format (see section 7.1.1) with primary radar locations. This is the method utilized by KNMI and ARSO.

The second method uses local ADS-B/Mode-S receivers that are owned and maintained by national meteorological services or other entities. The data is received and decoded without ATM interaction. ATM Mode-S radars are still required and must be interrogating aircraft for the Mode-S EHS or MRAR parameters. The data can be decoded to the maximum precision. Aircraft positions are found by decoding aircraft ADS-B messages. These are normally of higher accuracy than the radar position but rely on aircraft GNSS systems. This data collection method is sometimes referred to as Mode-S EHS /ADS-B data and is the method employed by the Met Office in the UK and KNMI in The Netherlands.

4.3 E-AMDAR

The principle of AMDAR (Aircraft Meteorological Data Relay) consists of the use of ACARS (Aircraft Communications Addressing and Reporting System) as the communication backbone. This nearly global functionality is supplied by the providers Rockwell Collins (formerly Aeronautical Radio Incorporated,

known as ARINC) and SITA (Société Internationale de Télécommunication Aéronautique). Airlines are using ACARS for surveying the operational status of their fleets and ACARS is also used for transmitting relevant flight planning information to ATM.

Along with the transmission of flight operational information ACARS is also able to send the meteorological data that is generated on-board for display in the cockpit, which are required for navigation purposes as well as for safety control e.g. icing conditions.

Since the 1980's meteorological services realized the potential for ACARS to be configured for the near real-time transmission of meteorological data. Both the on-board ACARS unit and the ACMS (Aircraft Condition Monitoring System) are programmable such that data sampling and transmission rates can be adapted to meet the meteorological requirements. This programming can either be performed by specialists within each airline or by the corresponding avionics system vendor. However, a data licence agreement has to be signed with the airlines, which specifies the communication software changes that are necessary to the aircraft avionics systems.

In Europe AMDAR is realized as a work sharing programme EUMETNET-AMDAR (E-AMDAR) which is centrally managed by a Coordinating Member (CM) acting on behalf over all EUMETNET members. Currently the CM for E-AMDAR is the Met Office. The CM holds the contracts with each of the participating airlines who each contribute their data to a common AMDAR data infrastructure. All E-AMDAR data is processed and checked via a central data hub, called E-AMDAR Data Acquisition System (E-ADAS), which is hosted at the Met Office at its headquarters in Exeter, UK. See Figure 10 showing the E-AMDAR infrastructure and data flow with E-ADAS at the centre.

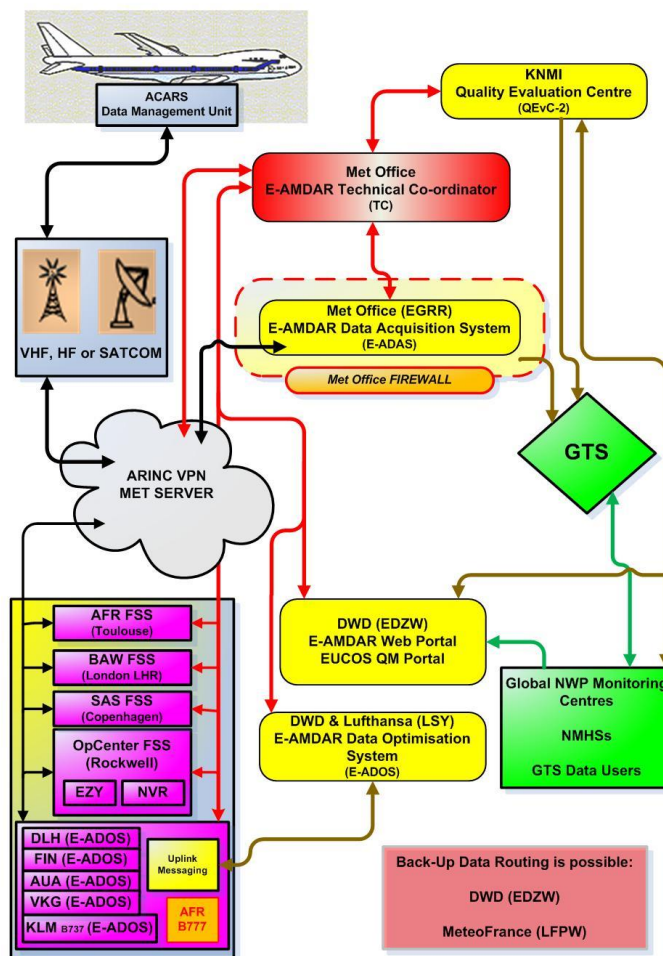


Figure 10: E-AMDAR infrastructure diagram

The E-ADAS functions can be summarized as follows:

- Reading of the AMDAR data input coming from all European AMDAR airlines
 - > either via the service provider ARINC or SITA
 - > or via the airline's data centres
 - > or via the meteorological services being in contract with the corresponding airlines
- Sense checking of the data
- Exclusion of dubious and erroneous data
- Conversion into BUFR
- Dissemination onto GTS

E-ADAS consists of two identical systems being operated in separate buildings. The counterpart system is working in a standby mode to be able to take over the job if the actually working system may fail. A secure operation of 24 hours per day, 7 days a week is given.

Figure 10 also shows the flight selection systems (FSS) and optimisation system (E-ADOS) used to control the selection of aircraft and which destinations are chosen for generation of data, based upon knowledge of each airlines flight schedules. Flight selection and optimisation are needed to keep costs for data to a minimum while generating the most amount of data as required in both time and space.

The data sampling and transmission during ascents and descents (profiles) have higher priority over land areas while en-route data is taken mainly over data sparse/oceanic areas.

Within the global community of the aircraft-based observation methods called AMDAR, the unique characteristic of E-AMDAR are:

- the cooperation of several national weather services to operate one central data acquisition system;
- the use of optimisation systems for configuration and activation of the flight segments' measurement process (targeted measurements) or at least the use of flight selection systems to be adjusted by the program management.

The airlines' charges for providing the data to E-AMDAR and the national weather services are within the range of 0.05€ to 0.15€ per observation.

- An E-AMDAR observation consists of one measurement each of air temperature, wind speed and wind direction at a single level in the atmosphere, where the level is reported as pressure altitude. Note: there is provision within an AMDAR message for measure of icing, turbulence and humidity to also be reported but apart from a few exceptions the vast majority of reports only contain temperature, wind speed and direction. An ascent or descent profile consists of up to 35 separate single level observations.

Charges are also made for uplink commands sent from the ground to the aircraft to re-configure data sampling when needed for each aircraft; these are approximately 7% of data communication cost.

Total charges to E-AMDAR include the uplink/data downlink fees (which also vary depending on whether VHF or Satcom is used) as well as the software maintenance and administration costs.

Since 2006 the E-AMDAR data do not only consist of those generated by aircraft instrumentation (i.e pressure, temperature and wind) but on a very few aircraft (3) humidity sensor systems have been added. Their output is connected to AMDAR's on-board data acquisition unit, such as ACARS or ACMS. Only when the humidity can be added, the set of essential parameters observed by aircraft for weather forecast gets complete. Most of the ACARS systems (plus eventually ACMS) are correspondingly configurable under the responsibility of the airline and its system integration partners. This procedure for installing humidity sensors to aircraft has now been certified for selected aircraft types.

By the end of 2015 there will be 9 Lufthansa aircraft of the Airbus A320 type family that will be equipped with humidity sensors (WVSS-II Version 3). Since February 2015 the first E-AMDAR humidity observations have been sent to GTS.

A EUMETNET action is ongoing to build the business case for an extended fleet of E-AMDAR aircraft to be fitted with humidity sensors.

To be accessed by ADS-C or Mode-S MRAR, the humidity data should be written in the register 4.4. Actually the output of the humidity sensor is written via a serial interface type ARINC 429 directly into the ACARS unit or into data acquisition unit ACMS. The latter one itself is connected to the ACARS unit. However, for the transmission of humidity samples via ADS-C or Mode-S MRAR the following things would have to be implemented:

- an interface between the humidity sensor and the transponder.
- an amendment of the transponder for reading and transmitting of the additional humidity samples and quality parameter.

The infrastructure concept of AMDAR is able to include more parameters, such as turbulence, icing and the altitude of the satellite navigation to achieve direct information about the geopotential altitude of each observation.

The following tables show the possible sets of parameters transmitted via AMDAR.

Table 15: Standard report variables of AMDAR

| Data type | Resolution | Unit |
|----------------------------|--|---|
| Aircraft Identification | | |
| Day | 1 ... 31 | 1 Day |
| Time | Hour, Minute | 1 Hour, 1 Minute |
| Observation Type Indicator | 1 ... 9 | |
| Latitude | 0.1 Minutes | Degrees and Minutes |
| Longitude | 0.1 Minutes | Degrees and Minutes |
| Pressure Altitude | 10 | ft |
| Static air temperature | 0.1 | Degrees Celcius |
| wind speed | 1 | kt |
| Wind direction | 1 | Degrees |
| Humidity | Floating-point number with mantissa of 2 digits 1 to 10 % rel. accuracy | kg / kg Water Vapour Mass Mixing Ratio |
| Roll angle flag | | |

Table 16: Additional observation elements being available, when the on-board software complies with the latest versions of ARINC 620 or AOSFRS

| Data type | Resolution | Unit |
|--|---|-----------------|
| Water Vapour Mass Mixing Ratio or Humidity | Floating-point number with mantissa of 4 digits 0.01 to 0.001 % rel. accuracy | kg / kg |
| Relative Humidity | 0.01 | % rel. humidity |
| Routine Eddy Dissipation Rate (EDR) | see AOSFRS/ARINC 620 | |
| Derived Equivalent Vertical Gust (DEVG) | 0.1 | m/s |
| True Airspeed | 1 | Kt |
| True Heading | 0.1 | Degree |
| GNSS Altitude | 10 | Ft |
| Anti-Ice | see AOSFRS/ARINC 620 | |
| A/C configuration indicator | | |
| Icing | Boolean | yes / no |

For each flight phase the sampling interval durations can be configured by the flight selection systems to values between 1 s and some hours.

E-AMDAR alone produces approximately 60,000 reports per day while worldwide the daily total is around 700,000. The biggest yield is over the USA ($\approx 600,000$). The spatial distribution of AMDAR is shown in Figure 11. At a first glance this looks like having a good worldwide coverage but the effective three-dimensional coverage is shown by Figure 12. The display's reduction to the data points in the lower 5,000 ft show the biggest agglomeration of vertical profiles are over the continental USA, Central Europe, Eastern Asia, Australia/New Zealand and South Africa. A more homogeneous worldwide coverage with aircraft observations would only be attainable, if all ACARS equipped airlines would be able to join AMDAR, or in case aircraft derived data could be obtained in different ways as highlighted in this report.

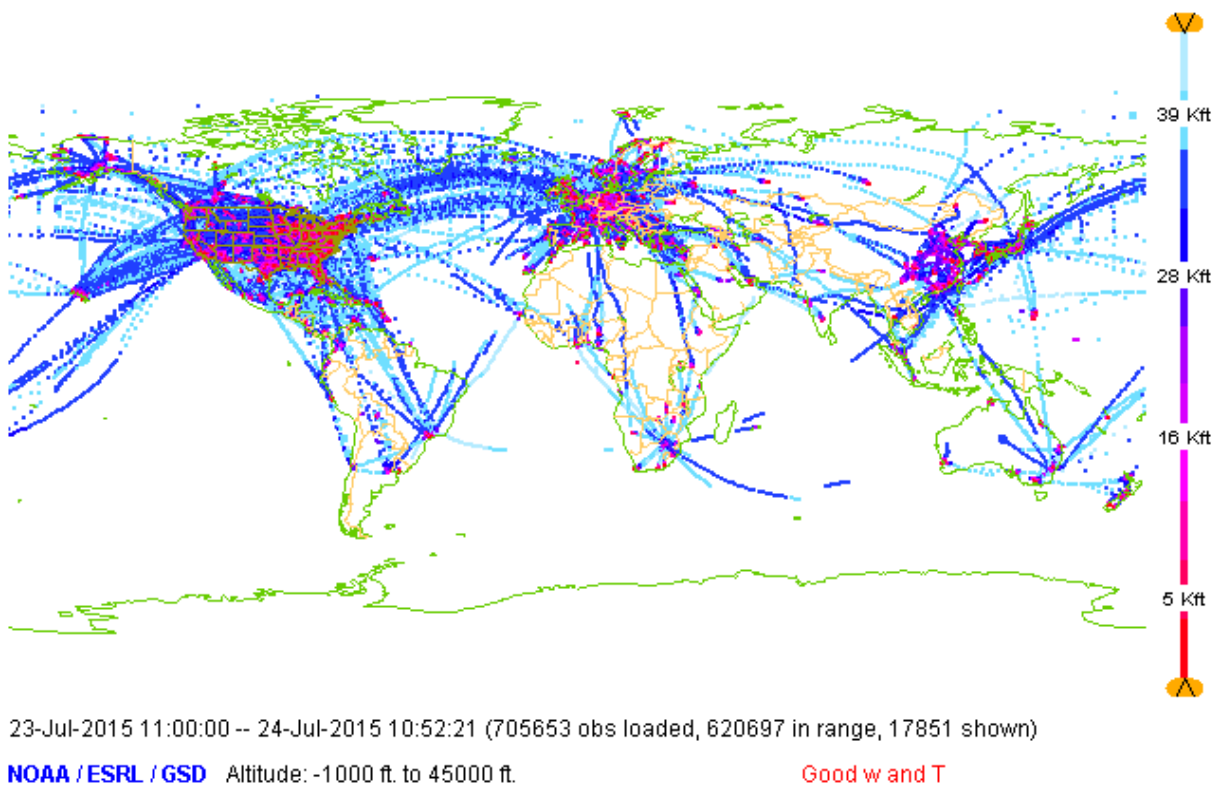
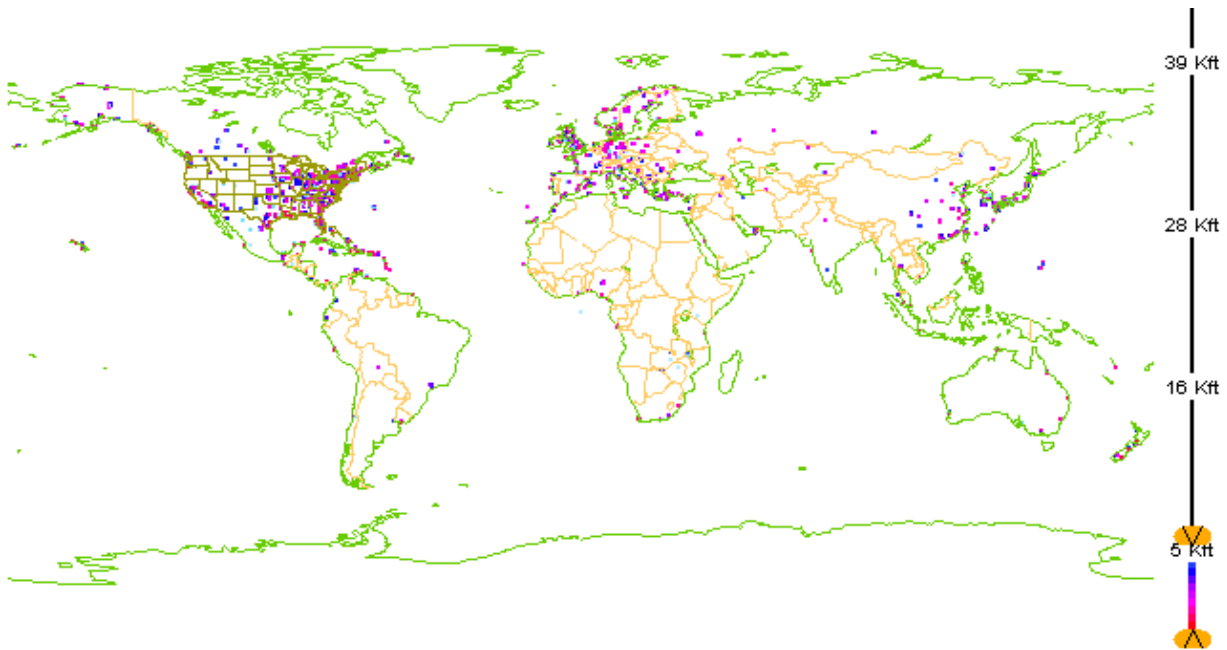


Figure 11: Worldwide distribution of AMDAR measurements over 24 hours. The altitude range goes from ground to 45,000 ft.



23-Jul-2015 11:00:00 -- 24-Jul-2015 10:52:21 (705653 obs loaded, 130292 in range, 1105 shown)

NOAA / ESRL / GSD Altitude: -1000 ft. to 5000 ft.

Good w and T

Figure 12: Worldwide distribution of AMDAR measurements over 24 hours. The altitude range goes from ground to 5,000 ft. Only the locations of vertical profiles can be seen.

For the national weather services who wish to start their own AMDAR programme it is necessary to first identify suitable ACARS equipped airlines that are providing the meteorologically appropriate routes and destinations with their fleets. The direct contract partners of the weather services could then be either the airlines themselves or as used in the USA, a network provider who then has the job of contracting the corresponding airlines.

The airlines will have to order or at least to allow for the programming of the ACARS management units on their aircraft. The programming needs to conform to the latest versions of specification standards such as ARINC 620 or AOSFRS. Depending on the type of ACARS unit it may be that there already is an installable program version available.

As mentioned above the business case concerning humidity (HU) observation is on-going but should report in autumn 2015. The ultimate network solution may be a combination of E-AMDAR observation and commercially sourced TAMDAR data. With TAMDAR the humidity data has no chance of being available from ADS-B or MODE-S-MRAR but WVSSII sensors through E-AMDAR could be made available in BDS register 4.4.

Table 17 : Quality of Meteorological parameters from AMDAR

| Meteorological parameter | Presence | Observed | Quality | Accuracy wrt. NWP model |
|--------------------------|----------|-------------------|---------|-------------------------|
| Wind speed | Yes | selected aircraft | Good | 2-2.5 m/s |
| Wind direction | Yes | selected aircraft | Good | 10-15 degrees |
| Temperature | Yes | selected aircraft | Good | 1 K |
| Humidity | Yes | selected aircraft | Good | 10% |

5 Description and analysis of data collection possibilities

This chapter describes the current and future availability of the different types and sub-types of aircraft derived data as identified in the previous chapter. This includes tables and geographical maps in which country what data types are currently in theory available for meteorological purposes. When relevant, information is provided on the number of observations, horizontal and vertical coverage, collection time and frequency aspects.

5.1 ADS-Addressed (ADS-A) / ADS-Contract (ADS-C)

ADS-C (or ADS-A) is based on a negotiated one-to-one peer relationship between an aircraft and a ground facility. In the Future Air Navigation System (FANS) ADS-C reports are employed using the Aircraft Communications Addressing and Reporting System (ACARS) as the communication protocol. During flight over areas without radar coverage (e.g. oceanic and polar), reports are generally sent over ACARS, while over areas with radar coverage the reports are collected by the ATC radar. The reports are transported to the requesting agency through SITA and ARINC.

The number of potential observations of ADS-C in The Netherlands is limited by the current low ADS-C equipage rate of aircraft operating at Schiphol Airport. Measurements over a period of nine months showed that on average 16% of Schiphol inbound and outbound aircraft operating under Instrument Flight Rules (IFR) is equipped with ADS-C. This group consists primarily of wide-body aircraft. In the specific period from 04:00 till 06:30 hours (local time) the ADS-C equipage of inbound aircraft increases up to 80% because of a high number of incoming intercontinental wide-bodies.

Currently there is no active North-American or European regulation mandating ADS-C and it is also not foreseen within a time scope of 5 years. Standardisation material for ADS-C is readily available though. It consists of a number of Standards and Recommended Practices and other guidance material from the International Civil Aviation Organisation (ICAO) and several documents of the European Organisation for Civil Aviation Equipment (EUROCAE) and the Radio Technical Commission for Aeronautics (RTCA).

Main aircraft operators at Schiphol, like Royal Dutch Airlines (KLM), EasyJet and Transavia do not plan to extend their ADS-C equipage rates unless regulations will force them to. KLM currently has its Boeing 747-400, Boeing 777 and Airbus A330 aircraft equipped with ADS-C while EasyJet and Transavia with solely Airbus A320 and Boeing 737 aircraft, have no ADS-C equipage on board.

Conclusion: ADS-C offers global opportunities for acquiring good quality meteorological observations. The number of aircraft equipped with ADS-C is low and requesting and receiving ADS-C data involves data communication costs. It is not foreseen that this situation will change in the foreseeable future. Furthermore, cooperation with airlines, ATC or aircraft manufacturers is imperative to receive the data. There are opportunities to request and receive meteorological observations from global regions where observations are sparse. The advantage over AMDAR is that this does not require dedicated AMDAR software in aircraft. There are also opportunities to receive already available, and thus paid for, ADS-C data from aviation stakeholders to be used in the meteorological domain.

5.2 ADS-Broadcast (ADS-B) and ADS-Broadcast Extended Squitter (ADS-B ES)

ADS-B equipment is currently mandatory in portions of Australian airspace, the United States requires some aircraft to be equipped by 2020 and the equipment will be mandatory for some aircraft in Europe.

EUROCONTROL has set mandates for all new aircraft from 8th June 2016 to carry ADS-B equipment, with retrofit mandated for 7th June 2020, this is the implementation date for REGULATION (EU) No 1028/2014 (which updates REGULATION (EU) No 1207/2011). Depending on the aircraft and flights flown this may be ADS-B or ADS-B ES. Locally some national airspace rules already have mandates in place for aircraft wanting to use them, there are normally exceptions applied on request to the regulatory authority or directly to a flight controller during the flight. Because of these mandates most airlines operating from major international airports in Europe can be assumed to comply to the ADS-B ES standard.

The ADS-B data is routinely collected by aviation enthusiasts and provided to services such as FlightRadar24 (<http://www.flightradar24.com>), a snapshot of data is shown in Figure 13. The equipment used comprises an antenna, decoder box (many varieties are available and modified digital television (DVB-T) receivers can be used) and a computer to archive, monitor and transmit the data. The range of any given receiver depends on line of sight to an aircraft, and the antenna. Range should therefore be limited by the local environment and curvature of the earth. Experimental evidence from the UK Met Office has shown that anomalous propagation can occur with at least one incident of aircraft messages being received at 150 m altitude 300 km from the receiver site. This same receiver technology can be used to collect the Mode-S messages, albeit with different software.

Both KNMI (De Haan et al, 2013) and UK Met Office have experience with, and local receivers in place to receive, ADS-B and ADS-ES data. The ADS-B position data is also imperative in the decoding process of Mode-S EHS and MRAR data received via local ADS-B/Mode-S receivers.

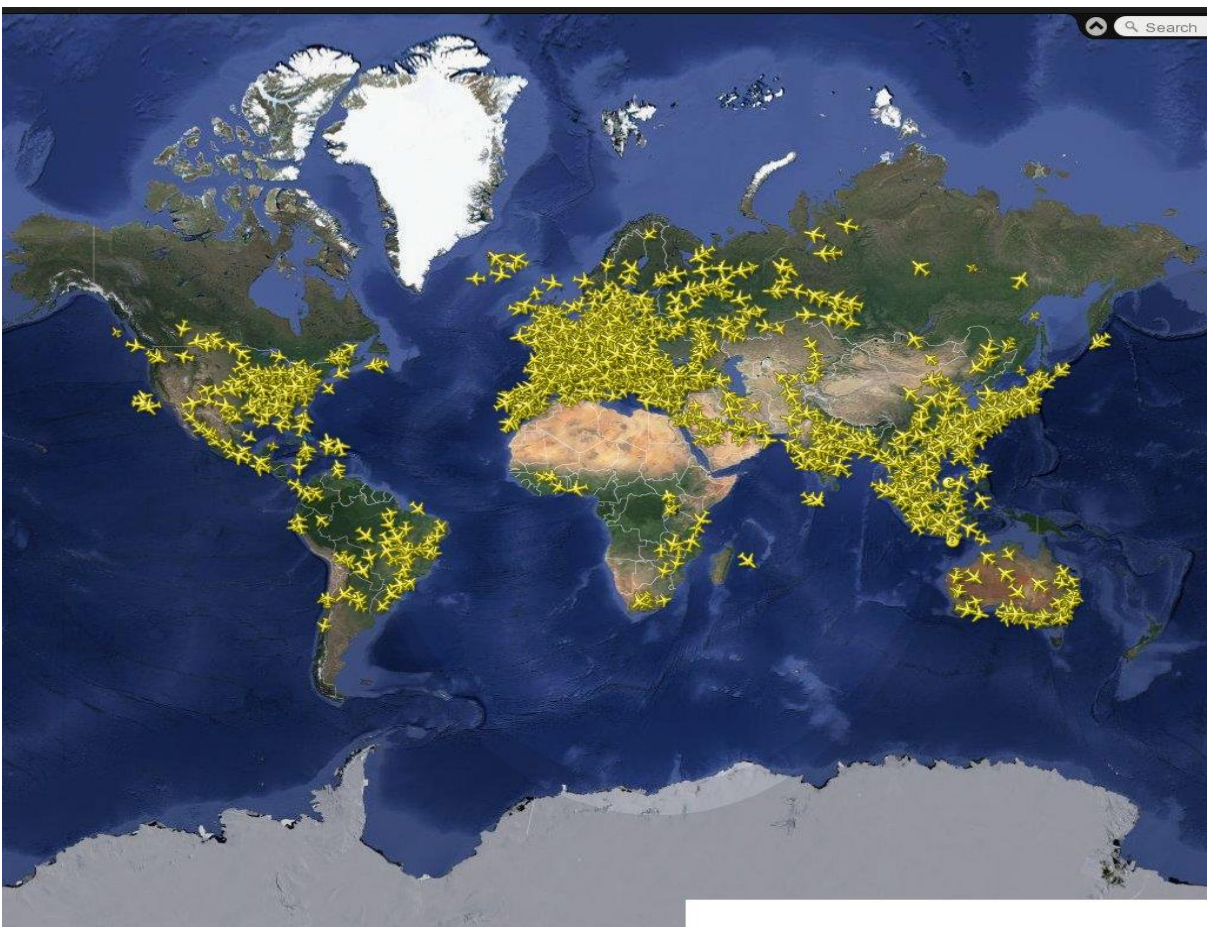


Figure 13 FlightRadar24.com snapshot of global data ADS-B at 10:10 UTC on 27th May 2015.

Conclusion: although widely available ADS-B and ADS-B ES data offer limited opportunities for acquiring meteorological observations. The ADS-B position data however is imperative for the decoding of Mode-S EHS and MRAR data received by local receivers.

5.3 Secondary Surveillance Radar (SSR) Mode-S

The previous chapter identified several opportunities to receive or derive meteorological observations from Mode-S data. It also made very clear that this is depending on the specific sub-type of Mode-S data. The data availability of the various mode-S sub-types is depending on ground based surveillance systems, owned and maintained by air traffic organizations, and airborne surveillance systems, owned and maintained by airlines. The following sections provide more detail on the relations between surveillance infrastructure and data availability, and current and foreseen status of the infrastructure and the link with national and international legislation.

5.3.1 Secondary Surveillance radars in Europe (EU regulation 1206/2011 and 1207/2011)

Member States responsible for the provision of air traffic services in the airspace defined in Figure 14 shall ensure that a capability is implemented to be able to establish individual aircraft identification using downlinked aircraft identification for:

- a) at least 50 % of all over-flights of the defined airspace of the individual Member State and;
- b) at least 50 % of the combined total number of all arriving flights and departing flights within the defined airspace of the individual Member State.

Air navigation service providers establishing individual aircraft identification using discrete SSR codes in the airspace as defined in Figure 14.

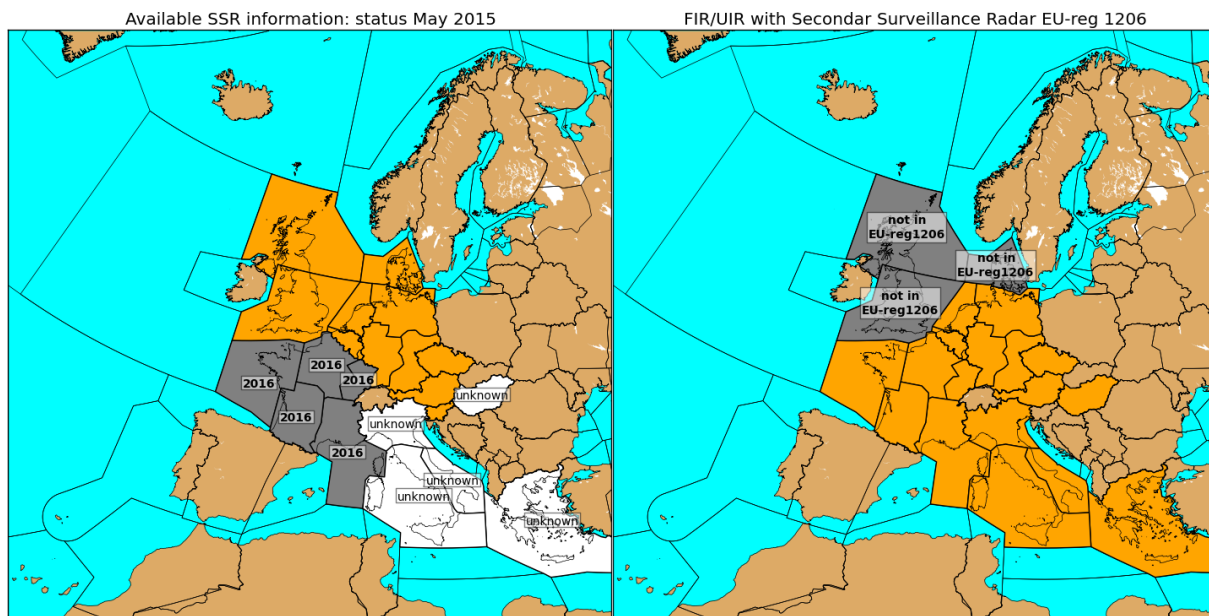


Figure 14 : Legal obligations for aircraft to be EHS equipped for the different Flight Information Regions (FIR) and Upper Flight information Regions (UIR); Left panel: current status. The year denotes the expected readiness of the ground segment. Right panel status of State obligations to be equipped with secondary surveillance radar capability on 2 January 2020 (EU regulation 1206/2011 and 1207/2011). Regions that currently provide EHS data, and that are not included in the regulation, are coloured grey in the right panel. The expectation is that the data provision for these regions will not cease in time.

Currently Mode-S EHS ground infrastructure is available in United Kingdom, Netherlands, Belgium and Germany, and this is foreseen for France in 2016. There is proof that some Mode-S EHS infrastructure exists in Spain as well.

In 2020 a number of States are obliged to have secondary surveillance radar in place and this constitutes to a significant part of Europe as shown in figure 14. It is not clear from EU legislation if this means that this area is Mode-S ELS equipped only, or if this means that the radar is obliged to interrogate Mode-S EHS.

Aircraft flying over the regions where it is obliged to be Mode-EHS equipped are expected to keep the responder on over other flight information regions as well. From an air infrastructure perspective this offers great potential to receive Mode-S EHS data from other regions as well if the ground infrastructure would interrogate these aircraft.



Figure 15 : The coverage of known Mode-S EHS/MRAR information. Some locations are in test phase like in Auch (France) and Denmark and is expected to become operational in the near future, and is to be extended as shown in the previous figure on EU regulations.

Figure 15 :Figure 15 shows the coverage of known sources of Mode-S EHS/MRAR meteorological information, either being operational or expected to be disclosed in the coming years. In grey are depicted the routinely available Mode-S EHS/MRAR observations and the other points depict example datasets obtained from different sources valid at different times.

Conclusion: secondary surveillance radar capability requesting Mode-S EHS data is already available and operational in United Kingdom, Netherlands, Belgium, Germany, Slovenia, Czech Republic and soon to be in France. Based on EU regulations it is expected that secondary surveillance radar capability will be expanded towards Italy, Greece, Austria, Hungary and Romania before 2020. At the moment it is unclear if all of these radars will interrogate Mode-S EHS. Several other countries have or are developing Mode-S EHS capabilities but an overall picture of the ATC landscape is not available at present. Note that the airspace of Spain, Portugal and Poland have already Mode-S EHS capability.

5.3.2 Mode-S ELS

Mode-S ELS is an elementary method of surveillance, as the abbreviation suggests. Within European Mode-S airspace:

- Aircraft intending to fly IFR as GAT must be Mode-S ELS compliant.
- Aircraft intending to fly VFR: requirements differ for VFR flights within the participating States. Consult appropriate AICs/AIPs for the states in which flights will be conducted.
- State aircraft: Co-ordinated exemption arrangements have been established (consult the Civil-Military ATM Coordination Division).

As concluded in 5.2.1 the Mode-S ELS data is of no direct use for meteorological purposes. There are a large number of Mode-S ELS radars in Europe (see Figure 16) and as these radars can be used to interrogate Enhanced surveillance (EHS) the coverage shows an enormous potential for Mode-S EHS. However, updating from ELS to EHS is not trivial for air traffic organizations and results, amongst others, in a significant increase of data load on ATC networks.

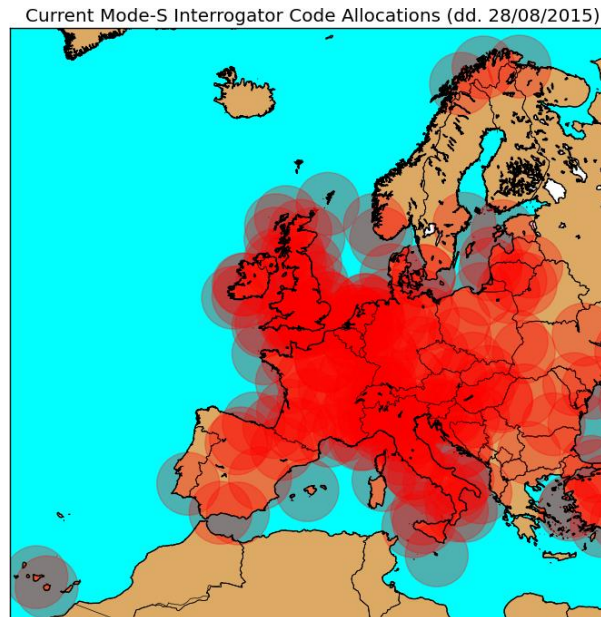


Figure 16 : Coverage of Mode-S ELS or EHS (see Figure 5 and Figure 6) radars⁸ in Europe using a default radius of 200km. As Mode-S ELS and EHS use the same ground infrastructure, this graph shows the enormous future potential for EHS interrogation by ATC. However, updating from ELS to EHS is not trivial for air traffic organizations and results, amongst others, in a significant increase of data load on ATC networks.

Conclusion: the European region is almost entirely covered with secondary surveillance radar systems. At the moment many of these radars are only interrogating Mode-S ELS. Mode-S ELS and Mode-S EHS use the same ground based surveillance infrastructure. This offers an enormous future potential for Mode-S EHS interrogation by air traffic control organizations. However, updating from ELS to EHS radar interrogation is not trivial for air traffic organizations for several reasons. These are amongst others bandwidth of radar data communication and ATC network capacity issues.

5.3.3 Mode-S EHS (registers 4.0, 5.0, 6.0)

EU regulation 1207/2011 (and amended by 1028/2014) states that all fixed wing aircraft with a maximum certified take-off mass exceeding 5.700 kg or having a maximum cruising true airspeed capability greater than 250 knots, operating flights referred to in all flights operating as general air traffic in accordance with instrument flight rules within the airspace ICAO EUR and AFI⁹, with an individual certificate of airworthiness first issued on or after 8 June 2016 are equipped with secondary surveillance radar transponders. This shall be ensured by the aircraft operators by 7 June 2020 at the latest.

This implicates that a large number of airlines are, or will be in due time, Mode-S EHS capable. And as such offer potential to serve as provider of aircraft derived data. However, in certain circumstances

⁸ Source of locations: EUR DOC 024 amendment July 2013. Latitude and longitude of radar locations extracted from openstreetmap.org. Notice that not all city or village names were present in this database. No information from Finland, Greece and Sweden. Stockholm was manually added.

⁹ Article 1(3) of Regulation (EC) No 551/2004 of the European Parliament and of the Council

airlines can apply for a limited time exception to the requirements, and this can have a significant impact on ADD availability where regional airports have a single main airline.

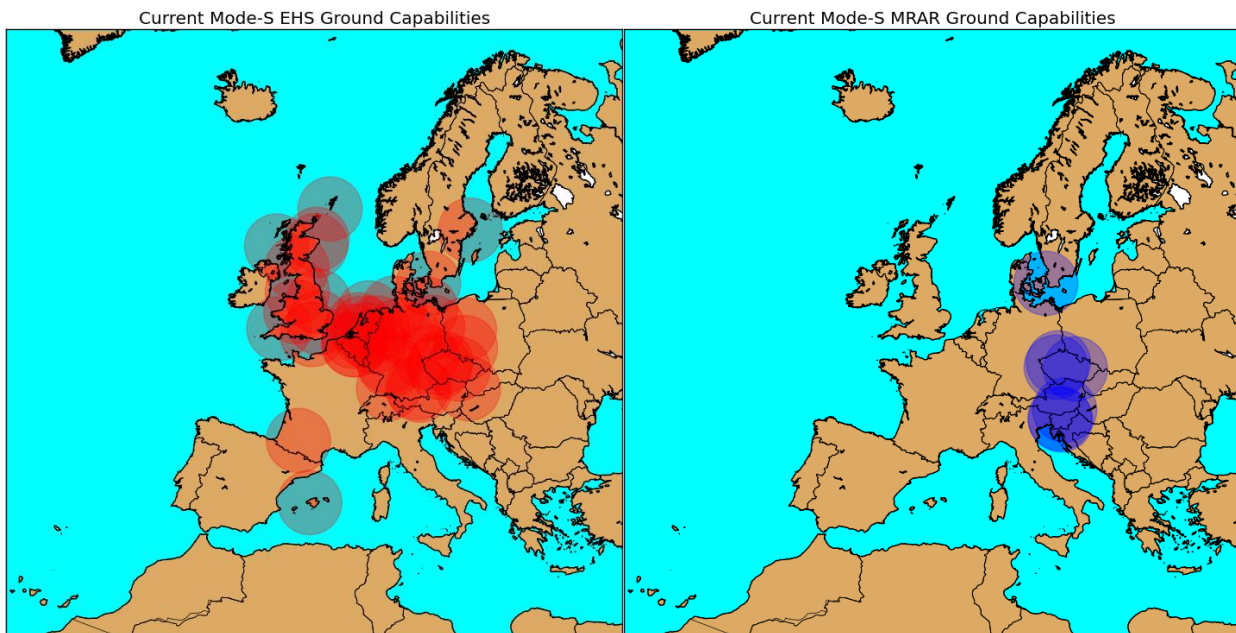


Figure 17 : Currently known (25/08/2015) ground capabilities of Mode-S EHS (left) and Mode-S MRAR (right).

Figure 17 provides an overview of currently known ground capabilities of Mode-S EHS and MRAR. Not included in the map is Ireland, where also Mode-S EHS capabilities exist. More detail on the three hotspots, being UK, MUAC and Slovenia area is provided underneath.

In November 2012 a Non-Disclosure Agreement was signed between Maastricht Upper Area Control Centre (MUAC – EUROCONTROL) and KNMI. Operational Mode-S EHS data of Germany, Belgium and The Netherlands is provided to KNMI by MUAC every 15 minutes. KNMI uses this data to derive wind and temperature observations for operational assimilation in numerical weather prediction models. The ASTERIX data is received with a latency of 8 minutes, processing of all data takes less than 2 minutes.

The aircraft derived wind and temperature are available for the meteorological community after roughly 10 minutes. The oldest data in a batch is 25 minutes old, while the youngest data is 10 minutes old. At present KNMI has agreements in place to deliver the derived observations data on a continuous basis to Meteo France (CNRM), Deutsche Wetter Dienst (DLR for EU UFO Project; Hans-Ertel-Zentrum (HerZ) and Ludwig Maximilians Universität München for COSMO-MUC-KENDA project), Danish Meteorological Institute (HIRLAM-B and DMI-HARMONIE), CNMCA (Italian Nat. Met. Center), MeteoSwiss, RC LACE (Regional Cooperation for Limited Area modelling in Central Europe) and the University of Warsaw .

Due to the high density of air traffic in this part of Europe the number of observations are staggering. In a single day more than 20 million raw Mode-S EHS observations are being received. The number of derived and quality controlled observations are close to 3.5 million, of which more than 300.000 below FL100, see the two figures below.

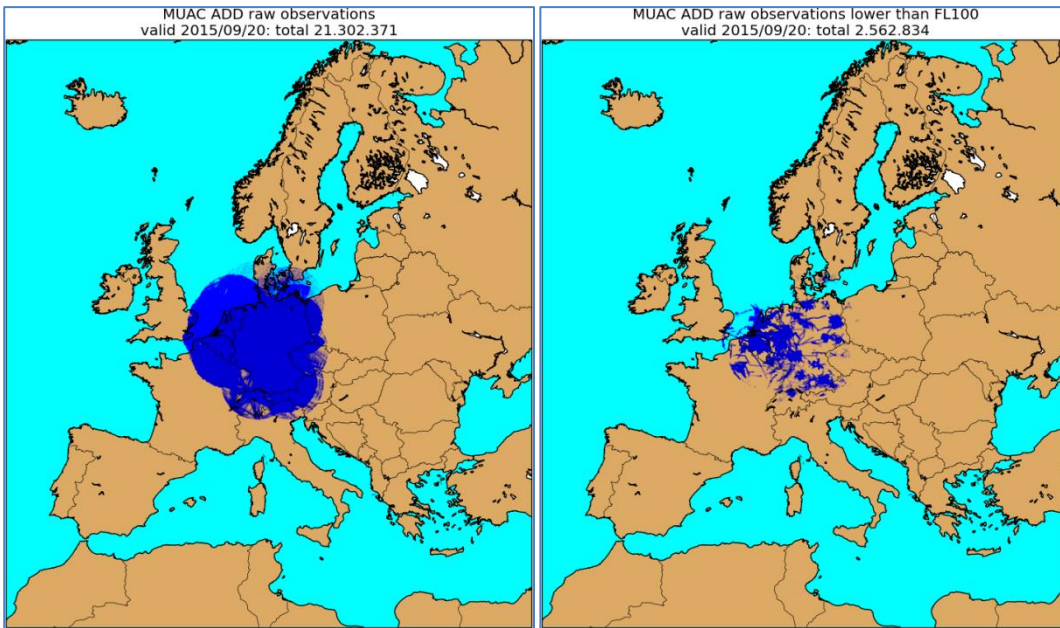


Figure 18 : Current coverage of raw Mode-S EHS data as received from Maastricht Upper Area Control of EUROCONTROL at KNMI. The example shows the observations for the 20th of September 2015 over western Europe. Source: MUAC in ASTERIX Cat 48 format, processed by KNMI. The left panel shows all raw observations, the right panel the raw observations below Flight Level 100. Notice the volume of the raw observations that is over 20 million observations each day.

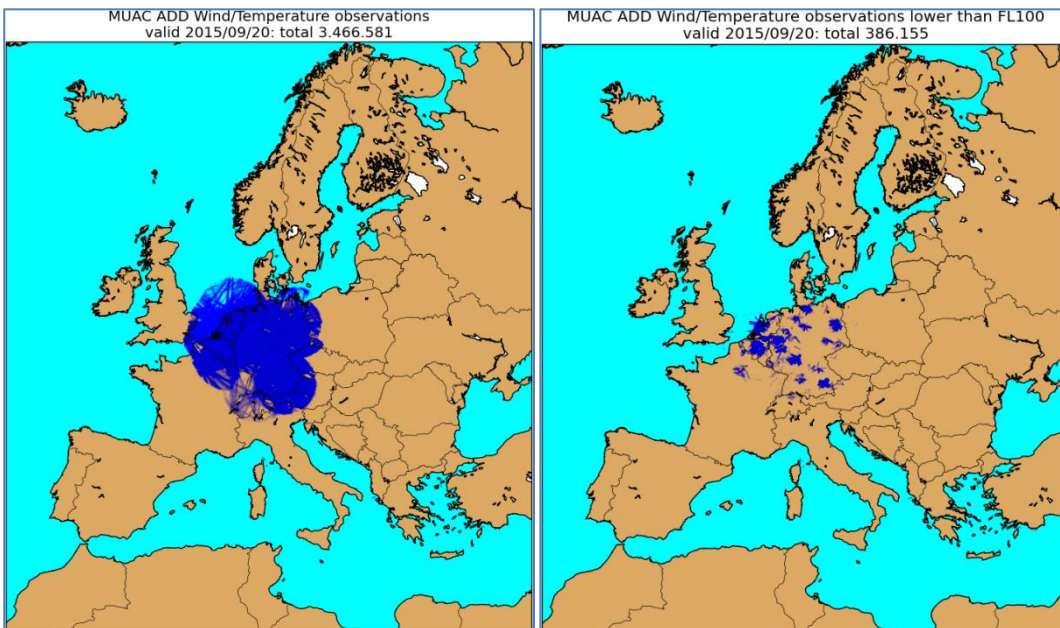


Figure 19 : Current coverage of Mode-S EHS derived and quality controlled wind and temperature observations available at KNMI. The example shows the observations for the 20th of September 2015 over western Europe. Source: MUAC in ASTERIX Cat 48 format, processed by KNMI. The left panel shows all derived observations, the right panel the derived observations below Flight Level 100. In total there were almost 6 times as many (21 million) BDS 4.0, 5.0 and 6.0 observations available in this time period. The reduction is related to the quality control that is part of the derivation process and is dependent on the number of aircraft with heading corrections in the dynamic database, and the applied one minute smoothing.

The ATM infrastructure in the UK appears to request registers 4.0, 5.0, 6.0 within all airspace within range of a NATS on-route radar, this includes all airspace above 10,000 ft although it is not mandated that all aircraft flying in this airspace are equipped to the Mode-S EHS standard. The Met Office have five Mode-S receivers over the UK, providing between 3 and 20 MB of Mode-S EHS/ADS-B ES data/10 mins

peak (a single message record is 51 bytes). This data is collected using bespoke software developed to run on Linux systems remotely deployed.

It is estimated that there are 7 million unique Mode-S EHS message sets and 14 million unique ADS-B ES message sets per 24 hours. The location of the data implies that both data interrogated from the national network of NATS SSR and local airfield SSR are collected.

During a small scale trial in the UK, the Met Office showed that meteorological data could be generated from the Mode-S messages within seconds of the first message being received using a local processing system. It is unlikely that a centralised processing solution would operate at this speed due to the time taken to transfer data, this will depend on the available bandwidth. Currently the UK data packages are transmitted to a central system every 10 minutes, which produces a latency of less than 20 minutes for more than 90% of the data. Due to the methods used to find temperatures and winds using ADS-B ES data the latency is somewhat increased. The minimum time between receiving the first message and calculating the meteorological parameter could be of the order of 20 minutes.

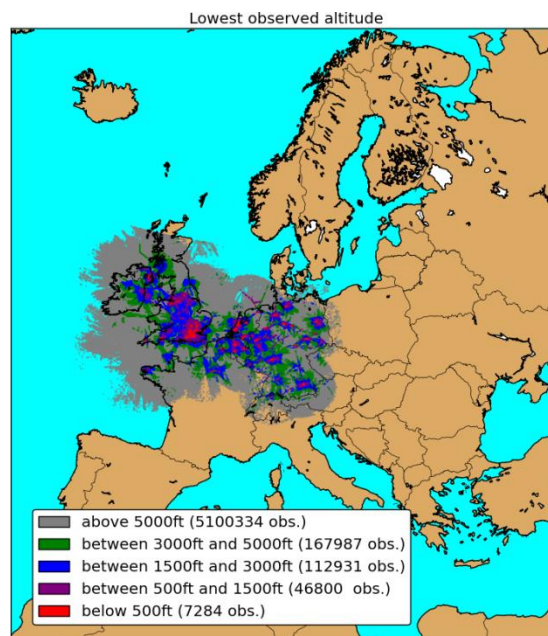


Figure 20: Current coverage and volume of raw Mode-S EHS data; colours indicate the height in pressure altitude (in feet) for a period of 1 hour.

Figure 19 shows the current coverage and volume of the raw Mode-S EHS data over UK and the MUAC area. Though more research on volume is necessary to provide solid statements it is clear that there is significant potential to derive huge quantities of wind direction, wind speed and temperature observations over the earlier identified European area.

Conclusion: based upon EU regulations a significant number of aircraft are Mode-S EHS compliant and this number will further increase for all aircraft (maximum take-off mass exceeding 5.700 kg or maximum true airspeed capability greater than 250 knots) in the near future (2020). Mode-S EHS ground-based surveillance infrastructure currently exists in United Kingdom, Netherlands, Belgium, Germany, Czech Republic and Slovenia. Interrogation by these radars results for the MUAC area alone in more than 20 million Mode-S EHS reports per day. After quality control and corrections more than 3,5 million observations of wind direction, wind speed and temperature are available daily for use in meteorological applications. These numbers can be further increased by improvements of the derivation process and by increasing the numbers of ATC radars interrogating the Mode-S EHS registers. The latter is e.g. foreseen in France in 2016 and enlarges the area covered with aircraft observations. The latency of the observations is depending on the data source, local NMHS receiver versus ATC data stream, and varies from near real time to 20 or 30 minutes.

5.3.4 Mode-S MRAR (register 4.4)

The content of Mode-S MRAR (register BDS 4.4) is defined in Annex 10 to the Convention on International Civil Aviation (ICAO, 1995). Since then it was not requested by regulation. Its availability therefore depends on the interest and willingness of the air navigation server providers to request and provide such data for use in meteorology, and aircraft to be able to respond. The SSR radars need to be additionally configured to request MRAR data.

Such a modification has so far been implemented by Slovenia Control (2 radars), AustroControl (1 radar), ANS-CR (Czech Republic, 3 radars) and Naviair (Denmark, 1 radar), and the coverage is shown in Figure 21.

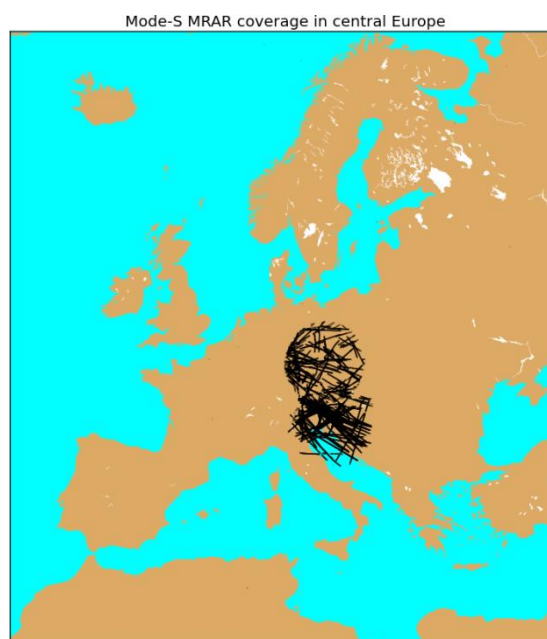


Figure 21: Area currently covered by MRAR data from 6 Mode-S radars in central Europe (Kastrup data is not shown).

The number of MRAR reports is around 80 thousand of about 1.5 million (5%) Mode-S EHS reports per day from the Slovenian radars and 100 thousand of about 4 million (3%) from the radars in Czech Republic.

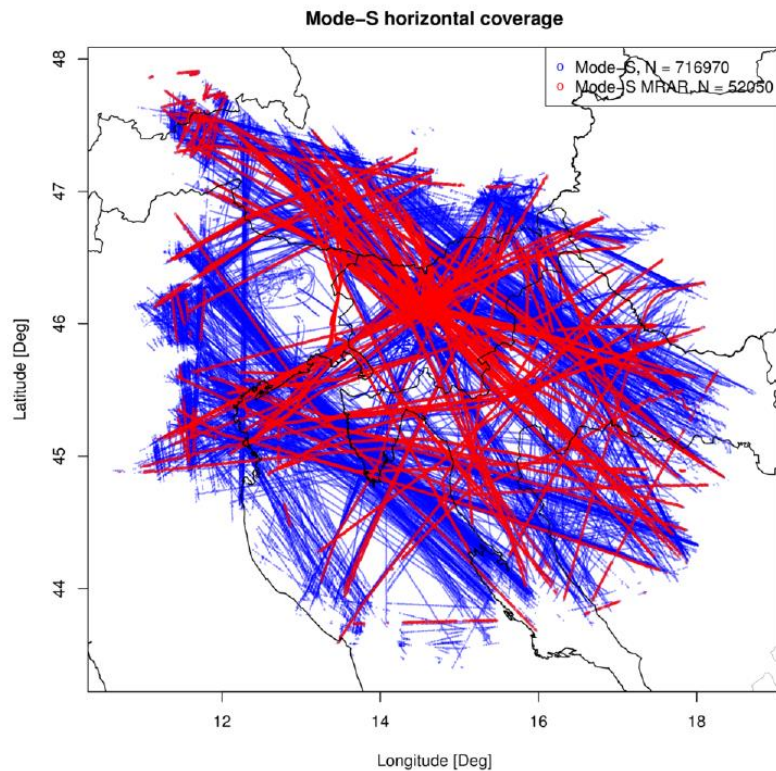


Figure 22: Coverage maps of all Mode-S responses (EHS parameters) and Mode-S MRAR observations (wind or temperature) around Slovenia on 15 April 2011. Note the much smaller number of Mode-S MRAR.

Mode-S MRAR is provided by a relatively small fraction of all Mode-S equipped aircraft, depending on the type of transponder on board. It is observed that Mode-S MRAR is generally available from aircraft equipped with Rockwell Collins transponders (typically installed on CRJ aircraft type) and is generally not available from aircraft equipped with Honeywell transponders (typically installed on Airbus aircraft. Although humidity is included in BDS 4.4 the data are not available (no aircraft type responding with MRAR has humidity sensor installed).

The BDS 4.4 is not a mandatory register within EHS and is generally not requested in a typical configuration of a Mode-S SSR radars. It is recently observed by Slovenian ATC that the amounts of data transferred by MRAR are slightly decreasing which can be related to recent upgrades of transponder software.

Apart from cooperation of air navigation service providers, the main limiting factors of Mode-S MRAR collections are transponder type and configuration, and density of air traffic. The availability of Mode-S MRAR in some regions may be limited by the bandwidth of the radar communication. Depending on the density of air traffic, the interrogation/reception of BDS 4.4 register on top of EHS registers may not be possible as this limits the number of registers that can be provided to SSR during each antenna turn. Furthermore, only limited number of transponders currently provide MRAR. For example, a large part of Mode-S data received in Slovenia stem from aircraft equipped with transponder type Rockwell Collins TDR-94. The transponder manufacturer Rockwell Collins stopped servicing register 4.4 in the version TDR-309/-409 due to several reasons (Rockwell Collins, personal communication): lack of internal

memory in the transponder, no requirement stating that these registers must be serviced, no known users of such data at the time of upgrade.

This presents a danger of losing the data during the regular upgrades. Mode-S MRAR can therefore not be considered as a fully reliable and stable data type. Efforts from meteorological community are required in the direction of changing the status of MRAR register, e.g. change the status of wind and temperature contained in BDS 4.4 by ICAO. The efforts to extract Mode-S MRAR where possible and keep or improve availability of Mode-S MRAR is important especially because it contains direct high-quality temperatures which is an advantage over from Mode-S EHS derived temperatures.

Conclusion: there are no EU regulations on Mode-S MRAR and only very few secondary surveillance radars interrogate the BDS 4.4 register (MRAR). These radars are located in Slovenia (2), Austria (1), Czech (3) and Denmark (1). There are no EU regulations for aircraft to be Mode-S MRAR capable and only very few aircraft are Mode-S MRAR equipped. The number of Mode-S MRAR equipped aircraft is slightly decreasing and can therefore not be considered as a fully reliable and stable data type. The amount of Mode-S MRAR reports is circa 3% of overall Mode-S EHS reports and amounts to approximately 180.000 observations per day for Slovenia and Austria. The advantage of MRAR observations over derived observations from Mode-S EHS is the better quality of the temperature, as described in the previous chapter. The latency of the observations is depending on the data source, local NMHS receiver versus ATC data stream, and varies from near real time to 20 or 30 minutes.

5.3.5 Meteorological Hazard Report (register 4.5)

There is currently no example of data transmitted through register BDS 4.5. This register was interrogated over a longer period by Slovenian ATC but the aircraft's response contained no valid data. This register is therefore considered as not supported by any common transponder type but can be exploited in the future to transmit severe weather related information.

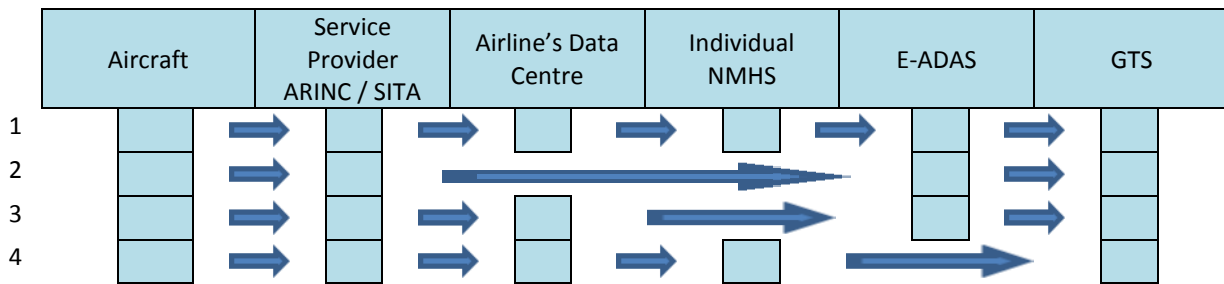
5.4 E-AMDAR

The method of data collection consists of two parts:

- Air to ground:
The ACARS on-board units send blocks of sampled data via the provider's broadcasting network (ARINC/SITA) to their data routing center.
- On ground:
From the provider's data routing center the ACARS data flow goes to the fleet management center of the corresponding customer airline.
Depending on the contractual situation the weather service or E-AMDAR directly can receive the flow of separated meteorological data. E-AMDAR can get the data from the involved airline or directly from the provider.
However, software has to be put in place which separates the downlinked meteorological data and converts them into a format being finally readable by the weather services (e.g. BUFR).

The flow of the data may take different ways into the GTS (see Table 18). Meanwhile all of the data go via the central data hub E-AMDAR Data Acquisition System (E-ADAS).

Table 18: Different possibilities of data flow from the aircraft to the Global Telecommunication System. Line 4 is just shown for historical reasons.



More than 80 % of the latencies by transmissions, buffering and processing is kept within half an hour. The latest EUMETNET Quality Monitoring Report outlines a portion of more than 95 % of the data being received within 50 Minutes after the measurement (see Table 19).

Table 19 : Excerpt from a table shown in the First Quarterly Quality Monitoring Report 2015 of the EUMETNET Observations Programme Management.

| Q1 2015 Network | Data availability | Timeliness HH+50 (Radiosondes: TEMP AB) | Timeliness HH+100 (Radiosondes: TEMP CD) | Achieving 100 hPa | Achieving 50 hPa | Individual targets subprogrammes |
|-----------------|--|--|---|-------------------|------------------|--|
| E-AMDAR | | | | | | |
| AMDAR aircraft | Annual target: 11 Mio. obs 3.08 Mio. obs (equals 28%) EUMETNET funded observations | Target: 90% → 96.1% | Target: 95% → 98.4% | — | — | Profile distribution daily profiles Target: 718 960 ↓ daily airports Target: 129 → 169 |

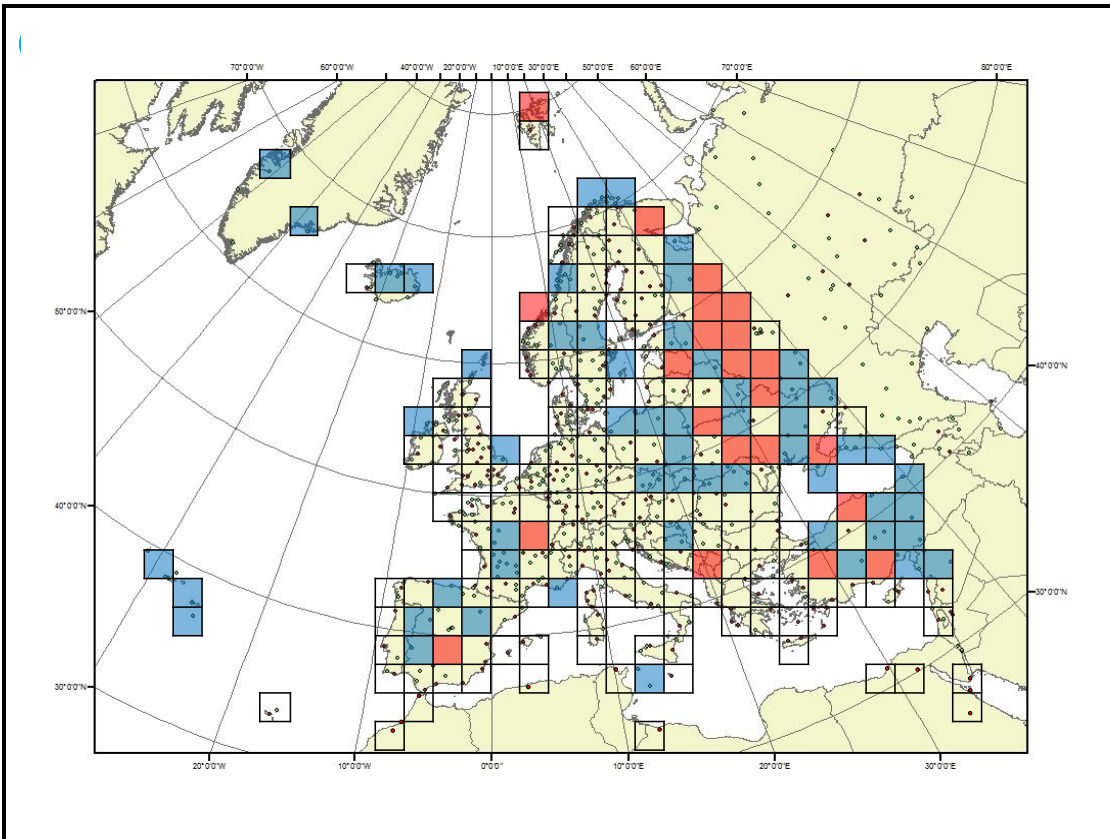


Figure 23. Current E-AMDAR coverage in Europe

Current E-AMDAR observation profile coverage is shown in Fig 23. Each blank square represents areas (approx. 250km x 250km) where profile observations are generated at least once per day from airports within the area. Blue squares are areas of potential coverage, i.e. no E-AMDAR airlines currently operate to and from airports in these areas. Red squares contain no commercial airports and therefore no possibility of AMDAR profile observations.

6 Descriptions and proposals on ADD data processing

Obtaining or deriving meteorological information from aircraft derived data requires processing and quality control. This chapter describes the processing that is required for the various ADD types and sub-types. Focus is given to the secondary surveillance radar data (Mode-S) as this data type is most promising for meteorological purposes. The processes of KNMI, UK Met Office and SEA are being described including technical details on collection process of the data, processing and quality control, amount of data storage and an estimate of resources and costs involved. Finally several options on how to process the data on a pan-European scale are being addressed. The last section looks at the possible use of the E-AMDAR Data Acquisition System (E-ADAS) for ADD purposes.

6.1 Automatic Dependent Surveillance (ADS)

In the following sections the processing of ADS-C, ADS-B and ADS-B ES are addressed. The focus of this report will be on secondary surveillance radar and as such the ADS sections are kept brief.

6.1.1 ADS-Addressed (ADS-A) / ADS-Contract (ADS-C)

ADS-C message have the following properties:

- Since ADS-C is a point-to-point connection no raw processing can be performed;
- Data delivery depends on connection to airline, ATC, aircraft or engine manufacturer.

Processing of ADS-C data requires implementation of quality control and is different from Mode-S EHS because a large part of the processing is performed at airlines and or ATC. As such the processing of ADS-C data is more similar to the current processing of E-AMDAR data.

In order to address the above more research on the processing of ADS-C data is advised.

In order to disclose ADS-C information one of the following steps could be taken to exploit already existing infrastructure (i.e. ADS-C request):

- Contact airlines to disclose existing ADS-C information;
- Contact ATC to disclose existing ADS-C information;
- Contact aircraft and/or engine manufacturers to disclose existing ADS-C information.

At the same time these partners could be asked to include meteorological information in all ADS-C messages or to expand the number of ADS-C messages in specific regions or specific altitudes. This will probably result in an increase of the data communication costs and needs to be addressed. Please note that apart from direct available meteorological information in ADS-C messages it is also possible to derive wind direction and wind speed observations from ADS-C data. From Mach number and heading data points, using additional temperature information from for example ECMWF, wind vectors can be derived (De Haan et al, 2011). This is not further addressed in this report.

6.1.2 ADS-Broadcast (ADS-B)

At this time it is suggested to defer further work on this as there is little work done in the area and the data is of significantly less value than the other ADD types.

- At present no meteorological information is directly available from ADS-B
- In case the data is not provided by ATC a spatial coverage of local ADS-B receivers is required every 200km and at major airports

- Requires implementation of quality control

6.1.3 ADS-Broadcast Extended Squitter (ADS-B ES)

At this time it is suggested to defer further work on this as there is little work done in the area and the data is of significantly less value than the other options.

- At present no meteorological information is directly available from ADS-B ES, other than information triggered by Mode-S EHS
- In case the data is not provided by ATC a spatial coverage of local ADS-B receivers is required every 200km and at major airports
- Requires implementation of quality control
- Only (layer) temperature can be inferred from pure ADS-B ES data (i.e. without Mode-S EHS requests)

6.2 Secondary Surveillance Radar (SSR) Mode-S

In the following sections the processing of Mode-S EHS and MRAR are addressed. The focus of this report is on these data given the significant opportunities to derive considerable numbers of quality controlled wind and temperature observations in Europe.

6.2.1 Mode-S EHS (registers 4.0, 5.0, 6.0)

Both UK Met Office and KNMI process Mode-S EHS data and the setup is described in more detail in the following sections. This includes a number of options on e.g. central or decentral processing and correction database, and some figures on resources and costs.

6.2.1.1 KNMI current set up

Since 2013, KNMI processes Mode-EHS messages of around 20 Secondary Surveillance Radars that are received by MUAC (Maastricht Upper Area Control Centre which controls the upper air space of Belgium, the Netherlands, Luxembourg and north-west Germany). At MUAC the data streams are merged into 15 minute batches that are available 10 minutes after the 15 minute period. Next to MUAC data, KNMI receives Mode-S EHS data of The Netherlands directly from Air Traffic Control The Netherlands (LVNL), and KNMI has a local ADS-B receiver on the roof of its head quarter in De Bilt.

Processing Mode-S data is shown in Figure 24 and involves:

1. Collection of data (data can be pulled or pushed) by a variety of protocols (ftp, rsync, etc.). Processing occurs synchronized to the availability of data.
2. Unpack the various formats into a common (ASCII) format to allow for further processing, filter out erroneous data, standardize file names, and other preprocessing necessary. A number of decoders are available: ASTERIX CAT048, ASTERIX CAT062, ASCII, ADS-B receiver.
3. Derive meteorological parameters from Mode-S EHS data.
4. Distribution of meteorological data (BUFR, ASCII, netCDF) at KNMI's ftp server.

Steps 1-4 only takes a minute. Processing step 3 consist of:

- a) quality control of Mode-S EHS values (speeds, heights, angles, etc.)
- b) conversion of magnetic heading to true heading
- c) heading correction (for each individual aircraft)
- d) (optional) smoothing of MACH and TAS (depending on purpose)

e) temperate correction (again for each individual aircraft)

Corrections (step c and e) depend on acquired statistics for each individual aircraft. Both heading and temperature corrections are based on comparison with NWP model (which serves as the statistical truth) and are calculated on a daily basis. The more Mode-S EHS messages are received in time the better the statistics for the corrections. Step d) depends on the usage. For example now-casting applications may request a smoother profile because it is better interpretable, while NWP can handle more noisy information.

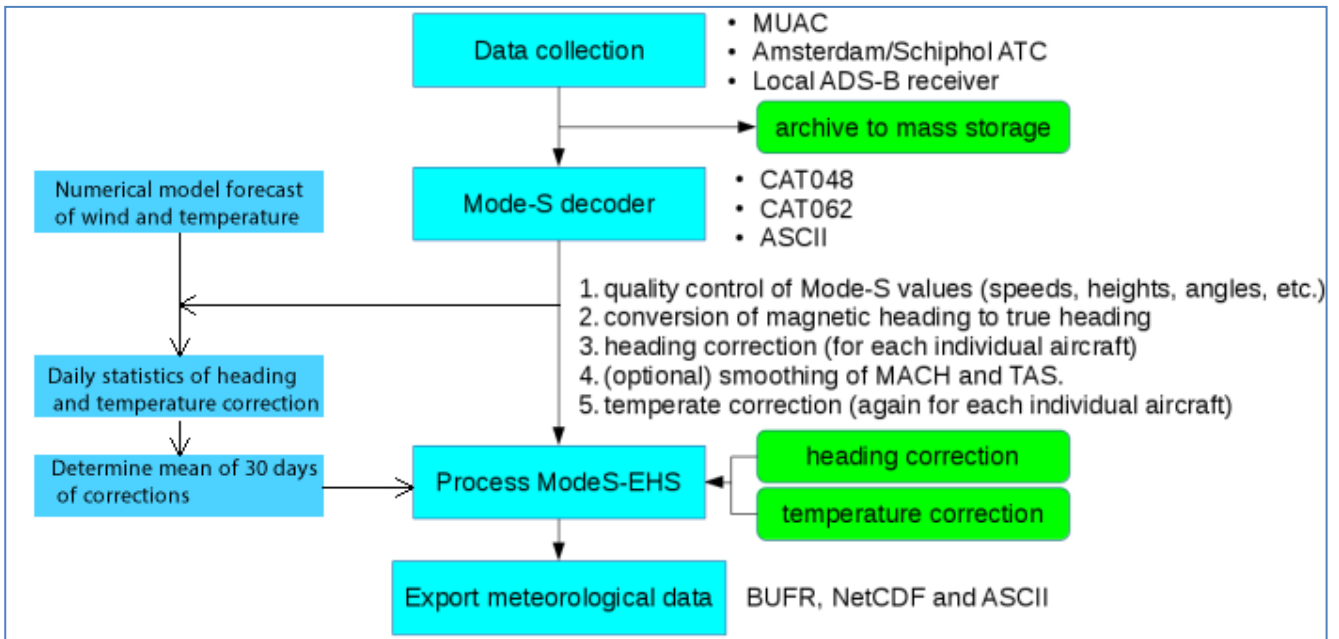


Figure 24: Semi-operational¹⁰ KNMI Mode-S EHS processing chain

In the actual processing system a number of housekeeping tasks can be identified: cleaning of directories, archive data to mass storage, monitor for hiccup's in both data streams as processing pipeline, and generate status and statistics for web output.

The KNMI Mode-S EHS production pipeline for MUAC is operational since medio 2013 and can serve as a solid basis for extending it to more countries or FIRs. As explained MUAC receives SSR data from 20 different ATCs and combines them in one stream. A number of filters and error checking is applied by MUAC and results in **20+ million Mode-S EHS messages per day**. These data hubs are ideal: these collect data from all radars, have local knowledge about the quality of the data and networks, can apply some

¹⁰ Semi operational due to the fact that 24x7 maintenance support has not been formally realized yet. The data processing stream is running continuously and almost without any interruptions and can be followed online at mode-s.knmi.nl in the folder data status, which shows the actual number of raw and derived observations in time.

geo-filtering, etc. Examples of other hubs could be: NUAC, France, UK, central Europe, etc., so quite a limited number.

By its design KNMI Mode-S processing can easily incorporate new feeds and data formats. Data acquisition is a separated phase, so it can perform unpacking and preprocessing. After preprocessing all files have homogeneous content and file names.

6.2.1.2 Current setup at UKMO

In 2011 the Met Office began investigating using their own receivers to collect Mode-S/ADS-B data to derive wind and temperature data over the UK. After some short feasibility studies it was decided to invest in a small research and development network of receivers. There are currently 5 receivers mostly collocated with operation a weather radar. Each Mode-S or ADS-B message is timestamped and sent to a central processing system in 10 minute batches. The messages are then decoded and written to a database. When all of the require messages are received from an aircraft within 10 seconds a wind and temperature is calculated. For calculating a wind a heading correction is applied. The heading correction is found using a comparison between the UKV NWP model and previously calculated data. The data is currently stored in the operational observations database in a modified AMDAR BUFR format.

The processing is very similar to that employed at KNMI

1. Collection of data (data can be pulled or pushed) by a variety of protocols (ftp, rsync, etc.). Processing occurs synchronized to the availability of data.
2. Decode the Mode-S and ADS-B messages.
3. Derive meteorological parameters from Mode-S EHS data.
4. Storage of meteorological data (BUFR) in the Met Office operational data store.

Steps 1-4 only takes a minute. Processing step 3 consist of:

- a) quality control of Mode-S EHS values (speeds, heights, angles, etc.)
- b) conversion of magnetic heading to true heading
- c) heading correction (for each individual aircraft)

The Met Office system utilizes the Met Office central systems for housekeeping, file movements etc. reducing the complexity and overheads. The Mode-S processing is built into a modular system. The nature of the systems allows for new receivers to be added with no significant modifications required. Independent data streams of both encoded and decoded data can be easily included into the processing. Data duplicates are removed where multiple receivers have an overlap where the first data to be received takes precedence.

6.2.1.3 Options for Mode-S EHS processing

General Mode-S EHS data needs processing to obtain good quality wind and reasonably temperature observations. The processing steps consist of for **each individual aircraft** :

1. Quality control (small roll angle, realistic Mach, ground speed, airspeed and temperature, difference between track angle and heading);
2. Conversion of magnetic heading to true heading;
3. Heading correction;
4. (Optional) Smoothing of Mach and TAS;

5. Temperature correction.

Data collection can be setup using the ATC infrastructure (eg. RADNET) or by local ADS-B/Mode-S EHS receivers. In cases where ATC is reluctant to cooperate with the meteorological community the only way to receive Mode-S EHS registers is through local reception.

The heading correction and temperature correction are based on comparison with NWP over a 30 day period and are at present calculated on a daily basis. The more observations are available in time the better the statistics. There are three possibilities to set up the complete processing chain:

1. Completely centralized
2. Completely decentralized
3. Combination of centralized and decentralized processing

6.2.1.3.1 Centralized processing

Mode-S processing can take place completely central and somewhat decentralized at these hubs. The infrastructure for a completely centralized solution is most easy. The hubs collect data from all radars, merge and filter the data, possibly convert mono-radar messages into system track data (so combining more sightings of an aircraft to do a better position calculation) as can be done from Asterix CAT048 messages to CAT062 data. With some delay the hubs generate batches of 10 to 15 minutes of observations (although it possible to receive the ATC data near real time as well) which can be handed over to the centrally positioned processing server. Advantages are clearly the need for only one processing server and it's easy hard and software maintenance. Dataflow is somewhat delayed by the batch-like output and more risk of interruptions, but probably the ATC organizations will have very reliable network connections. And with the centralized processing option the end user products are available at one location in convenient sized areas.

6.2.1.3.2 Decentralized processing:

Depending whether these hubs have synchronous connections to the ATC's or radars, processing speed can significantly be improved to (almost) real-time if the Mode-S EHS processing runs at these hubs (acting on separate radar messages), maybe even on synthesized system track data. Now these processing centres must upload their end user data (again in batches of 10 or 15 minutes) to a common server, so users can acquire the data at a single location. The end user data can also be used directly at the local centre if so required by local users. If these processing hubs do not have real-time connections to the SSR's the speed improvement will be much less. The decentralized option comes with a cost: a number of servers must be available, and software maintenance will be more difficult. Also the generation and distribution of the correction files (containing the individual aircraft corrections) will be more complicated: in order to make the best correction files, all data from all decentralized nodes is required at one server. After generating the correction files these must be distributed once a day along the processing hubs.

The costs in terms of CPU power, disk space and storage space of Mode-S processing are low. The processing of 15 minutes of MUAC data is about 2 minutes (that includes fetching the file first). One minute later the end user products are on the ftp-server. For MUAC, we employ a seven day disk cache and that takes 20GB in size. Mass storage consumes 2.5GB a day. Comparing MUAC with other ACC's it will be one of the biggest along with UK and France to a lesser degree. A single server could process several hubs with ease.

As MUAC combines the 20 radars KNMI has not developed software to do so. If the above decentralized option will be taken these areas are reasonably non overlapping and will result in non-overlapping data files. The processing hubs can filter out exactly their region.

In time, there is probably a need to be able to merge and combine different Mode-S data streams into one, cleverly making use of the oversampling of different radars. About a month's work to implement a smart multiplexer.

6.2.1.3.3 Combined processing

There are two possibilities of combined processing

- A. Centralized corrections and decentralized processing
- B. Centralized corrections and processing, and decentralized processing

Centralized corrections will result in a uniform aircraft correction data set, while decentralized processing can feed time-critical applications. A first overview, not fully mature yet, is provided in Table 20.

Table 20 : Summary of possibilities for processing

| Processing Setup | Advantages | Disadvantages |
|--|--|--|
| 1. Completely centralized <ul style="list-style-type: none"> • Corrections • Processing | 1. Good statistics for corrections 2. One product with consistent quality 3. Unique set of observations 4. Efficient use of resources | 1. Bandwidth capacity may be an issue 2. Single point of failure |
| 2. Completely decentralized <ul style="list-style-type: none"> • Corrections • Processing | 1. Short latency 2. Small risk of data loss 3. Data processing choices can be made to best match the application used. | 1. Worse statistics for corrections → Less observations 2. Different quality per local processing centre 3. Overlap of observations on edges of SSR regions 4. Inefficient use of resources |
| 3. Combination A <ul style="list-style-type: none"> • Centralized : Corrections • Decentralized : Processing | 1. Short latency 2. Good statistics for corrections 3. One product with consistent quality 4. Small risk of data loss 5. Data processing choices can be made to best match the application used. | 1. Overlap of observations on edges of SSR regions 2. Inefficient use of resources |
| 4. Combination B <ul style="list-style-type: none"> • Centralized : Corrections + processing • Decentralized : Processing (additional) | Centralized: <ul style="list-style-type: none"> 1. Good statistics for corrections 2. One product with consistent quality 3. Unique set of observations Decentralized | 1. Processing twice 2. Overlap of observations on edges of SSR regions 3. Requires identifier for processing type |

| | | |
|--|--|--|
| | 4. Short latency 5. Small risk of data loss 6. Data processing choices can be made to best match the application used. | |
|--|--|--|

The preferred option is centralized processing and correction database with additional decentralized processing. This will result in an efficient processing centre providing a single set of data to all users, and at the same time guaranteeing that the aircraft correction database is maintained to the best level possible. At the same time local processing could be arranged for if the local situation requires so, hence the additional. One of the locations where decentralized processing is available could also be used as a back-up centre for the centralized processing centre.

The centralized processing also offers opportunities and efficiencies to arrange for standard contracts with ATC and end-users, and provides users with a one-stop service to receive all the obtained and derived observations.

| | Centralized | Decentralized | Combination |
|--------------------------------------|---|---|---|
| number of servers | 1 + backup | N + N backup | (N+1) + (N+1) backup |
| algorithms | 1 set | N sets | (N+1) sets |
| regional aspects of processing | ? | ? | ? |
| quality control | <ul style="list-style-type: none"> one list of corrections one access point to GTS and end users | <ul style="list-style-type: none"> multiple list of corrections multiple access points to GTS and end users | <ul style="list-style-type: none"> one list of corrections one access point to GTS and end users daily distribution of list of corrections |
| technical methods of collecting data | <ul style="list-style-type: none"> ATC infrastructure ADS-B/Mode-S receivers Push/pull data to central facility Central data server Settle exchange format | <ul style="list-style-type: none"> Local network Local exchange format | To be added in next phase |
| storing data | To be added in next phase | To be added in next phase | To be added in next phase |
| amount of data storage | To be added in next phase | To be added in next phase | To be added in next phase |
| costs, man hours involved | To be added in next phase | To be added in next phase | To be added in next phase |
| Etc. | To be added in next phase | To be added in next phase | To be added in next phase |

Based on the experiences of KNMI and UK MET Office some initial numbers and thoughts on costs and resources involved are included in the next tables. A division has been made in initial set up costs (Table 22), operational costs (Table 23) and expansion costs (Table 21). In a next phase these figures can be worked out in more detail.

Important to realize is the significant difference between the situation where data is being provided by ATC and where data is received by own local receivers. The latter requires installation and maintaining of own infrastructure.

Given the information provided in previous chapters it is foreseen that the number of radars interrogating Mode-S EHS will increase significantly. The system is set up in such a way (modular) that adding an additional data stream is easily possible and requires a relatively small investment in man hours. First estimates are around 200 hours, see Table 21, and that could be for a large region if the data is provided by ATC in the regular ASTERIX format.

Table 21 : Expanding costs (based on UKMO and KNMI experiences)

| Task | hours |
|--|-------|
| Implement a new Mode-S packet decoder in the processing chain | 15 |
| Adding a feed with a common network protocol (ftp, sftp, rsync, scp, etc.) to the processing chain | 1 |
| Coordination with ATC/airlines | 70 |
| Setting up agreements | 70 |
| Setting up dissemination agreements | 30 |
| Setting up ADS-B receiver | 1 |
| Setting up local processing | 5 |
| Setting up central processing | 5 |

Table 22 : Initial costs (based on UKMO and KNMI experiences)

| Task | hours |
|--|-------|
| Coordination with ATC/airlines | 100 |
| Set up of standard data agreements with ATC/Airlines/? | 300 |
| Set up of standard dissemination agreements | 125 |
| ADS-B receiver | 10 |
| Local processing | 10 |
| Central processing | 300 |
| Infrastructure (collection network) | ? |
| Infrastructure (dissemination network) | ? |
| Software development (monitoring processing etc.) | 200 |

Table 23 : Operational (24/7) costs (based on UKMO and KNMI experiences).

| Task | Hardware depreciation | Hours |
|--|------------------------|-------------|
| ADS-B receiver (1+backup every 400x400km ²) | 1500 euro/ 4 year/site | 2/year/site |
| Local collection pc (1+backup every 400x400km ²) | 1500 euro/ 4 year/site | 2/year/site |
| Infrastructure (collection network) | ? | 25/year |
| Local processing | (1 +backup) pc/4 year | 25/year |
| Central processing | (1 + backup) pc/4 year | 40/year |
| Infrastructure (dissemination network) | ? | 5/year |
| Storage | ? | ? |

| | | |
|---------------------------|---|----------|
| Coordination with E-AMDAR | - | 200/year |
| Monitoring | - | 400/year |

6.2.2 Mode-S MRAR (register 4.4)

SEA processes Mode-S MRAR data and the setup is described in more detail in the following section. This includes a proposal for MRAR processing.

6.2.2.1 The preprocessing of Mode-S MRAR at SEA

The MRAR data is provided to SEA from ATC as comma-separated values in 30-minute intervals. The preprocessing steps are the following:

1. gross error checks
2. removal of winds at high roll angles
3. removal of data at the airport runways and parking areas
4. data selection by aircraft address based on pre-calculated whitelist
5. weak temporal smoothing of data
6. encoding into ASCII files suitable to enter ALADIN NWP model
7. dissemination of data within central Europe (LACE) countries

The white lists are generated based on a long term quality statistics for each aircraft. This is currently implemented by comparing the Mode-S data set with NWP over a period of 2 years.

6.2.2.2 Proposal for Mode-S MRAR data processing

The proposal for a common Mode-S MRAR data processing tightly follows the proposed strategy for Mode-S EHS. It could be implemented in a centralized, de-centralized or combined way (as above for Mode-S EHS and with the same advantages and risks). The most important difference with respect to Mode-S EHS is that a large part of processing can be skipped for Mode-S MRAR (e.g. calculation of temperature, heading correction). So far the number of Mode-S MRAR data is much smaller than the number of Mode-S EHS. A joined processing of Mode-S MRAR with Mode-S EHS would not increase much the of the computational and archiving cost of the Mode-S EHS processing. As such it is proposed to include the Mode-S MRAR processing within the Mode-S EHS central processing and correction database and additional decentralized processing, as proposed in the previous section.

6.2.3 Mode-S (register 4.5)

As described in Section 4.2.4, no relevant meteorological has been observed from other registers than EHS and MRAR. Therefore no proposal to process these registers is made.

6.3 E-AMDAR Data Acquisition System (E-ADAS)

E-ADAS is designed to handle and process AMDAR aircraft data (wind and temperature observations) for E-AMDAR and could potentially be suitable for hosting Mode-S EHS/MRAR processing. However, the process applied to Mode-S EHS/MRAR differs significantly and would require a major redesign of E-ADAS.

The processing of Mode-S EHS in itself is different and requires much more processing power. AMDAR is an operational program and aircraft oriented with ACARs and on-board software installation. The ADD process is more like a (pioneering) development program, and involves research and development on

aircraft corrections and improved derivation methods. As well as identifying other opportunities like for example side slip angle. Where E-AMDAR is addressing airlines mainly the ADD program has an active coordination with other stakeholders in the ATM domain as Air Traffic Control, regulators (CAA) and airports. As such, it is more appropriate to perform the processing of Mode-S EHS/MRAR outside E-ADAS at this stage of E-ADD.

The E-AMDAR infrastructure, as described in 4.3, is already providing several of the functions that would be required for an operational ADD data distribution system.

Although it would be possible to merge the two processing systems for data encoding and distribution into one system there is probably merit in keeping the functions separate even though they may ultimately exist as virtual servers on the same physical hardware

Due to the significant crossover of capability between the two systems, it would be advantage to develop the systems together. It may also be more cost effective and allow for easier coordination if the final operational program is a combined E-AMDAR/E-ADD program processing all of the Aircraft Based Observations. Especially the ADS-C data type that contain direct meteorological information is more related to AMDAR observations than the other data types reported here. However, for ADS-C data where wind information has to be derived the ADD process is more similar.

In case E-ADAS will be used for ADD data processing the following will need to be addressed:

- E-ADAS will need software developing to handle “raw” Mode-S data,
- ADD decoded messages will need to be in “AMDAR format” for quality checks – otherwise will require further E-ADAS development to handle these data,
- E-ADAS will need to have the Mode-S BUFR Template added,
- Server capability, disc space – need to cater for daily datasets of Mode-S in addition to AMDAR data
- Will the Mode-S bulletin headers have geographical indicators like AMDAR?
- Met Office Message switch capability to handle additional data needs to be assessed to avoid possible data queues.
- GTS – RTH capability of taking data,
- AMDAR has Tivoli Monitoring (of processes) –Mode-S data would need to be added, so data quality/monitoring flags will need to be assigned.

These and other issues would need to be discussed with the relevant teams within the Met Office.

7 Proposal for ADD data dissemination

This chapter describes the various used data formats for exchanging ADD data and the obtained or derived meteorological information from ADD data. A number of potential users are identified and the conditions under which the information could be provided are discussed.

Exchange formats for ADD data may come from different sources in different data level types. ADS-C data will most likely be delivered in an internal airline/ATC format. The format of ADS-B Mode-S EHS data (i.e. Mode-S EHS data received by a local ADS-B receiver) depends on the receiver software and is generally stored in a so-called Mode-S Beast AVR-format. Mode-S EHS and MRAR data within the ATC domain is generally encoded in the so-called ASTERIX format, of which several types exist. However KNMI receives this data also in plain ASCII comma separated files from LVNL.

An easy and self-explanatory exchange format for obtained and derived meteorological observations from ADD is important to provide users quick and easy access to the data. Within the meteorological community BUFR is well accepted and seen as the format for exchanging this data between the meteorological community e.g. via the GTS. But outside the meteorological community other formats are generally more common, like netCDF and ASCII. BUFR requires additional so-called BUFR tables together with matching decoding software to be able to read a BUFR message. NetCDF is much easier to handle because a generic reader exists for almost all platforms. Another relatively easy readable format is ASCII. This format is very flexible and thus requires a header or a description. The latter format is more suitable for internal exchange. It is proposed to disseminate obtained and derived meteorological information from ADD data in both BUFR as well as netCDF.

7.1.1 ASTERIX format

When data is received from ATC it is generally encoded in an ASTERIX format. This is an ATM Surveillance Data Binary Messaging Format which allows transmission of harmonized information between any surveillance and automation system. The parameters of interest can be encoded with a different resolution than was observed. The table below shows the resolutions for the three most common ASTERIX formats CAT021, CAT048 and CAT062. CAT021 is most preferable, since it contains the best resolution for location and Mach. CAT062 is less preferable since the resolution of the Mach is generally 0.008, and thus the derived temperature is noisy. KNMI has developed software to decode all three data formats. ASTERIX CAT021 describes the structure for the transmission of ADS-B messages, ASTERIX CAT048 contains (multiple) mono-radar target reports and ASTERIX CAT062 describes the message structure for the transmission of System Track Data.

Table 24 Resolution of ASTERIX CAT021, CAT048 EN CAT 062 encoded parameters

| | Cat021 | Cat048 (Mode-S MB) | Cat062 |
|----------------------------------|------------------------------|---------------------------|------------------------------|
| | <i>ADS-B messages</i> | <i>mono-radar reports</i> | <i>System Track Data</i> |
| Latitude/longitude ¹¹ | $180/2^{23}$ or $180/2^{30}$ | | $180/2^{25}$ or $180/2^{23}$ |
| Flight level | 25 ft | 25 ft | 25 ft |
| True air speed | 1kt | 2kt | 1kt |

¹¹ $180/2^{23}$ corresponds to $\approx 2.4\text{m}$; $180/2^{25} \approx 20\text{cm}$; $180/2^{30} \approx 2\text{cm}$

| | | | |
|------------------|----------------------------------|-------------|----------------------------------|
| Magnetic heading | $360/2^{16} \approx 0.0055$ deg | 90/512 deg | $360/2^{16} \approx 0.0055$ deg |
| Ground speed | 2^{-14} Nm/s ≈ 0.22 kt | 2kt | 2^{-14} Nm/s ≈ 0.22 kt |
| Track angle | $360/2^{16} \approx 0.0055$ deg | 90/512 deg | $360/2^{16} \approx 0.0055$ deg |
| Roll | 0.01 deg | 45/512 deg | 0.01 deg |
| Mach | 0.001 | 0.004 | 0.001 (not used), 0.008 |
| Wind speed | 1 kt | 1 kt | 1 kt |
| Wind direction | 1 deg | 180/256 deg | 1 deg |
| Temperature | 0.25 K | 0.25 K | 0.25 K |

Note that wind speed, wind direction and temperature are placeholders and can be obtained only from BDS4.4 messages, or in cases where ATC has derived these parameters by internal process, in which the quality of the data is unknown.

7.1.2 BUFR format

The proposed BUFR template for ADD data as currently used by UK Met Office is presented in Appendix A. Note that due to the relation between temperature, Mach and true airspeed, all three parameters can be exploited for quality control of the temperature observation. It is proposed to use the following BUFR data category type and subtypes.

Note that by using new BUFR descriptors for “position source indicator”, and “data source indicator” the number of subtypes can be reduced to three (note that ADS-B is not included) . These descriptors are currently not defined.

Table 25 : Proposed data category type and subtypes for ADD observations.

| ADD type | Data category | |
|-------------|---------------|--------------|
| | Data type | Data subtype |
| Mode-S EHS | 4 | 146 |
| Mode-S MRAR | 4 | 147 |
| ADS-C | 4 | 148 |

7.1.3 ASCII format

KNMI uses plain ASCII files for internal and external dissemination of both ADD data and obtained and derived meteorological information from ADD data. LVNL provides KNMI with near real time Mode-S EHS data in plain ASCII comma separated files. KNMI uses ASCII as internal format is because of its easy access and readability.

7.1.4 NetCDF format

KNMI uses netCDF as an external format as this format is widely used for the exchange of information together with meta information by web-services. It is expected that this will be one of the dissemination types of the foreseen System Wide Information Management within the aviation domain. This could also be used for local services that require near real time updates of wind observations, e.g. Air Traffic Control.

7.2 Assessment of (potential) customers and end-users of ADD

End-users and customers of the meteorological observations obtained or derived from ADD data are aviation stakeholders and the meteorological community at large. This includes commercial and non-commercial organizations and the general public. The data provision can be seen as part of the European Meteorological Infrastructure and could be offered to these users as official duty range or ‘open data’ in line with EU regulations on the re-use of public sector information, see also next section.

7.3 Legal conditions and data provision

A pending question is who is owner of the ADD data and who owns the IPR rights. Especially as large numbers of ADD data can be received by local ADS-B/Mode-S receivers. And is there a difference between ADD data being provided by ATC or airlines and ADD data being received by local receivers. The next question is who is owner and has the IPR of the obtained and derived meteorological observations.

In some cases it is stated that the ATC organization owns the data, and significant license fees including restrictions on the use of the data, have been offered. This is strange in the sense that the ADD data is measured in an aircraft, and both the aircraft, the data communication costs, and the ATC infrastructure and service provision are paid for by the aircraft operators. However, it is fair that the meteorological community pays for dedicated costs of ATC in order to provide ADD data to them.

The current agreement between KNMI and MUAC stipulates that the provided ADD data will:

- not be further transmitted or otherwise provided to a third party without the explicit agreement of MUAC;
- not be used for any commercial purpose;
- be protected and kept confidential in line with MUAC Data Classification and handling rules; and,
- not be used for any other purposes than outlined in the agreement.

With commercial purpose the direct use of ADD data is meant. Assimilating derived observations in NWP and selling the NWP forecasts is not seen as commercial in this perspective.

Agreed with MUAC is that KNMI can share the derived meteorological data from Mode-S EHS within the global meteorological domain in line with current World Meteorological Organization (WMO) practice of cooperation between national meteorological and hydrological institutes. The sharing of data within the meteorological domain is free of charge; all users of meteorological data may benefit.

Only the derived meteorological observation can be shared, and not the original ADD data. It is agreed that ADD data that can be further transmitted are aircraft ID (anonymized), Flight Level and time.

Both the meteorological community and users in the aviation domain will benefit from these data in many ways, this is described in more detail in chapter 8. As such a win-win situation was identified and the ADD data is provided for free by MUAC. This is based on the understanding that KNMI, or the meteorological community, will not increase the costs for meteorological services that are of higher quality due to the usage of the derived meteorological observations.

Section 5.3.3. provides an overview of meteorological organizations that receive the derived observations on an operational basis. The data is also being used in EU research programs as UFO and SESAR. Other agreements are in place to submit prior to publication in any form or format to MUAC.

Discussions with MUAC are taking place with the objective to change the agreement in such a way that the obtained and derived upper air observations can be used as 'open data', in line with EU regulations on the re-use of public sector information. In this regard the pan-European operational processing of ADD data by EUMETNET is seen as part of the European Meteorological Infrastructure.

This would also create a level playing field for other parties, commercial and non-commercial, aviation and non-aviation, to make best use of these observations and as such provide the highest added value for the European community.

Data can be centrally provided by the ADD data processing center in the formats as described in the previous sections. There would be no license costs involved, and open data would be provided with little guarantees for data availability and so on. A more operational service could be provided at a small distribution fee, and as such financing the internal handling costs.

More analysis and work on these particular and important aspects of ADD data has to be carried out by the meteorological community, and coordinated with legal experts, regulators, airlines, air traffic organizations and airports. This, and drafting standard data provision agreements, both for ADD and obtained an derived observations, is seen as next step in the implementation of operational ADD processing.

In the UK some coordinating took place with the regulator on the use of Mode-S data that is received with local receivers, and is described underneath.

It could be considered that Mode-S data (as opposed to ADS-B) have an intended recipient (the interrogating radar). Therefore under the Interception and disclosure of messages - Wireless Telegraphy Act 2006, section 48 it is illegal to act upon the messages without authorization. Therefore permission to receive the Mode-S data is needed from all aircraft operators.

Having said that, the Met Office has personal correspondence with the CAA (the enforcement and licensing body for aviation telecommunications) where they state that they consider Mode-S messages to be broadcast with no intended recipient (therefore legal to receive and use). If this approach is taken in other countries it is recommended to approach the local aviation authority for their view on the data.

If the CAA view changed at any time, in the UK there is provision within the act for designated persons to authorize the interception. In that case the approach would be to show that the data is significantly useful and approval to intercept the data would likely be provided. Currently there is no case law to show whether this kind of message is broadcast or not, so the CAA guidance is followed.

8 Expected added value of ADD

This chapter describes the added value for aviation, general weather forecasting and climate. Examples and references are provided, as well as identification of new products.

8.1 Expected added value for aviation

8.1.1 Air traffic management

Air navigation service providers nowadays use general meteorological information like cloud satellite imagery and forecasts of winds, thunderstorms, jet streams and turbulence which enables a general awareness of the meteorological situation. However, the use of real-time meteorological observations in the navigation process is currently at the very initial state.

For example, the Slovenia Control routinely visualizes vertical profiles of Mode-S MRAR data, but they are not yet exploited by the air-traffic controllers in their routine work, see Figure 25. Also UK Met Office provides non-operational winds for meteorologists at London Gatwick Airport, see Figure 26.

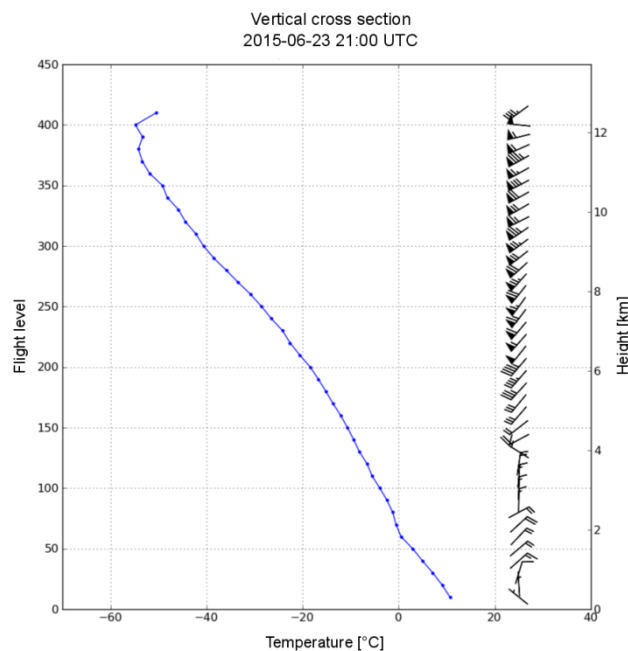


Figure 25 : Vertical profile of smoothed 3-hourly average of Mode-S MRAR temperature and winds as visualized at ATC of Slovenia.

Additional wind information has several possible applications within the Air Traffic Management domain:

1. as input in Arrival Management (AMAN) & Extended Arrival Management (E-AMAN) applications: higher granularity and improved forecast of wind information will increase the predictability of the arrival traffic.
2. as input in the flight data processing tools of the ANSPs in support of e.g. separation management (spacing of aircraft): better wind observations and nowcast information will lead to better prediction of aircraft locations by the Flight Data Processor. This is an important step towards 4D trajectory management where wind (amongst other weather phenomena) have an impact on the "Controlled Time of Arrival (CTA)" or "Controlled Time Over (CTO)" timings.

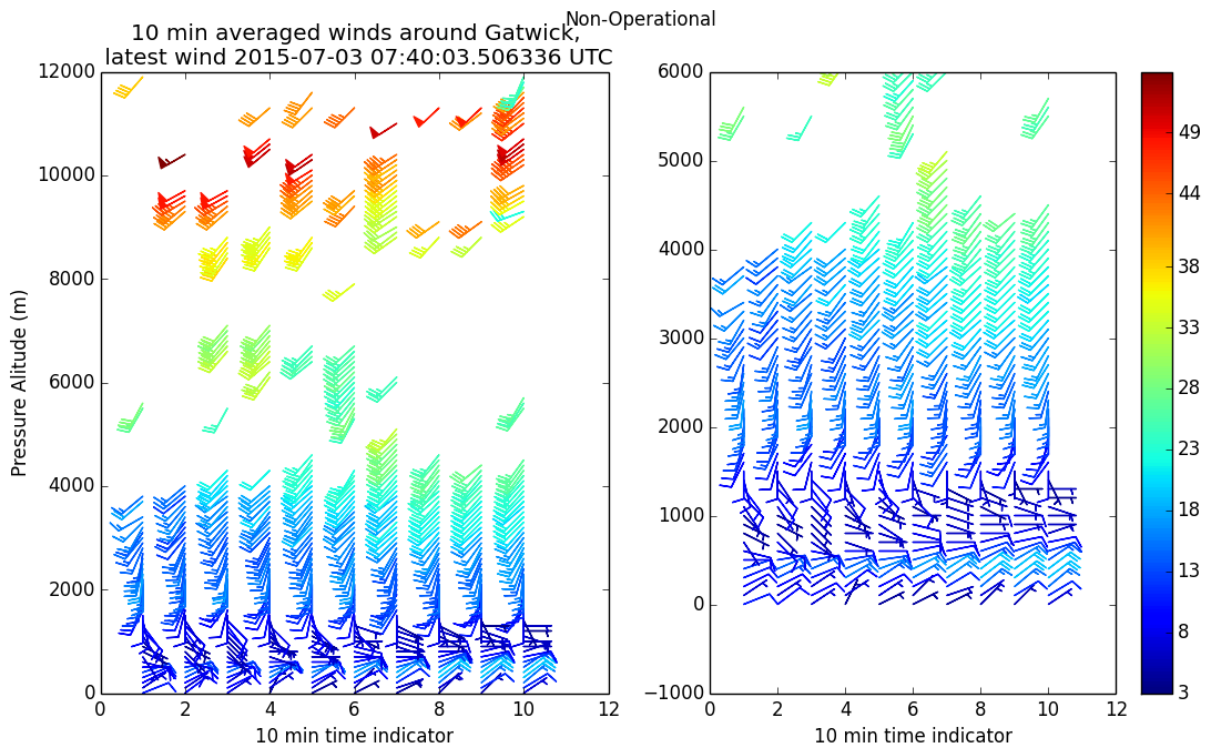


Figure 26 : Mode-S EHS (Mode-S/ADS-B) wind data plotted over London Gatwick airport. Each profile is a 10 min average of data in altitude bins of 100 ft. The latest data is shown on the left of each graph. The right hand graph shows a zoomed in view of the lower atmosphere.

3. as input in Time Based Separation (wake vortex) tools: better wind information will lead to better predictability of wake vortex movement and dissipation. Mode-S EHS/ADS-C derived data may offer a cheaper solution than surface based sensor equipment.
4. as input in Continuous Descent Operations (CDO): aircraft FDP are limited to 5-7 flight levels; in order to optimize the descent, additional post-processing of wind information in the descent path could optimize the wind information to be used in the aircraft FDP (i.e. the "best" 5-7 levels should be selected in such a way that the resulting wind profile is as close as possible to the "real" wind profile). These trajectories and updates for Flight Management Systems are offered by e.g. Aventus Nowcast from AVTECH or Boeing Wind Updates.
5. as input to runway selection: when vertical wind shear is present, it is well possible to have a runway selection that is ideal for surface wind conditions but not in relation to the wind in approach; this can lead to missed approaches due to too much tailwind aloft. Such situations can be prevented by also taking actual wind conditions aloft into account. ADD data may offer a cheaper solution than surface based sensor equipment. Mode-S EHS/ADS-C derived data may also show well in advance the arrival of a horizontal wind shift, either directly or via an improvement of the NWP model predictions.

The above described expected added value for ATM is identified in SESAR and described in WP B4.2: Wind/temp info Update Provision: Provides flight crew with last winds / temperatures to improve the trajectory predictions computed by aircraft system. As well in Time Based Separation see WP 6.8.1. Wind for TP calculation is described in projects WP 4.7.2 and WP 5.7.2 and AMAN is described in WP 5.6.4.

8.1.2 Opportunities for flight efficiency

One of the important inputs to improved flight planning is accurate weather information, especially wind data. On the one hand ADD will contribute to this via the improved NWP (next section). On the other hand, the development of specialized application of ADD to improve flight efficiency around busy airports may be foreseen. High-resolution NWP models may be used to rapidly provide very short-range numerical forecasts of 3D wind fields around the airports. This could assist dynamical aircraft separation, e.g. wake vortex separation distances between landing aircraft may be decreased in some weather situations without compromising safety. The US (NOAA and airlines) are convinced of the advantages of ADD observations. The Airline Southwest have demonstrate a great impact in hazard fore-and-nowcasting of fog, thunderstorm and other events that have a great impact on aviation.

These advantages are important enough to convince some airlines (UPS and Southwest Airlines) in equipping more than 100 aircraft with WVSSII sensor. [NOAA Aircraft Data Workshop, 2014]

So, improved wind nowcasts and forecasts will not only be beneficial for improved trajectory prediction, both for air-borne and ground-based systems, but also for use in arrival and departure management systems (AMAN and DMAN).

As an aside benefit, airlines will be able to receive the calibrated offsets in the downlinked headings of aircraft, produced as part of the Mode-S EHS derivation process. As described earlier there could also opportunities to provide systematic side slip angle of aircraft to airline operators and that could evolve into a tool for each airline to optimize the aerodynamic performance of their aircraft.

8.1.3 Weather forecasting

The weather forecasting for aviation focuses on very short-range weather forecasts. Here, the main advantage is the timeliness of ADD data and its accuracy (this may depend on type). The following potential usefulness of ADD data are recognized by aviation weather services:

1. Determining wind shear,
2. Determining precipitation type (especially in a case of freezing rain),
3. Determining the zero-degree line height,
4. Determining the location of vertical temperature inversions,
5. Detection of unstable layers in the lower atmosphere (to assist gliders).
6. Help to determine convection using low level vertical profiles of temperature and wind.

An application for visualization of Mode-S MRAR observations has already been developed by aviation forecasting offices at SEA, Slovenia. It is focused on detection of wind shear.

The data are assimilated by the NWP and in case of missing radiosonde observation, the vertical profiles of wind coming from the ADD is used by the forecasters.

In many platform, information of wind is provided from the short range models and in-situ information is missing mainly concerning wind. The second priority is temperature and the third is humidity. ADD is the cheapest mean to cover these needs in the extended planetary boundary layer.

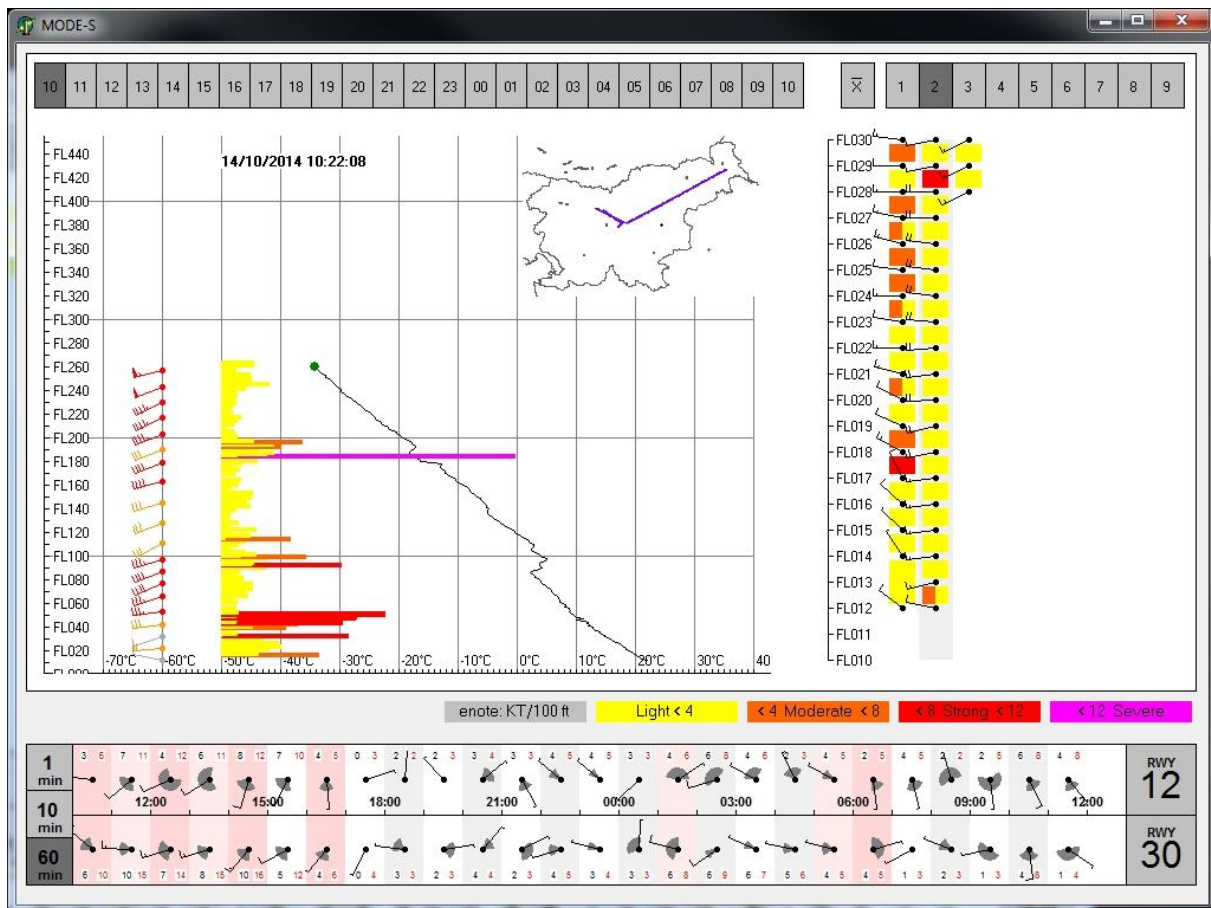


Figure 27: Vertical profile of Mode-S MRAR temperature and winds with indication of wind shear in colors. The wind shear can be computed as hourly average or separately for each flight. The application is used operationally at aviation forecasting department of SEA

8.2 Expected added value for meteorological community

8.2.1 General forecasting

ADD is expected to be useful to general weather prediction especially as a timely observation of the vertical profiles of the atmosphere (e.g. when other data such as radiosonde observations are not available) and indirectly through improved weather forecasting. The expected value for general forecasting are related to low level winds and convection, and include:

1. Low level winds are an important parameter for general forecasting because it affects the daily life of people. Additionally in places near the sea this may help to a more accurate forecast of the sea breeze, in both time and strength aspects.
2. Convection and convective precipitation are the most important parameters for severe weather events. Due to the high spatial and temporal scales of these events nowcasting and very short range forecast are still very useful to help Civil Protection Authorities in managing the consequences of these weather events. In that sense improving the information forecasters have in real time about low level vertical profiles of temperature and wind will help to improve those forecasts. In particular in the Spanish Mediterranean coast convective events happen every autumn (with several hundreds of millimetres of rain in a few hours) that depend strongly on a low level jet of warm and wet air coming from the Mediterranean Sea. The exact position and strength of this low level jet is a key piece of information helping

to decide where and when convection will happen. ADD data may help to improve the information to know better about this phenomena. ADD observations may allow for monitoring the temporal evolution of the vertical profile of the atmosphere during convective days and support nowcasting of severe storms.

3. Monitoring and forecasting the precipitation type during winter. ADD can be used to improve the diagnosis and forecasting of the snowline. This has many important applications especially in the mountainous countries (road maintenance and safety, runoff in hydrology etc.). The second important application is the diagnosis of the danger of freezing rain, which is a high-impact but often a very transient weather situation and thus difficult to be detected by other observation systems.

The localization of the source of the data is important, as discussed in the next section as well, and ADD data could be used for that as well in NWP. It is clear that, as shown in many papers in the literature and AEMET reports for projects like PREVIEW and HYMEX, severe weather in Southern Europe (Spain, France and Italy but not only) has what are called sensibility areas outside Europe. "Sensibility areas" mean areas where the meteorological situation will influence the weather in some places sometime after. For example, the exact position of a shallow low pressure at the African coast is one of the key factors to know where and when will be place the low level jet in the Spanish Mediterranean coast and this is the most important factor to know where, when and how much convective rain will fall in the next hours.

EUMETNET should be aware on that and try to reach agreements with Aeronautical Authorities in Morocco, Algeria and Tunisia and other Northern African countries to have access to ADD data in case those data are available.

8.2.2 NWP

Newly developed ADD methods can be seen as important extensions to the coverage of AMDAR which is one of the key observational platform over Europe. Regional convection-permitting NWP models with horizontal resolution of 1 to few kilometres nowadays experience a lack of dense and frequent observations which makes any additional upper-air observation of sufficient quality a priori very important. While satellites mostly provide mass-based observations, the advantage of ADD is especially in providing lots of additional wind information. This is especially important on the smaller (convective) scale where the balance between mass and wind information is weaker than on the synoptic scale; both types of observations are therefore required by the current data assimilation techniques.

Several studies already evaluated the impact of Mode-S EHS derived observations in operational regional NWP models. At first, observations from single radars were assimilated. De Haan and Stoffelen (2012) used collected data at the Amsterdam Airport in HIRLAM NWP model and found improvements on wind and temperature forecasts for up to 2-3 hours. This study was then extended by assimilating an extended set of Mode-S EHS data within Maastricht Upper Area Control Centre (MUAC), and extended positive impact up to 9 hours for wind speed and up to 24 hours for wind direction was observed (De Haan 2013). Recent study of Strajnar et al. (2015) described impact of Mode-S MRAR observations collected by a single SSR radar at the Ljubljana Airport on the very short range forecasts of ALADIN NWP model. The study also highlights the impact of ADD on initialization of humidity which is the only of the main atmospheric variables not observed by any of the current ADD methods. The ADD data sets used in the current studies only covered a relatively small part of the model domains, the impact may be expected to increase with better observation coverage.

Other studies made by AEMET people in the framework of PREVIEW and HYMEX projects (Ducrocq et al. "Final Report on the impact of DTS-observations during HyMeX SOP1" 2014) have shown the relative importance of sensible areas in the Atlantic and Northern Africa to improve the NWP forecasts over Europe (see figure below which is the figure 3.6d of the report). This figure shows the area where atmospheric condition is sensitive for forecasting a blocking case 42 hours ahead. It is foreseen that sampling this area with more observations will improve the forecast of a blocking case.

These results show the importance to have as much observations as possible in the sensitive areas and this may advice EUMETNET trying to get ADD data from airports in Northern Africa and the Atlantic (Madera and Azores islands).

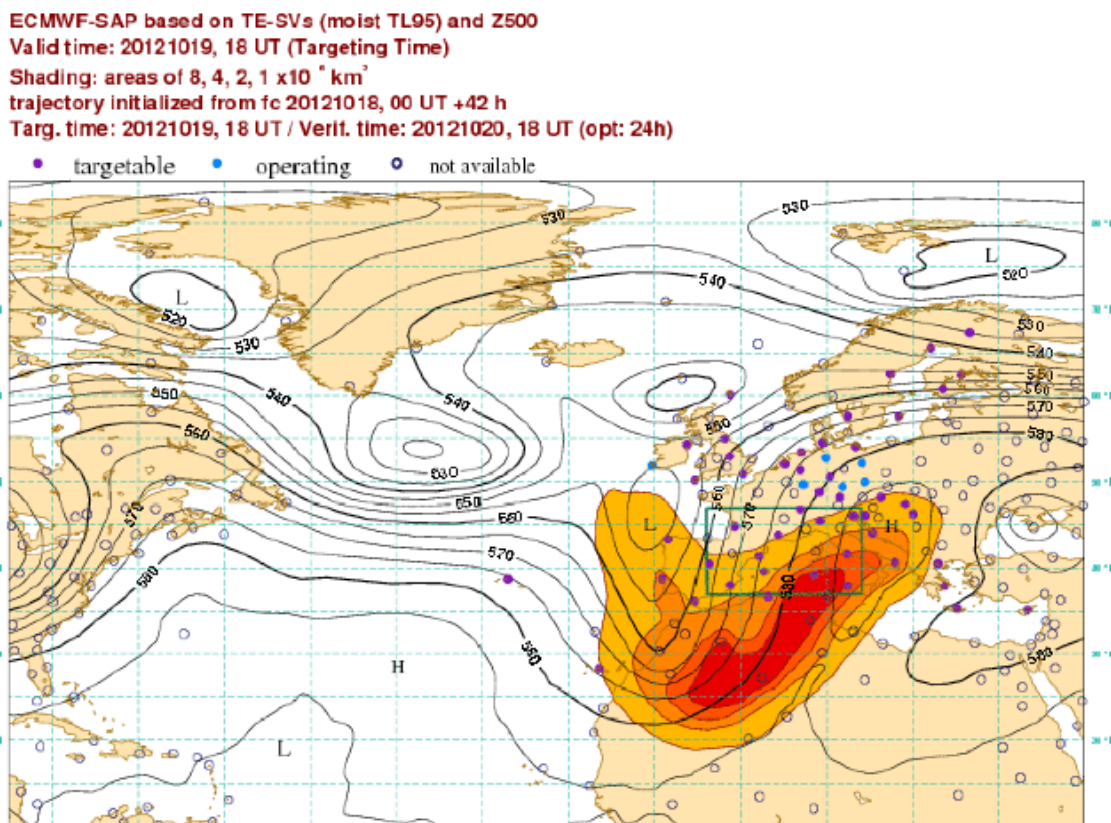


Figure 29 : Sensitive Area Prediction (SAP) for a blocking case of individual periods.

In the coming years in Europe mesoscale models will be run operationally in the form of RUC (Rapid Update Cycle). This means that the model will run almost every hour up to 12 or 18 hours forecast. For these kind of operations (see <http://ruc.noaa.gov/> for more information) traditional sources of meteorological observations doesn't have enough time frequency to appropriately feed these models. This is the reason why high temporal resolution observations will play a key role in the future of mesoscale NWP. This fact is also mentioned in the WMO statement of guidance for global numerical weather prediction (see <http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html>). As such ADD data as Mode-S EHS and MRAR could be very important due to its high temporal resolution.

8.2.3 Energy forecasting

The high penetration of renewable energy in a number of European countries requires high quality forecasts of the weather dependent production potential. Otherwise in particular the electricity markets and the transmission system operators (TSO's) cannot work efficiently. The markets function on the two

day ahead to the few hour ahead time horizon, whereas the TSO's need to maintain balance on the power network down to second timescale. For the TSO's even sub-hourly updates are of value, as better forecasts can help reduce the cost of maintaining system balance. ADD can be expected to have significant impact in two areas:

1. Improving the quality of NWP winds and solar radiation estimates via inclusion of the ADD in the NWP assimilation system. Increasing the benefit of frequent (e.g. hourly) forecasts, by providing (part of) the necessary additional observations. In NWP assimilation not all ADD will be used, it is necessary to thin the data according to NWP model resolution and certain other aspects of the assimilation system.
2. Statistical enhancement of NWP forecasts of wind and solar radiation. By determination of NWP error correlations with observations, it is possible to NWP based energy forecasts by advanced statistical methods. Because the ADD provide additional observations at low levels of the atmosphere, with high frequency, and of properties directly related to wind power, they can be expected to be very valuable for this. The statistical models run very fast, and will likely be able to benefit from the full sample of ADD observations, which will be of particular benefit to the TSO's.

8.3 Expected added value for climate monitoring

8.3.1 Assumptions about the future ADD observing system

To assess the potential impact of ADD winds and temperatures on climate monitoring the coverage of the future ADD observing system must be addressed

Spatial coverage

Figure 20 provides an example of the coverage at an early phase of the system set up at KNMI. Based on this we assume that on a daily basis coverage will be complete over Europe at high levels (10 km), and incomplete at lower levels. Remote regions of Europe may have less coverage.

Time coverage and variations in spatial coverage during the day

Demand and regulations on aircraft movements limit the amount of ADD available during the late night to early morning hours, Figure 30 shows the result of this. During night time much fewer observations are available, and the majority of the night observations are from aircraft passing high over the airports, above 10 km.

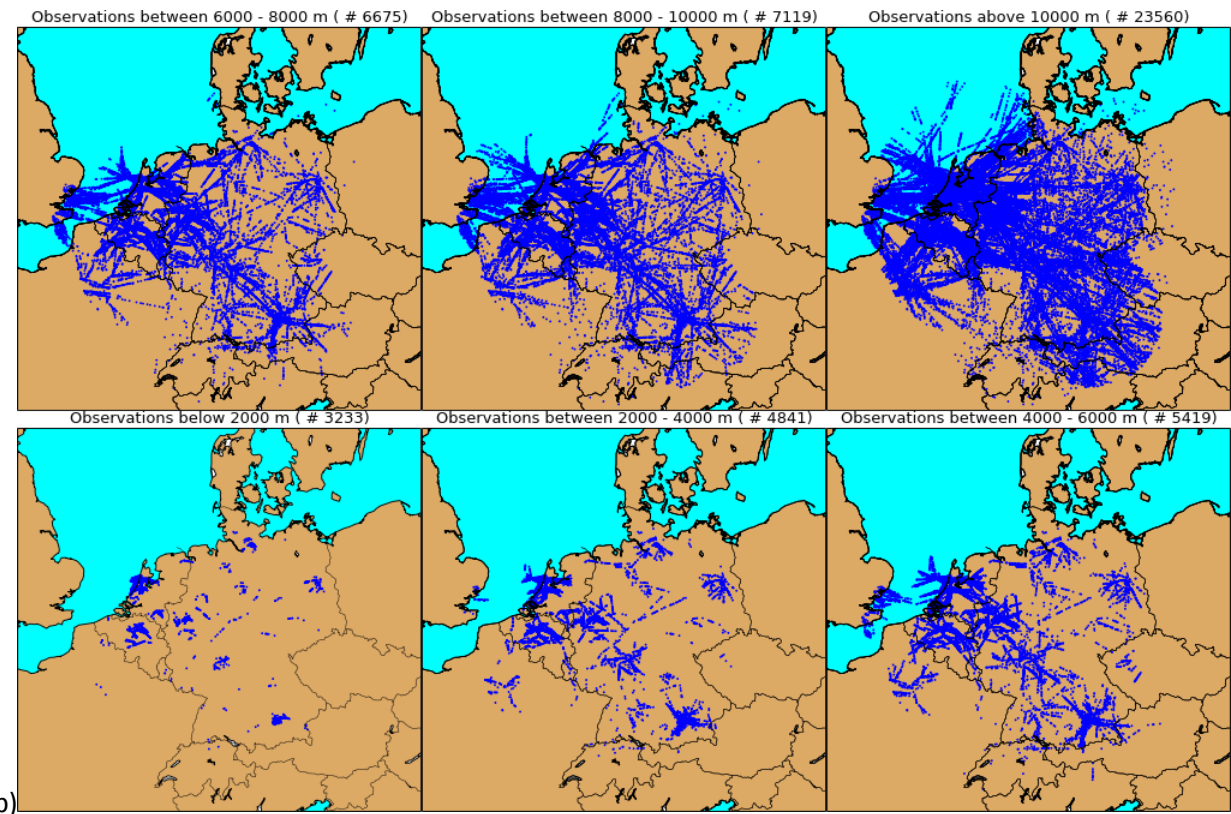
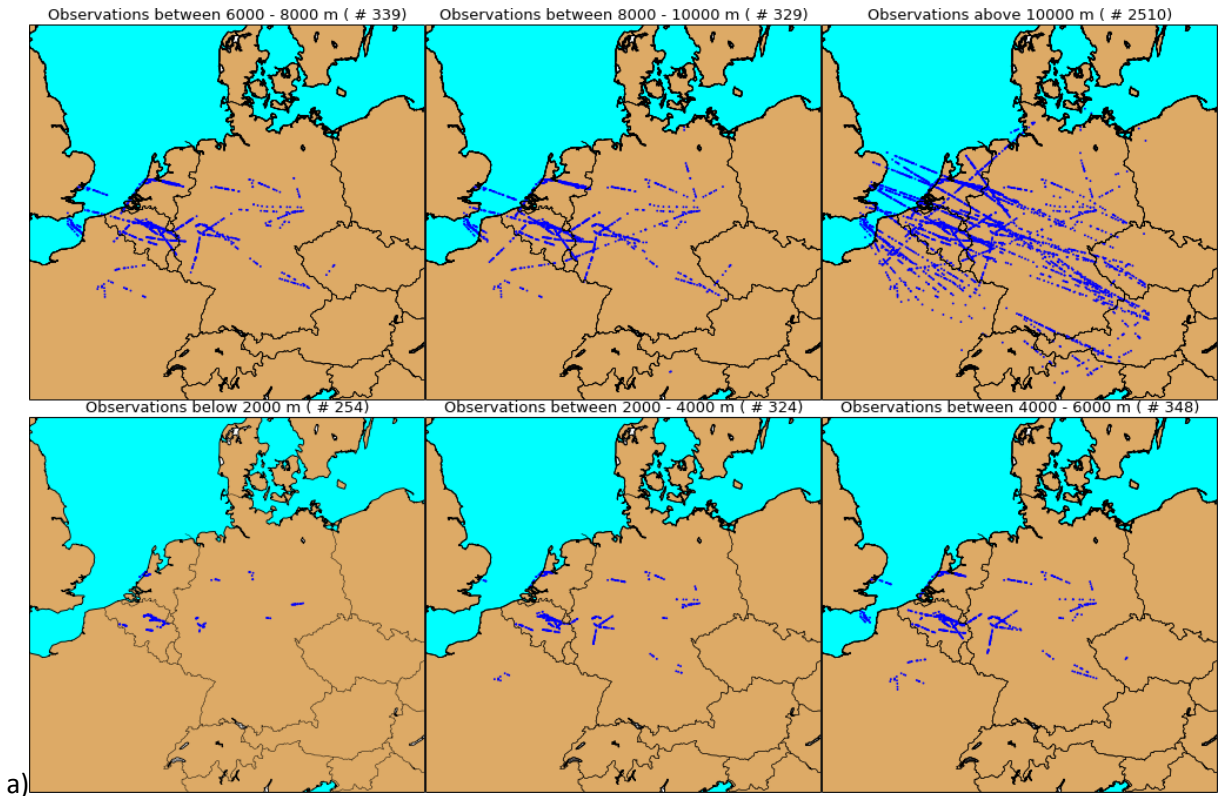


Figure 30 : Spatial distribution of ADD data assimilated in DMI HIRLAM T1T model at UTC 00 (top) and UTC 12 (bottom) in 6 different height bins. The assimilation time window for ADD data is +/- 1 h.

From Figure 30 it appears that in areas where ADD are available, the spatial coverage is much better than for radiosondes, in regions the spatial density is high enough to speak about 3D data rather than

sounding profiles. In addition the timeliness is very high, with data becoming available more often than once per hour. The late night and early mornings provide an exception, at these times fewer airports provide data, and the data become profile-like as soon as the height drops below cruising level.

Precision, bias corrections, preprocessing of ADD

As seen in other parts of this report, the precision of ADD data is in general quite high, level with data from AMDAR and radiosondes. Temperatures from Mode-S EHS is an exception, but here it should be noticed that statistical treatment of the massive amount of those data enable determination of average temperatures, which will have smaller errors. More important is that many NWP centers bias correct aircraft AMDAR (and similar) temperature data before or as part of the data assimilation. In both cases against NWP model data. These corrections can be quite elaborate, with different offsets for ascent, decent and cruising.

For direct usage in climate monitoring, it is important that the ADD data are corrected by the same methods for the entire sample, using an NWP model that is stabilized against drift, for example by assimilation of both radiosonde and GNSS RO data. In practice this points toward usage of a global model, possibly ERA interim data could be used.

8.3.2 Usage of ADD data in climate monitoring

Climate monitoring

Under global warming conditions, the largest temperature increase is expected just below the tropopause, i.e. close to the cruising level of the airplanes. A main benefit of ADD and other (aircraft observations) is that different from satellites, wind and temperature variability and change can be directly observed in situ. Different from other observing systems, there is also data available in many otherwise data-sparse regions, in particular if the ADD observing system is expanded beyond Europe and North America. We note the potential benefits of higher resolutions and higher timeliness compared to other observing systems. Satellite data need an extra step for calibration to absolute values. For this, in situ data is required, and ADD can help deliver this data.

Re-analyses

ADD data can be included in re-analyses, either as an augmentation of already existing satellite datasets or for the purpose of validation. In data-rich regions they have an advantage over satellite data in being essentially three-dimensional in structure. In regions with sparse conventional data they could give additional data in the lower troposphere, augmenting the satellite observations further aloft. The ADD data will be useful for validation of the re-analyses.

The high time frequency is possibly the largest advantage of ADD data. This can help resolve better the diurnal cycle in re-analyses.

Improving climate models

The ability to resolve the diurnal cycle will benefit preparation of boundary conditions for climate models. And it will enable better verification of climate models, which can lead to improvement of climate model physics.

Observing system stability over time

Many other sounding systems suffer from systematic errors or stability problems over time. An example of the former is the insolation correction which has to be applied to daytime radiosonde measurements,

depending on the type of sonde. An example of the latter problem are calibration issues and orbital changes in the polar orbiting satellites carrying the microwave sounders. Compared to these observing systems, ADD data are consistent and their biases are stable over time, a prerequisite for climate monitoring systems. We note however that it must be ensured to that the bias corrections are applied consistently. Therefore it would be useful to conduct the data processing at a central facility to ensure that a homogeneous dataset is created.

Coverage

Different from all other observing systems, ADD provides lower troposphere data with high temporal and spatial resolution even in data-sparse regions, provided an airport contributing to the ADD is nearby, which potentially could be the case in many rather remote regions, for example in Australia, and large parts of South America and Africa. Also parts of the polar regions would benefit.

Expanding the ADD observing system to regions of the Earth which are today data sparse, can be expected to provide better higher impact in climate monitoring and modelling, than ADD data from Europe.

For climate monitoring and modelling, stimulating the buildup of a global ADD observing system should have a high priority.

8.3.3 Conclusion

A pan European collection of ADD data will increase the amount of in situ upper air wind and temperatures dramatically, by at least an order of magnitude. A significant amount of the data will be from relatively low levels over land, where satellite radiances are difficult to use. Today it is mainly radiosonde data, AMDAR data, and wind profiler data that provide such measurements. The data could also be used to validate satellite wind observations.

Potentially the ADD derived winds and temperatures might be beneficial not only for weather forecasting, but also for climate monitoring and climate modelling. Based on some assumptions about how a large scale European and global ADD based observing system might appear in the not too distant future, we attempt to address the question whether these data can be expected be of importance for climate monitoring and modelling, and whether there are specific issues regarding the required handling of the data, beyond what is necessary for NWP and general weather forecasting usage.

ADD data will be useful for climate monitoring with regard to temperature trends. The ADD data require centralized bias corrections to provide a sufficiently homogeneous data set for this type of usage. Here the good coverage near the tropopause is a main asset.

ADD data will be useful in re-analyses, and in improving the preparation of boundary conditions for climate models, and the physics of climate models. In particular due their high timeliness, resolving the diurnal cycle.

The largest impact from ADD data on climate monitoring and modelling is expected if data from otherwise data sparse regions become available. If ADD data can be obtained from the vicinity of large airports outside Europe and North America, it would be very valuable. However it is beyond the scope of this report to investigate the possibility for that.

9 Roadmap for implementation of an operational ADD collection and delivery

Based on the evidence in this study it is proposed to implement an operational ADD data processing center that focuses primarily on Mode-S EHS and MRAR data in Europe. As a second step the potential of ADS-C data can be exploited using currently available, and as such paid for, global data and possibly extend that in the future towards e.g. data sparse regions.

Although it may be obvious it is important to realize that aircraft observations are only available in areas and regions where aircraft are flying, and that significant differences in volume do exist between e.g. day and night time. Similar differences exist e.g. with regard to the vertical distribution of the aircraft observations, in general more observations are available on cruise altitude and less at lower levels.

With regard to the operational processing a central processing facility is proposed, see Figure 31. This centre can perform central processing and corrections, including the operation of the dynamic aircraft database with individual heading and temperature corrections. Additional local processing is foreseen for situations where data provision is time critical, and one of these centres could act as a back-up for the central processing facility.

It is optimal to have a centralized processing for data consistency and quality, and it is therefore foreseen that the raw data is collected and shared as well as the corrections. The different collection, correction and processing software, as developed by KNMI and the Met Office, could be made generic under the EUMETNET flag. In this way, NMHS can install their local network, and thus share their ADD information within the EUMETNET domain, when contacts with local ATC are unsuccessful.

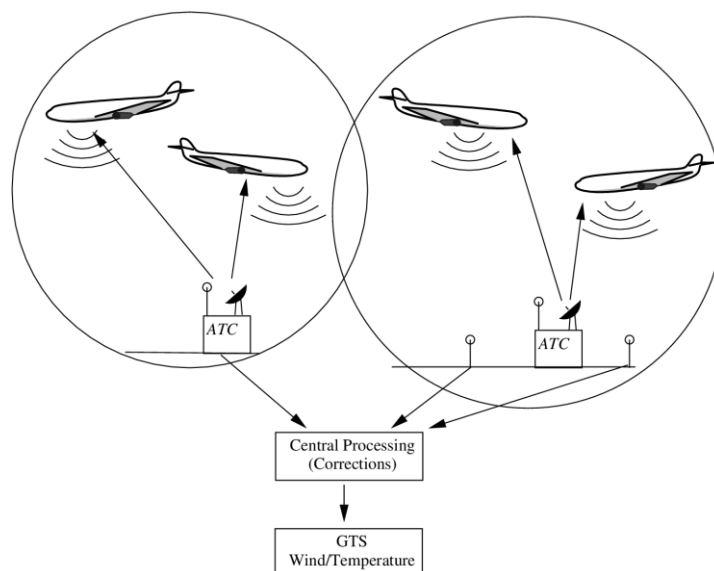


Figure 31 : Centralized processing

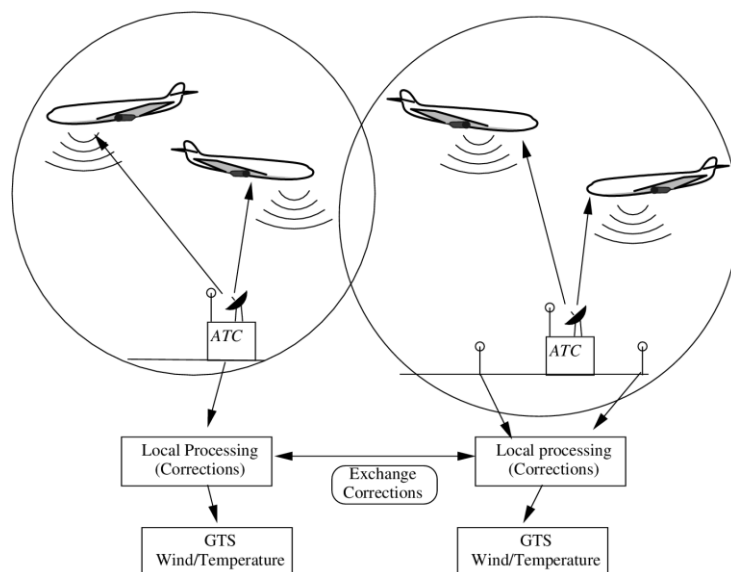


Figure 32 : Decentralized processing

9.1 Prioritization of delivery to different user groups

As discussed in chapter 8, there are several potential internal meteorological “customers” for observations obtained or derived from ADD data. These all have slightly different requirements, which are summarized in Table 26. Whilst it is possible to meet all of their requirements, it is likely that these will need to be prioritized such that those with the highest priority have their requirements met earlier in the life of an operational service.

Table 26 Meteorological "customers" requirements summary.

| Application | Coverage | Target latency | Threshold latency |
|----------------------|---------------------|----------------|-------------------|
| Nowcasting/local NWP | Local coverage | 05 minutes | 15 minutes |
| Regional NWP | “European” coverage | 30 minutes | 90 minutes |
| Global NWP | Maximum coverage | 01 hour | 06 hours |
| Climate | Maximum coverage | n/a | n/a |

9.2 Analyze link with AMDAR data provision

With a new method obtaining aircraft observations of an appropriate quality and quantity it may be feasible to reduce the number of AMDAR observations in regions where aircraft observations are available. It is not within the scope of this document to discuss the level of reduction nor where the resources will be redistributed. It is worth noting that it is likely the resources will either go to currently data sparse regions or increasing the number of humidity observations. This will require coordination between the ADD processing and E-AMDAR. There is a significant processing overlap between E-AMDAR and any ADD centralized processing, see 6.3. There are possible efficiencies in merging these functions, although there are also distinct differences in the processing of aircraft derived observations. Before ADD processing becomes operational four pieces of work should be conducted to understand the impact of these new observations on the E-AMDAR program:

- A case study where E-AMDAR data is reduced and supplemented by Mode-S EHS/MRAR data, and taking into account the lower quality of temperature derived from Mode-S EHS.
- An agreed coordination plan for the redistribution of E-AMDAR resources.
- An analysis of E-AMDAR processing for combined ADD/E-AMDAR processing.
- Agree the BUFR format to be used, including a policy on geographical indicators.

It should be noted that with a redistribution of AMDAR resources some airlines may choose to leave the current E-AMDAR program.

9.3 Differentiate between non-recurring and recurring cost.

The investment to obtain and derive meteorological observations can be categorized as follows:

- Initial set-up of operational aircraft derived data processing center, including algorithms for processing and quality control, dynamic aircraft correction database, data storage, and data dissemination.
- Initial set-up of legal conditions, standard contracts for data collection and data provision, in line with EU regulations on re-use of public sector information.
- Coordination with air traffic control organizations, airlines, aircraft and engine manufactures, airports, radar tracking organizations and regulators on data provision and distribution conditions.
- Exploitation costs for maintaining and operating the EUMETNET ADD data processing center.
- Further development of the program to explore new opportunities of ADD data, e.g. ADS-C with global geographical coverage potential, to increase the geographical coverage of ADD data (Mode-S EHS and MRAR), and explore opportunities for added value utilizing the meteorological observations.
- Deployment of local ADS-B/Mode-S receivers in parts of Europe, if needed, including the necessary infrastructure to maintain and operate these receivers operationally.
- Further action research to investigate current and future potential of collecting and using ADD data for meteorological purposes.

A first and rough estimation provided by KNMI is that the center can be operated for the first five years with approximately 2,5 fte per year, including set-up, operational processing, coordination with aviation stakeholders, and improvements to the program. The annual costs for data communication, processing and storage is estimated at € 100.000. Not included are the cost for ADS-B/Mode-S receivers that are operated locally. This would lead to an annual program cost of € 500.000. The expectation is that after five years the center can be operated with 1,5 fte.

As stated this is a rough estimate and costs could be reduced via in-kind contributions from members, or through delaying e.g. the investigation on opportunities other than Mode-S EHS and MRAR data. At the same time there may exist opportunities to receive co-funding, e.g. via SESAR 2020 (development) or SESAR deployment.

10 Technology developments related to ADD and survey

In the upcoming years there are likely to be further developments in aircraft technologies which may yield useful data for the meteorological community. This section will describe briefly how we currently perceive these technologies developing.

Within Europe ADS-B and Mode-S EHS are likely to be the leading technologies in SSR, with some regions substantially supplementing their civilian primary radar infrastructure as ADS-B becomes universally installed on aircraft. As described in the rest of this document and the references, this will provide the opportunity for substantially more observations throughout Europe. In other areas and potentially some regions of Europe multilateration may become the prevalent secondary radar system. There is currently no evidence that this data will be of use for the meteorological community, although aircraft that have ADS-B transponders do not routinely turn them off on leaving mandated airspace.

In some regions there may be the potential to persuade ATM organisations to request the BDS (4.4) MRAR registers. The advantages of this are discussed above. This will not be possible in many areas as the airspace is too busy for the radar to have sufficient bandwidth to request the additional messages. Due to the small number of aircraft that currently respond to these requests it may be required to try and influence airlines to install this equipment. This will probably require the development of a suitable business plan for the airline. It would likely take airlines several years to update their fleet due to their maintenance regimes.

In Europe and North America there are ongoing projects looking at the future of the ATM community, these are SESAR and NEXTGEN. These are very large projects covering many aspects of traffic control, management and safety. The RTCA are developing consensus standards based on the work being done in these projects.

Special Committee 206 of the RTCA are working on a system where regular meteorological observations would be reported to the ground. DO-339 discusses the required parameters for meteorology and wake vortex applications. The document at hand does not discuss the technologies required to transmit the data to the ground, only what is available on-board an aircraft and meteorology requirements. This is added to further in DO-252 in which the Automated Meteorological Transmission (AUTOMET) is detailed. The AUTOMET standard is not concerned with the method of transmission of data only on the data itself. It is envisaged that the data will be transferred over 3G/LTE, SatCom and Terrestrial Broadband to a central data centre before being sent onto the meteorological community in a similar way to AMDAR. The AUTOMET standard is fairly inclusive with standards laid down for wind, temperature, humidity, turbulence, icing, wind shear etc. The standard has also the potential to be extending, for example it could include carbon dioxide measurements.

The availability of these data depends on the introduction of affordable broadband in the cabin of commercial airliners resulting in the data bandwidth available having increased significantly. Aero engine manufacturers such as Rolls Royce are currently using near real time data to assess engine performance for maintenance although there is a constant drive to reduce the bandwidth used for this. The aviation industry is preparing for significantly more data being made available with future sensor developments. In parallel to this more cost effective data transmission methods are being investigated. Currently in development is mesh type network infrastructure for airliners where communications pass from aircraft to aircraft before being transmitted to a land based receiver to reduce the amount of satellite bandwidth required (Medina and Hoffmann 2011).

The WMO Study SSA-2604-14 is being conducted into the currently developing and future communications and technology impact on AMDAR. It would not be practical to include the full report or even large extracts here, but the following is quoted from the Summary and Recommendations.

Cabin connectivity comes with a quantum leap in performance in bandwidth and cost per bit. In addition cabin services are backed by powerful generic computing resources. This combination of cheap connectivity and flexible processing has clear implications and potential to optimise the operational cost of AMDAR. Still, legacy air-ground communication systems will maintain a central role in AMDAR in the coming years, and significant efforts are engaged to improve safety-dedicated communication systems, including the possibility to route non critical traffic to non-safety systems. However, a paradigm shift from voice to data coupled with aeronautical safety spectrum scarcity will limit operational cost optimisation possibilities.

In this context and in the medium to long term, ADS-B can be seen as a natural complement to “traditional” AMDAR. ADS-B systems are being mandated by civil aviation and will thus become standard aircraft equipment in the coming years. ADS-B has the capability to deliver through broadcast, essential weather parameters with much greater volume and frequency and with global coverage. However, based on the current ADS-B standard, aircraft must be interrogated and ‘requested’ to deliver weather data. This limits the applicability of this technique to radar-covered areas. However, it would be feasible to update the standard specifications to include weather fields as mandatory broadcast elements, although this type of change is likely to be slow in being realised and made operational. In addition, new possibilities to collect ADS-B data using satellite constellations would offer worldwide collection capability of essential airborne weather measurements.

Broadband on aircraft has additional advantages for airlines. There has been a gradual introduction of weather data being presented to pilots on the flight deck. With improved communications capabilities there would be an increase in this data being sent to the aircraft improving airline flight planning and safety.

In order to get a better view on the European developments a first draft of a questionnaire has been developed and is enclosed in appendix B. The questionnaire aims to facilitate a dialogue between ATM and airlines and the air navigation service provider for meteorology. The aim of the questionnaire is to get a better understanding of both current and planned ground infrastructure, as maintained by air traffic management, and the air infrastructure, as exploited by airlines. At the same time this offers an opportunity for the MET community to inform ATM stakeholders about the potential of ADD data, and to get more involvement from the ATM community.

11 Summary table ADD characteristics

The relation between the availability and quality of meteorological information and the different aircraft data types is complex. Depending on the aircraft configuration and capabilities, and in combination with the ATM ground infrastructure, several opportunities exist to utilize aircraft derived data. A summary of the information provided in the previous chapters is given in the table below.

Although it may be obvious it is important to realize that aircraft observations are only available in areas and regions where aircraft are flying, and that significant differences in volume do exist between e.g. day and night time. Similar differences exist e.g. with regard to the vertical distribution of the aircraft observations, in general more observations are available on cruise altitude and less at lower levels.

Please note that the table does not include Mode-S ELS data although the availability and use of Mode-S ELS data is widespread in comparison to the Mode-S EHS data. The reason for not including Mode-S ELS data is that this data source offers no opportunities for gathering meteorological observations.

Note that humidity is not included in the table, although a few AMDAR aircraft are capable to provide humidity information. In theory

Note that there are two types of accuracy listed in the table: one denoting the accuracy compared to the model, and one denoting the accuracy against the (unknown) truth. The first “error” contains also an additional term due to the model uncertainty. We have included both measures of accuracy because of their mixed appearance in the literature cited here.

Table 27 : Summary of different types of Aircraft Derived Data and their characteristics

| | ADS-A/ADS-C | ADS-B | ADS-B ES | Mode-S EHS | Mode-S MRAR | AMDAR |
|---------------------------------------|------------------------|---|---|-----------------------------|-----------------------------|-----------------------|
| aircraft | selected ¹² | all | all | almost all ¹³ | subset ¹⁴ | subset ¹⁵ |
| data transport | ACARS | VHF | VHF | VHF | VHF | ACARS |
| data reception | ARINC/SITA | ATC radar or local receiver | ATC radar or local receiver | ATC radar or local receiver | ATC radar or local receiver | ARINC/SITA |
| data initiation | triggered by ATC | continuous | continuous | triggered by ATC radar | triggered by ATC radar | automatic |
| communication costs | yes | no | no | no | no | yes |
| data restrictions | restricted? | free? | free? | ? | ? | restricted |
| coverage | global | ground based ADS-B-stations, specific areas | ground based ADS-B-stations, specific areas | radar-view, specific areas | radar-view, specific areas | global |
| update frequency | on-demand | 1 s | 1s | 4-20s | 4-20s | 10s-60s ¹⁶ |
| latency | 1s-1h | 1s | 1s | 1s-10min | 1s-10min | 1s-1h |
| direct wind | yes | no | no | no | yes | yes |
| direct temperature | yes | no | no | no | yes | yes |
| derived wind | yes | (?)yes | yes | yes | no | no |
| derived temperature | yes | no | yes | yes | no | no |
| wind speed accuracy | 1m/s? | unknown | 10kts | 1m/s | 1m/s | 1m/s |
| wind direction accuracy | 10-15 deg? | unknown | 30 deg | 10-15 deg | 10-15 deg | 10-15 deg |
| wind vector accuracy | 1m/s? | unknown | ? | 1m/s | 1m/s | 1m/s |
| temperature accuracy | 0.5K | n/a | 0.5-2K ¹⁷ | 1-1.5K | 0.5K | 0.5K |
| wind speed accuracy ¹⁸ | 2-2.5m/s | unknown | unknown | 2-2.5m/s | 2-2.5m/s | 2-2.5m/s |
| wind direction accuracy ¹⁸ | 10-15 deg | unknown | unknown | 10-15 deg | 10-15 deg | 10-15 deg |
| wind vector accuracy ¹⁸ | 2-2.5m/s | unknown | unknown | 2-2.5m/s | 2-2.5m/s | 2-2.5m/s |
| temperature accuracy ¹⁸ | 1K | unknown | unknown | 2K | 1K | 1K |

¹² ADS-C equipped aircraft

¹³ mass > 5 700 kg or TAS > 250 knots, flying IFR in ICAO EUR

¹⁴ mass > 5 700 kg or TAS > 250 knots, flying IFR in ICAO EUR and transponder reply to BDS44

¹⁵ selected aircraft with dedicated software installed

¹⁶ depends on many things

¹⁷ two alternative methods, de Leege or average layer temperatures

¹⁸ compared against numerical model

12 Acronyms

| | |
|-----------|--|
| A/C | Aircraft |
| ACARS | Aircraft Communications Addressing and Reporting System |
| ACAS | Airborne Collision Avoidance System |
| ACC | Area Control Centre |
| ACMS | Aircraft Condition Monitoring System |
| ADD | Aircraft Derived Data |
| ADD FS ET | Aircraft Derived Data Feasibility Study Expert Team |
| ADS | Automatic Dependent Surveillance |
| ADS-A | Automatic Dependent Surveillance-Addressed |
| ADS-B | Automatic Dependent Surveillance-Broadcast |
| ADS-C | Automatic Dependent Surveillance-Contract |
| AEMET | Agencia Estatal de Meteorología (Espagne) |
| AFI | ICAO African Region |
| AFIRS | Automated Flight Information Reporting System |
| AIC | Aeronautical Information Circular |
| AIP | Aeronautical Information Publication |
| AIREP | Aircraft Reports |
| ALADIN | Aire Limitée Adaptation Dynamique Développement InterNational (international co-operation in Numerical Weather Prediction) |
| AMAN | Arrival Manager |
| AMDAR | Aircraft Meteorological Data Relay |
| ANS-CR | Air Navigation Services of Czech Republic (Czech Republic National Meteorological Center) |
| AOSFRS | AMDAR Onboard Software Functional Requirements |
| ARINC | Aeronautical Radio Incorporated |
| ARSO | Agencija Republike Slovenije za Okolje (Slovenia National Meteorological Center) |
| ASCI | American Standard Code for Information Interchange |
| ASTERIX | All Purpose Structured Eurocontrol Surveillance Information Exchange |
| ATC | Air Traffic Control |
| ATM | Air Traffic Management |
| ATN | Aeronautical Telecommunication Network |
| AUTOMET | Automated Meteorological Transmission |
| BDS | Comm B Data Selector |
| BUFR | Binary Universal Form for the Representation of Meteorological Data |
| C | Celsius |
| CAA | Civil Aviation Authority |
| CM | Coordinating Member |
| CNMCA | Centro Nazionale di Meteorologia e Climatologia Aeronautica (Italian National Meteorological Center) |
| CPR | Compact Position Report |
| CPU | Central Processing Unit |
| DA | Data Assimilation |
| DAP | Downlinked Aircraft Parameter |
| DEVG | Derived Equivalent Vertical Gust |
| DMAN | Departure Manager |
| DMI | Danmarks Meteorologiske Institut (Danish Meteorological Institute) |
| DO | Document / Department Order |
| DOC | Document |
| DTS | Data Targeting System |

| | |
|-------------|--|
| DVB-T | Digital Video Broadcasting Terrestrial |
| DWD | Deutscher Wetterdienst |
| E-ADAS | E-AMDAR Data Acquisition System |
| E-ADD | EUMETNET-Aircraft Derived Data |
| E-ADOS | E-AMDAR Data Optimisation System |
| E-AMDAR | EUMETNET-Aircraft Meteorological Data Relay |
| ECMWF | European Centre for Medium-range Weather Forecasting |
| EDR | Eddy Dissipation Rate |
| EHS | Enhanced Surveillance |
| ELS | Elementary Surveillance |
| EMI | European Meteorological Infrastructure |
| ES | Extended Squitter |
| ESRL | Earth System Research Laboratory |
| ET | Expert Team |
| ET-AO | Expert Team on Aircraft-based Observations |
| EU | European Union |
| EUCOS QM | EUMETNET Composite Observing System Quality Monitoring |
| EUMETNET | European Network of Meteorological Service |
| EUR | Europe Region |
| EUROCAE | European Organization for Civil Aviation Equipment |
| EUROCONTROL | European Organization for the Safety of Air Navigation |
| F2F | Face-to-face |
| FABEC | Functional Airspace Block Europe Central |
| FANS | Future Air Navigation System |
| FIR | Flight Information Region |
| FIS | Flight Information Service |
| FIS-B | Flight Information Service-Broadcast |
| FL | Flight Level |
| FMI | Finnish Meteorological Institute |
| FMS | Flight Management System |
| FS | Feasibility Study |
| FSS | Flight Selection Systems |
| ft | Feet |
| FTP | File Transfer Protocol |
| GAT | General Air Traffic |
| GB | Gigabyte |
| GNSS | Global Navigation Satellite System |
| GSD | Global Systems Division |
| GTS | Global Telecommunications System |
| GVA | Geometric Vertical Accuracy |
| HF | High Frequency |
| HIRLAM | High Resolution Limited Area Model |
| hPa | HectoPascals |
| HU | Humidity |
| HyMeX | Hydrological Cycle in Mediterranean Experiment |
| IAS | Indicated Airspeed |
| ICAO | International Civil Aviation Organisation |
| ID | Identification |
| IFR | Instrument Flight Rules |
| iso | Instead of |
| K | Kelvin |
| kg | Kilogram |

| | |
|-------------|---|
| KLM | Royal Dutch Airlines |
| km | Kilometer |
| KMI | Royal Meteorological Institute of Belgium |
| KNMI | Royal Netherlands Meteorological Institute |
| LACE | Limited Area Modelling in Central Europe |
| LVNL | Luchtverkeersleiding Nederland, Air Traffic Control The Netherlands |
| LSB | Least Significant Bit/Byte |
| LTE | Long-Term Evolution |
| m | Meter |
| MB | Megabyte |
| MCP/FCU | Mode Control Panel/Flight Control Unit |
| Met | Meteorological |
| Met Office | UK National Meteorological Institute |
| MF | Météo-France (French National Meteorological Service) |
| Min | Minute |
| Mode-S | Mode-Select |
| Mode-S BDS | Mode-Select Meteorological Hazard Report |
| Mode-S EHS | Mode-Select Enhanced Surveillance |
| Mode-S ELS | Mode-Select Elementary Surveillance |
| Mode-S MRAR | Mode-Select Meteorological Routine Air Report |
| MRAR | Meteorological Routine Air Report |
| MSB | Most Significant Bit/Byte |
| MUAC | Maastricht Upper Area Control Centre of EUROCONTROL |
| NAO | North Atlantic Oscillation |
| NATS | National Air Traffic Services (Air Navigation Service Provider in the UK) |
| NetCDF | Network Common Data Form |
| NextGen | Next Generation Air Transportation System |
| nm | Nautical Mile |
| NMHS | National Meteorological and Hydrological Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NUAC | Nordic Unified Air Traffic Control (joint subsidiary owned by Danish Naviair and Swedish LFV) |
| NWP | Numerical Weather Prediction |
| obs | Observed |
| OSE | Observations System Experiment |
| PBL | Planetary Boundary Layer |
| PC | Personal Computer |
| PFAC | Policy and Finance Advisory Committee |
| PIREP | Pilot Reports |
| PREVIEW | Prevention, Information and Early Warning, EU FP6 project for risk management |
| QEvC | Quality Evaluation Centre |
| RADNET | Radar Data Network |
| RC LACE | Regional Cooperation for Limited Area modeling in Central Europe |
| Rel | Relative |
| RTCA | Radio Technical Commission for Aeronautics |
| RTH | Regional Telecommunication Hub |
| RUC | Rapid Update Cycle |
| s | Second |
| S/w | Software |
| SAP | Sensitive Area Prediction |
| SATCOM | Satellite Communications |
| SC | Special Committee |

| | |
|--------|--|
| SCP | Secure Copy Protocol |
| SEA | Slovenian Environment Agency (also known as ARSO) |
| SESAR | Single European Sky ATM research |
| SFTP | SSH File Transfer Protocol |
| SITA | Société Internationale de Télécommunication Aéronautique |
| SPI | Special Position Indication |
| SSR | Secondary Surveillance Radar |
| STAC | Scientific and Technical Advisory Committee |
| TAMDAR | Tropospheric Airborne Meteorological Data Reporting |
| TAR | Track Angle Rate |
| TAS | True Airspeed |
| TCAS | Traffic Alert and Collision Avoidance System |
| TDR | Transponder |
| TSO | Transmission System Operator |
| UAT | Universal Access Transceiver |
| UAV | Unmanned Aerial Vehicle |
| UIR | Upper Flight Information Region |
| UK | United Kingdom |
| UKMO | United Kingdom Meteorological Office |
| UKV | Variable Resolution UK |
| USA | United States of America |
| UTC | Coordinated Universal Time |
| V | Velocity |
| VDL2 | VHF data Link Mode 2 |
| VFR | Visual Flight Rules |
| VHF | Very High Frequency |
| VPN | Virtual Private Network |
| WGS84 | World Geodetic System 1984 |
| WIGOS | World Meteorological Organization Integrated Global Observing System |
| WMO | World Meteorological Organization |
| WVSS | Water Vapor Sensing System |
| ZAMG | Zentralanstalt für Meteorologie und Geodynamik |

13 References

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DO-353 Interoperability Requirements Standard for Baseline 2 ATS Data Communications, ATN Baseline 1 Accommodation, Initial Release (ATN Baseline 1 – Baseline 2 Interop Standard), 2003 RTCA SC-214

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A. Appendix : Met Office modified AMDAR BUFR format:

At the Met Office, the Mode-S EHS data (using MET Office owned local receivers and ADS-B data for positions) is stored in the operational observations database using a BUFR format which is derived from the current standard AMDAR table. This modified BUFR format is detailed below. This includes enough information for dynamic error calculations to be done for NWP.

| BUFR Reference | Content | Data Format | Units | Description | Precision |
|----------------|---------------------------|--------------------|-----------------|--|-----------------------------|
| 002065 | Site code | Character (len=32) | None | Site Code, e.g., location of radar or receiver | |
| | Data Source indicator | Integer | NA | Code defining the source of the data <ul style="list-style-type: none"> • Direct wind / temperature • Derived wind/ temperature • Heading correction • True airspeed correction • Temperature correction • Smoothing | |
| 004001 | Year | Integer | Calendar Year | | |
| 004002 | Month | Integer | Calendar Month | | |
| 004003 | Day | Integer | Days | | |
| 004004 | Hour | Integer | Hours | | |
| 004005 | Minutes | Integer | Minutes | | |
| 004006 | Seconds | Integer | Seconds | | |
| 005001 | Latitude (decimal) | Double Precision | Decimal Degrees | Range -90.0 to +90.0 | 5 m, up to 6 decimal places |
| 006001 | Longitude (decimal) | Double Precision | Decimal Degrees | Range -180.0 to +180.0 | 5 m, up to 6 decimal places |
| ----- | Position source indicator | integer | NA | Code defining source as "ADS-B" or "Tracking radar" | |
| 007007 | Pressure Altitude | Long Integer | Feet | Range -500 to 50000 | 25 ft |

| BUFR Reference | Content | Data Format | Units | Description | Precision |
|----------------------------------|--------------------------------|--------------------|--------------|--|------------------------|
| 010053 | GNSS Altitude | Double Precision | Meters | | Up to 3 decimal points |
| --- | Barometric Pressure | Float | hPa | | Up to 6 decimal points |
| 001006 | ICAO Address | Character (len=6) | Hexadecimal | Mode-S transponder 24-bit address (which should be unique) | |
| 001110 | Call Sign / Tail Number | Character (len=8) | Alphanumeric | Airline allocated flight code. | |
| 001009 | Aircraft Type | Character (len=10) | Alphanumeric | Airframe Manufacturer code | |
| 011100 | Indicated Air Speed | Integer | Knots | | 0 decimal points |
| 011100 | True Airspeed | Integer | Knots | | 0 decimal points |
| 011104 | True Heading | Float | Degrees | Range 0 to 359, Clockwise from North | Up to 6 decimal points |
| 011104 | Geomagnetic Deviation | Float | Degrees | Range -180 to +180, from North. Default zero | Up to 6 decimal points |
| 011104 | Aircraft Magnetic Heading Bias | Float | Degrees | Instrument bias – expected to small ~ ± 10 degrees. Default zero | Up to 6 decimal points |
| 011100 | Ground Speed | | Knots | Reported to nearest integer value. But normally derived | Up to 6 decimal points |
| 011104 | Ground Heading | | Degrees | Range 0 to 359, Clockwise from North | Up to 6 decimal points |
| 002063 | Roll Angle | Float | Degrees | | Up to 6 decimal points |
| 10 bits, LSB=2.048/512 MSB=2.048 | Mach Speed | Float | None | | Up to 3 decimal points |
| 011100 | Radar Ground Speed | Integer | Knots | | |
| 011104 | Radar Ground Heading | Integer | Degrees | Range 0 to 359, Clockwise from North | |

| BUFR Reference | Content | Data Format | Units | Description | Precision |
|-----------------------|-------------------------|--------------------|--------------|---|------------------------|
| 011002 | Wind Speed | Float | Knots | Computed Wind Speed using Aircraft Air and Ground Vectors | Up to 6 decimal points |
| 011001 | Wind Direction | Float | Knots | Computed Wind Direction using Aircraft Air and Ground Vectors | Up to 6 decimal points |
| 012101 | Air Temperature | Float | Kelvin | Computed Temperature using Aircraft Air Vector | |
| 011002 | Wind Speed (Radar) | Float | Knots | Computed Wind Speed using Aircraft Air and Radar Derived Ground Vectors | Up to 6 decimal points |
| 011001 | Wind Direction (Radar) | Float | Knots | Computed Wind Direction using Aircraft Air and Radar Derived Ground Vectors | Up to 6 decimal points |
| --- | Air Temperature (Radar) | Float | Kelvin | - not computed at this time - | Up to 6 decimal points |
| --- | Wind-U Vector | Double Precision | Knots | U-Component of Wind Vector using Aircraft Air and Ground Vector | Up to 6 decimal points |
| --- | Wind-V Vector | Double Precision | Knots | V-Component of Wind Vector using Aircraft Air and Ground Vector | Up to 6 decimal points |
| --- | Wind-U Vector (Radar) | Double Precision | Knots | U-Component of Wind Vector using Aircraft Air and Radar Derived Ground Vector | Up to 6 decimal points |
| --- | Wind-V Vector (Radar) | Double Precision | Knots | V-Component of Wind Vector using Aircraft Air and Radar Derived Ground Vector | Up to 6 decimal points |

B. Appendix : Questionnaire for ATM and airlines

This questionnaire is a first attempt to summarize a number of questions that can be put forward to Air Traffic Control and airlines by air navigation service providers for meteorology. The purpose of the questionnaire is to get a better understanding of both current and planned ground infrastructure, as maintained by air traffic management, and the airborne infrastructure, as exploited by airlines .

The questionnaire aims to facilitate a dialogue between ATM and airlines and the meteorological service provider in a country. This offers an opportunity for the MET community to inform ATM stakeholders about the potential of ADD data. At the same time this may lead to more involvement from the ATM community.

A short description of the current use and potential of aircraft derived data, including the win-win situation for ATM to share the ADD data with the MET community, has to be developed and can be extracted from this report.

Questions for ATM:

What are your plans for SSR?

- Multilateration
- Mode-S
- Other

Do you currently have Mode-S SSR equipment?

- Yes (how many?)
- No

(If Mode-S SSR) Are you requesting the Mode-S EHS (4.0, 5.0 and 6.0) parameters?

- Yes (which radars, which BDS registers)
- No
- No but we intend to.

(If Mode-S SSR) Do you have enough bandwidth to request the MRAR (4.4) register?

- Yes
- No

Are you aware of the use of Mode-S EHS derived data for time based separation?

- Yes
- No

Are you intending to implement the next stage in meteorological observations systems as described in RTCA DO-339

Do you request for ADS-C information?

- Yes
- No

(if ADS-C) do you extract meteorological information from ADS-C?

- Yes
- No

Questions for airlines

Are your aircraft equipped with ADS-B/Mode-S EHS transponders?

Yes

No

No but we are intending to implement them

Will you be providing broadband data to aircraft?

Yes

No

(if broadband is yes) Are you considering sending aircraft information via broadband?

Yes

No

Do you request for ADS-C information?

Yes

No

(if ADS-C) do you extract meteorological information from ADS-C?

Yes

No

C. Appendix : Loose ends

Pending opportunities

- MRAR humidity connection
There is a possibility to store the humidity information in the BDS4.4 MRAR register. Aircraft equipped with a humidity sensor could, when interrogated with BDS4.4, transmit this information to the ground, when the connection between the transponder and the humidity is present.
- Contact airlines on ADS-C data to be disclosed
Airlines use ADS-C to communicate with the aircraft. Around 25% of ADS-C messages contain meteorological information. If airlines are willing to share the ADS-C messages there is potential to receive additional global meteorological observations for little cost.
- Registration of aircraft to link ICAO id with type
It can be informative to categorise for example the heading correction per aircraft type. At present an official and complete database is lacking.
- Improve EHS processing by using other NWP models
 - Heading corrections: by using other NWP models, the calculation of the heading correction can be optimized. The number of days required for a valid correction could be reduced which could result in an increase of the amount of valid observations.
 - Side slip estimation can improve the wind derivation because this is a systematic error currently not separated. Moreover, side slip information could be very valuable for flight efficiency.
- Super obbing for nowcasting
It is likely that the significantly increased number of observations over AMDAR will allow for SuperObbing (averaging of individual observations) before assimilation into models.
- Age of register information
Further research is needed to determine the exact measuring time for each variable contained in the BDS registers. Currently, the same timestamp (i.e., the timestamp of the radar interrogation) is used with all reported quantities. If the measuring time is not the same for all parameters this may be taken into account during the preprocessing, especially in Mode-S EHS.

Future opportunities to be considered

- Use of ADS-B ES pressure and height observations in data assimilation
ADS-B ES provides both a true (GNSS) altitude and a pressure altitude (which can be directly mapped to a pressure). This allows for an altitude-pressure relationship to be found. It is intended that future AMDAR observations will also include this data. With further developments of NWP it is likely that assimilation of this additional information will become possible.
- Perform an NWP “observation system experiment” with additional Mode-S EHS derived data and reduced AMDAR using (at least) a regional non-hydrostatic model to show the opportunity to redistribute E-AMDAR without loss of quality.
- UAV / drones
With the increasing use of UAVs/Drones it is likely these will become a useful source of observations. Several uses are currently proposed from very local delivery services to high altitude communications systems, there may also be some scope for UAVs being used for targeted observations in regions of particular interest.
- Ryanair transmit data post flight via terrestrial telecommunications links back to their central system, this business model may be adopted by other low cost airlines. Whilst data of this type will be of limited use for rapid update systems there may be some value in validation, global models etc.

Topics not covered

Other sources of Aircraft data

D. Appendix : Members of EUMETNET Aircraft Derived Data (ADD) Feasibility Study ET

Member list version 1.0
26-02-2015

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