Royal Netherlands
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The use of a commercial ADS-B receiver to derive upper air wind and temperature observations from Mode-S EHS information in The Netherlands

Siebren de Haan, Marijn de Haij and Jan Sondij

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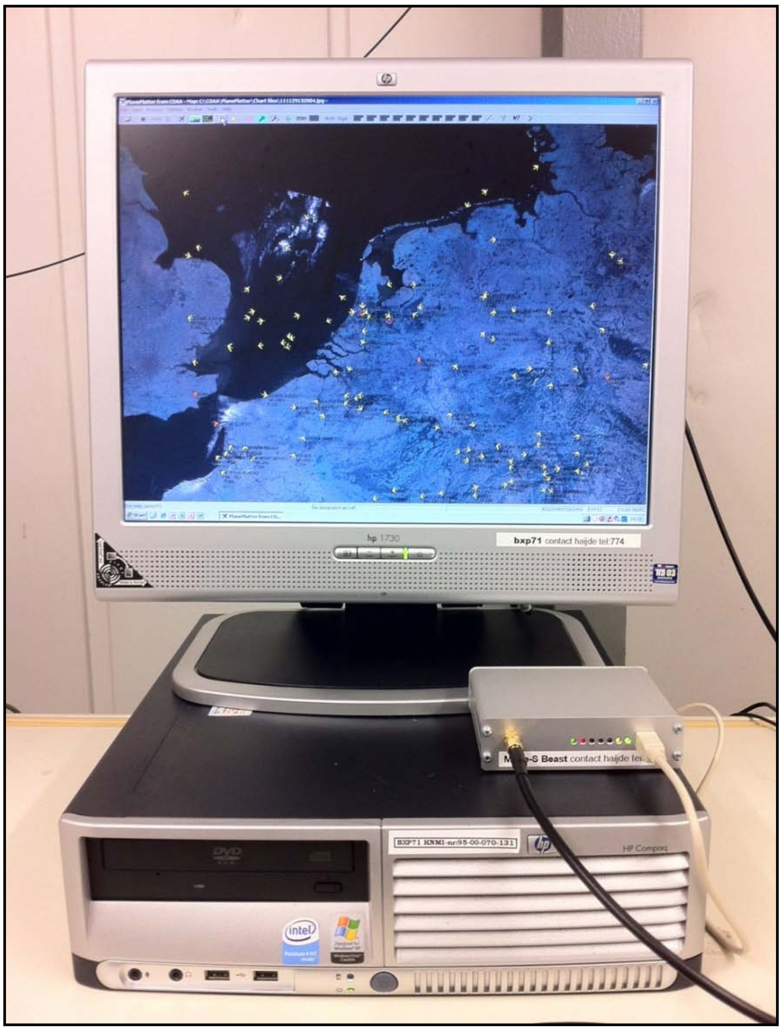

Data acquisition PC and Mode-S EHS 'Beast' receiver.

Siebren de Haan, Marijn de Haij and Jan Sondij
KNMI
De Bilt, July 2013

Executive summary

Only recently, a new method to derive weather information from aircraft has been developed and tested on quality, availability and applicability for use in operational meteorological applications. This method exploits the information retrieved from an enhanced surveillance (EHS) terminal area radar at an airport. This radar interrogates all aircraft in the range of the radar in a special or selective mode (Mode-S) on which the aircraft responds with information on e.g. heading, airspeed, Mach number and ground track. These messages are transmitted through UHF channels using the Broadcast Dependent Surveillance (BDS) protocol. The so-called Automatic Dependent Surveillance Broadcast (ADS-B) data is gathered by ATC and can be combined with tracking information to create Mode-S EHS derived wind and temperature observations in the upper air. The derived observations are of good quality (De Haan, 2011, 2013b) and have proven to be valuable for numerical weather forecasting (De Haan and Stoffelen 2012, De Haan 2013a).
The ADS-B messages can be collected with a wide range of commercial 1090 MHz receivers. This is widely done by aircraft spotters all over the world. The data protocols are described in ICAO and EUROCAE/RTCA documentation and this opens the opportunity to install an ADS-B receiver to downlink the Mode-S EHS data as interrogated by ATC The Netherlands.

In this report we describe the installation of a commercial Mode-S/ADS-B receiver, the software to extract meteorological information from Mode-S EHS/ADS-B EHS data and a first quality assessment by comparing the ADS-B EHS with the Mode-S EHS observations provided by ATC The Netherlands. Horizontal coverage density plots will reveal some shortcomings of the new method, that is, only a small fraction of the Mode-S EHS messages are also retrieved by our ADS-B receiver. However, the messages that are received are of fairly equal quality and have a more southward coverage due to the different location of the antenna.

The limited capability of the ADS-B receiver to derive wind and temperature observations is mainly due to a lack of simultaneously available parameters which is necessary to derive meteorological information from the transmitted messages. During rush hours the percentage of received valuable ADS-B EHS information drops to 8% compared to the Mode-S EHS data provided by ATC.

In this report it is shown that

1. ADS-B EHS data can be received independently from ATC, on the condition that aircraft are interrogated by a Mode-S EHS radar. A commercial ADS-B receiver is capable of receiving the Mode-S EHS information.
2. The received ADS-B EHS parameters contain information which can be used to derive wind and temperature observations.
3. The volume of the received meteorological data is a fraction, around 8 %, from the Mode-S EHS data flow in use by ATC The Netherlands.
4. The quality of the derived meteorological information is slightly worse than the meteorological data derived from the Mode-S EHS data received from ATC. Wind speed and direction are within meteorological requirements. Air temperature derived from ADS-B EHS is not compliant to these requirements.

As at present the rapid update cycle of the numerical weather prediction model of KNMI uses about 2 % of the Mode-S EHS data it is expected that the same relevant meteorological information can be received through a local ADS-B receiver. For reasons of coverage, amount and quality of the data, as well as cost efficiency, the reception of Mode-S EHS data from ATC is preferred.

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1 Introduction

1.1 Meteorological upper air observations

An accurate analysis of the current state of the atmosphere is very important for a good weather forecast. Present day Numerical Weather Prediction (NWP) models therefore have a strong requirement for quality controlled upper air measurements of wind, temperature and humidity with sufficient temporal and spatial resolution. Budget cuts on traditional sounding systems like radiosonde increase the demand for alternative sources of meteorological upper air data. Retrieval of meteorological information deduced from onboard sensors of aircraft using the Mode-S (“Mode-Selective”) transponder in Mode-S EHS (Enhanced Surveillance) designated airspace seems one of the answers to the existing gap of observational data.

An important advantage of Mode-S EHS compared to AMDAR (Aircraft Meteorological Data Relay) is that data can be obtained from all commercial aircraft, and not only from those participating in the AMDAR program. Moreover, the costs for the data communication are (already) paid for by the Air Traffic Management community. Recent research on Mode-S EHS data retrieved with the ATC (Air Traffic Control) radar at Amsterdam Airport Schiphol (De Haan, 2010, 2011, 2013c) revealed that wind observations have at least similar quality as wind observations from aircraft equipped with AMDAR. However, the temperature observations derived from Mode-S EHS have a lower quality and should be used accordingly to be beneficial for NWP.

1.2 Existing and new aircraft surveillance technologies

Mode-S and ADS-B (Automatic Dependent Surveillance Broadcast) are new technologies that have been developed to eventually replace the Primary Surveillance Radars (PSR) which tracks all flying objects in the airspace.

The main purpose of an ATC system is to provide an appropriate surveillance picture. With the new techniques, it may employ a combination of sensors and techniques (EUROCONTROL, 2013) which can be summarized as:

- *Non-Cooperative Independent Surveillance* which is based on ground sensors able to detect and determine the 2D position of all aircraft, whether or not they are equipped with a transponder. Non-cooperative surveillance is typically provided by Primary Surveillance.
- *Cooperative Independent Surveillance* which is based upon targets equipped with transponders capable of responding to ground interrogation. The 2D position of aircraft is determined by the ground sensors while the altitude and identity of the aircraft are provided by the aircraft. Cooperative independent surveillance is nowadays typically provided by Secondary Surveillance Radar / Mode-S.
- *Cooperative Dependent Surveillance* which is based on aircraft providing their position, altitude, identity and other parameters by means of a data link; it is therefore fully dependent on the aircraft systems (ADS-B).

Mode-S

Mode-S is a Secondary Surveillance Radar (SSR) technique that permits selective interrogation of aircraft by means of a unique 24-bit aircraft address; the “S” in Mode-S refers to the selective interrogation mode. The assignment of a unique ICAO 24-bit address is the fundamental concept of Mode-S Elementary Surveillance (ELS). In this way, risk of confusion or mis-identification due to overlapping signals is avoided. Mode-S employs ground-based interrogators and airborne transponders and operates in the same radio frequencies (1030/1090 MHz) as conventional SSR systems.

Mode-S Enhanced Surveillance (EHS) consists of Mode-S ELS supplemented by the extraction of downlink aircraft parameters (DAPs) for use in the ground Air Traffic Management (ATM) systems (EUROCONTROL, 2012).

ADS-B

ADS-B (Automatic Dependent Surveillance-Broadcast) is an ATM surveillance system that will be replacing radar as the primary surveillance method for controlling aircraft worldwide. ADS-B enhances safety by making an aircraft visible, real time, and providing position and velocity data, to ATC and to other appropriately equipped ADS-B aircraft, transmitted every second. It also provides the data infrastructure for inexpensive flight tracking, planning and dispatch. The data link that is used for transmitting ADS-B data is the 1090 MHz Mode-S data link.

Mode-S ADS-B and Mode-S EHS messages

Mode-S ADS-B technology has two types of squitter, a short, 56 bit, acquisition squitter which can contain Downlink Formats (DF) 0, 4, 5 and 11 (DF0/4/5/11) and the 112 bit extended squitter (ES) which can contain DF17. The definition of squitter is a reply format transmission without being interrogated. Hence these DF messages are sent by Mode-S transponders automatically at a nominal rate of 1 Hz. Commercial ADS-B receivers on the ground are able to receive the radio pulses transmitted by Mode-S transponders and decode them to readable, but still compressed, downlink format data messages that can be further interpreted. The description of the installation of such a receiver and its software is described in Chapter 2. The ADS-B messages (acquisition and extended squitter) form the core of Mode-S ELS.

Additionally, a Mode-S EHS equipped radar can interrogate an aircraft. The messages to which an aircraft has to respond are down linked in DF20 and DF21. The obligatory EHS messages are BDS4.0, BDS5.0 and BDS6.0, where BDS stands for Binary Data Store.

Note that also other BDS registers can be interrogated by ATC, for example BDS 4.4 which contains wind and temperature information (Strajnar, 2013). Currently this register is not being interrogated by ATC The Netherlands. Throughout this document, where we refer to Mode-S EHS, the BDS registers 4.0, 5.0 and 6.0 are meant.

Table 1: Presently used acquisition squitter, extended squitter and Mode-S EHS downlink formats.

Message type	Downlink Format	Content
ADS-B (56 bits)	DF0	Short air to air ACAS (BDS 0.E)
	DF4	Surveillance altitude
	DF5	Surveillance identity
	DF11	Mode-S only all call reply
ADS-B ES (112 bits)	DF17	Airborne position (BDS 0.5) Surface position (BDS 0.6) Extended squitter status (BDS 0.7) Aircraft type and ID (BDS 0.8) Airborne velocity (BDS 0.9)
Mode-S EHS	DF20	altitude reply: (BDS 4.0/5.0/6.0)
Mode-S EHS	DF21	identity reply: (BDS 4.0/5.0/6.0)

Mode-S EHS functionality

Aircraft compliant with Mode S EHS provide basic ADS-B functionality features (see above) plus the following eight downlink aircraft parameters (DAPs)

Table 2: Mode-S EHS downlink aircraft parameters.

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)

Note that in order to derive wind and temperature data for application in meteorology, one needs to be able to receive and decode both DF17 (ADS-B ES) and DF20/21 (interrogated) Mode-S EHS frames in a proper way. As only the interrogating radar knows which type of downlink information was requested in the DF20/21 messages, it is not trivial to retrieve the navigational information correctly from these messages. This requires some intelligence in the decoding algorithm, which will be described in Chapter 3.

1.3 Mode-S EHS in designated airspace in Europe

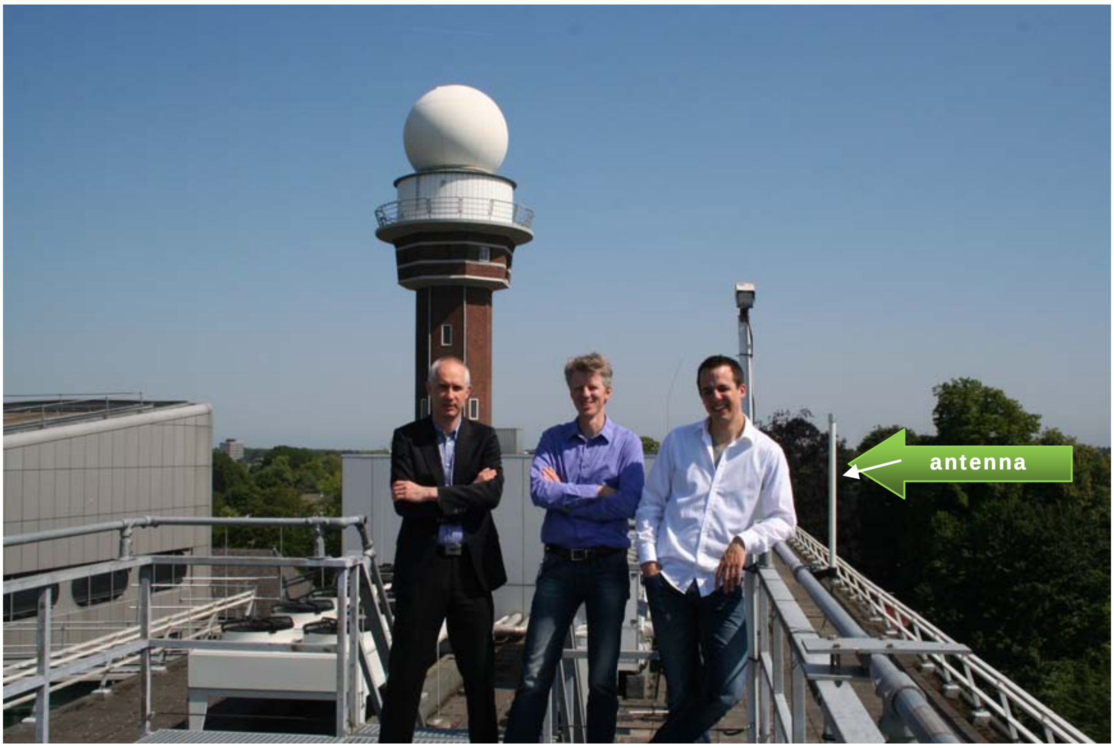
The requirements of Mode-S Enhanced Surveillance (EHS), which includes the full functionality of ELS, apply to Instrument Flight Regulations (IFR) flights as General Aviation Traffic (GAT) by fixed wing aircraft having a maximum take-off mass greater than 5700 kg or a maximum cruising true airspeed in excess of 250 kt in the designated airspace notified by the Civil Aviation Authorities of Germany, United Kingdom, France, Belgium and The Netherlands (AIC-A 05/08). As of March 2007, all aircraft should be Mode-S ELS compliant. If not, the aircraft will be excluded from the airspace (AIC-B 02/05). The Mode-S EHS radar at Schiphol Airport interrogates all aircraft every 4,2 seconds.

1.4 Goals of this study

The use of dedicated Mode-S EHS receivers for meteorological purposes on the ground might be useful in areas which are covered by ATC radars but where users of observational information are not able to receive the Mode-S EHS data from local ATC organizations. In order to analyze what kind of information is exactly available and how it compares to the Mode-S EHS information received from ATC The Netherlands, KNMI purchased a 1090MHz ADS-B receiver system and started an assessment of this receiver in December 2011.

The main objectives of this study are:

- To purchase and install a commercial off-the-shelf Mode-S/ADS-B receiver at the KNMI premises in De Bilt, The Netherlands.
- To build up a data set of at least 1 year of (raw) Mode-S EHS data.
- To establish a proof of concept for the retrieval of wind and temperature observations from Mode-S ADSB EHS data recorded by this receiver.
- To determine the pros and cons of the experimental Mode-S ADSB EHS data stream compared to the current operational Mode-S EHS data stream from the terminal area radar received from ATC The Netherlands (LVNL).



The ADS-B team of KNMI on top of the B building of the KNMI premises at De Bilt. On the right the omnidirectional ADS-B antenna, in the background the weather radar dome. From right to left Marijn de Haij, researcher observation technology, Siebren de Haan, senior scientist, and Jan Sondij, Senior Advisor Aviation Meteorology.

2 Data acquisition chain

2.1 Hardware

A variety of commercial off-the-shelf Mode-S receivers is currently available on the market. Dependent on their intended use, ranging from aircraft spotters to airports and professional ATC organizations, these receivers have different specifications and hence also different price tags. In this project it was decided to purchase the low-cost Mode-S Beast[1] (approx. €275). This receiver fulfilled our general data requirements and showed promising results with respect to noise suppression and decoding capabilities. An important consideration to use a low-cost receiver was that it was considered more important in this stage to make a good proof of concept rather than building an operational production chain with maximum performance. It is important to note that there is an active community still improving Beast decoding algorithms and releasing new firmware versions. The Mode-S Beast can be used with various UHF antennas. We used the WiMo GP1090 antenna, which costs around €80. Because of the relatively short cable (6m) that was used in our setup, no pre-amplifier was needed to achieve a reasonable range and the installation therefore only consisted of the Beast receiver, the antenna and a regular desktop PC. An overview of the data acquisition and storage chain described in this chapter is shown in Figure 1.

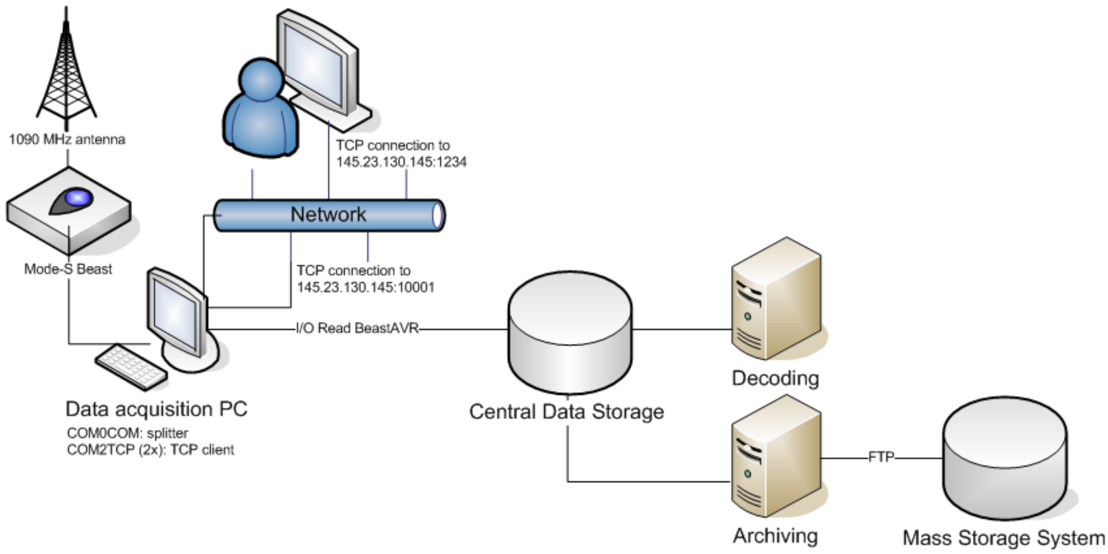


Figure 1 : Schematic overview of the Mode-S Beast data acquisition chain.

The Beast receiver

The Mode-S Beast is a high performance 1090 MHz Mode-S and Mode-A/C receiver and decoder. The receiver was built on the existing miniADS-B concept, but with improved electronics to improve the noise figure and sensitivity. The internal FPGA-based processor regenerates the received signal and detects the preamble pulses. Subsequently, three frame decoders take care of the actual decoding of the received pulses, or discard them if they are too noisy. The serial frame builder component then reformats the received data into hexdump, adds the special characters that identify the frame format, and finally transmits it as RS232 with start and stopbits towards the interface device. In most cases this will be a FT232R serial to USB converter. Optionally a Lantronix Xport (Ethernet) or a BTM-222 (Bluetooth) device can become added on the bottom side of the Mode-S Beast. In USB mode the data rate of the Beast is 1MBit/s.

[1] See www.modesbeast.com for more information.

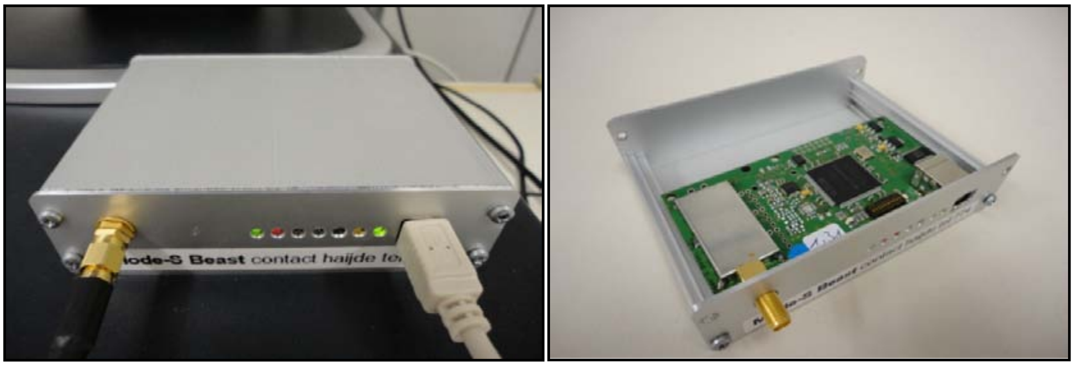


Figure 2 :The Mode-S Beast "Series 2" in operation (left) and the PCB inside the housing (right).

The USB port fitted at the front side of the Beast housing (see Figure 2) is used for data communications with a PC, but also for 5V DC power supply. Hence no external power source is needed. Note that optionally up to 3 external miniADS-B receivers with separate antennas can be connected. This for example allows you to connect an omnidirectional antenna to the internal receiver and use in parallel a high gain antenna pointed towards an area of special interest. The Mode-S Beast is normally delivered as a pre-equipped PCB for completion through the user. It comes with a small aluminium housing (dimensions 110x85x30 mm) and is equipped with an SMA female socket for the antenna connection.

The Beast used at KNMI is a so-called "Series 2" receiver, sold from September 2011 onwards. This version is prepared for firmware updates via USB. The Mode-S Beast supports two open and non encrypted output formats, first the so called "AVR-Format", an open format just like hexdumping of the frame contents. Secondly there is a binary data format, in which also signal level information is provided. A decoder for Mode-S downlink frames (DF) is active in the processor of the Mode-S Beast. It is able to decode DF types DF0, DF4, DF5, DF11, DF17, DF18, DF20 and DF21.

A heart beat is active using LEDs fitted in the front cover of the Mode-S Beast. A certain combination of LEDs (dependent on the firmware version) flashes once each second when no antenna is connected. This is to inform that the receiver is active and working. In normal operation, the LEDs indicate (from left to right) the reception of DF0/4/5 (green), DF11 (red), DF17/18 (red), DF20/21 (green) messages, output overload (blue), RS232 transfer (orange) and power on (green). Inside the Beast a total of 10 DIP switches on the PCB allow the user to configure various optional functions, like e.g. switching between the AVR and binary data formats, an option to decode DF11 and DF17 (ADS-B) frames only, or suppression of downlink formats DF0, DF4 and DF5. The Beast installed at KNMI was configured applying the default settings which are listed on the website. Note that starting from firmware v1.32, all functions of the DIP switches (except the baudrate setting) can also be controlled over the serial interface.

Antenna

The WiMo GP1090 is an omnidirectional ADS-B antenna, which has 5 dB gain at the 1090 MHz frequency band. It is 53 cm long and weighs approximately 700 g. The mounting clamp can be fitted on a mast with diameters 30-50 mm. The antenna has an N-type female connector, and can be easily connected to the Mode-S Beast receiver by using a coaxial cable (type N/SMA).

2.2 Software

The AVR (ASCII) output from the Mode-S Beast is logged on a regular desktop PC running Windows XP. First of all, the USB port connected to the receiver was configured as virtual COM port using the FTDI FT232R driver. In addition, the freeware tools COM0COM and COM2TCP are deployed to split the data stream and feed the Beast data twice via TCP/IP on the local network, making the data available for any system within the KNMI LAN. An important advantage is that the data acquisition does not need to be interrupted in case of testing, or realtime continuous feeding to dedicated software (e.g. Planeplotter, Google Earth visualization) installed elsewhere.

A Labview acquisition tool "Read BeastAVR" (Figure 3) was developed and runs locally on the Beast PC to perform the data acquisition described below:

- Initialization of the communications; TCP/IP read on 127.0.0.1 port 10001
- Initialization of the output file, with file name convention yyyymmddhh.txt
- The acquisition tool reads the Beast output in a buffer of 2000 bytes.
- After each semicolon character (;), the actual PC time stamp is inserted.
- When the buffer is full, the data is written into the output file located at the Central Data Storage (CDO).

Figure 3 : Screenshot of the "Read BeastAVR" data acquisition tool.

Below an example of the data records in the hourly output files is shown, together with a description of the individual elements. Note that the resolution of the time stamp is 1 second, which is sufficient for our purposes. On average, the frame rate is around 1600-1800 messages per second (v1.41) during peak hours. It should be noted that in fact only a small fraction of these messages contains the aircraft navigational data, and is therefore relevant for deriving wind and temperature information. This will be discussed in more detail in Section 3.2.

```
20120528 12:37:53 *A8000800E6DA2123FDD7BE5052FE;
20120528 12:37:53 *0000000000000B;
20120528 12:37:53 *A00002130000000000000005F8BAE;
20120528 12:37:53 *5D400CD2A23C21;
20120528 12:37:53 *A800098B200464B1C72820DA9D20;
|        |         |
Date     |         |
         UTC time  |
                   ADS-B frame
```

Figure 4: 56-/112-bit ADS-B frames

During hours with busy air traffic an hourly data file with Beast DF messages contains around 6 million records. This corresponds to a file size of roughly 250 MB. After storing the AVR format output data in hourly files, the Beast data is compressed and archived once a day via FTP to the central Mass Storage System (MOS) of KNMI. This offers the opportunity to reprocess the data with improved versions of the decodeADSB processing software (see Section 3).

2.3 Installation

The Mode-S Beast was installed on top of the B building of the KNMI premises in De Bilt (N 52.10 E 5.18) on 2 December 2011. The Beast receiver and PC for data acquisition were installed in the computer room on the roof. Special attention was paid to the location of the antenna. As it cannot see through obstacles, and line of sight rules apply for wave propagation, it is required to install the antenna it as high as possible and use a low loss feeder coaxial cable with the proper connectors. The GP1090 antenna was mounted at 24 m above MSL on the platform directly above the computer room. This location was selected since it has a nearly free horizon. The only significant obstruction is caused by the radar tower to the North with an elevation of 16° extending maximally 8° in azimuth. In our case the antenna was connected to the Mode-S Beast by a 6 m long H-155 cable (€25) with N/SMA connectors. Two photographs of the set up in De Bilt are shown in Figure 5.

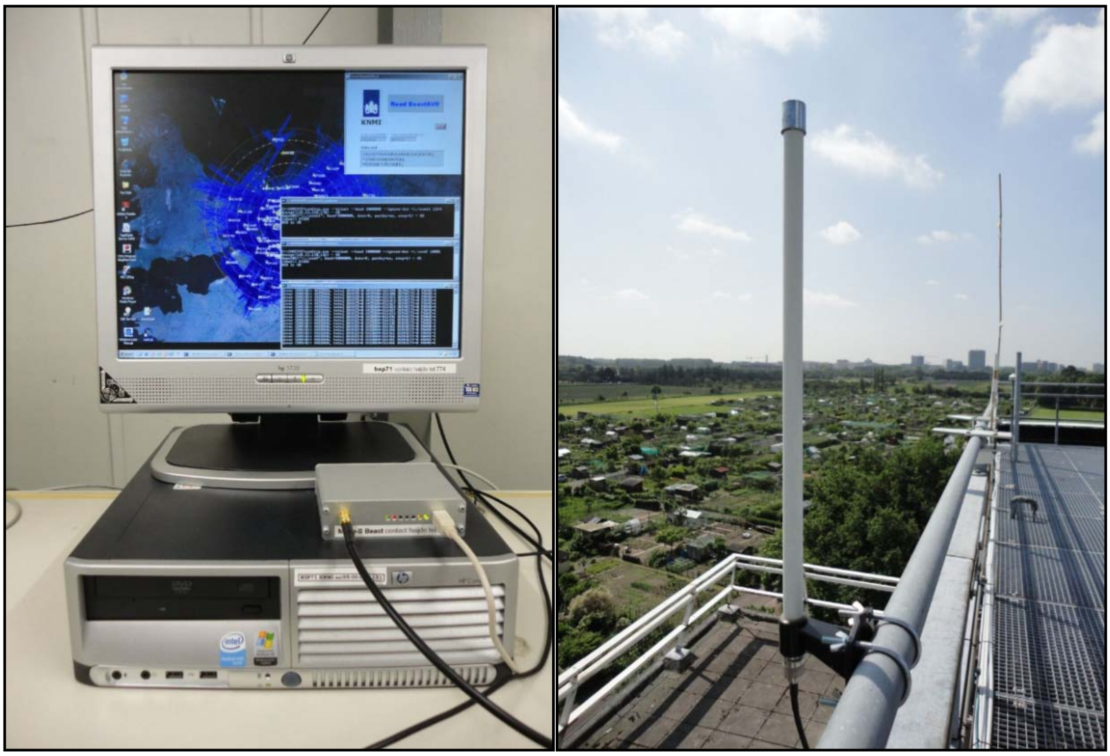


Figure 5 : Data acquisition PC and Mode-S Beast (left) and GP1090 antenna on the roof of the KNMI premises (right).

New firmware versions for the Beast became available during the evaluation period and were installed via the USB interface. In four successive upgrades the firmware version changed from v1.31 (December 2011) to v1.41 (May 2012). Major changes in the data output rate were introduced during the upgrade to v1.40 in March. This resulted in a fairly lower amount of Mode-S frames, because the suppression of corrupt frames was significantly improved. However, luckily the fraction of relevant and correct frames for our purpose was not touched. A description of the changes implemented in all firmware versions can be found on the website (www.modesbeast.com).

2.4 Monitoring the system

A simple monitoring system has been set up to check the performance of the Mode-S ADS-B receiver. Figure 6 shows an example of the received number of frames per second for three different downlink formats for the month December 2012. Clearly visible is the reduced air traffic around the Christmas days.

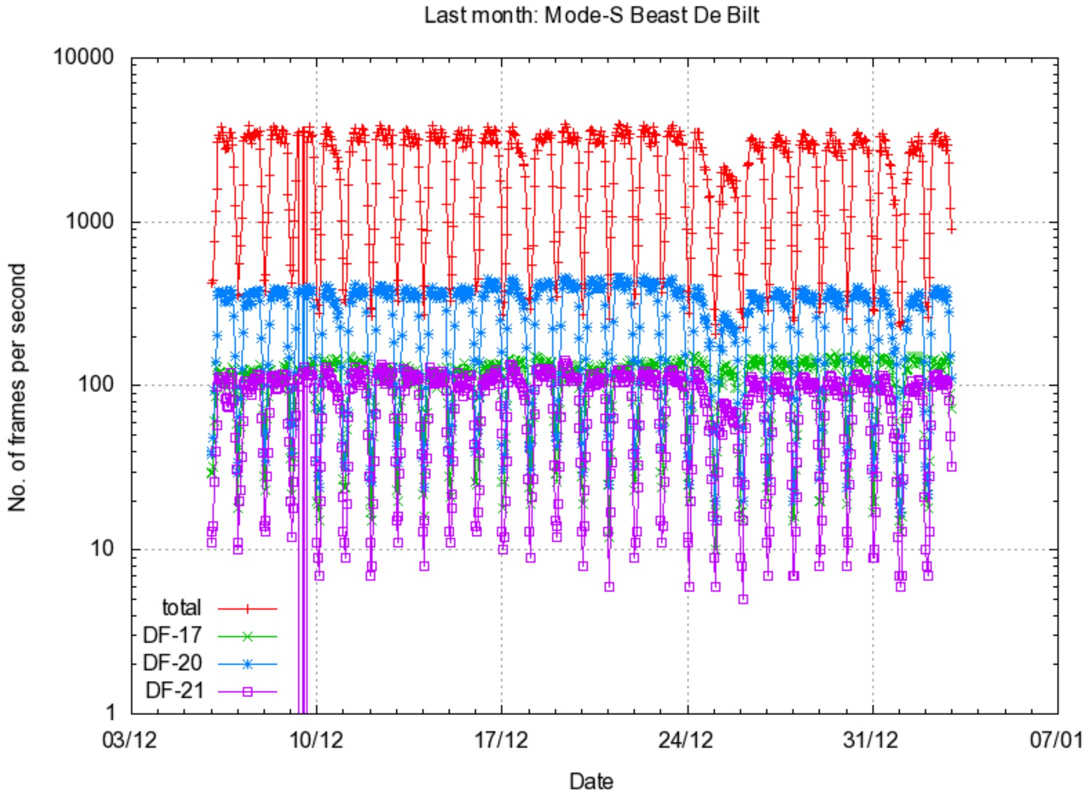


Figure 6 : Number of frames per second or DF17, DF20 and DF21 messages over the month December 2012.

3 Decoding of Mode-S ADS-B EHS data

The program decodeASDB decodes the raw output of The Beast and converts it into readable output. The type of output is managed by option given on the command line. The program decodeASDB is written in c and is compiled using gcc and the math-library. The decoding software is developed based on the binary ADS-B data description given in ICAO Annex 10-III edition 1.

3.1 Input description

The input of the decodeASDB program is the output of The Beast and contains one message for each line consisting of a time stamp and the message itself, separated by an asterisk (*). An example was given in Figure 4, and is repeated here for clarity.

```
20120524 14:20:04 *A00001B8000000000000000F42DDB
20120524 14:20:04 *8D400CD258C9138294F2C8DBDCBC
20120524 14:20:04 *20000815772311
20120524 14:20:04 *5D4785E2054129
20120524 14:20:04 *00000000000000
```

The first two bits of the message denote the downlink format. The other bits contain the information as defined by the downlink format. The 24-bit ICAO address is found in the third, fourth and fifth byte. The position, height and the tail-number of the aircraft can be found in DF17 and in DF20/21 to BDS6.0 as a parity check. The BDS4.0, BDS5.0 and BDS6.0 messages, which contain heading, airspeed, etc. information, are contained in downlink format DF20/21. The table below shows all downlink formats decoded by the Beast receiver. The average frequency of occurrence of the messages necessary for wind and temperature (DF17 and DF20/21) is around 10% (period 1-29 May). In principle a masking filter on all other downlink format could be switched on without any problems in order to reduce the overall data load and the run time of the decodeADSB software. Note that it is also possible to turn off the reception of DF0, DF4 and DF5 by switching a dipswitch inside the Beast receiver.

Table 3 : Received messages

DF message	Start character	Description	Processed?
DF0	*00	Short Air to Air ACAS	No
DF4	*20	Surveillance (Altitude)	No
DF5	*28	Surveillance (Identity)	No
DF11	*5D	Mode S Only All Call	No
DF17	*8D	1090 Extended Squitter	Yes
DF20	*A0	Comm. B Identity	Yes
DF21	*A8	Comm. B Altitude	Yes

3.2 Parameters decoded

The ADS-B acquisition, extended squitter and Mode- EHS information is decoded. The parameters retrieved by the decoding software are listed in Table 4.

Table 4 : Decoded parameters

Variable	**Description**	**Source**
Time	Time in seconds	external time-stamp
date	Date	external time-stamp
acid	Aircraft ID	ADS-B header
tail	Tail number	DF5
Lat	Latitude in degrees	DF17 , type 9-18
lon	Longitude in degrees	DF17 , type 9-18

Hmetric	Metric height	DF17 , type 9-18
Hfoot	Height in foot	DF17 , type 9-18
Halt	FCU/FMS altitude	DF20/21, BDS4.0
Hbar	Barometric altitude	DF20/21, BDS4.0
gsp	Ground speed	DF20/21, BDS5.0
tan	Track angle	DF20/21, BDS5.0
tas	True airspeed	DF20/21, BDS5.0
rol	Roll angle	DF20/21, BDS5.0
bar	Barring	DF20/21, BDS6.0
ias	Indicated airspeed	DF20/21, BDS6.0
ivv	Inertial vertical velocity	DF20/21, BDS6.0
mhd	Magnetic heading	DF20/21, BDS6.0
mac	Mach number	DF20/21, BDS6.0

3.3 Algorithm

The data derived from DF20/21 frames are essential to derive meteorological wind and temperature information. However, these messages will only be broadcast dependent on groundbased interrogation and as such can only be received in areas of the world where those message types are being requested by the ATC ground radar. The messages themselves do not have any unique identifiers to define their content; only the interrogating radar site knows which information was requested. Therefore it was necessary to equip the decodeADSB software with some checks in order to determine what type of BDS register is included in the DF message.

There are essential bits in a message for the different BDS registers. These can be used as a first filter to choose between BDS 4.0, 5.0 and 6.0. The table below gives the necessary bits.

BDS4.0	bits 1,14,27
BDS5.0	bits 1,12,24,35,46
BDS6.0	bits 1,13,24,35,46

The DF20/21 messages do not contain specific BDS information when these bits are not set. These essential bits do not uniquely determine which BDS information is contained in the message. Therefore, the decoded variables are checked for validity and consistency using the following criteria:

0.95< tas/ias <1.5	[-]
tas – ias < 5	[kt]
-30 < mhd - tan < 30	[deg]
-50 < gsp - ias < 50	[deg]
-100 < gsp - tas< 100	[kt]
0 < gsp < 500	[kt]
0 < tas < 500	[kt]
0 < ias < 500	[kt]
rol < 30	[deg]
0 < mac < 1	[-]
bar < 5000	[ft/min]
ivv < 5000	[ft/min]
$-100^{o}C < T_{air}=CONST(tas/mac)^{2} < 50^{o}C$	
49 < lat < 54	[deg]
0.0 < lon < 10	[deg]

Note that some variables, such as true airspeed (tas) and ground speed (gsp), are included in different. A proper validity check can only be performed when the times of reported variables are close. Currently, the maximum time difference between consecutive data messages used in one observation is set to 1 second.

The algorithm to derive a valid Mode-S EHS observation for meteorology is applied when all three BDS-messages are detected for a specific aircraft identifier. The validity and consistency of a BDS-message is defined previously. The position, height and aircraft are decoded from DF17. For a message with the DF20/21-format, the aircraft identifier is determined using a parity check. A new Mode-S EHS meteorological observation is derived only when all three BDS-messages have been updated.

3.4 Output description and command line options

The following command line options are implemented:

```
-h     write help
-d     print debug information
-a     print all positions  (date time acid lat lon  "P01")
-D     print DF20/21 information (date time acid lat lon BDS-flags
       "DF20/21"
-m     print meta information (for debugging)
-P     print position and Mode-S information
       (date time tail acid  lat lon Halt gsp tan tas ias mhd mac
       "WIND")
```

An example of the output is shown below (options -aDP).

```
20120524 140011 AA92F9 51.021580 4.532928 P01
20120524 140011 AA92F9 51.021580 4.532928 BDS100  DF20/21
20120524 140011 3C5CB2 51.415695 7.562973 P01
20120524 140011 3C5CB2 51.415695 7.562973 BDS100  DF20/21
20120524 140011 4CA911 51.501534 5.432053 P01
20120524 140011 4CA911 51.501534 5.432053 BDS010  DF20/21
20120524 140011 3C6746 50.530964 5.313523 P01
20120524 140011 40067F 52.568207 4.070129 BDS101  DF20/21
20120524 140011 C061C8 51.149094 5.667387 BDS111  DF20/21
20120524 140011 TSC181  C061C8 51.149094 5.667387 320.00 462\
274.746 460 287 277.0312 0.7880  WIND
```

4 Results

In this chapter we present the results of a collection of one year of ADS-B EHS data recorded by the local ADS-B receiver in De Bilt. Statistics of the intercomparisons between wind and temperature observations retrieved from Mode-S EHS received from ATC, ADS-B EHS and AMDAR are presented.

4.1 Introduction

All aircraft in the Dutch airspace are interrogated by the Mode-S EHS radar. In essence, the aircraft's reply to this interrogation can be received by the 1090 MHz Mode-S receiver described previously. Some aircraft are AMDAR equipped and meteorological information from these aircraft is received through the ARINC system independently of Mode-S EHS. In the figure below the horizontal and vertical coverage of these three data sources is shown for the 3rd of July 2012 at 12UTC.

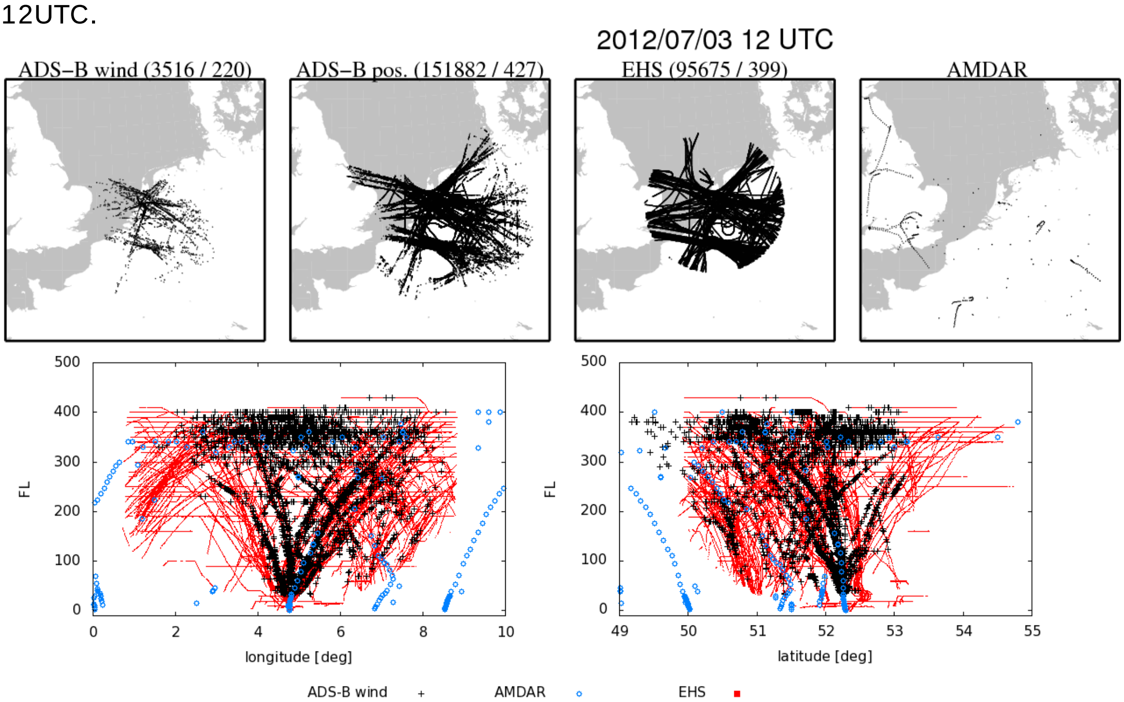


Figure 7: Example of the horizontal (upper panels) and vertical coverage (bottom panels) of meteorological upper air observations retrieved from Mode-S EHS via ATC The Netherlands (labelled EHS), Mode-S EHS from the local receiver (labelled ADS-B wind) and AMDAR.

4.2 Number of observations and coverage

Figure 8 shows the number of wind observations per day for the period considered in this analysis, 5 January 2012 to 5 January 2013. The number of ADS-B EHS observations is about 8% of the Mode-S EHS observations, that are received directly from ATC, in the beginning of the measurement period. In early April there was an increase of the number of ADS-B EHS observations, likely caused by an upgrade of the receiver software. At the end of the period the percentage of ADS-B EHS wind observations has increased to nearly 9%. Note that the acquisition of Mode-S EHS data and ADS-B EHS data both suffer from system disruptions. Mode-S EHS data was not available during some periods in August 2012 and ADS-B EHS data was not available for a small period in October 2012. Note that both systems are not operational and are maintained during office hours. The events most relevant for the functioning of the local receiver are listed in the logbook in Appendix B.

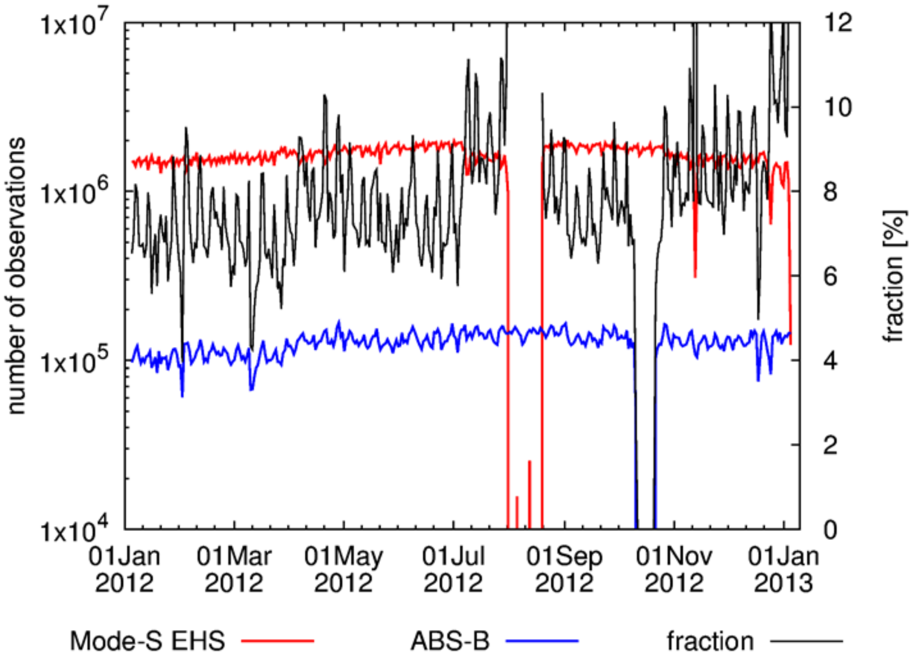


Figure 8: Number of ADS-B EHS and Mode-S EHS wind observations per day.

Figure 9 shows the average number of wind and temperature observations per hour retrieved by the ADS-B receiver and the Mode-S EHS data from ATC. Clearly, when there is a lot of air traffic, mainly during daytime, the number of observations retrieved by both systems is the highest. For Mode-S EHS received from ATC the average number of observations per hour is in the order of 100,000, whereas the Beast receiver in combination with our decoding algorithm only delivers around 7,000 observations per hour during those busy periods. An important thing to note is that the number of ADS-B EHS observations as a fraction of the Mode-S EHS data from ATC increases during nighttime. The receiver then has to decode less overlapping messages which results in a relatively higher number of decoded downlink data.

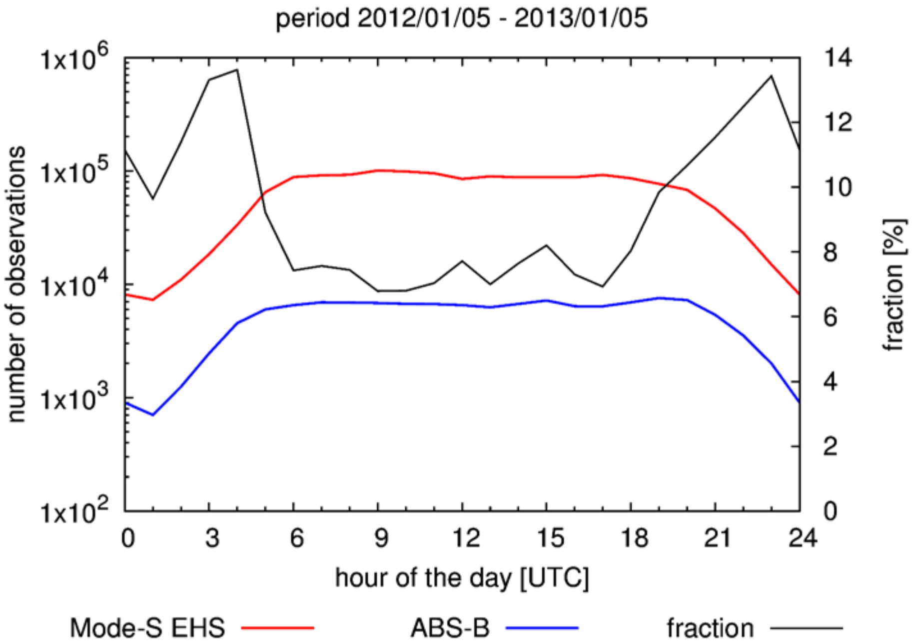


Figure 9 : Number of ADS-B EHS and Mode-S EHS observations per hour.

Figure 10 shows in blue the coverage of LVNL Mode-S EHS wind and temperature observations retrieved between 1 and 9 April 2012, and in red the ADS-B EHS coverage for the same period. The lines show the 99% (large areas) and 50% (small closed areas) coverage of wind and temperature observations. Clearly visible are the areas from where the Beast antenna receives significantly less data compared to ATC reception, mainly in the northern and western part of the airspace in view by the Beast antenna. In contrast to this, the ADS-B antenna receives more observations from aircraft which fly more south. The difference in coverage is related to antenna sensitivity, obscuring objects and saturation of the signals. The latter occurs when too many aircraft send out ADS-B messages simultaneously and the local receiver is not able to distinguish the messages separately. Good agreement of both systems is visible for areas where 50% of the data is observed, like the area around Schiphol Airport where most aircraft are landing and where the TAR-1 radar used by LVNL is located.

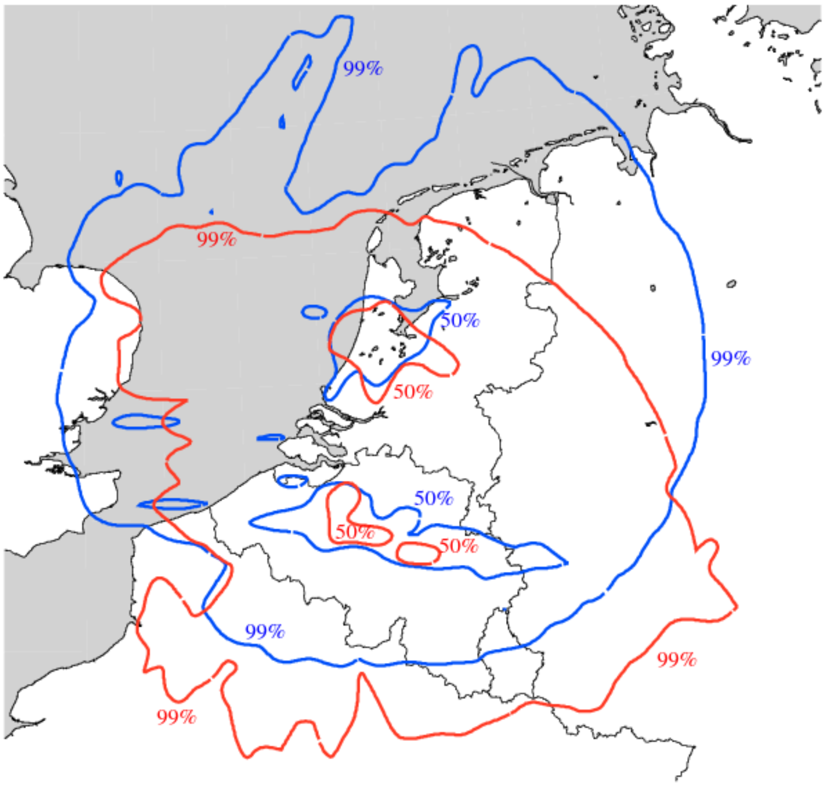


Figure 10 : Relative horizontal coverage of the total number of Mode-S EHS wind and temperature observations retrieved from ATC (blue) and ADS-B EHS (red) data during nine days (1-9 April 2012).

The vertical coverage of Mode-S EHS and ADS-B EHS wind and temperature observations along the longitude is shown in Figure 11a; Figure 11b shows the vertical coverage along the latitude.

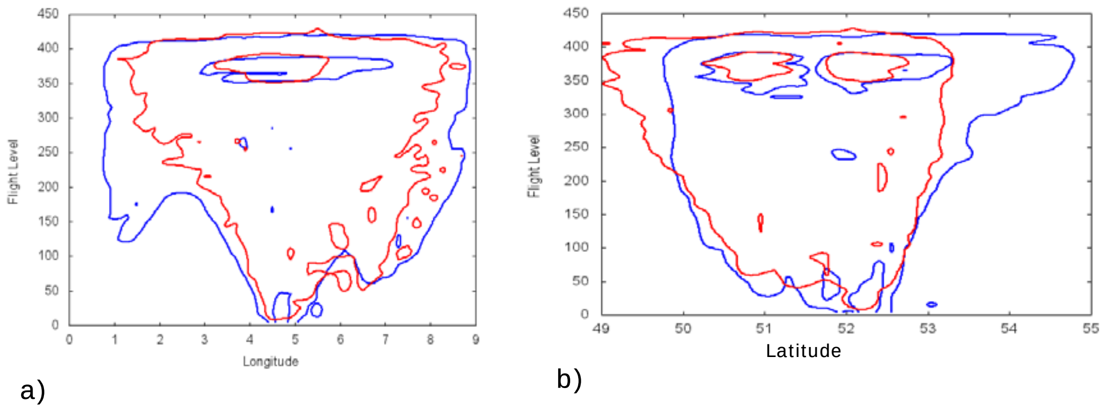


Figure 11: a) Vertical coverage along the longitude of Mode-S EHS from ATC (blue) and ADS-B EHS from KNMI receiver (red); b) Vertical coverage along the latitude.

Clearly visible is the better coverage of the wind and temperature observations from the KNMI ADS-B receiver toward the south at flight levels 250 and higher (Fig 11b) and the better coverage of ATC Mode-S EHS of aircraft landing in the United Kingdom in the westward direction (Fig. 11a).

The distribution of the time difference between subsequent observations from the same aircraft is shown in Figure 12. The ATC Mode-S EHS distributions show that 98% of the observations have a time difference of 4,2 seconds. The observations retrieved from the Beast receiver in De Bilt shows a completely different signal: 20% is within 4s, 10 % within 5 to 8s. Furthermore, since all three BDS registers need to be filled before a new observation is generated, a delay in the reception of one register causes an evident delay in the derived wind observation. Note that the saw-tooth signature is directly related to the application of this criterion. When two registers are recorded, the next may arrive within 4 seconds, since the aircraft is interrogated every 4,2 seconds.

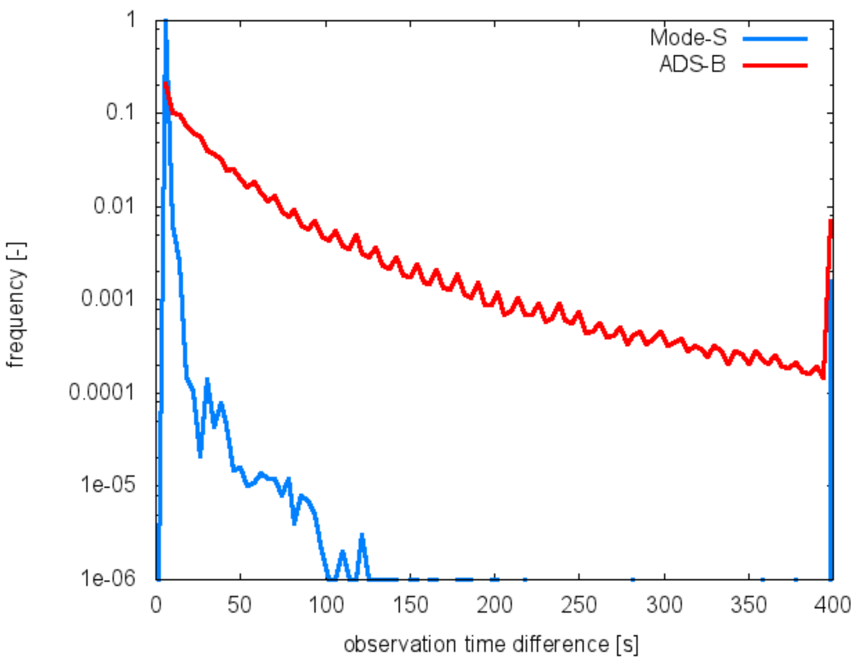


Figure 12: Frequency distribution of the time difference of subsequent wind observations from Mode-S EHS (blue) and ADS-B EHS (red).

4.3 ADS-B and EHS flight information content

The information of the ADS-B messages as retrieved by The Beast and decoded using decodeADSB is presented in this section and compared to Mode-S EHS parameters. The statistics of the retrieved navigational parameters from the aircraft are presented in Table 5. Only Mode-S EHS and ADS-B EHS observations generated at exactly the same time are considered here. Gross errors in position are excluded from the comparison.

Table 5: Statistics of the difference between parameters from Mode-S EHS and ADS-B EHS.

Parameter	unit	Number	mean difference	standard deviation
Mach Number	[-]	2455339	0.000012	0.002750
True Airspeed	[kt]	2455339	-0.019728	2.146631
Indicated Airspeed	[kt]	2455339	0.014572	0.983670
Magnetic Heading	[deg]	2455339	-0.015847	0.676729
Ground Speed	[kt]	2455339	-0.022967	1.409117
Track Angle	[deg]	2455339	-0.014581	0.811473

The comparison of the Mach-number is shown in Figure 13. The red line shows the distribution of scatter within two times the standard deviation; the blue line shows the single standard deviation level. As the statistics show the match between ADS-B EHS and Mode-S EHS is good. There are a few outliers, but the number is small.

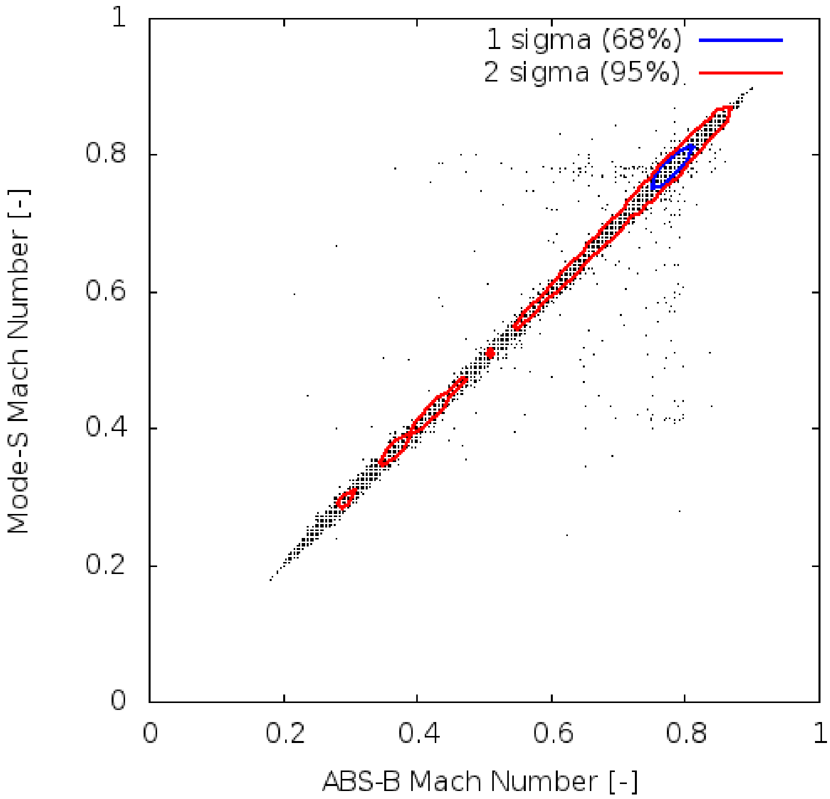


Figure 13 : Comparison of Mach-number observations from ADS-B EHS and Mode-S EHS.

The comparison of the true airspeed is shown in Figure 14. The comparison shows a similar behavior. Only now the outliers show a clear signal. This might be due to problems with selecting the right BDS; that is the BDS reports cannot be uniquely identified as BDS4.0, BDS5.0 or BDS6.0. The comparison of the indicated airspeed is shown in Figure 15. The agreement is very good and shows no extreme outliers. Also the magnetic heading shows a very close relation with the reported Mode-S EHS magnetic heading, see Figure 16. The comparison of the ground speed is shown in Figure 17. This parameter again shows a set of outliers. The comparison of the track angle is shown in Figure 18. The track angle comparison is also rather good with the exception of ADS-B track angles of around 210 degrees. The number of outliers for the current dataset is around 1000, and these outliers can easily be removed from the dataset by checking the subsequent positions and determine in this way the track angle of the aircraft. When these outliers are removed from the dataset the outliers in true airspeed, ground speed and indicated airspeed will disappear. Next to quality control based on track angle, the position information can be exploited to check the ground speed.

In general, it seems that the quality of all parameters shows a similar behaviour and is of an acceptable level, except ground speed and track angle which suffer from inaccuracies. Since these parameters are essential for an accurate derivation of the wind vector, these inaccuracies will influence the quality of the wind observations.

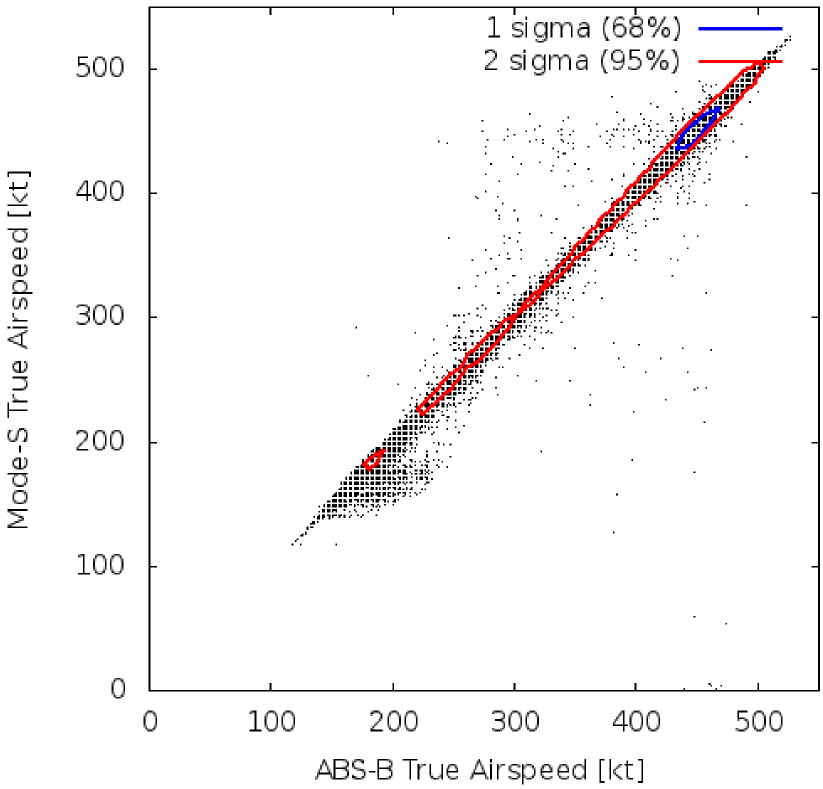


Figure 14 :Comparison of true airspeed observations from ADS-B EHS and Mode-S EHS.

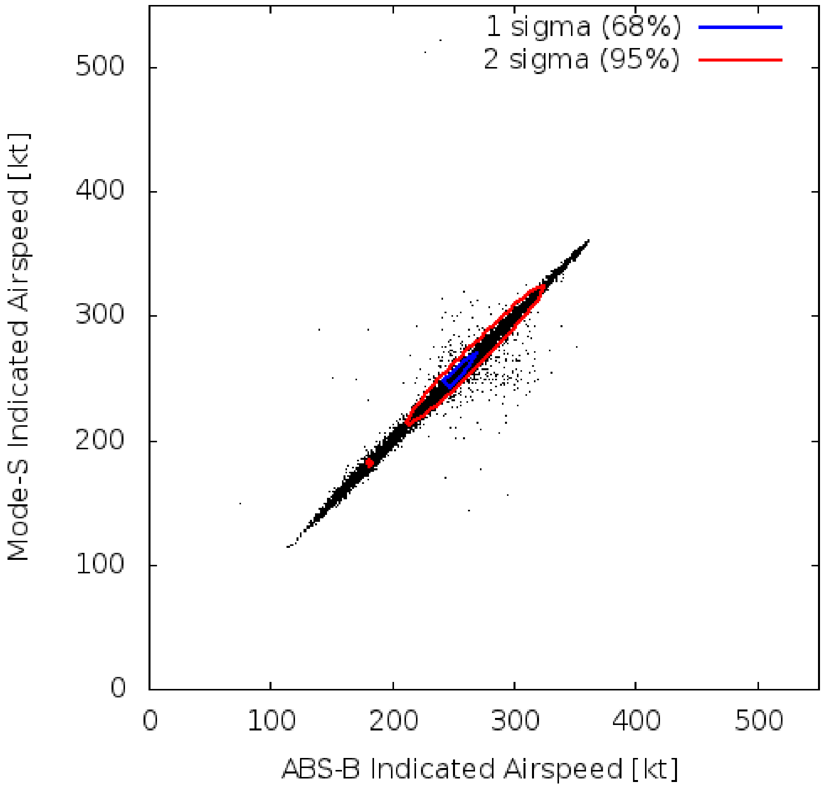


Figure 15 : Comparison of indicated airspeed observations from ADS-B EHS and Mode-S EHS.

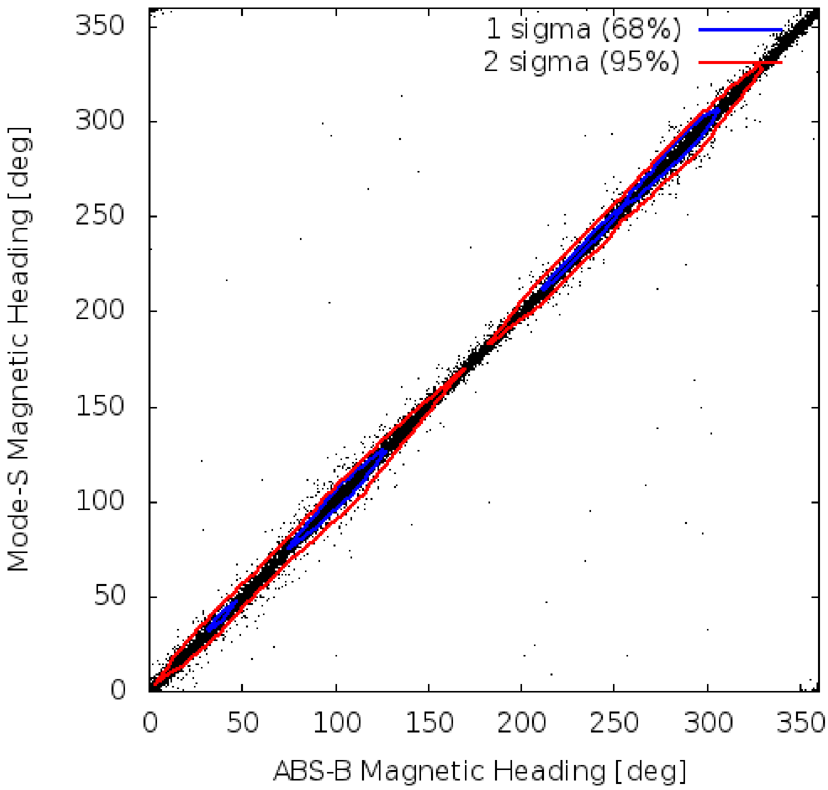


Figure 16 : Comparison of magnetic heading observations from ADS-B EHS and Mode-S EHS.

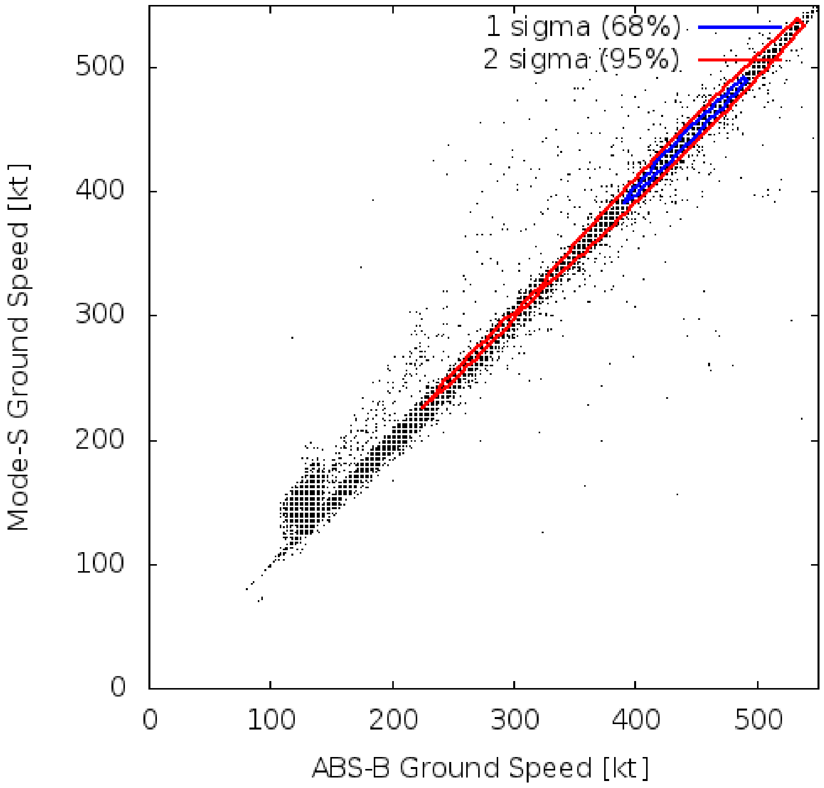


Figure 17 : Comparison of ground speed observations from ADS-B EHS and Mode-S EHS.

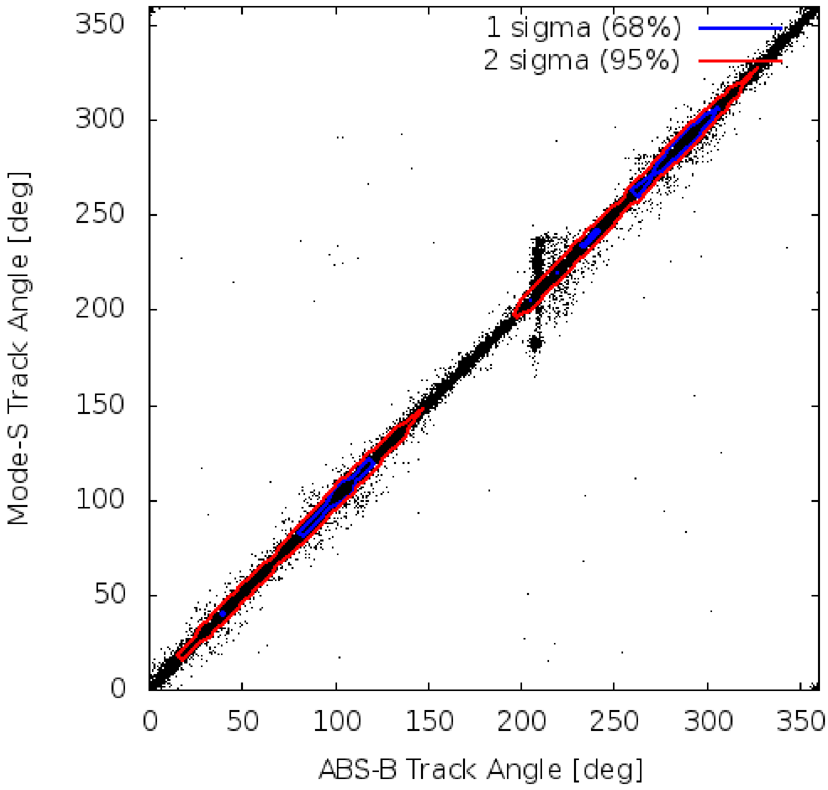


Figure 18 : Comparison of track angle observations from ADS-B EHS and Mode-S EHS.

4.4 ADS-B and EHS meteorological information content

This section presents the comparison between meteorological information derived from Mode-S EHS and ADS-B EHS. The high time resolution of Mode-S EHS can be exploited to perform a consistency and quality check of flight information received. This is not possible on the ADS-B EHS information because the sequential observations from the same aircraft are generally not available within 4 seconds (see Figure 12). Comparison between raw (not smoothed) Mode-S EHS and ADS-B EHS for wind and temperature are therefore only shown. The heading is corrected based on correction values determined for the year 2008 and 2013 (De Haan, 2011, 2013c). For the period considered, matching AMDAR observations in the area of interest are used to perform a reference check.

Mode-S EHS and ADS-B EHS data points are collocated when the time difference is less than 2 seconds. Gross errors in position are excluded from the comparison. In Table 6 the statistics of the comparison between Mode-S EHS and ADS-B EHS is presented for the period from 5 January 2012 to 5 January 2013. As expected the standard deviation of the temperature observations is high (almost 2 K) which is related to the method of temperature derivation using the Mach number and the true air speed (see De Haan 2011, 2013c, for discussion on the effect and method). The wind direction statistics are calculated only for wind speeds higher than 4 m/s for both Mode-S EHS and ADS-B EHS, because comparing wind direction at low wind speeds will increase the scatter.

Table 6 : Statistics of comparison of meteorological parameters from ADS-B EHS and Mode-S EHS

	Number	Mean difference	Standard deviation
Temperature	2097835	0.00 K	1.81 K
Wind Speed	2097835	0.04 m/s	1.15 m/s
Wind direction	2054346	-0.00 deg	4.64 deg

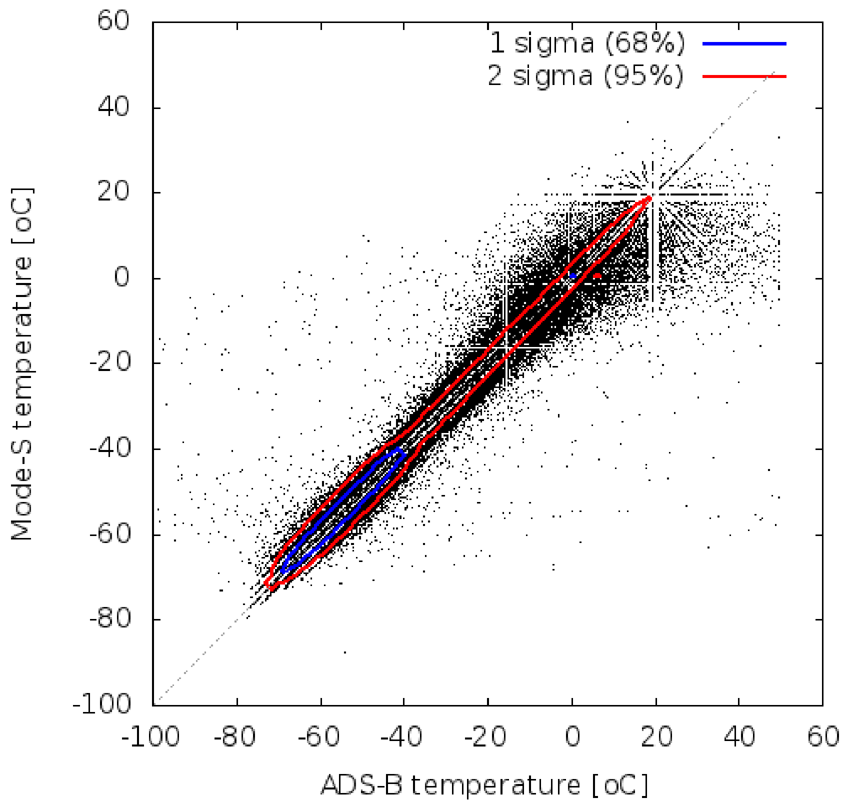


Figure 19 : Comparison of Mode-S EHS and ADS-B EHS temperature observations.

The number of collocations is much smaller than when the flight parameters (e.g. Mach number, track angle) are compared. This can be explained by the fact that the heading correction is not available for all aircraft detected in the airspace. The mean difference and standard deviation of both wind speed and wind direction are acceptable.

Figure 19 shows the scatter plot for temperature observations, together with the one and two sigma intervals. Clearly, the ADS-B EHS temperature above -20°C appears to be very noisy. This could be related to bad or corrupted reception/decoding of the DF20/DF21 messages. If this is really the case, this may be improved by the development of a stricter quality control for the observations retrieved from aircraft flying at a lower elevation with respect to the antenna. Figure 20 presents an identical scatter plot, but for the derived wind speed. No signal with respect to wind speed is observed.

Figure 21 shows the wind direction scatter plots. Note that all points with a wind speed lower than 4 m/s are removed from the dataset, because comparing wind direction at low wind speeds will increase the scatter. The majority of the wind has a direction of around 270 degrees, which shows the prevailing westerly wind for the Netherlands. The scatter plot clearly reveals the outliers, but the fraction is rather small as they all fall outside the 2 times standard deviation area. Apart from the scatter, no other strange signal is observed.

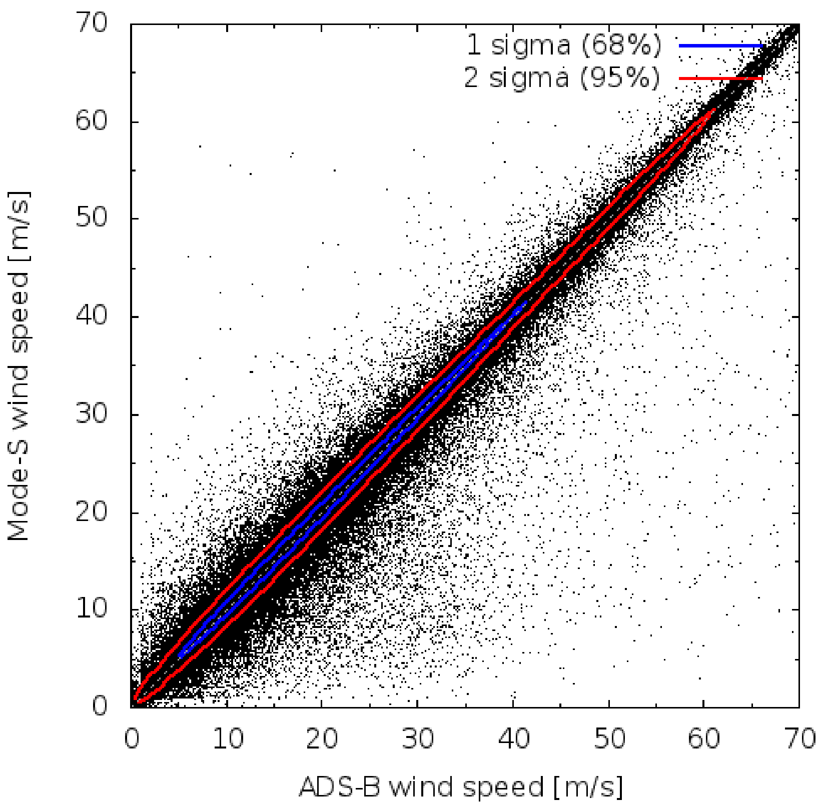


Figure 20: Comparison of Mode-S EHS and ADS-B EHS wind speed observations.

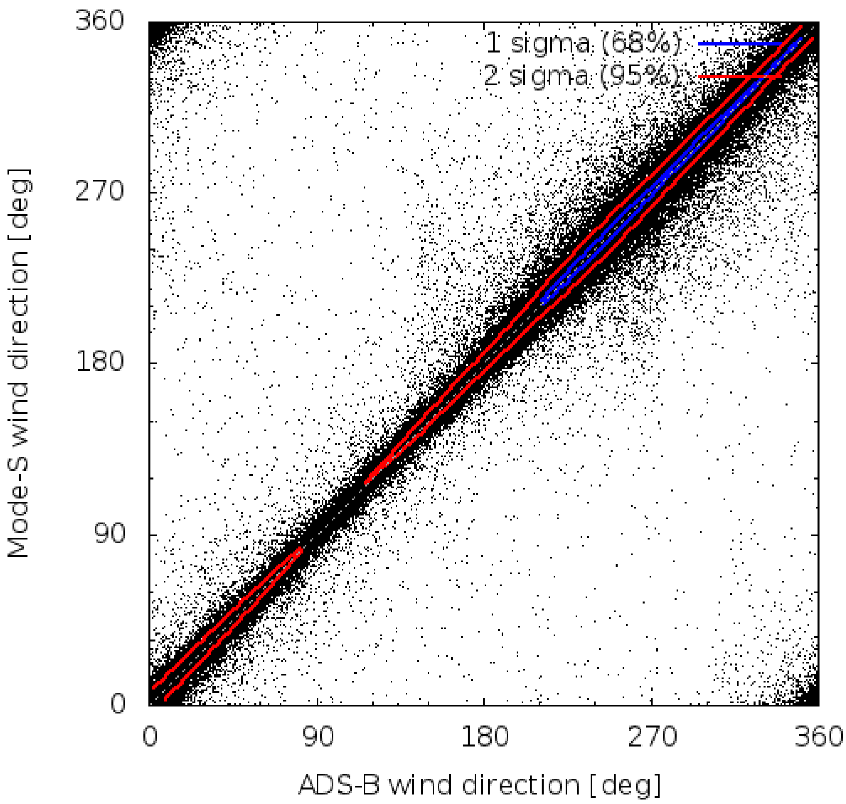


Figure 21: Comparison of Mode-S EHS and ADS-B EHS wind direction observations.

Comparing the Mode-S EHS and ADS-B EHS wind and temperature information with AMDAR gives only 1456 collocated observations for the period under consideration. AMDAR, Mode-S EHS and ADS-B EHS observations are collocated only on the condition that the following criteria are satisfied:

1. The AMDAR and Mode-S EHS identifier match;
2. The time difference between AMDAR and Mode-S EHS (or ADS-B EHS) is less than 30 seconds;
3. The difference in horizontal position is less than 2 km; and,
4. The difference in flight level is less than 200ft.

Table 7 shows the statistics of the triple comparison of AMDAR, Mode-S EHS and ADS-B EHS for temperature, wind speed and wind direction. For temperature the mean difference for all comparisons are very close, while the standard deviation for both ADS-B EHS versus Mode-S EHS and AMDAR is almost 50% more than the standard deviation of Mode-S EHS versus AMDAR. The standard deviation between Mode-S EHS and ADS-B EHS for this subset is also higher then for the whole dataset (see Table 6)

For wind speed a different signal is observed. For this parameter Mode-S EHS has the same standard deviations when compared to ADS-B EHS and AMDAR, while AMDAR and ADS-B EHS has a slightly larger standard deviation. The statistics for wind direction are again different. For this parameter it is demonstrated that the AMDAR has a bias in wind direction when compared to Mode-S EHS and ADS-B EHS. This could of course be related to the heading correction applied. Mode-S EHS and AMDAR compare best with respect to wind direction standard deviation. Note that due to the difference in space and time the observations will differ due to the natural variability of wind and temperature. However, the observed values are large, and can mainly be related to observation errors.

Table 7: Statistics of comparison of meteorological parameters from ADS-B EHS and Mode-S EHS.

Temperature [K]	Number	Mean difference	Standard deviation
ADS-B - AMDAR	1456	-0.15	4.09
Mode-S - AMDAR	1456	-0.05	2.59
ADS-B - Mode-S	1456	0.09	3.54
Wind Speed [m/s]			
ADS-B - AMDAR	1456	-0.65	3.04
Mode-S - AMDAR	1456	-0.41	1.85
ADS-B - Mode-S	1456	0.24	2.31
Wind direction [deg]			
ADS-B - AMDAR	1408	-1.09	11.20
Mode-S - AMDAR	1408	-0.92	9.44
ADS-B - Mode-S	1408	0.18	6.47

Again the temperature observations of ADS-B EHS are of worse quality than the Mode-S EHS temperature observations. The wind statistics of Mode-S EHS versus ADS-B EHS are worse in the triple collocation than in the previous collocation. The difference in heights of the observations causes the increase in standard deviation as shown in Figure 22. This figure shows the difference in temperature between AMDAR and Mode-S EHS and AMDAR and ADS-B EHS with respect to flight level. Clearly, ADS-B EHS observations at low flight levels have worse quality. A possible cause for this behavior could be related to a fallible reception/decoding of the ADS-B EHS messages under certain conditions. This effect is also visible in the wind speed difference plot versus height shown in Figure 23 and should be investigated in more detail.

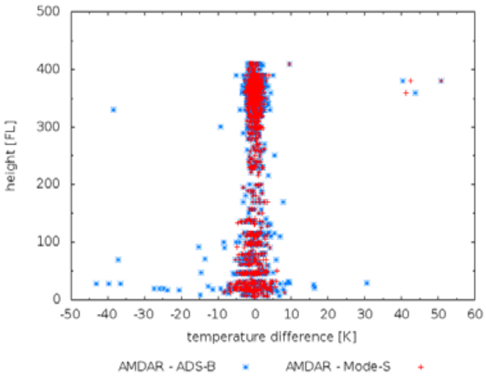


Figure 22: Temperature difference of AMDAR and Mode-S EHS (red crosses) and ADS-B EHS (blue stars), respectively versus height.

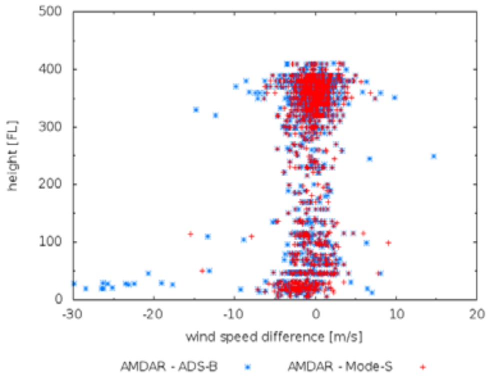


Figure 23: Wind speed difference of AMDAR and Mode-S EHS (red crosses) and ADS-B EHS (blue stars), respectively versus height.

5 Conclusions and outlook

This chapter describes a summary of the outcome of this study and presents the most important conclusions. An outlook on future Mode-S EHS capabilities in Europe is provided. Finally it also presents several anticipated improvements, and concludes with acknowledgements.

5.1 Conclusions

Several objectives were established at the start of this project. These objectives are addressed below and for each the outcome is given.

1. **To purchase and install a Mode-S/ADS-B receiver at the KNMI premises in De Bilt.**

This has been achieved within budget and time. The system will remain semi-operational in order to enlarge the data set and enable future research on the retrieval of meteorological information.

2. **To build up a data set of at least 1 year of (raw) Mode-S ADSB EHS data.**

This has been achieved and the data is stored in the mass storage system of KNMI since 12 December 2011. KNMI will continue to store this data until further notice, see also 1.

3. **To establish a proof of concept for the derivation of wind and temperature observations from Mode-S ADSB EHS data recorded by this receiver.**

This has been achieved by storing the data as received from the system, see also items 1) and 2), and applying algorithms and analysis on one full year of data. Since meteorological information is not directly measured in the EHS data, a preprocessing is necessary to obtain atmospheric information with adequate quality. Temperature is deduced from the Mach number and airspeed. 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 described in De Haan (2013c).

4. **To determine the pros and cons of the experimental Mode-S ADSB EHS data stream compared to the current operational EHS data stream from the TAR radar operated by ATC The Netherlands (LVNL).**

This been achieved, based on items 1), 2) and 3), and the results can be summarized as follows:
a) ADS-B EHS data can be received independently from ATC, when aircraft are interrogated by a Mode-S EHS radar. A commercial ADS-B receiver is capable of receiving and decoding the Mode-S EHS information in suitable data formats.
b) The received ADS-B EHS parameters contain information which can be used to derive wind and temperature observations. In general, it seems that almost all parameters are similar, except ground speed and track angle which suffer from inaccuracies. Since these parameters are essential for an accurate derivation of the wind vector, these inaccuracies will influence the quality of the wind observations.
c) The volume of the received meteorological data is a fraction from the official Mode-S EHS data flow. Due to time difference and blocking of the reception of the ADS-B signal
e) The horizontal coverage is different from the Schiphol TAR-1 coverage due to blocking and the difference in position of the antennas; it is centred around the local antenna
f) The vertical coverage is also different from the Schiphol TAR-1 coverage.

g) The quality of the derived meteorological information is slightly worse than the meteorological data derived from the Mode-S EHS data received from ATC. Wind speed and direction are within meteorological requirements; temperature from ADS-B EHS is not compliant to these requirements.

The amount of ADS-B EHS derived wind and temperature observation is about 8% of the number of observations that can be received through the official data flow from ATC. Nevertheless, the local ADS-B EHS receiver installed at De Bilt can receive around 7000 observations per hour. The primary goal of this project is to show that this data can be used as input for a rapid update cycle (RUC) of a numerical weather prediction model. At present, the RUC uses about 2% of the Mode-S EHS data received from LVNL, to prevent overfitting of wind and temperature observations in the assimilation. It is thus expected that the same relevant information can be received through a local ADS-B receiver.

Installing a local Mode-S ADS-B receiver is a good alternative in case the transmission of Mode-S ATC data is not possible. However, direct reception of Mode-S EHS ATC data has advantages with respect to coverage, amount and quality of the data. Moreover, it decreases the costs because existing infrastructure is utilized for multiple purposes. For these reasons, the reception of Mode-S EHS data from ATC is preferred.

5.2 Anticipated improvements of ADS-B EHS data retrieval

The current ADS-B EHS observation infrastructure used at KNMI can be improved by the following steps:

1 Improve the coverage of ADS-B EHS by:
   a. installing more dedicated receivers; or,
   b. cooperating with the aircraft spotter or glider communities; or,
   c. cooperating with the ADS-B software community.

2 Investigate whether an upgrade to a 2 or 4 channel version of the receiver with multiple antennas offers increased performance.

3 Compare the reported ground track with a calculated ground track; there is more position data available than currently used (ADS-B DF17) and this can be exploited to have better quality groundspeed and track angle information.

4 Apply consistency checks on subsequent ADS-B EHS observations:
   a. Position and height;
   b. Aircraft parameters;
   c. Meteorological parameters.

5 Apply gross error checks on the temperature profile (climatology).

6 Investigate the dependence of quality of the parameters on the range from the antenna.

Note that the successor of the Mode-S Beast (the so-called “Radarcape”) was released by Mid 2012. It offers extended options at a similar price tag. However, it is not sure whether these extras offer discernible added value for the meteorological purposes described in this report.

5.3 Outlook of Mode-S EHS capabilities in Europe

The opportunity for the meteorological community to derive good quality wind and temperature observations out of Mode-S EHS information is dependent on three factors.

1. The condition that ATC interrogates aircraft to provide the EHS BDS registers 4.0, 5.0 and 6.0.
2. That aircraft are capable to respond to this interrogation.

3. The opportunity for the meteorological community to retrieve the EHS information via:
    a. ATC directly, or
    b. via a public Mode-S ADSB EHS receiver.

Currently EHS designated airspace is notified by the Civil Aviation Authorities of Germany, United Kingdom, France, Belgium and The Netherlands. Within this airspace Mode-S EHS data is available in all countries except for France. It is expected that Mode-S EHS data will be available in France as of 2014. The Mode-S EHS data of Germany, Belgium and The Netherlands is being made available to KNMI by Maastricht Upper Area Control Centre (MUAC) of EUROCONTROL as of November 2012. The Mode-S EHS data of the United Kingdom is currently not available within KNMI. A request will be made to the National Air Traffic Services (NATS) of the United Kingdom to provide for this data.

At the moment KNMI has no clear picture of the Mode-S EHS capabilities in Europe. Some Mode-S EHS radars exist in the Scandinavian countries and Slovenia. A small study to investigate current and future Mode-S EHS capabilities in Europe is advised.

It is also not known till what extent Mode-S EHS is used outside Europe. In general ADS-B and ADS-B Extended Squitter is more common than Mode-S EHS. Generally speaking it could be possible to derive wind and temperature observations in a similar way using ADS-B ES data as is performed by using Mode-S EHS data. However, some of the quality control steps used in Mode-S EHS data cannot be performed due to the fact that e.g. roll angle and track angle are not available. Furthermore, it is mentioned that as of 2018 true airspeed will no longer be part of the ADS-B ES broadcast. In that case the derivation of wind information from ADS-B ES will no longer be possible.

With regard to the capability of aircraft to respond to a Mode-S EHS interrogation the following. The European Commission has recently promulgated an Implementing Regulation, laying down requirements for the performance and the interoperability of surveillance for the single European sky. This Rule lays out the requirements for the carriage and operation of specified airborne surveillance equipment, and the dates by which qualifying aircraft must be equipped by. The rule in question is 'Commission Implementing Regulation (EU) No 1207/2011', published on 22/11/2011.

The key objective of this European Commission implementing Regulation is to establish performance requirements for surveillance. In addition to a range of additional requirements for ANSPs, the regulation requires the following: *All aircraft operating IFR/GAT in Europe are to be compliant with Mode S Elementary Surveillance (ELS). The applicability dates for this requirement is 8th January 2015 for “new” aircraft and 7th December 2017 for retrofit. Aircraft with a minimum take-off mass greater than 5,700 kg and/or with a maximum cruising true air speed greater than 250 knots are required to be compliant with Mode S Enhanced Surveillance (EHS) and, through the carriage and operation of an extended squitter transponder, with “ADS-B Out” requirements in support of ground and airborne surveillance applications. The applicability dates for these requirements is 8th January 2015 for “new” aircraft and 7th December 2017 for retrofit. Local mandates to extend the ADS-B Out carriage to all IFR/GAT in areas where ADS-B is used for surveillance are permitted.*

The European Directive will lead to more opportunities for the meteorological community to receive Mode-S EHS data in Europe.

The following table provides an overview of the Mode-S EHS radars for which KNMI receives the Mode-S EHS data via MUAC.

Table 8: Overview of current ATC Mode-S EHS data available at KNMI, in brackets the originating organisation, followed by the update frequency of the ATC radar.

Auersberg (DFS) [11.8s]	Bertem (Belgocontrol)[11.8s]
Brocken (DFS) [5s]	Deister (DFS) [11.6s]
Duesseldorf-Sued (DFS) [4.8s]	Frankfurt-Sued (DFS) [4.8s]
Grosshaager Forst (DFS) [11.5s]	Gosheim (DFS) [5s]
Leeuwarden (RNLAF) [4s]	Muenchen-Sued (DFS) [4.8s]
Neunkircher Hoehe (DFS) [11.6s]	Nordholz (DFS) [11.8s]
Schiphol TAR-1 (LVNL) [4.2s]	St. Hubert (Belgocontrol) [11.8s]
Schmooksberg (DFS) [11.8s]	Woensdrecht (RNLAF) [4s]

Note that there is a difference between the update frequency of the various ATC radars, ranging from 4 to 11 seconds. Other ATC radars are known to have an update frequency of 20+ seconds. This is of relevance as some of the algorithms to derive wind and temperature observations use smoothing in time.

The area of coverage is provided on a map of Western Europe in figure 24. The graph shows the amount of quality controlled observations that are derived in a time frame of 15 minutes on a day in August. The graph on the right shows all derived observations below FL100.

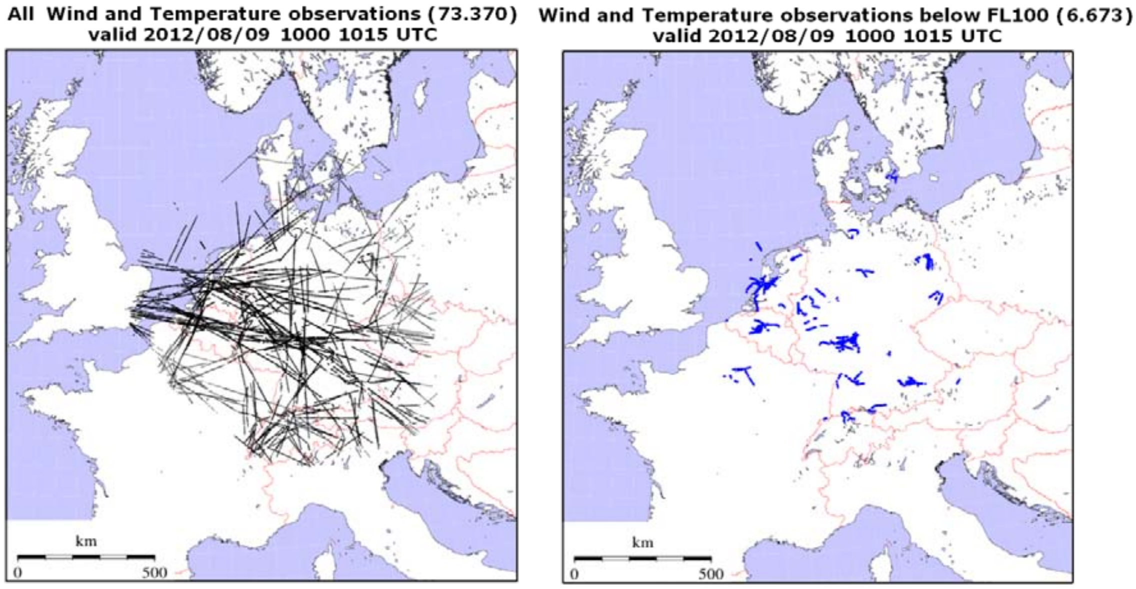


Figure 24: Example of 15 minutes of derived Wind and Temperature observations from Mode-S EHS data (quality controlled) of a day in August 2012 over Western Europe, source Maastricht Upper Area Control Centre (MUAC) of EUROCONTROL, processed by KNMI.

It is foreseen to expand this coverage by using the Mode-S EHS data of France and United Kingdom in the near future. Depending on future Mode-S EHS capabilities the area can be enlarged over Europe. It is important to bear in mind that Mode-S EHS data can only be downlinked when the data is broadcasted as an answer to an interrogation of ATC. As a consequence, there is no Mode-S EHS data available over the oceans for example.

Another method to receive good quality upper air observations for wind and temperature is to use other BDS registers that are available (see also RTCA DO260) and contain meteorological observations. For example BDS register 4.4

contains a direct read out of the temperature of similar quality as the AMDAR temperature. More research in this field and intensified collaboration with ATC and the ATM community in this area is advised.

5.4 Acknowledgements

The contribution of Günter Köllner, Rainer Müller and Gunther Kruse, who assisted us with the installation and configuration of the Beast receiver, is greatly acknowledged and appreciated. In addition, we would like to thank ATC The Netherlands (LVNL) for providing KNMI with the Mode-S EHS data, as received by the terminal area radar at Amsterdam Airport Schiphol, which enabled us to perform the analysis as described in this technical report.

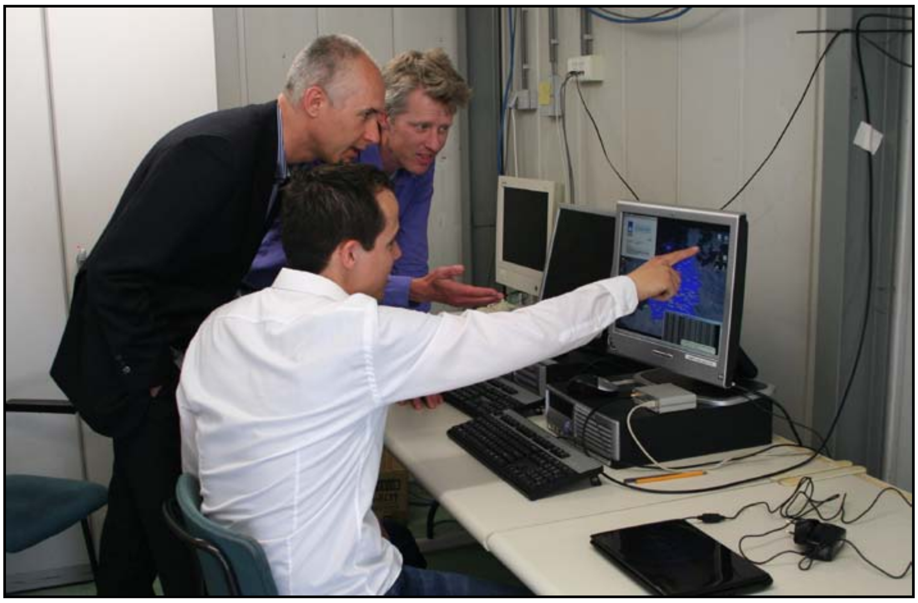


Figure 25: Marijn de Haij, Siebren de Haan and Jan Sondij evaluate the ADS-B EHS data reception in the computer room at the roof of the KNMI premises.

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Appendix A – List of acronyms

ADS-B	Automatic Dependent Surveillance Broadcast
ADS-B ES	ADS-B Extended Squitter
AMDAR	Aircraft Meteorological Data Relay
ANSP	Air Navigation Service Provider
ATC	Air Traffic Control
ATM	Air Traffic Management
Belgocontrol	Belgocontrol (ATC of Belgium)
BDS	Binary Data Store
CDO	KNMI Central Data Storage System
COTS	Commercial Off-The-Shelf
DAP	Downlink Aircraft Parameters
DFS	Deutsche Flugsicherung (ATC of Germany)
DF	Downlink Format
EUROCONTROL	European Organisation for the Safety of Air Navigation
FL	Flight Level
FPGA	Field-programmable Gate Array
ICAO	International Civil Aviation Organization
KNMI	Royal Netherlands Meteorological Institute
LAN	Local Area Network
LVNL	Air Traffic Control The Netherlands
Mode-S	Mode-Selective
Mode-S ELS	Mode-S Elementary Surveillance
Mode-S EHS	Mode-S Enhanced Surveillance
MOS	KNMI Mass Storage System
MSL	Mean Sea Level
MUAC	Maastricht Upper Area Control Centre of EUROCONTROL
NWP	Numerical Weather Prediction
RNLAF	Royal Netherlands Air Force
RUC	Rapid Update Cycle of NWP
SSR	Secondary Surveillance Radar
TAR	Terminal Area Radar
TCP/IP	Transmission Control Protocol / Internet Protocol
UF	Uplink Format

Appendix B – Mode-S Beast logbook

29-11-2011: Mode-S Beast and GP1090 antenna installed at the roof of the KNMI B-building. First results show aircraft up to 250 nm from De Bilt.

30-11-2011: Installed the PC for the Beast data logging and configured two utilities for continuous data replication:

<u>COM0COM (Virtual serial port driver)</u>
1 instance running: Beast_hub.bat
This program splits the Beast virtual COM port (created by the FTDI driver) into two virtual COM ports.

<u>COM2TCP (Serial connection to TCP redirector)</u>
2 instances running: Beast_loc.bat & Beast_ext.bat
This program forwards the serial data stream from both virtual COM ports to a specific IP address through TCP.

Beast_ext.bat (to make data available on 145.23.130.143 port 1234)
```
com2tcp.exe --telnet --baud 3000000 --ignore-dsr .com11 1234
```

Beast_ext.bat (to make data available on 145.23.130.143 port 10001)
```
com2tcp.exe --telnet --baud 3000000 --ignore-dsr .com9 10001
```

At a later stage the PlanePlotter software developed by COAA (Centro de Observação Astronómica no Algarve) was also used on this system for direct visualization of the received data frames (see Figure 26).

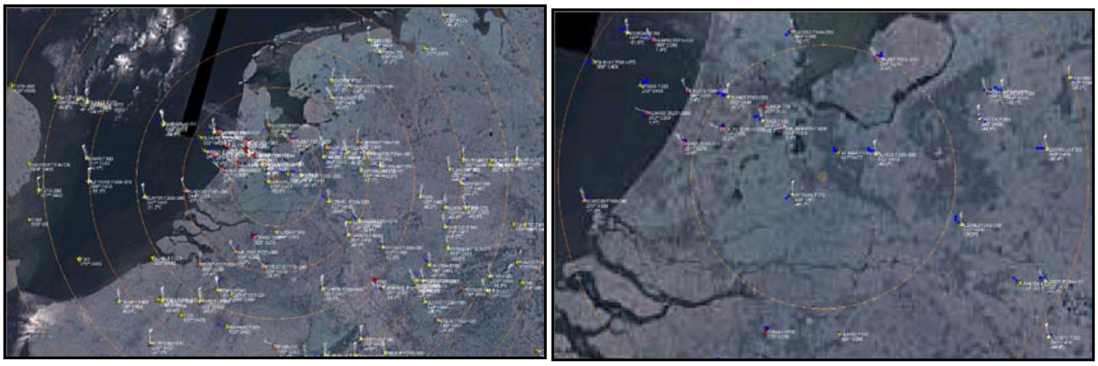


Figure 26 : Screenshots of realtime Mode-S EHS data from the Beast receiver visualized by PlanePlotter software. The images show the decoded information for aircraft in two different areas around the receiver location in the centre of the Netherlands on June 28th at 08:40 UTC.

02-12-2011: Starting from 12:00 UTC, the LabView tool Read BeastAVR acquires raw data from the Beast and logs hourly data files consisting time stamped 56-bit/112-bit AVR strings. The frame rate is on average 2400 messages/s. During the peak hours 3500 messages/s are observed.

09-12-2011: First images of spatial coverage of ADS-B positions generated by the processing software (decodeADSB).

12-12-2011: Data is now archived in daily tgz files on the MOS (/fa/ao/airborne/adsb). Data volume is approximately 2GB/day.

19-12-2011: Monitoring page extended with spatial coverage of Beast winds and lat/lon intersections.

03-01-2012: Beast firmware upgraded to v1.32. Minor loss of data.

25-01-2012: Beast firmware upgraded to v1.32a. Minor loss of data.

02-02-2012: Data acquisition due to Windows updates. Minor loss of data.

11-03-2012: Data acquisition terminated for unknown reason. No data between 11 March 15 UTC and 12 March 08 UTC.

28-03-2012: Beast firmware upgraded to v1.40. The total number of frames is lowered approximately by a factor 2, but the amount of useful and valid data is similar to previous firmware versions.

03-04-2012: Beast firmware upgraded to v1.41a. This solves some major bugs that were recognized in v1.40.
04-04-2012: Beast firmware upgraded to v1.41b. Minor loss of data.

02-05-2012: Beast firmware upgraded to final v1.41. Minor loss of data.

09-07-2012: Tested alternative Beast settings. Minor loss of data. Suppression of DF0/DF4/DF5 messages (SW7) was turned "ON". The reduction of the total number of messages received is about 35%.

22-10-2012: Data acquisition terminated due to unknown reason. After recovery the suppression of DF0/DF4/DF4 messages (SW7) was "OFF".

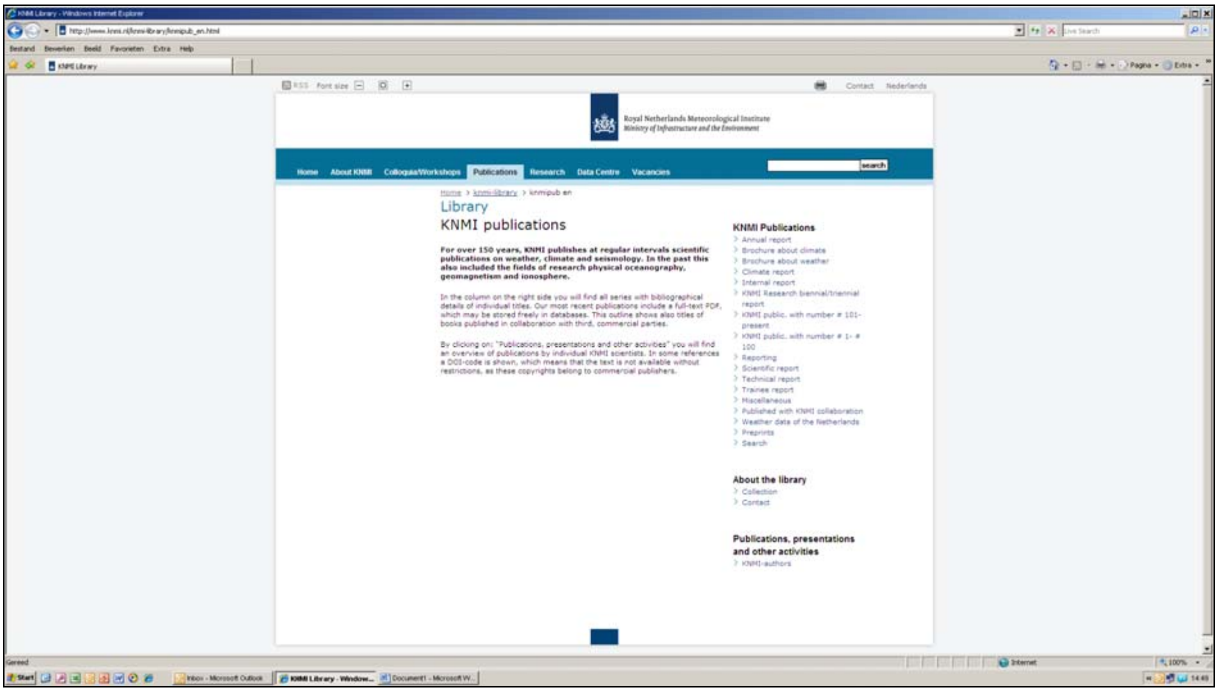
08-11-2012: Suppression of DF0/DF4/DF5 messages (SW7) was turned "ON" again.

19-12-2012: Restarted the Beast logging application. No data between 18-12-2012 15 UTC and 19-12-2012 08 UTC.

24-12-2012: Suppression of DF0/DF4/DF5 messages (SW7) was turned "ON" again.

A complete list of all KNMI-publications (1854 – present) can be found on our website

www.knmi.nl/knmi-library/knmipub_en.html



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