German Institute of Navigation

Deutsche Gesellschaft für Ortung und Navigation

Koelnstraße 70

53111 Bonn

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Title: ACAS-Monitoring by an Experimental Groundstation in Braunschweig

IEV TU-Braunschweig

Dipl.-Inf. Jens Gottstein

Alexander Burkert

Prof. Dr.-Ing. Peter Form

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Introduction - Summary

Within the SATT-Project the IEV of the Technical University of Braunschweig developed tools to identify airspaces in which and why Airborne Collision Avoidance Systems ACAS on board of aircraft detect collision threats, output Resolution Advisories to the pilot and coordinate escape maneuvers with threatening aircraft if they are also ACAS-equipped.

During the last three years, an experimental groundstation was developed, listening into the 1030/1090MHz SSR Mode S-interrogations, broadcasts and replies transmitted by aircraft in the North German airspace.

In spite of frequently superimposing signals, the tools realized until now allow successful validation of received Mode S telegrams, selection of ACAS-relevant dialogs between threatening aircraft and interpretation of their evidence.

ADS-B is used to track aircraft and identify relevant airspaces. To filter malformed ADS-B position reports adequate validation techniques have been developed.

Some examples will be presented in this paper.

1 ACAS Transmissions

This chapter gives a short introduction into the functionality of ACAS. Figure 1 shows the course of action in an ACAS-Event.

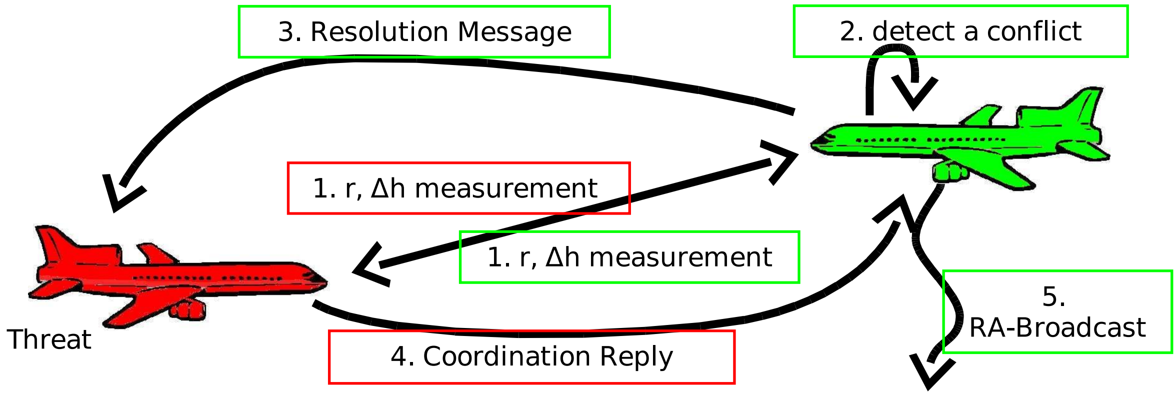

Figure 1: ACAS Transmissions

ACAS equipped aircraft continuously emit DF11-Squitter containing their own Mode S-Address. By listening into these Squitters, aircraft acquire the information which planes are in their vicinity.

ACAS constantly interrogates neighbored aircraft using UF00 Air-Air-Surveillance-Messages (1 in Figure 1). The queried aircraft responses with a DF00 Air-Air-Surveillance Message which includes the senders altitude. From the round trip delay of the UF00/DF00 dialog, the interrogating plane computes the slant distance between both planes.

ACAS uses altitude, distance and their derivatives for the threat-detection (2) and the computation of Resolution Advisors and their coordination.

Each Resolution Advisory is followed by a UF16-30 Resolution Message (3) to the threatening Aircraft if it is ACAS-equipped. The UF16-30 Resolution Message has to be confirmed by a DF16-30 Coordination Reply (4).

Each Resolution Advisory is also followed by a UF16-31 RA-Broadcast (5) explaining the on board indicated Resolution Advisory for ATC-monitoring purposes. Unfortunately this RA-Broadcast contains the Squawk-ID instead of its Mode S address.

2 Listen into Mode S Aircraft Transmissions by Groundstations

Mode S messages (1030MHz Uplink and 1090MHz Downlink) have a common Structure: The first bits define the used format. The second part forms the message body. The last 24 bits hold a CRC-polynomial-checksum which is used to identify transmission errors:

Mode S message structure

Format Bits	Message Body	Checksum-Field 24-Bit

Normal interrogations **and** replies contain the Mode S address of the **interrogated** Aircraft. The Checksum-Field results in this address if no transmission error has occurred:

Mode S interrogation (uplink format - UF)

UFXX	Message Body	Interrogated Address

Mode S reply (downlink format - DF)

DFXX	Message Body	Interrogated Address

The exception to the rule above are the Downlink Formats 11 an 17. They are named Mode S Squitter. Every Mode S transponder repeatedly emits Squitters without being interrogated. The message body of a Squitter contains the sending Mode S Aircraft Address as plain text. The Checksum-Field results in 000000_{hex} if no transmission error has occurred.

Unelicited Squitter structure

DF11/DF17		Plain Mode S Address	000000 overlaid with Checksum

By listening into these Squitters, the Groundstation receiver can acquire the information which planes are within the range of the receiver and validate interrogations and replies.

3 Groundstation and ACASMON Software

Figure 2 depicts the Experimental Groundstation of the Institute consisting of the 1030/1090 MHz receiver including appropriate tolerant correlation and demodulation techniques. Figure 2 also illustrates in more detail the software ACASMON. ACASMON is responsible for the validation of the received Mode S Messages, the extraction of their content for the knowledge base, the particular selection of ACAS-relevant messages and their grouping into a sequence called ACAS-Event.

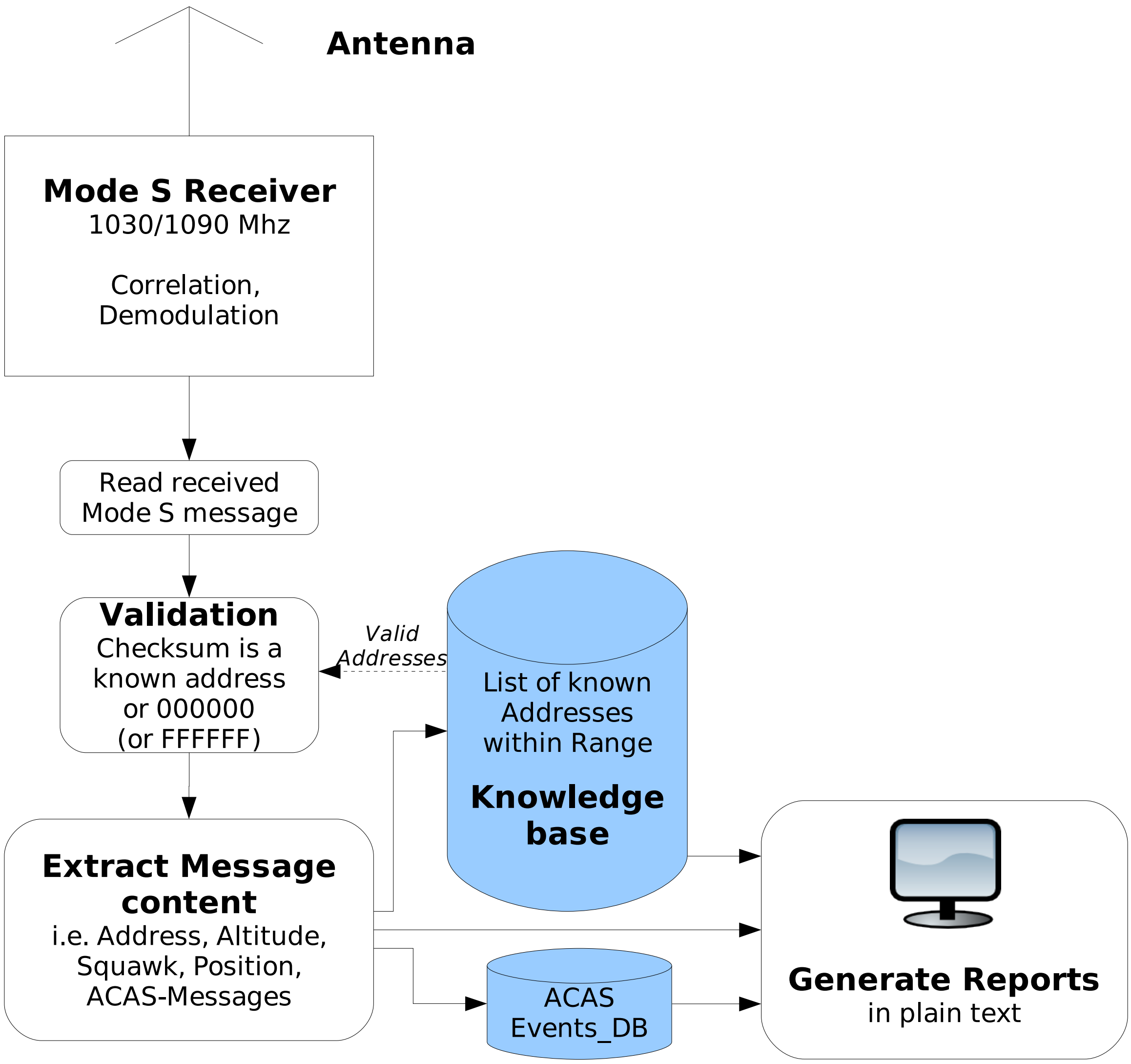

Figure 2: Structure of the Groundstation and ACASMON

3.1 Range of Groundstation

Figure 3 gives a glimpse into aircraft positions in the North German airspace detected by the TU-Braunschweig Groundstation.

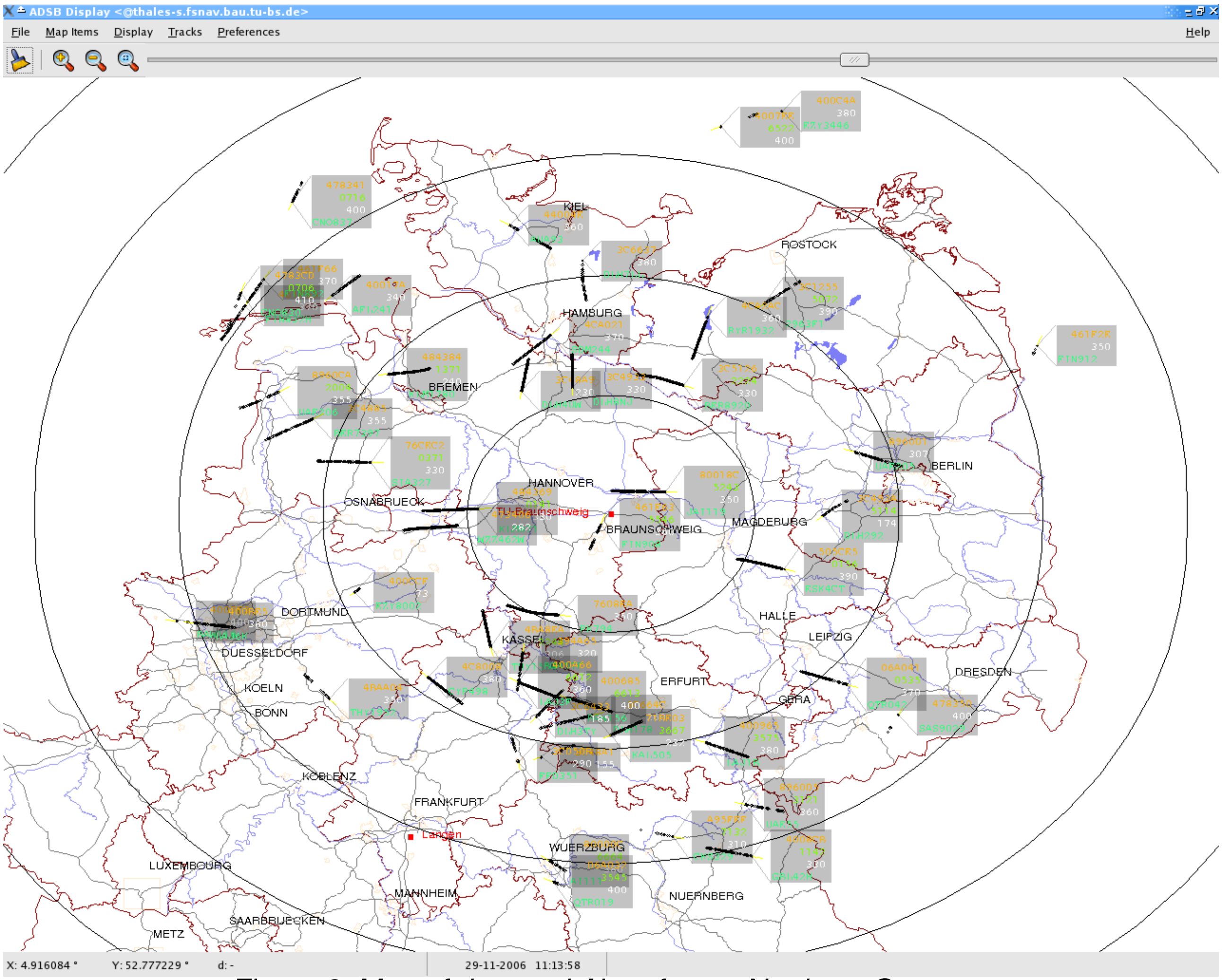

Figure 3: Map of detected Aircraft over Northern Germany

During daytime from 6.00 till 21.00 o clock the receivers correlate the beginnings of 2000 replies/second and 300 interrogations/second starting the bit clock for reading the content of the telegrams. 600 replies/second and nearly all 300 interrogations/second can be correctly read.

3.2 Position decoding

The aircraft altitudes can be taken from received DF00 and DF04 replies for the description of the vertical traffic situation. However the horizontal description of the traffic situation can only be taken from radar data or from ADS-B Mode S data transmitted by adequate equipped aircraft.

At present about 60% of Mode S transponder equipped aircraft also transmit ADS-B position data as DF17 extended squitter formats. This makes ADS-B a rather perfect source of position data for horizontal traffic situation interpretation, although radar data are also foreseen for this purpose.

ADS-B uses CPR-coded position data packed into DF17 Squitters. Part of the ACASMON software was developed for the decoding of the ADS-B Compact Position Report Data.

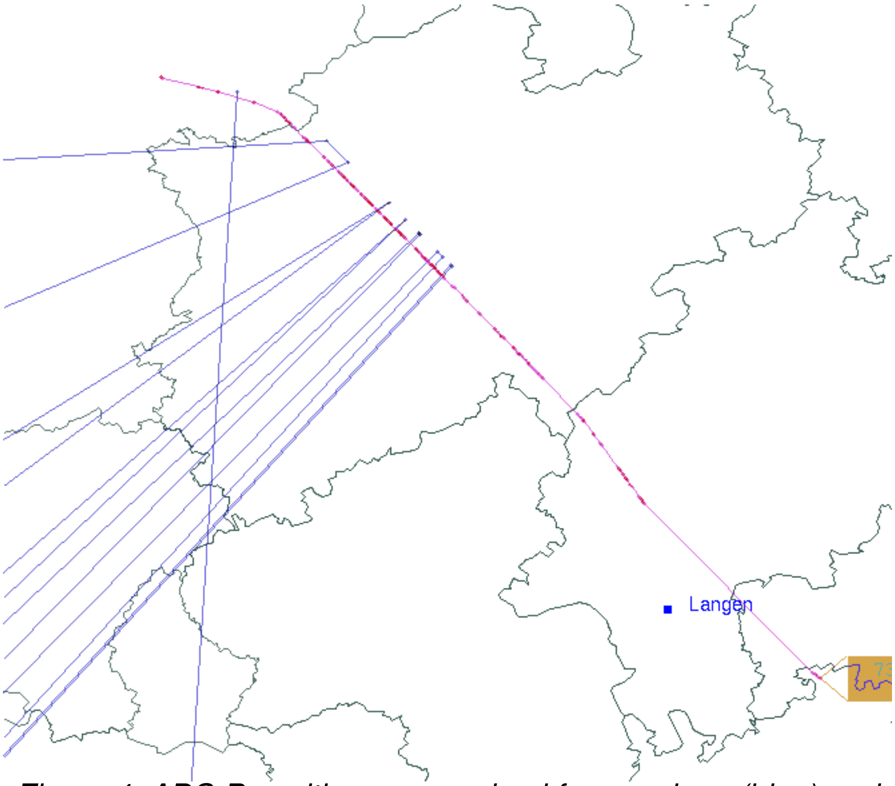

Figure 4: ADS-B positions as received from a plane (blue) and filtered by tracking (red)

Note: the track is intentionally shifted away from the raw-data for better presentation

Figure 4, for instance, shows the ADS-B positions of a plane and their extreme large deviations caused by errors of various sources. To filter out these deviations a tracking method has been developed.

4 ACAS-Event Monitoring

Every airplane sends out distinct data packets during flight, including ACAS specific signals, which are necessary for the communication between the collision protection devices in the airplanes (see ICAO Standard Annex 10 or Figure 1).

The following three formats contain all necessary information about the current ACAS conflict. To detect ACAS-Events by listening into Mode S transmissions, theses three formats were mainly analyzed:

- *UF16-30 Resolution Message* - Computed Resolution Advisory Complement, sent by the coordinating aircraft to coordinate the collision avoidance maneuverer with threatening aircraft.
- *DF16-30 Coordination Reply* - Confirmation of Resolution Message issued by the threatening (coordinated) aircraft.
- *UF16-31 RA Broadcast* - includes the on board indicated Resolution Advisory for ATC-monitoring purposes and the Squawk identity instead of the Mode S address of the aircraft. The correlation between Squawk and Mode S address can be taken from DF05 replies if receivable.

To understand their functionality these messages had to be translated into a plain text readable by humans. As a first step in the development of ACASMON this translation of bit sequences into plain text was developed. Every line in Table 1 is an example for a human readable translation of the bit sequence in an ACAS message.

But translating individual messages does not give enough information on ACAS activities. No single ACAS message contains all necessary information to interpret ACAS activities: Only the Resolution Message contains the Mode S addresses of both participating planes, while only the RA-Broadcast contains the issued Resolution Advisory.

Therefor individual ACAS messages have to be compiled to reconstruct all key messages of an evident standard dialog. This dialog of ACAS Messages defines an ACAS-Event.

On 14.12.2005 a first complete ACAS-Event was discovered, it is presented in Table 1. At first the messages were manually selected. With the gained knowledge an automatic ACAS-Event compilation process was developed, its function is presented in section 4.1.

No	Time	Message Format	Mode S Address *(Squawk)*	Content of Message
1	21:02:37	UF16/31 RA Broadcast	473402 *(3577)*	ARA: Upward sense RA generated, MTE: One threat, FL: 307
2	21:02:37	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat
3	21:02:37	DF16/30 Coordination Reply	3C492C	RAC: Do not pass above, FL: 280
4	21:02:38	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat; (DF16/30 not received) *)
5	21:02:39	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat; (DF16/30 not received)
6	21:02:40	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat
7	21:02:40	DF16/30 Coordination Reply	3C492C	RAC: Do not pass above, FL: 280
8	21:02:41	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat
9	21:02:41	DF16/30 Coordination Reply	3C492C	RAC: Do not pass above, FL: 280
10	21:02:42	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat; (DF16/30 not received)
11	21:02:43	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat
12	21:02:44	UF16/31 RA Broadcast	473402 *(3577)*	ARA: Upward sense RA generated, MTE: One threat, FL: 302
13	21:02:45	UF16/30 Resolution Message	473402 -> 3C492C	VRC: Do not pass above, MTB: One threat
14	21:02:45	DF16/30 Coordination Reply	3C492C	RAC: Do not pass above, FL: 280; (UF16/30 not received)
15	21:02:46	DF16/30 Coordination Reply	3C492C	RAC: Do not pass above, FL: 280
16	21:02:48	UF16/31 RA Broadcast	473402 *(3577)*	ARA: Upward sense RA generated, MTE: One threat, RAT: RA has been ceased, FL: 301

Table 1: List of all messages of the ACAS-Event from 14.12.2005, shown in chronological order.

*) Note: Also mentioned are missing interrogations and replies.

4.1 Automatic ACAS-Event compilation

The high count of ACAS relevant messages can not be analyzed manually. The required automatic compilation of messages into sequences - ACAS-Events - is shown in Figure 5.

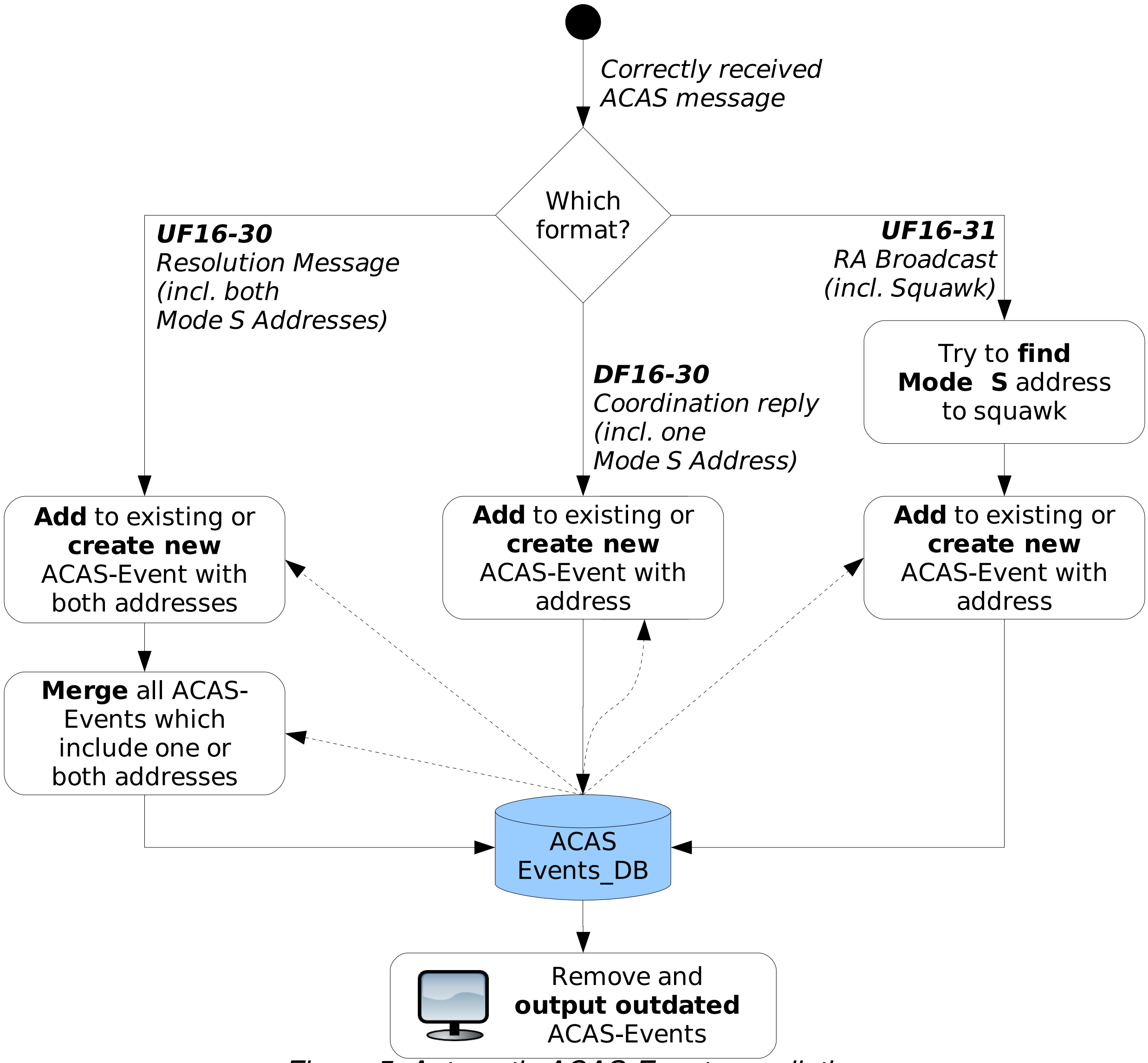

Figure 5: Automatic ACAS-Event compilation

All ACAS-Events are stored in the ACAS-Events_DB for lookups by the event extraction process.

Every correctly received ACAS-Messages is handled due to its format. A message with a new address opens a new ACAS-Event. A message with an address already existing in an ACAS-Event, is added to this ACAS-Event (dashed lines).

5 Observed ACAS-Events

To test the developed Groundstation and its software ACASMON, Mode S data was recorded from both, the 1090 and the 1030 MHz channel for 23 days. The resulting data of ca. 90GB could only be analyzed using computerized methods. For this reason the software ACASMON had been developed. With its help a set of ACAS-Events had been discovered, analyzed and printed in a human readable way. The human readable text output was then manually reviewed.

This section describes the ACAS-Events, which were standard-conform, were presenting a complete sequence of ACAS-messages, although some individual telegrams got lost, and were accompanied by ADS-B position data for the interpretation of the traffic situation.

Not standard conform ACAS-Events and ACAS-Events without ADS-B data were observed. They are not discussed in this paper.

ACAS-Event Examples in the Northern German Airspace

Employing ADS-B positioning Data, it is possible to understand the ACAS-communication and the maneuverers that led to the ACAS-Event and resolved the conflict. Therefore in the following examples the tracks of the airplanes are printed on a map, as well as the altitudes are printed versus time.

Included in the figures are the receipt times of the appropriate ACAS messages, the distances between airplanes and the distance traveled while ACAS-activities.

The presented ACAS-Events are from these dates:

- Record of 14.12.2005
- Record of 04.09.2006 until 05.09.2006
- Record of 07.09.2006 until 08.09.2006
- Record of 08.09.2006 until 11.09.2006

5.1 ACAS-Event on 14.12.2005 near Braunschweig

The first presented event was observed in close proximity to Braunschweig on 14th December 2005.

Interpretation of the received ACAS-Messages

Table 1 in section 4 lists the ACAS communication between the two involved airplanes in order to summarize the ACAS-messages and illustrate the complete dialog. The content of Table 1 is also graphically presented in Figure 6.

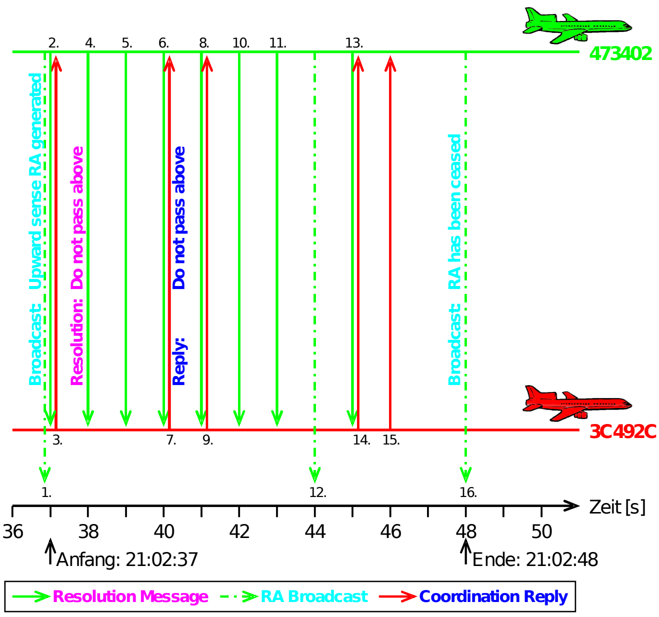

Figure 6: Time flow of the ACAS-Event on 14.12.2005 near Braunscheig

Reconstruction of the traffic situation

As previously mentioned, the altitude and ADS-B data can be employed to accurately reconstruct the traffic situation and gain a better understanding of the ACAS-Events.

Figure 7 shows the altitude plot versus time taken from DF00/DF04. To aid understanding, the plot is overlaid by the received ACAS-Messages.

Figure 8 depicts the horizontal ADS-B tracks of both involved aircraft. The map also includes a zoomed view of the area where ACAS was issuing a Resolution Advisory.

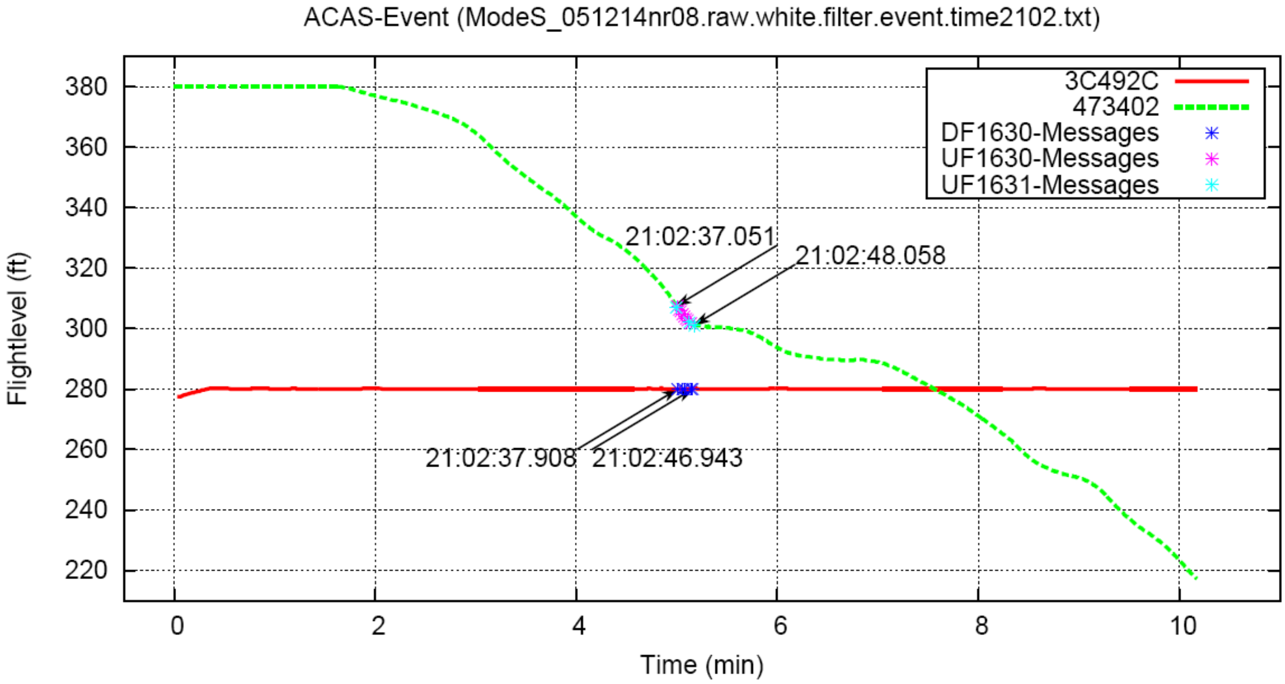

Figure 7: Altitude of the two airplanes in the ACAS-Event on 14.12.2005 at 21:02 near Braunschweig, 5 minutes before and after the event, overlaid with all received ACAS messages

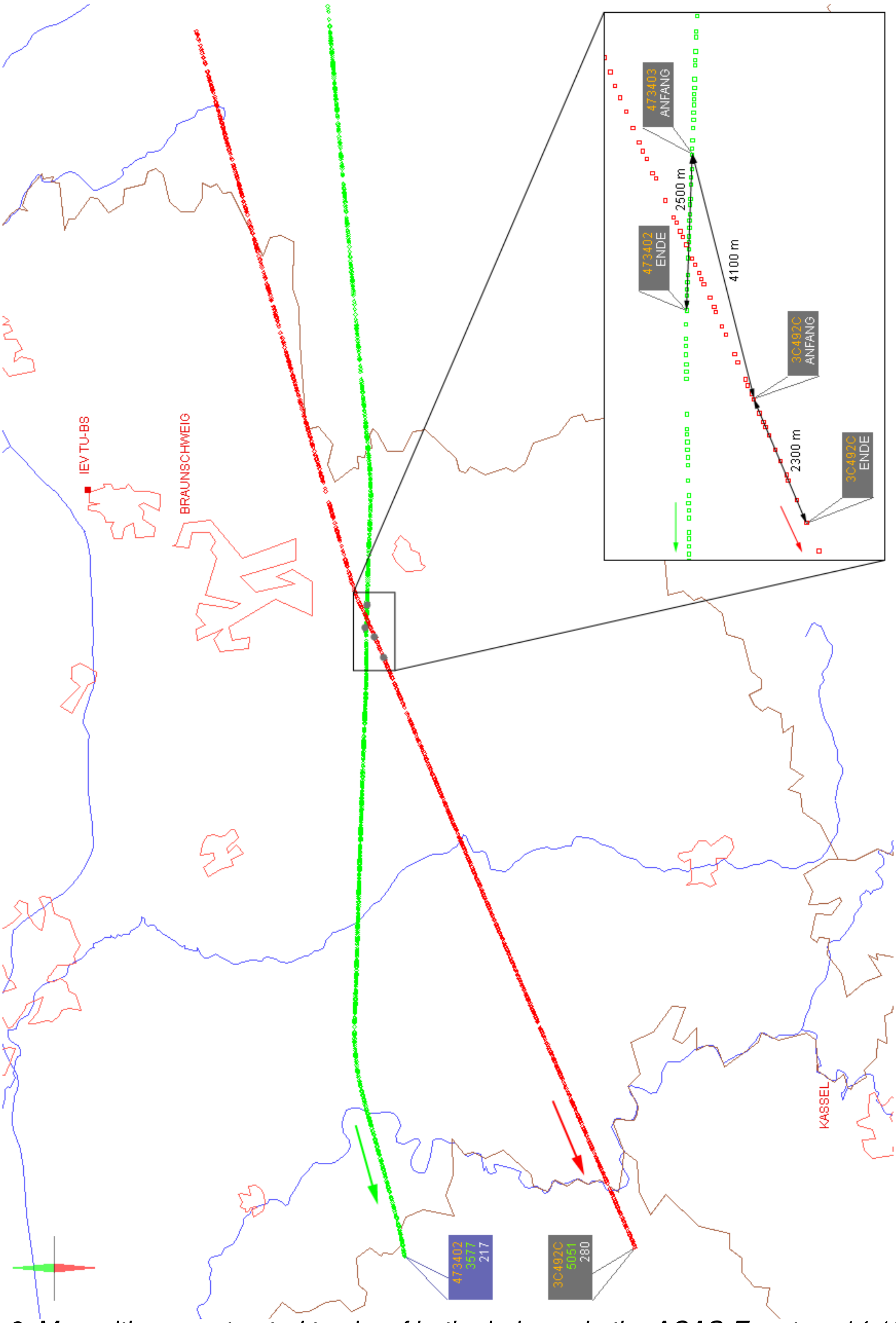

Figure 8: Map with reconstructed tracks of both airplanes in the ACAS-Event on 14.12.2005 at 21:02 near Braunschweig, 5 minutes before and after the event, and a zoomed view of the area where ACAS communication took place

5.2 ACAS-Event on 04.09.2006 near Kassel

Here an ACAS-Event is presented, that took place close to Kassel on 04.09.2006. The explanations are similar to the first event and are therefore not repeated here. Figures 9 to 11 display the ACAS-Event with the exchanged messages and the corresponding altitudes or respectively the corresponding tracks.

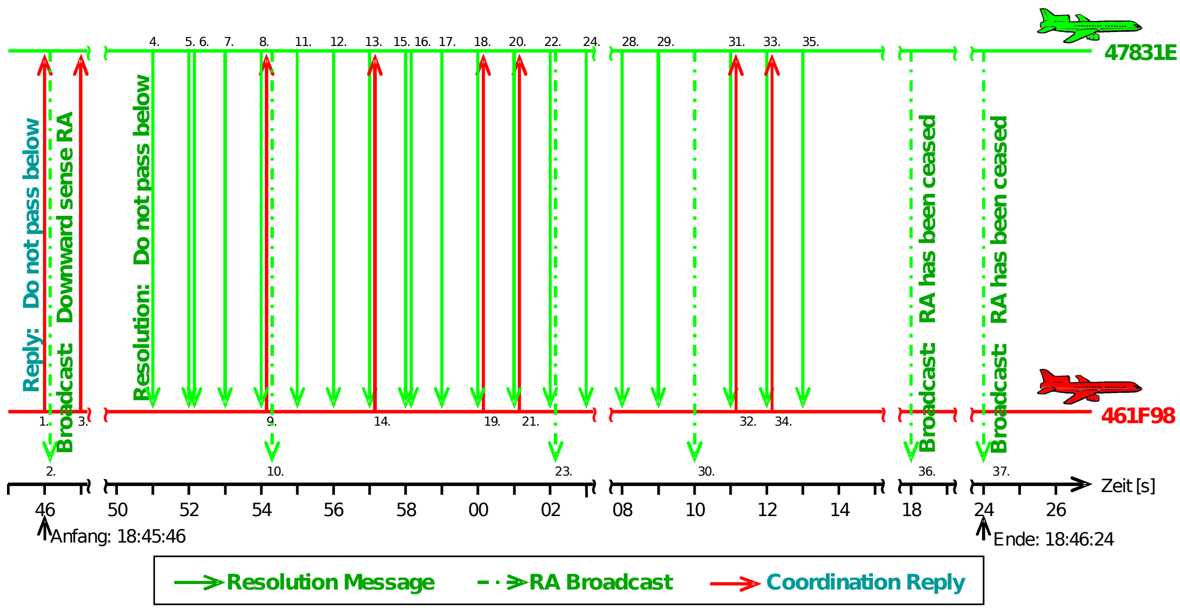

Figure 9: Time flow of the ACAS-Event on 04.09.2006 near Kassel

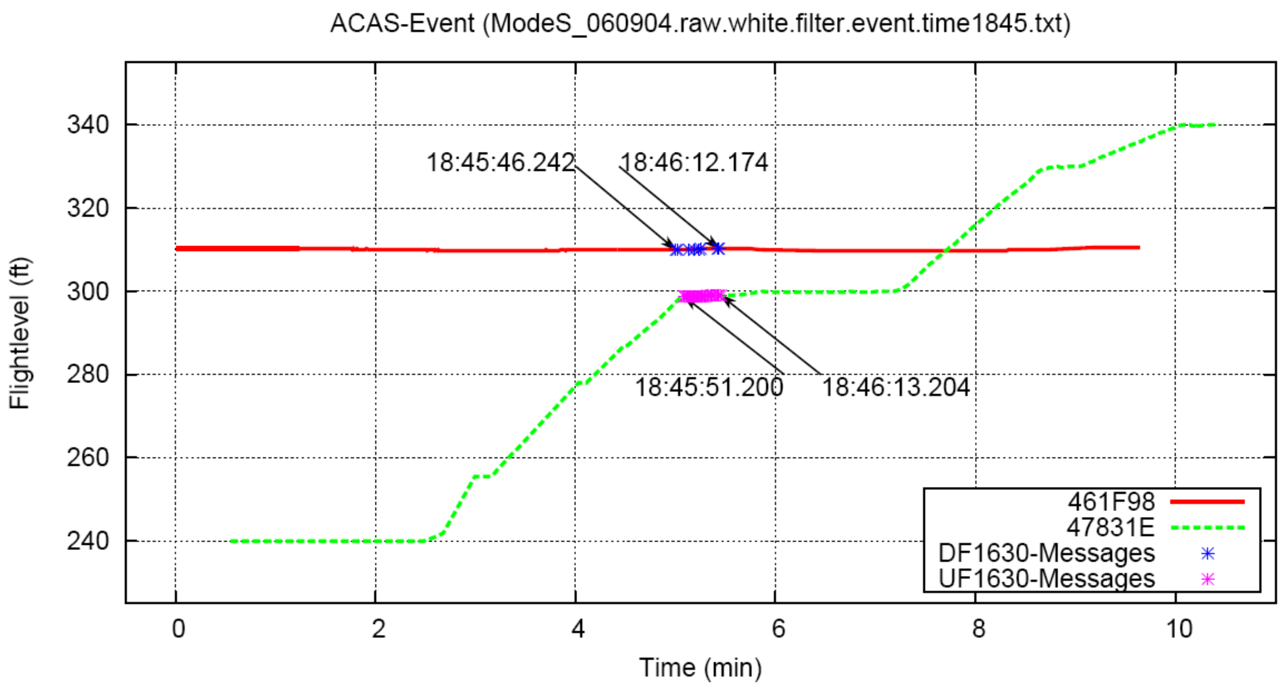

Figure 10: Altitude of the two airplanes in the ACAS-Event on 04.09.2006 at 18:45 near Kassel, 5 minutes before and after the event, overlaid with all received ACAS messages

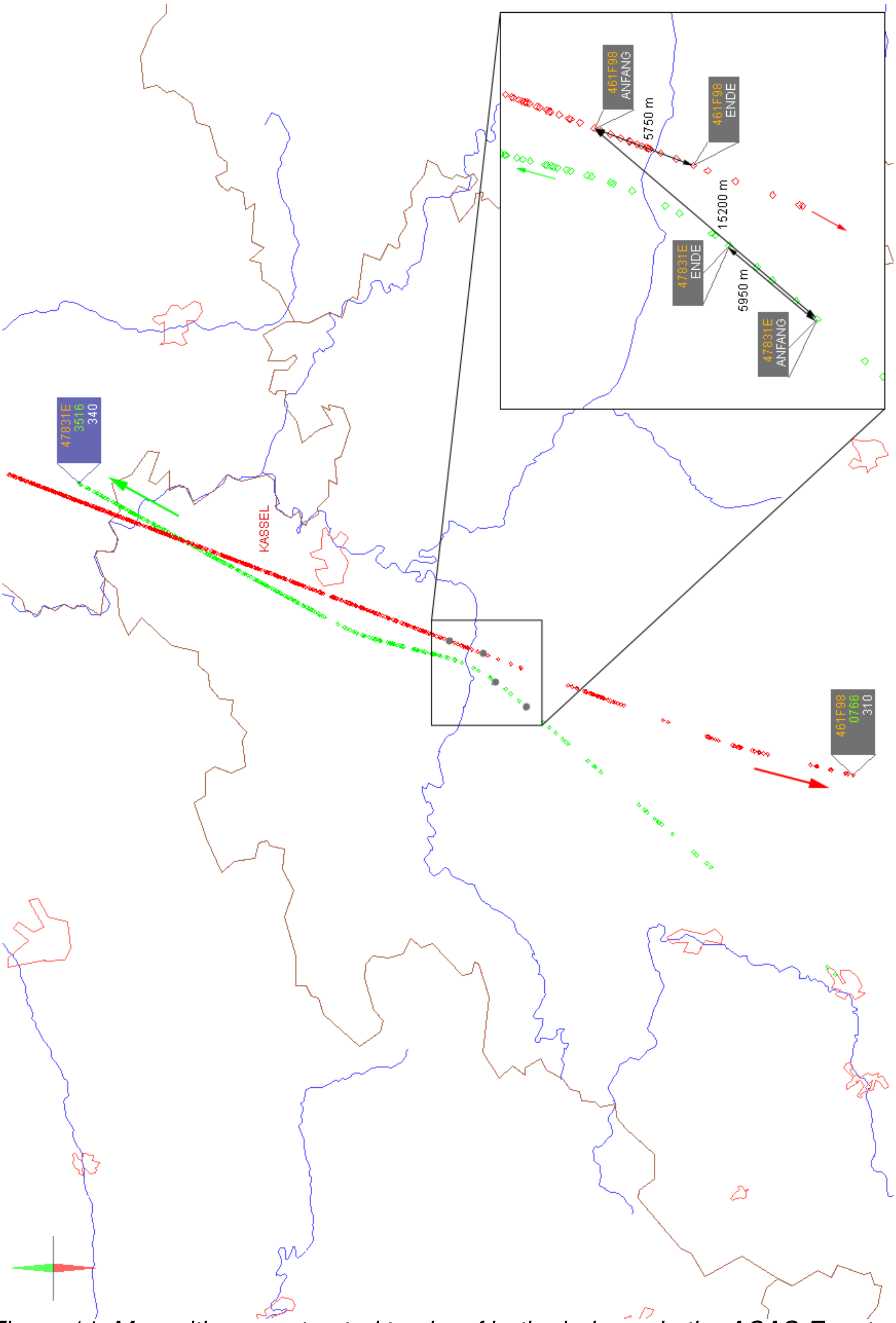

Figure 11: Map with reconstructed tracks of both airplanes in the ACAS-Event on 04.09.2006 at 18:45 near Kassel, 5 minutes before and after the event, and a zoomed view of the area where ACAS communication took place

5.3 ACAS-Event on 07.09.2006 near Kassel

Here an ACAS-Event is presented, that took place close to Kassel on 07.09.2006. The explanations are similar to the first event and are therefore not repeated here. Figures 12 to 14 display the ACAS-Event with the exchanged messages and the corresponding altitudes or respectively the corresponding tracks.

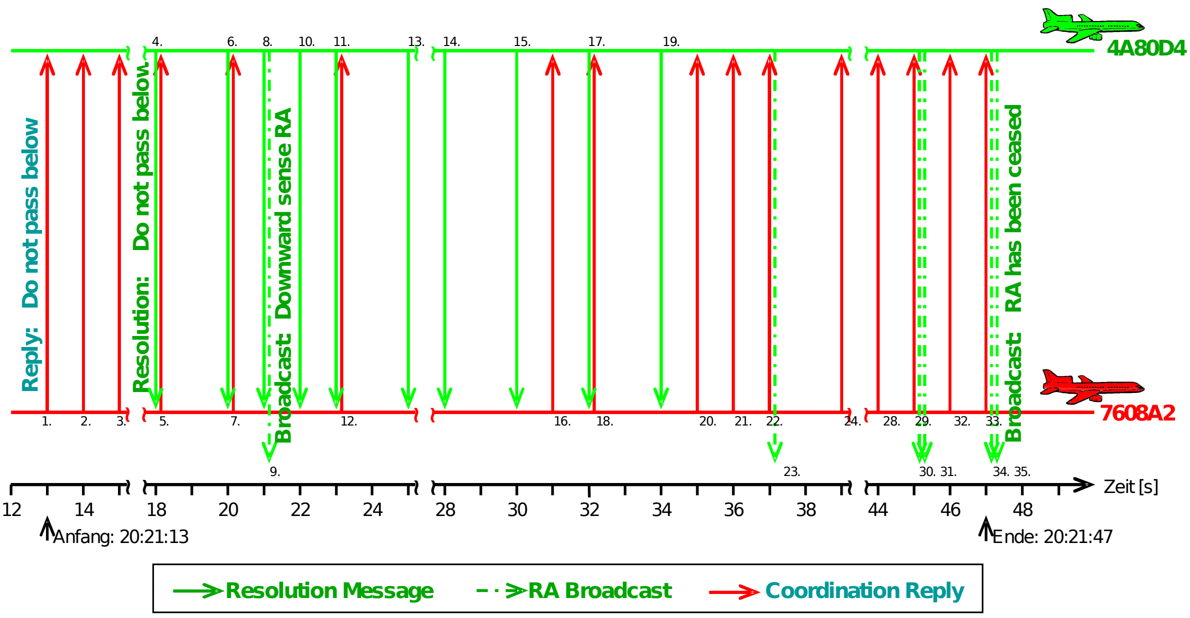

Figure 12: Time flow of the ACAS-Event on 07.09.2006 near Kassel

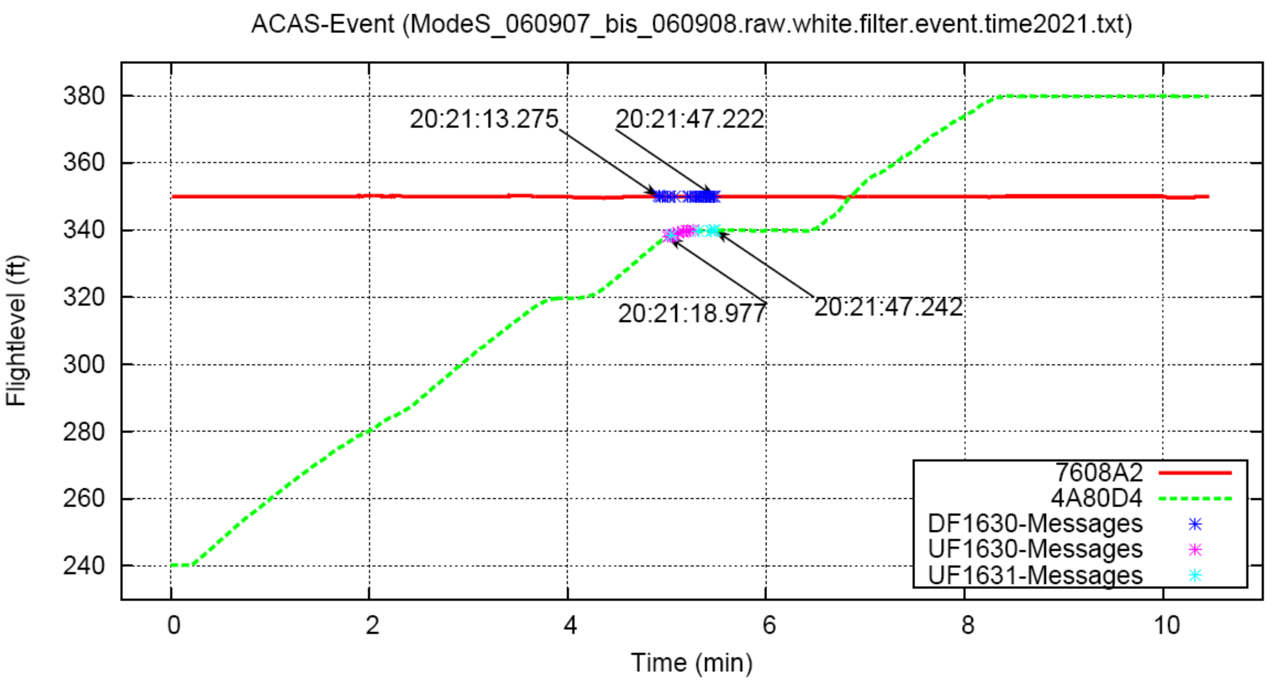

Figure 13: Altitude of the two airplanes in the ACAS-Event on 07.09.2006 at 20:21 near Kassel, 5 minutes before and after the event, overlaid with all received ACAS messages

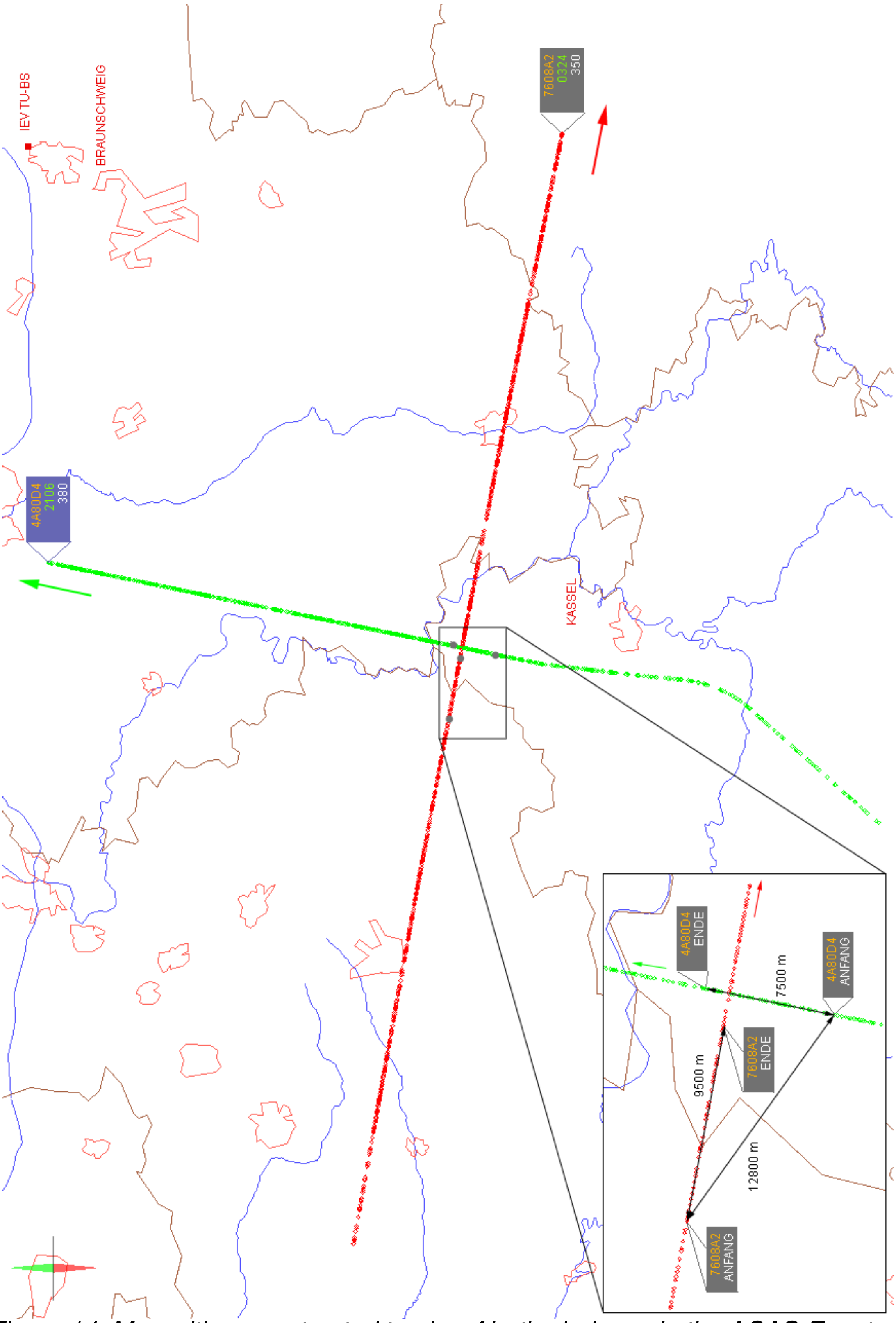

Figure 14: Map with reconstructed tracks of both airplanes in the ACAS-Event on 07.09.2006 at 20:21 near Kassel, 5 minutes before and after the event, and a zoomed view of the area where ACAS communication took place

5.4 ACAS-Event on 08.09.2006 near Dortmund

Here an ACAS-Event is presented, that took place close to Dortmund on 08.09.2006. The explanations are similar to the first event and are therefore not repeated here. Figures 15 to 17 display the ACAS-Event with the exchanged messages and the corresponding altitudes or respectively the corresponding tracks.

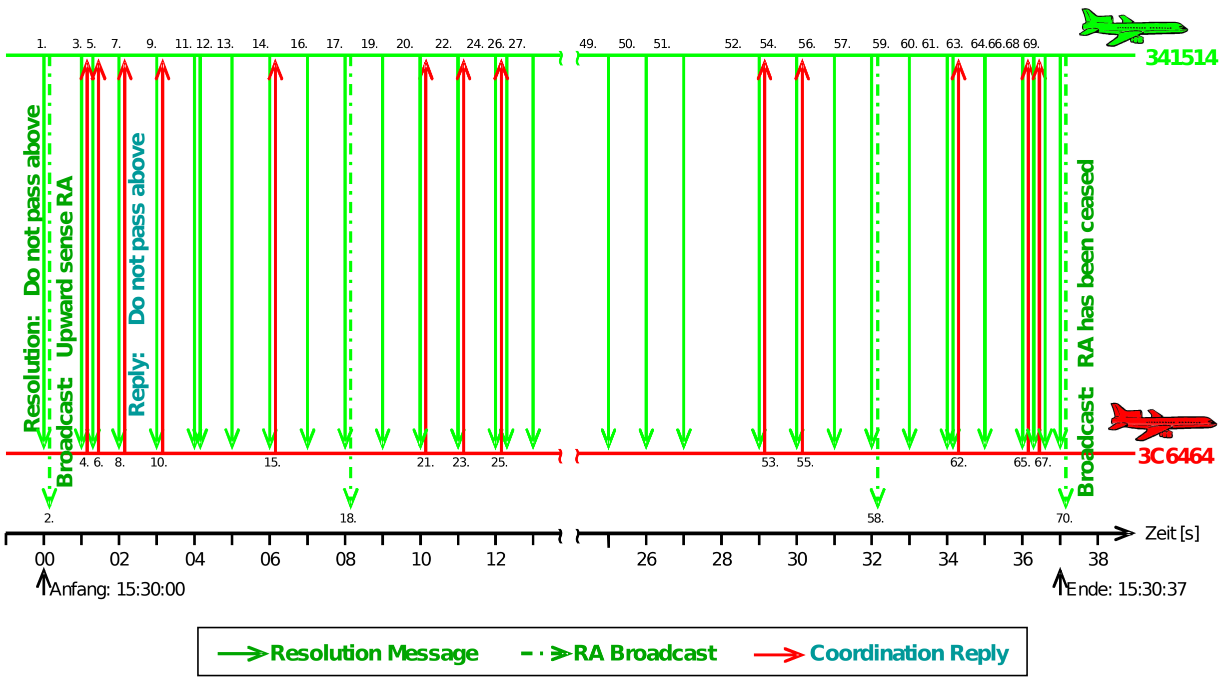

Figure 15: Time flow of the ACAS Event on 08.09.2006 near Dortmund

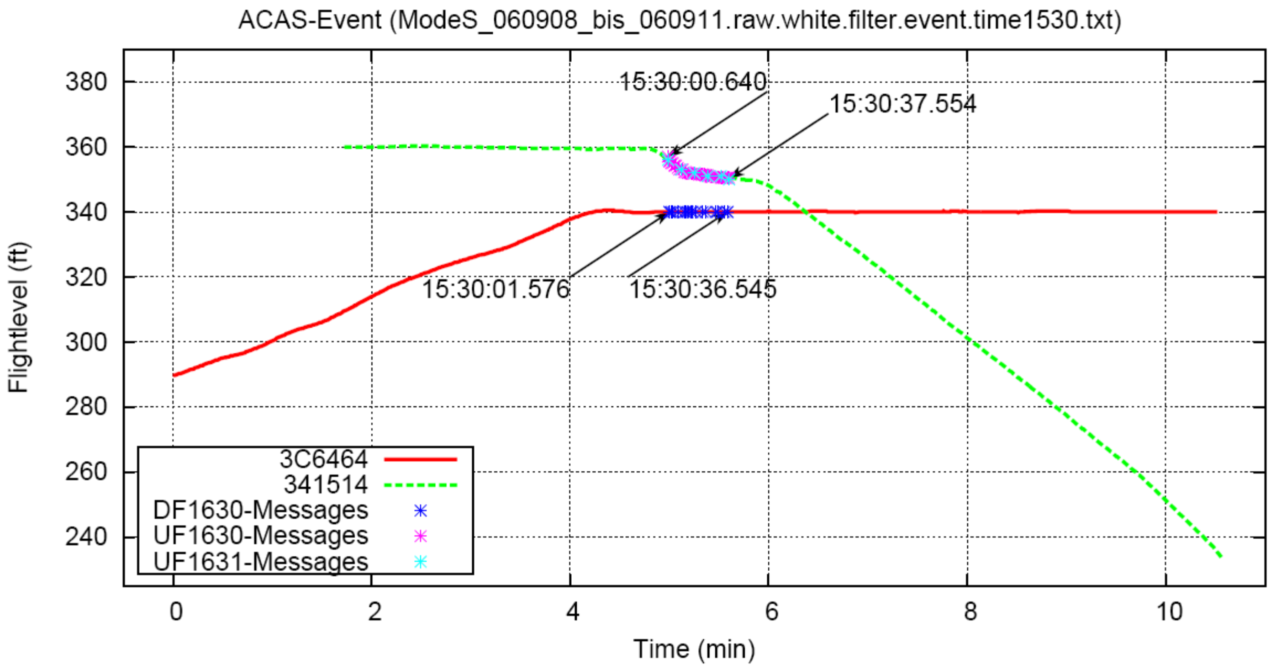

Figure 16: Altitude of the two airplanes in the ACAS-Event on 08.09.2006 at 15:30 near Dortmund, 5 minutes before and after the event, overlaid with all received ACAS messages

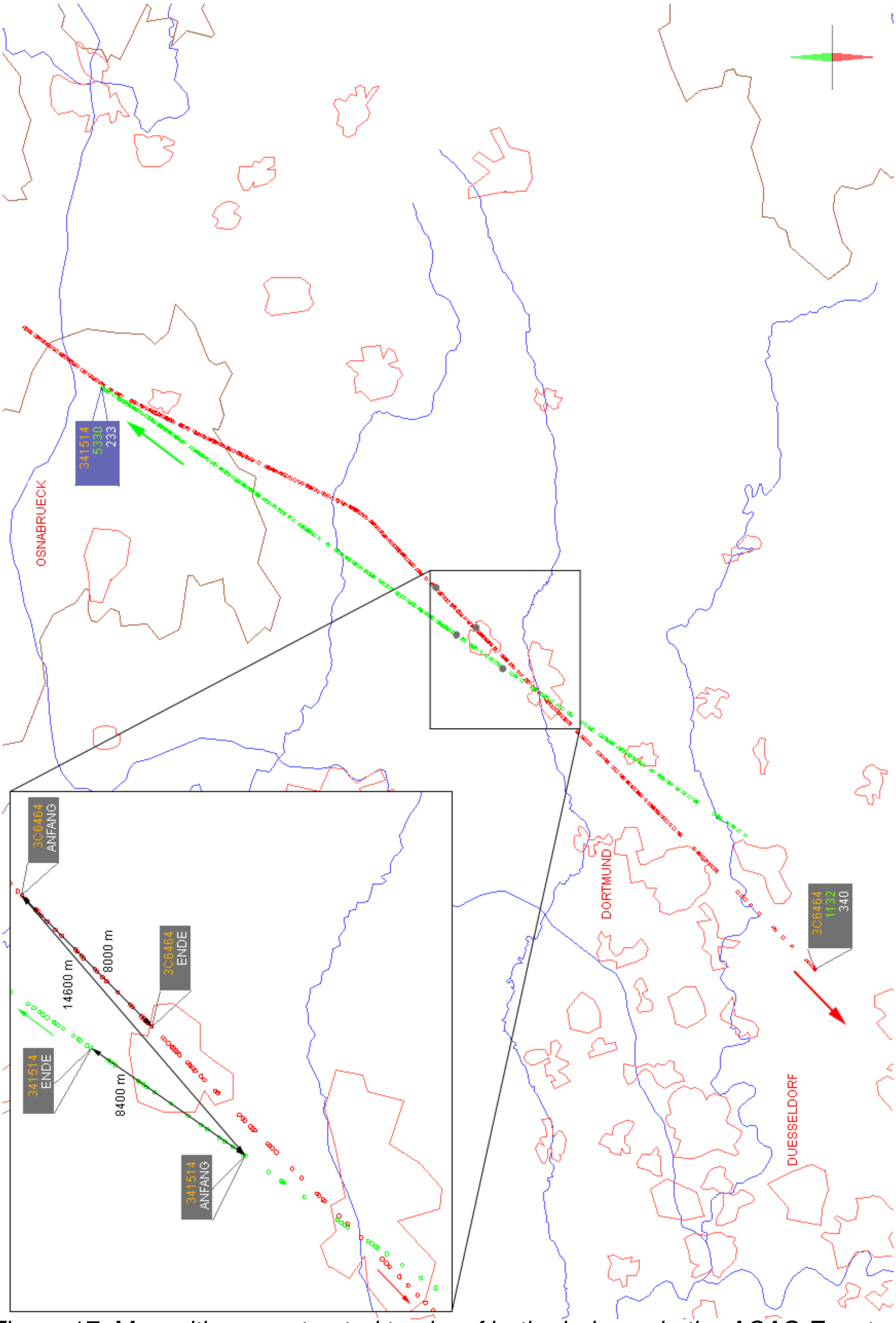

Figure 17: Map with reconstructed tracks of both airplanes in the ACAS-Event on 08.09.2006 at 15:30 near Dortmund, 5 minutes before and after the event, and a zoomed view of the area where ACAS communication took place

6 Conclusion

The described software ACASMON is obviously able to filter evidently correct ACAS-Events out of large - over 23 days long - data sets (approx. 90 GB). For the necessary operational interpretation of ACAS-Events, the corresponding altitude and position tracks from the involved airplanes are also extracted.

The observed ACAS-Events show throughout vertical conflicts, provoked by climbing or descending airplanes.

Although the ACAS-algorithm does not yet expressly level off the climbing or descending aircraft first, in these 4 ACAS-Events the ACAS of the descending or climbing aircraft fortunately reacts first by leveling off and by coordinating the cruising aircraft.

The cruising aircraft had little chance to satisfactorily solve the conflict by climb or descend.

Besides the evidently correctly observed ACAS-Events presented above, the recordings also contain a lot of fragmentary received dialogs and even some individual stray or wrong ACAS-messages. It is still an open question, how to deal with fragmentarily observed ACAS-Events and stray or wrong ACAS-messages.