Airborne Collision Avoidance System: ACAS/TCAS from the Accident Investigation's Point of View

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In 1980 he graduated in electrical engineering at the University of Applied Science in Dieburg/Darmstadt. From 1980 until 1987 he worked in various positions for the German Air Navigation Services (Bundesanstalt für Flugsicherung) and the German National Aviation Authority (Luftfahrt Bundesamt).

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On 1 July 2002 a collision between a Tupolev TU154M, which was on a flight from Moscow, Russia, to Barcelona, Spain, and a Boeing B757-200, on a flight from Bergamo, Italy, to Brussels, Belgium, occurred north of the city of Ueberlingen (Lake of Constance). Both aircraft flew according to IFR (Instrument Flight Rules) and were under control of ACC Zurich. After the collision both aircraft crashed into an area north of Ueberlingen.

A total of 71 people was on board of the two airplanes, none of which survived the crash.

The BFU investigation team identified the following immediate causes:

- The imminent separation infringement was not noticed by ATC in time. The instruction for the TU154M to descend was given at a time when the prescribed separation to the B757-200 could not be ensured anymore.
- The TU154M crew followed the ATC instruction to descend and continued to do so even after TCAS advised them to climb. This manoeuvre was performed contrary to the generated ACAS/TCAS RA.

The following systemic causes have been identified:

- The integration of ACAS/TCAS II into the system aviation was insufficient and did not correspond in all points with the system philosophy.
  The regulations concerning ACAS/TCAS published by ICAO and as a result the regulations of national aviation authorities, operations and procedural instructions of the TCAS manufacturer and the operators were not standardised, incomplete and partially contradictory.
- Management and quality assurance of the air navigation service company did not ensure that during the night all open workstations were continuously staffed by controllers.
- Management and quality assurance of the air navigation service company tolerated for years that during times of low traffic flow at night only one controller worked and the other one retired to rest.

Investigation

An essential part of the investigation done by the German Federal Bureau of Aircraft Accident Investigation (BFU) was the investigation of ACAS/TCAS. The accident was not prevented even though both airplanes were equipped with ACAS/TCAS II, Version 7.
One of the major questions in this investigation was:
Why was ACAS/TCAS not able to prevent the midair collision?

ACAS/TCAS System Description

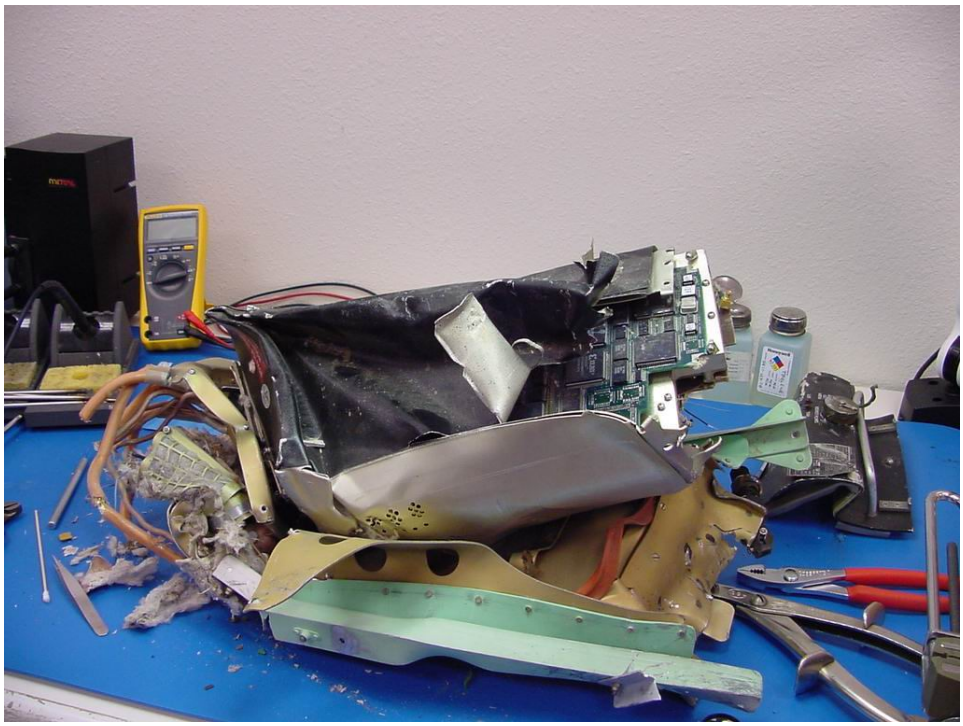
ACAS/TCAS operates by interrogating Mode C or Mode S transponders installed in other aircraft, and uses the responses to identify traffic conflicts within a protected volume of airspace around the aircraft. The system generates traffic advisories (TAs) to assist the flight crew to locate and monitor other traffic that may present a collision hazard. If ACAS/TCAS determines that an intruder aircraft will enter the protected airspace around the aircraft the system generates a resolution advisory (RA). The RA provides the crew with collision avoidance guidance.

ACAS/TCAS Data Recovered from Internal Processor Card

To rule out a technical malfunction of the ACAS/TCAS computer it was a most important aim to read out all data stored by the computers.

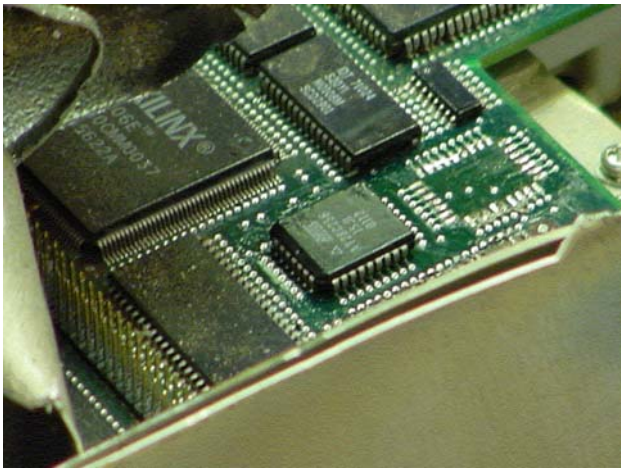
The ACAS/TCAS computer of the B757-200 was completely destroyed by impact forces and fire. Some data could be determined by reading out the TU154M computer because each ACAS/TCAS computer of the airplanes involved stores data of the other.

The non volatile memory of the ACAS/TCAS computer of the TU154M was read out at the ACAS/TCAS manufacturer under supervision of members of the BFU investigation team.



The damaged ACAS/TCAS computer of the TU 154M

The recovered ACAS/TCAS computer of the TU154M had been crushed during impact and the face-plate was partially detached from the processor chassis. Because of the damage to the computer, the unit was not bench testable. The processor card was not in a condition to be placed into another intact unit in order to download the contents of the memory chips into an serviceable unit. The two identified chips were cleaned and then removed (de-soldered) from the processor circuit card. The chips were placed into a microchip reader and the contents downloaded into a 3.5” floppy disk.



Processor card and de-soldered memory chip

The downloaded data was then imported into a software package called “TRAFFIQ System” (Traffic Resolution Advisories and Fault Failure Inspection and Query System). The event history file was opened and the resultant data examined by the investigation group. There were two situations during the flight for which the ACAS/TCAS computer generated event numbers and stored the course of events in the data memory.

The data included the measured values of own aircraft (altitude, bearing, distances) and the altitude information of the intruder received via the transponder. ACAS/TCAS calculated the values for the rate of climb and descent from the received altitude information and stored them. This data could also be analysed. Therefore, important information for the reconstruction of the flight paths of both airplanes was available.

The following ACAS/TCAS data of the TU154M was extractable from the memory:

Time (UTC)	Altitude (feet)	V/S (ft/min)	Intruder Range (NM)	Bearing (deg)	Advisory
21:34:32	35968	217	11.97	325	-
21:34:34	35968	140	11.56	326	-
21:34:36	35968	45	11.16	326	-
21:34:38	35968	49	10.75	328	-
21:34:40	35968	-70	10.31	328	-
21:34:42	35968	-101	9.94	328	TA
21:34:44	35968	-66	9.53	328	TA
21:34:46	35968	-62	9.12	328	TA
21:34:48	35968	-13	8.69	328	TA
21:34:50	35968	42	8.31	328	TA
21:34:52	35968	-65	7.88	329	TA
21:34:54	35968	-166	7.48	328	TA
21:34:56	35968	-155	7.11	326	RA Climb
21:34:58	35968	-168	6.69	325	RA Climb
21:35:00	35968	-451	6.31	323	RA Climb
21:35:02	35968	-705	5.91	322	RA Climb
21:35:04	35840	-1072	5.48	322	RA Climb
21:35:06	35840	-1117	5.09	323	RA Climb
21:35:08	35840	-1421	4.69	323	RA Climb
21:35:10	35712	-1871	4.30	322	RA Climb
21:35:12	35712	-1841	3.91	321	RA Climb
21:35:14	35584	-2025	3.52	321	RA Climb

21:35:16	35456	-2227	3.12	321	RA Climb
21:35:18	35456	-2347	2.73	319	RA Climb
21:35:20	35328	-2377	2.34	316	RA Climb
21:35:22	35328	-2212	1.96	315	RA Climb
21:35:23	35200	-2152	1.77	316	RA Climb
21:35:25	35200	-1920	1.40	315	RA Climb
21:35:27	35072	-1766	1.00	315	RA Climb
21:35:29	35072	-1957	0.63	314	RA Climb
21:35:31	34944	-1841	0.24	307	RA Climb
21:35:33	34944	-1335	0.00	162	RA Climb
21:35:34	34944	-1335	0	152	-

Note:

Instead of the relative time scale of the ACAS/TCAS devices (elapsed time) the UTC time was included by the BFU.

Altitude: resolution 128 ft, truncation, calculation based on a source with 25 ft resolution
V/S: Calculation based on altitude, resolution 25 ft
Intruder Range: distance from the B757-200 in NM
Intruder Bearing: Angle to the B757-200 related to the longitudinal axis of the TU154M

The advisory “increase climb” was stored in the memory and the time of storage determined on the basis of the raw data was 21:35:24 hrs.

The following information (Altitude, V/S and Advisory) is ACAS/TCAS data of the B757-200 interrogated and stored by the TU154M computer:

Time (UTC)	**Altitude (feet)**	**V/S (ft/min)**	**Advisory**
21:34:32	35968	0	-
21:34:34	35968	0	-
21:34:36	35968	0	-
21:34:38	35968	0	-
21:34:40	35968	0	-
21:34:42	35968	0	-
21:34:44	35968	0	-
21:34:46	35968	0	-
21:34:48	35968	0	-
21:34:50	35968	0	-
21:34:52	35968	0	-
21:34:54	35968	0	-
21:34:56	35968	0	RA Descent
21:34:58	35968	0	RA Descent
21:35:00	35968	0	RA Descent
21:35:02	35968	0	RA Descent
21:35:04	35968	-377	RA Descent
21:35:06	35840	-624	RA Descent
21:35:08	35840	-1222	RA Descent
21:35:10	35840	-1462	RA Descent
21:35:12	35712	-1541	RA Descent
21:35:14	35712	-1987	RA Descent
21:35:16	35584	-2047	RA Descent
21:35:18	35456	-2640	RA Descent
21:35:20	35456	-2617	RA Descent
21:35:22	35328	-2700	RA Descent
21:35:23	35328	-2535	RA Descent
21:35:25	35200	-2370	RA Descent

21:35:27	35072	-2452	RA Descent
21:35:29	35072	-2422	RA Descent
21:35:31	34944	-2392	RA Descent
21:35:33	34816	-4260	RA Descent
21:35:34	34688	-4260	-

Note:
Instead of the relative time scale of the ACAS/TCAS devices (elapsed time) the UTC time was included by the BFU.

Altitude: Resolution 128 ft, truncation, calculation based on a source with 25 ft resolution (transponder reply of B757-200)
V/S: calculation based on altitude, resolution 25 ft

The advisory "increase descent" as an individual command was not transmitted to the TU154M. This command was recorded on the CVR at 21:35:10 hrs.

The ACAS/TCAS investigation team also examined the maintenance fault information from the processor card. The following six faults were recorded:

1. XT Bus 2 Failure
2. Radalt Failure: No Radalt #2 Found
3. CFDS Bus Fail
4. XT Bus 1 Fail Label Error
5. XT Bus Fail No Active XT
6. TA Display 1 Failure

Design engineers from the ACAS/TCAS manufacturer indicated that there was no current method to correlate the maintenance fault information to the event flight history information.

ACAS/TCAS Operational Findings

Based on the recovered data the following timeline shows the functions of the ACAS/TCAS computers after the identification, the positioning and the transponder interrogation:

21:34:32 hrs
The airplanes flew at FL 360 (altitude difference was approximately 50 ft) and at a distance of 11.97 NM.
The ACAS/TCAS of the TU154M localized the B757-200 at an angle of 325° (-35° related to its own longitudinal axis).

21:34:42 hrs
The ACAS/TCAS devices of both airplanes generated a TA simultaneously. The distance between the two airplanes was 9.94 NM.

21:34:56 hrs
The ACAS/TCAS devices of both airplanes generated an RA simultaneously because they continued to fly at the same altitude.
The distance between the two airplanes was 7.11 NM.
The RA in the TU154M was "climb", "climb"
The RA in the B757-200 was "descend", "descend"
(FDR data showed that both airplanes started to descend at 21:34:57 hrs.)

21:35:10 hrs
The distance between the two airplanes was 4.3 NM.
The ACAS/TCAS of the B757-200 generated the advisory "increase descent".

21:35:24 hrs
The distance between the two airplanes was 1.54 NM.

The ACAS/TCAS of the TU154M generated the advisory “increase climb”.
Both airplanes were still in descent with almost the same rate of descent and an altitude difference of less than 100 ft.

21:35:34 hrs
Collision of the airplanes.

Evaluation of the Collision Avoidance System Logic (CAS Logic)

Prior to the issuance of the RAs the airplanes were in cruise flight with a vertical speed of almost zero and an altitude difference of approximately 50 ft.

Both airplanes reported their altitude in 25 ft increments. They tracked an altitude difference of one or two increments, whereas the B757-200 was below the TU154M. Thus the altitude difference was the decisive factor for the selection of the direction of the RA’s, CAS logic avoids crossing trajectories.
Following the RAs and the initiated avoidance manoeuvres the calculated distance at the CPA (Closest Point of Approach) normally increases until the ACAS/TCAS computer generates the aural annunciation “Clear of Conflict”.

Due to the contrary reaction of the TU154M crew the calculated distance to the B757-200 at the CPA did not increase. 14 seconds after the initial RA the CAS logic of the B757-200 generated an RA “increase descent” (increase the rate of descent from 1 500 ft/min to 2 500 ft/min) in order to resolve the persistent conflict. The CAS logic of the TU154M also generated an RA “increase climb” (increase the rate of climb from 1 500 ft/min to 2 500 ft/min) 28 seconds after the initial RA.

The “increase” advisories are not coordinated between the ACAS/TCAS computers of airplanes involved in the encounter. ICAO Annex 10 states that CAS logic computes an extrapolated trajectory instead of using real tracked values. This leads to different times for the issuance of strengthening RAs in the airplanes involved.

When the crew of the B757-200 complied with the advisory “increase descent” the altitude difference between the two airplanes decreased.

ACAS/TCAS II, Version 7 is capable of generating a Reversal RA, i.e. a coordinated RA into a direction contrary to the initial RA. The Reversal is a way out, if during the avoidance manoeuvre an inversion of the original geometrical situation of the flight paths occurred. This situation will arise in particular if the crews respond contrary to the initial RA.

Eurocontrol ACAS/TCAS II Analysis

A Eurocontrol ACAS/TCAS specialist team has analysed the accident based on three ACAS/TCAS simulations. Three different data sources and two different analysing tools for ACAS/TCAS II were used.

It is the BFU’s opinion that the following important insights can be drawn from the Eurocontrol study:

- The analysis confirmed that the TA’s and RA’s in both airplanes were triggered according to the design of the CAS-logic.
- The simulation and the analysis of the alert sequence showed that the initial RA’s would have ensured a safe vertical separation of both airplanes if both crews had followed the instructions accurately.

Moreover, Eurocontrol conducted a further analysis how TCAS II would have reacted in this case with the modification CP 112 which had already been developed prior to the accident. According to the results provided, ACAS/TCAS would have generated a Reversal RA after the initial RA which would have led to a sufficient vertical separation of both aircraft if the Boeing B757-200 crew would have reacted according to the Reversal RA.

Regulations and Procedural Instructions

As ACAS/TCAS II, Version 7 is designed as a semiautomatic system which shall serve as a "last line of defence" in collision avoidance, clear and unambiguous procedural instructions for the crews are an essential prerequisite. This prerequisite is so important, because the system philosophy of ACAS/TCAS II, Version 7 provides only one procedure after the issuance of an RA and that is to follow the generated RA.

The decision to follow an RA without reservation could mean that up to the resolution of the conflict the crew has to divert from other obligatory standards for instance, from instructions for vertical separation issued by ATC and from other general right-of-way rules.

Regulations of the International Civil Aviation Organization (ICAO)

In view of the international importance of ACAS/TCAS, the establishment and publication of standardised procedures by ICAO are an essential requirement.

ACAS/TCAS has been mandatory in the USA since 1993 and in Europe and the Middle East since 2000, but is not yet required in other parts of the world. Thus the installation of ACAS/TCAS was one prerequisite the operator of the TU154M had to fulfil in order to be allowed to fly to European destinations. For domestic flights within the Russian Federation ACAS/TCAS is not presently required.

The publications of the ICAO concerning ACAS/TCAS are evaluated by the BFU as follows:

Annex 2:
In Annex 2 (Rules of the Air) procedural instructions for the utilization of ACAS/TCAS are not taken into account sufficiently.
Though the wording,
"*The aircraft that has the right–of-way shall maintain its heading and speed, but nothing in these rules shall relieve the pilot-in-command of an aircraft from the responsibility of taking such action, including collision avoidance manoeuvres based on resolution advisories provided by ACAS equipment, as will best avert collision"* (Rules of the Air, Chapter 3. 3.2.2 Right–of–way),
allowed a deviation from the right-of-way rules in case of a ACAS/TCAS RA. It did not make clear, however, the required consequent action to be taken by the pilot in case of an RA.

Annex 10:
The note,
"*Contrary pilot response" […]* was adequate and clear, however, its placement in Annex 10 was unfavourable as this Annex contains mainly technical specifications. A better place for this instruction would have been Annex 2 or Doc 8168.

Doc 8168, PANS-OPS:
In Doc 8168 the "Operation of ACAS Equipment" was to be described. These objectives have not been achieved as the descriptions of the procedures were insufficient and unclear.
With the statements,
"*assists pilots in operation of the aircraft*" and "*Nothing in the procedures shall prevent pilots-in-command from exercising their best judgement and full authority in the choice of the course of action to resolve a traffic conflict*" (3.1.1. and 3.1.2 of Doc 8168)
the pilots were given freedom of decision which according to the ACAS/TCAS philosophy must not be granted. The procedural requirement to comply with an RA and to immediately report the avoidance manoeuvre advised by ACAS/TCAS to the controller responsible for the vertical separation was not described clearly enough in the Doc 8168. Thus the situation of a coincidence of an RA with an instruction given by the controller had not been dealt with either.

Doc 4444, PANS-ATM:
With the publication of the Doc 4444 a procedural description (15.6.3.2) has been issued for the Air Navigation Services pursuant to which the controller should not influence the flight path in case the pilot reports a ACAS/TCAS RA, until the conflict has been resolved.

A prerequisite for the effectiveness of this procedural instruction is the timely report of a ACAS/TCAS RA via radio as an automatic transmission from the aircraft to the ground is not provided.

State Letter AN 11/19-02/82:
In the State Letter dated 8 August 1997 the procedures to react to an RA and the necessary training procedures were described much more clearly. The wording, however, did not comply with the procedural descriptions in Annex 2 and Doc 8168, partially the interpretation was even contradictory.

TCAS 2000/TCAS II Traffic Collision and Avoidance System Pilots Guide

The specifications of the ACAS/TCAS manufacturer's "Pilots Guide" regarding the ACAS/TCAS system philosophy and the necessary procedures which ensure a safe function were not described distinct enough. The wording "*TCAS 2000 is a backup to the ATC (Air Traffic Control) system and the see and avoid concept"* could be interpreted that ATC takes priority over TCAS and that TCAS is designated to be implemental or a substitute. It was not made clear in the description of the system philosophy that ACAS/TCAS is exclusively meant as a "last line of defence" for the avoidance of a collision and that in this stage ACAS/TCAS advisories must be disconnected from instructions given by ATC controllers.

"TCAS 2000 Pilots Guide" does not state clearly enough that the safe separation accomplished through ATC and the tasks of ACAS/TCAS are two different functions. It is not clear that ACAS/TCAS is not part of the conceptual design of ATC.

In the chapter "Pilot Responsibilities" a sufficient directness is missing. On one hand it talks about "Backup for ATC" and on the other uses the following wording by contrary instructions of ATC and ACAS/TCAS.

- *Must not delay in responding to the RA.*
- *Must not modify a response to an RA.*
- *Must follow the RA manoeuvre, unless invoking "Emergency Pilot Authority.*

The descriptions in the "TCAS 2000 Pilots Guide" were the basis of ACAS/TCAS trainings within the operator companies and for the procedures in the Flight Operation Manuals.

TU154M Flight Operations Manual

The passage:
For the avoidance of in-flight collisions is the visual control of the situation in the airspace by the crew and the correct execution of all instructions issued by ATC to be regarded as the most important tool. TCAS is an additional instrument which ensures the timely determination of oncoming traffic, the classification of the risk and, if necessary, planning of an advice for a vertical avoidance manoeuvre.
made clear that ATC has the highest priority in the avoidance of collision risks.

Regulations from Eurocontrol

All Eurocontrol publications for ACAS/TCAS introduction, training and utilisation have a recommending character.

All Eurocontrol documents expressed a clear ACAS/TCAS philosophy and clear rules of action and procedural instructions following the issuance of an RA.

Regulation from the JAA

The JAA Leaflet No. 11 had no legal significance in the accident as the States of Registry and the States of the Operators of both airplanes were no JAA Member States.

National Regulations and Procedures

Aeronautical Information Publication (AIP) Germany
The explanations in the Aeronautical Information Publication Germany concerning ACAS/TCAS were not up to date for ACAS/TCAS II, Version 7. With regards to contents several terms, e.g. “Evaluation of ACAS/TCAS” were related to the introduction phase.

The procedural instruction for the actions to be taken by the pilots in case of an RA was not worded clearly enough.

Luftverkehrsordnung (LuftVO - Air Traffic Order):
Pursuant to § 13 subpara 9 a deviation from the right-of-way rules was possible.
With the wording,
“*This also applies to diversionary manoeuvres which are based on recommendations given by collision avoidance equipment on board*” the pilots are granted a freedom of decision which is not compatible with the system philosophy of ACAS/TCAS II, Version 7. For the purpose of the ACAS/TCAS philosophy the use of the term “recommendation” is inadequate. In case of an RA there can be only one reaction of the pilots: to follow the RA.

Furthermore the wording allows two different kinds of interpretation:
The paragraph can mean that independent of the right of way rules an RA must be followed in order to avoid a collision.
The paragraph can also mean that the pilots have the option to deviate from the right of way rules and the ACAS/TCAS RA's in order to avoid a collision.
In theory it might be possible in reality not really practicable. In principle it is correct to give the pilot the final power of decision, the pilot, however, has no better basis for his decision than ACAS/TCAS can give.

Advisory Circular (AC) by the Federal Aviation Administration (FAA):
In the AC which had no legal effect on the airplanes involved, the procedures following the issuance of an TA/RA as well as the responsibilities (for the individual flight crew members) and the training measures were described clearly and unambiguously. The training program of the B757-200 operator was based on this document.

Safety related conclusions

- In case of failure by ATC to provide safe separation between aircraft, ACAS/TCAS provides an independent safety net in preventing mid-air collisions.
- ACAS/TCAS is an effective system, but its ability to fulfil its role is entirely dependent on correct and timely flight crew responses to collision avoidance manoeuvres calculated and displayed by the system.
- The procedure for pilots has to include the following elements:
    - In the event of an ACAS/TCAS Resolution Advisory (RA) to alter the flight path pilots shall respond immediately and manoeuvre as indicated, unless doing so would jeopardize the safety of the airplane.
    - Never manoeuvre in the opposite sense to an RA, nor maintain a vertical rate in the opposite sense to an RA.
- The regulations concerning ACAS/TCAS published by ICAO and as a result the regulations of national aviation authorities, operational and procedural instructions of the ACAS/TCAS manufacturer have to be standardized, clear and unambiguous.

Note:
Focus of this paper is an ACAS/TCAS point of view. Further investigation aspects concerning ACAS/TCAS in the BFU final report are human factors (HF) and training. A download of the final report is available at http://www.bfu-web.de/ .