Analysis of RA Downlink data

Performance and Safety Aspects of Short-term Conflict Alert – Full Study

PASS project

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RECORD OF CHANGES

Issue	Date	Detail of changes
0.1	03-06-2008	Summary draft
0.2	30-06-2008	Initial draft presented during the 3rd progress meeting
0.3	11-07-2008	Draft with terminology changes and reduced images
1.0	03-09-2008	Integration of HD's comments + additions
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1.3	19-01-2009	Additions and corrections
1.4	02-02-2009	Released version
1.5	30-03-2009	Correction – figure 55

IMPORTANT NOTE: **EACH NEW VERSION SUPERSEDES THE PRECEDING VERSION, WHICH MUST BE DESTROYED OR CLEARLY MARKED *OBSOLETE VERSION* ON THE FRONT PAGE.**

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Abstract

EUROCONTROL launched the **P**erformance and Safety **A**spects of **S**hort-term Conflict Alert – Full **S**tudy (**PASS**) project in October 2007. The aim of this three-year study is to progress towards the establishment of quantified performance requirements for STCAs and to define a consistent overall concept for ground-based and airborne safety nets. The PASS study started with a monitoring phase in order to understand the current operational situation.

To support the monitoring phase, RA downlink data originating from six Mode-S radars with a coverage including most of the European core area were collected from September 2007 to March 2008. The captured traffic corresponds to more than 1,300,000 flight hours, and more than 350,000 RA downlink messages were gathered.

The initial RA downlink monitoring performed by the DSNA highlighted a number of deficiencies in the downlinked messages. A more in-depth analysis was therefore conducted, focusing on the reliability of RA downlink and on the operational view of ACAS performance that it can provide.

Cross-checks between RA downlink data, Mode-S track data and the results of ACAS simulations of aircraft trajectories, under the critical eye of an operational expert, made it possible to quantify not only those deficiencies which were already known in the downlinked messages but also a number of additional ones. The most prominent deficiency was the overwhelming proportion (96%) of empty RA messages, a problem already known but still not resolved. Another example was incorrect threat-position information, which was downlinked in one third of the cases in which the threat aircraft was a Mode-A/C aircraft. The cross-checking of "Communications and ACAS Capability" with the RA downlink data also highlighted errors such as incorrect format indicator (9%) and incorrect ACAS capability (17%). Although none of the aforesaid deficiencies had any operational impact, they should be considered for RA monitoring and for RA display on a controller working position. On the other hand, more serious faults were detected in relation to "Flight Status". In six cases, faulty aircraft on the ground caused RAs to be triggered on board aircraft on final approach.

Despite these faults, the RA downlink technique using RA reporting worked properly in general, and no major issues were identified. Thanks to the radars used, the observed mean refresh rate was about five seconds, decreasing to three seconds for a quarter of the encounters detected by several radars.

Nearly 1,030 aircraft downlinked valid RA downlink messages. On average, therefore, RAs were triggered every 960 flight hours. However, taking into account only unintentional encounters, a civilian aircraft experienced an RA every 1365 flight hours.

On average, the captured RAs lasted between 5 and 45 seconds (in 85% of cases), and some of them (5%) lasted more than one minute.

The corresponding 880 encounters were analysed. In each of them, there was at least one aircraft with an RA on board. Half of the encounters were between two TCAS-equipped aircraft, but only two thirds of them did not give rise to a coordinated RA. The main reason was the TCAS feature, designed to reduce the rate of RAs in 1,000-feet level-off geometries, which meant that no RA was issued on board the level aircraft. The second cause was a dissymmetric view either of the horizontal or of the vertical situation on board each aircraft. A number of threat aircraft were operating TCAS manually in TA-only mode, but this was mainly the case for military aircraft.

About 12% of the threat aircraft were equipped with Mode-S transponders only (without TCAS or with inoperative TCAS), and 29% were Mode-A/C equipped. Of the Mode-S threats, five were under TCAS mandate and suspected not to be TCAS equipped. One case of TCAS failure and another of TCAS switch-off were also detected.

About 70% of the encounters were unintentional, and 16% were classified as intentional. These intentional encounters were civilian-aircraft interceptions by fighters, military operations and also test flights with escorts.

A non-negligible part (7%) of the encounters corresponded to “ghost” threat aircraft. There were simulated threats during test flights, transponder tests on the ground with modified reported altitudes, false altitudes owing to garbling, originating mainly from a small number of military aircraft, and, lastly, self-tracking cases.

Among the unintentional encounters, the majority (61%) of RAs were solely “adjust vertical speed” RAs. In 24% of cases, the RA was a “climb” or “descend” RA, usually followed by a weakening RA to “adjust vertical speed”. About 10% were preventive RAs, occurring mainly between IFR arrivals and VFR flights.

1. Introduction

1.1. Context

1.1.1. EUROCONTROL launched the **P**erformance and Safety **A**spects of **S**hort-term Conflict Alert – Full **S**tudy (**PASS**) project in October 2007. This three-year study was undertaken on the basis of the recommendations resulting from the work of the SPIN Task Force, the FARADS study, and the ACAS & STCA Interaction and Interoperability Workshop (2007).

1.1.2. The aim is to progress towards the establishment of quantified performance requirements for STCAs, as well as the definition of a consistent overall concept for ground-based and airborne safety nets.

1.1.3. A more detailed description of the PASS project is available in paper [1], presented during the 2008 R&D Seminar in Southampton.

1.1.4. The PASS study is divided into three main phases:

- phase 1: monitoring and understanding of the current operational situation;
- phase 2: European STCA environment modelling and safety/performance analysis; and
- phase 3: enhanced modelling and analysis, synthesis and guidelines.

1.1.5. Within PASS, phase 1 includes the gathering of RA downlink data as one source of information in parallel to radar data, STCA data and incident reports (e.g. ATCO incident reports, air safety reports, incident investigation reports, etc.).

1.1.6. The initial RA downlink monitoring performed by the DSNA highlighted a number of deficiencies in the downlinked messages. A more in-depth analysis was therefore conducted following discussions at the third PASS progress meeting in Toulouse [2].

1.1.7. Since the results of this study may be of interest outside the PASS project, it was decided to not keep this document as an internal working paper but to give it external visibility.

1.1.8. The following study deals with this analysis of RA downlink data originating from six Mode-S radars with a coverage including most of the European core area. The data were collected from September 2007 to March 2008. This represents a little more than 1,300,000 flight hours.

1.1.9. The RA downlink data used for this study were Mode-S RA reports, and correspond to the extraction by Mode-S ground radar of a Comm-B message containing data about the RA.

1.1.10. This study is based on observed data relating to civilian aircraft and also to military aircraft potentially equipped with E-TCAS. Consequently, this report uses the term "TCAS" rather than "ACAS".

1.1.11. Although the structure of this report may imply that in-depth knowledge about Mode-S is assumed, readers can safely ignore all the technical details.

1.2. Objectives

1.2.1. The first objective of this report is to present quantified results relating to the quality and reliability of RA downlink data. The preliminary analysis of RA downlink data for the PASS monitoring highlighted a number of problems relating to the viability of those data. Most of the errors discovered had a technical origin, leading, for example, to the receipt of many empty messages. This issue was already known. Nevertheless, it occurred more frequently than expected. In addition, other errors were also identified.

1.2.2. The second objective is to provide a set of statistical figures dealing with the operational aspect in addition to the technical point of view. This objective has been achieved thanks to the amount of RA downlink data gathered as a consequence. This study is based on the monitoring of data from six Mode-S radars over seven months.

1.2.3. The last objective is to take advantage of the RA downlink data monitoring in order to draw up technical recommendations for the display of RA downlink on Controller Working Position (CWP). The operational usefulness of displaying RAs on CWP has not been investigated.

1.3. Methodology

1.3.1. Data from several Mode-S radars were recorded at DSNA/DTI/R&D via a connection to the DSNA/DTI radar test network (RSTNA).

1.3.2. Radar data files were processed off-line in order to extract RA downlink messages. For each sequence of RA downlink messages sent by a given aircraft, an extract of radar data was built in order to get all the data corresponding to that aircraft and to the traffic around it.

1.3.3. All RA downlink messages and radar-data extracts corresponding to a given encounter were associated. Therefore, when both aircraft involved in an encounter sent RA downlink messages, the data corresponding to both aircraft were associated. This was also the case if the encounter was seen by several radars.

1.3.4. A specific tool was developed in order to perform TCAS simulations directly from the multi-radar data (Asterix category 48). The tool performed fast-time simulations in order to obtain simulated RAs matching the RA downlink messages as closely as possible. TCAS simulation based on radar data is very sensitive to how the intruder data is computed, with a cycle of one second. This means that TCAS simulation is very sensitive to trajectory smoothing. The parameters used to smooth the trajectories were therefore slightly modified, taking care to stay within the radar-data error interval (altitude quantisation and range-azimuth radar accuracy). In addition, TCAS simulations were performed with the horizontal miss-distance filter inhibited or forced, in order to check its influence.

1.3.5. In 57% of the encounters (see 4.6.1), the TCAS simulation was fully validated because we were able to simulate a sequence of RAs matching closely the sequence of RAs from the RA downlink. In 25% of the encounters, the type of the simulated RAs were different or only TAs were simulated, but the threat was unambiguously identified. In both aforesaid cases (82%), the TCAS simulation was used as a reference to check the other contents of the RA downlink message, such as the threat identity, for example.

1.3.6. A case-by-case analysis was performed when the TCAS simulation failed to generate RA or TA. In 13% of the encounters, the threat or the ghost treat was identified. In these cases, the TCAS simulation failed due to partial radar detection (trajectories too short to analyse) or due to ghost encounter like self-tracking or garbling. The content of the RA downlink was used as the source of data for qualification of these encounters.

1.3.7. In 5% of the encounters, the threat was not identified. In some cases, expert judgement was used to qualify the encounter and the content of the RA downlink was considered here as valid.

1.3.8. The contents of BDS-10 were cross-checked against RA downlink messages, with altitude data (to check when there was a TA-only mode), and also with aircraft data derived from the ICAO address (mainly aircraft type, in order to deduce the ACAS mandate of the threat).

1.3.9. Mode A, the aircraft type and operator (derived from ICAO addresses), and the trajectories were used to qualify the encounter (e.g. military operation, test flight, transponder test, VFR).

1.3.10. All the encounter data were stored within a spreadsheet table. These data were raw data (decoded RA downlink messages, ICAO addresses, Mode A, aircraft identifications, altitudes), simulated data, derived data (aircraft type, military or civilian aircraft) and results of the analyses performed by a TCAS expert.

1.4. Terminology

1.4.1. **RA downlink message**: content of BDS-30 extracted by Mode-S ground radar and containing data about the resolution advisory (RA).

1.4.2. **Empty message**: an RA downlink message without an RA (ARA and RAC are set to zero, but the “RAT” bit may be set. See 2.3).

1.4.3. **Encounter**: a situation in which a TCAS sees a threat whose trajectory causes an RA. The threat may be another aircraft (with or without an RA) or a ghost track.

1.4.4. **Ghost encounter**: an encounter in which the threat track does not correspond to a flying aircraft.

1.4.5. **RA sequence**: a set of successive RA downlink messages sent by one aircraft.

1.5. Structure of this report

1.5.1. Section 1 gives the context and goal of this analysis of RA downlink messages. The methodology used is also described.

1.5.2. Section 2 provides a description of the RA downlink mechanism and a description of the content of the RA downlink messages. The radar data used are also described.

1.5.3. Section 3 provides figures about the amount of data gathered, such as monitoring duration, corresponding flight hours, number of RA downlink messages gathered and number of encounters.

1.5.4. Section 4 provides an evaluation of the quality and reliability of the content of RA downlink messages and of other linked data such as ACAS status (BDS-10) and flight status.

1.5.5. Section 5 provides results about this RA downlink monitoring. It gives figures and distributions relating to the encounters and RA types. This section focuses more on the operational aspect.

1.5.6. Section 6 provides a summary of the RA downlink messages' reliability and of the RA downlink monitoring results.

1.5.7. Appendix A provides examples and illustrations of typical encounters and ghost encounters.

1.6. References

[1] *Operational monitoring and modelling of airborne and ground-based safety nets performance*, paper delivered at the Safety R&D Seminar 2008 - SNET performance v1.0.

[2] Notes on PASS project progress meeting no. 3, PASS/WA0/WP2/15/D.

[3] *Minimum Operational Performance Standards (MOPS) for TCAS II RTCA DO-185A*, 16 December 1997.

[4] *Interpretation of the Resolution Advisory contained within the RA downlink messages*, DSNA (2008) DTI/R-D/0808511/SAS.

[5] EUROCAE WG49N8 2006.

2. Technical description

2.1. RA downlink

2.1.1. Principle

2.1.1.1. When TCAS triggers an RA, it uploads the BDS-30 register within the Mode-S transponder. The format used for BDS-30 depends on the capability of the associated TCAS transponder, which is known as the TCAS. Two formats are defined:

- DO-185A format for TCAS V7 associated with DO-185A-compatible transponder
- TSO-C119A for TCAS 6.04 or TSO-C119A-compatible transponder

2.1.1.2. When a ground Mode-S radar interrogates the aircraft to obtain normal surveillance information, the transponder replies, incorporating a flag specifying that an RA report is available.

2.1.1.3. The radar then re-interrogates the transponder in order to obtain the content of the BDS-30 register. This second interrogation-reply transaction is performed during the same radar-antenna turn. The radar station does not provide the RA downlink message as stand-alone data, but incorporates the RA downlink message into a radar-target report with the other surveillance data.

2.1.2. Encounter and RA downlink messages

2.1.2.1. At each radar-antenna turn, the radar beam illuminates both aircraft involved in the encounter and the radar downlinks the content of the BDS-30 register from the aircraft with RAs. When both aircraft have RAs, the radar gets two RA downlink messages (one per aircraft) at each antenna turn.

2.1.2.2. The radar-target report contains data about the last active RA. On board, the RA is updated every second and can change. A common antenna-turn period is between 4 and 10 seconds, so the radar station cannot catch all RAs.

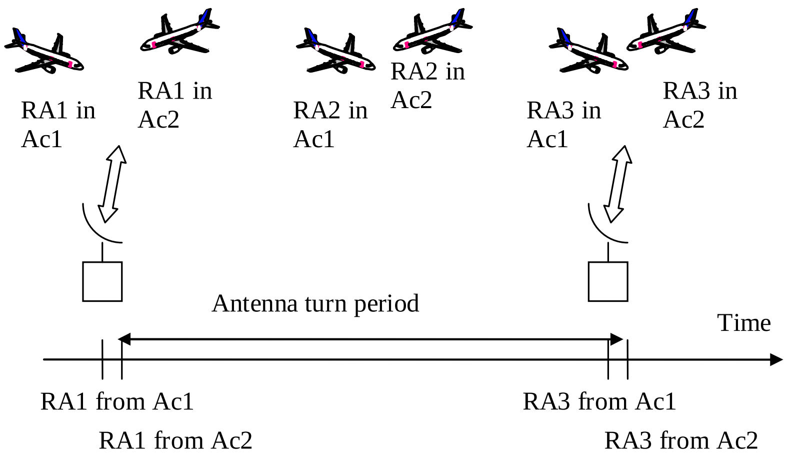


Figure 1: RA downlink messages during an encounter with RAs on board both aircraft

2.1.2.3. BDS-30 is not time stamped. Nonetheless, the time stamp of the radar-target report can be used to date the BDS-30 with a time error of between -1 s and 0 s, since BDS-30 is always older than the target-radar report.

2.1.2.4. The radars used for this study overlapped in several areas and an encounter could be seen by two or three radars. In these cases, the RA sampling was better, since RA reports were available every two or three seconds (see example 7.1).

2.2. Mode-S radar data

2.2.1. This study is based both on RA downlink messages extracted from Mode-S radar data and on the radar data themselves.

2.2.2. The Asterix category used for Mode-S radar data is category 48. Each item corresponding to a radar plot is referenced by an item number. The following are the most useful items for this study:

2.2.3. Item 260: ACAS resolution advisory report. This item contains the 56-bit message conveying Mode-S Comm-B message data from BDS-30. The content of BDS-30 is described in 2.3.

2.2.4. Item 230: this 16-bit item contains information about the communications and ACAS capability, and about the flight status. The most useful data are:

1. An extract from BDS Register 1.0: bit 16 and bits 37 to 40 of BDS-10 are available and mainly give information about:
   - the format used to code the content of BDS-30, which can be DO-185A or TSO-C119 format; and
   - the TCAS capability: TA-only or RA-capable, and whether or not TCAS is operational.
2. Flight status: among the five coded values, the most useful data indicate whether the aircraft reports that it is airborne or on the ground.
3. Altitude reporting capability, indicating whether the altitude is reported with a resolution of 25 ft or 100 ft. This information is very important for the TCAS simulations.

2.2.5. Item 220: 24-bit ICAO address, very useful in order to retrieve information about the aircraft, such as its type and operator.

2.2.6. Item 240: aircraft identification, which is useful in order to link data to external data such as ASR.

2.2.7. Not all aircraft have the capability to fill in all these items. Only aircraft equipped with a Mode-S transponder fill in the flight status, the altitude-reporting quantisation and the ICAO address. In addition, most of them correctly fill in the aircraft identification. These data are therefore available for the aircraft downlinking an RA, but not always for the intruder.

2.2.8. The other items contain data common to SSR (position, flight level, Mode A, time, etc.).

2.3. *BDS-30 Content*

2.3.1. TSO-C119A format

2.3.1.1. TSO format is used by TCAS v6.04 and by TCAS v7.0 coupled with a TSO-C119A Mode-S transponder. TSO format contains only the ARA and the RAC part.

2.3.1.2. Below are the field positions within BDS-30. Item 260 of Asterix category 48 contains only these 7 bytes.

Bit 33-40		41-54	55-58	59-88
BDS1=3	BDS2=0	ARA	RAC	empty

2.3.2. DO-185A format

2.3.2.1. DO-185A format is used by the majority of TCAS-equipped aircraft in the core area and contains all the items described here (ARA, RAC, RAT, MTE, TTI, TID).

2.3.2.2. The following are the field positions within BDS-30. The data field relating to threat (TID) is split into three fields, depending on the value of the TTI field.

Bit 33-40		41-54	55-58	59	60	61-62	63-75	76-82	83-88
BDS1=3	BDS2=0	ARA	RAC	RAT	MTE	TTI	TIDA	TIDR	TIDB
							TID		

2.3.3. Active RA (ARA)

2.3.3.1. This field summarises the last active RA.

2.3.3.2. TSO format uses 10 bits (bits 41 to 50) from the ARA field, and provides information about the vertical speed limit (VSL), but does not indicate whether the RA is preventive or corrective, or whether the RA is crossing, reversal or increased.

2.3.3.3. DO-185A format uses only 7 bits (bits 41 to 47) from the ARA field, plus the MTE bit, to code the RA. It provides information about the RA type (preventive/corrective) and whether the RA is crossing, reversal or increased. Nevertheless, the VSL value is not available.

2.3.3.4. Data coded in both formats need to be interpreted in order to have a precise idea about the RA announced and displayed on board the aircraft. For example, when the ARA is {RA corrective, upwards direction, not increased, no direction reversal, altitude crossing, RA is positive}, the announced RA is simply “climb crossing climb”.

2.3.3.5. The RA data sent by TCAS to its RA display (IVSI or PFD) is coded with more than 12 bits (12 bits for the RA + 7 bits for the rate to be maintained + crossing bit). The information conveyed by the ARA field is therefore less accurate than the information available on board.

2.3.3.6. The remaining bits of ARA (48 to 54 in DO-185A format) are unused because they are reserved for ACAS III.

2.3.4. RA complement (RAC)

2.3.4.1. The RAC part contains the RA complements (if any) received from all other TCAS through coordination messages.

2.3.4.2. Only two bits are used, indicating the four possible combinations involving “Do not pass below” and “Do not pass above”.

2.3.4.3. As coordination messages are sent only by a TCAS having an RA, RAC exists only when the threat also has an active RA. This feature can be used to check whether or not an RA downlink message has also been sent by the threat.

2.3.5. Data relating to the threat identity (TTI + TID or TIDA-TIDR-TIDB)

2.3.5.1. This threat identification data exists only in the DO-185A format.

2.3.5.2. When the threat is Mode-S equipped, the TTI field indicates that the TID field contains the Mode-S transponder address.

2.3.5.3. When the threat is not Mode-S equipped, the TTI field indicates that the TIDA, TIDR and TIDB fields are used to give, respectively, the altitude, range and relative bearing of the threat. The threat altitude is coded in the same way as Mode C.

2.3.6. RA terminated indicator (RAT)

2.3.6.1. This bit exists only in the DO-185A format.

2.3.6.2. After an RA has been terminated by TCAS, it still needs to be reported by the Mode-S transponder for 18 seconds. After the “Clear of Traffic”, therefore, the transponder memorises the data corresponding to the last active RA (ARA, RAC, MTE, TTI, TID) and keeps the data available for the RA downlink with the RAT bit set.

2.3.7. Multi-threat encounter bit (MTE)

2.3.7.1. This bit exists only in the DO-185A format.

2.3.7.2. This bit indicates whether two or more simultaneous threats have the RA status.

2.3.7.3. This bit is used in conjunction with the ARA bits to code the RA.

3. Gathered data

3.1. Radar-data recordings

3.1.1. Only Mode-S radar data were recorded in order to obtain RA downlink messages.

3.1.2. The recorded radars and their main features are described in the following table.

Location	Location code	Range	Period
Roissy	CD	165 NM	3.97 s
Chaumont	CH	200 NM	8.15 s
La Dole	LD	150 NM	5 s
Nice	CA	160 NM	3.96 s
Vitrolles	PV	165 NM	4.8 s
Toulouse	TS	170 NM	4.3 s

Table 2: Radar features

3.1.3. The areas of radar coverage overlapped. The following figure illustrates the global coverage area and the overlapping.

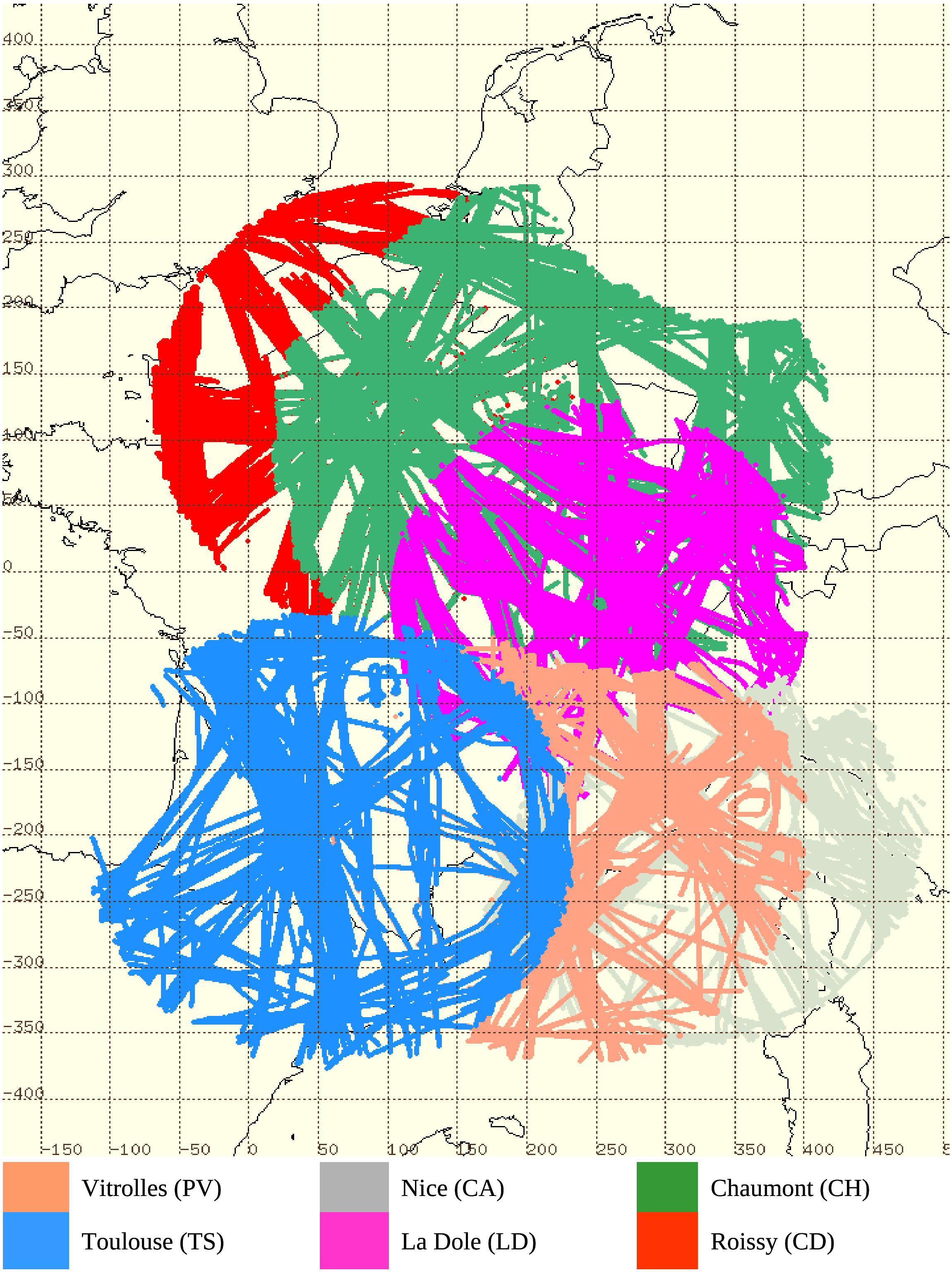


Figure 3: Radar coverage area and overlapping (radar location codes in the brackets)

3.1.4. The recording of Mode-S radar data started on 1 September 2007 and stopped at the end of March.

3.1.5. This set of radars covered a large part of France, Belgium and Switzerland, and partially covered the Netherlands, Germany, Italy and Spain.

3.1.6. The results presented in this report are based on this whole area of coverage, and all geographical references are removed.

3.1.7. Owing to technical problems such as maintenance, upgrading or network failure, not all of the radars were always available.

3.1.8. The La Dole radar was recording only after mid-October, and the Toulouse radar was not available after the beginning of December.

3.1.9. The duration of all the radar-data records is **15,200 hours**. Each radar-data record lasts 24 hours, and the graph below shows the number of records for each radar and for each month. The colours are the same as those used for the radar-coverage map (Figure 3).

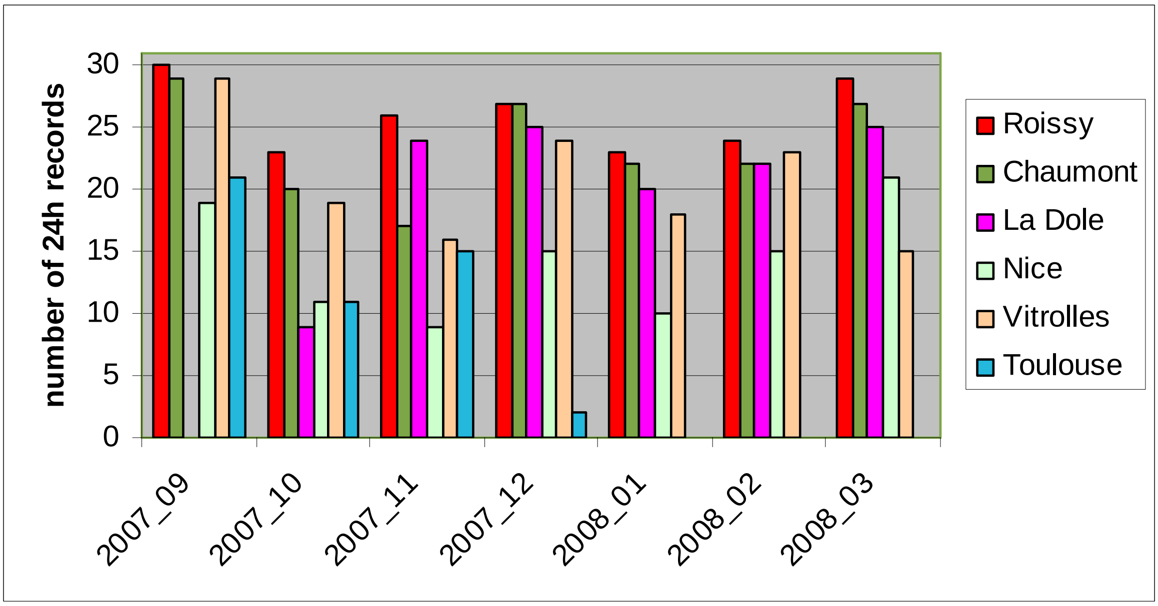


Figure 4: Number of radar recording hours

3.1.10. As radar data were not always available, the recording of these six radars is equivalent to a recording of three radars each day without interruption for seven months.

3.1.11. The following figure gives an approximation of the number of flight hours captured per radar and per day. This approximation is calculated on the basis of the total number of plots and the antenna-turn period.

3.1.12. The days for which no data are available correspond to network failures.

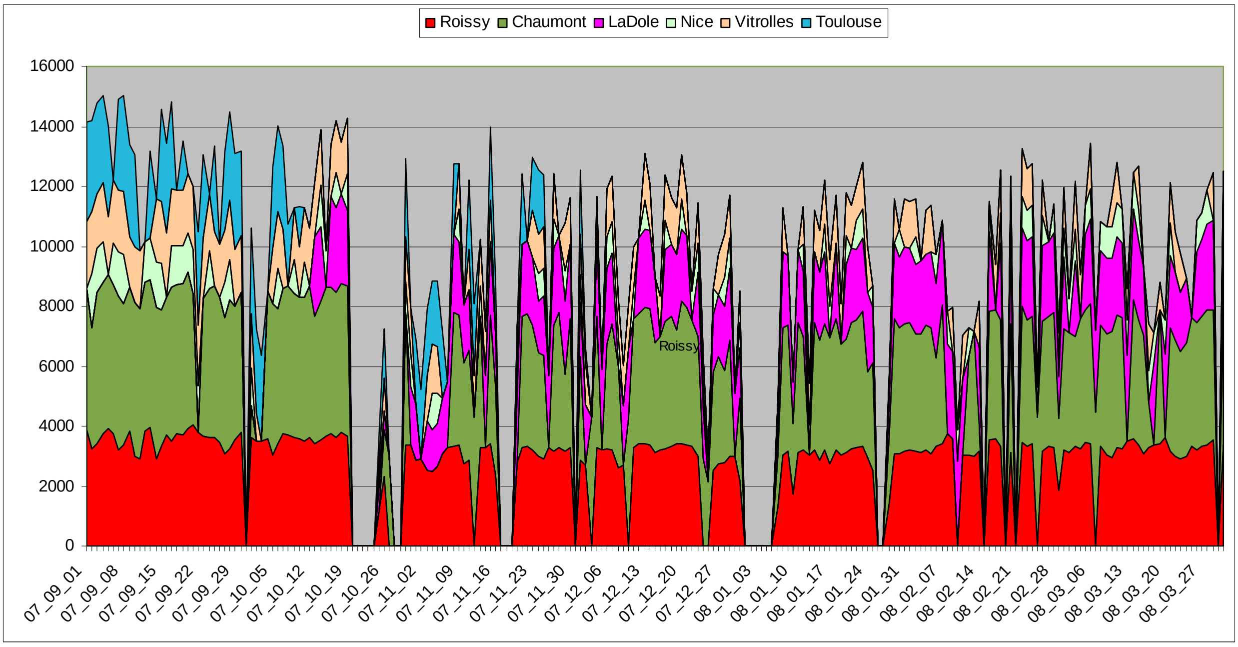


Figure 5: Flight hours per radar and per day

3.2. Captured flight hours

3.2.1. Owing to radar overlapping, the total number of captured flight hours could not be obtained by summing the number of flight hours captured by each radar. A software program was therefore developed to associate data which were captured by more than one radar but belonged to a single aircraft. The number of flight hours for a given aircraft corresponds to the length of time for which that aircraft was flying within the global radar coverage area for the day under consideration. The global radar coverage area depended on the radars connected that day, on their coverage and on their mutual overlapping.

3.2.2. Care was taken to remove data corresponding to aircraft on the ground and to “PARROT” (fixed transponders for radar monitoring). Almost half of the aircraft performed more than two flights a day and about 15% performed between four and seven flights a day.

3.2.3. The total number of flight hours captured over the 7-month period of monitoring was **1,330,000 hours**. The actual number of flight hours performed over this period and within this same area was greater, because some aircraft were only partially detected or not detected, mainly owing to radar unavailability and also to the lack of detection at low-elevation angles. With regard to the probability of detection, we can assume that its influence was very limited here and was visible mainly only on the fringe of the coverage area.

3.2.4. The actual number of flight hours performed over this period cannot be accurately evaluated. Nevertheless, the RA downlink messages were captured with the same “time-geographic” coverage as the flights. All figures relating to the captured RA downlink messages can thus be accurately connected to the number of captured flight hours.

3.2.5. During the assessment of the number of flight hours, the data contained in BDS-10 were analysed to determine whether the aircraft was TCAS equipped or not, and which format (TSO or DO) was likely to be used for the RA downlink. The category of the flight was also characterised on the basis of the Mode A and the aircraft identification.

3.2.6. The following figure gives the number of captured flight hours per day. The magenta part corresponds to the number of flight hours performed by aircraft with an RA-capable TCAS. The other part corresponds to TCAS always in TA-only mode and to aircraft equipped with transponders only.

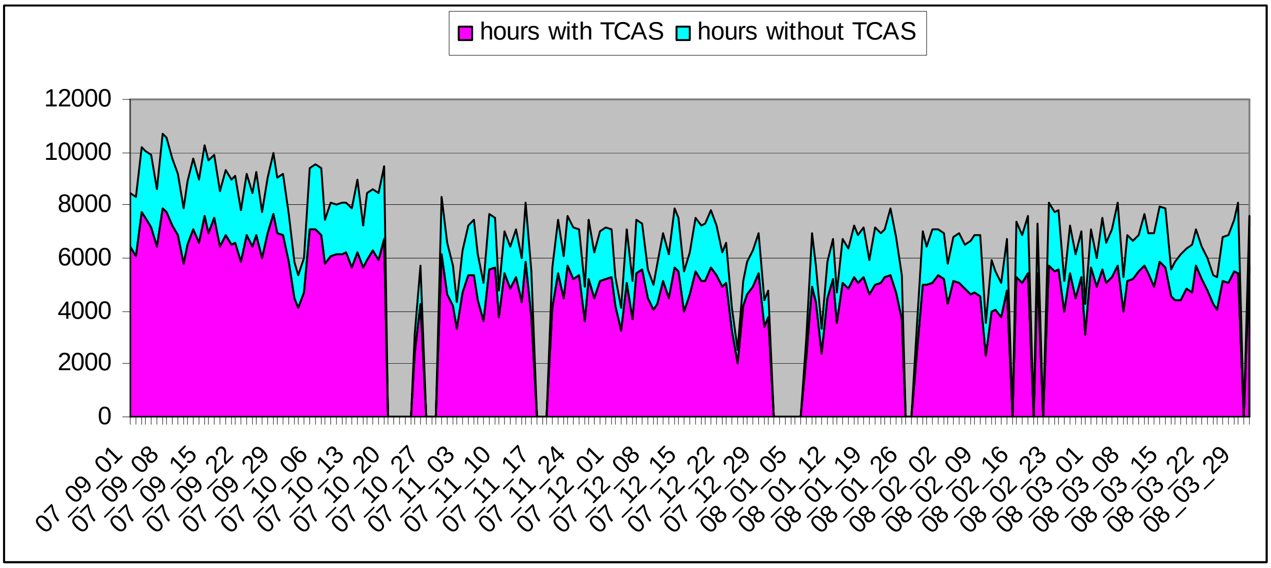


Figure 6: Captured flight hours with/without RA-capable TCAS per day

3.2.7. 74% of the captured flight hours were performed by aircraft with an operational TCAS. This proportion was in reality greater because some aircraft did not send correct BDS-10 data, as explained further in 4.3. The 26% of flight hours performed by aircraft with BDS-10 indicating no RA-capable TCAS can therefore be split into two parts: 22% for which BDS-10 can be trusted and 4% for which BDS-10 cannot be trusted. This is a rough approximation, because it was arrived at by extending a percentage split (83%-17%) computed for a fraction of flights to the whole number of flight hours.

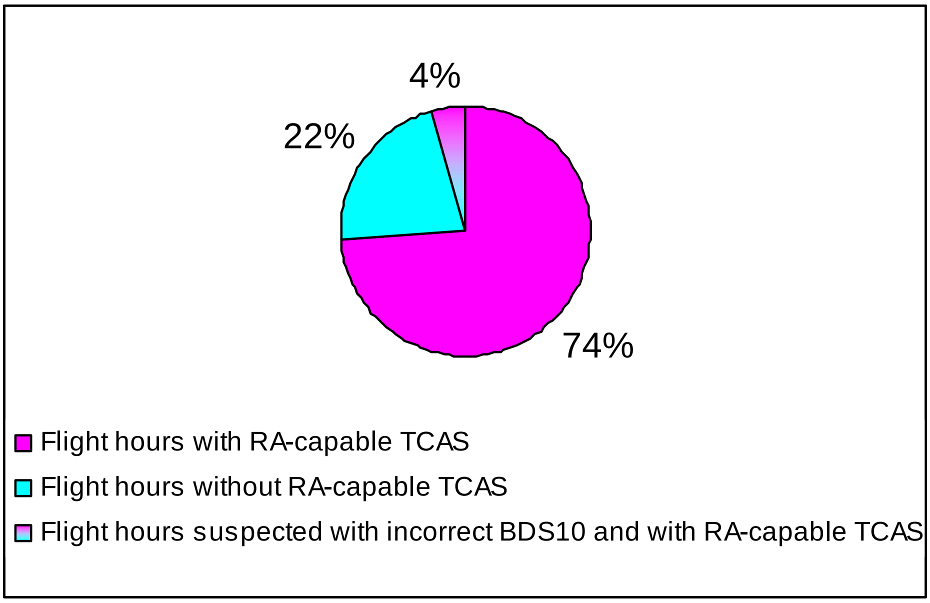


Figure 7: Captured flight-hour distribution with/without RA-capable TCAS

3.3. Aircraft equipment

3.3.1. The following table gives the number of flight hours performed by aircraft with an RA-capable TCAS, with TCAS always in TA-only mode, with only a Mode-S transponder and with a Mode-C transponder. Aircraft identified as military aircraft or as VFR flights are shown in separate rows. The term "general air traffic" (GAT) is used for all flights identified as neither military flights nor VFR flights. The TCAS equipped civilian aircraft (GAT+VFR) performed about 982.000 flight hours.

	TCAS RA capable	TCAS in TA-only mode	Mode-S transponder	Mode-C transponder	Total
GAT	978,930	2,439	217,960	52,790	1,252,119
VFR	624	4	21,806	46,278	68,712
Military	6,596	10	874	4,119	11,599
Total	986,150	2,453	240,640	103,187	1,332,430

Table 8: Captured flight hours for each equipment type and flight category

3.3.2. The following figure shows the distribution of the captured flight hours for each flight category. It should be noted that VFR and military flights were underestimated because not all the allocated Mode-A codes were tested.

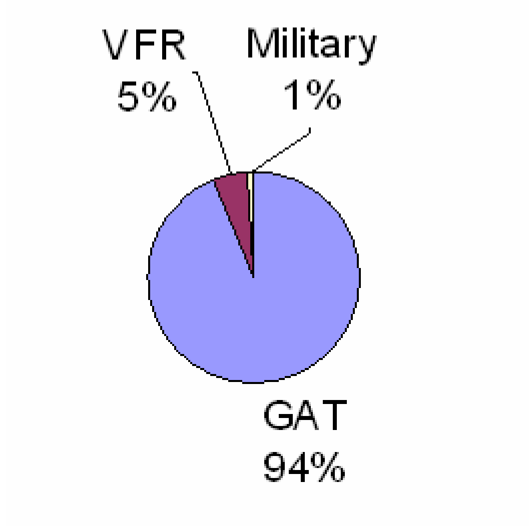


Figure 9: TCAS and transponder equipment distribution

3.3.3. The following figure shows the distribution of aircraft-equipment types for each flight category. The column on the right gives the distribution for all flight categories. It is very close to the distribution for GAT because the majority of flight hours were performed by GAT. The figure shows that almost 80% of GAT flight hours were performed by aircraft with RA-capable TCAS. A third of VFR flight hours were performed by aircraft equipped with a Mode-S transponder, and more than half of military flight hours were performed by aircraft equipped with TCAS or E-TCAS.

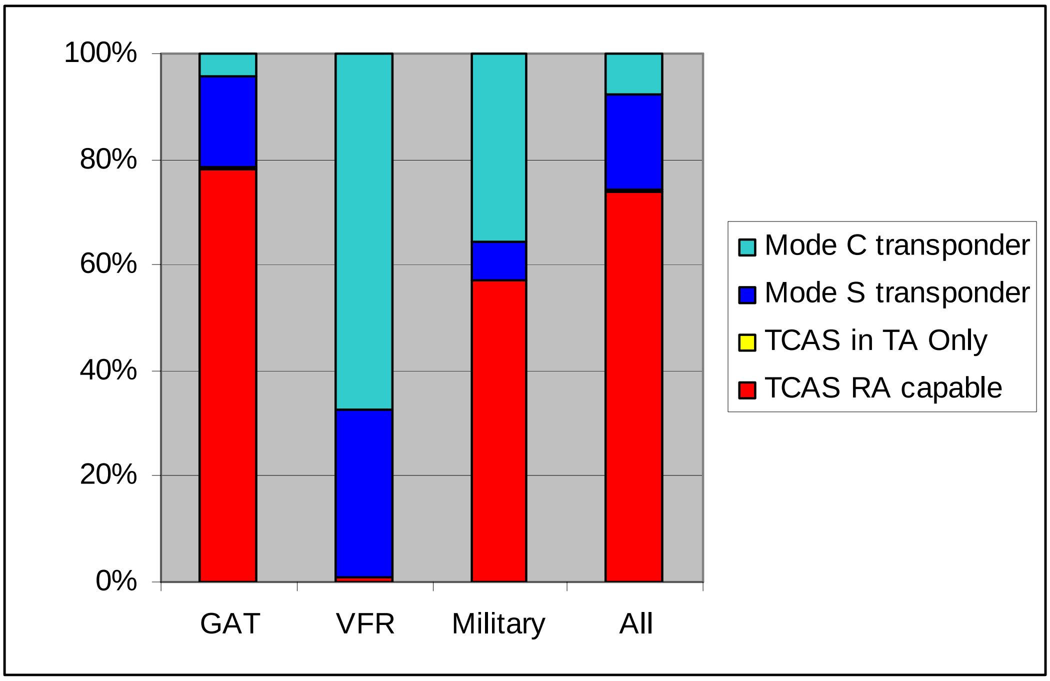


Figure 10: TCAS and transponder equipment distribution

3.3.4. Focusing only on TCAS-equipped aircraft, only 2% of these flights are likely to use the TSO-C119A format for RA downlink. As for all the figures in this section, this figure is based on the total number of flight hours captured by the six radars. This figure will be refined further, but only looking at aircraft which sent RA downlink messages (4.2.1).

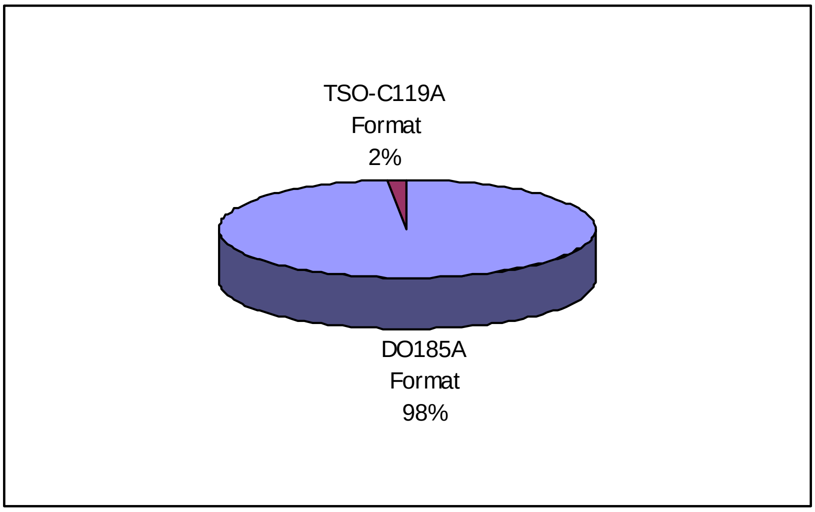


Figure 11: Distribution of BDS-30 format capability

3.4. RA downlink messages

3.4.1. **350,080 RA downlink messages** were extracted overall from the 15,200 hours of Mode-S radar data. Below is the number of RA downlink messages extracted from the radar data for the seven months of monitoring with the captured number of flight hours performed by TCAS-equipped aircraft.

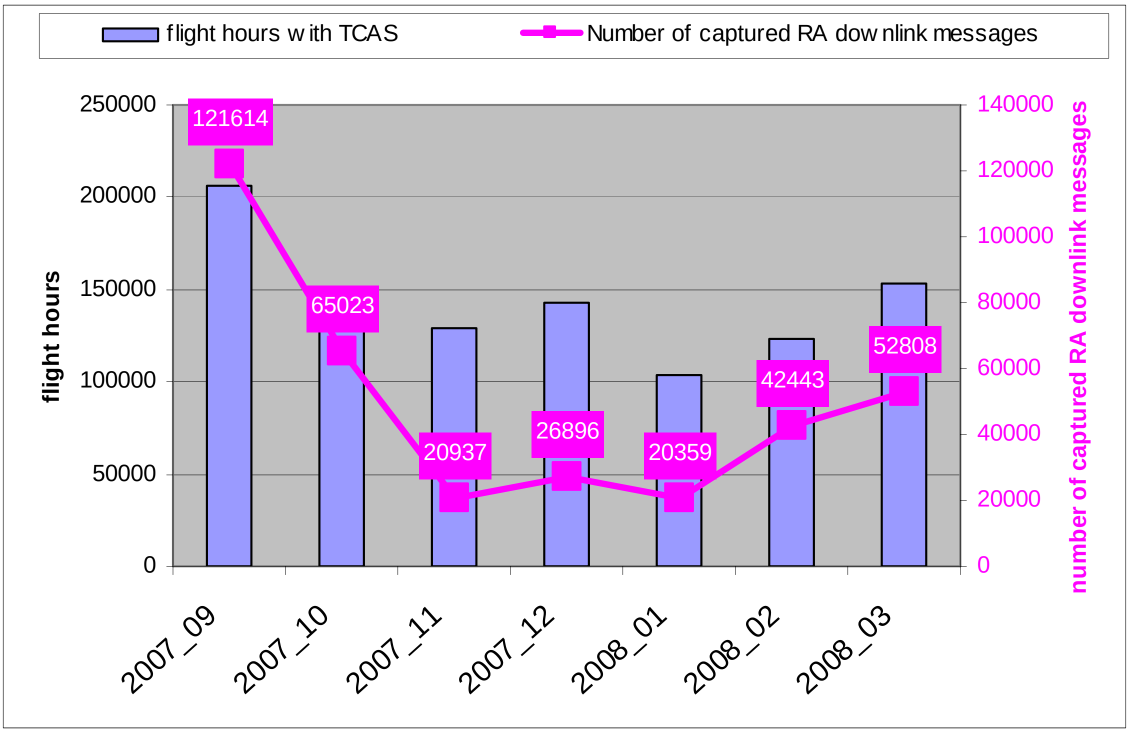


Figure 12: Number of captured RA downlink messages

3.4.2. The number of RA downlink messages is linked to the number of corresponding flight hours, but it is not accurately proportional. During the months of September and October more aircraft that were continuously sending empty RA were detected.

3.4.3. Each aircraft sent a number of RA downlink messages. These 350,000 messages were thus sent by only **1,332 aircraft**. The computed average number of messages sent by aircraft is meaningless because of issues on some aircraft which sent continuously empty RA downlink messages. These issues are explained in 4.5.1, and more accurate values relating to the duration of the sequence of RA downlink messages are given in 5.5.

3.5. Encounters involving RA downlink messages

3.5.1. **Of all these 350,080 RA downlink messages, only 12,476 messages corresponded to RAs triggered on board** (see 4.5.1).

3.5.2. These 12,476 RA downlink messages came from **1,029** aircraft involved in **880** encounters.

3.5.3. Computing an average using the number of flight hours performed by TCAS-equipped aircraft, **RAs were triggered on board one aircraft every 960 flight hours**.

3.5.4. Section 4 deals with the content of the RA downlink messages. Section 5 deals with the operational context of the encounters.

3.5.5. The 350,000 RA downlink messages were therefore processed to provide the results presented in section 4 (message quality). The 880 encounters were analysed to provide the results presented in sections 4 and 5 (operational monitoring). The message-quality analysis (section 4) cannot be detached from the encounter data, because we need to have the link with the TCAS simulation results to analyse the content of the RA downlink messages.

4. Quality of the RA downlink messages

4.1. Introduction

4.1.1. This chapter will describe all the errors discovered when decoding and analysing the RA downlink messages. Some errors related to the data within the RA downlink message itself and others were inconsistencies with other data linked to the aircraft, such as BDS-10.

4.1.2. The goal of this chapter is to quantify the reliability of RA downlink message items. All the percentages given will be based on all the gathered messages, disregarding the operational context.

4.1.3. All the faults and errors presented in this section existed within data coming from all the recorded radars. Five out of the six Mode-S radars involved were almost identical, but the sixth was made by a different manufacturer and was a priori different.

4.1.4. These faults were observed within messages coming from only one set of given aircraft, and they were exactly the same even when messages were collected by different radars. This fact leads to the conclusion that these errors were linked to the aircraft equipment (TCAS and Mode-S transponders) rather than to the radar systems. Therefore, although certain error types occurred more frequently within given geographical areas, this seems to have been due to traffic differences rather than radar features.

4.1.5. The first type of error was erroneous data within BDS-10, such as incorrect BDS-30 format or incorrect TCAS capability. The second one was wrong flight status. These were not errors within the RA downlink message itself, but were linked to it and detectable thanks to it.

4.1.6. The RA downlink message errors were empty messages and errors relating to the threat identity (Mode-S threat coded as Mode-C threat, incorrect relative bearing, incorrect altitude coding).

4.1.7. The first error type is easily detectable but greatly pollutes RA downlink processing and monitoring.

4.1.8. The second type of error needs specific processing (such as TCAS logic simulation) in order to be detectable, and may cause issues if the correct threat needs to be identified. This identification does not seem to be a need for the displaying of RAs on CWP, but is necessary for incident analysis and monitoring based on RA downlink messages.

4.1.9. These detected errors impact only ground processing (RA downlink on CWP and RA monitoring) and have no impact on board.

4.2. Inconsistency between BDS-10 and BDS-30 formats

4.2.1. Bit 39 of BDS-10 indicates the format used to code the content of BDS-30, which can be either DO-185A or TSO-119C format. Some aircraft indicated the use of TSO-119C format, while the presence of TID within the RA downlink message highlighted the use of DO-185A format.

4.2.2. Of the 1,029 aircraft sending RA downlink messages, 93 had BDS-10 indicating the use of TSO-C119A format, but were actually using DO-185A format for BDS-30.

4.2.3. No cases of BDS-10 indicating the use of DO-185A format and of BDS-30 not containing a valid TID were detected.

4.2.4. When bit 39 of BDS-10 was set, therefore, the DO-185A format indication was reliable. On the other hand, when bit 39 was not set and thus indicated the use of TSO format, the information was not reliable and it was preferable to identify the format on the basis of the presence or absence of a TID part.

4.2.5. The following figure shows the distribution of the BDS-30 format indicated by BDS-10.

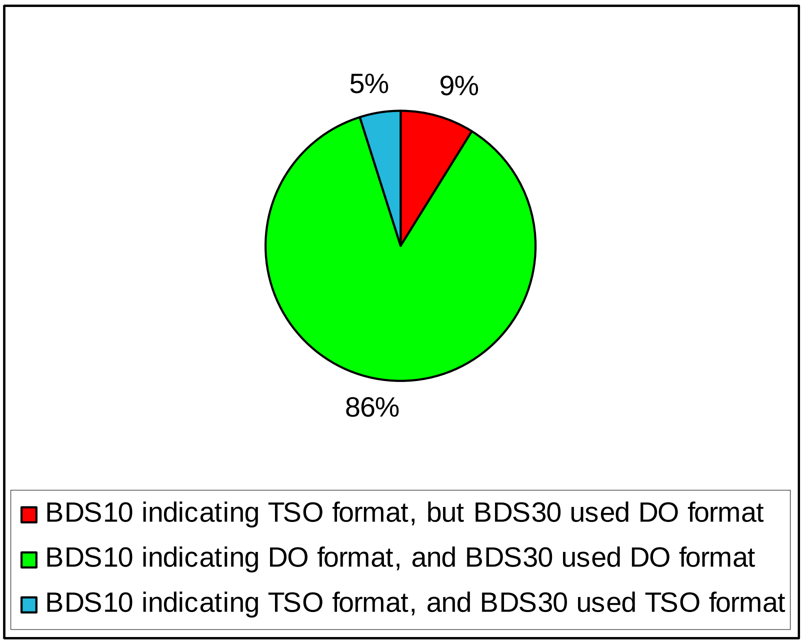


Figure 13: Distribution of BDS-30 format indicated by BDS-10

4.2.6. BDS-10 indicated TSO format in 14% (5% + 9%) of cases, but TSO format was actually used in only 5% of cases. About **64% of aircraft which had RA downlink messages and indicated the use of TSO format were therefore actually using DO-185A format**. Keeping this proportion based on aircraft downlinking RAs, we can correct the percentage given in 3.3.4, which was based on all aircraft but relied too heavily on the content of BDS-10. On the basis of all the captured traffic (1,330,000 flight hours), therefore, the percentage of **aircraft using TSO format** was lower and can be assumed to have been **less than 1%** (2%*(5/14)).

4.3. Inconsistency between BDS-10 and the presence of RA downlink messages

4.3.1. The combination of bit 16 and bit 70 of BDS-10 indicates the TCAS capability, which can be not operational, in TA-only mode or RA capable. “Not operational” means "not serviceable", and can correspond to a failed or switched-off TCAS, or to an aircraft not equipped with TCAS II.

4.3.2. Numerous cases were identified in which an aircraft reported an active RA while BDS-10 indicated a non-operational TCAS or a TCAS in TA-only mode. The following figure shows the distribution of BDS-10 content when an active RA was reported by BDS-30. The ratios were computed taking into account the number of flights involved.

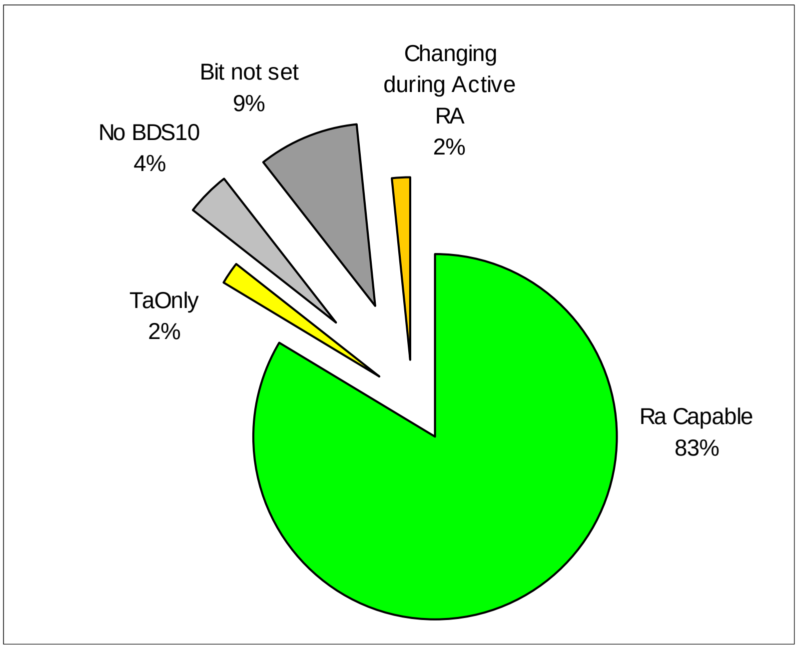


Figure 14: TCAS capability on the basis of BDS-10 during active RA report

4.3.3. The **TCAS capability status was reliable on only 83% of aircraft** which sent an RA downlink message.

4.3.4. The possibility that BDS-10 could be correct and that the reported RA could be erroneous was rejected because the reported RA was always consistent with the TCAS simulation. In addition, for encounters involving RAs on both aircraft, the presence of the coordination part (RAC) within the RA downlink message of the threat confirmed the existence of the RAs.

4.4. Inconsistency between flight status and the presence of RA downlink messages

4.4.1. Only one case was detected in which the flight status indicated that the aircraft was on the ground and the aircraft reported an active RA. The analysis of this case showed that only the flight status was wrong.

4.4.2. On the other hand, **there were six cases in which aircraft were actually on the ground and their flight status indicated that they were airborne**. **These aircraft were thus the cause of RAs triggered on board flying aircraft**. These cases were detected by analysing the 880 encounters.

4.4.3. There were 6 such cases out of 597 cases in which the threat was equipped with a Mode-S transponder. A single aircraft, a Fokker 27, was involved in 3 cases. These

3 cases happened at the same airport but on 3 different days. In each case, the faulty aircraft was waiting at a holding point and the RA was triggered within an aircraft on final. A faulty aircraft therefore has a high probability of causing an RA within an aircraft on final.

4.4.4. This problem is not linked to RA downlink but needs to be fixed in order to avoid the issuing of RAs against intruders on the ground.

4.4.5. The percentage of incorrect flight statuses (saying that an aircraft is airborne when it is actually on the ground) should be computed for all aircraft on the ground independently of the presence of an RA downlink message.

4.5. Active RA part (ARA)

4.5.1. Empty RA downlink messages

4.5.1.1. A huge number of RA downlink messages were empty. They had all bits set to zero within the ARA and RAC parts. When DO-185A format was used, the TID part was also empty. On the other hand, the “RA terminated” bit was often set to 1.

4.5.1.2. Below are the numbers of empty and non-empty RA downlink messages.

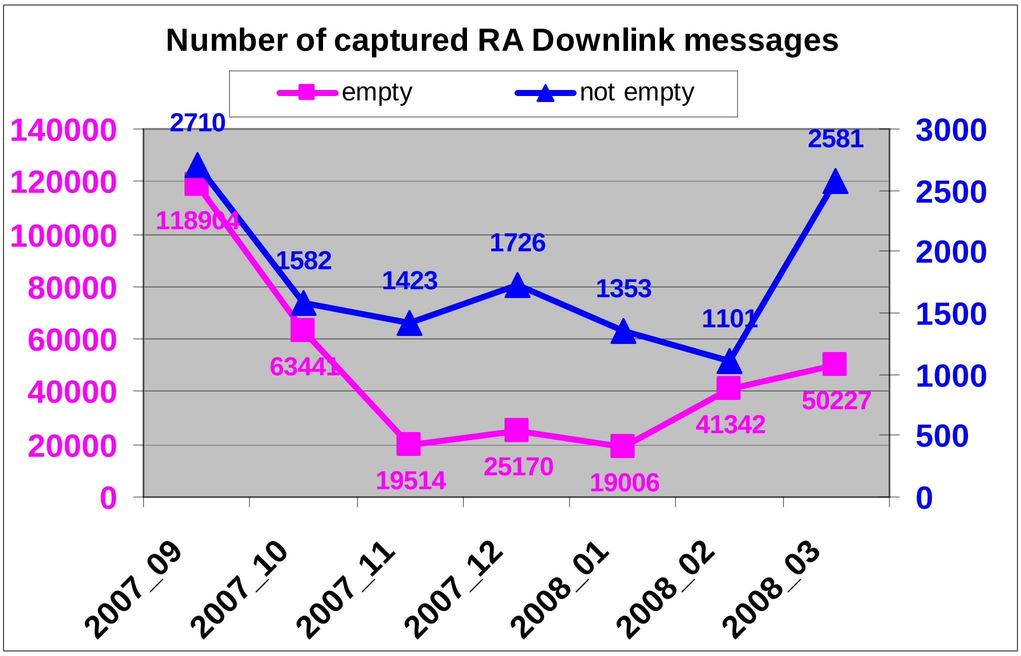


Figure 15: Number of collected RA downlink messages

4.5.1.3. Only 4% of all captured RA downlink messages were meaningful and actually corresponded to an RA on board.

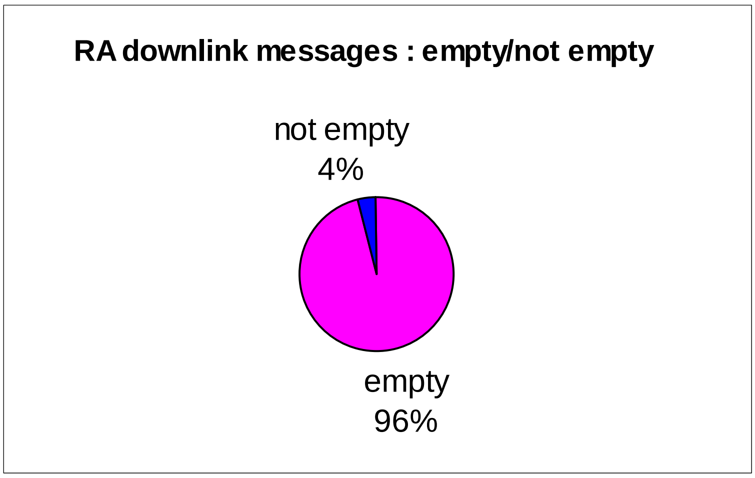


Figure 16: Ratio of empty/non-empty RA downlink messages

4.5.1.4. Most of these empty messages were sent by a limited set of aircraft continuously throughout their flight. This problem has been well known for a number of years, and various faulty transponders have been identified [5]. Nevertheless, the problem is ongoing.

4.5.1.5. In addition, it was observed that a number of the empty messages were not sent continuously throughout the flight but only sporadically and for short periods.

4.5.1.6. The following are two geographical plots of empty RA downlink messages over the seven-month period. The first plot corresponds to aircraft continuously sending empty RA downlink messages. This plot shows very long trajectories and highlights the routes used by the faulty aircraft, belonging mainly to an identified airline. The second plot corresponds to aircraft sending sporadic empty RA downlink messages, which are more dispersed over the whole radar coverage area.

4.5.1.7.

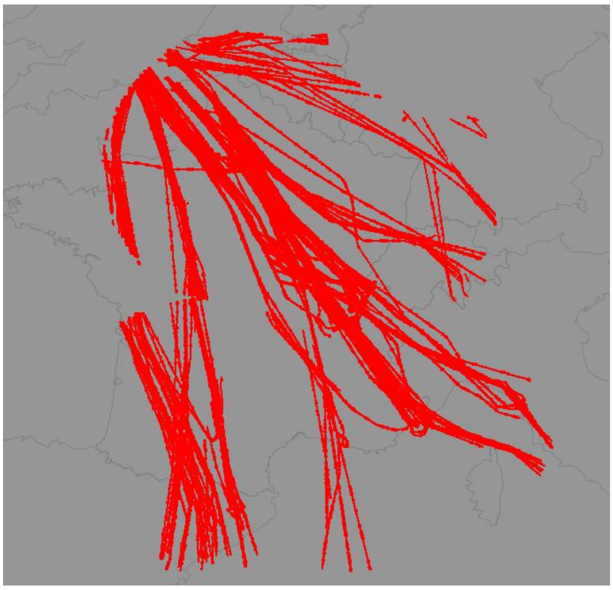
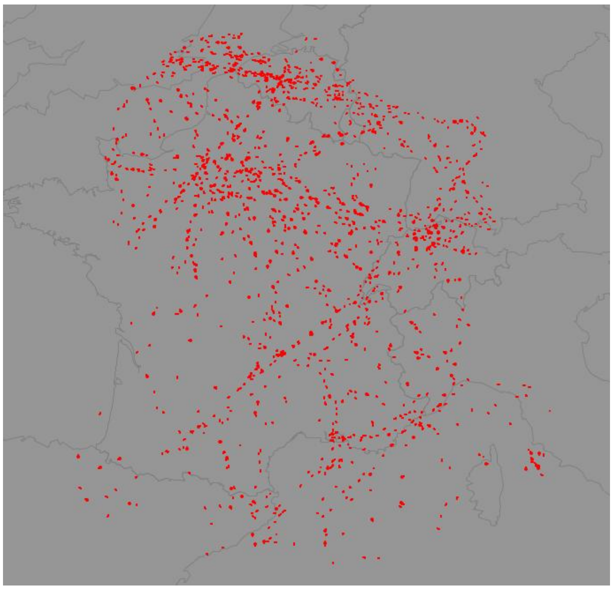
Continuous empty RA downlink messages	Sporadic empty RA downlink messages
	

Figure 17: Plots of empty RA downlink messages

4.5.1.8. TCAS simulations were performed in order to check whether or not RAs could potentially be triggered on board during the sending of sporadic empty RA downlink messages. Over one month of data, no RAs were simulated.

4.5.1.9. Nevertheless, the distribution of the durations of the sequences of empty RA downlink messages points to a possible cue, because 74% of the sequences lasted less than 20 seconds. Since this ratio is computed on the basis of all the sequences (2,168), including those sent continuously throughout the flight, this part is very representative of sporadic emissions of empty messages.

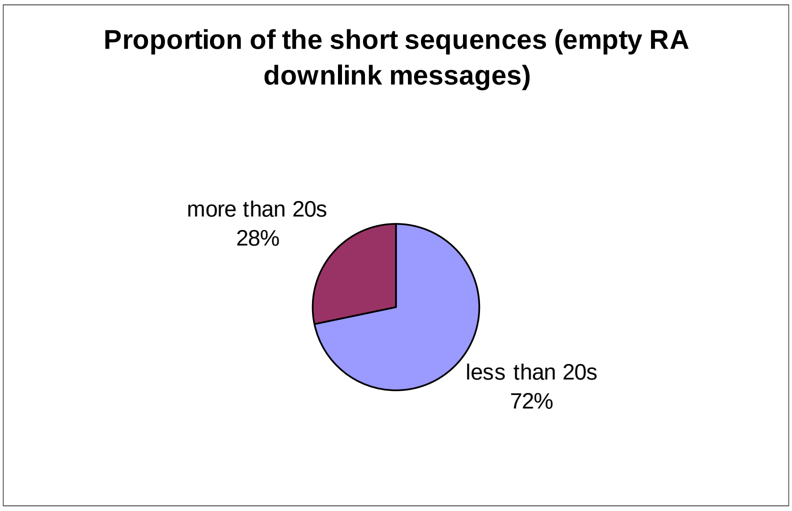


Figure 18: Proportion of short durations of downlinking of empty messages

4.5.1.10. The threshold value of 20 seconds was retained because of the peak in the distribution of the sequence durations. Below is this distribution for durations of less than 30 seconds.

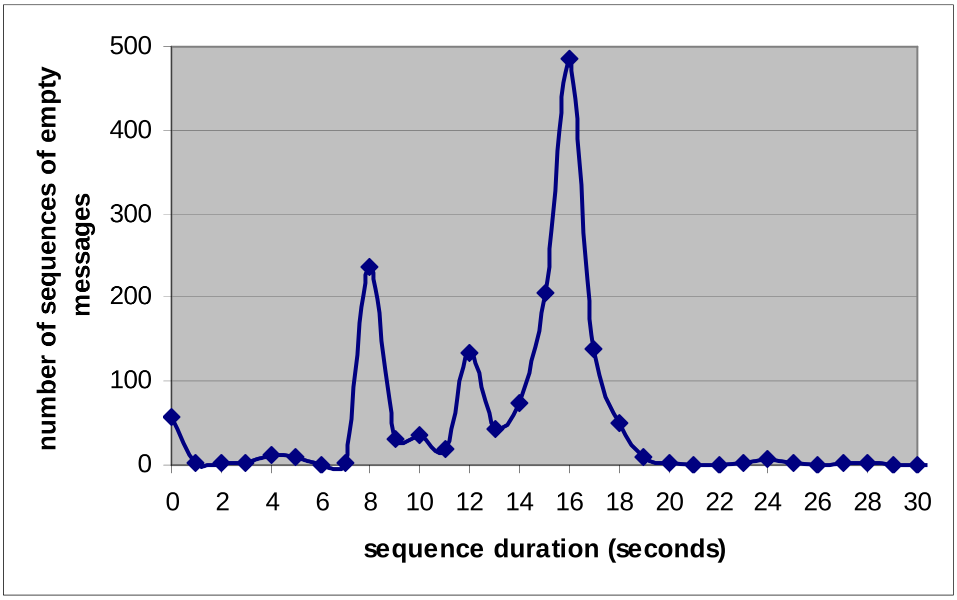


Figure 19: Distribution of the sending durations for empty RA downlink messages

4.5.1.11. The peak was close to 18 seconds, which was the value during which the Mode-S transponder is required to memorise and report the last active RA. In addition, since the empty RA downlink messages all had the "RA terminated" bit set, the implication is that **the sporadic empty messages may have been reported following the faulty activation of this "RAT" mechanism, whereas no RA was triggered on board**.

4.5.1.12. The fact that the main peak was at 16 rather than 18 seconds and that there was also a secondary peak at 8 seconds may appear to cast doubt on the preceding hypothesis. The hypothesis is correct, however, because the sequence durations presented here were linked to the radar-antenna-turn periods. The sequence durations corresponded to the time between the first captured RA downlink message and the last one. The messages were captured by various radars with antenna-turn periods of between four and five seconds and of eight seconds. A large proportion of them were captured by Chaumont radar, which has a long range and was located in the centre of the overall coverage area. This radar therefore gave the values of 8 and 16 seconds, depending on the time between the start of the 18 s memorisation and the time when the antenna was illuminating the aircraft. This is illustrated by the figure below. Similarly, the radars with a 4-second turn period captured 4 or 5 messages and gave sequence durations of 12 or 16 seconds. The other values were due to the various combinations of antenna-turn periods when the faulty aircraft was detected by more than one radar.

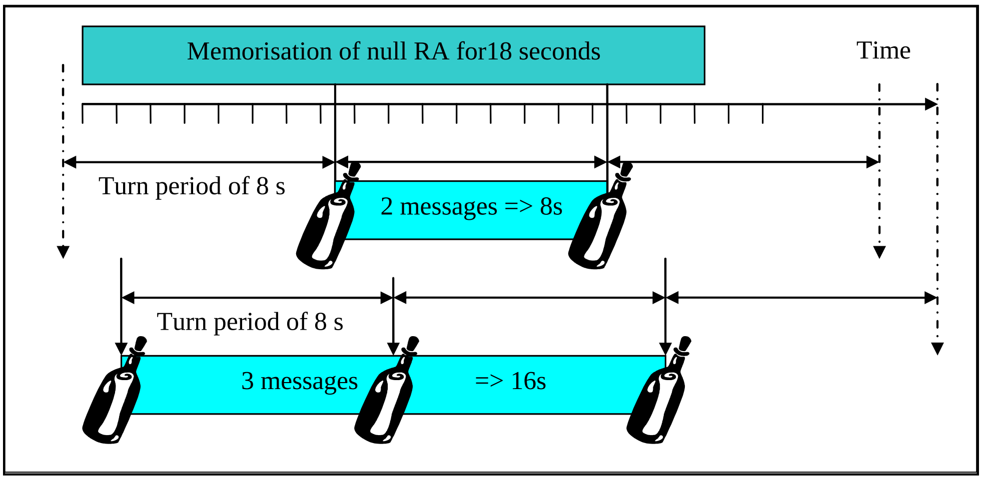


Figure 20: Radar capture of the "RA terminated" mechanism

4.5.1.13. For information, the following is the distribution of the sequences of empty RA downlink messages lasting more than three minutes. The duration depended only on the time for which the faulty aircraft was within the radar coverage area.

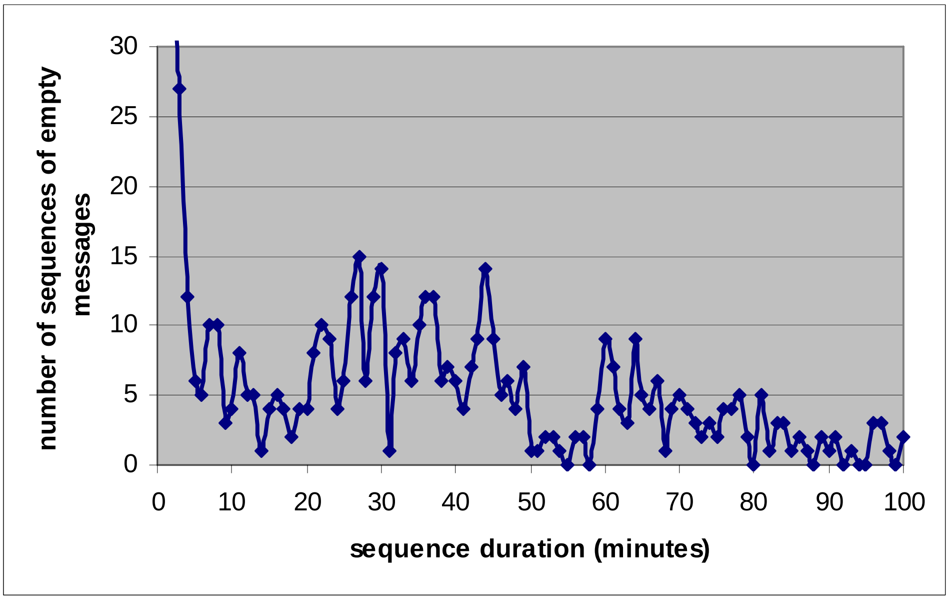


Figure 21: Distribution of long sequences of empty RA downlink messages

4.5.2. Non-empty RA downlink messages

4.5.2.1. All the following parts of this report will focus only on the analysis of the non-empty RA downlink messages.

4.5.2.2. The number of non-empty RA downlink messages can be compared with the number of flight hours performed by aircraft with operational TCAS. The following figure illustrates this connection for each month. The number of RA downlink messages is directly proportional to the number of flight hours, except for March. During this month, Airbus performed many test flights (AP/FD TCAS) during which a large number of RA downlink messages were sent. This partially explains the increase.

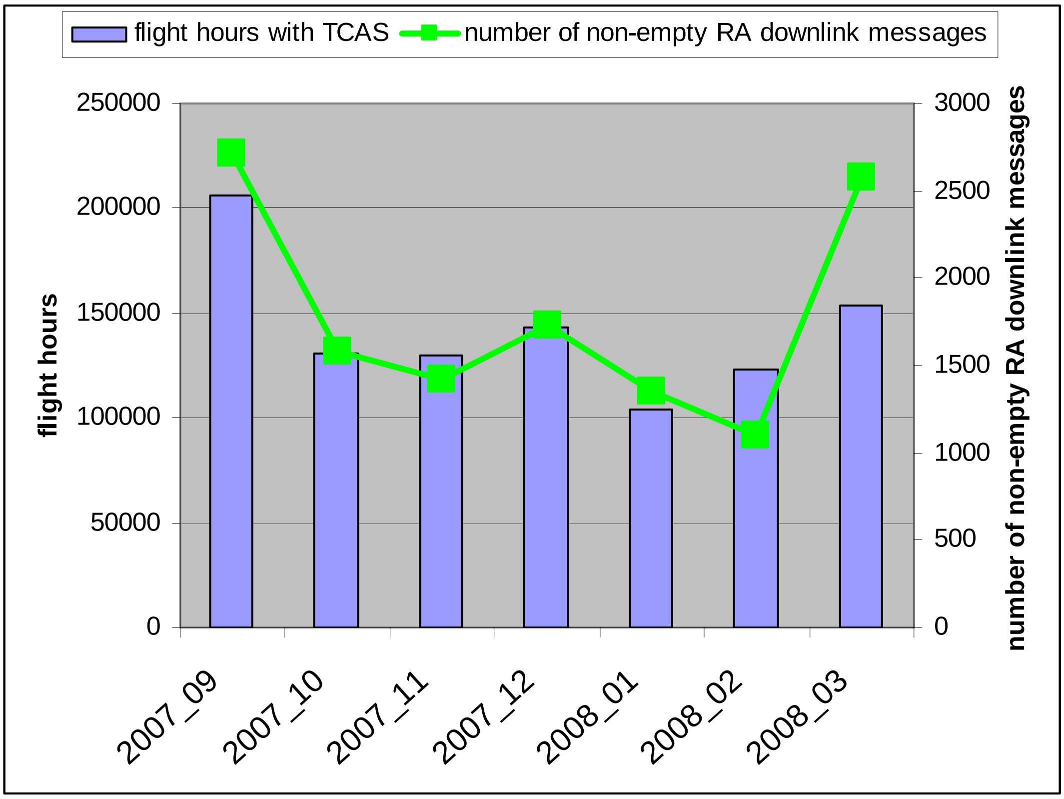


Figure 22: Non-empty RA downlink messages and flight hours

4.5.2.3. Below is the geographical distribution of non-empty RA downlink messages over the seven-month period. The position is the TCAS-equipped aircraft position when the RA downlink messages were captured. The colour depends on the threat equipment and also distinguishes particular flights. The green colour is used when the threat also sent an RA message. The light-blue colour indicates that the intruder was equipped with a Mode-S transponder and also possibly with TCAS, but did not send RA messages. Dark blue means that the intruder was only equipped with a Mode-C transponder. Lastly, the pink colour is for RAs triggered as a result of self-tracking, and magenta corresponds to test flights. The zoom shot on the right is centred on the Paris CDG airport area.

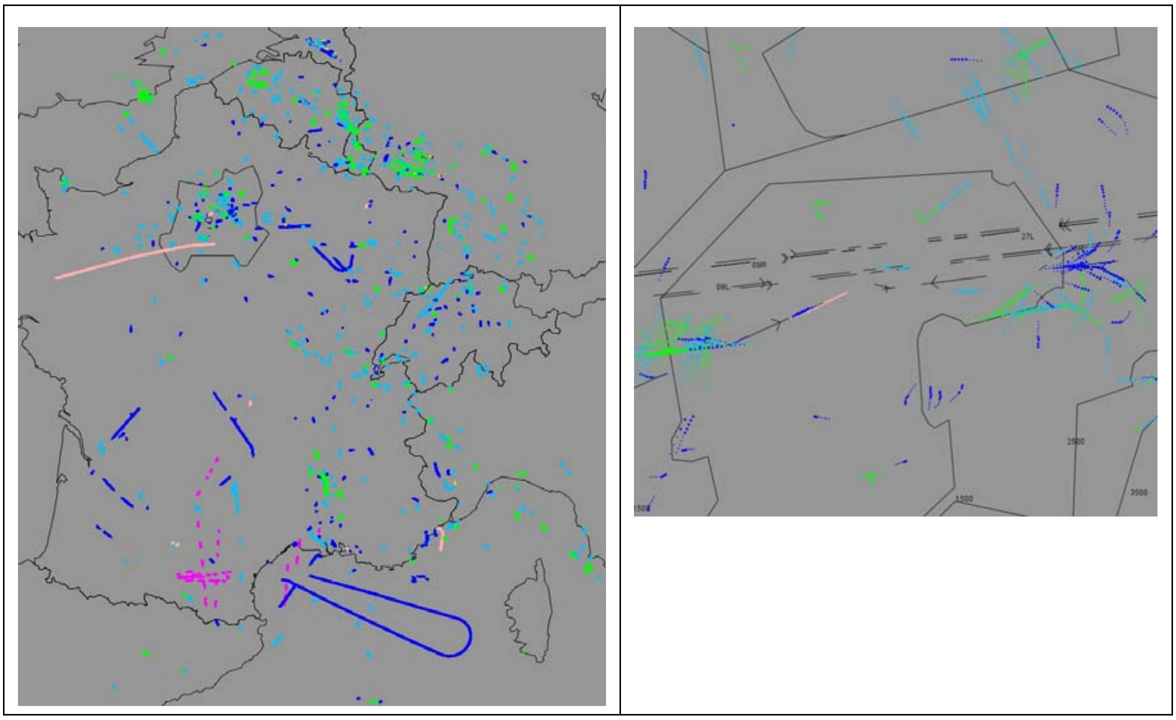


Figure 23: Geographical distribution of non-empty RA downlink messages

4.5.2.4. Below is the distribution of the durations of the sequences of RA downlink messages, for sequences with active RAs only. The duration is computed from the first message received until the first message with the RAT bit set (or until the last message for which TSO format was used). As explained in 4.5.1.12, the captured duration is a multiple of the turn period of the radar antenna. In order to smooth its influence, a five-second interval is retained for the bin used in this figure.

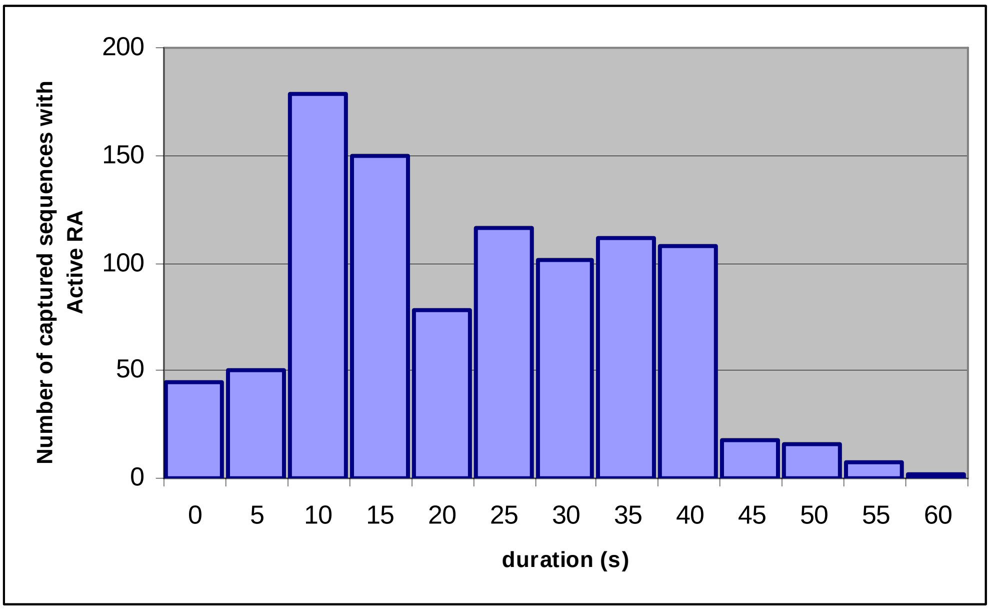


Figure 24: Distribution of the durations of active RAs

4.5.2.5. There were 45 sequences (4%) with a null duration. Of these, three sequences had only a single message with active RA, and no “RA terminated” message owing to the use of TSO format; the others were sequences with only “RA terminated” messages. The reasons were very short RAs or losses of detection on the fringe of the radar coverage area.

4.5.2.6. Except for encounters on the fringe of the radar coverage area, the distribution of the actual durations of RAs on board can be assumed to have been close to the distribution of the durations of the captured RA downlink messages with active RAs. Indeed, the time difference between the on-board triggering of the RA and the first captured RA downlink message, as well as between the “Clear of Traffic” and the first captured RA downlink message with the RAT bit, has a limited influence compared to the bin value of five seconds.

4.5.2.7. Therefore, **85% of the active RAs lasted between 5 and 45 seconds**. Less than **5% of the active RAs lasted more than one minute**. The number of cases was limited, but the duration was sometimes very long and reached four minutes. The following figure gives the distribution of the long durations. A more accurate view of the duration of RAs will be given in 5.5.1, when the corresponding encounters will be identified.

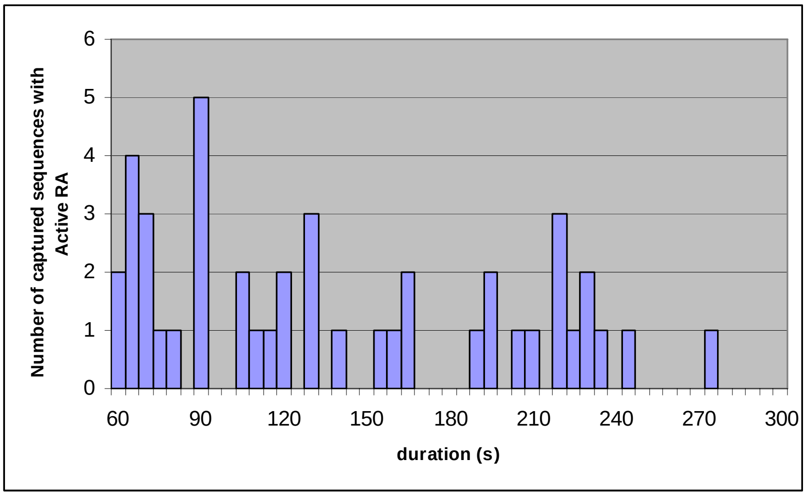


Figure 25: Long durations of active RAs

4.5.2.8. Computed from all the sequences, the **average duration of the active RAs was 33 seconds**.

4.5.2.9. Most of the time, the encounters were detected only by single radars. The Chaumont (CH) and Roissy (CD) radars between them detected about half of the sequences of RA downlink messages. It should be remembered that a given encounter could give either one or two sequences of RA downlink messages, depending on whether both aircraft had RAs or not. Therefore, **only 28% of the sequences of RA downlink messages were detected by more than one radar**. Although the radar coverages overlapped, detection by more than one radar was limited owing to radar availability on the test network and also owing to non-overlapping at low altitude.

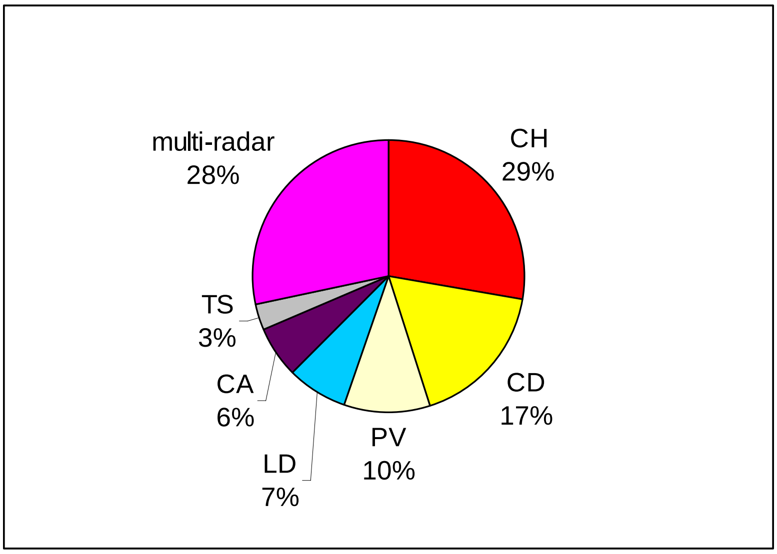


Figure 26: Distribution of the sequences captured by the radars

4.5.2.10. Below is the distribution of the average time between successive RA downlink messages. For sequences captured by only one radar and without detection problems, the time between successive captured RA downlink messages corresponds exactly to the turn period of the radar antenna. This is the case for the Chaumont radar peak at eight seconds and also for the Roissy radar peak at four seconds. The times longer than the antenna-turn period highlight losses of detection. On the basis of this observation, for the encounters detected by only one radar, **87% of the sequences were captured without any loss of messages**.

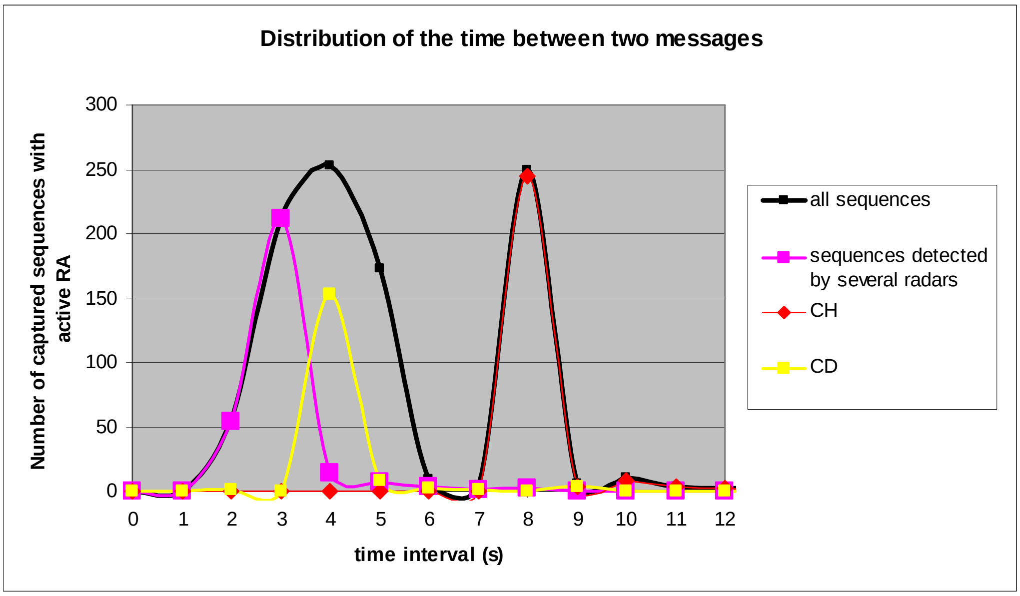


Figure 27: Distribution of the refresh rate of the RA downlink messages

4.5.2.11. When an encounter was detected by more than one radar, the average time between messages decreased. The magenta curve represents encounters detected by more than one radar (mainly by CH and CD). The refresh rate was better, 2.9 seconds on average.

4.5.2.12. The black curve is for all the sequences, regardless of how they were captured. **For all the sequences, the average time between successive RA downlink messages was 5.1 seconds**. This value is connected to the radars used and their availability. Only **28%** of encounters were detected by more than one radar, but the mean refresh rate was then **2.9 seconds**.

4.5.2.13. Taking into account only the role of the turn periods, the **mean latency to get the first RA** may be assumed to be one half, that is to say about **2.6 seconds**, and about **1.5 seconds for the encounters captured by several radars.**

4.5.2.14. The following sections of chapter 4 will focus on the content of each field of these non-empty RA downlink messages.

4.5.3. Active RA (ARA, MTE)

4.5.3.1. No errors were detected in the active RA part.

4.5.3.2. Decoding errors sometimes occurred when too much confidence was placed in the format indicator conveyed by BDS-10 (see 4.2). Nevertheless, using the right format, the analysis of the 880 encounters never led to doubt about the veracity of the reported RA.

4.5.3.3. The main difficulty in relation to the ARA part is its interpretation, especially when an accurate view of the RA displayed and announced on board is desired. This accurate view is necessary for event analyses, but seems not to be relevant for RA display on CWP.

4.5.3.4. The number of bits describing the RA is lower within the RA downlink message than on board. The issue linked with the missing value for the vertical speed limit (VSL) within the DO-185A format is well known. On the other hand, the double meaning of the bit called “Preventive/Corrective” is less well known and can lead to more than one interpretation of a given ARA set.

4.5.3.5. In addition, a given RA triggered on board can give different ARA values because the “crossing” and “reversal” bits do not have the same meaning or life span within the ARA part and within the data transmitted to the RA display on board.

4.5.3.6. The link between the ARA part from RA downlink and the RA displayed or announced on board is therefore not one to one.

4.5.3.7. A dedicated study was performed to build a conversion tab between ARA and RA displayed and announced on board. The methodology and the conversion tab are described in document [4].

4.6. Data relating to threat identity (TTI, TID)

4.6.1. TCAS simulations were performed for all encounters with non-empty ARAs. The simulated threat was unambiguously identified when the simulated RA sequence matched perfectly with the RA sequence built from the RA downlink messages. Then, the threat data from the RA downlink message could be compared with the result of the TCAS simulation. The following figures are based on analyses of the

880 encounters with valid ARAs. When the threat was not unambiguously identified, the case was considered without error by default. This occurred mainly when the threat was out of the radar coverage area (mainly at low altitude). Below is the distribution of the success of the TCAS simulations.

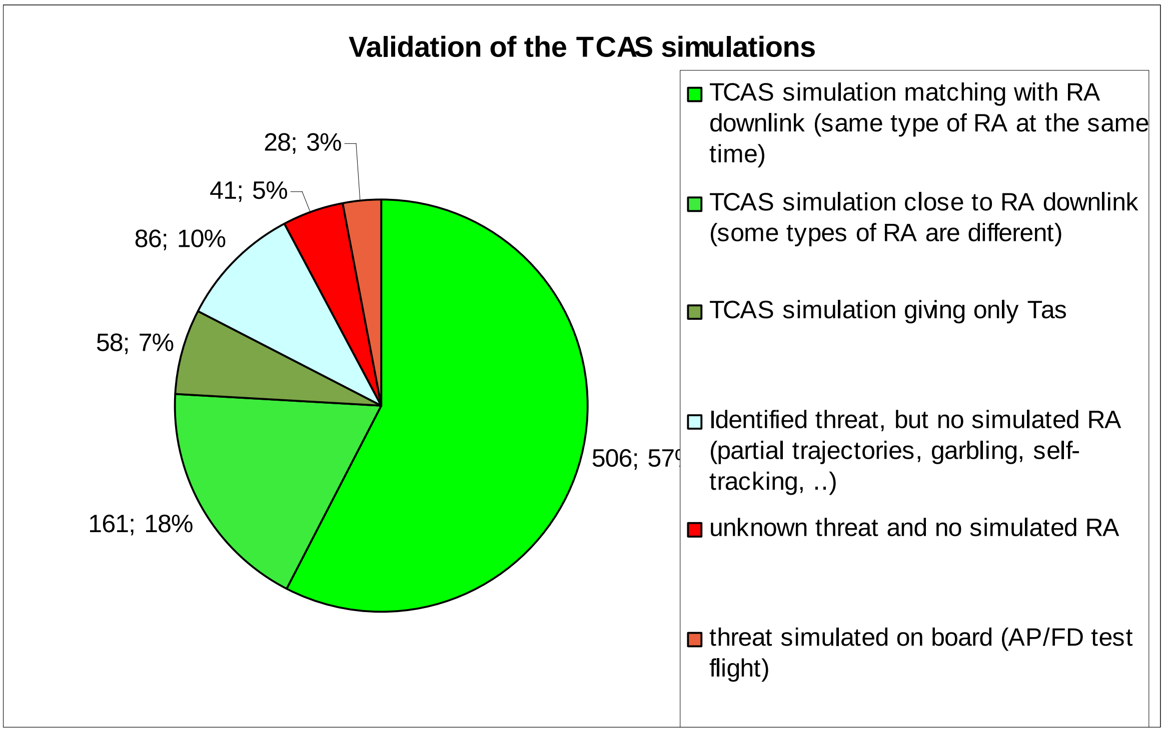


Figure 28: Success of the TCAS simulations

4.6.2. Threat-type errors

4.6.2.1. The ICAO address is normally used for Mode-S threats, whereas position data (distance, relative bearing and flight level) are used for Mode A/C threats. Nevertheless, we detected RA downlink messages in which position data were used for Mode-S threats. The following figure shows the distribution of the threat-type indicator for each aircraft with an RA (not for each RA downlink message).

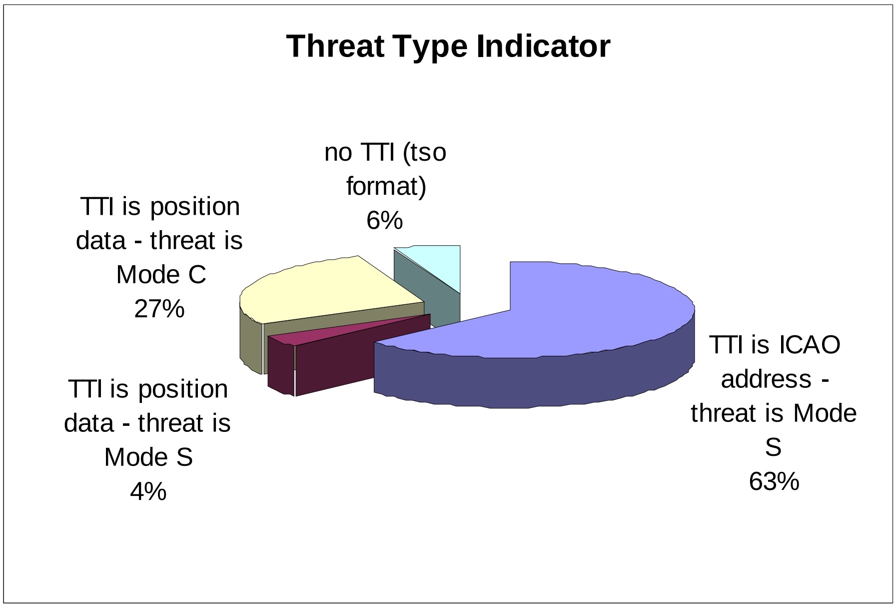


Figure 29: Threat-type indicator versus threat equipment

4.6.2.2. **About 4% of TCAS coded a Mode-S-equipped threat aircraft using the position data** instead of the aircraft's ICAO address.

4.6.2.3. There are two theoretical reasons why position data could have been used instead of the ICAO address:

- Incorrect standard implementation within these TCAS
- Mode-S transponder of the threat replying to "Mode C only" interrogations

4.6.2.4. Nevertheless, no different events involving the same TCAS aircraft or the same threat existed in the gathered data. No faulty transponders or faulty TCAS could therefore be identified.

4.6.3. Use of ICAO addresses

4.6.3.1. The threat ICAO address always corresponded to the actual threat identified through the TCAS simulation. These data were highly reliable.

4.6.4. Errors involving the use of position data

4.6.4.1. The position data coded within the RA downlink message can be checked via the results of the TCAS simulations. Below is the categorisation of all the detected errors involving the use of position data. The distribution takes into account 274 encounters where the position data was used (i.e. Mode C or Mode S threat). The data were classified as correct when the TCAS simulation was not validated or in case of doubt. No case when the aircraft reported both a wrong relative bearing and a wrong altitude was detected.

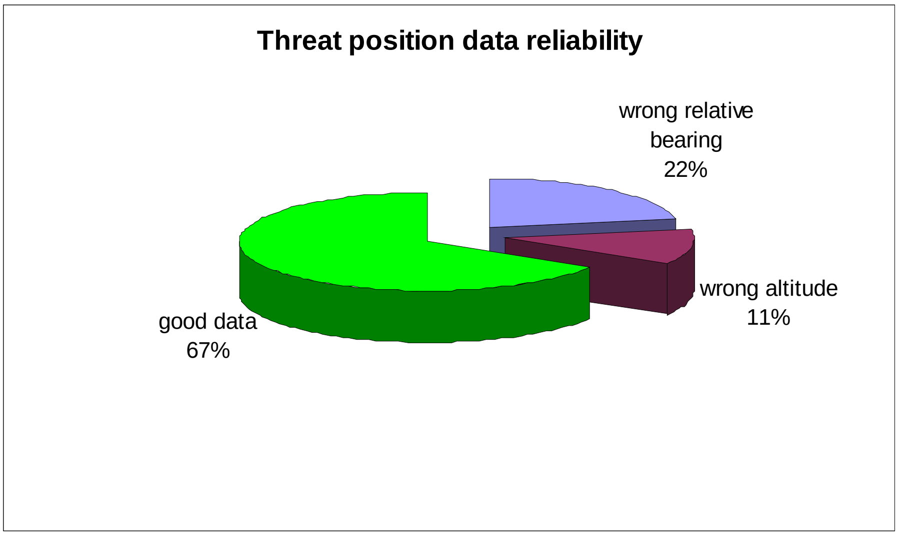


Figure 30: Reliability of threat-position data

4.6.4.2. **Only 67% of the threat-position data were correct**.

4.6.5. Relative bearing error

4.6.5.1. When the threat was Mode C equipped, **22% of TCAS downlinked an incorrect relative bearing**. The most common error was to have the absolute bearing (or azimuth) instead of the relative bearing. This error seems to have come from incorrect standard implementation by manufacturers. It should be noted that TCAS MOPS only mentioned in one instance out of many that the bearing was relative (see DO-185A 2.2.3.9.3.2.3.a1).

4.6.6. Altitude error

4.6.6.1. The **threat flight level was absurd for 11% of TCAS** reporting an RA. Each time the downlinked threat flight level was different from the simulated value, the downlinked data were not realistic (e.g. FL 948), so it was possible to detect this error easily.

4.6.6.2. It seems that these TCAS were not using the correct Gilham code for the threat altitude. The code uses 13 bits and contains the most recently reported Mode C altitude of the threat as it was reported within the Mode C reply. The bit order is the same as the order of the reply pulses (C1,A1,C2,A2,C4,A4,0,B1,D1,B2,D2,B4,D4).

4.7. RA complements (RACs)

4.7.1. No errors were detected within this part (except during self-tracking, see Annex).

4.7.2. The presence of an RAC within an RA downlink message indirectly indicates that the threat has also triggered an RA on board. For each RA downlink message with an RAC, we checked whether or not the corresponding threat had also sent an RA downlink message. Such a message had been sent for each encounter where the threat was within the radar coverage area.

4.7.3. On the basis of the above-mentioned check, **we observed that an RA downlink message seemed actually to be available for each triggered RA and could be downlinked depending on the Mode-S radar coverage**. The check carried out was not conclusive proof, but no counter-example was found. RA downlink messages thus always seemed to be available from the Mode-S transponder and the single obstacle to getting them seemed to be the Mode-S radar link.

4.7.4. Of course, since not all the radars were always recorded over this seven-month period and there was no detection at low altitude, and also owing to the probability of detection, there were more than 880 encounters in the real world. Nevertheless, we can reasonably assume that, although some RA downlink messages were missing, no encounters were missing within the captured traffic. The statistics, therefore, are not based on a full view, because only a partial view was captured, but the view itself seems to be accurate and the figures provided must be connected to the number of flight hours captured.

4.8. Terminated RA bit

4.8.1. Following the end of an RA, a DO-185A-compatible transponder retains the last RA downlink message for an additional 18 seconds (+/- 2 s) and downlinks it when it is interrogated by radars.

4.8.2. Below is the distribution of the duration of the RAT sequences following active RAs, captured by two radars with different antenna-turn periods. The duration is computed between the first and last messages received with the RAT bit set.

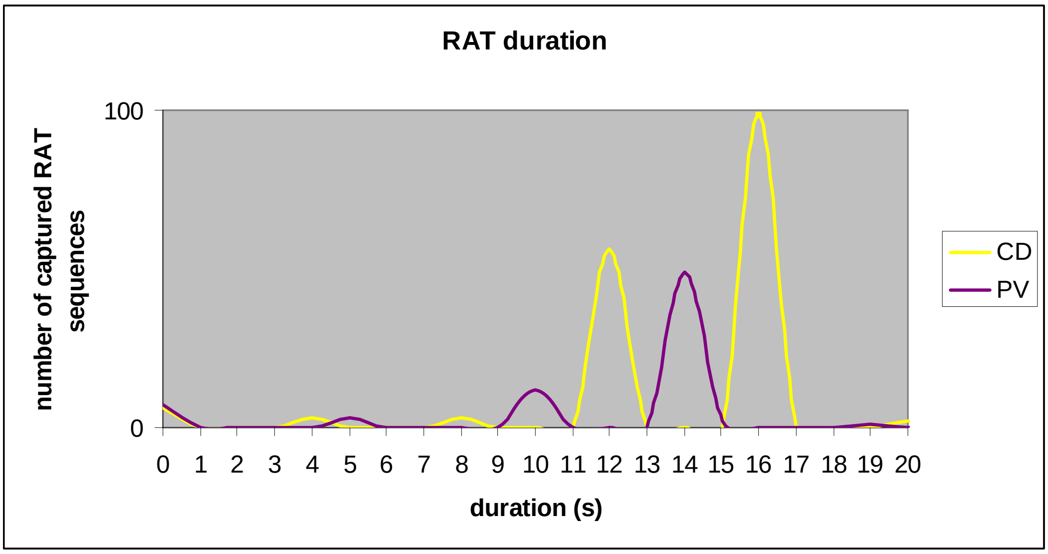


Figure 31: Distribution of the duration of the RA terminated sequences captured by two radars

4.8.3. As explained in 4.5.1.12, the captured duration is a multiple of the turn period of the radar antenna, and this is clearly visible here. The Roissy radar (CD) has a turn period of 4 seconds and gives samples at 16 and 12 seconds. This is fully consistent with a RAT duration of 18 seconds. Similarly, the Vitrolles radar (PV) has a turn period of 4.8 seconds and gives samples at 9.6 and 14.4 seconds. For these two radars, measurements below these values correspond to overly short memorisation or to detection losses.

4.8.4. Below is the same distribution, but for all the captured RAT sequences. The radars which captured the largest numbers of RA downlink messages are highlighted to show their influence on the final result.

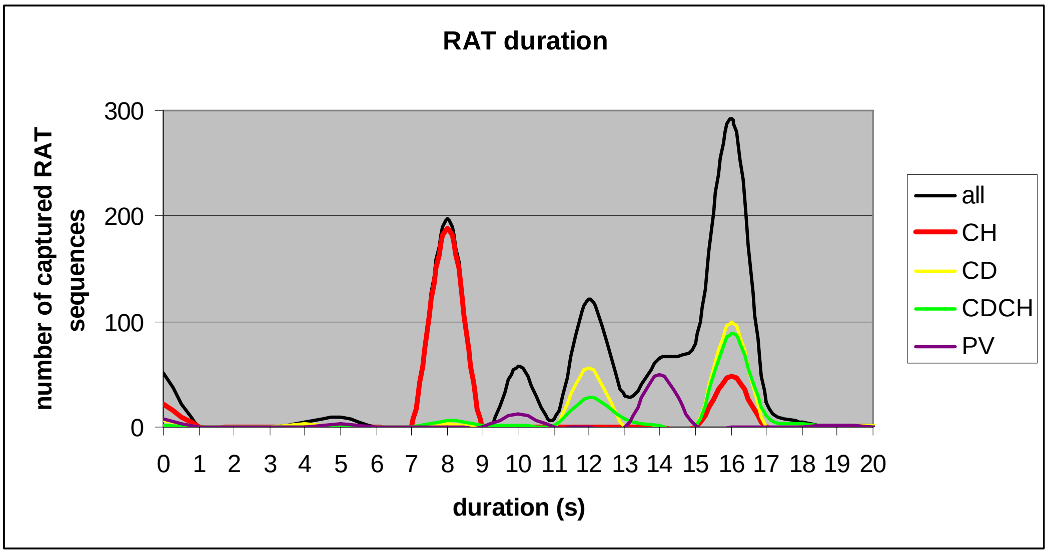


Figure 32: Distribution of the durations of all the captured RA terminated sequences

4.8.5. Out of 977 sequences sent by DO-185A transponders, **only one** transponder memorised the last active RA **more than 20 seconds**. Nevertheless, this was a very particular case because it was at the end of the RAs triggered as a result of self-tracking.

4.8.6. 7% of RAT durations were less than 8 seconds, which was the longest radar-turn period. This implies that **at least 7% of the cases were too short.** A systematic analysis of the cases with short RAT durations was performed, but only for sequences with only a single RAT message or with no RAT message at all. These cases represented 5% of the sequences and are visible in the “0 second” bin in Figure 31. For these 5% of cases, the various reasons why not enough RAT messages were captured are distributed as follows:

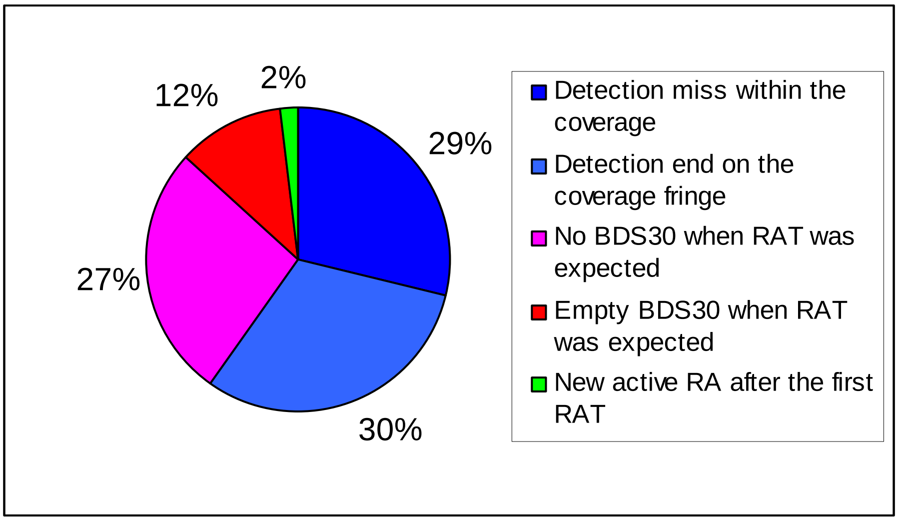


Figure 33: Distribution of the causes of short captured RAT durations

4.8.7. More than the half of short RAT durations were due to losses of detection. Plots were missing when the RAT messages were expected. This occurred within the radar coverage area and also just on the fringe of the radar coverage area, where the detection rate fell very sharply. So, at least 16 encounters were captured only partially because they were located on the fringe of the radar coverage area.

4.8.8. 39% (27%+12%) of short RAT durations were due to either no memorisation within the transponder or failed extraction of BDS-30 by the radar. In these cases, the plot was present but without an RA downlink message or with an empty RA downlink message.

4.8.9. The 2% part corresponds to only one case, in which new messages with active RAs were sent after the RAT message, owing to the triggering of a new RA after the first "Clear of Conflict".

4.8.10. To summarise, the RAT mechanism after an active RA seems to have worked properly in somewhat less than 93% of the cases. The memorisation time ensured that an **average of four messages with terminated RAs** were captured.

4.8.11. The total number of captured messages with terminated RAs was 4,166. The following figure shows the distribution compared to the number of messages with RAs still active.

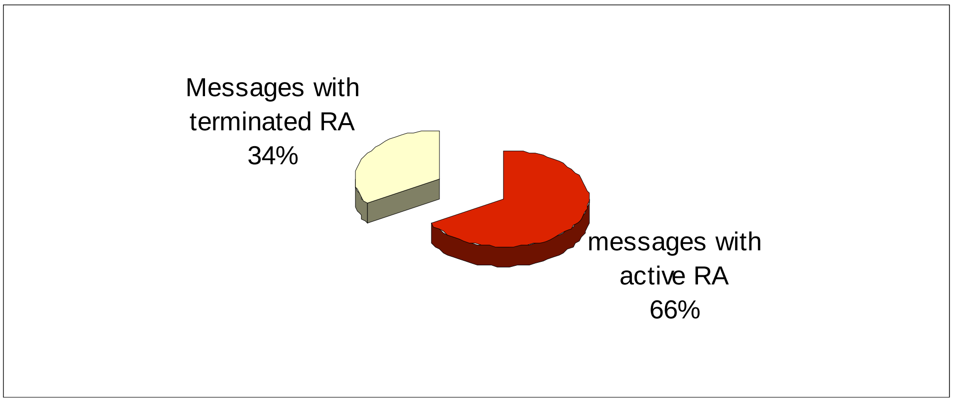


Figure 34: Distribution of messages with active RAs/terminated RAs

4.8.12. The large proportion of messages with terminated RAs was due to the fact that a terminated RA is maintained for 18 seconds, while an on-board RA lasted on average 33 seconds. These values come from the analysis of the sequence duration, for which the accuracy of measurements depends on the radar-turn periods.

4.8.13. We can also use the preceding distribution in relation to the number of messages in order to roughly estimate the duration of active RAs. Assuming that all messages with terminated RAs corresponded to a duration of 18 seconds, the average duration of an active RA was 66%*(18 s/34%) = 35 s. This quickly estimated value is close to the measured value of 33 seconds.

4.9. RA downlink message quality summary

4.9.1. Some aircraft send too many empty messages. These messages pollute ground processing but they can easily be rejected thanks to their features. Thus, all messages such as 30000000000000(h) and 30000020000000(h) can be rejected as soon as they are detected. No rejection based on identified faulty aircraft (using ICAO addresses) must be performed, because these aircraft are likely to send valid RA downlink messages. To summarise, this fault can be easily solved by an RA monitoring system and by a system dealing with RA display on CWP.

4.9.2. The low reliability of the BDS-30 format indicator from BDS-10 must be taken into account. It is reliable when it is set to DO-185A format. On the other hand, when it is set to 0 (TSO-C119A format), it is preferable to check the presence of a bit in the TTI-TID part and when using the DO-185A format. No DO-185A-formatted messages with empty TTI-TID fields were found, so it can be assumed that a non-zero bit in the TTI-TID field guarantees the use of DO-185A format.

4.9.3. The threat indicator can be used when it contains an ICAO address. On the other hand, it is not reliable in the event of incorrect TCAS implementation (bearing instead of relative bearing and incorrect altitude coding). This may cause difficulties where the threat must be identified on CWP. It should be pointed out that during the majority of encounters only one of the two aircraft had an RA (see 5.2.3). It is therefore not possible to identify both aircraft through their RA downlink messages.

4.9.4. The active-RA part is reliable, but its interpretation is not always obvious. Luckily, in the majority of cases, the RAs are common ("climb", "descend" or "adjust vertical speed") and ARA can be easily interpreted. Difficulties appear mainly for multi-threat encounters, which occur essentially during military operations.

4.9.5. The RAC (coordination received from threats) is reliable. It can be used to check the presence of RA downlink messages from the threat. Nevertheless, this data is not useful for RA displays on CWP.

4.9.6. When RAs were triggered, the "terminated mechanism" was reliable most of the time. It allowed us to catch very short RAs or RAs triggered just before the aircraft entered the radar coverage area. Nevertheless, 7% of the sequences were captured with an overly short RAT duration. Since the cause was detection loss in more than half of the cases, however, we may say that the 18 seconds of memorisation duration were generally well respected. On the other hand, and within the context of these radar-turn periods, the standard value of 18 seconds may seem oversized, because 4 messages were captured on average, but only one was useful.

4.9.7. The low turn periods of the radars used allow us to have a good sampling of the RAs triggered on board. The average time between successive captured RA downlink messages was 5.1 seconds, and only 2.9 seconds for 28% of cases, thanks to the redundant radar coverage.

4.9.7.1. Taking into account only the role of the turn periods, the mean latency to get the first RA is about 2.6 seconds for all the encounters, and about 1.5 seconds for the encounters captured by several radars. These figures are derived from the average time between successive captured RA downlink messages. This estimation does not include the latency between the time of the first RA triggering and the availability of the BDS30 data within the Mode S transponder.

5. Statistics from an operational point of view

5.1. Warning

5.1.1. All the statistics are based on the captured traffic and corresponding captured RA downlink messages. Not all “real-world” encounters were captured because the radars were not always recorded and their coverages were limited. The real number of encounters was thus greater than 880 over this 7-month period. The statistics must therefore be connected to the captured number of flight hours. Nevertheless, since the captured traffic is substantial (more than 1,330,000 hours) and spread over various countries and airspace types (airports, TMAs, en-route, military areas, etc.) we can assume that we have a representative view of the current situation.

5.2. Encounter classification on the basis of threat equipment

5.2.1. Distribution of all encounters

5.2.1.1. The captured encounters can be categorised on the basis of whether RAs were present on both aircraft or on only one aircraft. It is similar to categorising the encounter on the basis of whether or not the threat sent RA reports. If there was no RA report from the threat, it is worth detailing the threat equipment and its reported status.

5.2.1.2. The following figure gives the distribution of the captured encounters on the basis of the threat’s features. Each threat category is referenced by a letter. In case of change during the encounter, the category with the “lower” letter is retained for this distribution. For example, if an aircraft received an RA and the TCAS equipped intruder got nothing (category “B”), but later received a coordinated RA, this encounter will be in the “A” category.

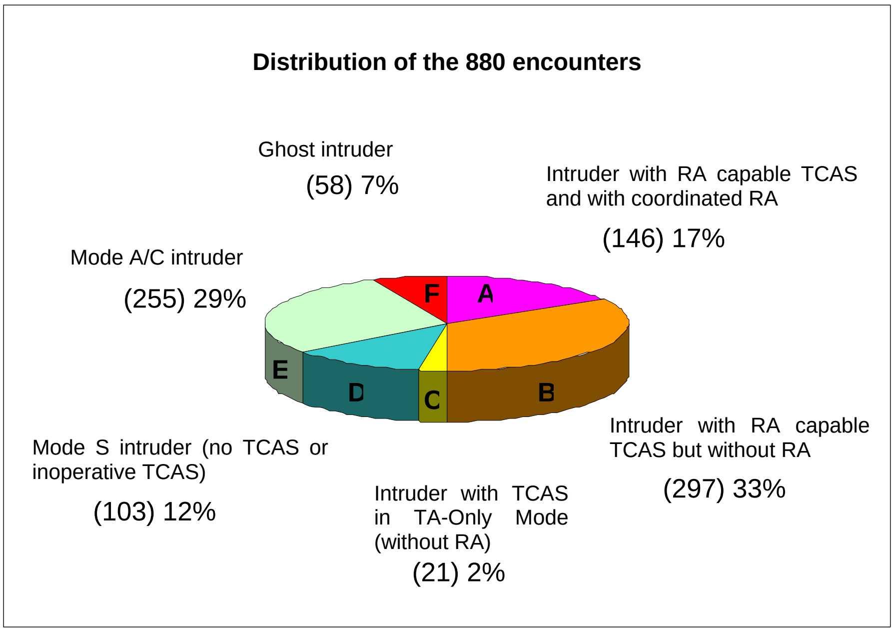


Figure 35: Distribution of all encounter categories

5.2.2. Category A: encounters with RAs on both aircraft

5.2.2.1. Only **17% of encounters** were encounters in which **both aircraft had RA**s on board. This proportion appears low, but will be explained by the size of the other categories.

5.2.3. Category B: encounters with an RA on only one aircraft against an RA-capable TCAS-equipped threat

5.2.3.1. This substantial part corresponds to 33% of the 880 encounters. The following figure splits the various causes of a lack of an RA on board the second TCAS-equipped aircraft.

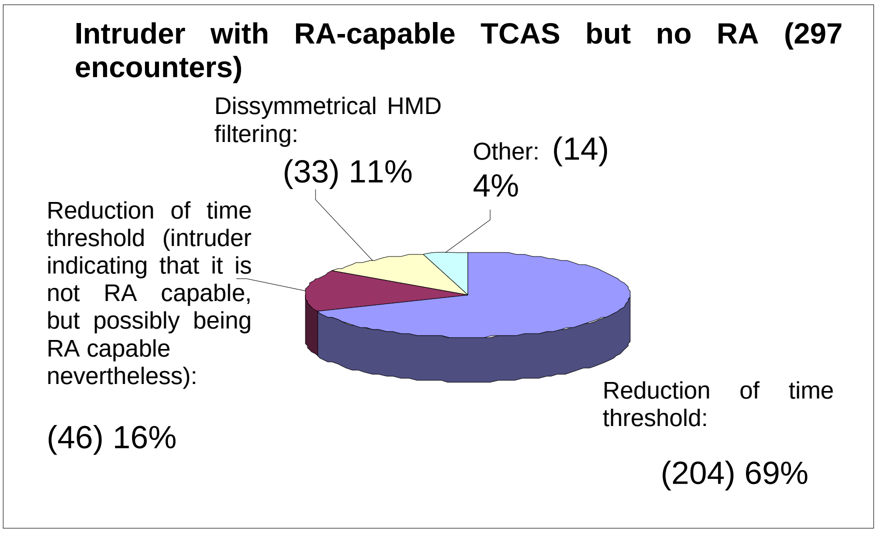


Figure 36: Distribution of reasons why there was no RA on TCAS-equipped threats

5.2.3.2. The main reason for having an RA in only one aircraft resulted from the reduction of the time threshold in the stable aircraft. This feature was designed for 1,000-ft level-off geometry in order to reduce the number of RAs. This geometry corresponded to 85% (69% + 16%) of encounters in which the threat had an RA-capable TCAS but did not trigger an RA. This part corresponded to **28% of all encounters**.

5.2.3.3. Where the threat had an empty TCAS status (part of BDS-10), and where the absence of an RA could also be explained by the vertical encounter geometry, the threat was considered to be TCAS equipped and the encounter was put in the "owing to reduction of time threshold" category. Otherwise, this threat would have been considered as having no operational TCAS and might have artificially increased the number of aircraft mandated as ACAS equipped and without TCAS.

5.2.3.4. The second reason why neither aircraft had an RA was asymmetric behaviour of the HMD filter within each TCAS, owing to asymmetric vision of the relative bearing evolution. These cases were identified using the possibility of inhibiting and forcing the HMD filtering independently for both aircraft during the TCAS simulations.

5.2.3.5. Among the “other” reasons, three cases were identified as resulting from a dissymmetric view of the vertical situation on board each aircraft. The aircraft involved reported their altitude with increments of 25 ft. In both TCAS, therefore, the threat was tracked with a 25-ft quantisation, but the each aircraft’s own altitude was tracked with better resolution. The slight differences were enough to trigger an RA in one aircraft and not in the other one.

5.2.3.6. All the other “other reasons” (11 cases) should more accurately be called “unknown”, because no certainty was drawn from the TCAS simulations. Sometimes two reasons seemed probable, and the RA was not reproducible on seven encounters. Taking into account the 880 encounters, the TCAS simulations were accurate in 57% (see 4.6.1) and compatible in 18%. The success rate is better on this reduced set of 297 encounters owing to their altitude due to better radar detection.

5.2.3.7. The case by case study of these “other raisons” cases has provided us with illustrative examples about the sensitivity of TCAS simulations, highlighting the CAS logic’s own sensitivity.

5.2.4. Category C: encounters with an RA on only one aircraft against a threat with TCAS in TA-only mode

5.2.4.1. The following figure details the distribution of threats with TCAS in TA-only mode.

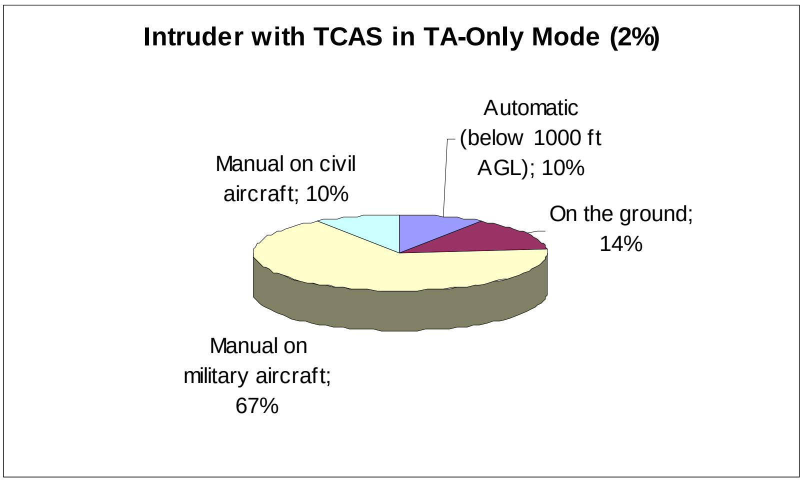


Figure 37: Distribution of threats with TCAS in TA-only mode

5.2.4.2. Threats which were in TA-only mode because they were on the ground also sent an incorrect “airborne” flight status.

5.2.4.3. The percentage of civilian aircraft in manually selected TA-only mode was 10% of 2% of the 880 encounters and corresponds to only 2 aircraft.

5.2.4.4. Most of the aircraft whose pilots had manually selected TA-only mode were military aircraft.

5.2.5. Union of categories A, B and C

5.2.5.1. The union of categories **A**, **B** and **C** corresponds to the set of encounters where both aircraft were TCAS equipped, and represents **52%** of all encounters.

5.2.6. Categories D and E: encounters with an RA on only one aircraft against a threat without TCAS or with inoperative TCAS

5.2.6.1. The following figure details the distribution of all threats which were not TCAS equipped. Category **E** (29% of encounters) is therefore merged with the split of category **D** (12% of encounters).

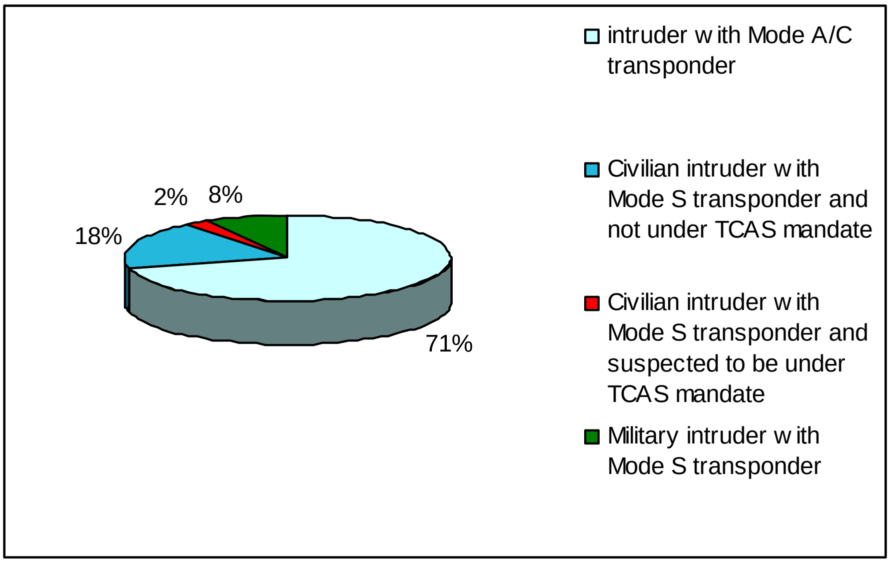


Figure 38: Distribution of threats without operative TCAS

5.2.6.2. The Mode-A/C threats constituted the largest part and corresponded mainly to VFR flights (80 identified cases) and military flights (81 identified cases).

5.2.6.3. The TCAS carriage mandate was searched for all civilian aircraft equipped with Mode-S transponders and without operative TCAS. The type of aircraft was found via the ICAO address. The TCAS carriage mandate was then deduced via the MTOW.

5.2.6.4. 2% of non-TCAS-equipped threats should have been under ACAS mandate. This percentage corresponds to only **eight** aircraft and must be viewed in the context of the 1,330,000 flight hours. Over the seven-month period, five of these eight aircraft always had their TCAS capability set to 0, i.e. never filled in. These five aircraft are suspected to be aircraft without TCAS. Nevertheless, the possibility must be considered that these aircraft had operative TCAS but were missing BDS-10 information, so that no probable cause can be found for their not having had an RA. On the other hand, the situation is less ambiguous for the three other aircraft.

5.2.6.5. For one aircraft (a CL60), the TCAS was operative over the preceding days and during the previous flight, which had taken place two hours before the flight during which the encounter occurred. The TCAS was inoperative throughout the flight during which the encounter occurred, and the aircraft was not detected until three days later, with an operative TCAS. The most probable cause was a TCAS failure followed by a three-day repair period.

5.2.6.6. Over the seven-month period, the TCAS of another aircraft (a Falcon 2000) was inoperative on ten different, non-grouped days, but operative on the neighbouring days. Flights with TCAS switched off seem to be more probable than failed TCAS for these ten days.

5.2.6.7. The TCAS of the third aircraft (a Fokker 70) was operative for all the flights preceding the flight during which the encounter took place. It was inoperative from the beginning of that flight, but became operative again two minutes after the RAs were triggered within the second aircraft. It seems that the TCAS was switched off from the beginning of the flight and then turned on only after the encounter with the other aircraft (following ATCO transmission?).

5.2.6.8. Because of the low reliability of the BDS-10 data, it is impossible to draw clear conclusions about the five aircraft suspected not to be TCAS equipped. Nevertheless, one case of TCAS failure was detected, as was a case of failure to switch on the TCAS. These cases are insignificant in relation to the 880 encounters, but may have greater importance because the research was performed on only the aircraft involved in encounters captured via RA downlink messages, rather than on the traffic as a whole. Nevertheless, it seems unrealistic to try to assess, for example, the ten-day MEL period, given that the BDS-10 data are not fully reliable.

5.2.7. Category F: ghost encounters

5.2.7.1. This category groups together all the ghost encounters, during which the TCAS triggered RAs against tracks not corresponding exactly to a threat. The identified causes were:

- On-board simulated threat during test flight
- Transponder test on the ground with modified reported altitude
- False altitude owing to garbling (small number of military aircraft)
- Self-tracking
- Aircraft on the ground reporting an airborne flight status

5.2.8. The following figure gives the number and distribution of these ghost encounters.

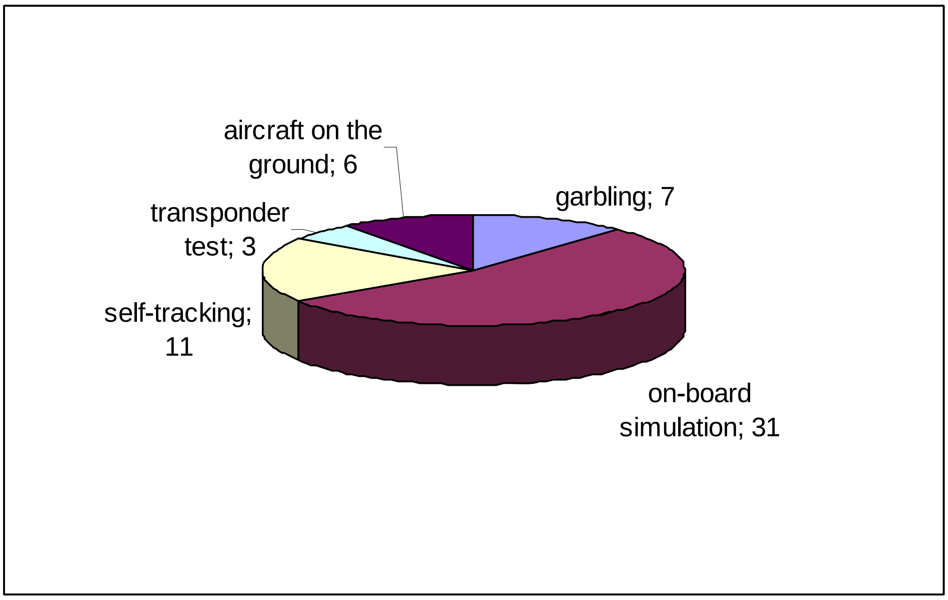


Figure 39: Distribution of ghost encounters

5.2.8.1. Examples of these ghost encounters are given in Appendix A.

5.3. Classification of encounters by operation type

5.3.1. Some differences between RA downlink message sequences can be explained by the type of operation during the encounters. For example, very long RA downlink message sequences correspond to intentionally close trajectories between military aircraft.

5.3.2. All the encounters were therefore analysed in order to be classified as intentional or unintentional. The decisions mainly were based on the encounter geometries and on the involved aircraft, and expert judgement. In the event of any doubt, they were classified as "unqualified encounters".

5.3.3. The 880 encounters can be split as follows:

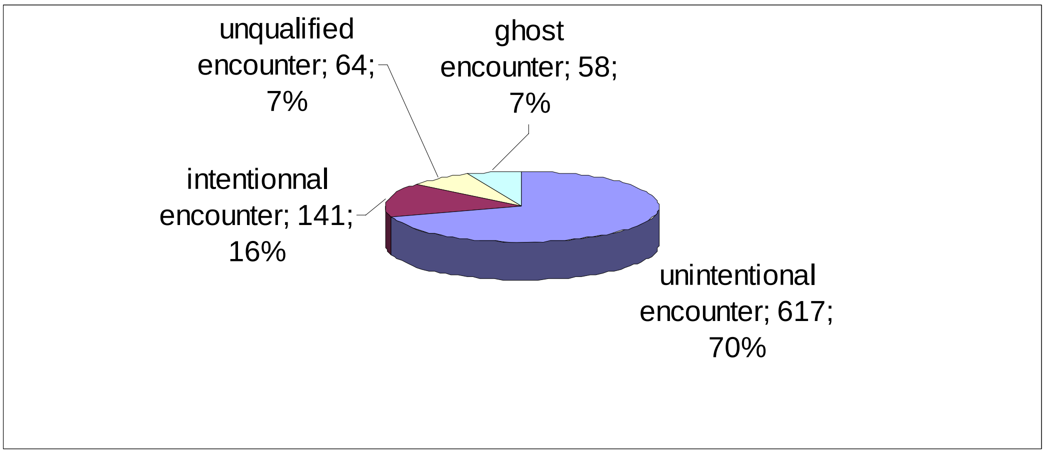


Figure 40: Distribution of encounters (intentional or unintentional)

5.3.4. To help in this classification task, the aircraft involved were also classified as civilian, military, VFR, rotorcraft, or test flights. This classification was done on the basis of Mode A, aircraft identification and ICAO address. Military aircraft in OAT were mixed with military aircraft in GAT.

5.3.5. By grouping together VFR, rotorcraft and civilian aircraft under the label "civilian", and military aircraft and test flights under the label "military", the unintentional encounters can be split as follows. The first label corresponds to the aircraft with RAs. So, the "civilian-military" label corresponds to RA triggered on board a civilian aircraft due to a military aircraft, and the "military-civilian" label corresponds to RA on board a test flight due to a civilian aircraft.

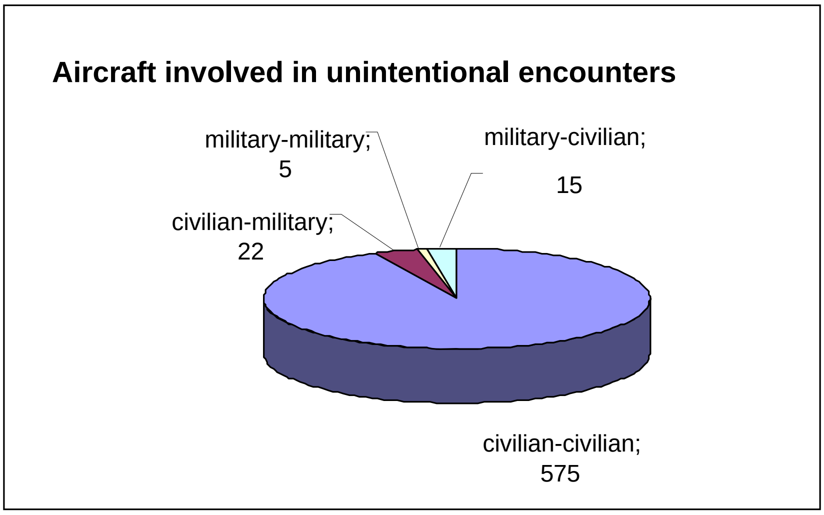


Figure 41: Distribution of unintentional encounters in terms of the aircraft involved

5.3.6. The majority of unintentional encounters occurred between civilian aircraft (575 encounters) and RAs were triggered on board both aircraft in 122 of them.

5.3.7. The unintentional "civilian-military" encounters correspond to RAs triggered on board civilian aircraft by military aircraft just on the border of their military zone (at high speed) or in GAT. During these 22 encounters, RAs were also triggered on board the military aircraft only in three cases.

5.3.8. During these unintentional encounters, 719 civilian aircraft received RAs (575+122+22).

5.3.9. The unintentional "military-military" encounters correspond to encounters between test flights at an air force test centre, and between military aircraft at military airport. Often, it was a departing aircraft that triggered an RA against an overflying aircraft in which case RAs were followed correctly. During intentional encounters between military aircraft, RAs were rarely followed by the pilots.

5.3.10. The unintentional "military-civilian" encounters correspond to encounters between test flight (mainly Falcon or Learjet) and civilian aircraft without or with TCAS but when the RAs were not triggered owing to the time threshold reduction.

5.4. Vertical distribution of the encounters

5.4.1. Below are the vertical distributions of the encounters. They are presented for unintentional and intentional encounters.

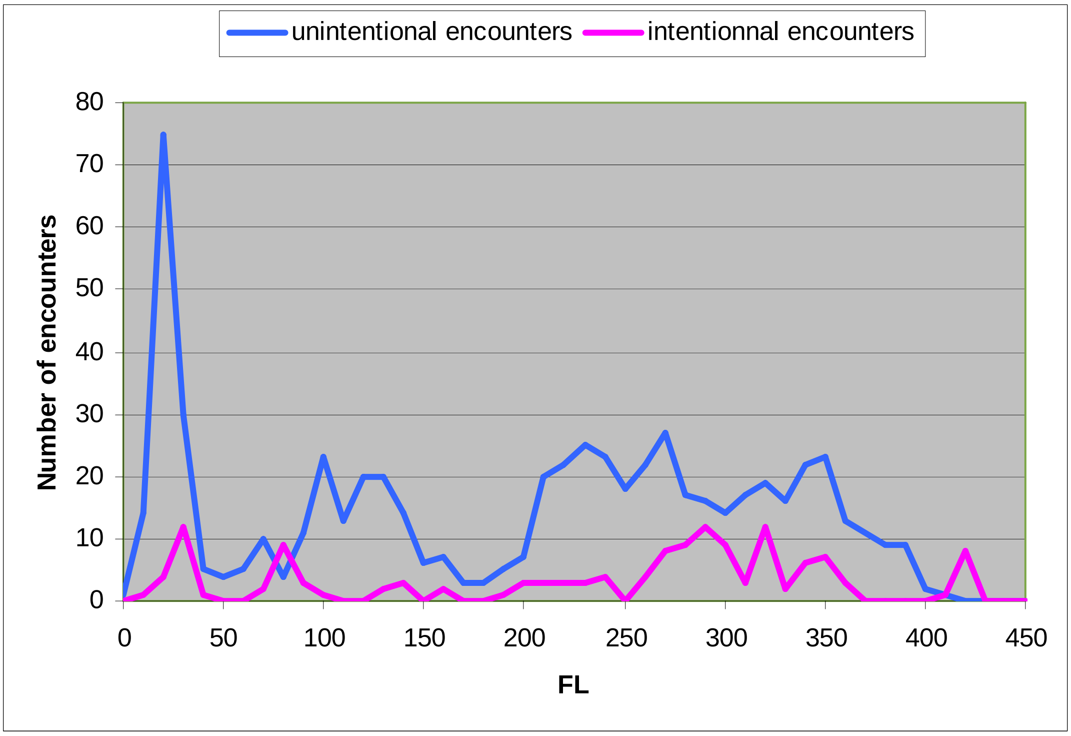


Figure 42: Vertical distribution of unintentional and intentional encounters

5.4.2. The increase in unintentional encounters below FL 40 corresponded to encounters between IFR flights and VFR flights.

5.4.3. There were two main altitude bands within which unintentional encounters occurred. The first one was between FL 90 and FL 140. The second one was between FL 210 and FL 360.

5.4.4. The intentional encounters were more evenly distributed. RAs above FL 400 corresponded only to military operations.

5.4.5. The following figure gives the vertical distribution of the unintentional encounters in which the threat was not TCAS equipped. We thus have an idea of the transponder-type equipment of the general aviation aircraft and of some of the military aircraft.

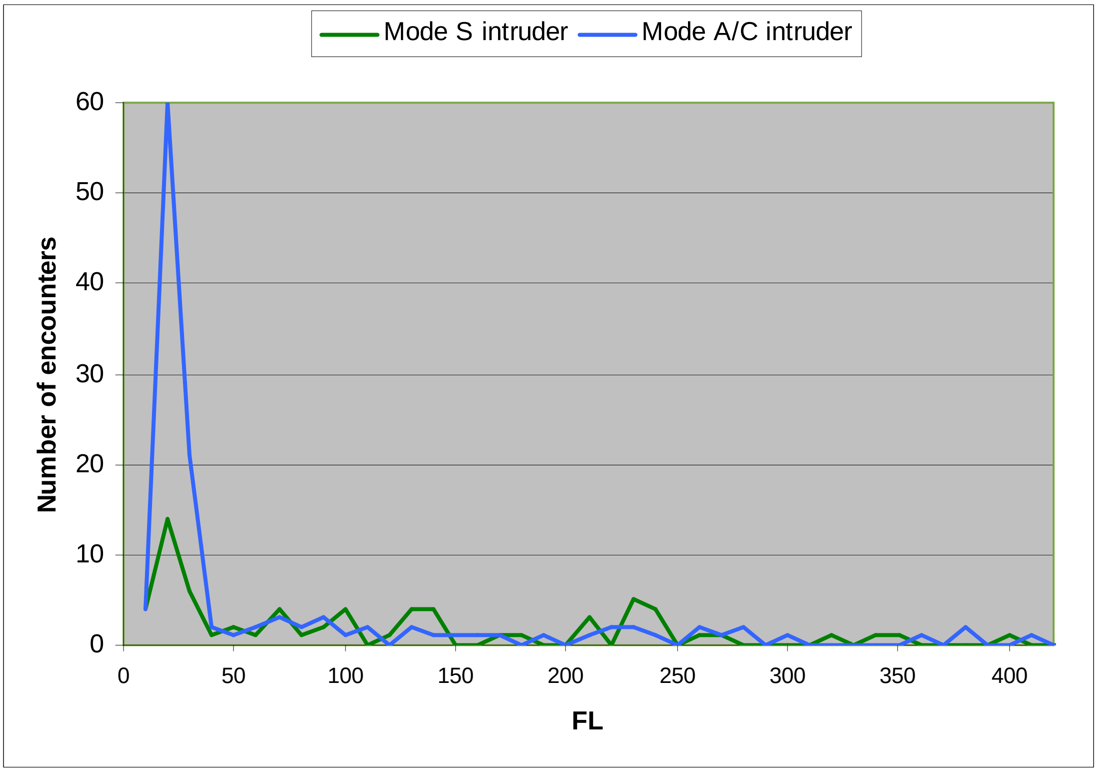


Figure 43: Vertical distribution of unintentional encounters in which threats were only Mode A/C or Mode-S equipped

5.4.6. Below FL 40, the majority of threats were only Mode A/C equipped. This part corresponded mainly to VFR flights.

5.4.7. Above FL 150, the Mode-A/C-equipped threats were mainly military aircraft in GAT, while the Mode-S-equipped threats were mainly from general aviation.

5.4.8. The following figure shows the vertical distribution of the unintentional encounters in which the threats were TCAS equipped. This distribution is split into two parts. The first one corresponds to encounters where RAs were triggered on board both aircraft, and the second one corresponds to encounters where RAs were triggered on board only one aircraft and the identified cause was the VTT reduction.

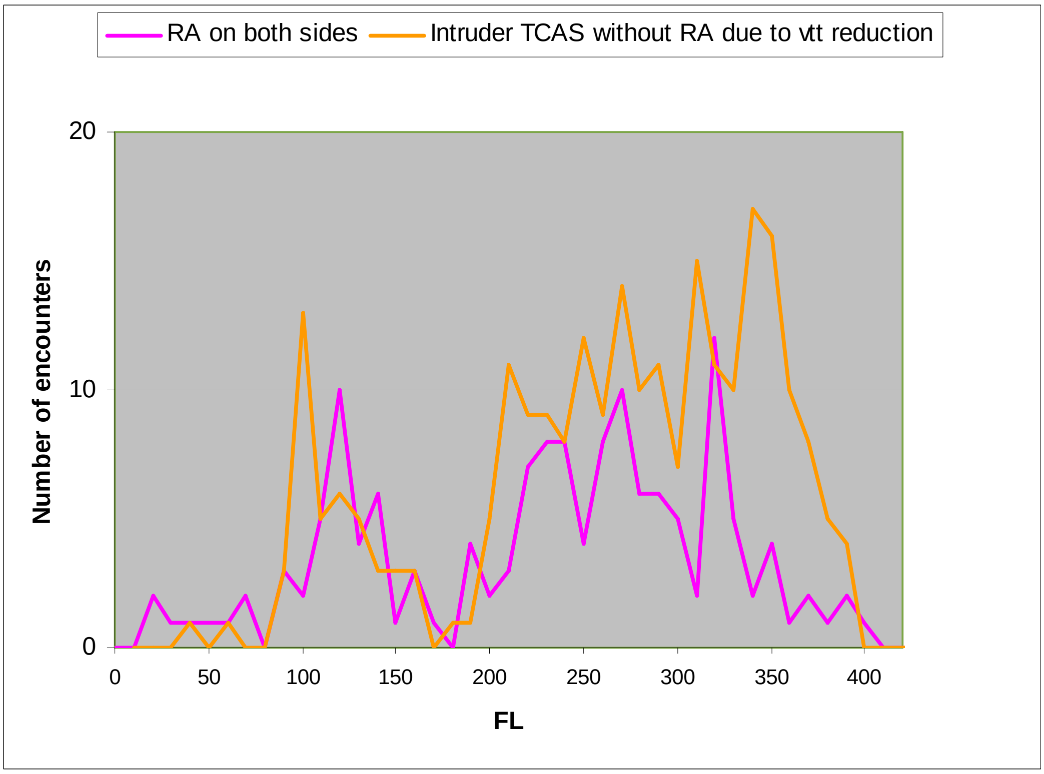


Figure 44: Vertical distribution of unintentional TCAS-TCAS encounters

5.4.9. The aim of the split is to highlight the altitude bands within which the level-off geometries occurred and where RAs were avoided owing to the VTT reduction action. An altitude band centred on FL 100 is clearly visible. The other level-off geometries occurred within a larger altitude band between FL 200 and FL 360.

5.5. RA-sequence duration connected with the encounter categories

5.5.1. The distribution of the durations of active RAs within the sequences of RA downlink messages has already been presented, in 4.5.2.4. This presentation, however, took into account all the sequences, with no knowledge of the corresponding encounters. The following figure focuses on sequences lasting less than one minute, and the distribution is presented for the various encounter types which were not identified as "ghost encounters".

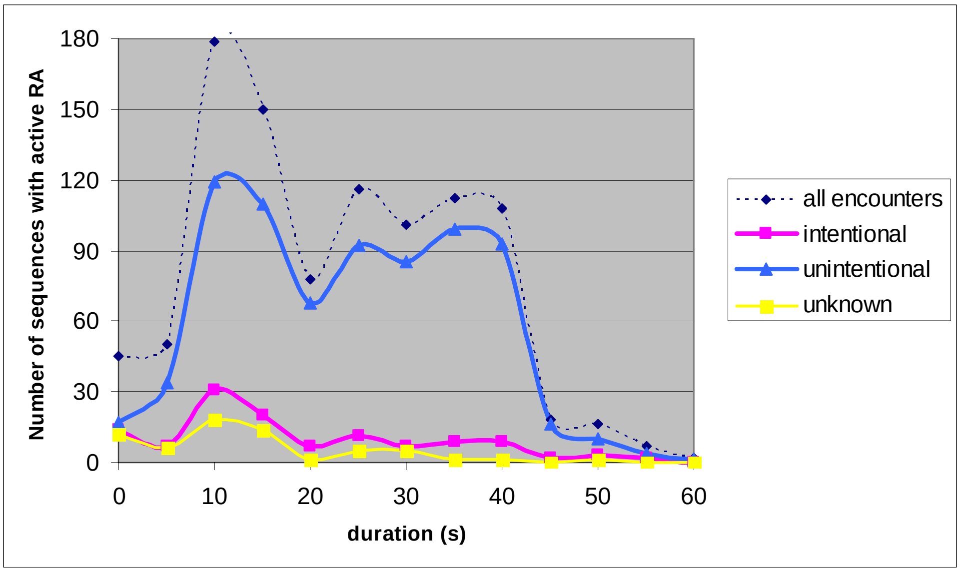


Figure 45: Distribution of RA-sequence durations for real encounters

5.5.2. The form of the curves is similar in all encounter categories. Generally, the RA duration was mainly linked to the encounter altitude because of the increase in the threshold values with altitude. The following figure was produced in order to check this fact and corresponds to only the unintentional encounters. The x-axis gives the duration, from 0 to 50 seconds, from left to right. Only the peak at 15 seconds below FL 20 and the peak between 20 and 35 seconds located around FL 100 are explainable by the CAS logic threshold values. The figure on the right shows the distribution in terms of the horizontal geometry. Most of the unintentional encounters were crossings at 90° and head-on encounters (between 150° and 180°). The short durations (15 s) above FL 200 may have been linked to horizontal manoeuvres during these geometries.

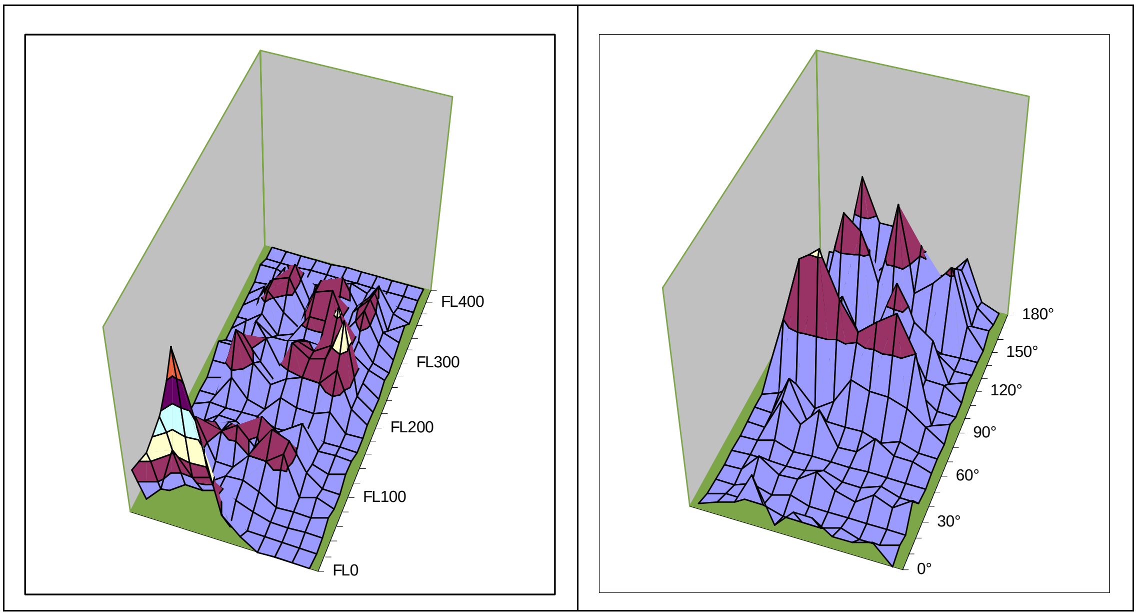


Figure 46: RA-duration distribution for unintentional encounters in terms of altitude and geometry

5.5.3. The trough at 20 seconds is surprising. The form of the distribution depends on the bin value, which is 5 seconds here, in order to smooth the curves. The following figure, however, uses a bin of 1 second and is also only for unintentional encounters. We can see that the trough at 20 seconds does not result from the radar-turn periods.

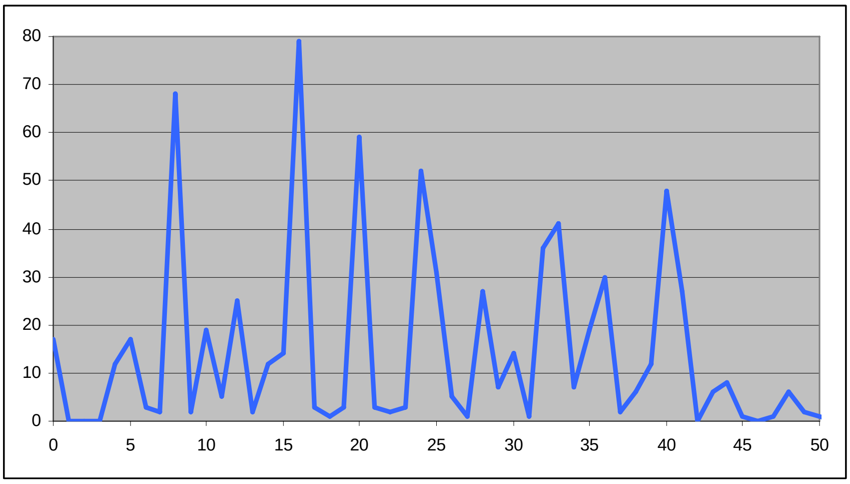


Figure 47: Distribution of RA-sequence durations with a bin of 1 second

5.5.4. The following distribution is for the ghost encounters. The RAs triggered as a result of self-tracking had various durations which corresponded a priori to the time needed by the pilot to diagnose the fault and act on the relevant equipment. On the other hand, the RAs triggered during test flights, where the threat was simulated on board, give a duration distribution similar to the real encounters. It is suspected that the parameters of the simulated encounters were more discrete than in the real world, and this could be the reason for the sharpness of the peaks at 10-15, 25 and 40 seconds.

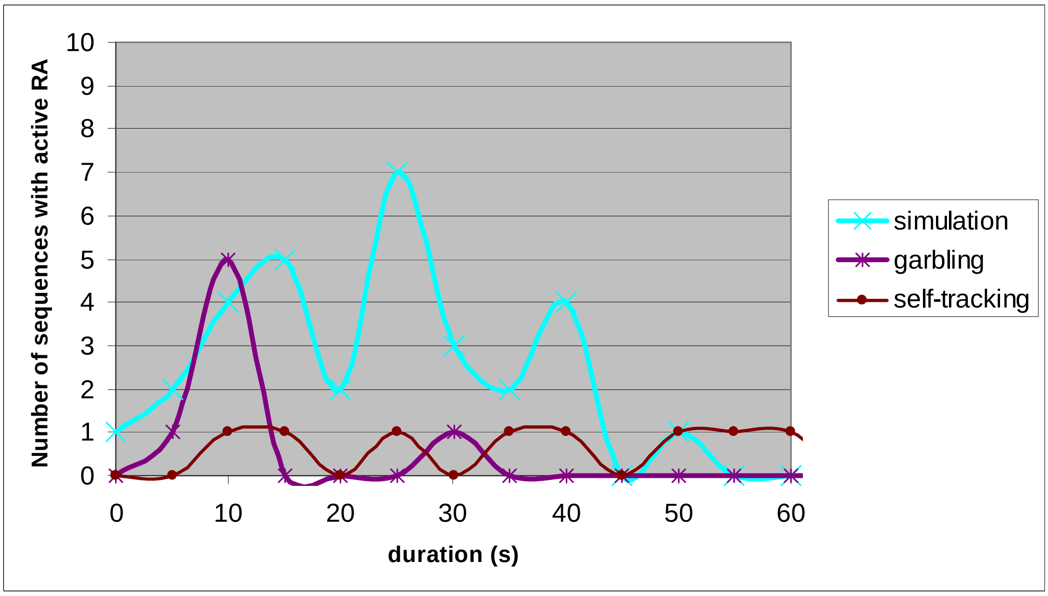


Figure 48: Distribution of RA-sequence durations for ghost encounters

5.5.5. A large majority of active RA sequences lasted less than one minute, but 5% were longer and a number were very long. The following figure gives the duration distribution for the long durations. Only the unintentional and intentional encounter categories are retained here, because all the active RA sequences triggered during the other encounters lasted less than 70 seconds. The very long sequences corresponded to intentional encounters, such as a merging followed by an escorting. Nevertheless, there were also unintentional encounters in which the RA sequence duration was very long. This was often due to very slow range diverging after overtaking (see example 7.2.6).

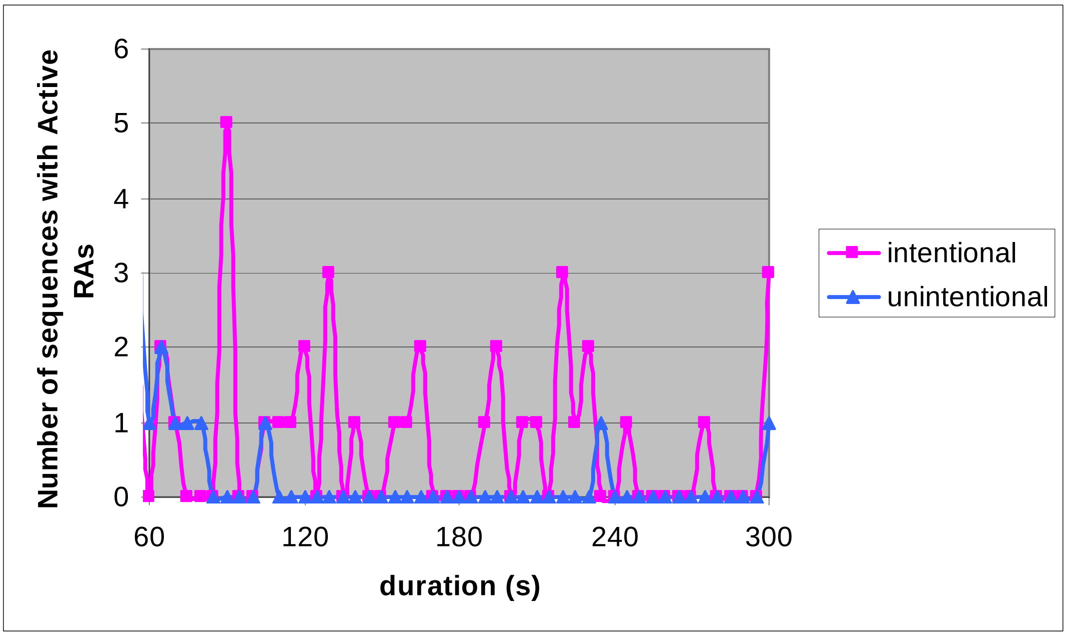


Figure 49: Long RA-sequence durations

5.6. RA type during unintentional encounters

5.6.1. RA-sequence type

5.6.1.1. During an encounter and until the “clear of conflict” (CoC), TCAS re-assesses the situation each cycle (close to 1 second) and may then update the type of RA. This can give various types of RA sequence. For example, the sequence can be simple, such as a “climb” RA maintained until the CoC, or more complex, such as a “climb” RA followed first by an “increase climb” RA and then by a “descend now” RA. This section will detail the different RA sequence types captured over the seven-month period.

5.6.1.2. Because RA downlink messages are captured only when the radar antennas illuminate the aircraft, it is probable that some RA types are missing within the sequence. Nevertheless, the systematic comparison of the captured RAs with the simulated RAs has highlighted only a small number of cases in which RAs were probably missing. These cases correspond mainly to a potentially not captured preventive RA before the first captured RA.

5.6.1.3. Despite these losses, the following study is based on the captured RAs and not on the simulated RAs, in order to remain based on observations. In addition, this simplifies the sequences of successive "adjust vertical speed" RAs with different vertical speed limits (VSLs).

5.6.1.4. The sequences of RAs during intentional encounters are not presented here, because they are often complex, involving reversals, multi-threats or even split RAs, and are of no interest from an operational point of view.

5.6.2. Distribution of all RA sequences for unintentional encounters

5.6.2.1. The following figure shows the number of RA sequence types during unintentional encounters. Among the 617 unintentional encounters, only 126 encounters had RAs on both aircraft. Therefore the figure is based on 743 RAs sequences. Each sequence is represented by a succession of abbreviations for the RAs involved. The abbreviations are: cl = climb, de = descend, icl = increase-climb, ide = increase-descend, ld = limit-descend (adjust vertical speed), lc = limit-climb (adjust vertical speed), mo/ma+ = monitor or maintain positive vertical speed, mo/ma- = monitor or maintain negative vertical speed, mo-lc = monitor vertical speed limit climb, and mo-ld = monitor vertical speed limit descend. For example, the sequence "cl icl de" means a "climb" followed first by an "increase climb" and then by a reversal "descend".

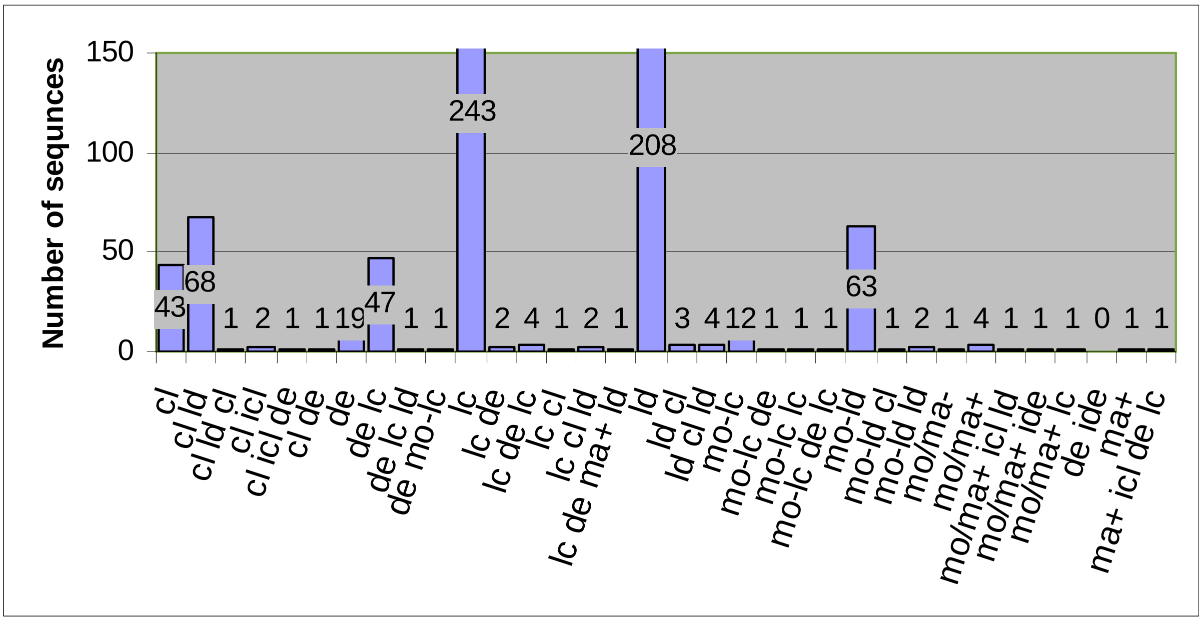


Figure 50: Types and occurrences of RA sequences for unintentional encounters

5.6.2.2. The most common sequences are clearly visible in this figure. The vertical scale is truncated in order to show the low occurrences and the crossing information is masked here in order to reduce the number of bins.

5.6.2.3. The following figure shows the distribution of the most common sequences, merging the minority sequences into a single bin called "other".

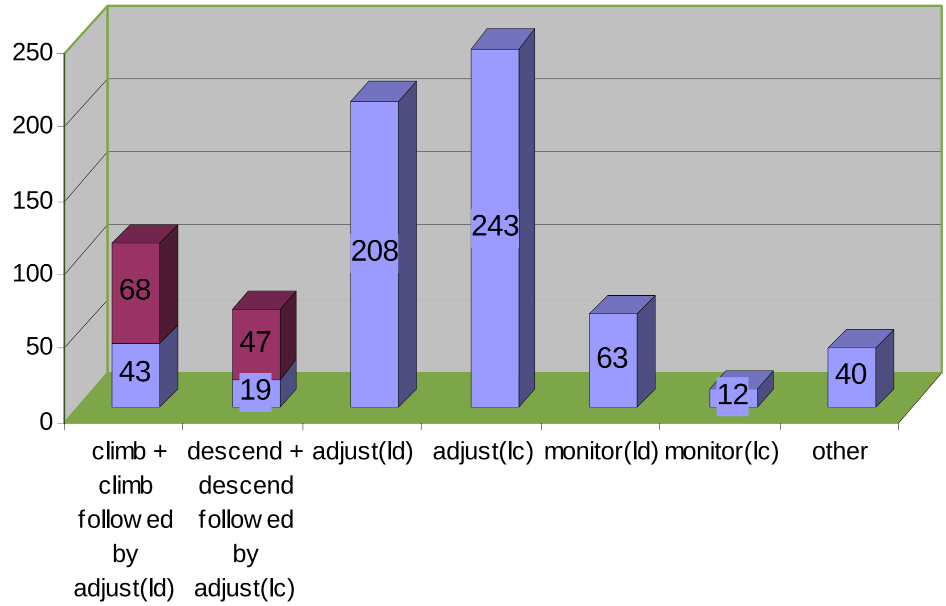


Figure 51: Distribution of the RA sequences for unintentional encounters

5.6.2.4. The "climb" sequences (in blue) are merged with the "climb" followed by "adjust vertical speed" sequences (in magenta). The same goes for sequences in the other direction, i.e. downwards. The majority of RA sequences correspond to a single "adjust vertical speed".

5.6.2.5. The distribution of RAs can be shown as follows:

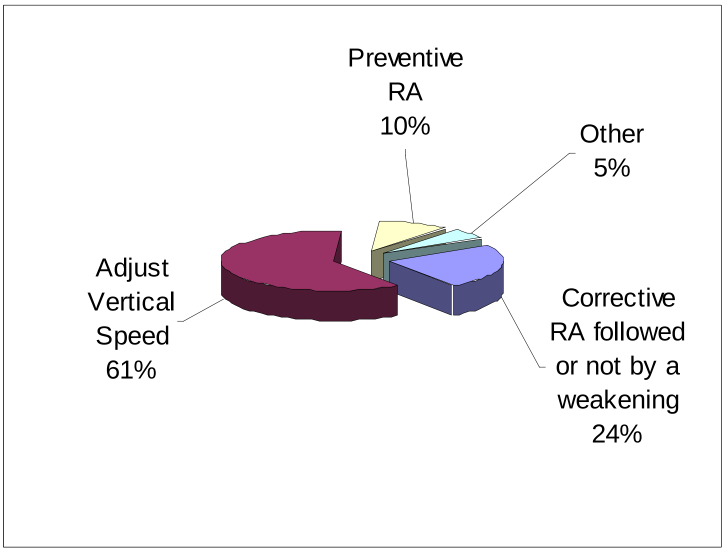


Figure 52: Distribution of RA types during unintentional encounters

5.6.3. Type of RA depending on altitude during unintentional encounters

5.6.3.1. The following figure shows the distribution of the RAs among the altitude band limits highlighted in section 5.4.

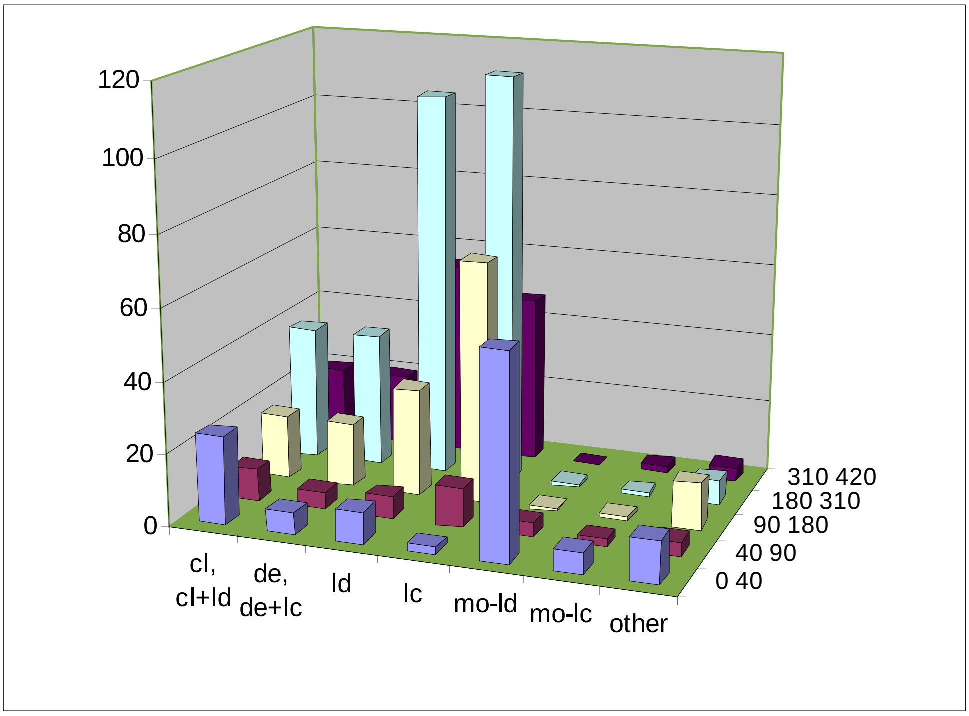


Figure 53: Distribution of RA types with regard to altitude

5.6.3.2. The preventive RAs (“monitor vertical speed” with limit descent) occurred mainly below FL 40 and corresponded to arrival flights levelled just above G airspace with VFR close to its ceiling.

5.7. Time-of-day distribution

5.7.1. Below is the time-of-day distribution for unintentional encounters and for combined intentional and simulated encounters. For unintentional encounters, the distribution seems to be linked to the traffic amount, but the common traffic peaks are not visible here. On the other hand, the intentional encounters occurred uniquely between 7.00 and 17.00 UTC, which corresponds not only to common working hours but also to daylight hours. This may be of interest for visual acquisition during the test flights. It should be remembered that the study was performed over the winter period.

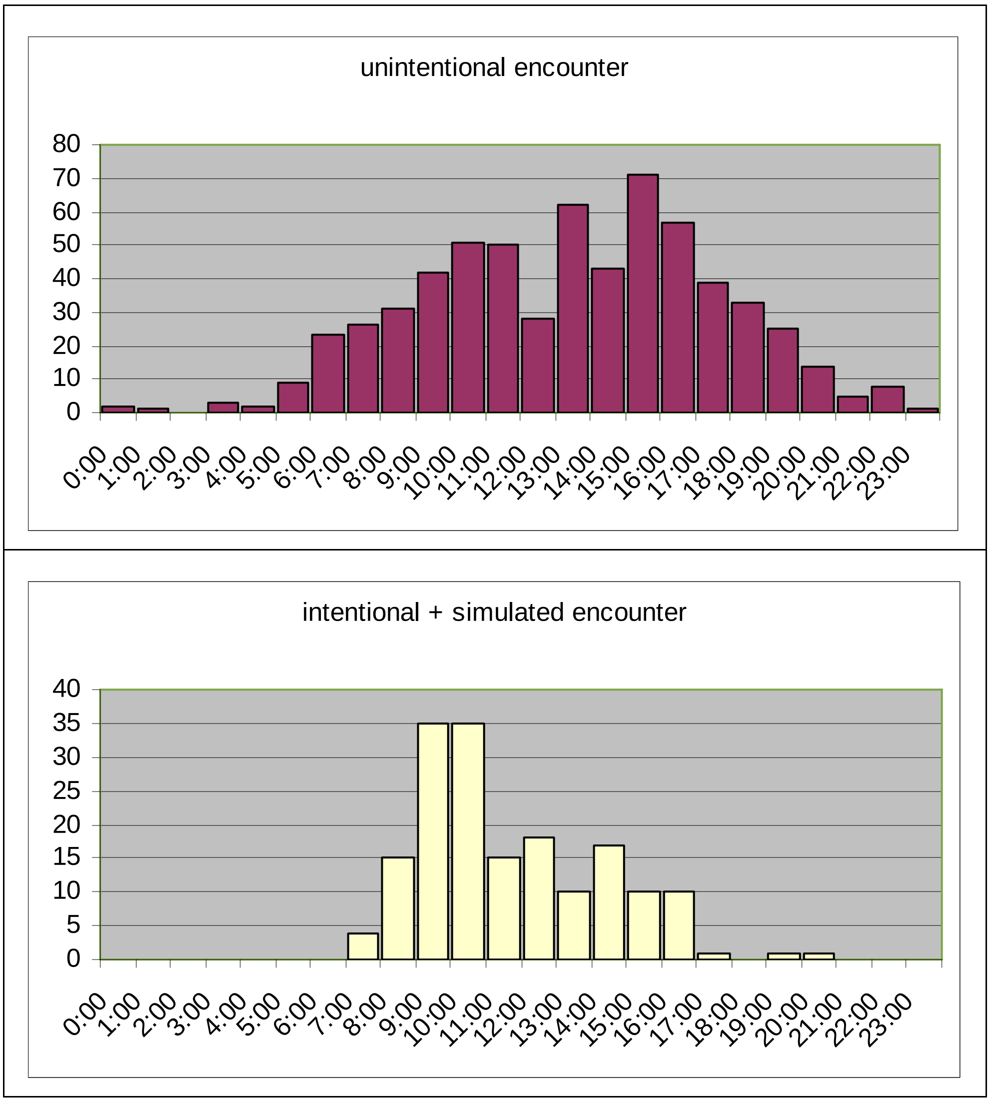


Figure 54: Time-of-day distribution of the encounters

5.8. Unintentional encounter classification on the basis of threat equipment

5.8.1. Here, the unintentional encounters are classified on the basis of the threat equipment as previously performed in section 5.2.1.

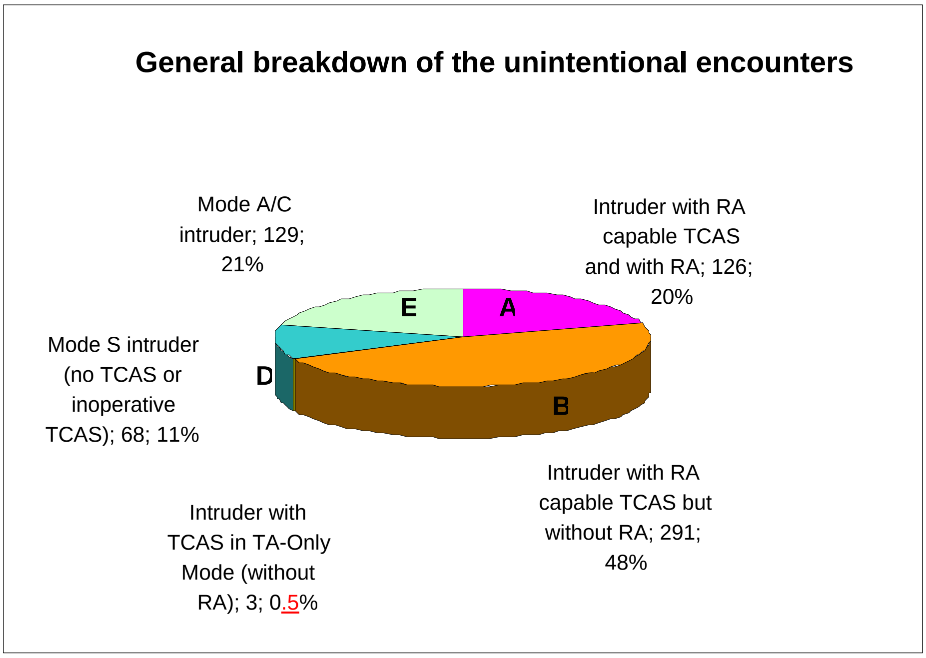


Figure 55: Distribution of the categories of the unintentional encounters

5.8.2. The unintentional encounters occur mainly between TCAS equipped aircraft (68%). The proportion was only of 52% when all the encounters were taken into account. Similarly, the proportion of Mode A/C intruders decreases from 29% to 21%.

6. Conclusions and recommendations

6.1. RA downlink monitoring results

6.1.1. The results are based on radar data captured from six Mode-S radars in the European core area over a seven-month period. The captured traffic represents 1,330,000 flight hours, of which 980,000 were performed by TCAS-equipped aircraft. 350,000 RA downlink messages were captured from 1,332 aircraft, but only 12,500 messages were non-empty. These messages correspond to RAs triggered within 1,029 aircraft involved in 880 encounters.

6.1.2. For each RA downlink message with an RAC, the checking of whether or not the corresponding threat also sent an RA downlink message leads us to confirm that an RA downlink message was available each time the aircraft involved were within the Mode-S radar coverage area. This is not absolute proof that RA downlink messages were always available, but, since no counter-example was found, we are convinced that RA downlink based on RA reports by the transponder worked properly.

6.1.3. Comparing the sequences of RA downlink messages with the TCAS simulation results, generally no obvious time shift larger than the turn period was observed. This leads us to assume that the Mode-S radar stations involved generally managed to capture the data in a single antenna turn.

6.1.4. The limitation of the Mode-S radar coverage and the probability of detection seem to have been the single cause of lack of RA downlink messages. This was observed on the fringes of the radar range and also at low altitude (below 2000 ft).

6.1.5. Various types of fault were identified in the content of RA downlink messages. These faults seem to have come solely from airborne equipment (TCAS and Mode-S transponders), because they were exactly the same even when messages were collected by different radars, and because they were observed only from a set of given aircraft. However, since five of the six Mode-S radars involved were almost identical, these faults could also be linked to the radars. Nevertheless, this possibility seems quite improbable, especially for the threat identification fault.

6.1.6. A set of faulty aircraft sent numerous empty RA downlink messages, polluting the ground processing. This meant that 96% of RA downlink messages were empty. Nevertheless, these messages can be ignored, because no case was detected in which an RA was potentially triggered on board while empty RA downlink messages were sent. These messages can easily be rejected on the basis of their content.

6.1.7. The faulty aircraft can be divided into two groups. A number of aircraft (37) sent empty RA messages throughout their flight, whereas the others (266) sent empty RA messages sporadically. For the latter aircraft, it is suspected that the RA-terminated mechanism was triggered at an inappropriate time, without a previous active RA. The list of the Mode-S addresses of these faulty aircraft is provided separately from this report.

6.1.8. The use of BDS-10 to detect the format (DO-185A or TSO-C119A) to decode the RA downlink messages was not reliable. Nevertheless, this issue can be resolved by looking into the RA downlink message (TTI field).

6.1.9. For the captured traffic as a whole, it is estimated that only 1% of aircraft used the old format (TSO-C119A), and that another 1% of aircraft incorrectly indicated that they were using TSO format but were in fact using DO-185A format.

6.1.10. The TCAS capability status conveyed by BDS-10 was reliable only on 83% of aircraft (aircraft with active RA downlink messages reporting that they were RA capable).

6.1.11. 1% of Mode-S-transponder-equipped aircraft sent incorrect flight statuses (6 cases out of 597). They reported an airborne flight status while they were on the ground and caused nuisance RAs on board flying aircraft.

6.1.12. No errors were identified in the active RAs or RA complements (received coordination messages).

6.1.13. The threat-identity data using ICAO addresses was reliable. On the other hand, 22% of TCAS gave the absolute bearing of the threat instead of its relative bearing, and 11% of TCAS did not use the correct Gilham code for the threat altitude.

6.1.14. In addition, 4% of TCAS used the threat-position data instead of the ICAO address for Mode-S-equipped threats. The cause of this fault is not explained yet, and may come either from the TCAS or from the threat transponder.

6.1.15. Only 17% of encounters led to RA downlinks from both aircraft, whereas 52% of encounters were between two TCAS-equipped aircraft. RAs were triggered on both aircraft only in 31% of the TCAS-TCAS encounters.

6.1.16. In 54% of the TCAS-TCAS encounters, RAs were not triggered within the second aircraft owing to the reduction of the Vertical Time Threshold (VTT) during 1,000-ft level-off geometry

6.1.17. In 7% of the TCAS-TCAS encounters, RAs were inhibited within only one aircraft owing to asymmetric behaviour of the Miss Distance Filtering.

6.1.18. Cases in which TCAS was manually switched to TA-only mode and therefore prevented to have any RA in the second aircraft correspond to 4% of the TCAS-TCAS encounters. There were very rare for civilian aircraft (only two cases), but were more common during military and intentional encounters.

6.1.19. Out of the 880 encounters analysed, 5 aircraft under the ACAS mandate were suspected not to be TCAS equipped. Nevertheless, the low reliability of the BDS-10 data does not allow us to be sure of this.

6.1.20. One case of TCAS failure was detected, as was one case of omitting to switch the TCAS on. These cases are insignificant in relation to the 880 encounters, but may be more important. Indeed, the research was performed only on the aircraft involved in encounters captured via the RA downlink messages, and not on the traffic as a whole. Nevertheless, it seems unrealistic to try to assess, for example, these cases or the 10-day MEL period, as long as the BDS-10 data are not fully reliable.

6.1.21. On average, there were RAs triggered on TCAS-equipped aircraft every 960 flight hours. (1029 RAs sequences for about 988.000 flight hours performed by TCAS equipped aircraft). This rate takes into account intentional and unintentional encounters and also military and civilian aircraft, and then does not reflect the real RA rate for civilian aircraft.

6.1.22. The main part of the encounters involving RAs (70%) was identified as unintentional. However, 16% of the encounters were identified as intentional. They correspond mainly to military operations and to test flights with escorts. Within these encounters, there were several cases of civil interception by a fighter with its transponder left with altitude reporting on.

6.1.23. Keeping only unintentional encounters, RAs are triggered on board civilian TCAS equipped aircraft every 1365 flight hours. (719 captured RAs sequences from civilian aircraft, during 597 unintentional encounters, and for about 982.000 captured flight hours performed by civilian TCAS equipped aircraft)

6.1.24. The cases of self-tracking, garbling, test flights and transponder tests correspond to 7% of the encounters and should not be neglected.

6.1.25. For unintentional encounters:

- 61% of RA sequences comprised a solitary “adjust vertical speed” RA.
- 24% of RA sequences were RAs to “climb” or “descend”, followed in two thirds of cases by a weakening RA to “adjust vertical speed”.
- 10% of RAs were preventive RAs, occurring mainly between IFR arrivals and VFR flights.

6.1.26. For 85% of all encounters, the mean duration of the RA was between 5 and 45 seconds.

6.2. Technical findings and recommendations for RA display on Controller Working Position

6.2.1. On the basis of the observations made with this specific Mode-S radar coverage, the average period between two RA downlink messages is about 5.1 seconds. Excluding the data transfer delay and the CWP processing delay, the average latency for the first RA can be assumed to be close to half that time, i.e. 2.6 seconds. 28% of the encounters were captured by more than one radar, given a mean refresh rate of 2.9 seconds, leading us to expect latency of about 1.5 seconds. These good latency values are only estimates and correspond to the delay between the triggering of the RA and the message’s availability at the radar output. These observed values are linked only to the radars’ performance, for example turn period and detection probabilities. They are not easily comparable with the theoretical values from the FARADS studies.

6.2.2. The “terminated” mechanism is generally reliable and allows us to catch the very short RAs which are terminated when the radar antenna illuminate the aircraft.

6.2.3. Specific filtering must be planned for ghost encounters. Depending on the operational interest or nuisance, the cases of self-tracking, garbling, test flights and transponder tests may be taken into consideration.

6.2.4. 5% of RA sequences last more than one minute and may lead to a long display.

6.2.5. In the majority of cases, an alert will be displayed on only one aircraft, because only 17% of the encounters involved RA downlinks from both aircraft.

6.2.6. In these cases, it may be useful to identify the threat in order to allow the ATCO to give a turn instruction if necessary. However, the threat identification is not reliable when only the position data are available, and position data are used in about a third of the encounters.

6.2.7. The active RA (ARA) field is reliable. Nevertheless, care must be taken for the interpretation of some non-frequent RAs (multi-threat) and to avoid misinterpretation between “monitor” and “maintain” RAs.

6.3. Proposition to fix observed faults

6.3.1. The term “relative bearing” should replace the term “bearing” everywhere within paragraph 2.2.3.9.3.2.3.a1 of TCAS MOPS [3], in order to avoid TCAS implementation coding the threat azimuth instead of its relative bearing within the RA downlink message.

6.3.2. TCAS MOPS [3] (paragraph 2.2.3.9.3.2.3.a1 part TIDA) should also stipulate that the reported Mode-C altitude code of the threat must use the Gilham code. The term “Mode-C altitude” already implies this, but the observed errors imply that the text has been misinterpreted by certain TCAS manufacturers.

6.3.3. A practical suggestion is to create a change proposal (CP) for RTCA SC147 and to inform all TCAS manufacturers about these two stipulations. It should be noted that the faults were observed only in the content of RA downlink messages and in any case on the TCAS traffic display. These faults do not, therefore, have any negative operational impact.

6.3.4. Incorrect reporting of the flight status of a number of aircraft on the ground was the cause of six cases of RAs’ being issued on board aircraft on final approaches. This seems to be sufficiently important to merit further action and the extension of the current efforts to intercept and correct incorrect flight status reports.

6.3.5. In order to simplify monitoring (and display on CWP), it is desirable to increase the reliability of BDS-10 data in terms of ACAS capability.

6.3.6. In the same way, and also in order to limit the number of Comm-B transactions, it is desirable to extend current efforts to correct empty message downlinks.

6.4. List of Acronyms

ACAS	Airborne Collision Avoidance System
AGL	Above Ground Level
ANSP	Air Navigation Service Provider
ARA	Active Resolution Advisory
ATC	Air Traffic Control
BDS	Comm-B data selector
CFL	Cleared Flight Level
CoC	Clear of Conflict (TCAS – end of Resolution Advisory)
CPA	Closest Point of Approach (TCAS)
CWP	Controller Working Position
DSNA	Direction des Services de la Navigation Aérienne [French Air Navigation Services Directorate]
EHQ	EUROCONTROL Headquarters
GAT	General Air Traffic
HMD	Horizontal Miss Distance
MDF	Miss Distance Filter
OAT	Operational Air Traffic
PASS	Performance and safety Aspects of Short-term Conflict Alert – full Study
RA	Resolution Advisory
RAC	Resolution Advisory complement (Coordination received from threat)
RAT	Resolution Advisory Terminated
STCA	Short Term Conflict Alert
SPIN	Safety nets Performance Improvement Network
TCAS	Traffic alert and Collision Avoidance System
TID	Threat Indicator Data
TTI	Threat Type Indicator

VTT	Vertical Time Threshold
WA	Work Area
WP	Work Package

7. APPENDIX A – Examples of encounters

7.1. Unintentional encounter involving RA downlink from both aircraft

7.1.1. The following figure is a picture from the tool used to display and analyse an encounter involving RA downlink. The option masking all references (aircraft identification, Mode A and map) is used here. Raw data, such as ICAO addresses and the full content of BDS-30 and BDS-10, have also been removed, in order to reduce the picture size.

7.1.2. The horizontal view of the trajectories is at the top right. The white trajectory corresponds to the aircraft always having RA downlink and is called “Ac1”. A marker on the top left of this panel gives an idea of the scale. The arrows on both trajectories are positioned to show where the two aircraft were at the time selected on the vertical view.

7.1.3. On the vertical view, dots with no circles around them correspond to raw plots coming from different radars. A plot surrounded by a red circle corresponds to a plot with an RA downlink message. When the circle is pink, the RA is terminated. Each plot with an RA downlink message is linked by a leader to a tape-VSI on which the RA interpretation is drawn. The other tape-VSIs, which are smaller and exist for every second, display the simulated RAs. When the VSI is empty, only TAs were simulated at the corresponding time. For both aircraft, the proximity of both VSIs allows us to compare the downlinked RA with the simulated RA.

7.1.4. The black vertical line corresponds to the selected time, which is set by default to the time of the first RA downlink message and can be modified by dragging the mouse.

7.1.5. Both VSIs at the top left display the RA and the TCAS traffic at the selected time. We can display RAs downlinked from Ac1 and from Ac2, or a downlinked RA (on the top) and a simulated RA (below) for Ac1 or for Ac2. In this first example, we have the interpretation of RA downlink from both aircraft. Since both RA interpretations are “adjust vertical speed” where the VSL value is not known, the red part is dashed to show that the VSL value could be 0, 500, 1,000 or 2,000 feet.

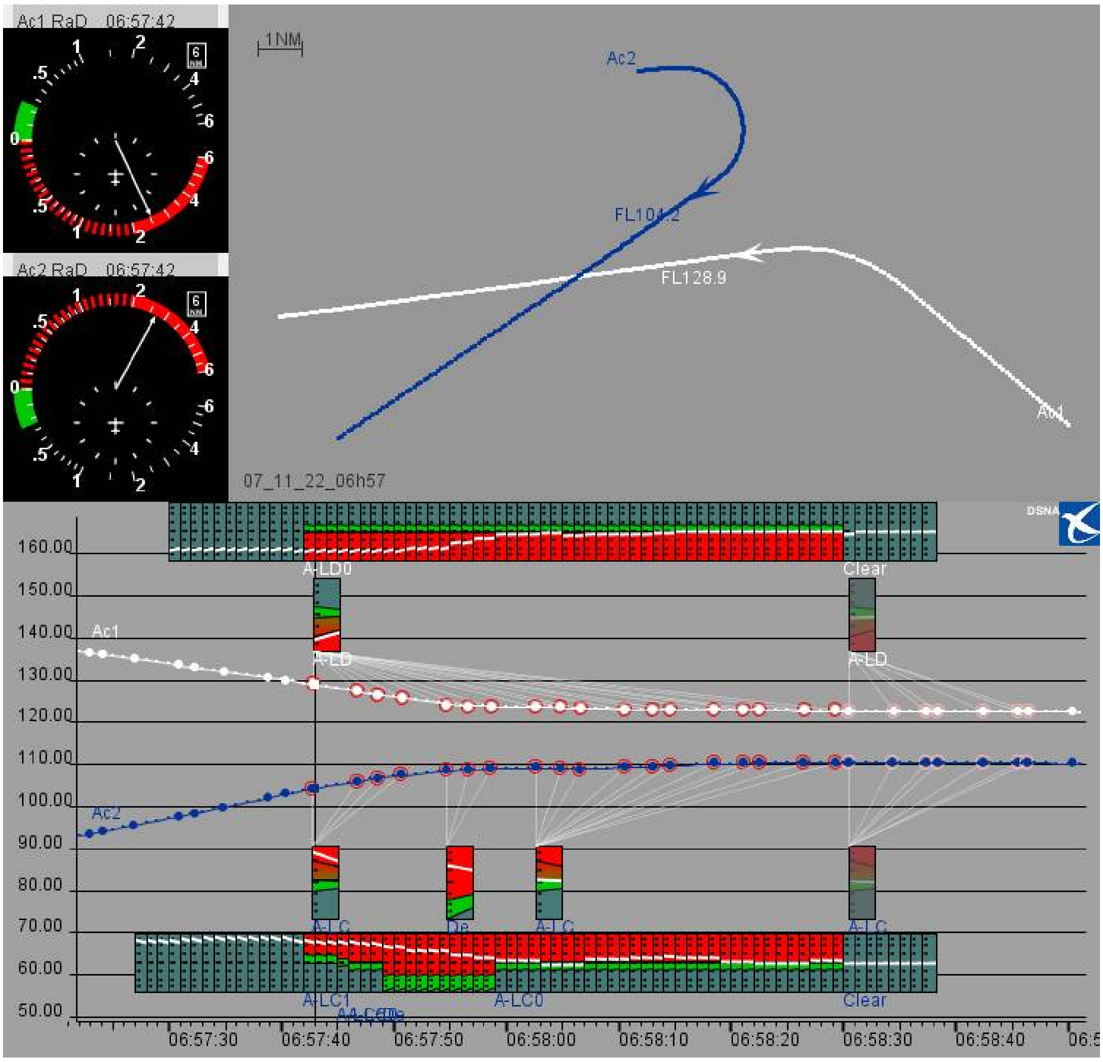


Figure 56: Illustration of an encounter involving RA downlink from both aircraft

7.1.6. This encounter was seen by three radars and the RA report sampling was very good.

7.1.7. Each RA downlink message contained an RAC corresponding to the threat RA. This is not shown on this view.

7.1.8. For Ac1, the simulated RAs matched the RA downlink messages very well. The first RA occurred after a plot without RA downlink and just before the first RA downlink. The simulated "Clear of Conflict" also happened just before the first RA downlink message with the "terminated" indicator.

7.1.9. For Ac2, the simulated RA sequence was LC1000, LC500, LC0, descend and LC0. This sequence also matched the downlinked RAs.

7.2. TCAS-TCAS encounters involving RA downlink from only one aircraft

7.2.1. In order to reduce the number of RAs occurring during 1000-ft level-off configuration, the TCAS V7 logic uses a reduced vertical time threshold (VTT) when the TCAS's own aircraft is almost stable (vertical speed less than 600 fpm). When the climbing (or descending) aircraft reacts correctly to its RA, the stable aircraft triggers only a TA and no RA.

7.2.2. This TCAS logic feature explains why there were many encounters in which both aircraft were TCAS equipped but only one aircraft sent RA downlink messages.

7.2.3. In this example, Ac2 was TCAS equipped but did not trigger RAs because of the VTT reduction. This fact was confirmed by the simulation, which provided only TAs from Ac2.

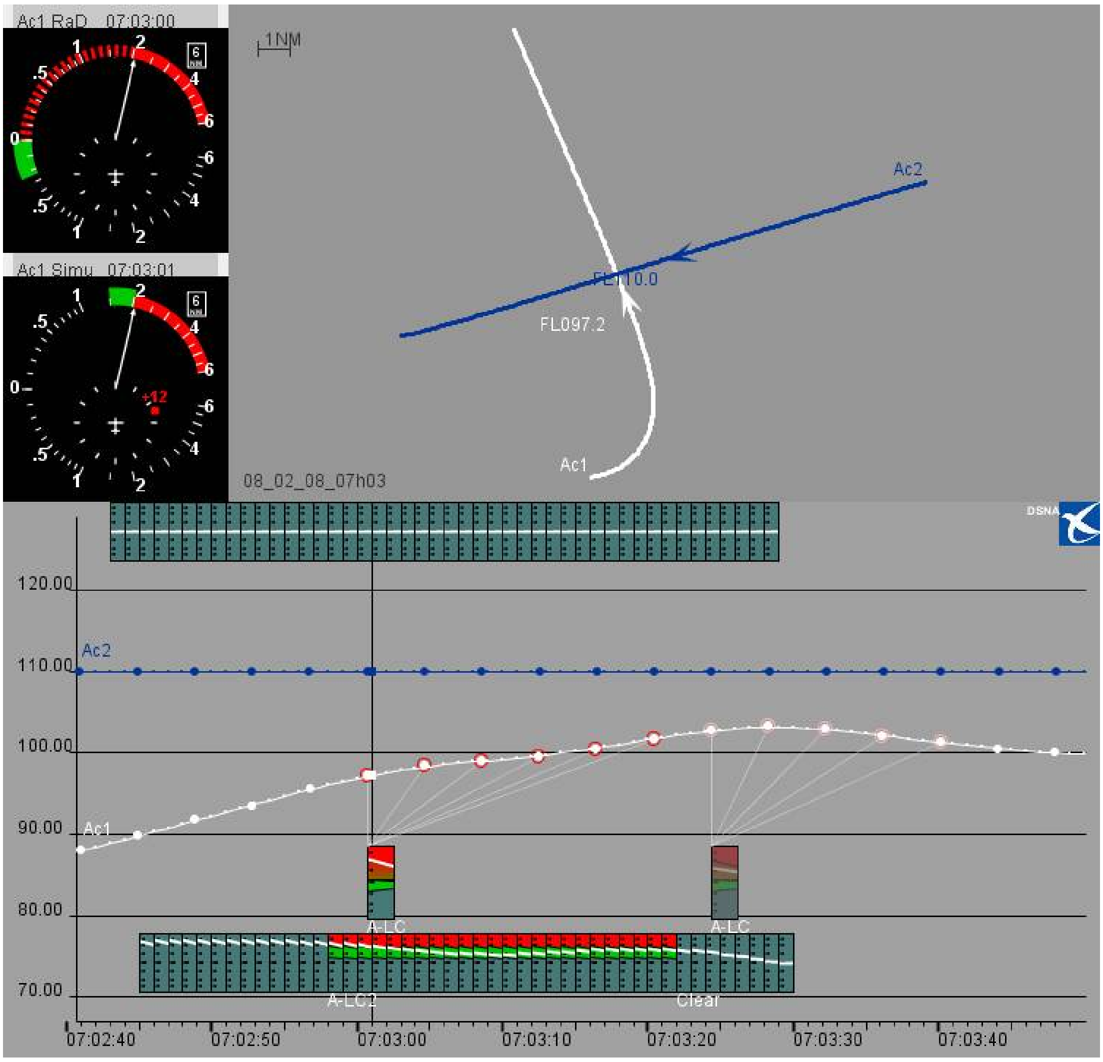


Figure 57: Illustration of a TCAS-TCAS encounter involving "1000-ft level-off" geometry

7.2.4. The circular VSIs display the downlinked RA on the top, and the simulated RA and simulated TCAS traffic below.

7.2.5. In this example, the pilot of Ac1 followed its RA, keeping the vertical speed within the green area, meaning that the aircraft overshot its cleared FL. The vertical speed is shown by the white needle on the VSI.

7.2.6. The following figure shows another example in which the second TCAS did not trigger an RA owing to the VTT action. The unusual feature of this example was the very long duration of the RA. Although the aircraft were well separated vertically, the RA was maintained for about six minutes, until the distance between the two aircraft increased.

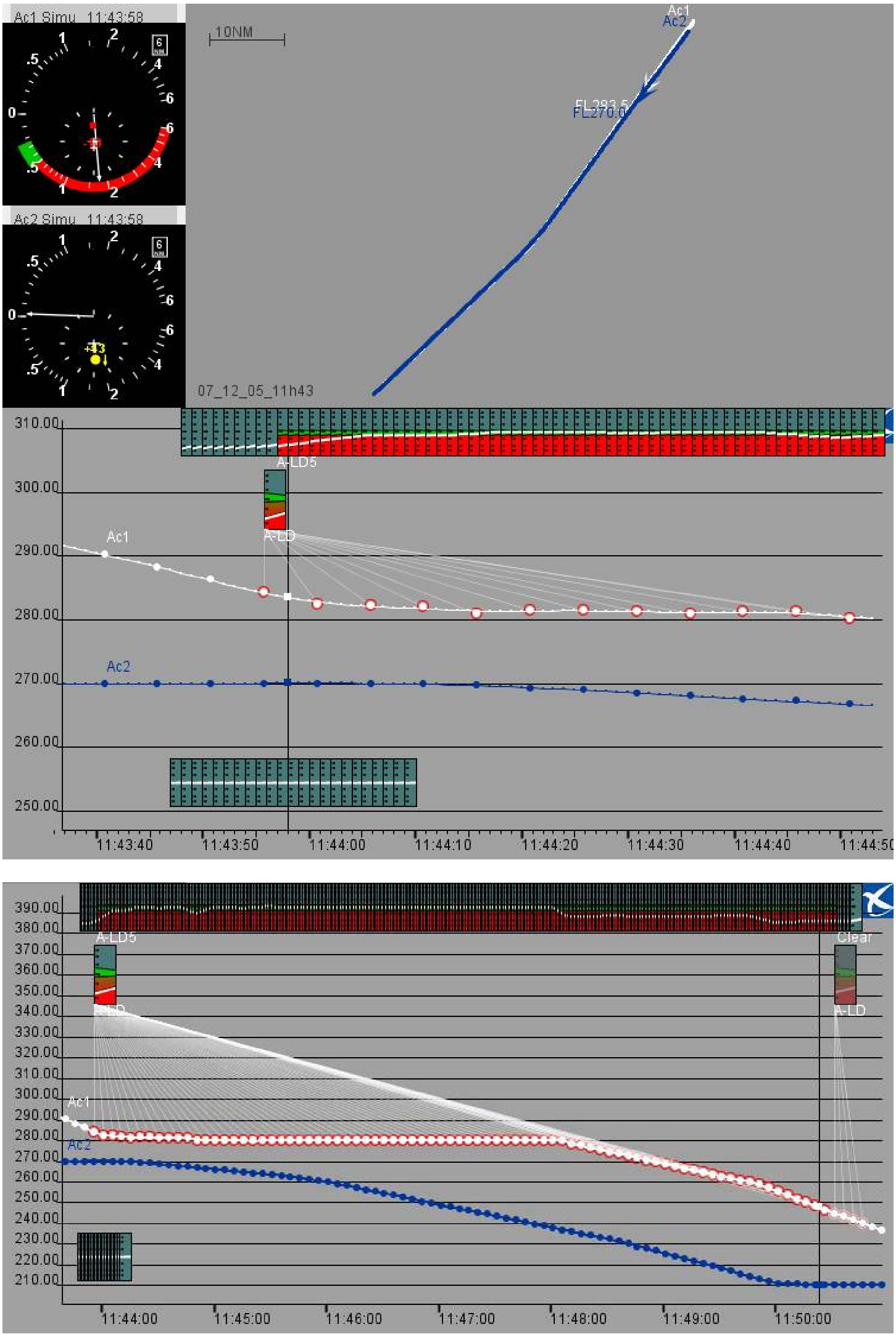


Figure 58: Illustration of a TCAS-TCAS encounter involving very long RA duration

7.2.7. The following figure shows an example in which the second TCAS did not trigger an RA owing to asymmetrical HMD filtering.

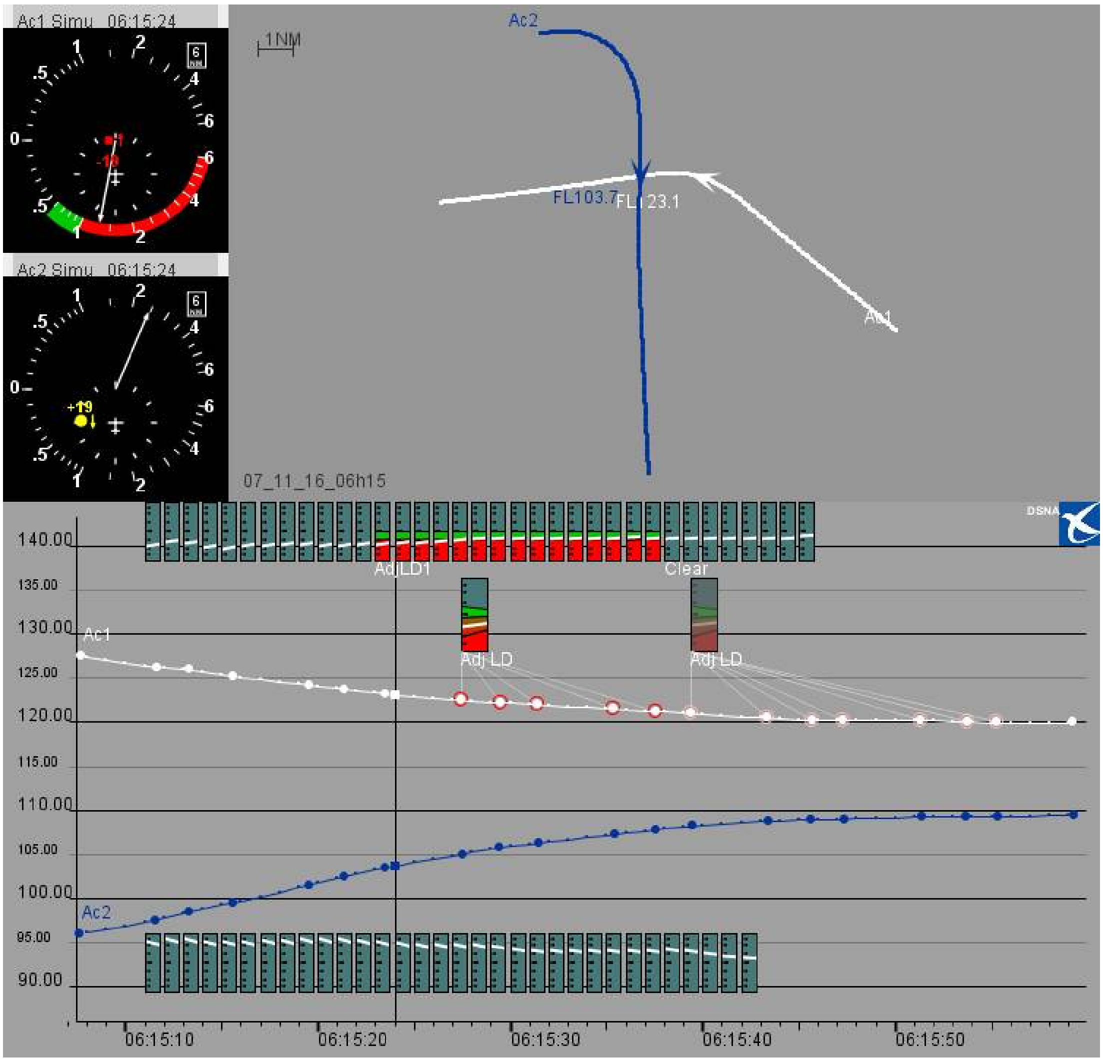


Figure 59: Illustration of an encounter in which RAs were inhibited within only one aircraft by the Miss Distance Filter

7.3. Intentional encounters

7.3.1. This example corresponds to a civilian aircraft identified by two Mode-C-equipped military aircraft which kept the altitude report active during the interception.

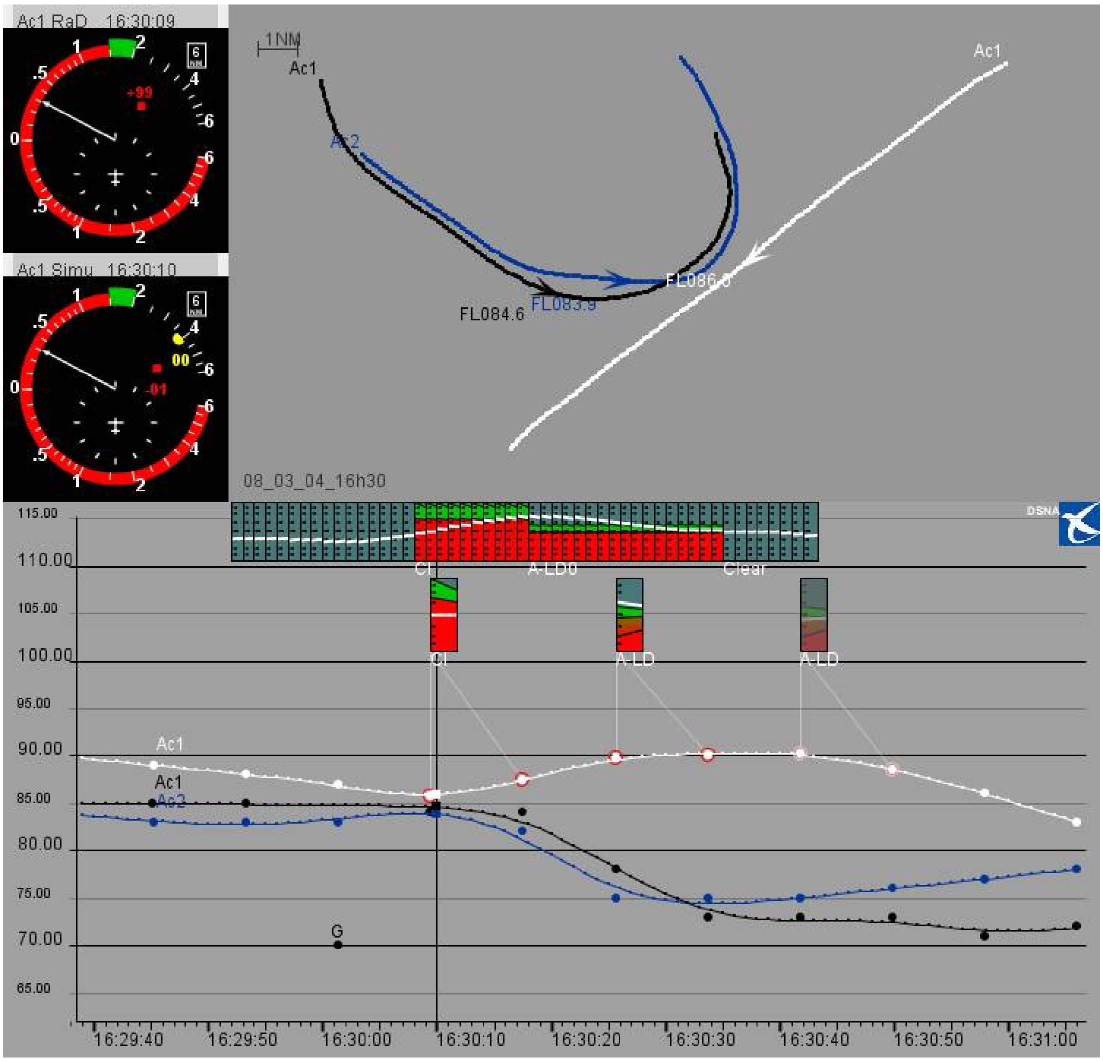


Figure 60: Illustration of an intentional encounter (civilian aircraft identified by fighters)

7.3.2. The altitude of the threat within the RA downlink message was false and is tagged as +99 on the top circular VSI.

7.3.3. Civil aircraft intercepted by a military aircraft

7.3.4. The following example also involved a civilian aircraft intercepted by a military aircraft which was using Mode A 7400, corresponding to a security mission. The military aircraft did not switch off its transponder until very late.

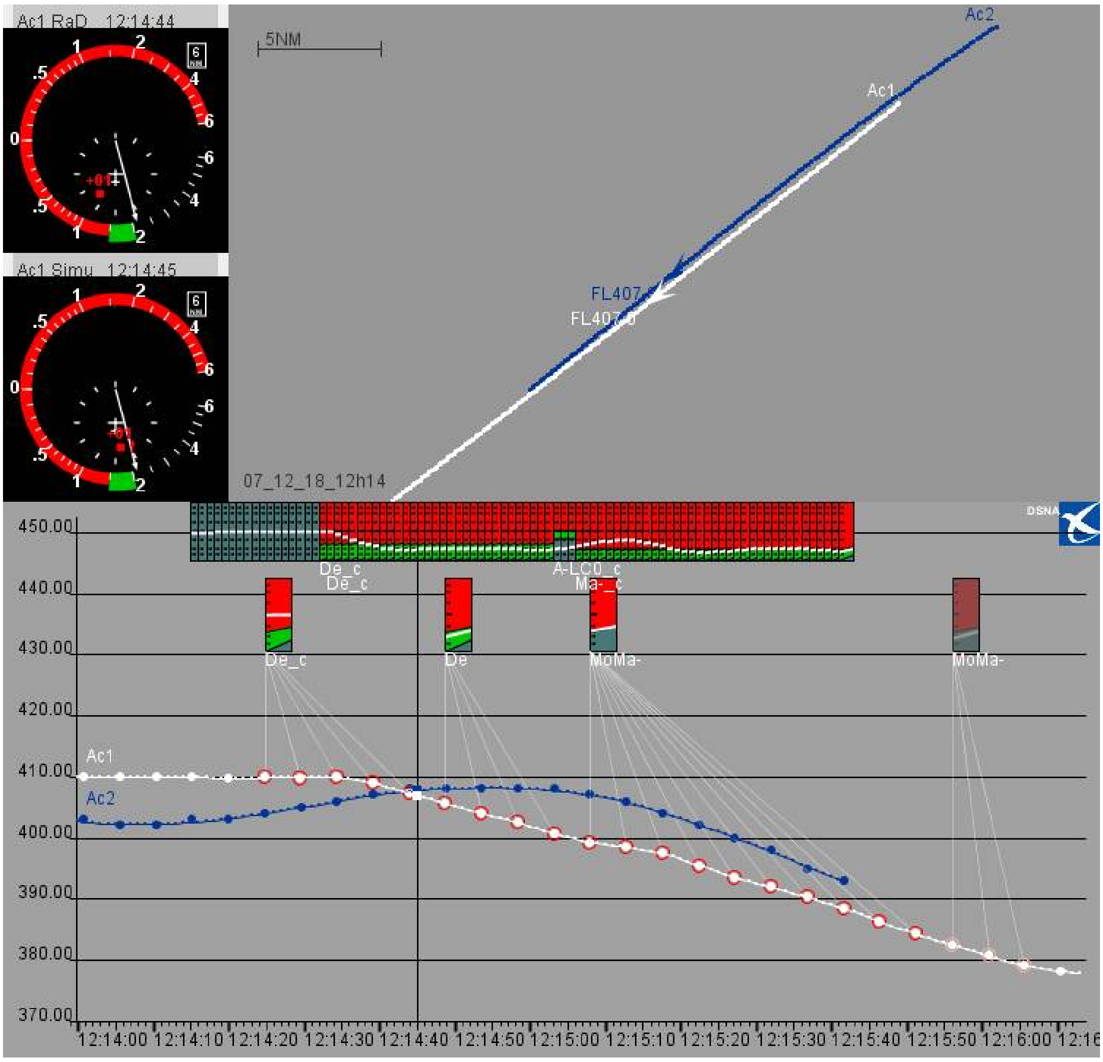


Figure 61: Intentional encounter (long interception)

7.3.5. The isolated interpretation of the bits of the last downlinked RAs could be either a "Monitor Vertical Speed" or a "Maintain Vertical Speed". This is indicated by the tag "Mo/Ma". Thanks to the presence of previous corrective downlinked RAs, we can affirm that the correct RA was the "maintain". This was confirmed by the simulation.

7.4. *Military operation*

7.4.1. This was an intentional encounter in which fighters joined a TCAS-equipped military aircraft.

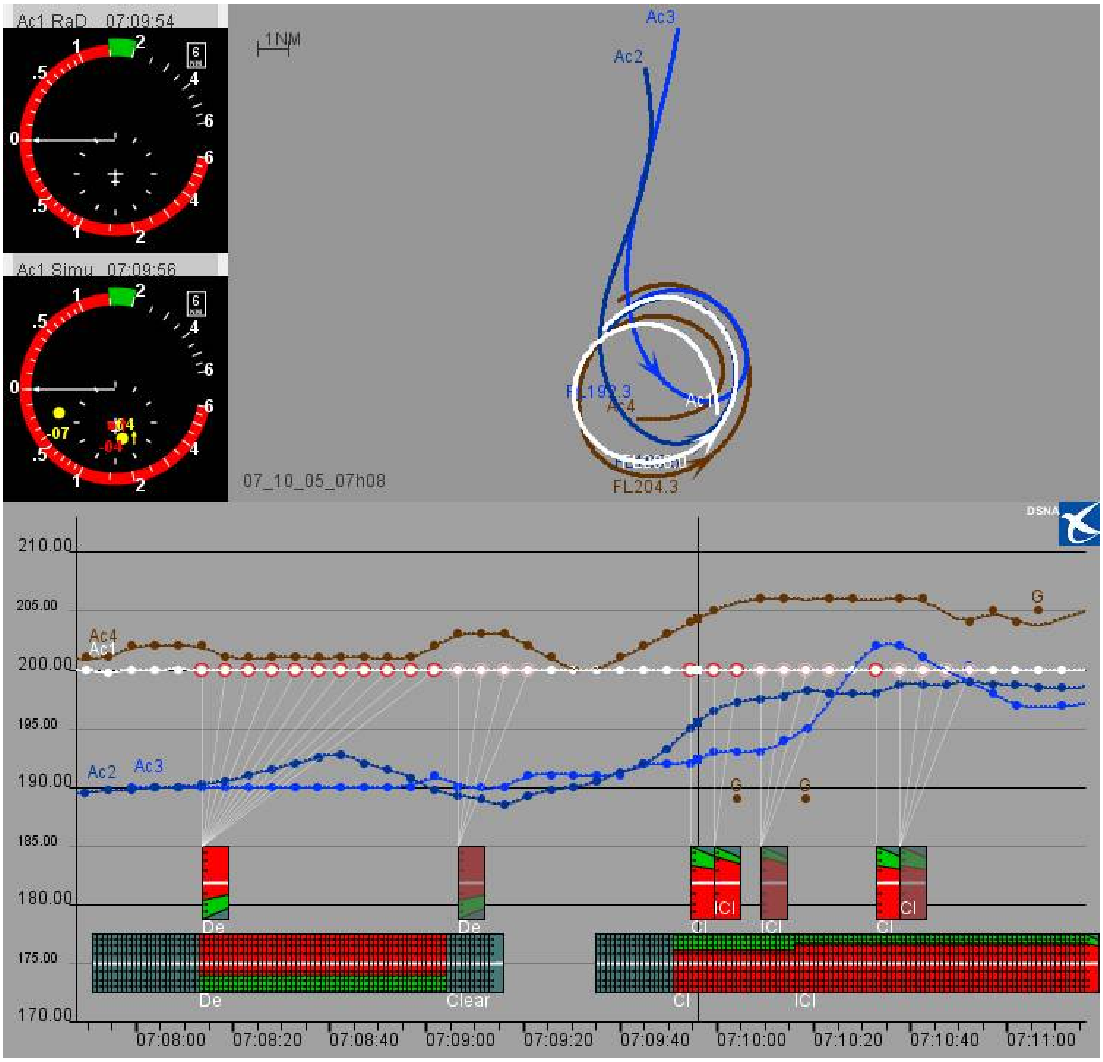


Figure 62: Intentional encounter during a military operation, involving successive sequences of RAs

7.5. Self-tracking

7.5.1. The ICAO address of the threat within the RA downlink message is the same as the TCAS-equipped aircraft's address. Self-tracking occurs owing to faults affecting the "suppression line", which should protect the transponder when the TCAS transmits. In this example, the pilot followed the initial RAs. As a result of differences in altitude tracking (same altitude, but 25 ft quantised for the threat tracker and 1 ft quantised for the aircraft's own tracker) the RAs were updated.

7.5.2. The coordination mechanism is active during self-tracking, but it is incorrect because the TCAS (via its transponder) receives the coordination message it sent previously. It was "do not pass below" throughout this sequence of RAs.

7.5.3. Following take-off, the first RA was triggered when the TCAS passed from TA-only mode to TA/RA mode at 1000 ft AGL (ground at FL 4.5). It can be assumed that the pilot stopped the self-tracking by switching the aircraft's transponders. This assumption is consistent with the fact that no terminated RA was retained and sent by the transponder.

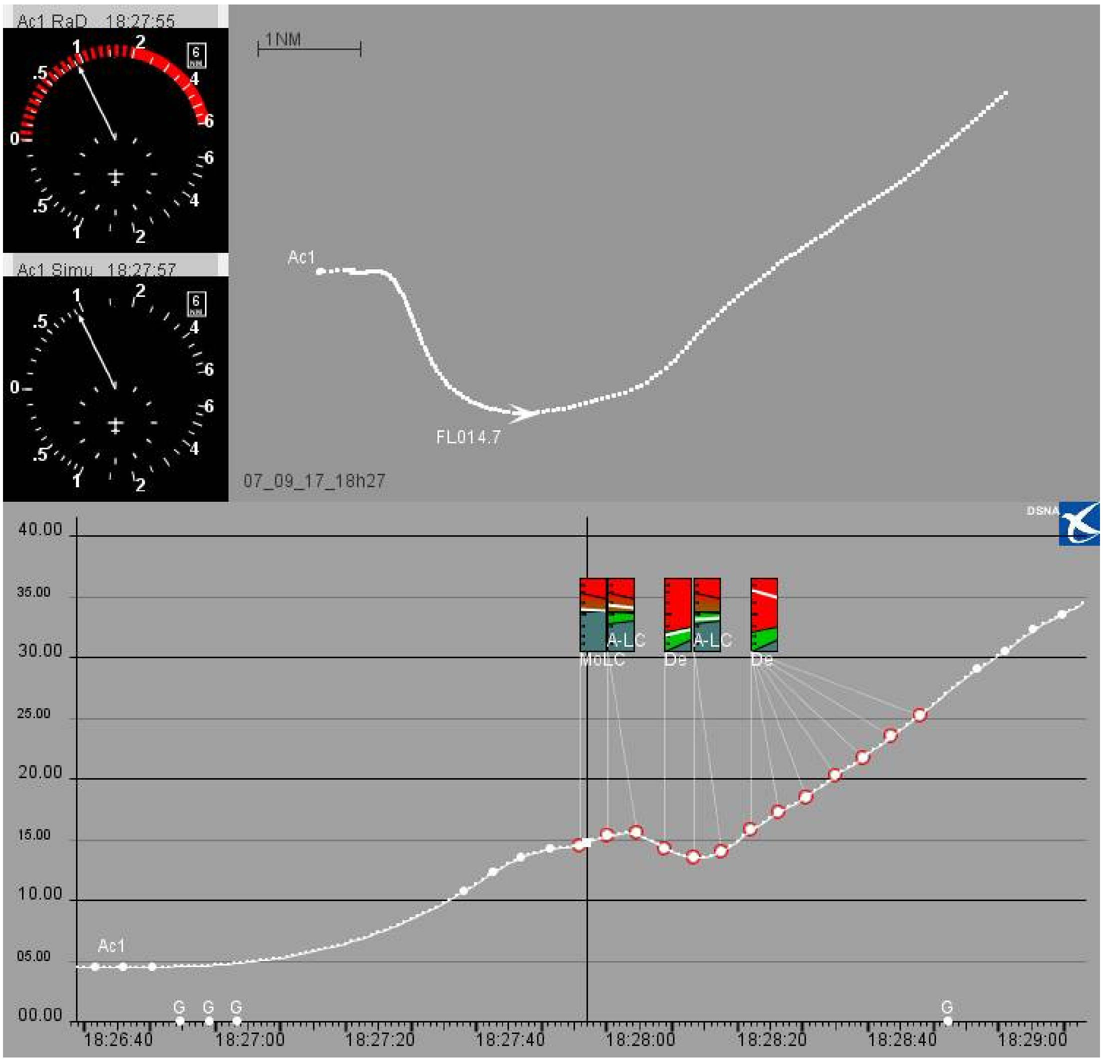


Figure 63: Illustration of a ghost encounter: self-tracking

7.6. Test flight

7.6.1. The threat is simulated on board and fed directly to the TCAS. Consequently, there is no corresponding transponder that the radar can detect. Many RA downlink messages were sent during this test flight.

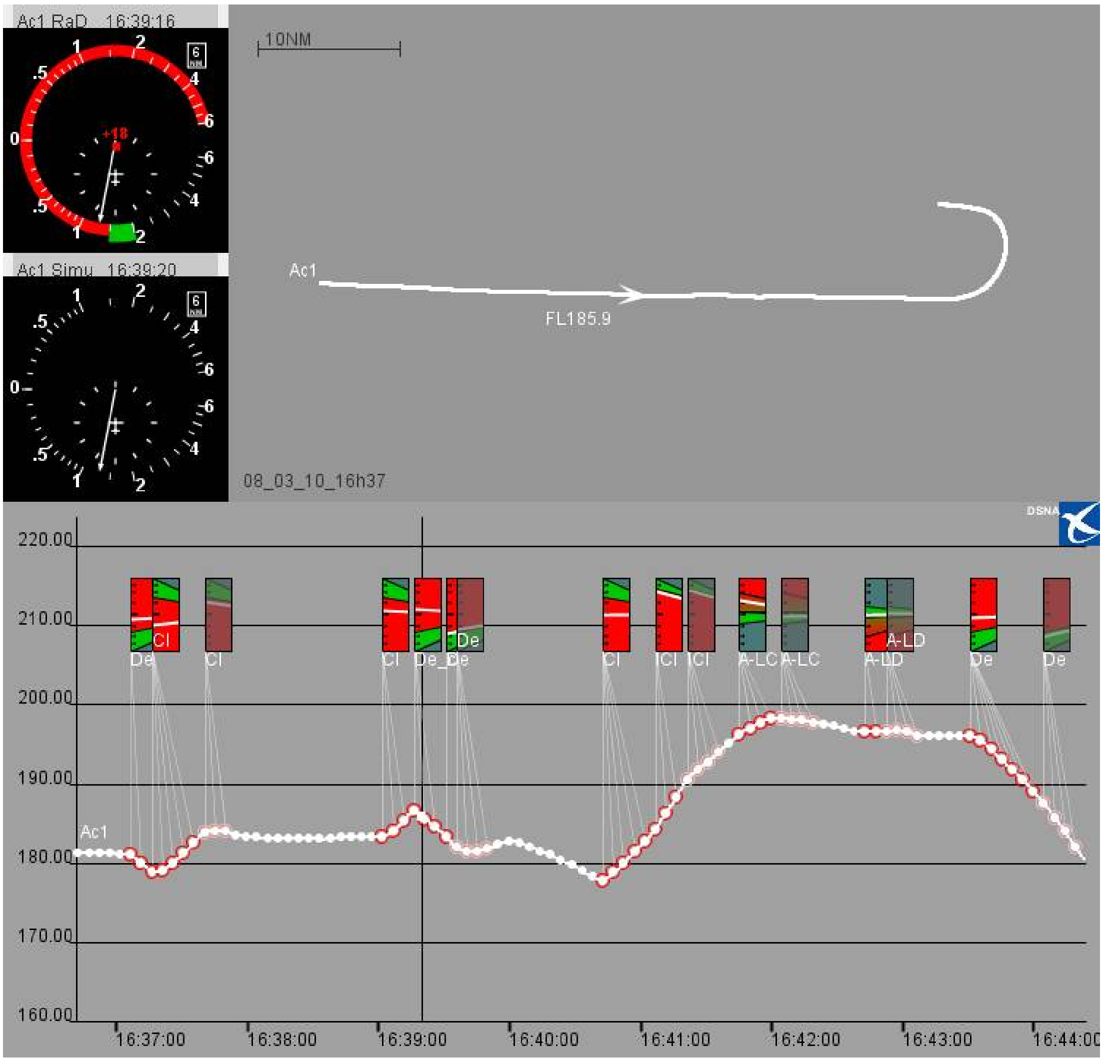


Figure 64: Illustration of a ghost encounter: AP-FD TCAS test flight

7.7. RA triggered owing to garbling

7.7.1. Two military aircraft were approaching from in front, but 26,000 ft above. Both military aircraft had parallel tracks separated by more than 2 NM. Unfortunately, their slant ranges to the TCAS differed by less than 1.6 NM and garbling occurred. The garbling on the Mode-C replies led the TCAS surveillance to build a track with an incorrect altitude, mixing the pulses of both replies. The TCAS then triggered RAs based on the incorrect threat altitude.

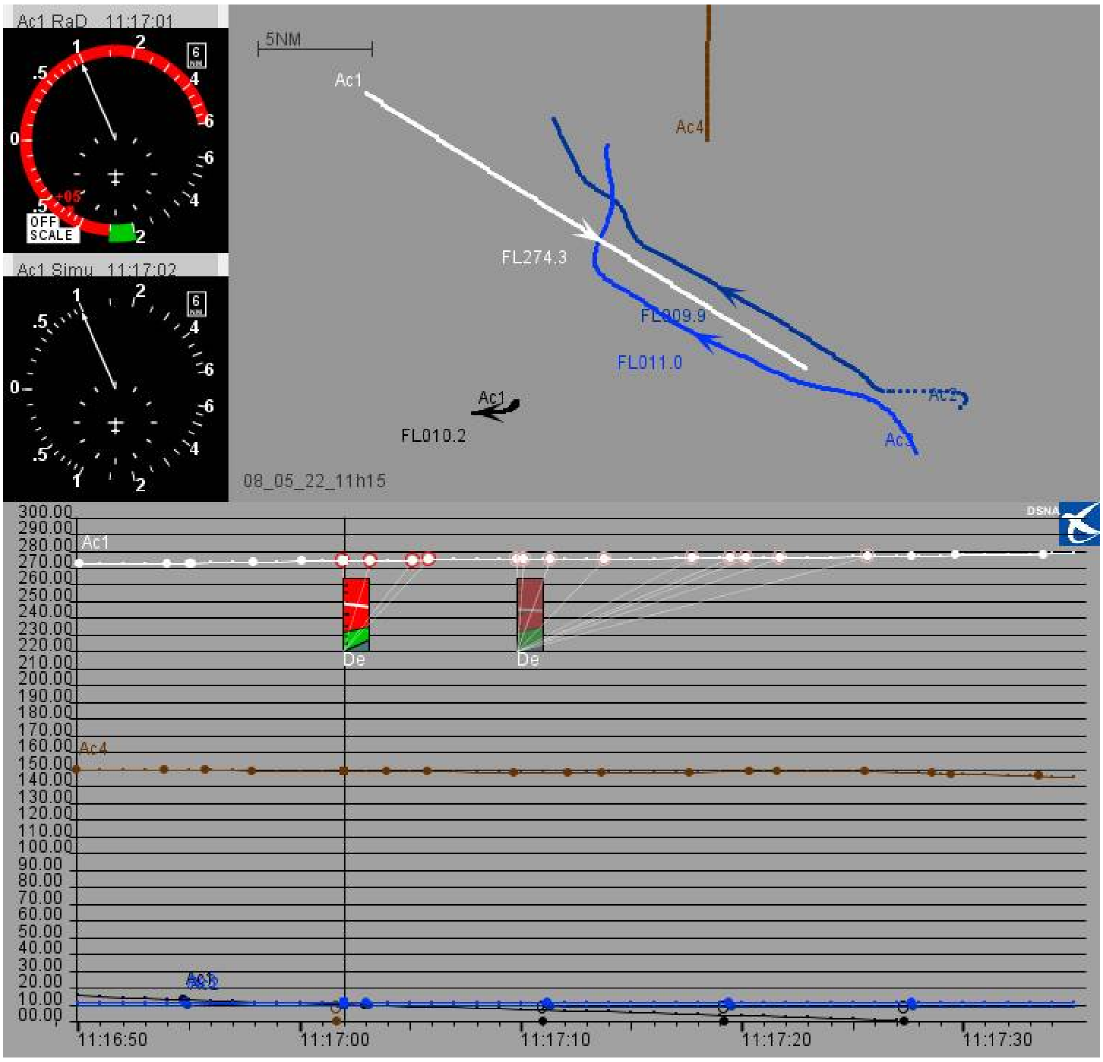


Figure 65: Ghost encounter: RAs owing to garbling from aircraft 26,000 ft below

7.8. RA triggered owing to a transponder test on the ground

7.8.1. The tested aircraft (Ac2 in the following figure) was still on the ground and replied with a modified flight level, FL 30. Its Mode A was correctly set to 7777 and its transponder indicated, also correctly, that its TCAS was in TA-only mode. Unfortunately, the tested aircraft reported an incorrect flight status and indicated that it was "airborne" instead of "on the ground". It thus triggered an RA on board a departing flight. The RA was followed by the pilot.

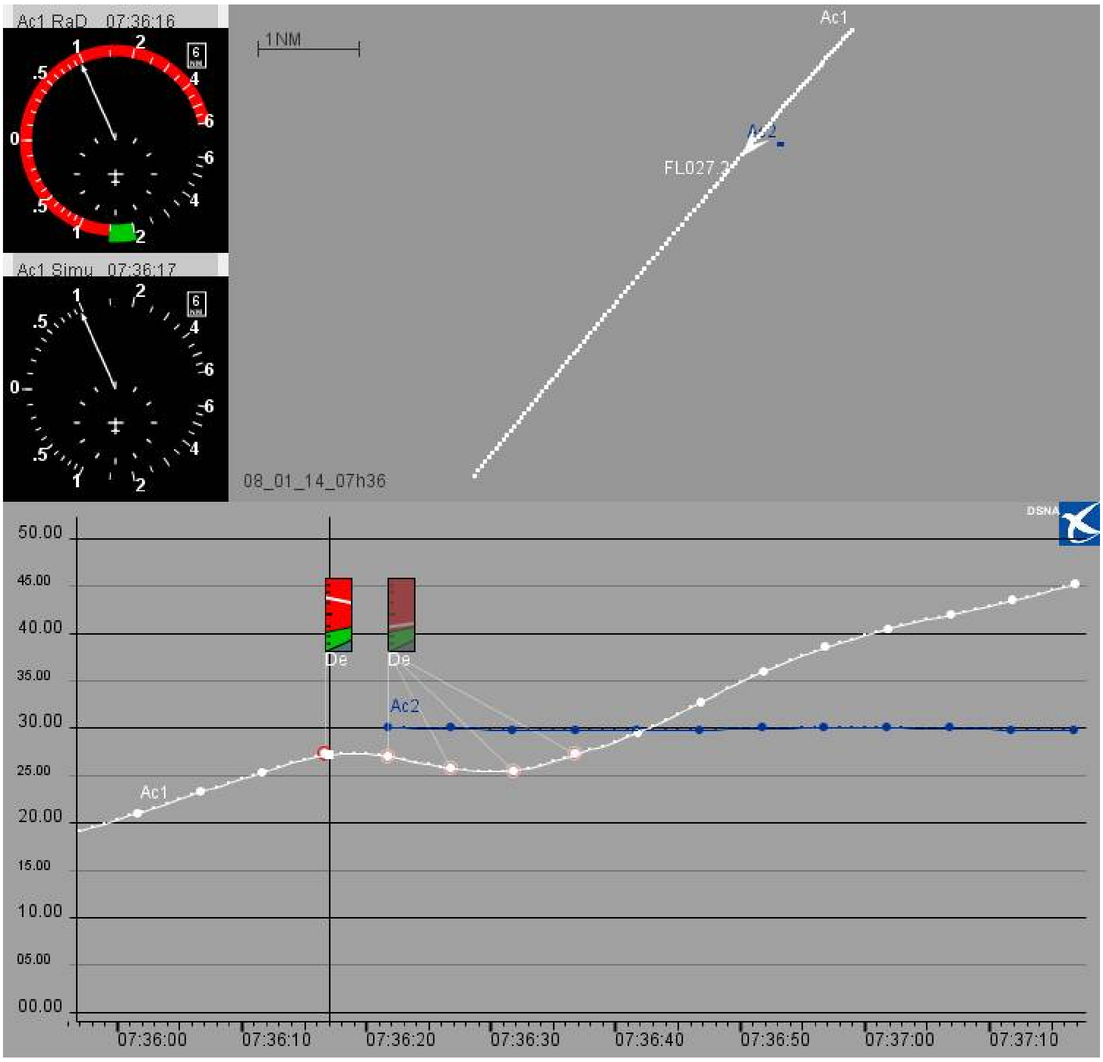


Figure 66: Ghost encounter: transponder test

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