Technical feedback on proposed TCAS changes

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Abstract

This document provides a preliminary assessment of the system impact for two TCAS II improvements proposed in the frame of the SESAR 4.8.2 project: reduced RA thresholds, and use of ADS-B data in horizontal miss distance filter. Both proposed changes aims to reduce number of operationally unwanted (nuisance) RA and increase thus performance of the current TCAS II system while maintaining at least the same level of safety.

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Executive summary

This document provides a preliminary assessment of the system impact for two TCAS II improvements proposed in the frame of the SESAR 4.8.2 project: reduced RA thresholds, and the use of ADS-B data in horizontal miss distance filter. Both proposed changes aims to reduce number of operationally unwanted (nuisance) RA and to increase thus performance of the current TCAS II system while maintaining at least the same level of safety.

After a description of the proposed improvements, an overview of the validation exercises performed within the project 4.8.2 is provided followed by a discussion of the published results and of the potential system impact.

As it is not expected that the work on these two improvements will continue within either 9.47 or the 4.8.2 project, the aim of this document is also to summarize the status of the performed work from a technical perspective and thus simplify any potential follow-up activities in this area.

1 Introduction

The objective of enhanced TCAS operations studied within the SESAR WP 4.8.2 is to reduce airborne collision risk whilst enhancing the compatibility with ATM operations, both in current and future traffic environments. The associated operational, functional and performance requirements were consolidated in the initial OSED [1].

There have been six improvements proposed to ACAS functions:

- ✓ Improvement 1: Reducing ACAS RA threshold (AUTO)
- ✓ Improvement 2: ACAS uses FMS climb and descent profiles (CLIMB-RATE)
- ✓ Improvement 3: Increase compatibility of non-ACAS aircraft with ACAS (NON-ACAS)
- ✓ Improvement 4: ACAS use of ADS-B horizontal information (TRAJ)
- ✓ Improvement 5: Increase ACAS capability with existing separation modes. Ground puts aircraft into TA-only mode (COMPA-G)
- ✓ Improvement 6: Increase ACAS compatibility with new separation modes. Pilot puts aircraft into TA-only mode against one other aircraft (COMPA-A)

Improvements 2, 3, 5 and 6 have been validated to V1 level and addressed the operational improvement CM-0804: ACAS adapted to New Separation modes.

Enhancement of ACAS logic adapted to trajectory-based operations (CM-080X) is addressed in Improvements 1 and 4: Optimizing the RA thresholds and the use of ADS-B horizontal information by ACAS. The objective for both proposed changes is to improve compatibility with ATM through the reduction of unnecessary RAs, while maintaining at least the same level of safety.

Improvements 1 and 4 were originally planned to be validated until V3 level within the SESAR WP 4.8.2 project. However, due to a recent scope change of the project, only the V2 validation was actually performed for them. This document aims to provide technical feedback on these two proposed changes and to summarize the results of validation exercises performed in the 4.8.2 project.

1.1 Purpose of the document

This document provides a preliminary assessment of the system impact for two TCAS II improvements proposed in the frame of the SESAR 4.8.2 project: reduced RA thresholds, and use of ADS-B data in the horizontal miss distance filter. As it is not expected that the work on these two improvements will continue within either 9.47 or the 4.8.2 project (due to the project’s scope changes adopted during preparation of this document), the aim of this document is also to summarize the status of the performed work from a technical perspective and thus simplify any potential follow-up activities in this area.

1.2 Intended readership

4.8.2 project members; 9.47 project members; 4.2, 5.2 projects.

1.3 Inputs from other projects

- WP 4.8.2 – 04.08.02.D08: ACAS modifications for time & trajectory-based operations initial Operational Service and Environment Definition (OSED)
- WP 4.8.2 – 04.08.02.D10: Validation Report on Upgrading ACAS RA Thresholds
- WP 4.8.2 – 04.08.02.D12: Feasibility report of using trajectory data in ACAS
- WP 4.8.2 – 04.08.02.D23: ACAS modifications for trajectory based operations – Updated OSED (Iteration 1).

1.4 Structure of the document

After an introduction to the context of the proposed TCAS II changes in Chapter 1, the two improvements are analyzed separately in Chapters 2 and 3. Each of these chapters consists of a description of the proposed improvement, an overview of the validation exercises performed within the project 4.8.2 followed by a discussion of the published results, and of the potential system impact. General conclusions are described in Chapter 5.

1.5 Improvements Addressed – Overview

Improvement	Functional area addressed	Proposed Change	Key Driving Factor
Reduced RA thresholds	Definition of RA thresholds	9 values changed for: higher (>FL200) and low (<FL50) altitudes	Adaptation of the thresholds values to the current ATM environment
Use of trajectory data in ACAS	Horizontal miss distance filter (MDF), surveillance function	Use of ADS-B (target) and own position information to improve performance of MDF	Improve quality of relative bearing data

1.6 TCAS Functional Overview

A high-level functional structure of TCAS II system is shown in Figure 1 (from the FAA introduction to TCAS II [6]). The surveillance function on this diagram provides the input to the Collision Avoidance System (CAS), which includes slant range, target's altitude and bearing for each tracked target. The functional components potentially affected by the proposed improvements are highlighted with orange (reduced RA thresholds) or blue (use of trajectory data in ACAS) colours.

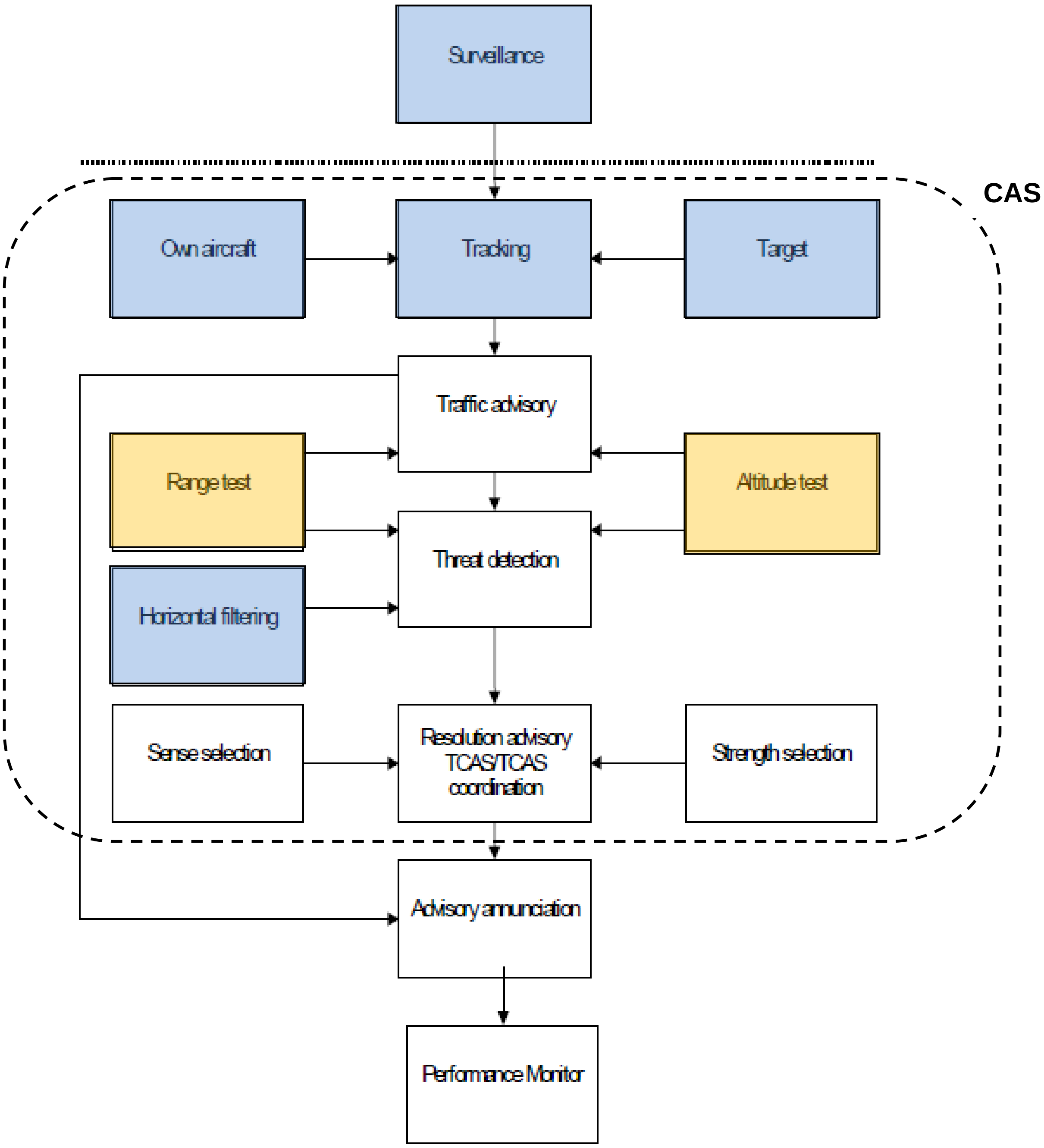

Figure 1: TCAS II CAS logic functions (adopted from FAA Introduction to TCAS II [6]). Potential impact of the proposed improvements is shown in different colours (orange for reduced RA thresholds and blue for use of trajectory data in ACAS).

1.7 Glossary of terms

Undesired (nuisance) RA – According to the OSED [1], an RA is considered "undesired" unless, at some point in the encounter in the absence of ACAS, the horizontal separation and the vertical separation are simultaneously less than the following values: 5.0NM and 750ft in En-route airspace or 3.0NM and 750ft in TMA airspace.

Wide RA – an RA which would be filtered out by the horizontal miss distance filter implemented in the TCAS II v7.1 if ideally accurate position information about the target is provided as its input.

1.8 Acronyms and Terminology

Term	Definition
ACAS	Airborne Collision Avoidance System
ADS-B	Automatic Dependent Surveillance - Broadcast
ALIM	Altitude LIMit (RA threshold)
ATC	Air Traffic Control
ATCo	Air Traffic Controller
ATM	Air Traffic Management
BBT	Bearing Based Tracker
CAS	Collision Avoidance System
CPA	Closest Point of Approach
DMOD	Distance MODified (RA threshold)
FAA	Federal Aviation Administration
FHA	Functional Hazard Analysis
FL	Flight Level
FMS	Flight Management System
HMD	Horizontal Miss Distance
ICAO	International Civil Aviation Organization

Term	Definition
IFR	Instrument Flight Rules
MDF	horizontal Miss Distance Filter
MOPS	Minimum Operational Performance Standards
MTOM	Maximum Take-Off Mass
NMAC	Near Mid-Air Collision
OHA	Operational Hazard Assessment
OSED	Operational Service and Environment Definition
PRT	Parabolic Range Tracker
RA	Resolution Advisory
RTCA	RTCA Inc., American Standardization Body
SESAR	Single European Sky ATM Research Programme
SJU	SESAR Joint Undertaking (Agency of the European Commission)
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TCAS-XP	A collision avoidance system using passive surveillance (intended primarily for general aviation)
TCAP	new Altitude Capture laws for ACAS RA prevention
TMA	Terminal Maneuvering Area
VFR	Visual Flight Rules
VR	Validation Report
VTT	Vertical Threshold Test (RA threshold)
WP	Work Package

2 Reduced RA Thresholds

Even though there are no safety issues identified with the current ACAS, with growing amount of traffic and thus an increasing number of unnecessary RAs, an adaptation of the RA thresholds to evolving ATM environment is a key candidate for future ACAS improvement. Concretely, the objective of the proposed RA thresholds change is to improve compatibility with ATM with respect to:

- Reduced altimetry error, and
- The progress made on aircraft navigation precision and altitude station keeping since the 90s.

2.1 Objectives of the Improvement

- Reduction of the number of unnecessary RAs
  - → Less unnecessary stressful situations for pilots
  - → Increased RA compliance rates
- Maintaining at least the same level of safety
- Improved compatibility with ATM
- Increased compatibility with ATC

2.2 Description of the Improvement

ACAS fundamentally operates on the concept of two tests: the horizontal (range) and vertical (altitude). The range test uses time-to-go to Closest Point of Approach (CPA) estimated as range divided by rate of closure. Similarly, the altitude test uses an estimated time-to-go to co-altitude computed from relative altitude and vertical rate. The above times are compared with the altitude-dependent TAU thresholds to determine whether a Resolution Advisory (RA) shall be triggered.

The time-based criteria described above are not suitable for encounters with low rate of closure or vertical rate, when the aircraft may be effectively very close to each other despite a relatively large time-to-go's to CPA or co-altitude. For these reasons two additional criteria based on a distance threshold (DMOD) and a relative altitude threshold (ZTHR) were introduced to correctly handle such situations.

Another two thresholds used in the altitude test are ALIM (Altitude Limit) and VTT (Vertical Threshold Test). ACAS generates a positive RA if the intruder is projected to be within ALIM at the time of CPA. VTT is a reduced TAU used to delay or prevent the unnecessary RAs during level-off maneuvers onboard the leveled aircraft.

All these thresholds are defined in TCAS MOPS [5] and the standard values are provided in Table 1. They were identified in order to minimize the nuisance alert rate, whilst allowing adequate time for effective avoiding maneuvers to take place.

Table 1: Values of the TCAS time and distance thresholds as defined in the MOPS [5].

Flight Level / Altitude	Alarm Time (vertical rate threshold) [TAU in sec]	Vertical Rate Threshold for Leveled Aircraft [VTT in sec]	Vertical Distance Threshold for RA [ZTHR in ft]	Distance Modification [DMOD in NM]	Vertical Distance Threshold for Positive RA - Altitude Limit [ALIM in ft]
FL > 420	35	25	800	1.1	700
FL200-420	35	25	700	1.1	600
FL100-200	30	22	600	0.8	400
FL50-100	25	20	600	0.55	350
2,350ft-FL50	20	18	600	0.35	300
1,000ft-2,350ft	15	15	600	0.2	300
0-1,000ft	No RA	No RA	No RA	No RA	No RA

The proposed change aims to reflect the improvements in aircraft and avionics performance achieved since the original definition of these thresholds values and to adapt them better to the current ATM environment. For instance, better aircraft altimetry required for Reduced Vertical Separation Minima operations impose weaker requirements on increased vertical thresholds at higher altitude.

Within the SESAR 4.8.2 project a set of RA thresholds which could be potentially upgraded was identified and then the most promising values were determined through an iterative process aiming to maximize the reduction of unnecessary RAs without negatively affecting safety. The resulting list of the RA thresholds values with highlighted changes is shown in Table 2.

Table 2: Updated values of the TCAS time and distance thresholds as proposed in the SESAR 4.8.2 project [3].

Flight Level / Altitude	Alarm Time (vertical rate threshold) [TAU in sec]	Vertical Rate Threshold for Leveled Aircraft [VTT in sec]	Vertical Distance Threshold for RA [ZTHR in ft]	Distance Modification [DMOD in NM]	Vertical Distance Threshold for Positive RA - Altitude Limit [ALIM in ft]
FL > 420	**30**	**22**	**700**	1.1	700
FL200-420	**30**	**22**	**600**	1.1	600
FL100-200	30	22	600	0.8	400
FL50-100	25	20	600	0.55	350
2,350ft-FL50	20	**17**	**550**	0.35	300
1,000ft-2,350ft	15	15	**500**	0.2	300
0-1,000ft	No RA	No RA	No RA	No RA	No RA

2.3 Performed Validation

The validation of the proposed improvement was undertaken in 2012 within the SESAR 4.8.2 project by DSNA, EUROCONTROL and NATS with the goal to assess safety and performance of the TCAS with upgraded RA time and distance thresholds. The validation was performed both for Core European airspace and U.S airspace and considering en-route airspace as well as TMAs.

Study was split into two exercises using two different methodologies:

- Exercise #1: Safety assessment (April-July 2012) led by NATS, with the goal to validate the safety of upgrading time and separation ACAS RA thresholds, performed through identification of potential high-level hazards and of their impact during several workshops.
- Exercise #2: Performance assessment (September 2011-October 2012) led by DSNA – Egis Avia, with the objective to identify an appropriate set of "Upgraded ACAS RA Thresholds" and to demonstrate that such modification will improve the performance of collision avoidance system.

Metric	Success Criterion	Technique
Risk Ratios[1] (safety)	The risk ratios computed with ACAS operating with upgraded time and separation RA thresholds are not increased when compared to the latest version of ACAS (TCAS II v7.1)	Fast Time Simulations
Number of encounters and aircraft with RAs (performance)	ACAS operating with upgraded time and separation RA thresholds significantly decreases the number of RAs triggered when compared to the latest version of ACAS (TCAS II v7.1)	Fast Time Simulations
Adequate hazard mitigation is possible (safety)	Hazard analysis shows that all risks of using upgraded time and separation RA thresholds can be adequately mitigated	ATM Risk assessment and mitigation using the SESAR methodology

2.3.1 Safety assessment (Exercise#1) description:

The safety evaluation of upgrading time and separation ACAS RA thresholds relied on the hazard and risk assessment technique supported by three Functional Hazard Analysis (FHA) workshops. Their goal was to:

- Identify the hazards related to the implementation of upgraded RA thresholds.
- Assess the severity and frequency of occurrence previously identified hazards, their comparison to the current TCAS II v7.1 and deriving a perceived risk classification.
- Suggest new and/or future mitigations if necessary.

The hazards were identified using the knowledge and experience of ACAS experts, pilots and ATCos to focus on the key issues for consideration, while the risk classification was carried out using the knowledge and experience of a EUROCONTROL ACAS expert.

[1] The risk ratios were found via encounter-modeling simulations analysis performed during Exercise #2.

Within the workshops, four high level hazards were identified that could potentially be impacted by the introduction of the proposed change. Those, considered to be impacted to a degree requiring a risk assessment were assessed with the result "no impact" when compared to the current version or "low" risk, which was considered to be acceptable.

Although the risk was assessed as "acceptable", potential future mitigations were identified with the aim of recommending measures that could further enhance the safety of ACAS.

2.3.2 Performance assessment description

This assessment was built on the model-based methodology, which is used already for decades in ACAS studies, and acknowledged at ICAO and RTCA level. The methodology relies on a set of tools and on several models replicating the environment in which ACAS is being operated. TCAS II v7.1 implementation was used as a reference (baseline) scenario.

The following elements were varied within the exercise:

- **Threshold values**. The values used as a standard for the assessment conforms to TCAS II v7.1 which is already mandated (from 1st March 2012) for all new aircraft above 5,700kg MTOM (Maximum Take-Off Mass) or a maximum seating capacity of more than 19 seats[2]. The simulated environment is therefore compliant with the future European airspace.

- **Pilot response models.** The pilot response and its impact on safety benefits was the key factor to assess during the exercise. Simulations were run both with *manual* and *automatic* responses. Manual responses used two types of models:

  - *Standard Pilot Response* model, which is based on 5s reaction time for initial RA.

  - *Typical Pilot Response* model, which provides the wide range of pilots' behaviour observed during current European operations.

  - Simulations were also run with different automatic CAS responses.

- **Encounter-models** allow generating a very large number of encounters on which ACAS logic can be simulated and indicators computed. Two types of encounter models were used for this validation:

  - Safety encounter models – to compute safety related indicators such as risk ratios; these models addresses only risk bearing encounters and they are used to stress the ACAS logic.

  - European ATM encounter model – used to simulate day-to-day operations and to compute more operational (performance) indicators (such as number of RA triggered).

  Five encounter-models were used in this validation addressing two different airspaces (both en-route and TMA being considered):

    - Core European airspace was modelled in two safety models (one for pair-wise encounters and one for 3-aircraft encounters) and one ATM model;

[2] For all aircraft currently equipped with v7.0 is the mandate date 1st December 2015 (E.U).

- The US airspace was investigated using one safety model (pair-wise encounters) and one ATM model.

Each encounter-model included at least 100,000 encounters.

2.4 Summary of Validation Results

Results of the validation performed for reduced RA thresholds within the SESAR 4.8.2 project [3] are provided in Table 3.

Table 3: Summary of the results obtained from the validation exercises performed within the SESAR 4.8.2 project.

Validation Objective	Exercise Result/Conclusions
Validate the safety of upgrading time and separation ACAS RA thresholds [safety assessment]	→ No new hazards were identified with the introduction of ACAS operation with "Upgraded RA Thresholds" when compared to the current version of ACAS (TCAS II v7.1). → All the risks assessed were considered as "Low" according to qualitative risk analysis conducted on 16th July 2012. This was considered as "acceptable" (at least as safe as the current version). As a result, there is no requirement to implement additional mitigations to those already in place. However, some additional mitigations were identified that may provide a safety benefit. TCAS safety is maintained
Validate that upgrading time and separation RA thresholds improves ACAS performance [performance assessment]	→ Risk ratios are not increased on pair-wise encounters (Europe and U.S.) and they are decreased on multiple-aircraft encounters (Europe). → Operationally unnecessary RAs are significantly reduced: ○ **34%** of RAs avoided on European airspace; ○ About **10%** of RAs avoided on U.S. airspace ○ **2/3rd** of "Unnecessary RAs" avoided on 1,000ft separation IFR/IFR encounters – Europe ○ **1/4th** of "Unnecessary RAs" avoided on 500ft separation IFR/VFR encounters – the US → ACAS is not degraded in classes of operationally frequent geometries when operating with Upgraded Thresholds (Europe and U.S.). → Proposed changes were proven to be interoperable with TCAS II v7.1, and TCAP (new altitude capture laws). → Remaining TCAS RAs are less disruptive to ATC.

2.5 System Impact

From a system impact perspective, the implementation of this improvement requires only a modification of the thresholds values in the TCAS software.

Hardware/Interface changes:

- NONE

Software changes:

- Changes of thresholds values
- No algorithms changes

3 Use of Trajectory Data in ACAS

Target's bearing and slant range information used in the current TCAS II are obtained from transmission characteristics of the target's transponder replies (reply's delay, incoming direction) triggered by own periodic interrogation[3]. The accuracy of this data is therefore affected by antenna design restrictions and especially the bearing measurements may be affected by non negligible errors in this context.

Within the current TCAS II, the bearing information is used for two purposes: for displaying a target on the TCAS display and in the horizontal Miss Distance Filter (MDF).

MDF is used to reduce the number of RAs against intruder aircraft when a large horizontal separation (Horizontal Miss Distance (HMD)) is predicted at CPA. In addition, the MDF can also terminate an RA prior to ALIM being obtained when the filter is confident that the horizontal separation at CPA will be large. It has been introduced with TCAS II v7.0; after the simulations and testing have shown that horizontal MDF would reduce the number of RAs by approximately 25% in the U.S airspace and up to 40% of RAs in the European airspace [7].

The considered improvement addresses a potential use of target's horizontal position available via ADS-B reports together with own position (from onboard navigation systems) to improve quality of MDF input data (in particular the bearing) and thus considerably increase its performance.

Note, that the use of ADS-B data in TCAS is not a completely new function as since v7.1 there is an optional TCAS enhancement, called hybrid surveillance, which uses a similar principle to reduce TCAS active interrogation through determination of CAS inputs (slant range, bearing and altitude) from ADS-B (target) and own positions rather than from target's transponders replies. However, there is an important difference: ADS-B tracking for hybrid surveillance is used only for distant targets and before such target could potentially trigger any TA or RA, a switching to standard active tracking shall happen. On the other hand, the proposed improvement considers using such tracking in the MDF, i.e., in the situations when an RA is triggered.

3.1 Objectives of the Improvement

- Provide timelier and more effective RAs
- Reduce nuisance RAs with large HMD (a provisional target reduction of nuisance RAs by 10% was set in the initial OSED [1])
- Maintain ACAS safety performance (any increase in risk ratio less than 0.1% in absolute value)

The 10% nuisance RA reduction represents an expert judgement of the minimum operationally worthwhile improvement.

3.2 Description of the Improvement

Current MDF (
Figure 2) uses two types of trackers to independently estimate HMD:

[3] With optional hybrid surveillance capability [9], the ADS-B based tracking can be used for distant targets when some prerequisites are met.

- Parabolic Range Tracker (PRT) that uses only range data (and its numeric derivations).
- Bearing based tracker (BBT) that uses both range and bearing data (together with bearing numeric derivation).

The two HMD estimations are then combined to provide a single estimate of the HMD (the smaller one is used). In addition, MDF performs a set of tests aiming to detect potential maneuvering of the target (turns, acceleration) or excessive noise in the tracking parameters. If the HMD estimate is greater than an altitude dependent threshold (DMOD) and no maneuver is detected, then any RA that would have been generated is filtered out.

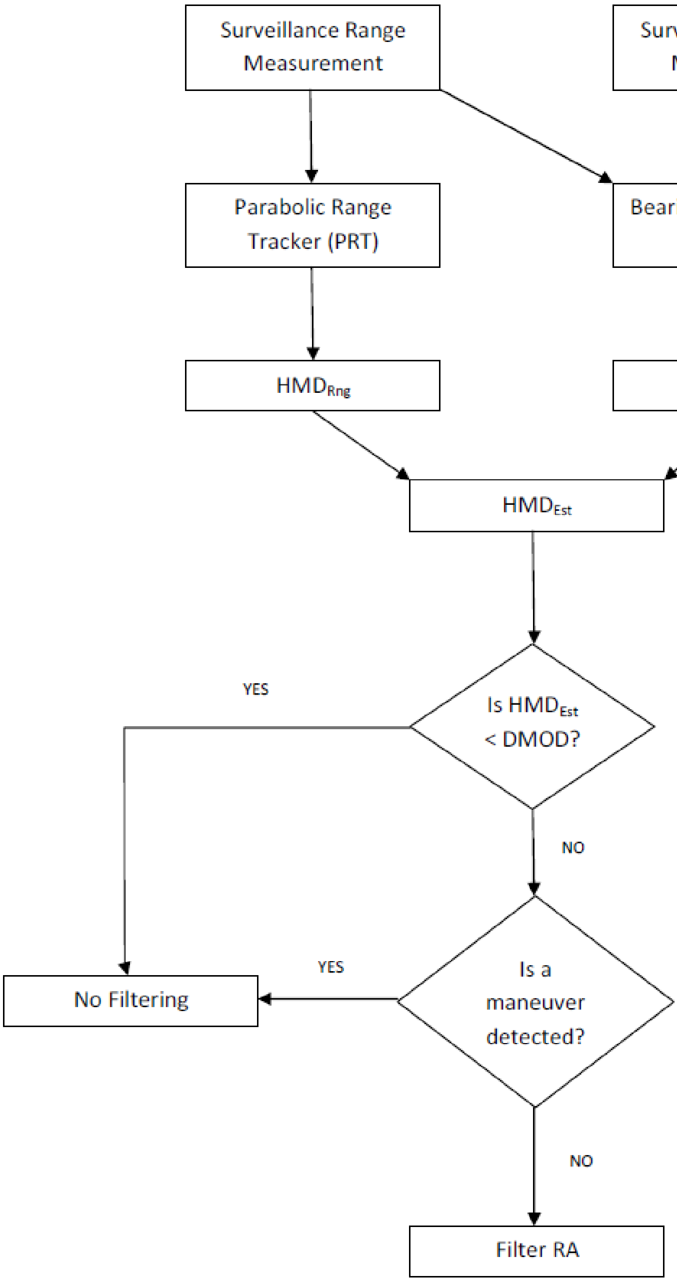

Figure 2: Current MDF design

Practical experience shows that the poor quality of bearing data from TCAS active surveillance often cause that the BBT underestimates HMD, and therefore allows RAs to be issued even though it might be filtered out.

The 4.8.2 project does not specify one selected way how the ADS-B information should be used in MDF but rather multiple options are discussed (Appendix A of [4]) or analyzed in the validation report [4]. Concerning the validation exercises performed in SESAR 4.8.2 (described in the following section), they are based on the use of existing MDF implementation with varying quality of input data. Furthermore, an assumption (A-016): "Adequate modelling can be performed without specifying the technique required to combine ADS-B and ACAS horizontal data" is considered in the validation report [4].

As different applicable techniques are essential for evaluation of the system impact, potential implementation options are elaborated a bit further in the following.

3.2.1 Operational Requirements on potential implementations

Concerning requirements on the potential implementation, the initial OSED [1] provides the following requirements (REQ-04.098.02-OSED-TRAJ.01 and REQ-04.098.02-OSED-TRAJ.02):

- ACAS will receive the horizontal position and velocity of the intruder either passively via ADS-B or actively via ACAS cross-link.
- ADS-B data shall be validated against ACAS range measurements.
- The HMD filter shall incorporate ADS-B data into its algorithms.
- Safety will not be degraded by the use of ADS-B horizontal data in the HMD filter.

Only the latter requirement was kept in the updated OSED [2] (REQ-04.08.02-OSED-TRAJ-0002).

3.2.2 Potential Implementation Alternatives

The basic additional requirement to any potential implementation of this improvement is that the TCAS collision detection & avoidance logic shall remain independent of ADS-B data (as these data may be used for separation management and it is necessary to avoid any common failure mode with collision avoidance). As this logic uses only slant range (and its derivations determined in PRT) it leads to the following assumption.

ASSUMP-09.47-01: Surveillance function will always provide a slant range determined through TCAS active interrogation of the target's transponder (outside of hybrid surveillance applicability area) and there will be a PRT instance using this data in CAS.

Concerning the use of ADS-B data in MDF there are two basic approaches:

1. Use the current MDF design which means that the ADS-B and own position data will need to be first transformed into slant range, and relative bearing before provided to MDF.
2. Adapt the MDF design to the type of information available in the ADS-B reports.

In addition, for both of these alternatives there are several options depending whether:

a. Only ADS-B information is used within MDF, or

b. Both ADS-B information and the interrogation-based slant range are used in MDF (with different design options depending how they are combined).

Independently of the options described above (although the detailed safety requirements may differ for these options), any implementation will need to address the following aspects (the list is not exhaustive):

- ADS-B position information is **reported** by other aircraft avionics, i.e., it is not directly determined/measured by own system, and it is therefore important to carefully assess quality and reliability of such reported information. Validation of this information with respect to the interrogation-based slant range is a natural mitigation means, however, it has to be proved whether it is sufficient.
- Availability of ADS-B information – there shall be mitigation means to handle the situation when ADS-B data are not (or stop to be) available. ACAS cross-link or parallel processing of ADS-B and interrogation-based data are possible candidates. Again, the detailed safety requirements may vary among different options.
- It shall be proved that there are no common failure modes between ADS-B –based separation management and collision avoidance provided by TCAS using ADS-B data in MDF.

Safety requirements addressing these aspects will depend on the selected implementation option and the way how the ADS-B data will be used in MDF. This implies that the adequate mitigation means should be considered only in the context of a selected alternative.

3.3 Performed Validation

Two validation exercises were conducted within the SESAR 4.8.2 project:

- Quantitative exercise #6 (performance & safety assessment), led by EUROCONTROL, measured the performance and stability of using trajectory data. The objective was to validate that the use of ADS-B horizontal information in the ACAS MDF improves collision avoidance performance; and to validate that potential large ADS-B horizontal information errors do not disable necessary ACAS RAs.

- Qualitative exercise #7 (safety assessment), led by NATS, evaluated safety of using ADS-B horizontal data in MDF. During this exercise, the hazard and risk analysis were performed through a series of Safety workshops attended by knowledgeable and experienced personnel in accordance with 4.8.2 Validation Plan [8].

The following metrics and success criterion were used for validation:

Metric	Success Criterion	Technique
Number of RAs produced (performance)	At least 10% reduction in the number of nuisance RAs[4].	ACAS simulation of trajectories (modified radar data) with added TCAS II and/or ADS-B noise.

[4] According to the OSED (in validation report [4], the word "nuisance" is missing in some places).

Metric	Success Criterion	Technique
Number of RA produced (safety)	No RA filtered out in safety critical cases	ACAS simulation of encounters with 0 HMD
Collision risk (risk ratios) (safety)	No increase	Not performed
Adequate hazard mitigation is possible (safety)	Hazard analysis and mitigation shows that all risks of using responsive coordination can be adequately mitigated. The operational concept can be agreed with suitable modifications.	OHA technique. E.g. Brainstorming, hazard identification, risk assessment, identification of mitigations and safety requirements where appropriate.

3.3.1 Performance & safety assessment (4.8.2 Exercise #6):

This 4.8.2 exercise investigated impact of the surveillance data noise on the current TCAS (and MDF) design. An arbitrarily selected set of 100 RA sequences (representing 91 different events, some events having more than 1 aircraft receiving RAs) from European Mode S radar recordings (identified through ACAS RA downlink) was used as an initial traffic sample.

The smoothed radar data for these situations was used to reconstruct the corresponding encounters and TCAS II (v7.0) of the involved aircraft was simulated by Eurocontrol's Interactive Collision Avoidance Simulator (InCAS) V2.9 tool. The surveillance input to the TCAS was modelled as radar data (assumed to represent the "real" trajectories) degraded with different types of noise.

Performance simulations were based on the following elements:

- **Traffic sample –** as the adopted approach does not consider impact of the original surveillance error (either associated with onboard sensors of involved aircraft or with the Secondary Surveillance Radar (SSR)), it was not possible to reproduce all 100 considered (downlinked) RA sequences with smoothed radar data. In this context, only 59 RA sequences were reproduced directly while another 25 RA sequences were triggered after some minor vertical adjustments (imitating potential surveillance error) of the radar trajectories. This left 15 wide RAs which were not reproduced (even with minor vertical adjustment) and which can be therefore filtered out by MDF if accurate data are available. **The traffic sample for each simulated scenario consists of these 15 wide RA encounters each of them being simulated 7 times.**

- **Noise models** – three types of noise models were used within the simulated scenarios to emulate:
  - **Slant range noise for TCAS active interrogation surveillance** – this noise was modelled using a bias on a uniform -125ft to +125ft distribution and a Gaussian jitter with standard deviation of 50ft.
  - **Bearing noise for TCAS active interrogation surveillance –** this noise was modelled as Gaussian error with σ (bearing error) = 9.4°.
  - **ADS-B position noise –** this noise was modeled as Gaussian random walk with σ(position error) = 47.2m, and σ(velocity error) = 2 m/s.

In addition, an **along-track offset** was considered for ADS-B and own position information associated with possible **latency effects** (the worst case of 600ms for ADS-B and 250ms using actual speed and heading).

1. **Testing scenarios –** scenarios were defined by the use of different types of noise for slant range and bearing inputs. For each scenario the 15 wide encounters were simulated 7 times with The following noise combinations were simulated:

Noise Option	Range Errors	Bearing Errors	Purpose
NN	None	None	Control Case
TT	TCAS II	TCAS II	Current system estimate
AAG+	ADS-B Gaussian walk + offset	ADS-B Gaussian walk + offset	Simple ADS-B tracker performance
TAG+	TCAS II	ADS-B Gaussian walk + offset	Combined TCAS II & ADS-B tracker performance
AAG	ADS-B Gaussian walk	ADS-B Gaussian walk	Assess Effect of offset errors
TAG	TCAS II	ADS-B Gaussian walk	Assess Effect of offset errors

Safety simulations were based on the modelling of the worst case noise (ADS-B noise with offset for slant range and TCAS II noise for bearing) and simulating 90 NMAC encounters derived from the original 100 RA sequences (NMAC encounters were obtained through adjustments of the original trajectories to achieve HMD<0.1NM and VMD<100ft).

3.3.2 Qualitative safety assessment (4.8.2 Exercise #7):

To provide a qualitative safety analysis, the safety assessment was conducted through Safety workshops in July and August 2012.

For high level operational hazards identification, structured brainstorming technique was used. This led to identification of potential casual factors, mitigations and operational outcomes. The safety impact was considered for each of the hazards sequences and once there was a safety impact considered (according to the performer's knowledge and experience), perceived risk classification[5] was assigned. Where an identified risk was greater than "Low", the previously identified potential mitigations were considered and the hazard sequences were re-assessed. Finally the suitable safety requirements from the mitigations were generated where necessary.

Outputs of the workshops were documented in the form of:

- Bow Tie diagrams (output of initial workshop and subsequent reviews)
- Consolidated list of casual factors

[5] Risk classification was based on the scheme used previously within 4.8.2 for ACAS Xp, as this was the preferred scheme suggested by the project and deemed suitable for the purpose

- Proposed future mitigations for consideration and potential mitigations (against the identified casual factors, with no indication of the level risk associated with individual hazard sequences)
- Risk analysis table

3.4 Summary of Validation Results

Within this section an overview of the results provided in the 4.8.2 validation report [4] is presented together with their extended analysis.

3.4.1 Performance of the current MDF design with different types of noise

As described in the previous section, performance of the current TCAS II system was simulated on the set of 15 encounters (each of them being simulated 7 times, i.e., the testing sample consists of 105 events) with the input surveillance data degraded with different types of noise. The Table 1 shows the numbers of RAs issued within each scenario.

Table 4: The number of RAs issued during the simulations of 15 "wide" encounters. Note, that the encounter E033 was not included in the results analysis (due to the results of the control scenario (TT)).

Wide RA	NN	TT	AAG	TAG	AAG+	TAG+
	Control Case	Current system estimate	Assess Effect of offset errors (ADS-B Range)	Assess Effect of offset errors (TCAS II Range)	Simple ADS-B tracker performance	Combined TCAS II & ADS-B tracker performance
E001	0	7	1	5	2	5
E015	0	2	0	1	0	1
E027	0	2	0	0	0	0
E033*	1	7	5	6	6	7
E047	0	1	0	0	0	1
E071	0	1	0	0	0	0
E080	0	6	3	6	7	5
E098	0	0	0	0	0	0
E104	0	5	3	3	2	4
E119	0	0	0	0	0	0
E120	0	3	3	5	0	3
E126	0	0	0	0	0	0
E132	0	0	0	0	0	0
E143	0	1	0	1	0	1
E165	0	0	1	0	3	0
TOTAL (without E33)	0	28	11	21	14	20

The published results show that in the reference case with the modelled TCAS II range and bearing noise 28 RAs were issued. In the remaining testing scenarios it was possible to further reduce the number of RA by the factor varying between 60% and 25%: 60% of RA was removed when ADS-B noise without latency was used, while 25% reduction was obtained for TCAS II range noise and ADS-B (without latency) bearing noise.

3.4.2 Potential generalization of the published results

Generalization of the results obtained on a limited sample is always a difficult task and as the 4.8.2 experiment was not designed with statistical significance in mind, there are several elements that require some further research.
In order to be able to perform a generalization of the obtained results two questions should be answered:

1. **Maximal achievable performance** – i.e., how big ratio of the nuisance RAs (note, that the performance requirement for the proposed TCAS changes is defined in the 4.8.2 OSED as at least 10% reduction of the **nuisance** RA) can be potentially achieved through the improvement.
2. **Performance of a concrete implementation of the improvement** – only if the improvement has a potential to provide sufficient benefits, it makes sense to consider limitations of different possible implementations for this improvements (discussed in Section 3.2.2) as well as the associated system impact (costs).

Both these questions are partially addressed within the 4.8.2 performance simulations but their full answers require further research.

Maximal achievable performance

In order to have a representative answer (for a given environment[6]) to this question a statistical analysis of the real traffic should be performed. Results based on an initial traffic sample of (arbitrarily selected) 100 RA sequences are too sensitive on this initial selection and therefore they can be quite far from the true statistical results.

In addition, a good understanding of encounters geometries/flight profiles that are typically affected by reduced MDF performance (due to poor input data) is essential to assess complementarity or overlap of this improvement with other planned/proposed ACAS changes such as altitude capture law or reduced RA thresholds. Without this knowledge there is a risk that two proposed improvements will address the same type of events and consequently it does not make sense to implement them both.

The analysis performed in the 4.8.2 project showed that:

- There are 15 “wide” RAs (within the considered 100 RAs sample) that can be potentially filtered out by MDF (with ideal data) – this represents a rough indication of achievable performance with respect to **all RAs** (not nuisance RAs)[7].
- Only 59 of 100 RAs were directly reproducible with smoothed radar data – this provides some rough indication about the impact of surveillance errors. This effect is affected by two types of error: ground surveillance error associated with SSR and airborne surveillance error associated with onboard sensors; however from the available data it is not possible to identify their relative contributions.

[6] It can be expected that the ratio will vary for different types of environment e.g., the US and European airspace.
[7] The ratio of nuisance RAs within the considered 100 RAs sample is not provided in the validation report [4], and therefore all results can be compared only with respect to the number of all RAs.

Performance of a concrete implementation of the improvement

As discussed in Section 3.3.1, the validation exercises were performed with the current TCAS and MDF design by changing the quality of inputs data (slant range and bearing). This approach allowed testing of several possible uses of ADS-B data however there are other options which can provide better performances. The potential candidates include in particular:

- The option where PRT is operating with the TCAS-based slant range while BBT is operating with ADS-B based data (both range and bearing originating from ADS-B in this tracker). BBT performance is in simulated scenarios TAG and TAG+ (shown as option (a) in Figure 3) affected both by TCAS range noise and ADS-B noise (in bearing) which means that its HMD prediction is influenced by a combined effect of two errors of quite different nature. It would be useful to analyze the performance of the system where BBT is using only ADS-B based information (as shown by option (b) in Figure 3) to see whether performance is increased.
- The performance of potentially modified MDF design with HMD estimation adapted to the use of relative position data rather than range and bearing. Note, that the sensitivity of the HMD estimation does not depend only on the noise of the input data but also on the numerical process leading to this result (formula used for computation, numeric derivation of the tracked data, etc.). In this context, a different performance can be expected when the ADS-B and own position is first transformed to range and bearing and these parameters are tracked and differentiated or whether the relative position itself is tracked.

In addition, the existing ADS-B noise models are typically based on the current ADS-B Out versions 0 and 1 installations. When there will be more empirical data available for ADS-B version 2 (covered by the approved mandates) these models may require an update.

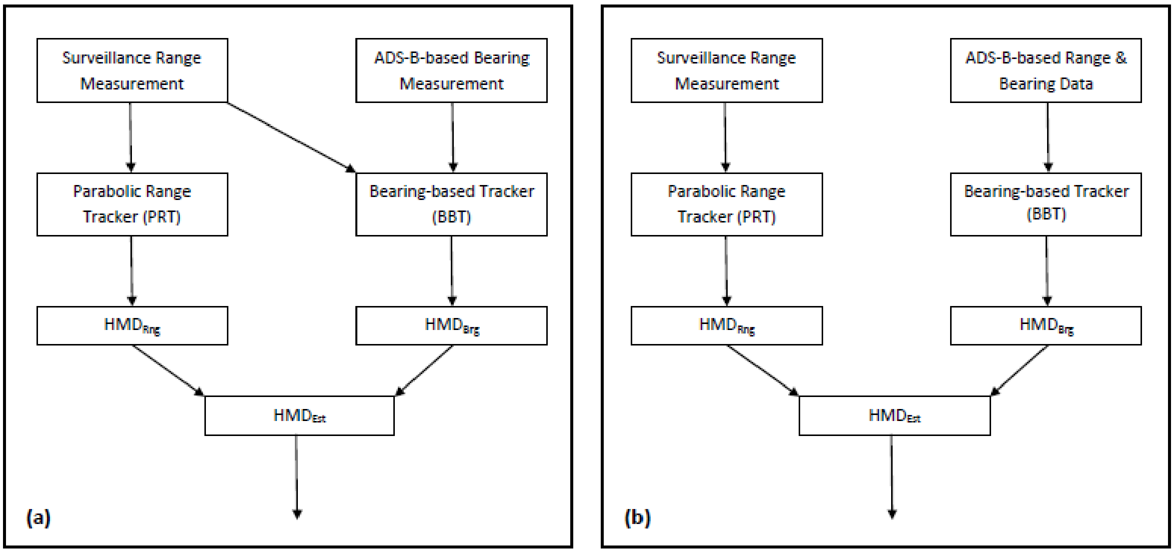

Figure 3: Two design options how to use ADS-B data in the current MDF design. The option (a) was used in the TAG and TAG+ scenarios simulated in SESAR 4.8.2 [4].

3.4.3 Validation of the noise impact on the issuing of RAs in safety critical situations

The potential impact of the noise on ACAS safety performance was simulated by considering the worst case noise option for both range and bearing. It means that the ADS-B noise including offset was considered for slant range while the TCAS noise was used for bearing. This setting was used to simulate 90 NMAC encounters derived from the initial sample. Within these simulations all 90 encounters generated sequences of RAs, however, there were some differences in the RA timing comparing to the simulations without any noise as shown in the table below.

Table 5: Number of cases when the RA timing was affected by the worst-case noise with respect to the simulations without any noise in the surveillance data (based on simulations of 90 NMAC encounters).

Offset	NN >1s before	NN 1s before	No difference	NN 1s after	NN >1 s after
Number of cases	3	11	61	12	3

The conclusions of this analysis provided in the 4.8.2 report [4] are:

- Surveillance errors can cause ACAS alerts to be triggered significantly earlier or later than in perfect surveillance conditions. However, the presence of additional noise has not been shown to cause any delays in issuing RAs, attributable solely to the MDF, in safety critical cases.
- A deeper level of testing is required with encounter models that can provide statistically significant safety assessments in the presence of TCAS II and ADS-B surveillance noise.

In this context it should be mentioned that the simulated scenario went beyond any considered design options as the ADS-B noise was used not only in MDF but also in collision detection and avoidance logic which is not allowed for the proposed improvement.

3.4.4 Qualitative Safety Assessment

The safety analysis identified three hazards (related to already pre-existing hazards):

- H1 – Aircraft Trajectory Conflict Not Avoided;
- H2 - Induced Trajectory Conflict;
- H3 –Wake Turbulence Encounter Not Avoided.

Qualitative risk analysis showed that (for the hazard sequences assessed in the exercises) the perceived risk associated with the implementation of ADS-B horizontal information in the ACAS MDF is either not negatively impacted or “Low”. However, some of the hazards sequences were not risk assessed due to lack of experience/knowledge of the sequence to be able to reach an informed conclusion about the level of perceived risk when compared to current TCAS II (v7.1). Those hazards would require additional work to be completed in order to reach a conclusion on the level of perceived risk associated with them.

Safety assessment was not completed within the 4.8.2 validation and the recommendations concerning missing point can be found in [4] (they include encounter modelling to evaluate risk ratio, quantitative safety analysis to verify that the safety criteria can be achieved, verification of the used assumptions, etc.).

3.5 System Impact

This improvement already represents a relatively complex change and the potential system impact strongly depends on the selected implementation alternative, associated safety and performance requirements (which may considerably differ for different implementation options), and also what kind of system is considered as a baseline. The TCAS logic functions that will be in general affected by this improvement are shown in Figure 1.

As described in Section 3.2.2 the basic assumption for any potential implementation of this improvement is that the surveillance function shall still provide the slant range determined through active interrogation and this slant range will be used to validate the ADS-B data.

Potential system changes can be split into two categories:

- Surveillance and tracking
- MDF (covering both HMD estimation and maneuver detection)

In addition, a hardware interface with own navigation system (typically GNSS) is required (however, this interface is already present for systems with hybrid surveillance or ADS-B In capabilities).

3.5.1 Surveillance and Tracking

The potential system impact (especially concerning surveillance) would considerably differ depending whether the baseline system has already hybrid surveillance capability or not. Furthermore, required changes will differ considerably according to the selected implementation alternative, so only high-level discussion is possible here.

In addition to the processing and tracking of ADS-B and own position reports (these functionalities are already needed for hybrid surveillance) probably the biggest new requirement is related to the fact, that each target would need to be tracked twice (once through active interrogation, and once through ADS-B and own position) which will result in higher storing and processing demands. Note, that it is not possible to combine the two types of data within one track due to different error biases which may cause discontinuities in the numerical derivations (this limitation was already identified and formulated in hybrid surveillance MOPS).

3.5.2 MDF design

Beyond the options where the current MDF design is used (with data of different origin) there are probably two main alternatives that could be envisioned:

- **A completely new MDF design targeting the use of ADS-B based information.** While for conventional TCAS surveillance, the slant range error and bearing errors are independent (as the measurement methods are different), in the case when range and bearing are determined from ADS-B and own position the two errors have a common origin and they are correlated. In this context when MDF uses only this type of data there is not really an added value to keep two types of trackers and a new HMD estimation can be more straightforward (option (b) in Figure 4). On the other hand, such approach requires also a modification of the maneuver detection as discussed in Appendix A of [4].
- **A modified MDF design** where PRT is used as now using the TCAS-based range, and BBT is replaced by a new (ADS-B optimized) tracker. Such design is shown as option (a) in Figure 4.

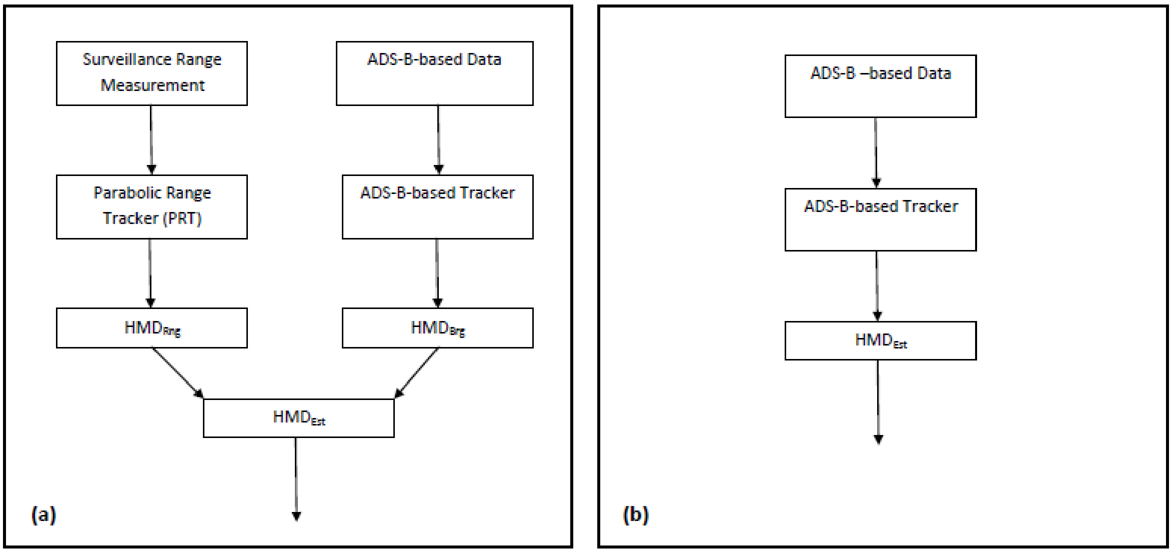

Figure 4: Two options of the modified MDF design.

4 Conclusions

The two TCAS II changes proposed in the 4.8.2 OSED [1] differ considerably both in their complexity (from technical perspective) and the achieved maturity of their validation.

Reduced RA thresholds represent a minor modification of the current system while providing important benefits (about 2/3rd, or 1/4th of nuisance RAs avoided in European and US airspace, respectively). Also the achieved validation level is high. This creates a very interesting business case for Airspace Users. The SESAR 4.8.2 project team recommends to go forward with the standardization for this proposed TCAS II change.

Use of trajectory data in MDF represents a relatively complex change of the system, although a potential system impact can be considerably reduced if hybrid surveillance capability is already implemented in the system. However, the achievable benefits are not well quantified for this improvement as well as safety requirements (which may considerably influence the system impact). In this context a considerable additional effort and time is required to reliably evaluate worthiness and feasibility of this improvement. Taking into account this fact, budget and time limitations, and the ongoing ACAS-X research activities, the SESAR 4.8.2 project team recommends to do not continue with research in this area. On the other hand, from technical perspective this improvement remains one of the candidates for potential future TCAS II performance improvements.

5 References

[1] P04.08.02-D08-OSED-INITIAL-ACAS modifications for time & trajectory-based operations initial OSED, December 2011

[2] P04.08.02-D08-OSED-ACAS modifications for trajectory-based operations – updated OSED (Iteration 1), November 2012

[3] P04.08.02-D10-VR-OT-Validation Report on Optimizing ACAS RA Thresholds-00.01.00, October 2012

[4] P04.08.02-D12-VR-TRAJ-Feasibility report of using trajectory data in ACAS, January 2013

[5] EUROCAE ED-143/RTCA DO-185B TCAS II MOPS, “Minimum Operational Performance Standards for Traffic Alert and Collision Avoidance System II (TCAS II)”

[6] FAA, Introduction to TCAS II Version 7.1; 2011, February 28

[7] FAA, TCAS Transition Program (TTP) Newsletter. (2000, February 25). TCAS Transition Program (TTP) Newsletter. p. 3.

[8] P04.08.02-D09-VP Validation plan of possible ACAS modifications for time & trajectory based operations, December 2011

[9] RTCA DO-300: MOPS for TCAS II Hybrid Surveillance, 2006

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