

Potential co-operations between the TCAS and the ASAS

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ABSTRACT

In the near future, capacity problems are foreseen both in the air and on the ground, due to an increase in air-traffic. The Airborne Separation Assurance System (ASAS) based on Automatic Dependent Surveillance Broadcast (ADS-B) is one of many proposals for improvement. The ASAS supports the delegation to the aircraft of separation responsibilities that are currently handled by ground controllers. Potential co-operations between the ASAS and TCAS (Traffic alert and Collision Avoidance System) are discussed. It is concluded that surveillance data fusion of ADS-B and TCAS could improve the airborne surveillance performance. Interactions on the level of the logic to reduce the number of nuisance alerts should be the subject of further study. Finally, it is recommended that TCAS and ASAS data are presented on the same traffic display.

Keywords

Collision avoidance, separation assurance, automation, integrated avionics systems.

INTRODUCTION

In the next fifteen years, air-traffic growth of at least fifty percent is foreseen. This will lead to capacity problems both in the air and on the ground. The solution for this capacity problem will be a combination of several sub-solutions. One of them is the limited or full delegation to the aircraft of some of the separation responsibilities that are currently handled by air traffic controllers on the ground. Pilots are no controllers though. One can not expect that they can assure their own safe separation with the means they currently have. An Airborne Separation Assurance System (ASAS) will provide the necessary assistance to enable the flight crew to accept the extra tasks and responsibilities [4].

By the time the ASAS will become operational, most aircraft will be equipped with the Traffic alert and Collision Avoidance System (TCAS). This is a last resort tool to prevent near mid-air collisions when the system that assures safe separation has failed. These days, many aircraft all over the world are already carrying TCAS equipment. ICAO has proposed a worldwide mandatory TCAS carriage for many aircraft categories by the year 2005.

Both the ASAS and TCAS are designed to keep aircraft apart, but with different criteria. The ASAS makes sure

that the aircraft are at least separated by the separation standard¹, while the TCAS makes sure that the aircraft do not come into contact. To provide conflict² (ASAS) or collision (TCAS) avoidance information, traffic information (identity, position, velocity, etc.) of aircraft in the vicinity is needed. The received traffic information is presented to the crew on a cockpit display to make them aware of the traffic situation. The traffic information is also fed into a logic function where every aircraft is checked for a potential conflict in the case of the ASAS, or a potential collision in the case of the TCAS. If necessary, an appropriate conflict resolution or collision avoidance manoeuvre is determined. If a hazardous situation is detected, the flight crew is alerted by special symbology on the display and by auditory alerts. An avoidance manoeuvre is presented on a cockpit display.

Although the ASAS and TCAS serve a different purpose, the architecture is very alike. It is therefore suggested that the systems co-operate to achieve a better performance in terms of safety. This co-operation can be seen as a data exchange or transfer between the two systems. There is potential for co-operation on three levels of the systems: on the level of surveillance, logic and data presentation. In this paper emphasis is laid on co-operation on the level of surveillance and data presentation.

DESCRIPTION AND COMPARISON OF ASAS AND TCAS

In this section, the purpose and system functions of both the ASAS and TCAS are described. The main differences are pointed out and summarised in Table 1.

The Purpose of the ASAS and TCAS

In the event of a limited or full delegation of separation responsibilities to the cockpit, the ASAS provides the necessary assistance for the pilot to accept these extra tasks and responsibilities. The ASAS thus aids the flight crew to avoid conflicts, i.e., to make sure that the safe separation standard between aircraft is maintained.

¹ Separation standards can be different for different airspace sectors. In current practice, aircraft flying en-route must always be separated horizontally by at least 5 NM or vertically by at least 1000 or 2000 feet, depending upon their altitude.

² A conflict is defined as a potential loss of the standard safe separation.

As the name says, the purpose of the TCAS is to avoid collisions. A collision occurs when two aircraft actually come into contact. The TCAS is designed to provide a final independent backup system in case the standard safe separation is lost. When the ASAS has failed to assure safe separation, the TCAS will step in and avoid a collision. Hence, the TCAS can be seen as a backup for the ASAS.

Description of the Surveillance Function

The ASAS receives position, velocity and other information on aircraft in the vicinity through Automatic Dependent Surveillance Broadcast (ADS-B). ADS-B gathers the required information from the aircraft’s navigation and other systems and forms a message. Every aircraft that is ADS-B equipped and within a certain range of the transmitting aircraft can receive the ADS-B report without the transmitting aircraft even knowing it.

TCAS makes its own independent measurements to obtain information on surrounding traffic. The system interrogates aircraft in its vicinity and listens for the transponder replies. The arrival time of the reply is a measure for the relative range of the target and the receiving antenna pattern gives an indication of the relative bearing. The altitude is contained in the reply message and is derived from the target’s altimeter. The measurements are correlated and input to a tracker. The output of the TCAS surveillance function consists of tracks for transponder equipped aircraft within a certain range.

Description of the Logic Function

The outputs of the surveillance functions are fed into the logic functions where a prediction is made of the future traffic situation.

The ASAS logic function looks far ahead (up to 20 minutes) and checks whether any of the surrounding aircraft violates the standard separation criteria. If a conflict is detected, the logic function calculates an appropriate resolution manoeuvre.

The TCAS traffic information is used to determine the Closest Point of Approach (CPA) for every aircraft paired with the own aircraft. If the relative range and altitude at the CPA are within certain limits, the closure rate of the aircraft pair is calculated in order to determine the time-to-go to the CPA. The alerting thresholds are dependent on the altitude level. The TCAS can issue two types of alerts. A Traffic Advisory (TA) is just a proximity warning to

assist the pilot in the visual acquisition of the threat. The pilot is not allowed to manoeuvre in response to a TA only. The TA is issued 20 to 40 seconds before reaching the CPA. Resolution Advisories (RAs) are issued 15 to 35 seconds before reaching the CPA. An RA is a vertical avoidance manoeuvre recommended to the pilot.

ASAS and TCAS Data Presentation

For both systems, the traffic information, alerts, and advisories are presented on cockpit displays.

The traffic information from the ADS-B reports is presented on a Cockpit Display of Traffic Information (CDTI). If a conflict is detected, the crew is alerted by auditory alarms. At the same time, special symbology on the CDTI indicates the conflicting traffic. Recommendations for an avoidance manoeuvre are presented visually. Dependent on the kind of recommendation, it can be shown on the CDTI (e.g., to present a new trajectory), or on the Primary Flight Display (PFD) (e.g., to indicate a desired speed) [8].

TCAS traffic information is presented on the Navigation Display (ND), whereas the required pitch angle or vertical speed is indicated on the PFD. The traffic is presented around the own aircraft in the centre of the ND. Special symbology is used to indicate aircraft issuing a TA or RA. This way, the ND is a kind of CDTI. When an RA is issued, the range of vertical speeds to be avoided is coloured red. A green area indicates the required vertical speed to avoid the collision.

THE USE OF ADS-B AND TCAS SURVEILLANCE DATA FUSION

An aircraft equipped with both an ASAS and TCAS has surveillance information available from two different sources: ADS-B reports and TCAS tracks. Although the information serves different purposes, it has to be investigated if a data fusion function that correlates and combines ADS-B and TCAS surveillance information could be useful to improve the overall system performance without decreasing the level of safety.

First, it is discussed if such a data fusion function is allowable in terms of safety. Next, several performance parameters are assessed to discuss whether the surveillance performance of the data fusion function with ADS-B and TCAS inputs is better compared to the surveillance performance of ADS-B alone.

	ASAS	TCAS
<i>Purpose</i>	Conflict avoidance	Collision avoidance
<i>Surveillance</i>	ADS-B <ul style="list-style-type: none"> ▪ All-to-all aircraft ▪ Automatic ▪ Dependent on target’s navigation system 	Own measurements <ul style="list-style-type: none"> ▪ One-to-one aircraft ▪ On interrogation ▪ Independent
<i>Logic</i>	<ul style="list-style-type: none"> ▪ Distance-to-go to the CPA ▪ Conflict detection about 10 to 20 minutes before the CPA 	<ul style="list-style-type: none"> ▪ Time-to-go to the CPA ▪ Traffic advisory is given 20 to 48 seconds before the CPA

	▪ Vertical collision avoidance manoeuvre
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Table 1: Overview of the ASAS and TCAS characteristics.

Performance is analysed in terms of:

- Accuracy,
- Integrity,
- Availability and continuity of service, and
- Coverage.

Is Data Fusion Allowable?

Before the use of ADS-B and TCAS surveillance data fusion is discussed, one should question if data fusion is allowable, considering the safety aspects of separation assurance and collision avoidance.

A requirement from the ASAS point of view is that there must be an independent backup system for ASAS failure. That is exactly what the TCAS is designed for: to prevent collision when the primary means of separation assurance has failed. This implies that the TCAS must be independent of the ASAS since a risk of collision implies a failure in the assurance of safe separation. It is assumed here that the TCAS independence is assured as long as it continues to make its own independent measurements and uses nothing but these measurements. Hence, the co-operation or data exchange between the surveillance functions of the ASAS and TCAS is limited to data transfer from the TCAS to the ASAS and not the other way around.

A second safety issue is that the output of the data fusion function may not be worse than the ADS-B report. The fusion has to be done in such manner that a wrong TCAS track does not affect the fused surveillance output report.

Accuracy

‘Accuracy is the degree of conformance between estimated or measured position ... of a platform and its true position (or velocity or time)’ [2].

TCAS is able to achieve an overall range measurement with a standard deviation not exceeding 50 feet. The TCAS bearing estimates have a standard deviation of less than 5 degrees and a peak error of less than 15 degrees [7]. The low bearing accuracy introduces a large uncertainty in the TCAS position that increases with range.

The position that is contained in the ADS-B report is derived from the target’s navigation system. The accuracy depends on the active source of navigation and is expressed in terms of a Navigation Uncertainty Category for the Position³ (NUC_p). The NUC_p is included in the ADS-B report. The error belonging to a certain NUC_p is described as the radius of a circle, centred on the estimated position, such that the probability that the actual value is within that circle is 0,95. The horizontal position errors for the different NUC_p are given in Table 2. In the ‘Comments’-column, the corresponding level of Required

Navigation Performance (RNP) or an example of a navigation source with the corresponding position error is given.

NUC_p	Horizontal position error (95%)	Comments
0	Unknown	No Integrity
1	<10 NM	RNP-10
2	< 5 NM	RNP-5
3	< 1 NM	RNP-1
4	< 0,5 NM	RNP-0,5
5	< 0,25 NM	DME-DME
6	< 0,1 NM	GPS-SPS
7	< 0,05 NM	GNSS (no SA)
8	< 10 m	GNSS with SBAS
9	< 3 m	GNSS with GBAS
...	to be defined	Future expansion

Table 2: Navigation Uncertainty Categories for the horizontal position error [6].

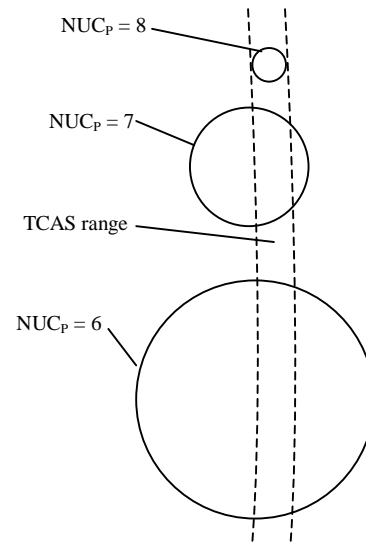


Figure 1: Illustration of the TCAS range accuracy, represented by the dashed ring-segment, compared with the ADS-B horizontal position error for different NUC_p values, represented by the 95% circles.

Figure 1 gives an indication of the ADS-B horizontal position error for different values of NUC_p in relation to the TCAS range error. When the TCAS range ring and the ADS-B circle intersect, there is a high probability that the actual position of the target is within the intersection. Especially at NUC_p values smaller than 7, where the ADS-B circle is rather large, TCAS can help to increase the ADS-B accuracy, so data fusion could be useful there.

Availability and Continuity of Service

‘Availability is the ability of a system to perform its required function at the initiation of the intended operation. The continuity of service is the probability of a system to

³ There are also NUCs for the vertical position, and horizontal and vertical speed.

perform its required function without unscheduled interruptions during the intended period of operations' [2].

The availability and continuity of service of a multiple data fusion function with several surveillance inputs will be better than that of a single data fusion function with only one input (ADS-B). When the surveillance source of the single data fusion function fails to give an error-free report, there is no surveillance output at all, while the multiple data fusion function still has inputs from other surveillance sources if one fails. However, in this particular case of ADS-B and TCAS data fusion, only TCAS information is fed into the data fusion function when there is an ADS-B failure. It is expected that the TCAS has insufficient accuracy – due to the bad bearing performance – to support any ASAS application on its own. Thus, ADS-B and TCAS data fusion can not improve the availability of a surveillance report for the purpose of airborne separation assurance.

Coverage

'Coverage is the operational geographic area (or volume) within which the system provides a service' [2].

The coverage of the ADS-B system depends on the equipage. For certain ASAS applications, a longer look-ahead time is necessary, requiring further coverage. For example, the fully autonomous mode requires further coverage than the station keeping procedure. Minimum operational ranges vary from 10 NM to 90 NM [6].

TCAS coverage depends on the traffic density. The nominal surveillance range is 14 NM [7].

Hence, aircraft that are beyond the ADS-B covering range are beyond the TCAS surveillance range as well, except for the minimum ADS-B equipage class. For separation assurance applications with a separation standard larger than 14 NM, TCAS can provide no help at all, because when the target is within the TCAS surveillance range, the separation is already lost. For some ASAS applications (such as fully autonomous conflict detection and resolution), TCAS data will come too late.

DATA TRANSFER ON THE LEVEL OF THE LOGIC FUNCTION

The ASAS and TCAS have their own logic function, each with the objective of detecting approaching traffic, though with different criteria. The alerts and advisories that are output by the TCAS and ASAS logic functions have to be consistent. The presentation of simultaneous alerts and advisories to the crew would lead to confusion in the cockpit, whether the presentations are contradictory or not. An ACAS operational evaluation [3] has shown that TCAS alerts are often triggered due to typical Air Traffic Control (ATC) clearances, such as for example aircraft levelling off 1000 feet above or below another aircraft. These alerts are mostly nuisance alerts. The same problem can occur when separation is assured with the ASAS.

To reduce the number of simultaneous and nuisance alerts in the cockpit, the ASAS and TCAS should communicate on the level of the logic function. The exchange of data between the logic functions of the TCAS and ASAS can be of great importance. Only two suggestions are made here.

To avoid simultaneous alerts, TCAS advisories could be input to the ASAS. The ASAS could then make sure no (long-term) ASAS alarms are given when a more urgent (short-term) TCAS advisory is present.

To reduce the number of nuisance alerts, it could be useful to include a simplified model of the TCAS algorithms in the ASAS logic function. The ASAS can then predict whenever the TCAS is likely to issue an advisory. This information should not be used to inhibit an ASAS manoeuvre, since valid manoeuvres can still generate an RA. Nevertheless, it can provide an additional selection criterion when choosing between several possible manoeuvres.

ASAS AND TCAS DATA PRESENTATION

The alerts and advisories that are issued by the ASAS and TCAS have to be presented to the crew. To find out what exactly should be presented and how, the following subsections describe a very simple analysis of the crew's tasks in response to an alert issued by the TCAS or ASAS.

Next, it is questioned where and how a TCAS advisory should be presented while the aircraft is in ASAS mode. Should the TCAS advisory be presented on the same CDTI as is used to present the ASAS information or should a separate CDTI be used?

Tasks in Response to a TCAS Advisory

The pilot is not allowed to manoeuvre in response to a TA only. An RA requires immediate pilot action. TCAS advisories are given maximum one minute prior to a potential collision. They call for very fast reactions from the crew and are often experienced as stressful. The alerts often come as a surprise. The crew may not hesitate and is aware that a mistake may lead to an accident.

In response to a TA, the pilot has to:

- Look outside for the threatening traffic (visual search).
- Decide whether to manoeuvre or not if an RA occurs.

To aid the pilot with the visual search for the fast approaching traffic, an indication of the relative position of the threat can be useful.

The TA is a warning that an RA may be coming up. It gives the crew time to decide whether to manoeuvre or not. By the time the RA is issued, this decision should already have been made to allow an immediate response to a potential RA. The pilots are recommended to follow an RA-trustful policy⁴. 'Pilots-in-command still have to

⁴ Following a trustful policy means that as long as it is not proven that a warning is incorrect, it is trusted. One must keep in mind that when the other aircraft is TCAS-equipped as well, the RA

exercise their best judgement and full authority in the choice of the best course of action to resolve a traffic conflict' [5]. It is shown that many pilots decide not to comply with the RA (26% of the reported events) [3]. Their decision can be based on the results of the visual search, extra information from the ground controller, or information on the system's reliability.

In response to an RA (whether the threatening traffic was visually acquired or not, unless of course it was decided not to follow the RA), the pilot has to:

- Decide upon the resolution manoeuvre (direction and magnitude of vertical speed).
- Turn off the autopilot.
- Take the appropriate actions for the manoeuvre.
- Monitor the manoeuvre.
- In a controlled airspace, inform the controller.

The pilot has insufficient traffic situation awareness to determine an appropriate resolution manoeuvre. Hence, it is calculated by the TCAS logic function and presented to the crew as a required vertical speed or pitch angle.

Tasks in Response to an ASAS Alert

An ASAS alert indicates a potential loss of safe separation within a time interval of several minutes. The attention of the crew has to be drawn to the conflict, but immediate countermeasure is not necessary. Again, the pilot's traffic situation awareness will be insufficient to determine an appropriate resolution manoeuvre.

When the ASAS issues a conflict detection alert, the pilot has to assess the traffic situation and be prepared for a conflict resolution alert that presents a recommended resolution manoeuvre that has to be initiated at an indicated time.

At the time of a conflict, the traffic situation should be presented on the CDTI. The relative position and identity of the conflicting traffic and an indication of who has priority may not be missing on the CDTI. Additionally, some other information such as the intent of the conflicting traffic and conflict and no-go zones⁵ can be presented.

TCAS Operation during an ASAS Application

The TCAS advisories are given maximum one minute prior to a potential collision and are therefore much more urgent than any ASAS alert. There must be a clear distinction between the aural and visual alerts of the TCAS and the ASAS, because they require different pilot responses.

When a TCAS advisory occurs, the pilots' performance in reaction to that advisory may not be affected by the ASAS

application. They should respond just as fast and accurate as they would if there was no ASAS procedure active.

On the other hand, TCAS advisories may not hide ASAS information. Because a pilot is not allowed to manoeuvre in response to a TA only, the ASAS procedure can continue when a TA occurs during an ASAS procedure, while a visual search for the threatening traffic is started. The presentation of the information required for the ASAS procedure may not be affected.

Finally, when a TA occurs, it is important to know for the pilot whether the advisory is related to the ASAS application or not.

The Presentation of a TCAS Advisory during an ASAS Application

During a TA, both ASAS and TCAS data have to be displayed to the pilots.

When two different CDTIs are used in the cockpit, the ASAS data presentation is not disturbed. However, attention has to be divided over the two displays. The TCAS and ASAS traffic information can not be compared, i.e., it is not clear if the TA is caused by an aircraft involved in the ASAS application. In addition, there is an extra time delay, because when scanning both CDTIs, the centre of the reference system has to be translated from the own aircraft position on the one CDTI to the own aircraft position on the other CDTI. Concluding, two CDTIs in the cockpit presenting different presentations of the traffic situation seem very confusing and time consuming.

If one CDTI is used, two aircraft positions are input that have to be correlated. This correlation can be done in the data fusion function. Most likely, the TCAS and ASAS position will differ. This could lead to an unacceptable cluttering of the display. The ASAS performance will be disturbed by the TCAS advisories, especially if the threat is involved in the ASAS application. In addition, it is in contrast with the philosophy that pilots should be provided with the best information available

If both systems are performing well, the difference between the ASAS and TCAS traffic information will not be visible on a display, and even if there is a small difference, it is still acceptable to use the ASAS traffic information to represent the TCAS advisories. Remember that for collision avoidance, the purpose of presenting the threatening traffic on a CDTI is to assist the pilot in the visual acquisition of the threat. It has to give an indication of the direction where to look for the threat and is therefore not bounded to narrow accuracy constraints.

In most cases, the output of the ASAS surveillance function or data fusion function will give a better estimate of an aircraft's position than the TCAS position because of its bad bearing performance. It is therefore suggested that only one CDTI is used, on which the surrounding traffic is presented by its ASAS position. When a TCAS advisory is

will be co-ordinated. Not following a co-ordinated RA can be very dangerous.

⁵ A conflict zone is an airspace zone that has to be avoided to avoid the present conflict. A no-go zone is an airspace zone that has to be avoided so that no conflicts with other aircraft are induced.

issued, the same ASAS position is used to indicate the relative position of the threat with a specific symbology. The only problem occurs when the difference between the TCAS and ASAS position is so large that it would result in a different search direction for the threat. In that case, one of the surveillance systems is most probably failing and this must be shown to the pilot. If the pilot can not visually acquire the threat because of this wrong search direction indication, it is not a disaster. Visual acquisition is not required for following an RA.

The Presentation of Traffic that is Not Involved in the ASAS or TCAS Operation

In this section, some advantages and disadvantages are given of presenting traffic on the CDTI that is not issuing any ASAS or TCAS alert.

If every target that is within a certain range of the own aircraft is presented, the crew will feel more comfortable in the airspace, now that they can see what is surrounding them. A flight crew often has more confidence in themselves than in the air traffic controllers on the ground. With the traffic information, they feel like they are more in control of their own aircraft. This comfortable and in-control feeling could lead to less mental workload in the cockpit. In addition, this presentation allows the crew to build up a 3-D picture of the surrounding traffic situation. With this improved traffic situation awareness, they may even foresee a conflict coming up. With the current plan view CDTIs, building up a 3-D representation of the traffic situation is not very easy. In addition, when a TCAS or ASAS alert is issued, the traffic that is not involved clutters the CDTI. The presentation of other traffic will disturb the perception of the relevant information. Experience with the current TCAS display shows that the presentation of traffic that is not issuing an alert can be annoying in controlled airspace. The improved traffic situation awareness in the cockpit can seriously increase the amount of radio-telephony communications and controller workload. 'Some pilots request information, or refuse a clearance, based upon aircraft data on the traffic display' [1].

To conclude, in some cases the presentation of traffic that is not issuing any alert is useful, while in other cases, it can be rather annoying. It is therefore suggested that the pilots are offered the choice to display non-relevant traffic or not.

Auditory Alerts for ASAS and TCAS

Both the ASAS and TCAS visual alerts are accompanied by aural alerts. As mentioned before, TCAS alerts are much more urgent than any ASAS alert. Therefore, the sound channel must be available for the possible RA. It is suggested that ASAS aural alerts are suppressed while a TCAS advisory is present.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that under certain conditions and for some ASAS applications, ADS-B and TCAS surveillance data

fusion can improve the performance of the airborne surveillance function.

In the assessment of the surveillance performance parameters, only fusion of the ADS-B horizontal position and TCAS range is considered. It has to be investigated if data fusion would be useful for the vertical position or velocity. Also the fusion of ADS-B reports with data coming from surveillance sources other than the TCAS has to be considered.

It is expected that data exchange on the level of the logic functions will be necessary to reduce the number of multiple and nuisance alerts. This should be the subject of further study.

Finally, it is recommended that only one CDTI is used to present ASAS and TCAS information. The ASAS plots then indicate the relative positions of the surrounding traffic and special TCAS symbology is used to indicate threatening traffic. Further, pilots should be offered the choice to de-clutter the display.

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ACRONYMS

ADS-B	Automatic Dependent Surveillance Broadcast
ASAS	Airborne Separation Assurance System
CDTI	Cockpit Display of Traffic Information

CPA	Closest Point of Approach
GBAS	Ground Based Augmentation System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
NM	Nautical Mile(s)
NUC _p	Position Navigation Uncertainty Category
RA	Resolution Advisory
RNP	Required Navigation Performance
SBAS	Space Based Augmentation System
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System