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FARADS - Technical Study of RA Downlink Methods

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Abstract

A study of all technical means for the downlink of ACAS RA information and to rank these techniques against evaluation criteria. Four candidate techniques were analysed in detail and several others in less depth. The four core techniques were: Mode S RA Report, RA Broadcast, ACAS Coordination Messages, and 1090 Extended Squitter.

Keywords

ACAS	Resolution Advisory	TCAS
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Mode S	RA Broadcast	
RA Report	ACAS coordination	

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The following table records the complete history of the successive editions of the present document.

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1.0	12/12/04	Initial release (Helios Technology)	All
1.1	3/1/2005	EUROCONTROL review	All
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1.3	4/5/2006	Modifications following review	20, 28, 43
1.4	14/05/2007	Added ALDA reference, formatting changes	All

CONTENTS

EXECUTIVE SUMMARY

This document is a study of techniques capable of supporting an ACAS Resolution Advisory (RA) downlink application. It has been produced for EUROCONTROL as part of the Feasibility of ACAS RA Downlink Study (FARADS).

The objective of this study is to examine all technical means for the downlink of ACAS RA information and to rank these techniques against evaluation criteria. The purpose of the downlink is to display information about the RA to the controller whilst the RA is in progress.

Four candidate techniques were analysed in detail and several others in less depth. The four core techniques were:

- Mode S RA Report: the extraction by a Mode S ground radar of a Comm-B message containing data about the RA from BDS 3,0.

- RA Broadcast: the spontaneous broadcast on 1030 MHz of ACAS RA data, repeated every 8 seconds or on RA change.

- ACAS Coordination Messages: air to air messages between aircraft coordinating their RAs.

- 1090 Extended Squitter: an event driven spontaneous broadcast of RA information using an extended squitter format.

The core solutions were compared against several evaluation criteria, prime among these being the time delay between the RA occurring on the aircraft and being successfully presented to the controller. The airborne and ground cost, reliability and message data content were also of high priority. Deployment timescales and the need for changes to SARPs and MOPS were considered to be of lesser importance.

The core techniques all fulfilled at least some of the criteria. Mode S RA Reports and 1090 ES were found to meet most of the criteria. It was concluded that:

- In areas covered by a Mode S ground infrastructure, Mode S RA Reports is the best method for RA downlink.

- In areas not covered by a Mode S ground infrastructure, 1090 ES is the best method for RA downlink assuming it can be economically implemented as part of an ADS-B system.

The other two techniques were not recommended:

- ACAS coordination messages: these are unsuitable as the target aircraft is not identified in the messages, they can only be used to detect less than 70% of ACAS conflicts and their detection on the ground has a low probability.

- RA Broadcast: these are unsuitable as the target aircraft is only identified by its Mode A code, the latency is too long in the worse case scenario and the intruder aircraft is not identified.

The study recommendations are that:

- Modifications should be undertaken to some ACAS/Mode S avionics to ensure consistent, correct operation of RA reports. SARPs should also be clarified.

- The 1090 ES message should be incorporated into the appropriate SARPs/MOPS.

- Co-ordination should be maintained with ADS-B implementation programs to ensure RA Downlink implementation happens in parallel with ADS-B.

- Further work is required to validate the requirement for maximum latency of 10 seconds.

1. INTRODUCTION

1.1 General

This document has been prepared by Helios Technology Ltd and presents an analysis of technical means for communicating ACAS RA information to an ATC centre on the ground. The document has been developed in support of the EUROCONTROL FARADS project.

1.2 ACAS

1.2.1 Introduction

The safe flow of air traffic requires close cooperation between flight crew and controllers. This cooperation becomes particularly crucial if, for whatever reason, the separation between two aircraft is lost and urgent steps are needed to prevent a potential collision.

1.2.2 Flight crew and ACAS

Flight crews on many aircraft have an Airborne Collision Avoidance System (ACAS), to help them avoid collisions. The implementation of ACAS is commonly referred to as TCAS – Traffic Alert and Collision Avoidance System.

ACAS is intended to improve air safety by acting as a 'last-resort' method of preventing mid-air collisions or near collisions, between aircraft. ACAS produces vertical collision avoidance advice in Resolution Advisory (RA) messages and displays it to the flight crew 15 to 35 seconds in advance of potential collisions. RAs instruct the flight crew to manoeuvre the aircraft vertically. ACAS RAs are automatically coordinated between the aircraft involved if both are suitably equipped.

By utilising Secondary Surveillance Radar (SSR) technology, ACAS equipment operates independently of ground-based aids and ATC. Aircraft equipped with ACAS have the ability to monitor other aircraft in the vicinity and assess the risk of collision by interrogating airborne transponders. Aircraft without active transponders are not detected.

The present implementation of ACAS is the ACAS II standard, and it is this standard that is discussed in this report.

1.2.3 Potential for controllers to use ACAS information using downlink

Currently, air traffic controllers are only made aware of ACAS RAs when and if flight crews give them radio notification. Hence, controllers' situational awareness may be diminished if an aircraft departs from its clearance as the result of an RA, if the flight crew has not communicated this fact reasonably quickly.

However, whenever an RA is generated in the cockpit, the aircraft's transponder provides detailed information about the nature of the RA, which could be downlinked to ground ATC for display on Controller Working Positions (CWP). The feasibility of doing so is being addressed by the EUROCONTROL FARADS (Feasibility of ACAS RA Downlink Study) study.

1.3 Description of FARADS

The high level European Action Group on ATM Safety (AGAS) [1] recommended a study to determine feasibility of downlinking ACAS RAs for display on controller screens. This led to the launch of FARADS the: 'Feasibility of ACAS Resolution Advisory Downlink Study'.

The objective of the Feasibility of ACAS RA Downlink Study (FARADS) is to assess the technical and operational feasibility of displaying ACAS RA information on CWP.

Some initial experiments have been conducted with the aim, among other things, of obtaining controller's views on potential different implementations of the RA Downlink concept. These experiments showed that the majority of controllers saw clear operational benefits, including:

- Improved air traffic controller situational awareness by helping them to anticipate aircraft manoeuvres.
- Reduced likelihood of contradictory ATC clearances to the conflict aircraft.
- Reduced risk of follow-up conflicts through better information and planning following the resolution advisory.

Whilst considering these benefits, a number of limitations were also recognised.

Whist RA Downlink may be technically feasible, it is important that its use is carefully validated prior to implementation. Such validation should include examination of many issues, including:

- Evaluation of different technologies;
- Safety impact;
- Evaluation of different procedural options;

- Human factors assessment of different display options.

FARADS have planned a number of studies to address these issues.

1.4 Technical study of RA Downlink methods

1.4.1 Purpose of the study

This technical study of RA Downlink methods should propose one or several suitable technologies for the downlink of ACAS RA information to the ATC centre.

The study shall take account of agreed criteria against which to assess the different technical options.

1.4.2 Assumptions

The proposed technical evaluation is applicable to European Civil Aviation Conference (ECAC) states.

Latency is considered to be zero on the aircraft (as soon as the RA coordination occurs the information is available in the BDS registers). It is estimated time from the aircraft to an ATC centre.

1.4.3 Terminology

The aircraft undergoing the RA and transmitting this information to the ground is referred to as the *target aircraft*,

The aircraft which the RA on the target aircraft is being generated against is called the *intruder aircraft*.

RA Downlink is the application of downlinking ACAS RA information to the controller, various technologies can support this application.

1.4.4 Introduction to the primary candidates

Four primary candidates have been identified for the downlink of TCAS RA information. These have been chosen as they are the most feasible, use proven technologies, are relatively cheap to implement and three of the four have already been mandated.

The methods are:

- Mode S RA Report: the downlinking of information from the aircraft in reply to an interrogating Mode S SSR radar station.
- RA Broadcast: the downlinking of ACAS RA information using a 1030 MHz message to a passive ground network.

- ACAS Coordination messages: the interception by a passive ground network of the ACAS resolution message and its coordination reply between two aircraft coordinating their RAs.
- 1090 Extended squitter: the broadcast of an event driven extended squitter message containing RA information to a passive ground network.

1.4.5 Document structure

The structure of this document is as follows:

- Section 2 provides a description of the evaluation criteria for the comparison of the candidate technologies. It also provides the rational for the prioritisation of criteria.
- Section 3 provides a description of the core solutions.
    - Mode S RA Report;
    - RA Broadcast (1030 MHz);
    - ACAS Coordination Messages;
    - 1090 Extended Squitter.
- Section 4 provides an evaluation of the core solutions against the evaluation criteria.
- Section 5 provides a summary of the evaluation, conclusions and recommendations.
- Annex A contains the references and provides a short review of each important reference on RA Downlink.
- Annex B provides a detailed review of the four core technologies, including a breakdown of their message structures.
- Annex C includes a detailed account of the Mode S receiver experiment.
- Annex D provides the details of the Helios Mode S FRUIT Model and its application to estimate probability of successful message reception.
- Annex E provides a detailed description of the latency calculations.
- Annex F provides a cost projection of a passive ground network.
- Annex G provides details on 1090 Extended Squitter Airborne Costs
- Annex H provides details of the expected 2015 ECAC coverage of Mode S.
- Annex I provides details of simulations done using the INCAS tool.

- Annex J details alternative datalink technologies that have not been considered as realistic options for RA Downlink.

2. EVALUATION CRITERIA

2.1 Introduction

This section describes the technical, operational and business criteria used in the assessment.

2.2 Technical criteria

The technical criteria used in the determination of the most suitable technology cover several areas. Primarily these are a consideration of the data content available from each technology, but also an indication of its maturity and an analysis of the quality of service.

2.2.1 Data content in messages

The quantity and integrity of information available in an RA downlink differs according to the technology chosen. RA information can take various forms, from a flag to indicate the aircraft is undergoing an RA to a full report containing details of the RA and intruder aircraft.

The exact makeup of the required data content is dependent on the requirements of the operational concept. The primary differentiators are the availability of information on the intruder aircraft, and the means of identification of the target aircraft.

The identity of the target aircraft is a high priority requirement as the aircraft undergoing the RA should be identified in a reliable and unique manner on the controllers screen.

The identity of the intruder aircraft is a medium priority requirement. For the controller to have knowledge of the aircraft the RA is being generated against may prove operationally useful. This requires further study.

The availability of an aircraft altitude or mode A code (in addition to a 24-bit address) is not a significant factor and provides no advantage for one technology over another. This information should already be available through traditional surveillance.

2.2.2 Quality of service (reliability)

The quality of service expected from the chosen technology should be sufficient to allow RA downlink to be a useful and reliable aid to the controller. Working figures have been supplied by EUROCONTROL [8] for the minimum performance of the system. These would permit:

- False negatives, i.e. an RA occurs on the aircraft but it is not successfully downlinked to the ground within a reasonable time, may have a maximum 5% probability. False negatives are analogous to the status quo, where no RA Downlink exists.

- False positives, i.e. an RA is reported at the controllers screen but did not occur, may have a maximum 1% probability. This is a more serious event, as it could cause ambiguity about who has responsibility for separation.

2.3 Business criteria

The Business criteria presented in this document were established for evaluation purposes and are not intended to replace a full Business Cost Analysis.

2.3.1 Aircraft equipage costs

It is a requirement [7] that no changes should be necessary to aircraft equipment specifically to allow RA Downlink. The exception to this is if a technology is being implemented for other purposes, which facilitates RA Downlink 'for free'. Any minor change, e.g. a software upgrade should be discussed and costed.

To minimise any additional aircraft equipage costs is therefore a high priority criteria. Significant aircraft equipage costs would make an RA Downlink application uneconomic.

2.3.2 Ground costs

The existence of a current ground infrastructure should be considered an advantage for RA Downlink. For regions without a suitable ground infrastructure in place, the cost, timescales and design of a suitable ground infrastructure should be discussed.

The possible cost of implementing a ground infrastructure is a high priority criterion; any significant ground equipage costs may make an RA Downlink application uneconomic.

2.4 Operational criteria

2.4.1 Latency

Latency is a high priority criterion, in order to be operationally useful to the controller, the information available on the CWP should be as recent as possible. A significant delay could result in the nature of the RA changing before the information is downlinked. A short latency would maintain a controller confidence in the information being displayed.

Latency is defined as the delay between the ACAS resolution advisory coordination being detected by the ACAS system onboard the aircraft and being successfully downlinked to an ATC centre. In order for the RA downlink to be most useful, this delay must be minimised.

Some aspects of latency are common to all technologies:

- Delay in the aircraft before transmitting the RA;
- Ground station processing time;
- Transmission through the ground network;
- ATC centre processing time;
- CWP refresh rate.

The latency shall only be considered to an ATC centre. It shall not be concerned with internal processing within the ATC centre, the refresh rate on the controllers screen or the controller reaction speeds.

The latency should be as short as possible. For this study it was to be within 10 seconds [7]. EUROCONTROL have chosen 10 seconds as a reasonable time within which the downlink should be successful. This figure has also been used within the wider FARADS project. However, further validation of it may be required.

The latency is expressed as a 95% downlink time. This 95% is the time at which, if 100 RAs were to randomly go off, and their actual time of first emission was subtracted from their time of arrival at the ATC centre, and these times then ranked from shortest to longest, the time of arrival of the 95^{th} message. The 10 second limit applies to the 95% time.

Figure 1 illustrates the concept of 95% downlink in the context of a single Mode S rotating radar. The timescale has been drawn in terms of the rotation period of the radar. It shows that for this example, while the majority of RAs were received within one rotation, three were required to reach a 95% level.

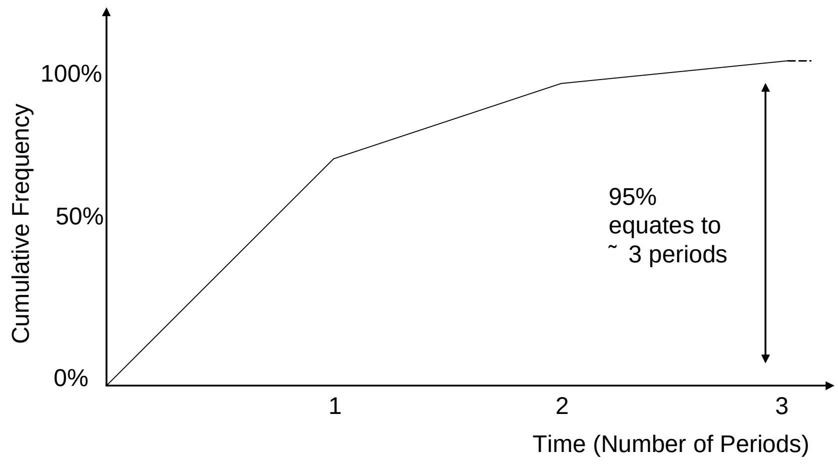

Figure 1: A graph illustrating the concept of 95% downlink time

2.4.2 Different solutions for different operating environments

The solution or combination of solutions should support RA downlink for the entire ECAC region. However, the chosen solution may be different in different geographical regions or in different types of airspace.

2.4.3 Changes to SARPs and MOPS

Changes to SARPs and MOPS shall be kept to a minimum and any changes required would be a disadvantage to the technology in question. This disadvantage is primarily due to the extended timescales such a change would entail.

Changes to SARPs and MOPS are medium priority criteria. Any changes would result in a delay to the implementation of the RA downlink application. The expected timescale to a full implementation of RA Downlink is sufficiently long that a small delay in implementation is not a serious disadvantage to the chosen technology.

2.5 Review of evaluation criteria

In discussion with EUROCONTROL [8] a prioritisation of these evaluation criteria was developed. The overall list and ranking of evaluation criteria is therefore summarised in the table below.

Priority	Evaluation Criteria
High	Latency, as short as possible but must be <10s (95%)
	Cost (Air and ground)
	Reliability (less than 1% false RA)
	Completeness (Reports of conflicts with Mode A/C aircraft)
	Identification of target aircraft
Medium	Deployment timescales (Air and ground, changes to SARPS/MOPS)
	Data content, identity of intruder aircraft
Low	Availability of Mode A code/altitude within message

Table 1: Summary of evaluation criteria and their priorities

3. CANDIDATE TECHNOLOGIES

3.1 Introduction

This section describes the candidate datalink technologies of Mode S RA Report, RA Broadcast, ACAS co-ordination and 1090 Extended Squitter.

A description of alternative datalink technologies is provided in Annex J. These are technologies that could support an RA Downlink application but are not considered realistic candidates. The reasons for their rejection are detailed in the annex.

3.2 Mode S

Mode S is an evolution of classical SSR radar which solves several problems currently present in the European surveillance environment.

The primary benefits of Mode S are:

- Selective interrogation to reduce the FRUIT and garbling problems inherent in conventional SSR.
- The long term elimination of Mode A code shortages.
- An integrated datalink capability.
- More precise (25 ft instead of 100 ft) altitude reporting.
- By design, Mode S is compatible with ACAS and conventional SSR.
- Mode S is already internationally standardised by ICAO.

At present, the UK, France, Germany, The Netherlands, Belgium, Luxembourg, Switzerland and Denmark have plans to implement Mode S surveillance. Successful operation of Mode S surveillance requires a ground infrastructure of rotating beam Mode S radars and also aircraft to be equipped with a suitable transponder. Several ECAC countries have mandated Mode S equipage [13], [14] and several more have plans to do so.

The ability to downlink ACAS RA information is one of the data link protocols built into the Mode S standard. The downlinked message is referred to as an RA Report [2], [9] and is defined in the ICAO SARPS [2]. It is a requirement of the ACAS II mandate that all ACAS II equipped aircraft shall be able to transmit this message [8]. It is also independently a requirement of some ECAC states Mode S mandates [13].

The extraction of the RA report is in several stages. The stages and message formats are discussed in detail in Annex B and summarised in the following table.

1	The aircraft's ACAS system determines it is undergoing an RA and uploads appropriate data to the BDS 3,0 register.
2	The aircraft sets a flag in its normal Mode S roll call reply indicating it has an RA report available.
3	The ground radar interrogates the aircraft to obtain normal surveillance information using a roll call interrogation.
4	The aircraft replies with a surveillance reply, including the flag specifying that an RA report is available.
5	The ground radar, upon receipt of the reply, recognises the flag and re-interrogates requesting the aircraft to reply with an RA report.
6	The aircraft replies with the RA report.

Table 2: Extraction of a mode S RA report

To extract an RA Report over Mode S, two transactions must be successful. These will normally both be carried out while the aircraft is still in the beamwidth.

The diagram below is an illustrative demonstration of the extraction of an RA Report.

- The two aircraft both generate an RA as they travel towards each other.

- Some time later (shown here for example at 6 seconds), the Mode S radar passes over the aircraft.

- The radar performs two interrogation/reply transactions with each aircraft (8 transmissions in total). These transactions occur over a very short period of time, within one beamdwell, which assuming a 3° beamwidth and 8 second radar rotation period is 0.06s.

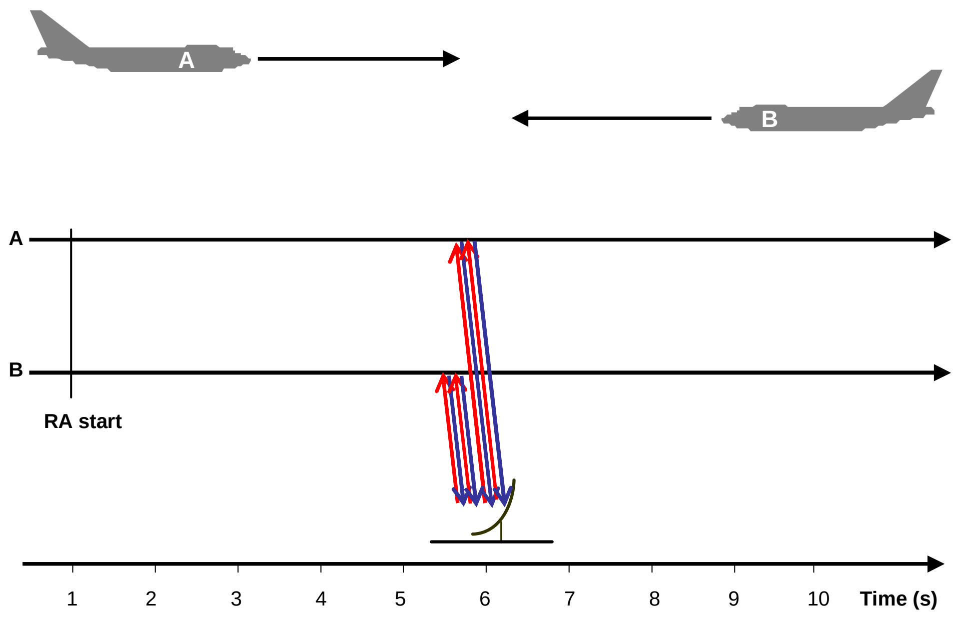

Figure 2: An illustrative diagram showing the downlink of an RA Report

The transmitted RA report contains details of the RA, details of the intruder aircraft and identifies both the target and intruder aircraft by their 24-bit addresses. The target aircraft's Mode A address is also available.

It has been assumed that the RA Report is made available as soon as the RA is determined onboard the aircraft. **One avionic manufacturer has implemented a design where the RA report is only available after the RA has terminated.** It has been suggested [21] that the SARPs are ambiguous on this point. Such an implementation would have to be changed to make Mode S RA Report a viable technological solution.

The downlink of RA reports over Mode S is a proven technology with several long term trials investigating its usefulness [22],[23],[24],[25]. At present a radar based at Gatwick airport, UK and run by the UK National Air Traffic Services (NATS) is continuing to extract RA reports from aircraft over the South of the UK. These reports are discussed later in the context of INCAS simulations and the Helios Mode S passive receiver experiment.

3.3 RA broadcast (1030 MHz)

The ACAS SARPS [2] define a resolution advisory broadcast, transmitted from the bottom antenna at full power on 1030 MHz. This broadcast is mandated as part of the ACAS II mandate [8], [15] and should be transmitted by all ACAS II equipped aircraft.

RA Broadcast was envisaged to allow ACAS RA activity to be monitored in areas where Mode S ground station surveillance coverage does not exist by using special RA broadcast signal receivers on the ground. However, at present, no ground infrastructure exists, or is intended for the detection of RA broadcasts.

Detection of RA broadcasts would require a passive ground network connected to an ATC centre. This passive ground network would have to be able to receive messages on 1030 MHz. To be interoperable with a possible future 1090 Extended Squitter ground network dual band 1030 MHz / 1090 MHz receivers would be necessary.

The RA Broadcast functionality was designed for monitoring purposes and is untested in operational circumstances. The RA broadcast is presently specified to repeat (with a jitter) approximately every 8 seconds. It is also transmitted whenever the RA changes.

RA broadcast is an untried technology, although it is mandated, no trials are presently known in which a complete analysis of the technology has been performed. Indeed, the experiment undertaken as part of this study to investigate the reception of RA downlink over the various technologies is the first known trial of RA Broadcast.

The diagram below gives an illustrative picture of RA Broadcast

- The two aircraft generate an RA at approx 1.5 seconds as the aircraft travel towards each other.

- Both aircraft transmit the RA Broadcast upon the initial generation of the RA.

- Eight second later the aircraft both retransmit the RA broadcast.

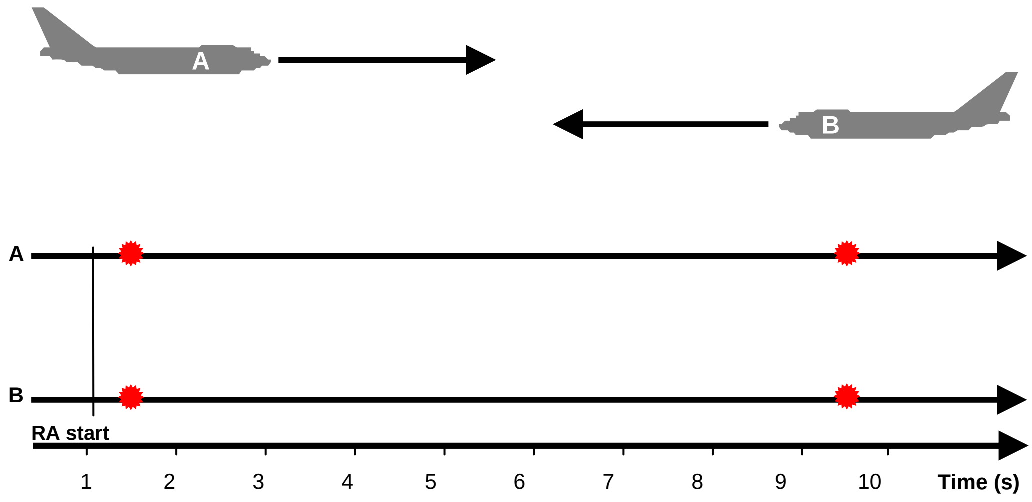

Figure 3: An illustrative diagrams showing an RA Broadcast

The RA Broadcast does not require any interrogation by the ground and details of the RA are spontaneously broadcast by the aircraft, it is therefore in some ways simpler than the RA report.

The ACAS information available from the RA Broadcast contains details of the RA occurring for the target aircraft. It contains no information on the intruder and it identifies the target aircraft only by its Mode A code.

It has been assumed that the RA Broadcast begins to transmit upon initiation of the RA onboard the aircraft. It has been suggested [26] that the SARPs are ambiguous on this point and can be interpreted to imply the RA Broadcast should only be transmitted after the RA has terminated. This would need to be addressed. **A detailed analysis of current RA Broadcast implementations is needed before it could be used operationally.**

3.4 ACAS Coordination

The normal operation of ACAS is performed by air–air interrogations and replies on 1030 MHz and 1090 MHz respectively. These interrogations and replies provide information to the ACAS system on the distance, bearing and altitude of other Mode A/C and Mode S / ACAS equipped in its neighbourhood.

These transmissions are made on either the (normally directional) top antenna or the (normally omnidirectional) bottom antenna. The choice of antenna is made automatically by the system depending on the location of the aircraft with which it is communicating and the best signal strength.

If the ACAS system determines that another aircraft poses a threat it does one of two things:

- If the intruder is either not operating ACAS, or operating in TA only mode, the target aircraft's ACAS generates an RA to the pilot.
- If the intruder is operating ACAS and is capable of generating RAs then the two ACAS systems coordinate their resolution advisories to ensure they are compatible.

Assuming the latter, that both parties are operating ACAS in RA mode then the final communications between them ensuring their RAs are compatible are called ACAS coordination messages.

The first aircraft to detect a threat transmits a resolution message on 1030 MHz advising the other aircraft that it has issued an RA and its intended course of avoidance. The other aircraft replies with a coordination reply on 1090 MHz. This is shown in Figure 3.

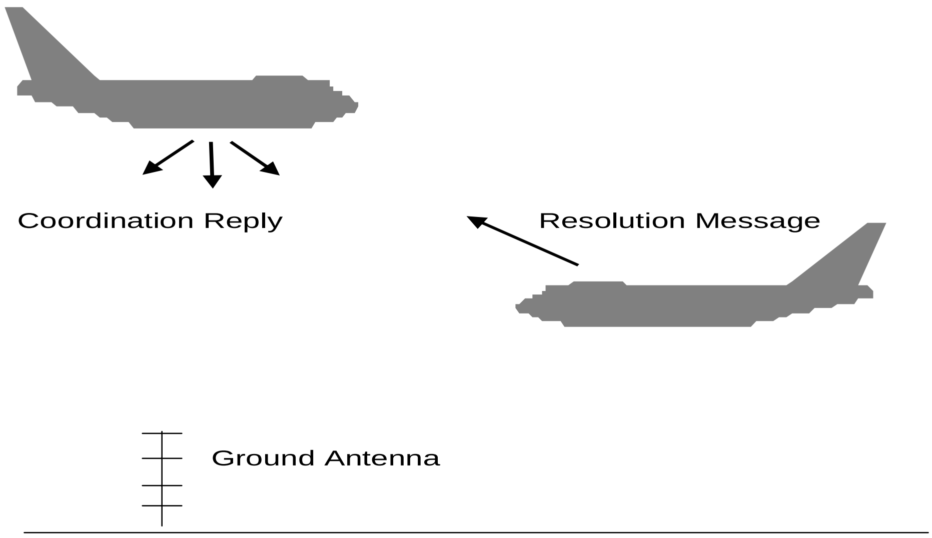

Figure 3: ACAS Resolution Messages and Coordination Replies

All current aircraft equipped with ACAS already transmit these messages in the normal use of ACAS, hence no additional airborne infrastructure would be required. These messages are, however, defined for air-air communications and ACAS typically uses a directional antenna, hence the reliable detection of these messages on the ground cannot be assumed.

Figure 3 demonstrates a possible problem with the detection of ACAS resolution messages. While the passive ground network is likely to be able to receive the coordination reply from the omni directional bottom antenna, it is unlikely to be possible to receive the resolution message from the directional top antenna.

At present a ground infrastructure does not exist for the reception of ACAS coordination messages. Aircraft are identified in these messages by their ICAO 24-bit addresses, therefore any ground infrastructure would also need to be able to interpret these addresses and correctly assign these to the aircraft display on operators' screens. This would be typical for infrastructures designed for Mode S radar but cannot be assumed for older systems. The 24-bit addresses are also encoded within an address-parity field and extraction of the address is not a trivial exercise.

Obviously these coordination messages are only transmitted if both aircraft are ACAS II equipped and running in RA mode, if one or both aircraft are not then no coordination messages will exist. At present approximately 80% of aircraft flying IFR in ECAC are operating TCAS II [7]. In the long-term, the figure may rise to about 85%.

Figure 4 shows a timeline for a typical series of ACAS coordination messages, the aircraft coordinate every second. The diagram assumes they are both generating an RA.

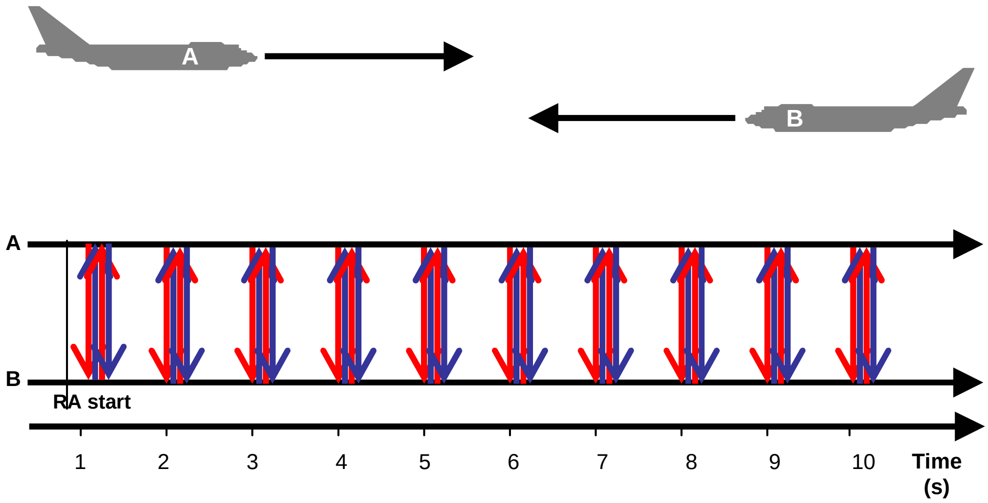

Figure 4: An illustrative diagram of ACAS coordination messages

An individual series of exchanges are detailed below in Figure 5. Two exchanges are shown. Aircraft A sends a resolution message to which aircraft B replies. Some time later, aircraft B sends a resolution message to which aircraft A replies.

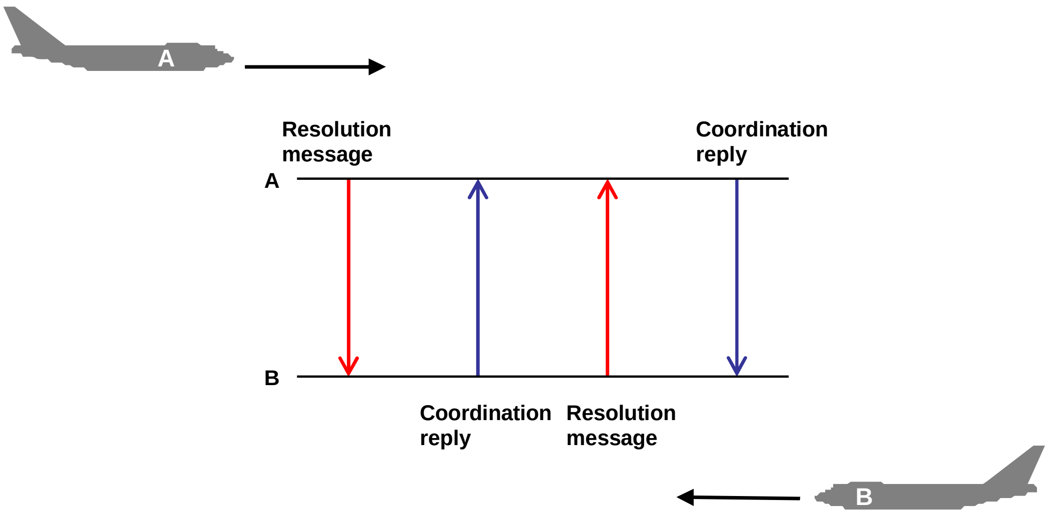

Figure 5: An illustrative diagram of ACAS coordination messages extracting the first two exchanges from Figure 4

3.5 1090 Extended Squitter

1090 Extended Squitter (1090ES) is an ADS-B technology primarily intended to periodically broadcast aircraft position, velocity and other aircraft parameters. It also has the ability to broadcast event driven data, and it would be using this technique that RAs would be transmitted.

At present, limited ground infrastructure exists for the detection and use of 1090 ES messages. However this is likely to improve with the expected deployment of ADS-B package 1. Hence the equipage of 1090 ES for ADS-B applications may provide an enabler for using 1090 ES to transmit ACAS RA's. In addition, multilateration infrastructure may be suitable to receive RA's transmitted using 1090 ES.

At present, no specific resolution advisory message is defined in the appropriate SARPs, and additional message formats would have to be considered and developed. A proposed message format has been suggested at the RTCA Special Committee 186 [16]. This message format is assumed for the analysis of 1090 ES in this report. A more detailed description and analysis of reception probability is provided in [18].

The proposed message uses the extended squitter aircraft status (emergency/priority status) message format. The RA information comes from the same MB field as used in the Mode S RA Report format message and would have the same data content.

The proposed message would be transmitted once per second. Typically 1090 ES messages are transmitted alternately from the top and bottom antennas. Reference [16] does not specify the antenna choice. It has been agreed [8] that these will be assumed to be transmitted once per second from the bottom antenna for the purpose of this study.

In the 1090 ES message, the target aircraft is only identified using its 24-bit address, information on the intruder is also provided using its 24-bit address, or its altitude, bearing and range.

Figure 6 below shows a timeline for a typical RA event with information downlinked over 1090 ES, both aircraft detect the RA at 1 second[1] and immediately transmit their 1090 ES RA message. Both aircraft then retransmit this message once per second for the duration of the RA.

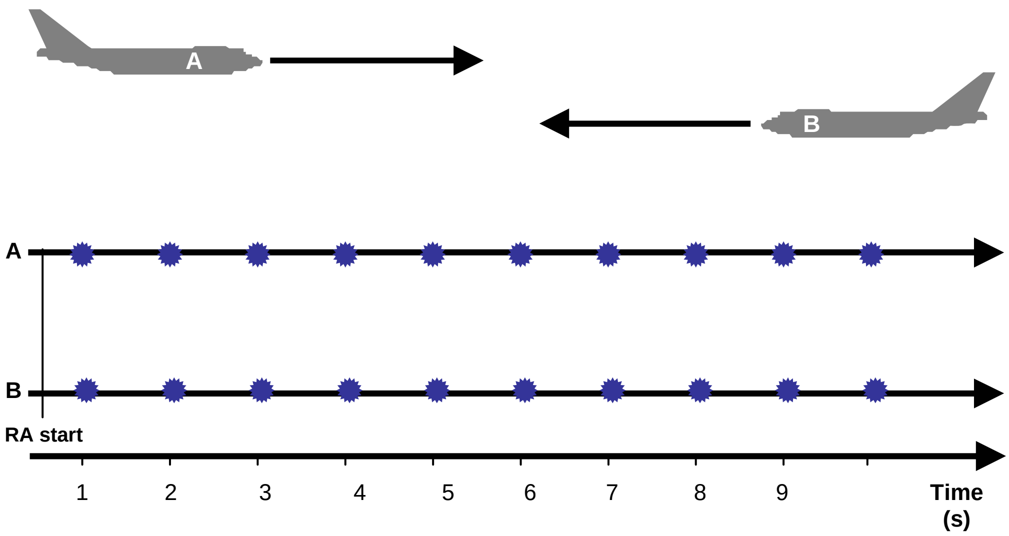

Figure 6: An illustrative diagram of 1090ES RA downlink messages

3.6 Interactions between ACAS and Mode A/C aircraft

The diagrams above all describe the interactions between two ACAS equipped aircraft. In Figure 7 below, an encounter between an ACAS equipped aircraft and a Mode A/C aircraft is described.

The ACAS equipped aircraft continues to send RA Broadcasts, extended squitters and has an RA Report extracted. However, no ACAS coordination messages are exchanged between the aircraft.

[1] If RA squitters are used for RA downlink, it should be possible to increase their frequency to meet tighter latency requirements.

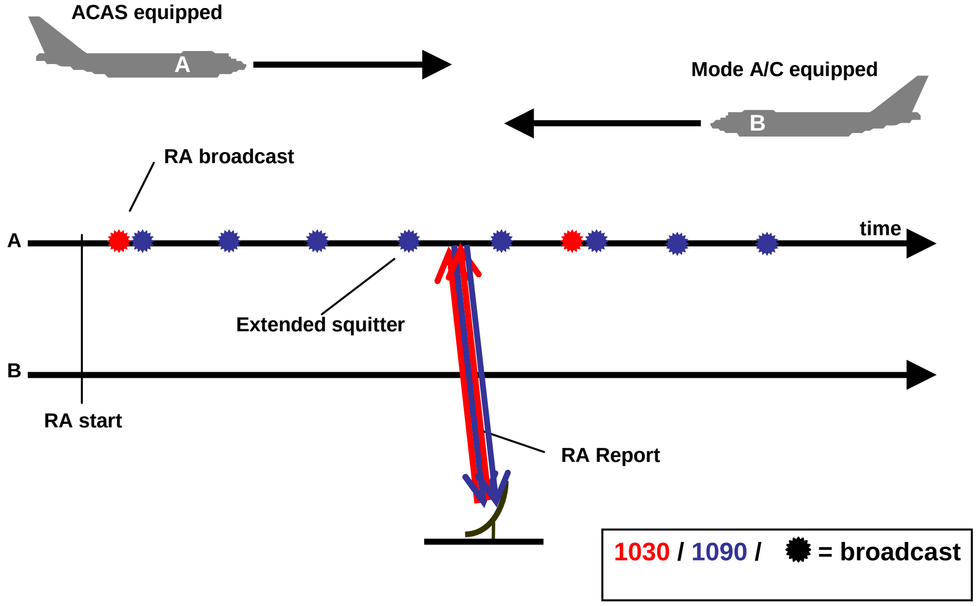

Figure 7: A diagram showing RA downlink over the different core technologies in the case of an ACAS equipped aircraft in an encounter with a Mode A/C equipped aircraft

3.7 Alternative technologies

Alternative technologies are detailed in Annex I, these are Data in Voice, ACARS, VDL modes 2/3/4 and UAT. These have not been studied in detail as they all fail a major evaluation criterion.

4. ANALYSIS OF TECHNOLOGY AGAINST CRITERIA

In this section, each candidate technology is compared with the criteria.

4.1 Technical

4.1.1 Data content in messages

The data content available from each message format is analysed in detail in Annex B, as summarised in Table 4.

Information	Mode S	RA Broadcast	ACAS Coordination uplink	ACAS Coordination down-link	1090 ES
24 bit address of aircraft	Yes				Yes
Mode A identity code (ID)	If DL 21	Yes			
Altitude Code (AC)	If DL 20	Yes		Yes	
Address-Parity (AP)	Yes	Yes		Yes	
Active Resolution Advisory (ARA)	Yes	Yes		Yes	Yes
Resolution advisory complement (RAC)	Yes	Yes		Yes	Yes
RA Terminated (RAT)	Yes	Yes		Yes	Yes
Multiple threat encounter (MTE)	Yes	Yes		Yes	Yes
Threat type indicator (TTI)	Yes				Yes
Threat type identity (TID)	Yes				Yes
Flight Status (FS)	Yes			Yes	
Multiple Threat Bit			Yes		
Cancel vertical RAC			Yes		
Vertical RAC			Yes		
ACAS Capability or Max Airspeed				Yes	
Parity (Pi)					Yes

Note: unused horizontal RAC fields not shown.

Table 4: Information content available from RA Report, RA Broadcast, ACAS Coordination and 1090 ES RA downlink

4.1.1.1 Fields relating to the RA

It can be seen that much of the same information is available from all the candidates. The important ARA, RAC, RAT and MTE fields specifying the details of the RA are identical between all 4 major technologies.

The ARA field specifies the details of the RA, e.g. the upward/downward, preventive/corrective, sense reversals. The content of the ARA field is subtly different for the case of multiple intruders but this is true for all technologies. The RAC field details the resolution advisory complement, i.e. the instruction from the intruder aircraft, the choice of RA will have been made to be consistent with the RAC. For multiple intruders this is the most recent RAC. The MTE field specifies if only one or more than one intruder is causing the RA. The RAT field specifies if the RA has been terminated or is currently occurring.

4.1.1.2 Fields identifying the target

There are some important differences in other information available from the messages. The target aircraft is identified in a variety of different ways. For Mode S RA Report and 1090 ES the target aircraft is identified via the aircraft's 24-bit address. The aircraft's Mode A code is also available as part of the RA Report if requested.

The aircraft's Mode A code is the sole means of identification in an RA Broadcast message. In the future, some States may stop using unique Mode A codes when they have Mode S fully implemented. In this case RA Broadcast would be an unsuitable technology for RA Downlink.

ACAS Coordination messages do not contain a 24-bit address in plain sight nor a Mode A code. Instead the 24-bit address is contained in the address-parity field, i.e. overlaid with parity information used for error checking the message. To decode the 24-bit address and parity information, the receiver must first know the 24-bit address of the aircraft. A passive receiver network therefore would have to know the addresses of all aircraft in its neighbourhood and try each one in turn attempting to decode the message. This is possible, e.g. by listening for one of the messages that contain the 24-bit address in plain sight. Note that the target and intruder 24-bit addresses are contained in different messages (the uplink and downlink ones) so both would need to be received to obtain both addresses.

Identification of the target aircraft is an essential element of the RA Downlink concept. Only Mode S RA Reports and 1090 ES provide a reliable and complete identification via the 24-bit address. The RA Broadcast is only suitable where the Mode A code is used to identify aircraft, which may not always be the case always in the future.

4.1.1.3 Fields identifying the intruder

Mode S RA Reports and 1090 ES messages identify the intruder aircraft (or most recent intruder in multi-aircraft encounters). This information is contained in the TTI and TID fields of the downlink messages. If the intruder is TCAS or Mode S equipped it is identified via its 24-bit address, otherwise it is identified by its altitude, range and bearing.

RA Broadcast messages provide no information on the intruder.

ACAS coordination messages provide no explicit information on the intruder. A 24-bit address could possibly be determined using the method outlined above but this would be complicated.

Identification of the intruder has been identified as an important element of RA Downlink as detailed in [17]. Only Mode S RA Reports and 1090 ES message formats contain sufficient information to satisfy this criterion.

4.1.1.4 Other available information

Some other information is available from some of the messages, ie data such as current altitude, the aircraft's Mode A code (in addition to its Mode S code) or maximum airspeed. This data is superfluous to the requirements of RA Downlink and does not represent an obvious benefit for any of the four primary candidates.

4.1.2 Quality of service

The chosen method of RA Downlink should exhibit a minimum quality of service as outlined in Section 2.2.2. This is a difficult parameter to fully analyse without thorough experimentation but several elements are considered here: the number of erroneous reports and availability of information from different types of encounter. Latency is considered in Section 4.3.1.

The number of erroneous reports to the ground should not differ significantly between the technologies. All technologies have a degree of error identification and correction included in their message formats which minimise the possibility of inaccurate reporting to the ground.

ACAS coordination messages have a particularly strong degree of error checking especially in the resolution message in which the vertical sense bits provide a secondary layer of protection.

The availability of information from different types of encounter varies between techniques. RA co-ordination messages are generated between ACAS II equipped aircraft (about 80% of aircraft flying IFR in ECAC [7]) and operating in RA mode. RAs are still generated against mode A/C aircraft, although no coordination messages are transmitted. Therefore the proportion of ACAS encounters (assuming a single intruder) in which ACAS coordination messages are transmitted is only 67%.

These coordination messages are transmitted from either the top or bottom antenna as discussed previously. Therefore reliable detection by a ground network may not be possible and this is being addressed in the experiment detailed in Annex C.

Mode S RA Report, RA broadcast and 1090 ES would be transmitted by all ACAS-equipped aircraft and would provide details of all ACAS encounters. An encounter between an ACAS and a Mode A/C aircraft would only produce a single RA and therefore only that report would be downlinked. An encounter between two ACAS equipped aircraft would, if they both generated an RA, produce two downlinked RAs.

4.2 Business

4.2.1 Airborne costs

All ACAS equipped aircraft are mandated [15] [8] to generate RA Broadcasts and be capable of downlinking Mode S RA Reports. The ability to downlink Mode S RA Reports is additionally mandated by several States as part of their Mode S elementary surveillance mandate. No additional airborne costs are required to downlink RAs over these technologies.

ACAS coordination messages are an intrinsic part of ACAS and their format is specified in the ACAS SARPs [2]. No additional airborne costs are required to downlink RAs over ACAS coordination messages.

1090 Extended Squitter is not a currently mandated technology and although some new aircraft are being supplied with 1090 ES as standard, the RA Downlink message is not yet available.

Use of 1090 ES for RA downlink would therefore require some changes to the airborne infrastructure and these would incur some costs. The costs would depend on the future level of 1090 ES equipage, as some currently fitted aircraft may require just a software upgrade. If 1090 ES was equipped for another purpose, then RA Downlink squitter could be added at no marginal cost. Only “ADS-B out” would be required to support RA Downlink.

A detailed cost analysis for fitting 1090 ES to the aircraft is given in Annex G. Its conclusion is that fitting 1090 ES-out would cost € 68,000 per aircraft. If elements of 1090 ES were already fitted and a software upgrade was required to support 1090 ES RA Downlink, this would cost €5,000 per aircraft.

4.2.2 Ground costs

The Mode S RA Report requires a Mode S rotating radar ground infrastructure. Several ECAC states are currently installing such an infrastructure and the expected coverage for the 2015 timescale is detailed in Annex H. To summarise, there will be good double or even triple Mode S coverage of Western Europe. Outside this region, there is no planned civilian Mode S coverage.

A Mode S ground station would be capable of extracting an RA Report with no further adaptation or cost.

A ground infrastructure to receive RA Broadcasts, ACAS Coordination messages or 1090 ES messages does not exist at present in ECAC. Such a network would consist of passive receivers connected to an ATC centre. These receivers would either be 1030 MHz receivers, 1090 MHz receivers or both 1030/1090 receivers depending on the technology requirements.

Such a ground network would incur an additional ground cost and this is analysed in detail in Annex F. The cost of installing such a ground network for all ECAC states is estimated at € 15m while the cost of installing such a network in only those States without Mode S radar is estimated at € 8m.

4.3 Operational

4.3.1 Latency

Latency is the delay between the RA occurring onboard the aircraft and the RA notification being successfully delivered to the ATC centre. It is an essential characteristic of the RA downlink concept. The delay must be minimised in order for RA downlink to be a useful technology.

An illustration of the times of different core technologies is shown below in Figure 8.

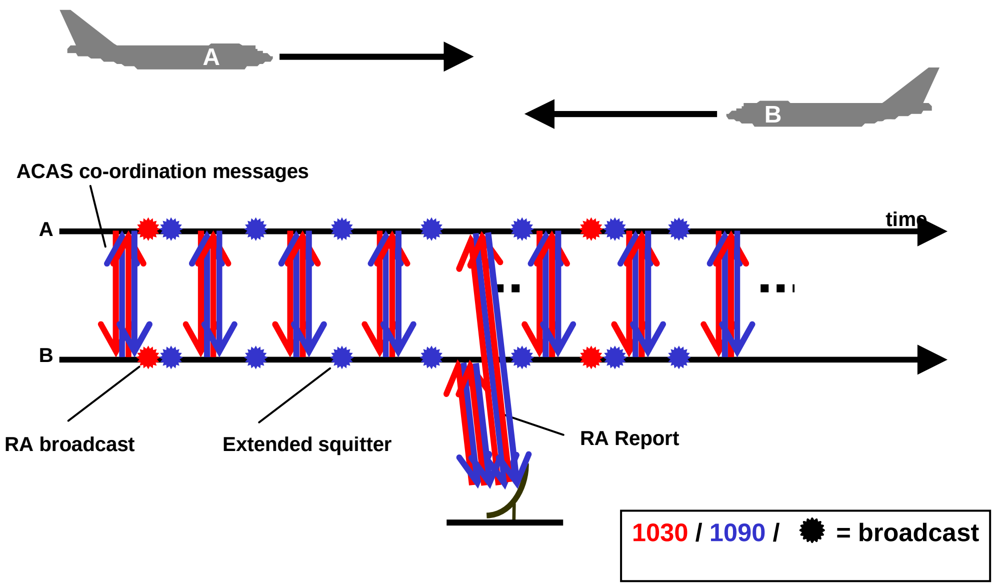

Figure 8: Illustrative of downlink for all four core technologies

The latency for the core technologies has been calculated in detail in Annex E. The time required for 95% of messages has been used as the benchmark for the comparison of technologies. ACAS coordination messages have been excluded from the calculation as they are unable to downlink 95% of RAs under any circumstances.

The latency is dependent on several factors such as the number of ground stations within range, the probability of detection (dependent on the interference environment) and the delay in transmission through the ground infrastructure. Two figures are given: the expected latency and a worse case assuming a high level of interference and limited ground infrastructure. The worse case assumes a low detection probability and limited coverage of ground receivers.

The total latency has been calculated using the calculations from Annex C. The final latency figures are then given in Table 6.

Two ground-induced delays are assumed: a 1 s communications delay from receiver to ATC centre and a 3 s centre processing time [8].

Technology	**Scenario**	**Assumptions**
Mode S RA Report, en-route	Expected	Triple coverage, 8 second radar with a probability of extraction in a beamdwell of 0.996.
	Worse case	Double coverage, 8 second radar with a probability of extraction in a beamdwell of 0.9.
Mode S RA Report, TMA	Expected	Double coverage, 4 second radar with a probability of extraction in a beamdwell of 0.996.
	Worse case	Single coverage, 4 second radar with a probability of extraction in a beamdwell of 0.9.
1090 ES	Expected	Two ground stations within range, 50% probability of detection.
	Worse case	One ground station within range, 50% probability of detection.
RA Broadcast	Expected	Two ground stations within range, 80% probability of detection.
	Worse case	One ground station within range, 50% probability of detection.

Table 5 : Assumptions made in latency calculations

The worse case scenario has been determined by assuming a lower probability of reception and a reduced coverage of ground stations. For 1090 extended squitter, the probability of detection has not been reduced as 50% represents a worse case for 2010 in core Europe.

Using these assumptions, the expected and worst case latencies for each technology have been determined, the four second ground delay has been included in these figures and are given below.

	Expected latency (s)	Worse case latency (s)
Mode S RA Report, en-route	9.1	10.9
Mode S RA Report, TMA	7.1	8.2
1090 ES	6	8
RA Broadcast	4	12

Table 6: Latency for core technologies including a ground delay

The latency calculations show that Mode S RA Report meets the 10 s maximum latency requirement except for the worst case en-route scenario. 1090 ES meets the requirements in all cases. RA Broadcast meets the requirements in the expected but not the worst case.

4.3.2 Different solutions for different operating environments

It is likely that different technologies that support RA downlink would be best suited to different operating environments.

In this work it has been assumed that an existing Mode S infrastructure would be used to extract the RA Report. A cost analysis has not been made for the introduction of Mode S in low density airspaces just to support the RA Downlink application. Therefore Mode S RA Report is not proposed as a technical solution for RA Downlink in regions outside the expected Mode S coverage area.

The passive receiver network required for RA Broadcast, ACAS Coordination messages and 1090 ES has been considered for both all ECAC and for just the regions not covered by Mode S.

The RA Downlink application will only work if the aircraft is within range of the ground network. For oceanic regions or large expanses of water, the different technologies will have different ranges out to which they can function. Beyond this range, RA downlink shall not be possible.

Mode S ground stations will have the longest range in remote areas such as over oceans and would be capable of extracting RA reports from aircraft up to 200 Nm from the ground station for an appropriate aircraft altitude. The other technologies relying on a passive ground network have a more limited range.[2]

4.4 Summary of evaluation

The above analysis can be summarised specifying how each technology ranks against each criteria. This is shown in the table below.

[2] The effective range of ADS-B ground stations to capture RA squitters and other data will require further research.

	Mode S RA Report	RA Broadcast	ACAS Coordination	1090 ES
High Priority				
Latency (95%)	**[E]**	**[E]**	**X**	
Airside cost				**[A]**
Ground cost		**[B]**	**[B]**	**[B]**
Quality of service/ completeness			**X**	
Identification of target		**[D]**	**X**	
Medium Priority				
Identification of intruder		**X**	**X**	
Changes to SARPS / MOPS				**[C]**
Deployment timescales (Air)				**[C]**
Deployment timescales (ground)		**[B]**	**[B]**	**[B]**

Table 7: Summary of Candidate Technologies against Criteria

Indicates a failure to meet a criteria	**X**
Indicates a criteria can only be met with qualification Z	**[Z]**
Indicates a criterion has been met.	

[A] The airside cost of fitting 1090 ES primarily for RA Downlink is prohibitive. However, if it was fitted for other purposes, the RA Downlink application could be included at no extra cost.

[B] A new ground infrastructure would be required for RA Broadcast, ACAS Coordination messages and 1090 ES. The cost of this is relatively small and could be implemented anyway for other purposes, such as ADS-B.

[C] An RA Downlink message is not finalised in the 1090ES SARPS and this would need to be done. The airside equipage of 1090 ES is limited at present and would need to be mandated if extended squitter were to be used. A mandate is possible for other reasons, such as ADS-B.

[D] Aircraft are only identified by their Mode A codes, not their 24-bit addresses.

[E] According to calculations, latency requirements are not met in the worst case. This may be overcome by increased ground station redundancy or reducing the other sources of latency.

4.5 Summary

The suitability of each candidate technology for RA downlink is discussed below.

Mode S RA Report

Mode S RA Reports meet all of the criteria with the exception of the worst case en-route latency. The latency requirement could be met where there is additional radar coverage or by reducing other elements of latency (eg centre processing time).

In terminal areas, the latency will be significantly reduced due to the faster rotation rates of the TMA radars. In these areas the required latency will easily be met.

Mode S RA Reports require a suitable rotating beam radar ground infrastructure. At present this is only planned in Western Europe and is expensive to construct elsewhere. Mode S RA Reports are therefore a good candidate for RA Downlink where the ground infrastructure is planned.

One avionics manufacturer has implemented RA Reports such that they are only transmitted at the end of the RA. **Modifications shall be required to some ACAS/Mode S avionics to ensure consistent, correct operation. SARPs should also be clarified.**

If Mode S were used in addition to 1090 ES for areas of Mode S coverage, the latency of the combined system would be significantly reduced. This dual system in core Europe would provide a highly reliable system with increased redundancy.

ACAS Coordination Messages

ACAS Coordination messages do not meet several of the criteria, including:

- Latency. This is because reliable detection of these messages is difficult on the ground as they are often transmitted from top-mounted antennas.
- Quality of service/completeness. ACAS co-ordination messages are only transmitted in encounters between aircraft that are both ACAS equipped and operating in RA mode. (Less than 70% of encounters.)
- Identification of the target or intruder. ACAS co-ordination messages do not identify the target, and the intruder identity is encoded with parity information. Target identity can be learnt if both aircraft generate RAs. Intruder identity can be determined if the ground stations maintain a database of 24-bit addresses present in the vicinity.

ACAS Coordination messages therefore do not appear to be a good candidate for RA downlink.

RA Broadcast

RA Broadcast has the potential to meet the criteria except for the identification of the intruder. In addition, it only identifies the target aircraft by the Mode A code (not 24-bit address). Finally, it does not meet latency requirements for the worst case, although this could be improved with increased ground station density

A new ground infrastructure to detect 1030 MHz would be required and would be unlikely to be implemented for any other purpose.

1090 Extended Squitter

1090 ES has the potential to meet all of the criteria. However the following steps are required before ES could be implemented for RA downlink:

- SARPs and MOPS updates are required to reflect the new ES.
- Airborne avionics updates are required. This may happen as part of a Mode S, ADS-B or ACAS upgrade.
- The necessary ground infrastructure must be implemented. This may happen as part of ADS-B introduction.

4.6 Conclusions

Conclusion 1: In areas covered by a Mode S ground infrastructure, Mode S RA Reports is the best method for RA downlink.

Conclusion 2: In areas not covered by a Mode S ground infrastructure, 1090 ES is the best method for RA downlink assuming it can be economically implemented as part of an ADS-B system.

4.7 Recommendations

Recommendation 1: Modifications should be undertaken to some ACAS/Mode S avionics to ensure consistent, correct operation of RA reports. SARPs should also be clarified.

Recommendation 2: The 1090 ES message should be incorporated into the appropriate SARPs/MOPS.

Recommendation 3: Co-ordination should be maintained with ADS-B implementation programs to ensure RA Downlink implementation happens in parallel with ADS-B.

Recommendation 4: Further work is required for the validation of technical and operational figures. In particular, the requirement of a maximum latency of 10 seconds.

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A.2 Review of Previous Studies on RA Downlink

A.2.1 MITRE Study – Baltimore, USA 1995

The 1995 MITRE study was conducted at the BWI (Baltimore Washington International Airport) approach facility. The evaluation consisted of interactive simulation with presentation of a variety of conflict geometries and resulting RAs. Contiguous Conflict Alert – Resolution Advisory event and varying pilot responses to RAs were modelled. The study assumed that the RA information is received via mode S.

The study showed that the majority of participants perceive the display of RA information to enhance the controller's situation awareness comfort level during an RA event. There was a consensus among participants that only a limited set of information (RA indication and sense) should be displayed.

The study concluded that approach (terminal) controllers see RA downlink to be an aid to their situational awareness.

A.2.2 MITRE Study – Boston, USA 1996-97

The MITRE study was conducted at the Boston Terminal Facility (TRACON) from July 1996 through January 1997. Boston had been selected for this study at it had an optimal number of RAs. The study concluded that the RA downlink had positive operational benefits for controllers. However, the capability does not constitute an ATC operational requirement.

RA data was extracted using Mode S RA Reports, the information was displayed on the CWP 1.3 – 6.1 seconds after being displayed in the cockpit and removed 18.3 – 19 seconds after removal in the cockpit.

This implies a minimum latency for this configuration of at most 1.3 seconds. This delay is the difference between the RA being reported to the pilot and appearing on the controllers screen. This does not account for the delay of the aircraft reporting the RA information to the pilot.

A.2.3 CENA Study (VICTOR project) – France 1994

CENA study (VICTOR Project – Visual Interface for Controllers for the Transfer of Resolution Advisories) was conducted in France in 1994. During this study a sample of traffic was generated with a number of conflicts that causing an RA to be generated. It was assumed during the experiment that all aircraft are ACAS equipped and visible on the radar screen (including military traffic).

The study concluded that the RA information cannot imply a controller's action, as the RA is under the pilot's responsibility. It is information for the controller about the event that taking place. The study also pointed out that the

RA events, due to transmission delays, might be presented to the controller when they are obsolete.

There was no clear conclusion in the study whether any RA should be presented to the controller. In any case, the authors of the study believe that only minimal information should be presented, i.e. no detail on manoeuvre is prescribed by ACAS.

A.2.4 UK CAA – Simultaneous Operation of STCA and TCAS II in En-route Airspace – United Kingdom 1994[3]

This extensive study aimed on investigating the potential effects upon UK airspace of the simultaneous operation of the NATS ground based en-route STCA system and the airborne TCAS.

The study showed that with TCAS 6.04 approximately 20% of the alerts examined which were common to TCAS and STCA might have resulted in pilot or controller disruption because of a controller instruction and an RA being issued at or near same time.

99.8% of encounters the ground system had generated an STCA alert and in 1.3% of cases had generated a TCAS RA. Roughly 2% of the encounters generated both an STCA and a TCAS RA.

Approximately 2 per 1000 STCA alerts, will be generated for which the controller does not receive an STCA warning. For roughly 20% of the encounters which generated both an STCA alert and a TCAS RA it is possible that some confusion concerning the resolution of the conflict may occur because of the controller's instructions and the RA could have been received by the pilot at or near the same time.

On average, 150 STCA alerts are generated per day. With 100% of TCAS equipage it can be expected that one alert may be received within UK's en-route airspace every other day which may result in confusion.

If no avoiding action is given by a controller upon receiving an STCA alert, approximately 55% of RAs, generated by either TCAS version, would result in an aircraft deviating from its cleared flight path.

A.2.5 Theoretical analysis of RA Broadcast via Extended Squitter, Dr V.A. Orlando.

A theoretical analysis of the latency in downlinking ACAS RA information over extended squitter has been carried out in [18]. This involved a Monte Carlo simulation of aircraft in both a low density and a very high density environment. The very high density environment was based on the maximum interference level at Frankfurt in May 2000 and reception by a single six sectored antenna was assumed.

[3] Original report not available, figures taken from [28]

The results were that the first squitter is received with greater than 95% probability only if the aircraft is within 10 Nm of the antenna. If the aircraft is 50 Nm from the antenna four squitters are required to receive 95% of downlinked RAs.

The results are consistent with those presented in Annex D, as the traffic level assumed in Annex D is a 2010 core Europe simulation.

B Detailed Analyses of the Candidate Technologies

B.1 Introduction

This section gives detailed analyses of the Mode S RA report, RA broadcast, ACAS broadcast and 1090 extended squitter.

B.2 Mode S RA Report

The Mode S transponder downlink of BSD 3,0 is the primary method defined in the ACAS SARPs [2] for the downlink of ACAS resolution advisories. The downlinked ACAS RA information transmitted to the ground over Mode S is referred to as an RA report. This technology requires a Mode S equipped aircraft and a Mode S ground infrastructure.

Core European states are presently implementing Mode S. The ability to downlink BDS 3,0 over Mode S is part of the European ACAS II mandate and is also specifically required by the Belgium, French and German Mode S elementary surveillance mandate [13].

The existence of an RA report is indicated to the ground system via a flag in the aircraft's Mode S roll call reply. This is specified via the 5-bit DR (Downlink Request) field in either downlink format 4 (surveillance, altitude reply), or format 5 (surveillance, identity reply) message. The relevant encoding for the DR field is:

DR Value	Meaning
2	ACAS message available
3	Comm-B message available and ACAS message available
6	Comm-B broadcast message 1 available and ACAS message available
7	Comm-B broadcast message 2 available and ACAS message available

Table 8: Summary of DR field reply encoding

A DR field of 2, 3, 6 or 7 will inform the ground interrogator of the existence of an ACAS message. The only defined ACAS message is an RA report.

The aircraft is then re-interrogated from the ground specifically requesting the ACAS message. This request by the ground station for the RA report is specified via the RR field in either uplink message format 4, 5, 20 or 21. The RR field is encoded as

RR Value	Meaning
19	Transmit a resolution advisory report

Table 9: Summary of RR field encoding

Upon successful receipt of this request, the aircraft then replies with a Comm-B message. This will either be in downlink format 20 or 21, depending if a Comm-B altitude reply or Comm-B identity reply was requested.

The format for downlink messages 20/21 is:

10101	FS:3	DR:5	UM:6	AC:13 or ID:13	MB:56	AP:24

Table 10: Mode S downlink message format 20/21

These fields contain the following information:

10100 / 10101	Specifies message 20 / message 21
FS:3	Flight Status, Informs if the aircraft is airborne or on the ground, and if there is an alert onboard (e.g. terrorist, TCAS alerts are not specified here).
DR:	Downlink request field, informs if a further ACAS, Comm-B or other message is available.
UM:6	Utility message containing transponder communications status with regards multisite communications.
AC:13	For downlink format 20 messages, the altitude code specifies altitude information in either 25 ft or 100 ft increments.
ID:13	For downlink format 21 messages, the identity code specifies the aircraft Mode A code.
MB:56	The Message Comm-B field, the RA report information is contained within this MB field.
AP:24	The address-parity field provides an error check by overlaying parity information on the aircraft 24-bit address.

Table 11: Downlink format 20 / 21 field encoding

The MB field contains information about the ACAS resolution advisory, as shown in the table below.

BDS1=3	BSD2=0	ARA	RAC	RAT	MTE	TTI	TID

Table 12: Structure of the MB field for an RA report

The subfields provide detailed information about the RA.

BDS1=3, BDS2=0	These registers specify that the information to follow is an RA report (DF20/21 could contain any Comm-B information).
ARA	The Active Resolution Advisory field specifies the characteristic of the RA. If there is only one threat then information regarding

	preventative/corrective, upward/downward, not increased rate/increased rate, not sense reversal/sense reversal, not altitude crossing / altitude crossing, vertical speed limit/positive. For more than one threat the information is different, does not require a correction in the upward sense/ requires a correction in the upward sense, does not require a positive climb/requires a positive climb, does not require a correction in the downward sense/requires a correction in the downward sense, does not require a positive descent / requires a positive descent, does not require a crossing / requires a crossing, is not a sense reversal / is a sense reversal.
RAC	Resolution advisory complement record, indicates RAC's received from other aircraft, from the list do not pass below, do not pass above, These can be either active or inactive. Horizontal options also exist that are not used in ACAS II.
RAT	RA terminated indicator, specifies if the RA specified in the ARA field is current or has been terminated.
MTE	The multiple threat encounter field specifies (in coordination with the ARA field) if 0, 1 or more threats are currently being processed by the threat resolution logic.
TTI	Threat type indicator subfield, specifies the type of identity data given in the TID field
TID	Threat type identity either specifies either no identity data, a 24 bit address or altitude, range and bearing of the target.

Table 13: A detailed description of the information content of the MB field of a Mode S RA Report

Mode S messages are extracted by the ground system by rotating antennas which can result in a delay. This is likely to be reduced in multi-radar environments and is investigated elsewhere in this report.

B.3 RA Broadcast

The ACAS SARPs [2] define a resolution advisory broadcast, transmitted from the bottom antenna at full power on 1030 MHz.

This functionality was designed for monitoring purposes and is untested in operational circumstances. The RA broadcast is presently specified to transmit (with a jitter) approximately every 8 seconds. It is also transmitted whenever the RA changes. Installations using directional bottom antennas operate such that complete circular coverage is provided every 8 seconds and the same RA sense and strength is broadcast in each direction.

RA Broadcast was envisaged to allow ACAS RA activity to be monitored in areas where Mode S ground station surveillance coverage does not exist by using special RA broadcast signal receivers on the ground. However, at present, no ground infrastructure exists, or is planned to be deployed for the detection of RA broadcasts.

The RA broadcast is transmitted using uplink message format 16 (long air-air surveillance – ACAS), this message format is also common to ACAS broadcasts and ACAS resolution messages. RA broadcasts are not designed to elicit a reply, hence some of the generic UF=16 fields are not meaningful.

The entire format for uplink message 16 is shown below.

10000	3	RL:1	4	AQ:1	18	MU:56	AP:24

Table 14: Uplink Format 16 message

The subfields specified in the message are shown below.

10000	Specifies message format 16
RL	Reply Length, specifies a reply with DF=0 or no reply. A RA Broadcast is not designed elicit a reply.
AQ	Acquisition, controls the content of the RI field in the reply. This is a generic UF=16 field and not meaningful for the specific RA Broadcast message.
MU	Message, ACAS.

Table 15: Uplink Format 16 message subfields

The MU field for an RA broadcast itself contains multiple fields, as shown below.

UDS1=3	USD2=1	ARA	RAC	RAT	MTE	2	AID	CAC

Table 16: MU field for an RA Broadcast

These fields are defined below.

UDS1=3, UDS2=1	Together, these UDS fields specify the type of message content in the rest of the MU field, 3,1 specifies an RA broadcast, alternatively an ACAS broadcast or a resolution message could be specified.
ARA	The Active Resolution Advisory field specifies the characteristic of the RA. If there is only one threat then information regarding preventative/corrective, upward/downward, not increased rate/increased rate, not sense reversal/sense reversal, not altitude crossing / altitude crossing, vertical speed limit/positive. For more than one threat the information is different, does not require a correction in the upward sense/ requires a correction in the upward sense, does not require a positive climb/requires a positive climb, does not require a correction in the downward sense/requires a correction in the downward sense, does not require a positive descent / requires a positive descent, does not require a crossing / requires a crossing, is not a sense reversal / is a sense reversal.
RAC	Resolution Advisory Complement record indicates RACs received from other aircraft, from the list do not pass below, do not pass above, These can be either active or inactive. Horizontal options exist that are not used in ACAS II.
RAT	RA terminated indicator, specifies if the RA specified in the ARA field is current or has been terminated.
MTE	The multiple threat encounter field specifies (in coordination with the ARA field) if 0, 1 or more threats are currently being processed by the threat resolution logic.
AID	The mode A identity code, denoting the mode A code of the reporting aircraft
CAC	Mode C altitude code, denoting the mode C altitude code of the reporting aircraft.

Table 17: A detailed description of the information content of the MU field of an RA Broadcast

The address-parity field for the RA broadcast is generated using parity information overlaid with the broadcast address [19]. This broadcast address is a series of 24 consecutive ones. Hence the aircrafts 24-bit address is not contained in the RA broadcast. Instead the aircraft is only identified via its mode A code.

No information is available from the RA broadcast about the identity or position of the intruder aircraft. Information is available to specify if it is a single or multiple encounter and the most recent RAC received. If two nearby aircraft were observed to be generating RA broadcasts it could not be assumed that they were generating the RA against each other.

To receive and process RA Broadcasts a passive ground network of 1030 MHz receivers would be required. These receivers, linked to the relevant ATC centre would be able to provide information about the current RA, associating it to the aircraft via the aircrafts Mode A identity code.

B.4 ACAS Coordination Messages

ACAS equipped aircraft coordinate their resolution advisories. The first aircraft to detect a threat transmits an ACAS Uplink Format (UF) 16 message on 1030 MHz (the resolution message) advising the other aircraft that it has issued an RA and its intended course of avoidance. The other aircraft replies with an ACAS Downlink Format (DF) 16 message on 1090 MHz (the coordination reply).

These messages contain the information that an RA is occurring and the actions that have been given by the RA to each aircraft..

The aircraft will be transmitting both on 1030 MHz and 1090 MHz, although a good situational awareness should be available by only listening on 1030 MHz. A detailed analysis is given below to show if listening on both frequencies would improve awareness.

All current aircraft equipped with ACAS already transmit these messages as part of the ACAS protocols, hence no additional airborne infrastructure would be required. These messages are however defined for air-air communications and ACAS typically uses directional antennas, so the reliable detection of these messages on the ground cannot be assumed.

At present a ground infrastructure does not exist for the reception of ACAS coordination messages. Aircraft are identified in these messages by their ICAO 24-bit addresses, therefore any ground infrastructure would also need to be able to interpret these addresses and correctly assign these to the aircraft display on operators' screens.

When an intruder aircraft that is equipped and operating with either horizontal only or horizontal and vertical capabilities is declared a threat, ACAS transmits a resolution interrogation with AQ=0 and RL=1, The MU field shall contain the resolution message in the subfields specified below. This UF = 16 interrogation is intended to cause a DF= 16 reply from the intruder.

ACAS resolution messages are sent via UF= 16 and shown below.

10000	3	RL:1	4	AQ:1	18	MU:56	AP:24

Table 18: ACAS resolution message

The subfields specified in the message are given below.

RL	Reply Length, specifies a reply with DF=0 or no reply.
AQ	Acquisition, controls the content of the RI field, referring to the RI field in the downlink format 16 reply to this message.
MU	Message, ACAS.

Table 19: ACAS resolution subfield descriptions

The structure of the MU field for the uplink resolution message is given by:

UDS 1=3	USD 2=0	-1-	MTB	CVC	VRC	CH C	HR C	-3-	HSB	VSB	MID

Table 20: MU field

These subfields are defined below.

MTB	Multiple threat bit, determines if either one or multiple threats exist
CVC	Cancel vertical RAC, specifies either no cancellation, cancel previously send “do not pass above”, or cancel previously send “do not pass below”
VRC	Vertical RAC, denotes a vertical RAC relating to the addressed aircraft, either no vertical RAC sent, do not pass below, or do not pass above
CHC	Cancel horizontal RAC, specifies either no cancellation, or cancellations relating to horizontal RAC’s.
HRC	Horizontal RAC, specifies horizontal RAC’s relating to the addressed aircraft.
HSB	Horizontal sense bits subfield, this protects the data in the CHC and HRC subfields.
VSB	Vertical sense bits subfield, this protects the data in the CVC and VRC subfields.
MID	Aircraft address, the 24 bit address of the interrogating aircraft

Table 21: MU subfield descriptions

The coordination reply has a structure as follows.

10000	VS:1	7	RI:4	2	AC:13	MV:56	AP:24

Table 22: Co-ordination reply

The subfields specified in the message follow.

VS	Vertical status, signifies if the aircraft is airborne or on the ground
RI	Air-air reply information field either indicates this is a tracking reply and yields the ACAS capability of the target aircraft (horizontal only, vertical only, horizontal and vertical or no operating), or the RI field indicates it is a acquisition reply and gives the maximum true airspeed capability of the interrogated aircraft. The choice of reply is defined by the AQ field of the interrogating UF = 16 message.
AC	Altitude code specifies altitude information in either 25 ft or 100 ft increments.
MV	Message, ACAS

Table 23: Co-ordination reply subfields

The MV field contain the air-air coordination reply contains the following information.

VDS1=3	VSD2=0	ARA	RAC	RAT	MTE	-28-

Table 24: MV field

Where the subfields are defined below.

ARA	The Active Resolution Advisory field specifies the characteristic of the RA. If there is only one threat then information regarding preventative/corrective, upward/downward, not increased rate/increased rate, not sense reversal/sense reversal, not altitude crossing / altitude crossing, vertical speed limit/positive. For more than one threat the information is different, does not require a correction in the upward sense/ requires a correction in the upward sense, does not require a positive climb/requires a positive climb, does not require a correction in the downward sense/requires a correction in the downward sense, does not require a positive descent / requires a positive descent, does not require a crossing / requires a crossing, is not a sense reversal / is a sense reversal.
RAC	Resolution advisory complement record, indicates RAC's received from other aircraft, from the list do not pass below, do not pass above. These can be either active or inactive. Horizontal options also exist that are not used in ACAS II.
RAT	RA terminated indicator, specifies if the RA specified in the ARA field is current or has been terminated.
MTE	The multiple threat encounter field specifies (in coordination with the ARA field) if 0, 1 or more threats are currently being processed by the threat resolution logic.

Table 25: MV subfield descriptions

B.5 1090 Extended Squitter

1090 extended squitter (1090 ES) is an ADS-B technology primarily intended to periodically broadcast aircraft position, velocity as well as several other aircraft parameters. It also has the ability to broadcast event driven data, and it would be using this technique that RA's would be transmitted.

At present, limited ground infrastructure exists for the detection and use of 1090 ES messages. However this is likely to improve with the progress on ADS-B package 1. Hence the equipage of 1090 ES for ADS-B applications may provide an enabler for using 1090 ES to transmit ACAS RA's. In addition, multilateration infrastructure also may be suitable to receive RA's transmitted using 1090 ES.

At present, no specific resolution advisory message is defined in the appropriate SARPs. A proposed message format has been suggested in [16],[18]. The proposed message uses the extended squitter aircraft status (emergency/priority status) message format. The RA information comes from the same MB field as used in BDS 3,0 Mode S format message and would have the same data content.

The proposed message would be transmitted once per second. It has been agreed [8] this may be assumed to be from the bottom antenna.

C Mode S Receiver Experiment

C.1 Introduction

A Beal Technologies 1030 / 1090 MHz passive receiver was loaned to Helios by EUROCONTROL. The receiver was set up in West London at the location shown below. It is approximately 15 miles from Heathrow and 20 miles from London City Airport.

An initial experiment, designed to test the ability of the receiver to pick up Mode S RA Reports, RA Broadcasts and ACAS Coordination messages was conducted for several weeks during October/ November 2004.

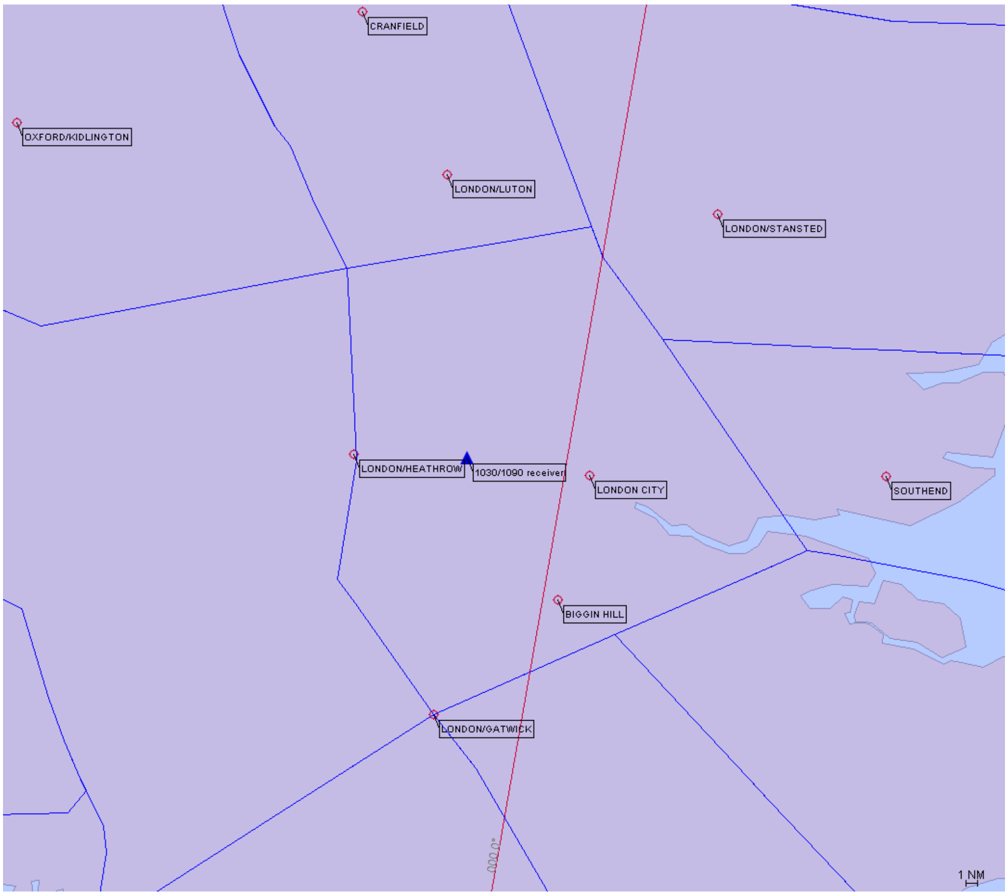

Figure 9: Location of 1030/1090 receiver, the sectors at FL185 are shown

The following picture shows the antennas mounted in West London.

Figure 10: 1030/1090 antenna installations

The receiver recordings were intermittent due to software unreliability and there are some long gaps. Nevertheless when operating, the receiver should have recorded all 1030/1090 messages that it could decode successfully. The receiver recordings are discussed below.

C.2 Results: Reception of DF=11 messages

To investigate the RF environment and general reliability of the receiver, the reception of downlink 1090 MHz messages with DF=11 was investigated. These are transmitted as short (acquisition) squitters spontaneously by the transponder and as all-call replies in response to all-call interrogations (with II code = 0).

The short squitters are transmitted on average once per s alternately from the top and bottom antennas. So when the aircraft is overhead, the receiver should receive an average of one short squitter per 2 s. All-call replies are sent in response to a rotating antenna and therefore several may be transmitted each radar scan.

Figure 11 below shows DF=11 messages recorded on 17 November 2004 from of aircraft with Mode S address 484165. The recording contains 61 DF=11 messages recorded over about 190s.

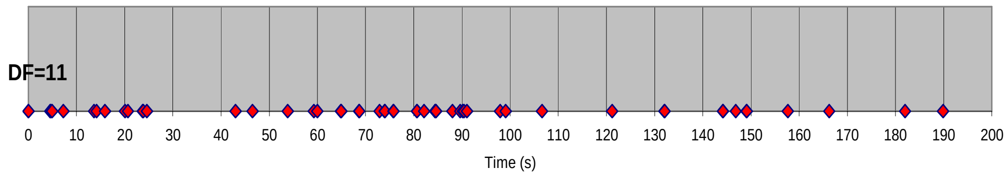

Figure 11: DF11s recorded from aircraft 484165 on 7 November 2004

The average time between squitters is 3.2 s, but they are unevenly distributed. For example, at one time 5 DF=11s are received within 0.143 s. At another time there were no DF=11s received for 18 s. The 'bursts' of squitters could be due to Mode S all call interrogations. However, the long gaps cannot be explained without further analysis but some possible reasons are given in the conclusions.

C.3 Results: Reception of DF=17 messages

Again, to investigate the general reliability of the receiver, DF=17 messages were monitored. These are extended squitters transmitted by aircraft equipped with the appropriate transponder. The rates of extended squitter transmitted will depend on the implementation, but will be at least 2.2 Hz. They are transmitted alternately from top/bottom antennas.

Figure 12 below shows received extended squitters from one aircraft on 7 November. The recording contains 50 squitters, with an average time between squitter of 3.3 s.

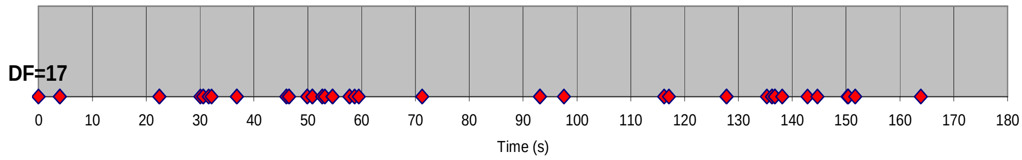

Figure 12: DF 17s recorded from aircraft 400A7C on 7 November 2004

As with the short squitters, the extended squitters are received in bursts with some long gaps in-between. Again this cannot be explained without further investigation.

C.4 Results: Reception of ACAS messages

The frequency of ACAS messages in the data recordings is shown in the table below.

Message type	Identifying characteristics	Frequency observed
RA report	DF=20; BDS1=3; BDS 2=0 or DF=21; BDS1=3; BDS 2=0. Transmitted in response to interrogation from ground station.	None
RA broadcast	UF=16; UDS1=3; UDS2=1. Transmitted from bottom antenna when RA occurs.	A few
ACAS broadcast	UF=16; UDS1=3; UDS2=2. Transmitted from top antenna every 10s.	Many
ACAS co-ordination message	UF=16; UDS1=3; UDS2=0 DF=16; VDS1=3; VDS2=0 Transmitted between aircraft when RA occurs.	None

Figure 13: Frequency of ACAS messages in recordings

Examination of the log files showed that even where an RA-specific message was broadcast (eg RA broadcast), no other RA-related messages (eg ACAS co-ordination messages, RA reports or other RA broadcasts) could be found at a similar time. In other words, only a single message was ever detected to indicate an RA event.

C.5 Conclusions

The recordings obtained showed considerable differences from what would have been expected, including:

A ‘bursty’ reception of squitter messages, including long apparent gaps between receptions.

Single message indications of an RA event, but no RAs that generated multiple messages that could be received.

The reasons for the unexpected behaviour could not be determined within this study, but may have included:

There may be an error in the recording software, which anyway crashed intermittently. This could not be resolved within the time available.

The receiver may be logging aircraft on the edge of coverage. Small changes in heading could then result in long gaps between successful message receptions. This could be investigated if simultaneous radar data was made available or the extended squitter position reports were decoded.

The receiver may be prone to errors (possibly due to background interference) that corrupt the messages. This might explain why occasional RA-related messages are observed without any other signs of an RA. Analysis of this would require much more detailed examination of the log files, and more planned experiments (eg recording data at quiet times of the day when interference is low).

The TCAS transponders may have anomalous or incorrect behaviour. This could be investigated through more data analysis and comparison to radar data.

The recordings obtained did not show the expected evidence of TCAS RAs and the reason for this is not clear.

The 1030/1090 recording raised some questions that could not be resolved without further work. For example, why where the rates of reception of squitters so variable? Where there RAs that were undetected by the receiver (but detected by a Mode S ground station)?

D Application of the Helios Mode S FRUIT model

D.1 Introduction

This section describes the Mode S FRUIT model developed by Helios for EUROCONTROL, and its application to estimate the probability of extended squitter reception.

D.2 Mode S FRUIT model

The Mode S model estimates the level of background interference that is expected to be present at 1090 MHz. This interference is known as FRUIT (the term is used here to mean all 1090 MHz interference and so is less strict than the precise definition of ‘false replies unsynchronised in time’.)

The model estimates interference from all sources, including Mode A/C/S radar, TCAS and extended squitter transmissions between all aircraft and radar stations in a user-defined scenario. The model reflects all Mode A/C/S, TCAS and extended squitter protocols.

For this project, the model has been configured in the same way as for other Mode S studies using a worst-case 2010 ground and aircraft scenario. This reflects the expected ground radar environment and the aircraft density at a peak hour in 2010.

The output of the model is a large sample of extended squitters and the interference affecting each one. This output was then processed with a 1090 MHz decoder model to estimate the probability of successful decode of each extended squitter. Each sample extended squitter was plotted on a graph, to see the overall trend.

The Mode S FRUIT model is complex and not described in detail here. However, some key points about the scenarios used are:

- Mode S ground stations are present in the scenario and almost all aircraft are TCAS/Mode S/Extended squitter equipped.
- The FRUIT has been estimated for a passive receiving ground station at the centre of the scenario. Both an omni-directional and sectorised antennas have been tested at the ground station. The sectorised antenna assumes six 60 degree antennas are arranged to provide increased range over 360 degrees.
- Validation of the model continues.

D.3 Reception probabilities

The following figures show the probability of successful reception of each sample extended squitter. Each dot represents a sample squitter.

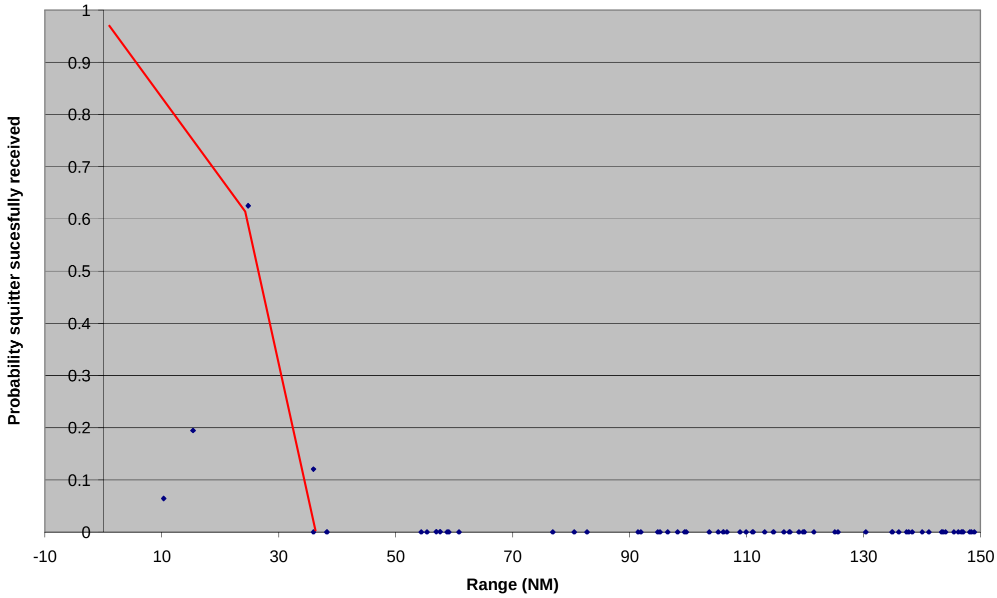

Figure 14: Probability of extended squitter reception (omni-directional antenna)

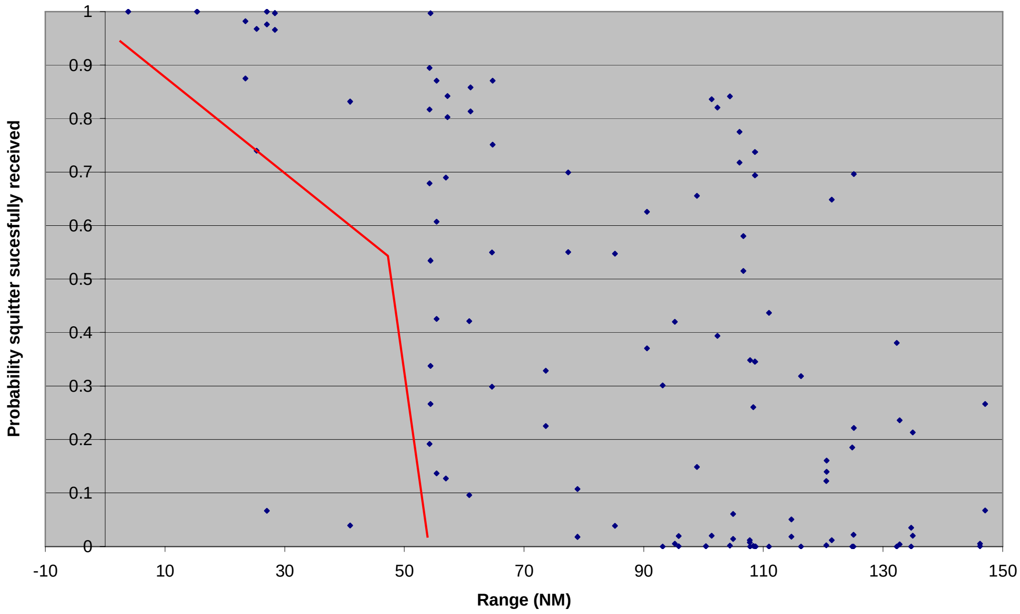

Figure 15: Probability of extended squitter reception (sectorised antenna)

A red-line has been drawn on the graphs to show some likely worst-case reception probability curves (some very low-lying points that are not expected to be representative are excluded).

The figures show that the probability of reception falls away quickly with range. The reception probability for the omni-directional antenna falls from about 60% to zero quickly after 30 NM. For the sectorised antenna, the reception probability falls from over 50% to zero quickly after 50 NM.

Some caveats apply to the model output:

- The model scenario is a 'worst case' one that represents the core of Europe at the busiest time. The performance of ground stations in other areas will be considerably improved.
- The model assumes the 'minimum' ground station performance compatible with relevant standards. There have been recent advances in ground station decoder techniques that are not reflected here.

1030 MHz FRUIT should be lower than 1090 MHz FRUIT due to the reduced number of transmissions on this channel (no squitters) and the fact that most transmitters are ground-to-air rather than air-to-ground. The probability of successful reception of the RA broadcast should be superior to this due to the quieter 1030 MHz frequency. The probability of reception is taken to be 80%.

D.4 Conclusions

The Mode S FRUIT simulation tool result suggests that the range of ground stations in the core area of Europe could be quite limited. Using worst case assumptions, a range of only around 30 - 50 NM may be achieved. Successful squitter reception probability falls quickly from 50 - 60 % down to zero after these ranges.

Greater ranges will be achieved in lower-density areas of Europe or where new advances in decoder techniques are used.

A similar analysis has been made by Dr V.A. Orlando in Reference [18]. The time to downlink a 1090 ES ACAS RA message was analysed using monte-carlo techniques. Some assumptions were different, especially the use of the measured 1090 interference environment from Frankfurt in May 2000. The results of this study show good agreement with the study presented here.

E Detailed Description of Latency Calculations

E.1 Introduction

The table below summarises the factors that affect latency for the principle methods. Also discussed are the assumptions made for latency calculations.

Mode S RA Report		
Radar rotation period	A rotation rate of 8 seconds is assumed for en-route and 4 seconds for terminal areas.	Reference [27] lists periods of 4, 6, 8, 13.3 s for the general operating model for a Mode S ground station. 4 s for terminal and 8 s for en-route was agreed [8]
Number of radars with surveillance responsibility	Dual coverage is assumed for en-route and single coverage for terminal areas.	Reference [20] states that for states installing Mode S, at least dual coverage, but triple in most instances will be available in en-route airspace. In TMAs coverage could be only single but is likely to be double.
Probability of successful extraction of RA report in a single interrogation-reply transaction.	The probability is assumed to be 90% for a single successful interrogation – reply transaction.	It is assumed that the Mode S roll-call interrogation-reply transaction and the request/ downlinking of the Comm-B have the same probability.
Number of re-interrogations in a beamdwell	It is assumed that four re-interrogations are possible in a beamdwell.	This is an implementation issue for the particular mode interlace pattern and radar setup. It is assumed that 4 interrogations are possible. These are ordered, with the request for the RA report not possible until the successful reception of the roll-call reply.
Availability of a ground infrastructure	A Mode S ground infrastructure should exist for Western Europe. Calculations are performed on the expectation of an infrastructure.	A ground infrastructure of Mode S SSR ground stations is expected to exist covering most of Western Europe by 2015. This is discussed in detail in Annex H.
RA Broadcast		
Probability of successful receipt of RA broadcast	The probability of detection of an RA report is estimated around 80% (although very dependent on external factors).	This probability depends on the interference environment, the distance from the aircraft to the receiver, terrain etc. The RA broadcast is transmitted at full power.

Availability of a ground infrastructure	A passive receiver network shall be required to receive the RA broadcast messages. The existence of a ground infrastructure will be assumed.	At present, no suitable ground infrastructure exists for the detection of RA Broadcasts. A similar passive network is required for RA Broadcasts, ACAS Coordination Messages and 1090 ES and the costs of such a network are discussed in Annex F.
Antenna Choice	The RA broadcast is broadcast from the bottom antenna. Aircraft are assumed to be in level flight.	A heavily banking aircraft may not transmit in an appropriate direction for the receiver network.
1090 Extended Squitter		
Probability of successful receipt of extended squitter	The probability of successful receipt of an extended squitter is estimated around 50% (although very dependent on external factors).	This probability depends on the interference environment, the distance from the aircraft to the receiver, terrain, transmission power etc. This figure has been generated using the Helios Mode S FRUIT model.
Availability of a ground infrastructure	A passive receiver network shall be required to receive the 1090 ES messages. The existence of a ground infrastructure will be assumed.	At present, no suitable ground infrastructure exists for the detection of 1090 ES messages. A similar passive network is required for RA Broadcasts, ACAS Coordination Messages and 1090 ES and the costs of such a network are discussed in Annex F.
Antenna Choice	It is assumed that the 1090 ES is transmitted from the bottom antenna and the aircraft is in level flight.	Typically 1090 ES messages are transmitted once per second, alternately from the top and bottom antennas. It is assumed that the ACAS RA report over 1090 ES will only transmit from the bottom antenna. Given this assumption, a heavily banking aircraft may not transmit in an appropriate direction for the receiver network.

Table 26: Factors affecting latency calculations

E.1.1 Mode S RA Report Latency

The latency period to downlink an RA Report over Mode S is dependent on several factors. In this section the latency is calculated and the assumptions made are discussed.

The latency period of an RA report depends heavily on the ability of the radar to extract the Comm-B message successfully on its first sweep over the aircraft. We refer to the probability to extract an RA in a beamdwell as α.

The value of α depends on two factors, the probability of successful extraction of a single message in an interrogation/reply transaction, p and the number of interrogation/reply transactions possible in a single beamdwell, n. The likely range of values for α is given below.

	Probability of extraction in a single transaction, p				
Number of re-interrogations in a beamdwell, n		p = 0.75	p=0.85	p=0.9	p=1
	n=2	0.563	0.723	0.810	1
	n=3	0.845	0.939	0.972	1
	n=4	0.950	0.987	0.996	1

Table 27: Probability of RA report extraction per beamdwell

The assumptions made in the above analysis are that the Mode S roll-call is required before the Comm-B extraction was made. That both these transactions occur with equal probability.

A reasonable assumption is that at least 4 re-interrogations are possible in a beamdwell and the probability of extraction is at least 0.9. Therefore we shall use a figure $\alpha = 0.996$.

The time for the downlink of an RA is determined by generating a probability density function $P_k(t)$. The period of rotation of a radar is T_k. The probability density function for a single Mode S radar is given below in Figure 16.

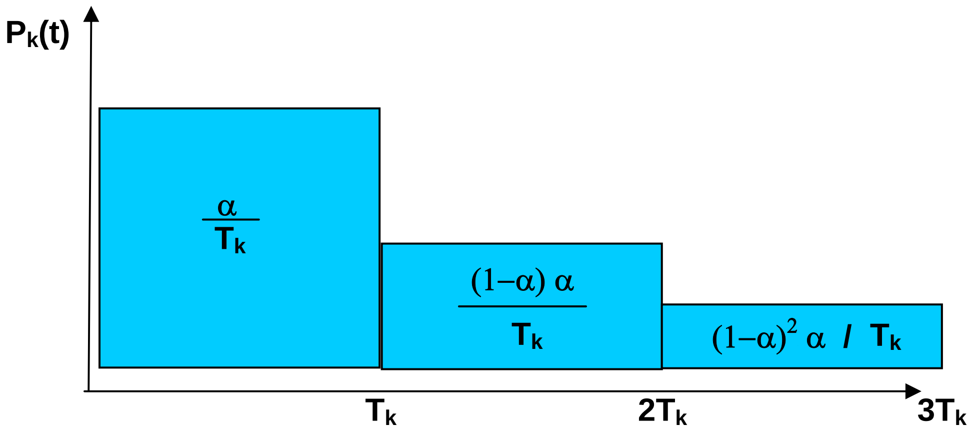

Figure 16: Probability of extracting an RA on successive radar periods

In Figure 16 it can be seen that there is a probability α / T_k that the RA Report is extracted in the first rotation period of the radar, with steadily diminishing probabilities it is extracted in later rotations. If $\alpha < 1$ this graph will continue indefinitely.

The average time for an RA Report to be downlinked $\overline{T}$ is then given by

$$\overline{T} = \int_0^{\infty} t P_k(t) dt$$

The time required to extract 95% of RAs, $T_{95\%}$ is then given by

$$T_{95\%} = \int_0^{t_{95}} P_k(t) dt$$

These equations can be solved to give the average and 95% times for single, double and triple Mode S radar coverage.

Coverage	**Radar Rotation Period (s)**	**Probability of reception within a beamdwell α**	**95% Downlink Time (s)**
Single Coverage	4	0.996	3.82
	4	0.900	4.22
	8	0.996	7.63
	8	0.900	8.44
Double Coverage	4	0.996	3.12
	4	0.900	3.44
	8	0.996	6.23
	8	0.900	6.90
Triple Coverage	4	0.996	2.53
	4	0.900	2.81
	8	0.996	5.07
	8	0.900	5.62

Table 28: Downlink time for different radar rotation rates and different reception probabilities

E.1.2 1090 Extended Squitter / RA Broadcast Latency

The latency period for 1090 ES and RA Broadcast is dependent upon several factors, the number of ground stations within view, the repetition rate of the squitter and the probability of receipt of the squitter.

For the calculation of latency, the RA broadcast can be considered as a squitter with a repetition rate of 8 seconds, it shall have a higher reception probability than the Extended Squitter as it is broadcast on 1030 MHz. It is assumed to be transmitted from the bottom antenna and geometric optimal distances have been used for base station calculations.

1090 Extended Squitter shall be considered to have a repetition rate of 1 second. It is assumed to be transmitted from the bottom antenna and the aircraft to be in level flight.

It is assumed that the first squitter is transmitted as soon as the ACAS box has determined there is an RA. It is then repeated as the prescribed repetition rate.

For a single reception antenna, given a reception probability of β and a repetition rate of λ, the probability of detection on the n^{th} period, P is given by

$$P(n,\lambda) = (1-\beta)^{n-1}\beta$$

The period within which 95% of messages will have been downlinked, N, is given by

$$\sum_{n=0}^{n=N} (1-\beta)^{n-1}\beta > 0.95$$

And the associated time for 95% of messages to be downlinked $t_{95\%}$ is given by

$$t_{95\%} = n_{95\%}\lambda$$

The equations can then be generalised to double and triple coverage of ground stations. The receivers are assumed to have equal probability of receiving the squitter. These equations are solved to generate the table below.

The aircraft is assumed to squitter the first message as soon as the RA is determined, it is then repeated at 1s intervals from this time. Given a very high probability of reception, the downlink with 95% certainty will occur immediately. With a lower probability of reception it will require 1, 2, 3 etc. squitters to receive the message with 95% certainty.

		Probability of reception β								
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
95% Downlink Time (seconds)	1090 ES Single Coverage	28	13	8	5	4	3	2	1	1
	1090 ES Double Coverage	14	6	3	2	2	1	1	0	0
	1090 ES Triple Coverage	9	4	2	1	1	1	0	0	0
	RA Broadcast Single Coverage	224	103	64	40	32	24	16	8	8
	RA Broadcast Double Coverage	112	48	24	16	16	8	8	0	0
	RA Broadcast Triple Coverage	72	32	16	8	8	8	0	0	0

Table 29: A Comparison of the 95% Downlink Time for 1090 ES and RA Broadcast for different reception probabilities and different ground station coverage.

F Cost projection of a passive 1030/1090 ground network

RA Broadcast, ACAS Coordination Messages and 1090 ES all require a ground infrastructure to be constructed to support RA Downlink.

F.1 Required number of ground stations

The required number of ground stations for ECAC can be estimated by proposing a ground network where ground stations are spaced 100 Nm apart. This figure of 100 Nm was chosen as in Annex D, a distance of 50 Nm was determined as a distance at which the 1090 ES probability of detection would fall to approximately 50%. A possible array of ground stations is shown below in Figure 17.

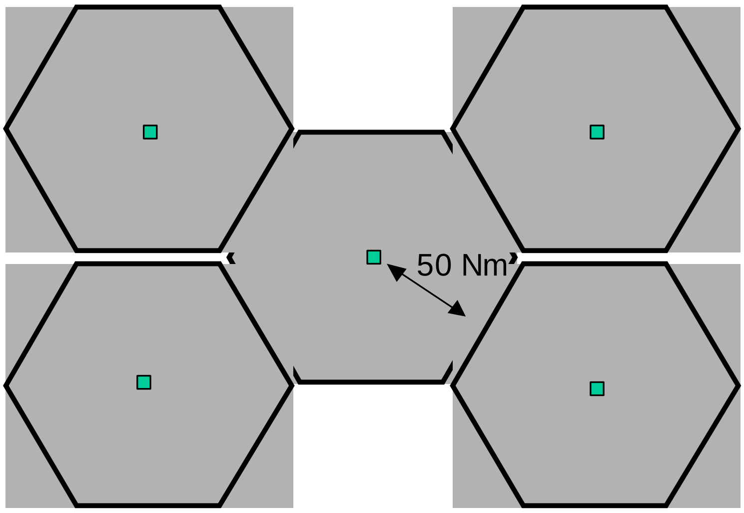

Figure 17: An example array of ground antenna, shown with a hexagonal area

Each ground station has a hexagonal area surrounding it of 8680 Nm^2. The area of all 41 ECAC member states is approximately 2,000,000 Nm^2. A simple calculation shows 250 ground stations are required to cover all ECAC states at this density.

A more realistic arrangement would to be to provide this high density of antennas in the regions of core Europe where the highest interference environment is expected (the region where Mode S is expected to be fitted as discussed in Annex H). This has an area of 555000 Nm^2. 84 ground antenna would be required to cover this region assuming antenna are spaced 100 Nm apart.

If outside of this region antenna could be spaced more widely, for example if the ground antenna were spaced 160 Nm apart, the hexagonal area around each antenna would become 22000 Nm^2. In this case, only another 83 antenna would be required to cover the rest of ECAC. Therefore a total of 167 antennas would be required to cover the entire ECAC region.

This figure correlates well with those made in other studies via different means. An estimate was made in [12] for the required number of ground stations in Europe. This was originally made in the context of 1090 ES and is based on 1 ground station per major airport (> 1 million passengers per year) plus 1 ground station per ACC. There are about 89 airports in Europe with more than 1 million passengers a year (1998 figures), and 61 ACCs. Thus 150 ground stations have been assumed to be required.

It has been assumed the same ground network is suitable for receiving RA Broadcast and ACAS Coordination Messages. A figure of 167 ground antennas is used to project the cost of a ground network.

F.2 Ground station costs

Specific equipment and operations	**Value (Euro)**	**Notes**
Cost of 1090 ES ground station	75,000	Cost from [12]
Installation	15,000	20% equipment cost
Total initial cost per ground station (1 receiver)	90,000	
Yearly maintenance costs per ground station (1 receiver)	7,500	10% initial hardware cost
Number of ground stations required	167	
Total ground station costs (1 receiver)	15,030,000	

Table 30: Cost projection for a passive 1030/1090 ground network

G 1090 Extended Squitter Airborne Costs

At present 1090 ES is not mandated and is limited in its uptake. The functionality required for the RA Downlink application is only ADS-B out. Hence the ground network does not require any uplink capability and the aircraft does not require any specific CDTIs or upgrades to the FMS as are required by a complete 1090 ES system.

G.1 Costs assuming transceiver and RCP require upgrade

This case will apply to a percentage, say x%, of the aircraft.

Specific equipment and operations	**Value for AT digital (euro)**	**Notes**
Hardware		
Cost of Mode S Extended Squitter transceiver	40,600	Cost from 12]
Radio control panel (x 2)	16,400	Cost from [12]
Integration, installation & certification		
Installation kit(s)	2,850	5% equipment cost
Service bulletin	5,700	10% equipment cost
Man-hours (80 euro/hour)	2,850	5% equipment cost
Total initial costs per aircraft (1 transceiver)	**68,400**	
Yearly maintenance costs per aircraft (1 transceiver)	6,840	10% initial hardware cost

Table 31: The costs associated with the upgrade of an aircraft for 1090 ES-out assuming a transceiver and RCP require upgrading

G.2 Costs assuming transceiver and RCP already installed

This case will apply to the remaining (1-x)%, of the aircraft.

Specific equipment and operations	**Value for AT digital (euro)**	**Notes**
Hardware		
Cost of Mode S Extended Squitter transceiver	0	already installed
Radio control panel (x 2)	0	already installed
Integration, installation & certification		

Installation kit(s)	2,500	Airbus figure quoted in [12]
Service bulletin	0	Airbus figure: included in cost of installation kit
Man-hours (80 euro/hour)	2,400	Airbus figure quoted in [12]
Total initial costs per aircraft (1 transceiver)	**4,900**	
Yearly maintenance costs per aircraft (1 transceiver)	490	10% initial hardware cost

Table 32: The costs associated with the upgrade of an aircraft for 1090 ES-out assuming a transceiver and RCP are already installed

H Expected ECAC Mode S coverage for 2015

The expected timescale for deployment of RA downlink for ECAC states is at least a decade [7]. Therefore the likely Mode S coverage in 2015 was considered.

In discussion with EUROCONTROL [20] a prediction of the Mode S coverage of ECAC in 2015 has been derived. The conclusion was that double, even triple in many instances, Mode S en-route coverage would be available in Belgium, Czech Republic, Denmark, France, Germany, Ireland, Italy, Luxembourg, The Netherlands Portugal, Switzerland and the United Kingdom. Coverage could be down to single radar in TMAs.

Mode S coverage would therefore cover Western Europe (with the exclusion of Spain) but not be available in Northern or Eastern regions. This is shown in Figure 18..

Figure 18: Expected Mode S implementation for ECAC in 2015.

Red indicates Mode S coverage, Black indicates ECAC state without Mode S coverage. White indicates non-ECAC state.

The ability to extract an RA Report over Mode S is part of the functionality of the Mode S ground station and a modern ATC system designed for a Mode S environment should be able to transmit this information to the controller's CWP.

I INCAS Simulations

A simulator of ACAS events has been supplied by EUROCONTROL to Helios for use in this project. The INCAS tool takes ASTERIX category 48 radar data and reconstructs an aircraft's flightpath. ACAS logic is then applied to this flightpath and to all other aircraft in the neighbourhood to determine if an RA is likely to have occurred and the form of that RA.

Independently, RA Reports have been extracted from aircraft using an experimental 6-second Mode S radar sited at Gatwick. These reports are time-stamped upon arrival and may be compared with the INCAS simulation of the same event. An output of this analysis would be the comparison of the arrival time of the RA Report with INCAS' expectation of when the RA occurred.

This analysis is limited and has several shortfalls. Primarily these are:

- INCAS typically does not immediately generate an RA. Often the path of the aircraft has to be smoothed to cause an RA event which introduces a significant ambiguity in the time of occurrence of the RA.
- The Gatwick radar is extracting RA Reports over a significant proportion of the South of the UK. This is greater than the likely surveillance responsibility of a real Mode S implementation. The probability of extraction of the RA Report on the first beam sweep is therefore likely to be lower than operationally and could cause errors in the estimates of the time of the RA.
- A large proportion of the RAs detected are false. While a spreadsheet of known false RAs has been supplied, this does not cover all data. Hence RAs that INCAS reports to have occurred but for which no RA Report was downlinked have been ignored.
- Some avionics manufacturers [21] have implemented RA downlink so that data is not made available to the transponder during the RA but only immediately *after* the clear of conflict. The message is correctly implemented in that the resolution advisory terminated (RAT) flag is set to 1 to indicate the RA has terminated. All messages with RAT=1 have therefore been ignored.

An initial evaluation of 52 RA Reports extracted by the Gatwick radar was carried out. It was found that:

- 16 were false RAs (determined from a list supplied by EUROCONTROL).
- 19 RA Reports were received by the radar but INCAS was incapable of generating an RA, even with significant manipulation of the aircraft trajectory.
- 18 RAs matched between the RA Report and the INCAS simulation.

The result of these 18 RAs are shown below in Figure 19. Note that:

- Two RAs appeared to have been received *before* INCAS indicates the RA occurred onboard the aircraft. These have been given a downlink time of zero seconds.
- Two RAs were received on the ground a significant time after INCAS indicates they should have occurred onboard the aircraft. This cannot be

easily explained and indicates that a more detailed analysis of Mode S and RA Broadcast may be required.

- The majority of the RA Reports (11 out of 18) occurred between one and five seconds after INCAS indicates the RA would have occurred onboard the aircraft. This is exactly as expected if the RA were extracted on the first beam sweep of the Gatwick radar. Three RAs appear to have been extracted 10 seconds after INCAS indicates it occurred onboard the aircraft. These may have been extracted on the second beam sweep.

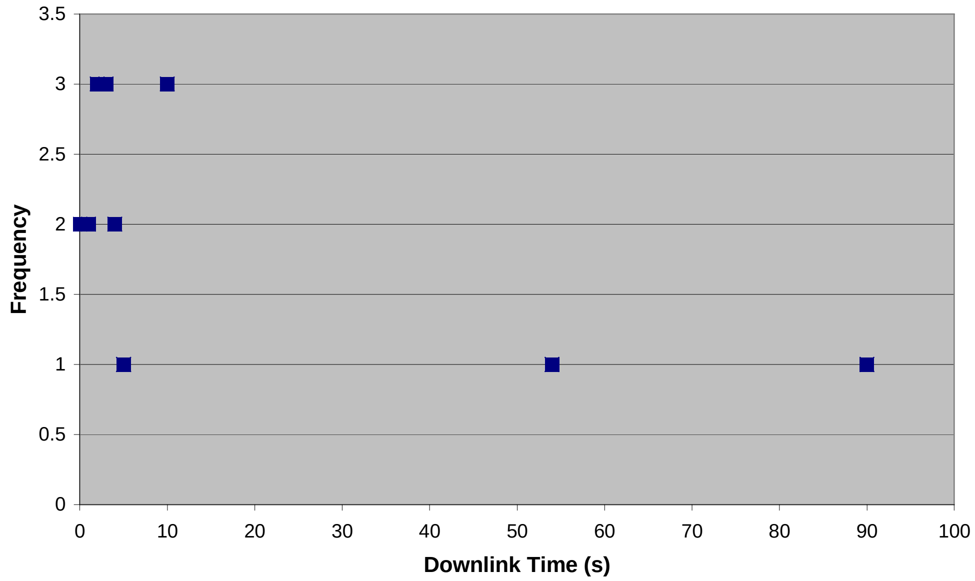

Figure 19: A frequency analysis of the time to downlink RA Report, INCAS simulation and radar data compared.

In conclusion, the INCAS tool has indicated that the Gatwick radar is probably extracting the majority of RAs on the first beam sweep. Some RAs appear not to have been downlinked until a significant time after the RA probably occurred. This deserves further study to determine if this is a result of INCAS' limitations, very distant RA events or a potential issue with the RA Report.

J Alternative datalink candidates

J.1 Introduction

This section describes some alternative datalink candidates that could be used for TCAS RA downlink:

- "DiV" Modification to VHF R/T;
- ACARS;
- VDL Mode 2/3;
- VDL Mode 4;
- UAT.

J.2 Data in Voice (DiV)

Frequentis Nachrichtentechnik GmbH [11] has defined a system to make a data transmission via the R/T system. Using the system, a short data message is transmitted on a 8.33 or 25 kHz voice channel either when the R/T microphone is pressed or automatically.

This system has been proposed specifically for RA downlink, although no message formats/transmission rates are defined for this.

There are no known plans to implement this system on aircraft in Europe. It has a potential to interfere with voice communications that may have to be investigated before it could be deployed.

J.3 ACARS

ACARS is a VHF data link that is widely used for transferring airline information. It was not designed for time-critical applications and can suffer from long transmission and network delays (tens of seconds).

Although ACARS is presently widely deployed, it will, in time, be replaced by VDL Mode 2 described below.

J.4 VDL Modes 2, 3 and 4

VDL Modes 2, 3 and 4 are "VHF Digital Links" standardised in ICAO.

VDL Mode 2 is built on the same underlying media access technique as ACARS, but is much more sophisticated. It is initially being deployed as an upgrade to ACARS and to support some ATC applications through the Link2000+ programme.

VDL Mode 2 has downlink transmission delay that has been estimated at 0.4 - 0.9s (95%) for a trial load [12]. However, the downlink delay is dependent on datalink load and will increase rapidly as the data traffic load increases. Furthermore there is no mechanism in VDL Mode 2 to allow prioritisation of some messages over others. Therefore downlink delays can be high when in the presence of only low priority traffic.

To date, VDL Mode 2 has a limited deployment in Europe and has not been mandated. Therefore, it is not known when a high equipage rate will be achieved.

VDL Mode 3 is an evolution of VDL Mode 2 that overcomes its downlink delay problems. It can ensure that high priority messages are very quickly dispatched to the ground. VDL Mode 3 is not deployed at all in Europe, and there are no known plans to do so.

VDL Mode 4 was designed initially for ADS-B and now supports communications applications also. It has an estimated downlink transmission delay of 1s [12]. The standard message formats include a flag set by the aircraft to indicate an ACAS RA, but no message for RA downlink is defined.

VDL Mode 4 has been the subject of extensive trials in Europe, but there are no known plans for widespread equipage.

J.5 UAT

Universal Access Transceiver (UAT) is a UHF datalink that is presently undergoing standardisation in ICAO. It is designed for ADS-B and ground broadcast applications (eg weather uplink).

UAT has been widely trialled in the US. There are no known plans for European deployment.

J.6 Summary

The datalinks discussed here have been standardised and/or deployed. However, each of them suffers from one or more of the following disadvantages when considered for TCAS RA downlink:

- Lack of integration into TCAS or definition of RA message formats;
- Lack of widespread deployment or plans for widespread deployment;
- Significant air-ground delays.

Therefore, none of the datalinks is considered in further detail.