ACAS PROGRAMME
ACASA PROJECT

Work Package 5

Final Report on Electromagnetic Environmental Effects of, and on, ACAS

ACAS/ACASA/02-016

Edition	**:**	**1**
Edition Date	**:**	**March 2002**
Status	**:**	**Released Issue**
Class	**:**	**EATMP**

DOCUMENT IDENTIFICATION SHEET

DOCUMENT DESCRIPTION

Document Title
ACAS PROGRAMME ACASA PROJECT

Work Package 5
Executive Summary
Electromagnetic environmental effects of, and on, ACAS

EWP DELIVERABLE REFERENCE NUMBER:

PROGRAMME REFERENCE INDEX:	**VERSION:**	1.1
	EDITION DATE:	March 2002

Abstract

This study report is a deliverable from work package (WP)5 of the ACAS Analysis (ACASA)Project, part of the ACAS Programme. The study focusses on the Electromagnetic environmental effects of and on ACAS.

Keywords

ACAS TCAS RVSM TA RA

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DOCUMENT STATUS AND TYPE

STATUS	CLASSIFICATION
Working Draft	General Public
Draft	EATMP
Proposed Issue	Restricted
Released Issue	

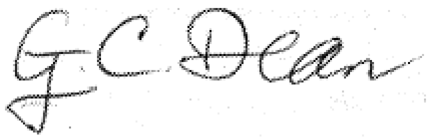
ELECTRONIC BACKUP

INTERNAL REFERENCE NAME:

HOST SYSTEM	MEDIA	SOFTWARE
Microsoft Windows	Type: Hard disk	
	Media Identification:	

DOCUMENT APPROVAL

The following table identifies all management authorities who have successively approved the present issue of this document.

AUTHORITY	NAME AND SIGNATURE	DATE
ACASA Project Manager	 Garfield Dean	4 March 2002
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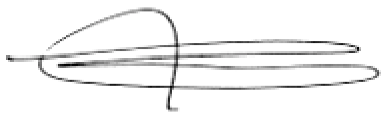
Director Infrastructure, ATC Systems & Support	 Guido Kerkhofs	20 March 2002

Document control sheet

Title:	**WP-5-Electromagnetic environmental effects of, and on, ACAS**	
Authors:	**Sven Halle (DFS)**	
Reference:	**ACASA/WP-5/201D**	
Pages:	**Cover & reverse + vi + 15**	
Version	Date issued	comments
1	15 November 2001	Final Report
1.1	1 March 2002	Editorial changes to merge WPs5/201D/198D/200D/211D in ACASA Project Report: Released Issue

TABLE OF CONTENTS

WP-5

Electromagnetic environmental effects of and on ACAS

WP-5: Final Report: Executive Summary on the study on the

Electromagnetic environmental effects of, and on ACAS

Version: 1.1

Prepared by Sven HALLE

1. INTRODUCTION

The Airborne Collision Avoidance System ACAS II is a co-operative surveillance system including an ACAS interrogator and a Mode S transponder on board of an aircraft. The ACAS interrogator tracks both Mode A/C and Mode S transponder-equipped aircraft in its vicinity. Tracking is accomplished using two entirely separate techniques. Mode A/C transponders are controlled via Mode C-only interrogations. Mode S transponders are acquired passively by listening for Mode S squitters. Surveillance is then performed by directly addressed UF0 Mode S interrogations challenging DF0 replies.

The utilisation of the SSR channels by ACAS may result in a degradation of the SSR system performance. In order to minimise the impact of ACAS upon the SSR system, ACAS interrogators are forced to limit their interrogation rates and their transmitter power by implementing a so-called interference limiting procedure (ILP). This procedure is expected to ensure that no transponder in the air is suppressed by ACAS activities for more than 2% of the time.

In addition to interference limiting, the simultaneous application of active and passive surveillance methods, termed "Hybrid Surveillance", is expected to improve ACAS surveillance performance while concurrently the effects on ATC processes and radio load will be minimised. Hybrid Surveillance is a technique based upon the Mode S Extended Squitter.

In order to evaluate the effectiveness of ACAS interference limiting algorithm as well as the concept of Hybrid Surveillance appropriate scenarios were developed and simulations were performed in order analyse the following aspects:

- impact of ACAS on MSSR/Mode S surveillance performance if ACAS implements the modified interference limiting algorithm,
- ACAS surveillance performance if ACAS implements the modified interference limiting algorithm,
- impact of ACAS on MSSR/Mode S surveillance performance if ACAS implements Hybrid Surveillance techniques,
- ACAS surveillance performance if ACAS implements Hybrid Surveillance techniques, and
- clustering.of ACAS equipped aircraft on ground based and airborne surveillance performance.

2. SIMULATION AND RESULT VALIDATION

Within the framework of the ACASA programme a study was conducted by the DFS/ESG to evaluate the effectiveness of ACAS interference limiting algorithms as well as the concept of Hybrid Surveillance. Therefore, several scenarios had been developed and a total of 14 (?) simulations were performed.

For validation purposes a second study with selected scenarios and simulation runs was conducted by QinetiQ afterwards. Even with some differences in several of their absolute values, which can be related to the different characteristics and assumptions that had been used within the two (DFS/ESG and QinetiQ) simulation tools, the QinetiQ results showed the same trends with the original DFS/ESG results.

On the first instances the results do not show the clear correlation between the QinetiQ and ESG modelling results. There are a number of variations which can be seen and potential explanations can be offered for each of these. Further investigation would be required to understand the source of these differences completely.

However, the simplest set of results, that of Transponder utilisation show reasonable agreement. More complex parameters show the same trends in both models but vary in absolute values. This is in the nature of simulation techniques and simulation validation using different models. In addition, within the models various equiment is modelled according to ICAO standards but with differing details. This reflects to a great extend the understanding during programing and the various possibilities of implementing such systems. Therefore, reasonable agreement in basic parameters and additional agreement in trends for derived data with reasonable deviation in absolute values results in a successful validation process. In this respect Quinetiq validated ESG results successfully.

3. IMPACT OF ACAS ON MSSR/MODE S PERFORMANCE

Since ACAS is using the SSR frequencies, ACAS interrogations and replies may cause additional impacts upon the SSR air traffic control system. On the downlink, replies generated in response to ACAS interrogations may interfere with replies challenged by SSR interrogators. On the uplink, two interference mechanisms have to be distinguished. Firstly, a transponder on-board of an ACAS equipped aircraft is suppressed during each own ACAS interrogation. Secondly, a transponder may be taken off the air by processing interrogations originating from other ACAS aircraft.

In order to limit the impact of ACAS on the SSR system, ACAS units are obliged to control their interrogation rates and transmitter power by the application of an interference limiting procedure (ILP).

To explore the effects of the ACAS surveillance and interference limiting concept on MSSR/Mode S system performance under various conditions, various scenarios were analysed in detail:

Scenario	***percentage of***						
	MS-I	***MAC-I***	***ACAS-I***	***MS-T***	***MAC-T***	***MKXII-T***	***MKXIIMS-T***
A01	0%	100%	90%	50%	50%	28%	72%
A02	24%	76%	90%	50%	50%	28%	72%
A03	24%	76%	50%	90%	10%	28%	72%
A04	100%	0%	50%	90%	10%	28%	72%
A05	24%	76%	75%	90%	10%	28%	72%
A06	24%	76%	75%	100%	0%	0%	100%
A07	100%	0%	50%	100%	0%	28%	72%
A08	24%	76%	75%	100%	0%	0%	100%
A09	100%	0%	75%	100%	0%	0%	100%

MS-I: civil ground stations equipped with a MSSR/Mode S interrogator,

MAC-I: civil ground stations equipped with a MSSR/Mode A/C interrogator,

ACAS-I: civil Mode S transponder-equipped aircraft with an ACAS interrogator,

MS-T: civil aircraft equipped with a Mode S transponder,

MAC-T: civil aircraft equipped with a Mode A/C transponder,

MKXIIMS-T: military aircraft equipped with a Mode S capable transponder,

MKXII-T: military aircraft equipped with a non-Mode S capable transponder.

From the investigations performed, the following conclusions could be drawn:

1. The ACAS interference limiting algorithm meets the 2% limit in all scenarios analysed. In all scenarios analysed, Mode A/C decode efficiency is about 5% below Mode S decode efficiency. Thereby, synchronous garbling is the main reason for the loss of Mode A/C replies. In all scenarios analysed, the Mode S detection is 100%, an effect that can be explained by the fact that Mode S avoids synchronous garbling by means of interrogation scheduling and, furthermore, in case of failure, the re-interrogation function can be invoked. Although reply efficiency and decode efficiency show some variations for the scenarios analysed, these variation are nearly not reflected in code and Mode S detection. This can be explained by the fact that the failure of a single interrogation/reply interaction can be compensated in case of Code A/C detection by the transmission of more than required interrogations during an antenna dwell and in case of Mode S detection by the re-interrogation function.

2. The order in which the ACAS interference limiting algorithms are applied warrants further investigation as it seems this may have a significant impact in the nature of any power reductions that are applied to an ACAS unit.

3. A transition from a mixed MSSR/Mode S interrogator environment to a full Mode S interrogator environment will reduce interrogator receiver utilisation by about 10% relative to mixed MSSR/Mode S interrogator environment. Mode S decode efficiency is 2-3% lower in a scenario with an equally shared Mode A/C and Mode S transponder environment than in the other scenarios analysed. Therefore the implementation of a Mode S ground infrastructure, especially within high-density TMA areas, would be beneficial. A transition from an equally shared Mode A/C and Mode S transponder environment to a predominated Mode S transponder environment will reduce interrogator receiver utilisation by about 40% relative to equally shared Mode A/C and Mode S transponder environment. In a predominated Mode S transponder environment and in a full Mode S transponder environment, the ACAS contribution to the overall transponder utilisation accounts for about 30%-40%.

4. The overall transponder utilisation is increased at least by a factor of two if military interrogators are taken into account. If military interrogators are taken into consideration, interrogator receiver utilisation will be more than doubled. The activity of military interrogators can reduce decode efficiency by 2-3%. However, it should be noted that the Mode S re-interrogation rate is slightly increased.

5. It should also be noted that the simulations were performed with all involved interrogators using monopulse SSR techniques, the use of sliding-window techniques would have further significant (negative) effects on the above results.

4. ACAS SURVEILLANCE PERFORMANCE

Concerning ACAS surveillance performance, it is postulated that ACAS is capable of operating in most air traffic densities without any significant performance degradation. Although ACAS is able to operate up to a range of 30 NM, the required nominal surveillance range of ACAS is 14 NM. However, when operating in high density, the interference limiting function may reduce system range to approximately 5 NM, which is still adequate to provide sufficient surveillance performance in the TMA. Furthermore, it is required that a track is established with a probability of at least 90% for aircraft within the surveillance range.

In order to explore the performance of ACAS surveillance under various conditions, the same scenarios were considered as analysed to determine MSSR/Mode S system performance.

<u>From the results achieved, the following conclusion could be drawn:</u>

1. The current solution for ACAS implementation offers a valid compromise between Interference Limiting and System Surveillance Performance. ACAS interrogators deployed in close proximity to Frankfurt airport are suffering more than twice the fruit seen by interrogators at greater distances. ACAS interrogators on the surface at Frankfurt airport have to reduce Mode C power and Mode S power to the absolute permitted limit of 10 dB and 13 dB. An increase of the number of ACAS interrogators from 50% to 75% in a full Mode S transponder and interrogator environment will raise the interrogator receiver utilisation by not more than 10% (relative to the 50% ACAS deployment).
2. In an equally shared Mode A/C and Mode S transponder environment, more than half of the interrogator receiver utilisation is caused by ACAS at interrogators deployed close to the airport. At greater distances, the ACAS contribution is approximately 20%. The Mode C round trip reliability can be quite low. Thereby, synchronous garbling is the driving factor. A transition from an equally shared Mode A/C and Mode S transponder environment to a predominated Mode S transponder environment will decrease the Mode C power reduction. Concurrently, the Mode S power reduction is raised. Mode A/C surveillance can significantly be improved due to the reduction of garbling. In a predominated Mode S transponder environment and in a full Mode S transponder environment, the ACAS portion of the overall interrogator receiver utilisation accounts for about 20-30%.
3. A transition from autonomous operated Mode S stations to an operation in clusters within a mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation by about 10% (relative to the autonomous scenario).

5. ACAS HYBRID SURVEILLANCE

Mode S transponders generate an unsolicited reply in the Mode S downlink format DF11 once per second known as "Mode S squitter". The squitter contains the unique Mode S address of the aircraft and is utilised by ACAS interrogators for the acquisition of Mode S transponders. For the future, an expansion of the squitter technique is intended by introducing so called Mode S Extended Squitters. Mode S Extended Squitters shall be used to broadcast aircraft-derived data to airborne and ground users.

The introduction of Mode S Extended Squitter provides further means to reduce ACAS interrogation rates by a new ACAS surveillance technique termed ACAS Hybrid Surveillance. The purpose of ACAS Hybrid Surveillance is to incorporate passively received data transferred via Mode S Extended Squitter while at the same time maintaining the independence of ACAS as an active surveillance system.

In order to explore the effects of ACAS Hybrid surveillance on MSSR/Mode S system performance, various scenarios were analysed in detail:

Scenario	***percentage of***							
	MS-I	***MAC-I***	***ACAS-I***	***ACAS-HS***	***MS-T***	***MAC-T***	***MKXII-T***	***MKXIIMS-T***
B01	0%	100%	100%	20%	50%	50%	28%	72%
B02	24%	76%	100%	20%	50%	50%	28%	72%
B03	24%	76%	75%	20%	90%	10%	28%	72%
B04	24%	76%	75%	80%	90%	10%	28%	72%
B05	100%	0%	75%	80%	90%	10%	28%	72%

MS-I: civil ground stations equipped with a MSSR/Mode S interrogator,

MAC-I: civil ground stations equipped with a MSSR/Mode A/C interrogator,

ACAS-I: civil Mode S transponder-equipped aircraft with an ACAS interrogator,

ACAS-HS civil ACAS-equipped aircraft applying Hybrid Surveillance

MS-T: civil aircraft equipped with a Mode S transponder,

MAC-T: civil aircraft equipped with a Mode A/C transponder,

MKXIIMS-T: military aircraft equipped with a Mode S capable transponder, and

MKXII-T: military aircraft equipped with a non-Mode S capable transponder.

<u>From the results achieved the following conclusion could be drawn:</u>

1. Neither set of modelling show any clear benefits in terms of RF impact of introducing Hybrid Surveillance and a reduction in the levels of Mode A/C FRUIT is in the near term a more important factor in improving the RF environment: In the environment simulated, ACAS Hybrid Surveillance affects the performance of ground interrogators only slightly.

However, in increasing traffic densities (especially in high-density TMAs) the ground environment will benefit in the future from the lower interference levels.

2. The application of ACAS Hybrid Surveillance will stabilise the surveillance range of ACAS equipped aircraft making it, to some extend, independent of most aircraft densities. In particular, in the vicinity of major airports power and surveillance range reduction will become effective later compared with normal ACAS operation.

6. IMPACT OF ACAS CLUSTERS ON THE ATM-ENVIRONMENT AND PERFORMANCE OF OTHER ACAS

To support save air traffic operation Airborne Collision Avoidance Systems (ACAS) have been standardised by ICAO. The Traffic Alert and Collision Avoidance System (TCAS) is the implementation available today. TCAS systems are divided in TCAS I, which is mainly operated by commuter aircraft, helicopter and general aviation, and TCAS II, which is foreseen for commercial air transport aircraft. While TCAS I supports “see and avoid” with the capability to generate Traffic Advisories, TCAS II are additionally capable of generating automatic Resolution Advisories against potential threat aircraft. TCAS II (Version 7) is compliant with ICAO ACAS II standards. Regional and global mandates have been published to equip aircraft with ACAS II. ACAS I is not foreseen to be operated in international airspace. However, industry is advertising products and therefore some of the important aspects were investigated. When the report is referring to ICAO compliant equipment, the acronym “ACAS” has been used, while special implementations are named “TCAS”.

The goal of the analysis was to explore effects of clustered ACAS/TCAS interrogators in the vicinity of Frankfurt airport upon the MSSR/Mode S, ACAS II, and TCAS I surveillance performance. In order to achieve this goal, three scenarios, denoted by C01, C02, and C03, were analysed in detail. The three scenarios under examination were defined on the basis of scenario A05 discussed in chapter 3.

The three scenarios C01, C02, and C03 defined for the analysis differed from scenario A05 with respect to additional numbers of aircraft equipped with ACAS/TCAS interrogators and Mode S transponders. Beside the interrogators and transponders deployed in scenario A05, the three scenarios under examination included in detail:

Scenario C01: 5 additional aircraft deployed in one cluster at Frankfurt/Kreuz (motorway junction), each equipped with an ACAS II interrogator and a Mode S transponder.

Scenario C02: 36 additional aircraft
5 at Frankfurt/Kreuz (the same as in scenario C01),
18 clustered at Frankfurt/Waldstadion (stadium),
13 clustered at Frankfurt/Messe (fairgrounds),
each equipped with an ACAS II interrogator and a Mode S transponder.

Scenario C03: 36 clustered aircraft (the same as in scenario C02),
each equipped with an TCAS I interrogator and a Mode S transponder.

It should be noted that the three scenarios considered in the present study included no military interrogators. Furthermore, it should be pointed out that the 12 Mode S interrogators were supposed to be operated as autonomous Mode S sites without any clustering.

Since Frankfurt has been defined as the area of interest, the ASR sites Frankfurt/Süd and Frankfurt/Nord were chosen as Interrogators of Interest (IoI) for the analysis of MSSR/Mode S system performance. Thereby, Frankfurt/Süd, referenced in the scenario data base by index 15, was modelled as a MSSR/Mode S station, while Frankfurt/Nord, index 9, was assumed to be operated as a MSSR/Mode A/C interrogator. For the ASR sites Frankfurt/Süd, all transponders within a surveillance range of 100 NM were defined as Transponders of Interest (ToIs). Concerning Frankfurt/Nord, all transponders within a coverage of 60 NM were regarded as ToIs. The selected IoIs along with their ToIs formed the sample of the SSR system, the performance had to be explored for. It should be noted, although the transponders within the surveillance range were considered as ToIs only, the signal load was produced by all interrogators and transponders deployed in the scenario.

In order to investigate the surveillance performance of ACAS II, the aircraft referenced in the scenario data base by the indices 1048 and 1049 were chosen as ACAS II IoIs. Thereby, IoI 1048 represented an overflight at an altitude of 15.000 ft and at a distance of 6.3 NM from the SSR site Frankfurt/Süd. IoI 1049, at a height of 5.000 ft and a distance of 5.2 NM, was regarded as an approach for landing at Frankfurt airport.

For the analysis of TCAS I surveillance performance, the aircraft with the index 1014 was selected as IoI. IoI 1014 is one of the 5 aircraft at Frankfurt/Kreuz added to the scenario.

6.1 Effects of ACAS clustering on ground performance

Due to the equal ground environment, Mode A/C interrogation rates, Mode A/C-only rates, and the UF11 rates induced by ground interrogators are the same for all scenarios analysed. The UF4 and UF5 rates are slightly increased due to higher numbers of Mode S equipped aircraft. The number of interrogations generated by airborne interrogators depends on the number of aircraft in the vicinity, but are tremendously raised by 3 to 8 times if aircraft in clusters are taken into account.

In all cases, the highest transponder utilisation is achieved in close proximity to the airport. In “normal” scenarios, the overall transponder utilisation is well below 2%. For the Frankfurt simulation, a small cluster of 5 additional ACAS increases transponder utilisation up to the 2 % limit. Further 31 ACAS II units in 2 clusters raise the maximum transponder utilisation induced by ACAS II to 7.7%, contributing with more than 70% to the peak overall transponder utilisation. In that case, the 2% criterion is not satisfied by almost all transponders within a range of 8 NM to the airport. Substituting the 36 ACAS II units by TCAS I interrogators reduces the maximum ACAS transponder utilisation. However, the limits are still violated by a remarkable number of transponders within 5.5 NM to the airport suffering a utilisation by ACAS of significantly more than 2%.

The decrease in transponder reply efficiency seems to some extend be proportional to the number of aircraft in a cluster (5, 13, 18), since the worst case degradation varies between 7% and 16%.

Although the Mode A/C interrogation rates remain the same, the Mode A/C fruit rates are increased with the density of aircraft. This is induced by replies of the additional transponders. The Mode A/C fruit rate is further increased when the additional ACAS II units are replaced by TCAS I interrogators due to a higher reply efficiency. The Mode C-only rates and the DF0 rates induced by ACAS II increase when the ACAS II density rises. A tremendous increase of the DF0 rates is predicted if three clusters with a total of 36 additional ACAS II units are taken into consideration, which reflects the significant increase of UF0 interrogation rates. If TCAS I equipage is assumed for the 36 additional aircraft, Mode C-only and UF0 fruit is considerably reduced, but a very huge rate of extra Mode C fruit is achieved. In both scenarios, the relevant amount of fruit (DF0 resp. Mode C) induced by the 36 additional units deployed in 3 clusters is increased by a factor of about 15.

The interrogator receiver utilisation caused by ground stations, and as a consequence decode efficiency, are only slightly affected by the scenario variations analysed. The moderate increase of receiver utilisation obtained is due to replies of the transponders added and slightly raises re-interrogation rates of the Mode S stations. 5 additional ACAS II units clustered in close vicinity of Frankfurt airport increase the interrogator receiver utilisation slightly, but 36 ACAS II units increase interrogator receiver utilisation significantly. In this case, the utilisation caused by ACAS II is raised by a factor of more than six. This results in a decode efficiency reduction of 3% for Frankfurt/Süd and even 11% for Frankfurt/Nord. The considerable reduction at the IoI Frankfurt/Nord is mainly caused by the additional aircraft which are deployed in three clusters resulting in a large number of garbling situations. As expected, the decoding of Mode S replies is less affected.

Furthermore, interrogator receiver utilisation caused by airborne systems is nearly doubled if those additional 36 interrogators are fitted with TCAS I (instead of ACAS II). Despite that, the Mode A/C decode efficiency is slightly improved, while the Mode S decode efficiency is reduced to nearly the same amount.

In summary, there is only a slight impact on the success of a single interrogation/reply interaction performed by the two IoIs, if the 5 ACAS II interrogators deployed at Frankfurt/Kreuz are taken into account. Especially at IoI Frankfurt/Nord, round trip reliability for Mode A/C interactions is reduced considerably, with the 36 additional airborne units.

In case of 36 clustered ACAS II units, Code A/C detection is significantly decreased at an MSSR sensor in particular. The mean values are reduced by 11% for Mode A and by 12% for Mode C. The decrease is mainly caused by the transponders deployed in the clusters causing a lot of garbled replies. Some of these transponders can not be acquired by the MSSR sensor (Code Detection < 20%). Equipping the additional aircraft with TCAS I units does not change the situation.

Contrary, in all cases Mode S detection probability varies only slightly and achieves 100% for more than 88% of the ToIs. The minimum detection probability obtained among the remaining ToIs drops to 95% in the worst case.

6.2 Airborne clusters and ACAS II surveillance performance

ACAS interrogators on the surface at Frankfurt airport have to reduce Mode C power and Mode S power to the absolute permitted limit of 10 dB and 13 dB, respectively. If the 5 ACAS II units at Frankfurt/Kreuz are taken into consideration, power reduction is only slightly increased for other ACAS II interrogators. The Mode C power reduction is between 7-8 dB within a range of 18 NM to the SSR site Frankfurt/Süd. Mode S power has to be reduced by most of the ACAS units deployed within 13 NM of Frankfurt/Süd by more than 7 dB. Adding the set of 36 ACAS II units, the surveillance range of ACAS II interrogators within a range of 30 NM and 20 NM respectively is affected to the same amount.

When the ACAS II interrogators on board of those 36 aircraft are replaced by TCAS I units, the remaining ACAS II interrogators in the Frankfurt area are allowed to transmit surveillance interrogations at slightly higher power again, reaching the values mentioned above.

Although Mode A/C interrogation rates are the same in all scenarios, the Mode A/C fruit rates are decreased when the 36 ACAS II interrogators are taken into account. This is due to two contrary effects. On one hand, the transponders added are producing extra fruit. On the other hand, the reply efficiency is significantly decreased which results in a reduction of reply rates. This effect overbalances the first one.

If the clustered 36 ACAS II units are replaced by TCAS I interrogators, reply efficiency is improved inducing much higher Mode A/C fruit rates. The significant variation of interrogator receiver utilisation for the three scenarios analysed is mainly caused by ACAS, the contribution of ground stations varies only weakly. Interrogator receiver utilisation is nearly doubled if the additional 36 clustered ACAS II units are taken into account. Converting these units to TCAS I interrogators, receiver utilisation at the two ACAS II IoIs analysed is further raised.

At ACAS II IoI 1048, decode efficiency for Mode C-only replies is only weakly affected by the scenario variations. But decode efficiency for Mode S replies is considerably reduced in the TCAS I scenario. This is a consequence of the huge Mode C fruit rates resulting in high interrogator receiver utilisation. Nevertheless, this IoI is an example, that the altitude and range filter improve ACAS surveillance performance while passing high density airports. However, the round trip reliability for the ToIs under surveillance (only two) is significantly decreased by the activity by clustered aircraft, since both ToIs are suffering a quite high signal load. This considerably reduces the ability of the transponders to reply to interrogations of the ACAS II IoI 1048.

On the other hand, IoI 1049, decode efficiency is significantly decreased, if clustered ACAS II interrogators are detected in the vicinity. Round trip reliability for the three Mode A/C ToIs under surveillance in particular is considerably reduced. Replacing the 36 clustered ACAS II interrogators by TCAS I units improves decoding of Mode C replies while Mode S decoding is further reduced, as already noticed for ground based sensors. In general, the variation of the probabilities for achieving at least one successful interrogation/reply interaction during a one second surveillance interval reflects the variation of the round trip reliability.

Concerning Mode S surveillance performance of the IoI 1049, round trip reliability for Mode S transactions is reduced by the activity of the clustered ACAS II units. The mean value, calculated across the 24 ToIs, is decreased from 90% to 84%. Round trip reliability is significantly further decreased when the 36 ACAS II interrogators are substituted by TCAS I units. The average across all 55 ToIs is reduced down to 61%. Thereby, especially the round trip reliability for the ToIs deployed in the clusters are significantly affected. Primarily, the reason for the reduction is the drop of decode efficiency to 79% caused by the huge Mode C fruit produced in response to TCAS I interrogations. But the loading at the transponders under surveillance of IoI 1049 is increased above average as well and, as a consequence, reply efficiency for the interrogations of IoI 1049 is also significantly decreased to 73%.

6.3 TCAS I clusters and surveillance performance in high density airspace

All TCAS I interrogators have to reduce transmitter output power by 15 dB relative to the peak power. The power reduction of the TCAS I units results in a surveillance range of 4.7 NM in the forward sector, 3 NM in the right and left sector, and 1.9 NM in the aft sector. For Mode A/C transponders with lower sensitivity, the surveillance range is further reduced to 3.3 NM in the forward beam, 2.1 NM in the right and left beam, and 1.3 NM in the aft beam.

In average, each ToI was able to reply to 90% of the interrogations of interest. However, since the majority of replies was garbled, the IoI was able to correctly decode only 4.7 % of the signals received.

A round trip reliability of 50% was obtained only for one ToI, located at a range of 4.3 NM. Two ToIs, very close to the IoI, achieved a round trip reliability of about 40% and the probability of successfully completing a single interrogation/reply transaction was below 20% for the remaining targets.

However, the probability of correctly decoding at least one valid reply during a one second surveillance interval is above 50% for 10% of ToIs . For about 31% of the ToIs the probability is equal to zero, which means that these ToIs are never seen by the TCAS I interrogator. For the remaining about 20% of ToIs, the probability is somewhere between 0.2% and 30%. Thereby, a probability of 0.2% can be interpreted such that the IoI gets an altitude information of the target only every 500s in average. A probability of 30% means an update every three seconds.

Final Report

List of tables

Table of Abbreviations

ACAS	Airborne Collision Avoidance System
ASR	Airfield Surveillance Radar
ATC	Air Traffic Control
dB	Decibel
dBm	Decibel (with reference to 1mWatt)
DE	Decode Efficiency
DF	Mode S Downlink Format
DFS	Deutsche Flugsicherung GmbH
ESG	Elektroniksystem- und Logistik-GmbH
Fruit	Friendly replies unsynchronised in time
FR	Fruit Rate
ft	Feet
Hz	Hertz
I	Interrogator
ICAO	International Civil Aviation Organisation
IFF	Identification Friend or Foe
ILI	Interference Limiting Inequality
ILP	Interference Limiting Procedure
IoI	Interrogator of Interest
IRU	Interrogator Receiver Utilisation
MB	Main Beam
MBIR	Main Beam Interrogation Rate
MHz	Megahertz
Mk	Mark
MS	Mode S
s	Microsecond
ms	Millisecond
MSSR	Monopulse Secondary Surveillance Radar
NM	Nautical miles
RE	Reply Efficiency
RF	Radio Frequency
s	Seconds
SICASP	Secondary Surveillance Radar Improvement and Collision Avoidance Systems Panel
SISEVA	SSR IFF System Evaluator
SISSIM	SSR IFF System Simulator
SL	Side Lobe
SLIR	Side Lobe Interrogation Rate
SSR	Secondary Surveillance Radar
T	Transponder
TCAS	Traffic Alert and Collision Avoidance System
ToI	Transponder of Interest
TU	Transponder Utilisation
UF	Mode S Uplink Format

Definition of performance parameters

Main Beam Interrogation Rate (MBIR):
The main beam interrogation rate denotes the mean number of main beam interrogations received by a transponder per second in a given Mode or Mode S format

Side Lobe Interrogation Rate (SLIR):
The side lobe interrogation rate denotes the mean number of side lobe interrogations received by a transponder per second in a given Mode or Mode S format

Transponder Utilisation (TU):
The transponder utilisation denotes the percentage of time a transponder is occupied by main beam and side lobe interrogations of a given Mode or Mode S format.

Overall Transponder Utilisation (OTU):
The overall transponder utilisation denotes the percentage of time a transponder is occupied by main beam and side lobe interrogations of all Modes and Mode S formats.

Reply Efficiency (RE):
The reply efficiency denotes the percentage of interrogations in a given Mode or Mode S format that are successfully received, processed and replied by a transponder.

Fruit Rate (FR):
The fruit rate denotes the mean number of replies received by an interrogator per second in a given Mode or Mode S format.

Interrogator Receiver Utilisation (IRU):
The interrogator receiver utilisation denotes the percentage of time reply signals are present at the receiver in a given Mode or Mode S format.

Overall Interrogator Receiver Utilisation (OIRU):
The overall interrogator receiver utilisation denotes the percentage of time reply signals are present at the receiver including all Modes and Mode S formats.

Decode Efficiency (DE):
The decode efficiency denotes the percentage of replies challenged by an interrogator which are correctly decoded.

Round Trip Reliability (RTR):
The round trip reliability denotes the percentage of interrogation-reply interactions initiated by an interrogator which are successfully completed.

Code A Detection (PCA):
The Code A detection denotes the probability that a target position report with correct Code A data is produced for a transponder during a scan.

Code C detection (PCC):
The Code C detection denotes the probability that a target position report with correct Code C data is produced for a transponder during a scan.

Mode S detection (PS):
The Mode S detection denotes the probability that a Mode S transaction for a Mode S transponder is successfully completed during a scan.

Reference tables for the scenarios analysed

Scenario	*Percentage of*						
	MS-I	*MAC-I*	*ACAS-I*	*MS-T*	*MAC-T*	*MKXII-T*	*MKXIIMS-T*
A01	0%	100%	90%	50%	50%	28%	72%
A02	24%	76%	90%	50%	50%	28%	72%
A03	24%	76%	50%	90%	10%	28%	72%
A04	100%	0%	50%	90%	10%	28%	72%
A05	24%	76%	75%	90%	10%	28%	72%
A06	24%	76%	75%	100%	0%	0%	100%
A07	100%	0%	50%	100%	0%	28%	72%
A08	24%	76%	75%	100%	0%	0%	100%
A09	100%	0%	75%	100%	0%	0%	100%

Scenario A01-A09: percentage of systems

Ground environment **Air environment**			**MAC-I 49**	**MAC-I/MS-I 12/37**	**MS-I 49**
MAC-T	**MS-T**	**ACAS-I**			
408	**409**	**353**	A01	A02	
81	**736**	**“**		A03	A04
“	**“**	**528**		A05	
0	**817**	**392**			A07
“	**“**	**586**		A06/A08	A09

ground and air environment (number of systems) for scenario A01-A09

Scenario	*percentage of*							
	MS-I	*MAC-I*	*ACAS-I*	*ACAS-HS*	*MS-T*	*MAC-T*	*MKXII-T*	*MKXIIMS-T*
B01	0%	100%	100%	20%	50%	50%	28%	72%
B02	24%	76%	100%	20%	50%	50%	28%	72%
B03	24%	76%	75%	20%	90%	10%	28%	72%
B04	24%	76%	75%	80%	90%	10%	28%	72%
B05	100%	0%	75%	80%	90%	10%	28%	72%

Scenario B01-B05 : percentage of systems

Ground environment **Air environment**				**MAC-I 49**	**MAC-I/MS-I 12/37**	**MS-I 49**
MAC-T	**MS-T**	**ACAS-I**	**ACASHS-I**			
408	**409**	**392**	**78**	B01	B02	
81	**736**	**528**	**106**		B03	
“	**“**	**“**	**422**		B04	B05

ground and air environment (number of systems) for scenario B01-B05

MS-I:	civil ground stations equipped with a MSSR/Mode S interrogator
MAC-I:	civil ground stations equipped with a MSSR/Mode A/C interrogator
ACAS-I:	civil Mode S transponder-equipped aircraft with an ACAS interrogator
ACAS-HS	civil ACAS-equipped aircraft applying Hybrid Surveillance
MS-T:	civil aircraft equipped with a Mode S transponder
MAC-T:	civil aircraft equipped with a Mode A/C transponder
MKXIIMS-T:	military aircraft equipped with a Mode S capable transponder
MKXII-T:	military aircraft equipped with a non-Mode S capable transponder

WP-5.1

Electromagnetic environmental effects of and on ACAS

This paper is a study on the Electromagnetic environmental effects of and on ACAS as described in the ACASA workplan section 5.

1. INTRODUCTION

The Airborne Collision Avoidance System ACAS II is a co-operative surveillance system including an ACAS interrogator and a Mode S transponder on board of an aircraft. The ACAS interrogator tracks both Mode A/C and Mode S transponder-equipped aircraft in its vicinity. Tracking is accomplished using two entirely separate techniques. Mode A/C transponders are controlled via Mode C-only interrogations. Mode S transponders are acquired passively by listening for Mode S squitters. Surveillance is then performed by directly addressed UF0 Mode S interrogations challenging DF0 replies. If collision threat is detected by the system, vertical resolution advisories are computed and exchanged via Mode S data link.

Due to the involvement of the SSR transponder in the collision avoidance system, ACAS interrogates at the SSR uplink frequency 1030 MHz and detects replies on the SSR downlink frequency 1090 MHz. The utilisation of the SSR channels by ACAS may result in a degradation of the SSR system performance. In order to minimise the impact of ACAS upon the SSR system, ACAS interrogators are forced to limit their interrogation rates and their transmitter power by implementing a so-called interference limiting procedure (ILP). This procedure is expected to ensure that no transponder in the air is suppressed by ACAS activities for more than 2% of the time.

Measurements performed on the SSR uplink channel revealed that the currently implemented interference limiting algorithm for TCAS 6.04A does not completely satisfy the criteria imposed upon ACAS. Problems were arising especially in the vicinity of airports. Therefore, the interference limiting algorithm has been modified by the responsible ICAO Panel (SICASP). A compromise was necessary to guarantee on one hand the desired reduction in the overall ACAS interrogation rates while maintaining on the other hand sufficient surveillance performance for collision avoidance. A validation of this compromise, which is certainly a significant improvement, was still required. Therefore, various scenarios were developed to cover the relevant aspects. While they are based on German data, several spots were analysed representing also different European scenarios.

In addition to the modifications of the interference limiting algorithm mentioned above, the simultaneous application of active and passive surveillance methods, termed "Hybrid Surveillance", is expected to improve ACAS surveillance performance while concurrently the effects on ATC processes and radio load will be minimised. Hybrid Surveillance is a technique based upon the Mode S Extended Squitter. It is anticipated that Hybrid Surveillance will meet the 2% limit set by SICASP especially in the vicinity of airports.

Therefore, appropriate investigations were required to demonstrate how the overall environment will be affected by the application of the new technique.

In order to evaluate the modified interference limiting algorithm as well as the concept of Hybrid Surveillance appropriate scenarios were developed and the existing simulation model SISSIM was upgraded in order to establish a basis for detailed investigations concerning the following aspects:

- impact of ACAS on MSSR/Mode S surveillance performance if ACAS implements the modified interference limiting algorithm,
- ACAS surveillance performance if ACAS implements the modified interference limiting algorithm,
- impact of ACAS on MSSR/Mode S surveillance performance if ACAS implements Hybrid Surveillance techniques,
- ACAS surveillance performance if ACAS implements Hybrid Surveillance techniques.

The analysis performed to explore the issues listed above constitutes the subject of the present report which is structured into seven parts. Following this introductory section, in section 2 the environment 2005 used for the study is discussed. Section 3 introduces the simulation model SISSIM, which was already used in the past for various national and multinational studies related to SSR channel load in civil and military environments. Section 4 describes the analysis performed to explore the effects of ACAS upon the MSSR/Mode S system performance in case of implementing the modified ACAS interference limiting algorithm. Based on the same condition, Section 5 explores ACAS surveillance performance. Section 6 is dealing with the impact of ACAS on MSSR/Mode S system performance if Hybrid Surveillance techniques are applied by ACAS. The effects of Hybrid Surveillance on the surveillance performance of ACAS itself is the objective of section 7.

Comparing the results discussed in the present report with those obtained by simulations performed in 1996 (see [4]) it should be borne in mind that the earlier analysis considered civil ground interrogators using sliding window techniques. Since that time all German civil sensors have been upgraded to Monopulse using improved reception techniques and lower interrogation repetition frequencies.

2. ENVIRONMENT 2005

An environment constituted the basis for the investigations of SSR/Mode S and ACAS system performance which represented the estimated air traffic situation over Germany for the year 2005. Additionally, the distribution of civil SSR sites and their technical and operational characteristics were included. The environment took into account the following interrogator and transponder types:

- civil MSSR (Mode A/C) interrogators,
- civil Mode S interrogators,
- ACAS interrogators,
- civil Mode A/C transponders,
- civil Mode S transponders,
- military non-Mode S capable transponders, and
- military Mode S capable transponders.

The basis for the development of the environment 2005, used in the present study, constituted a scenario which was developed for previous studies in close co-operation with the corresponding military and civil authorities.

The ground environment for the year 2005 included 49 civil SSR ground stations which were modelled either as Monopulse SSR (MSSR) sites or as Mode S stations. Interrogators using sliding window techniques were not considered. Furthermore, it should be noted that military interrogators were not taken into account.

The development of the civil air environment was based on a real busy day snapshot recorded by DFS in 1999. This environment was extrapolated to 2005 assuming an annual increase of 5% which resulted in a total of 775 civil aircraft for 2005. On the military side, a total of 145 aircraft was assumed. In accordance with prognoses of military authorities, an increase of military air traffic until 2005 is unlikely and was, therefore, not taken into consideration. The following Table 2-1 provides an overview of the number of platforms included in the environment 2005.

Platform type	Number
civil MSSR ground stations	49
civil aircraft airborne	775
military aircraft airborne	145
aircraft at apron Frankfurt	42
ACAS turned on at apron	4

Table 2-1: Environment 2005

A more detailed description of the environment 2005, including the technical and operational data used for the analysis, is provided in [1].

3. SIMULATION MODEL

The simulation model SISSIM (**S**SR **I**FF **S**ystem **Sim**ulator) was utilised for the analysis of MSSR/Mode S and ACAS surveillance performance. The model, designed as a discrete simulation programme, has been developed and successively upgraded since 1994. The original goal of the model consisted in the evaluation of the mutual interference arising from interactions between civil SSR and military IFF systems deployed within a common area. In the past, the model was used for various national and multinational studies related to the prediction of SSR and IFF system performance. Within international working groups the model was successfully validated against simulation programmes developed in US and UK.

The software of SISSIM is coded in MODSIM III, which is a modern language for object oriented programming with special capabilities for discrete-event simulation. For the time being, the model is running on PC under Windows NT.

The current version of the simulation programme is capable to handle Mode A/C, Mode S, ACAS, as well as military Mk XA and Mk XII interrogators. Models for four different transponder types are included: civil Mode A/C transponders, civil Mode S transponders, military Mode S transponders, and military non-Mode S capable transponders. It should be noted that the models for processing of interrogations by transponders as well as the models for the decoding and evaluation of replies by interrogators are based on measurements.

A detailed description of the simulation model SISSIM, used for the analysis discussed within the present report, is provided in [2].

4. IMPACT OF ACAS ON MSSR/MODE S PERFORMANCE

4.1 Objective of analysis

The Airborne Collision Avoidance System ACAS II is designed to provide effective surveillance of both Mode A/C and Mode S transponder-equipped aircraft. Mode A/C aircraft are tracked by using Whisper/Shout sequences consisting of Mode C-only all-call interrogations. A sequence is transmitted once per second. Mode S transponders are acquired passively by monitoring the Mode S squitter regularly transmitted by a transponder each second. Tracking is then accomplished using directly addressed interrogations of the Mode S uplink format UF0 which are challenging replies in the Mode S downlink format DF0.

Since ACAS is using the SSR frequencies 1030 MHz (uplink) and 1090 MHz (downlink), ACAS interrogations and replies may cause additional impacts upon the SSR air traffic control system. On the downlink, replies generated in response to ACAS interrogations may interfere with replies challenged by SSR interrogators. On the uplink, two interference mechanisms have to be distinguished. Firstly, a transponder on-board of an ACAS equipped aircraft is suppressed during each own ACAS interrogation. Secondly, a transponder may be taken off the air by processing interrogations originating from other ACAS aircraft. Both effects result in a reduction of the transponder availability and, as a consequence, in a potential degradation of the SSR system performance.

In order to limit the impact of ACAS on the SSR system, ACAS units are obliged to control their interrogation rates and transmitter power by the application of an interference limiting procedure (ILP). The interference limiting procedure is based on three interference limiting inequalities (ILI). If at least one of these inequalities is not satisfied, an ACAS interrogator adjusts its interrogation rate and transmitter power such that the three inequalities become true. The aim of this procedure is to minimise the impact of ACAS on the SSR system and to ensure a transponder utilisation by ACAS not exceeding 2%. Thereby, the 2% limit comprises interrogations from other ACAS interrogators as well as the mutual suppression caused by the on-board ACAS interrogator.

In order to analyse the effectiveness of ACAS interference limiting, investigations were performed for various scenarios. In section 4.2 the analysis methodology applied is described. The results obtained are presented in section 4.3.

4.2 Analysis methodology

In order to explore the effects of the ACAS surveillance and interference limiting concept on MSSR/Mode S system performance under various conditions, nine scenarios were analysed in detail. All scenarios considered were based on the environment 2005 described within section 2. The scenarios varied with respect to the interrogator equipage of the SSR ground stations and the transponder equipage of the civil and military aircraft deployed in the environment 2005. Within the following Table 4-1, the scenarios analysed are listed with regard to number and percentage of

MS-I: civil ground stations equipped with a MSSR/Mode S interrogator,
MAC-I: civil ground stations equipped with a MSSR/Mode A/C interrogator,
ACAS-I: civil Mode S transponder-equipped aircraft with an ACAS interrogator,
MS-T: civil aircraft equipped with a Mode S transponder,
MAC-T: civil aircraft equipped with a Mode A/C transponder,
MKXIIMS-T: military aircraft equipped with a Mode S capable transponder,
MKXII-T: military aircraft equipped with a non-Mode S capable transponder.

Scenario	***Number/percentage of***													
	MS-I		***MAC-I***		***ACAS-I***		***MS-T***		***MAC-T***		***MKXII-T***		***MKXIIMS-T***	
A01	0	0%	49	100%	353	90%	409	50%	408	50%	41	28%	104	72%
A02	12	24%	37	76%	353	90%	409	50%	408	50%	41	28%	104	72%
A03	12	24%	37	76%	353	50%	736	90%	81	10%	41	28%	104	72%
A04	49	100%	0	0%	353	50%	736	90%	81	10%	41	28%	104	72%
A05	12	24%	37	76%	528	75%	736	90%	81	10%	41	28%	104	72%
A06	12	24%	37	76%	586	75%	817	100%	0	0%	0	0%	145	100%
A07	49	100%	0	0%	392	50%	817	100%	0	0%	41	28%	104	72%
A08	12	24%	37	76%	586	75%	817	100%	0	0%	0	0%	145	100%
A09	49	100%	0	0%	586	75%	817	100%	0	0%	0	0%	145	100%

Table 4-1: Scenarios A01-A09[1]

It should be noted that all scenarios included no military interrogators. Furthermore, it should be pointed out that in scenario A06 the 12 Mode S interrogators were supposed to be operated in two clusters. For all other scenarios, autonomous operation of the Mode S sites was assumed.

Due to the fact that Frankfurt is the area with the highest air traffic density over Germany, the ASR site Frankfurt/Süd and the long range radar at Neunkirchen were chosen as Interrogators of Interest (IoI) for the analysis. Beside these two sites, the ASR stations at

[1] A removable table defining the scenarios A01-A09 is provided in Annex B to be used as a cross reference list for the following discussion of results.

München/Süd and Teufelsberg as well as the long range system at Nordholz were selected as further IoIs. All scenarios were based on German data. However, beside the German hot spot Frankfurt interrogators deployed in other areas were investigated as well in order to allow comparisons with other European air spaces.

Since scenario A01 represented a pure MSSR/Mode A/C interrogator environment, in the simulation performed the selected IoIs were also modelled as MSSR stations performing surveillance of both Mode A/C and Mode S transponders by means of Mode A/C interrogations.

In the scenarios A02 to A09, the selected IoIs were part of the SSR sites equipped with a Mode S interrogator. In the simulation programme, the Mode S interrogators were modelled in compliance with the multisite acquisition protocol. Therefore, the IoIs transmitted Mode S only all-call interrogations (UF11) and Mode A/C-only all-call interrogations during all-call periods and tracked Mode S transponders via selective Mode S transactions of the formats UF4/DF4 and UF5/DF21. When simulation started, each IoI was assumed to have already acquired all Mode S transponders within its surveillance volume. Thus, a steady state condition could be monitored during the whole simulation. The Mode S surveillance was modelled such that each of the two transactions (UF4/DF4 and UF5/DF21) was performed for all Mode S transponders during each antenna sweep. In case of failure, a transaction was repeated up to a maximum of two re-interrogations.

For the ASR sites Frankfurt, München, and Teufelsberg (Berlin), all transponders within a surveillance range of 100 NM of the IoI were defined as Transponders of Interest (ToIs). Concerning the long range systems Neunkirchen (near Frankfurt) and Nordholz (near Bremen), all transponders within a coverage of 150 NM were regarded as ToIs.

The investigations were performed using the simulation programme SISSIM described in section 3. For each scenario defined in Table 4-1 a simulation run was conducted. Each run was executed five times with different initial conditions (antenna pointing angles, transmission start times, etc.).

4.3 Results

4.3.1 ACAS contribution to RF load

The following Figure 4-1 depicts all kind of impacts upon a MSSR/Mode S surveillance process between an IoI and a ToI that may occur in the scenarios A01 to A09. The diagram shows the various types of interfering interrogations at the ToIs caused by Mode S (MS-I), Mode A/C (MAC-I), and ACAS (ACAS-I) interrogators as well as interfering replies at the IoI produced by civil Mode A/C (MAC-T), civil Mode S (MS-T), military non-Mode S capable (MKXII-T), and military Mode S capable (MKXIIMS-T) transponders. In this regard it should be noted that the IoIs were modelled as MSSR stations performing surveillance of both Mode A/C and Mode S transponders by means of Mode A/C interrogations only in scenario A01. In the scenarios A02 to A09 the IoIs were assumed to be operated as Mode S stations.

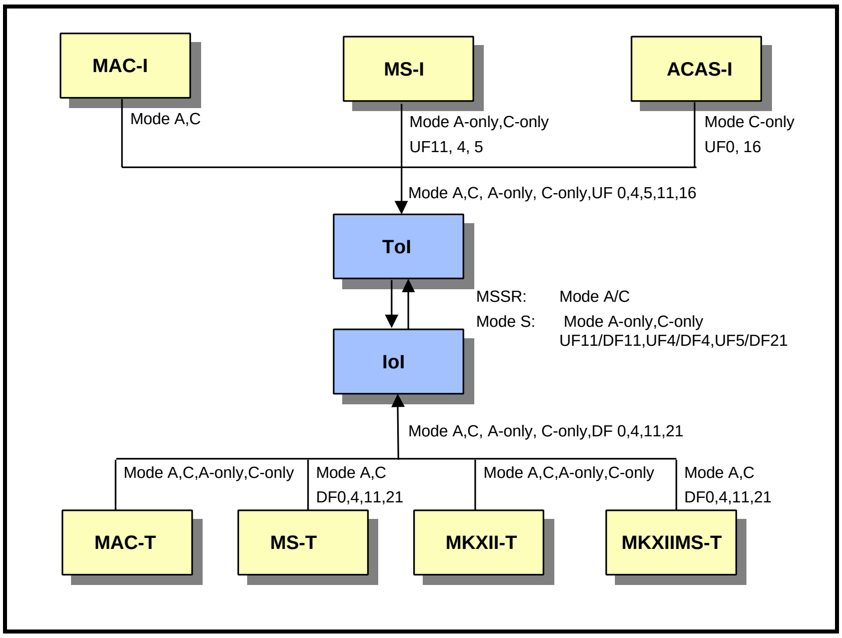


Figure 4-1: Scenario A01 to A09 - impacts on MSSR/Mode S surveillance

In the interest of brevity only, the following discussion of results will concentrate on the IoI Frankfurt because the simulations performed predicted Frankfurt as the most stressed area as far as RF loading is concerned. However, it should be noted that most of the conclusion drawn from the Frankfurt results are qualitatively valid for the areas covered by the other IoIs investigated too.

Concerning interfering interrogations, the simulations conducted predicted the long term mean rates of the main beam and side lobe signals received by each ToI. The following Table 4-2 comprise minimum, mean, and maximum values of the main beam and side lobe interrogation rates computed across the individual rates obtained for the ToIs of the IoI

Frankfurt in the scenarios A01 to A09. The rates are quoted in interrogations per second and are listed for the various Modes and Mode S formats separately. The rates are also grouped with respect to the interrogator types originating the respective signals.

Scenario		Main beam rates									Side lobe rates								
		A01	A02	A03	A04	A05	A06	A07	A08	A09	A01	A02	A03	A04	A05	A06	A07	A08	A09
		Mode A/C																	
Mode A	min	2	1	1	-	1	1	-	1	-	0	0	0	-	0	0	-	0	-
	mean	12	8	8	-	8	8	-	8	-	35	15	21	-	21	23	-	23	-
	max	27	20	20	-	20	20	-	20	-	358	123	179	-	179	179	-	179	-
Mode C	min	2	1	1	-	1	1	-	1	-	0	0	0	-	0	0	-	0	-
	mean	12	8	8	-	8	8	-	8	-	35	15	21	-	21	23	-	23	-
	max	26	20	20	-	20	20	-	20	-	358	123	179	-	179	179	-	179	-
		Mode S																	
Mode A-only	min	-	1	1	2	1	1	2	1	2	-	0	0	0	0	0	0	0	0
	mean	-	3	3	10	3	3	10	3	10	-	10	13	24	13	14	26	14	26
	max	-	5	5	23	5	5	23	5	23	-	117	117	181	117	117	181	117	181
Mode C-only	min	-	1	1	2	1	1	2	1	2	-	0	0	0	0	0	0	0	0
	mean	-	3	3	10	3	3	10	3	10	-	10	13	24	13	14	26	14	26
	max	-	5	5	23	5	5	23	5	23	-	117	117	181	117	117	181	117	181
UF4	min	-	0	1	2	1	0	3	1	3	-	0	0	0	0	0	0	0	0
	mean	-	2	4	12	4	2	14	4	14	-	7	16	26	16	12	30	19	31
	max	-	6	9	30	9	5	35	11	35	-	84	135	201	136	115	222	155	230
UF5	min	-	0	1	1	1	0	2	1	3	-	0	0	0	0	0	0	0	0
	mean	-	2	4	12	4	2	14	4	14	-	7	16	26	16	12	30	19	31
	max	-	7	9	30	9	5	34	11	34	-	85	136	201	136	115	222	156	231
UF11	min	-	3	3	4	3	3	4	3	4	-	0	0	0	0	0	0	0	0
	mean	-	5	5	20	5	5	20	5	20	-	19	26	48	26	28	51	28	51
	max	-	11	11	45	11	11	45	11	45	-	233	233	362	233	233	362	233	362
		ACAS																	
Mode C-only	min	0	0	1	4	2	3	6	3	7	0	0	0	0	0	0	0	0	0
	mean	14	14	20	20	29	34	26	34	34	7	7	5	5	7	0	0	0	0
	max	75	75	69	64	113	77	55	77	61	147	147	52	52	59	0	0	0	0
UF0	min	0	0	1	1	1	3	1	3	3	-	-	-	-	-	-	-	-	-
	mean	20	20	32	32	42	51	43	51	51	-	-	-	-	-	-	-	-	-
	max	66	66	98	98	117	136	120	136	136	-	-	-	-	-	-	-	-	-
UF16	min	0	0	0	0	1	1	1	1	1	-	-	-	-	-	-	-	-	-
	mean	2	2	3	3	5	6	4	6	6	-	-	-	-	-	-	-	-	-
	max	5	5	5	5	10	11	6	11	11	-	-	-	-	-	-	-	-	-

Table 4-2: IoI Frankfurt - interrogation rates

Interrogations received by a transponder are processed and, where applicable, are replied. During processing and reply transmission, a transponder is occupied making it unavailable for the access of other sensors. The time periods the ToIs were unavailable during simulation were recorded. From these data a performance parameter is derived termed overall transponder utilisation (TU). The overall transponder utilisation denotes the percentage of time a transponder is occupied by the main beam and side lobe interrogations received. Within Figure 4-2 the overall transponder utilisation obtained for the ToIs of the IoI Frankfurt is pictured versus the distance of the ToIs from the IoI for the scenarios A01 to A09. In addition to the overall transponder utilisation, the transponder utilisation caused by ACAS activities is inserted separately. The utilisation by ACAS comprises occupancy by interrogations from other ACAS units as well as mutual suppression by the on-board ACAS interrogator.

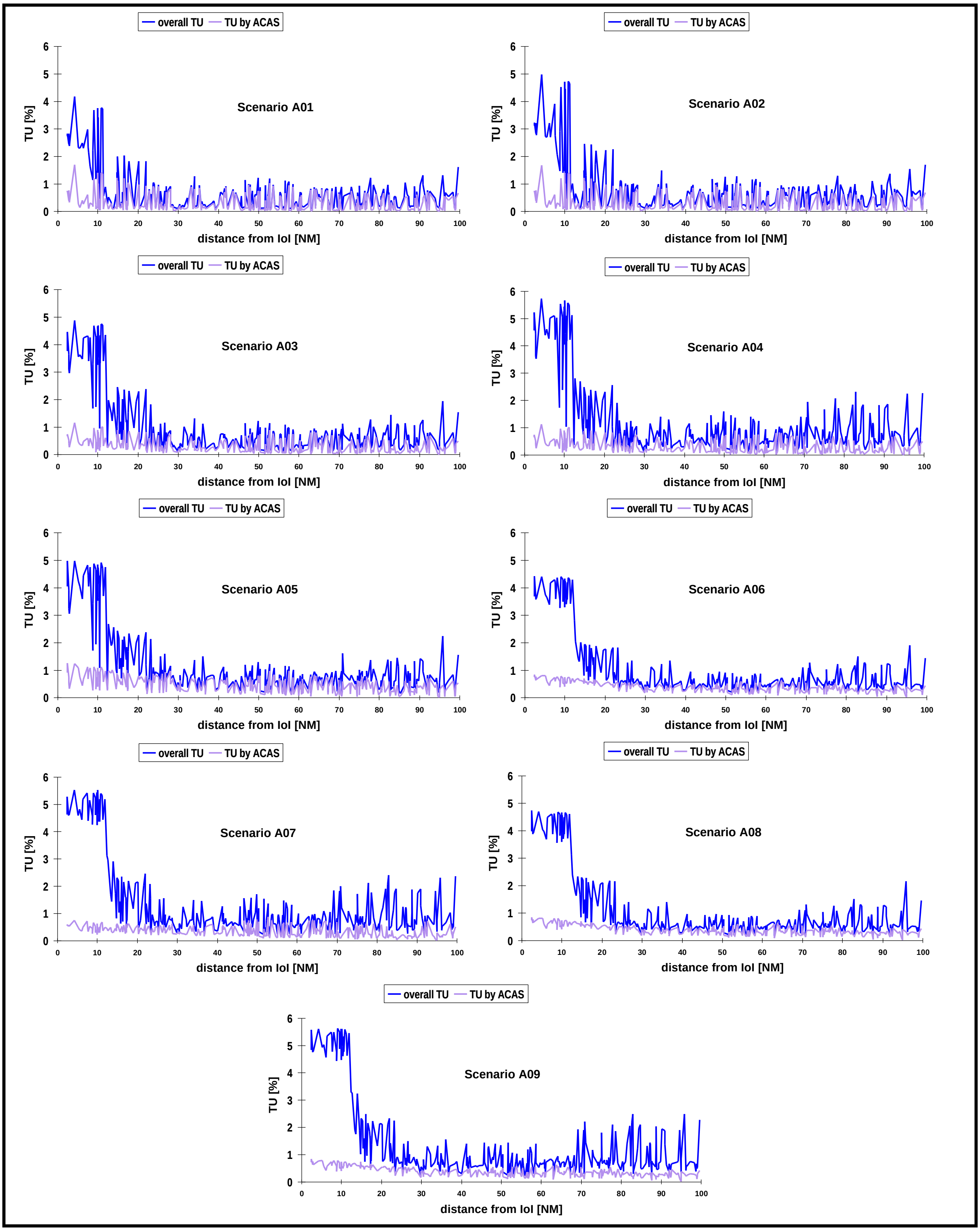


Figure 4-2: IoI Frankfurt - transponder utilisation

The following Figure 4-3 and Figure 4-4 provide statistics of the overall transponder utilisation as well as of the utilisation caused by ACAS. For each scenario, minimum, mean, and maximum values are calculated across the sample of all ToIs deployed within the surveillance area of the IoI Frankfurt.

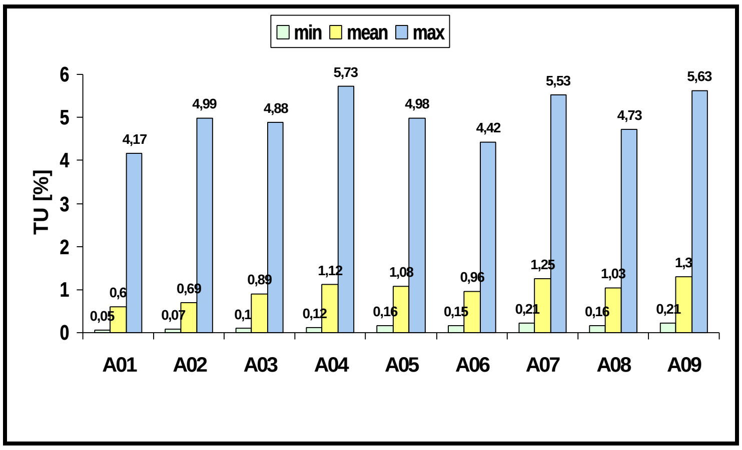


Figure 4-3: IoI Frankfurt - statistics of overall transponder utilisation

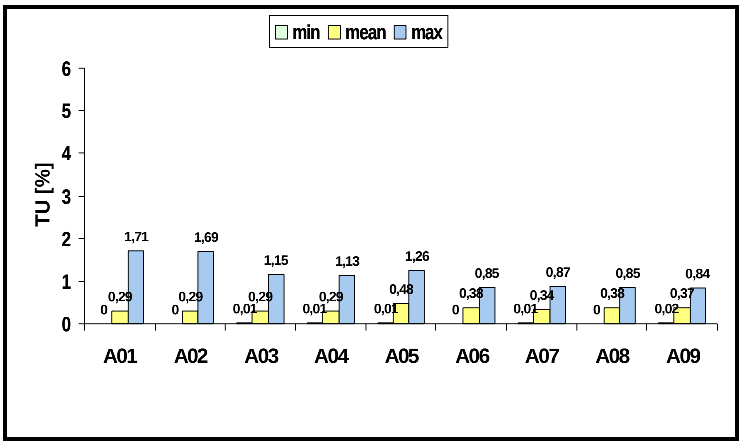


Figure 4-4: IoI Frankfurt - statistics of ACAS transponder utilisation

From the transponder utilisation presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. In each scenario, the peak transponder utilisation is achieved in close proximity to the airport.
2. In an equally shared Mode A/C and Mode S transponder environment (scenario A01, A02), transponder utilisation caused by ACAS is slightly below 2% in the vicinity of Frankfurt airport but it nearly scores the limit imposed on ACAS.

3. In an equally shared Mode A/C and Mode S transponder environment (scenario A01, A02), nearly half of the mean transponder utilisation is caused by ACAS.
4. In a predominated Mode S transponder environment (scenario A03, A04, A05), the peak ACAS transponder utilisation in the vicinity of Frankfurt airport slightly exceeds 1% but the 2% limit imposed on ACAS is fully met.
5. In a complete Mode S transponder environment (scenario A06, A07, A08, A09), ACAS transponder utilisation falls well below the postulated 2% threshold. The maximum ACAS utilisation is even below 1%.
6. In a predominated Mode S transponder environment (scenario A03, A04, A05) and in a full Mode S transponder environment (scenario A06, A07, A08, A09), the ACAS portion of the mean transponder utilisation accounts for about 30%-40%.
7. A transition from a full MSSR interrogator environment (scenario A01) to a mixed MSSR/Mode S interrogator environment (scenario A02) in an equally shared Mode A/C and Mode S transponder environment will increase mean overall transponder utilisation from 0.60% to 0.69%, i.e. by 15% relative to scenario A01.
8. A transition from a mixed MSSR/Mode S interrogator environment (scenario A03) to a full Mode S interrogator environment (scenario A04) in a predominated Mode S transponder environment will raise mean overall transponder utilisation from 0.89% to 1.12%, i.e. by about 25% relative to scenario A03.
9. A transition from a mixed MSSR/Mode S interrogator environment (scenario A08) to a full Mode S interrogator environment (scenario A09) in a full Mode S transponder environment will raise mean overall transponder utilisation from 1.03% to 1.30%, i.e. by 25% relative to scenario A08.
10. A transition from an equally shared Mode A/C and Mode S transponder environment (scenario A02) to a predominated Mode S (90%) transponder environment (scenario A03) in a constant mixed MSSR/Mode S interrogator environment will increase mean overall transponder utilisation from 0.69% to 0.89%, i.e. by about 30% relative to scenario A02. The maximum overall transponder utilisation will be slightly reduced from 4.99% to 4.88%, i.e. by 2% relative to scenario A02, which has to be attributed to the reduction of the Mode C-only rates generated by ACAS. The peak transponder utilisation caused by ACAS in the critical area of Frankfurt airport is considerably decreased from 1.69% to 1.15%, i.e. by 30% relative to scenario A02. This confirms that the reduction of the Mode C-only interrogation rates overbalances the concurrent increase of the UF0 rates in this area.

11. An increase of the number of ACAS interrogators from 50% (scenario A03) to 75% (scenario A05) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will raise mean transponder utilisation from 0.89% to 1.09%, i.e. by 20%. However, the peak is raised only from 4.88% to 4.99%, i.e. by 2% relative to scenario A03.
12. An increase of the number of ACAS interrogators from 50% (scenario A07) to 75% (scenario A09) in a full Mode S transponder and interrogator environment will raise mean overall transponder utilisation from 1.25% to 1.30%, i.e. by 4% relative to scenario A07.
13. A transition from autonomous operated Mode S stations (scenario A08) to an operation in clusters (scenario A06) will reduce mean transponder utilisation from 1.03% to 0.96%, i.e. by about 5% relative to scenario A08.
14. If military interrogators are taken into account it is estimated, based on studies previously performed, that overall transponder utilisation is increased at least by a factor of two.

The studies performed in 1996 [4] for a scenario of the year 2000 predicted Mode C-only rates induced by ACAS of the same magnitude as presented in Table 4-2 while the UF0 rates were to some extend higher. Furthermore, the studies of 1996 revealed that the 2% limit imposed on ACAS was not completely satisfied in the vicinity of the airport. This indicates the effectiveness of the changes made for the ACAS surveillance and interference limiting procedures during the last years as far as reduction of the ACAS uplink signal load is concerned.

The various types of interfering replies at an IoI in the scenarios under consideration are pictured within Figure 4-1. Concerning these interfering replies, the simulation performed predicted the long term fruit rates at the selected IoIs. Table 4-3 quantifies the fruit rates received by the IoI Frankfurt. The fruit rates, quoted in replies per second, are listed for the various Modes and Mode S formats separately. Additionally, the rates are grouped with respect to the originating interrogator type.

Scenario	A01	A02	A03	A04	A05	A06	A07	A08	A09
	Mode A/C								
Mode A	596	130	178	-	167	193	-	196	-
Mode C	595	128	176	-	164	191	-	192	-
	Mode S								
Mode A-only	-	213	55	67	55	-	12	-	-
Mode C-only	-	213	55	67	55	-	12	-	-
DF4	-	43	74	95	74	79	107	85	110
DF11	31	32	70	70	70	76	76	76	76
DF21	-	44	74	94	75	79	106	85	109
	ACAS								
Mode C-only	1384	1364	101	100	147	-	4	-	-
DF0	25	26	61	60	102	123	87	125	123

Table 4-3: IoI Frankfurt - fruit rates

From the fruit rates listed above, a performance parameter is derived that provides a measure for the total signal load at an interrogator. This parameter, termed interrogator receiver utilisation (IRU), takes into account the disparity between the length of Mode A/C and Mode S replies and denotes the percentage of time reply signals are present at the receiver of an interrogator. Within Figure 4-5 the interrogator receiver utilisation for the IoI Frankfurt is plotted. The figure shows the total interrogator receiver utilisation caused by all fruit replies as well as the utilisation by ACAS signals only for the scenarios analysed.

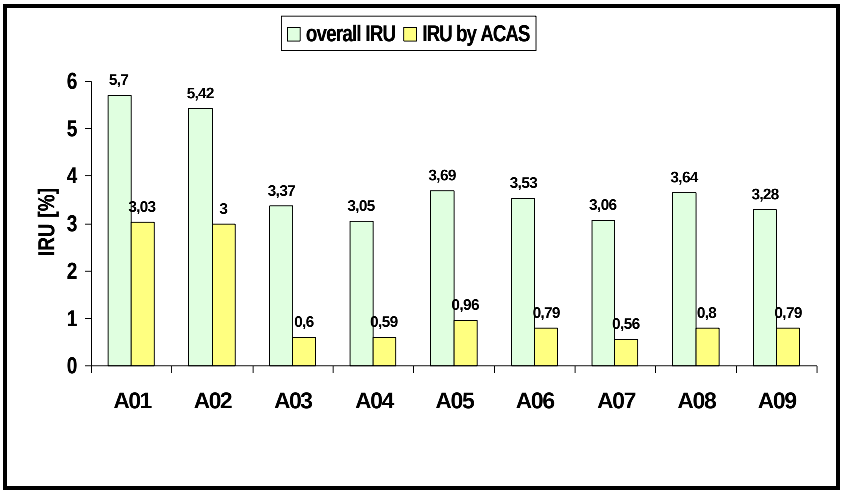


Figure 4-5: IoI Frankfurt - interrogator receiver utilisation

From the interrogator receiver utilisation presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. In an equally shared Mode A/C and Mode S transponder environment (scenario A01, A02), more than half of the interrogator receiver utilisation is caused by ACAS.

2. In a predominated Mode S transponder environment (scenario A03, A04, A05) and in a full Mode S transponder environment (scenario A06, A07, A08, A09), the ACAS portion of the overall interrogator receiver utilisation accounts for about 20%.
3. A transition from a full MSSR interrogator environment (scenario A01) to a mixed MSSR/Mode S interrogator environment (scenario A02) in an equally shared Mode A/C and Mode S transponder environment will reduce interrogator receiver utilisation from 5.70% to 5.42%, i.e. by about 5% relative to scenario A01.
4. A transition from a mixed MSSR/Mode S interrogator environment (scenario A03) to a full Mode S interrogator environment (scenario A04) in a predominated Mode S transponder environment will reduce interrogator receiver utilisation from 3.37% to 3,05%, i.e. by about 10% relative to scenario A03.
5. A transition from a mixed MSSR/Mode S interrogator environment (scenario A08) to a full Mode S interrogator environment (scenario A09) in a full Mode S transponder environment will decrease interrogator receiver utilisation from 3.64% to 3.28%, i.e. by 10% relative to scenario A08.
6. A transition from an equally shared Mode A/C and Mode S transponder environment (scenario A02) to a predominated Mode S transponder environment (scenario A03) in a constant mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation from 5.42% to 3.37%, i.e. by nearly 40% relative to scenario A02.
7. An increase of the number of ACAS interrogators from 50% (scenario A03) to 75% (scenario A05) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will raise interrogator receiver utilisation from 3.37% to 3.69%, i.e. by 10% relative to scenario A03.
8. An increase of the number of ACAS interrogators from 50% (scenario A07) to 75% (scenario A09) in a full Mode S transponder and interrogator environment will raise interrogator receiver utilisation from 3.06% to 3.28%, i.e. by about 7% relative to scenario A07.
9. A transition from autonomous operated Mode S stations (scenario A08) to an operation in clusters (scenario A06) within a mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation from 3.64% to 3.53%, i.e. by 3% relative to scenario A08.

10. A transition from a scenario without extended squitters (scenario A05) to a scenario with extended squitters (scenario B03, see section 6) will increase the interrogator receiver utilisation by approximately 50% relative to the values obtained for the scenario without extended squitters.
11. If military interrogators are taken into consideration, interrogator receiver utilisation will be more than doubled.

4.3.2 MSSR/Mode S surveillance performance

If an interrogation arrives at a ToI during transponder occupancy, the interrogation will fail. An interrogation may also fail if it overlaps and interferes with an interrogation of another interrogator. A parameter quantifying the success of interrogations is the so called reply efficiency (RE). The reply efficiency denotes the percentage of interrogations that are successfully received, processed, and responded by a transponder in the presence of interfering signals.

In scenario A01 the IoIs used Mode A and Mode C signals to interrogate the ToIs. In the scenarios A02 to A09, Mode A/C transponders are tracked by the IoIs using Mode A-only and Mode C-only interrogations. Surveillance of Mode S capable transponders was accomplished by transmitting interrogations of the Mode S uplink formats UF4 and UF5. Statistical data for the reply efficiency in the Modes and formats used are listed in the following Table 4-4 for the IoI Frankfurt. Thereby, minimum, mean, and maximum reply efficiency for Mode A-only and Mode C-only is based on the sample of the Mode A/C ToIs and the corresponding data for the Mode S reply efficiency are derived from the set of Mode S capable ToIs. Since there is no difference between the signal structure of an UF4 and an UF5 interrogation, a common Mode S reply efficiency is provided.

Scenario		A01	A02	A03	A04	A05	A06	A07	A08	A09
Mode A-only	**min**	89.	91.	96.	93.	97.	-	-	-	-
	mean	99.2	99.3	99.3	99.2	99.4	-	-	-	-
	max	100.	100.	100.	100.	100.	-	-	-	-
Mode C-only	**min**	90.	93.	94.	93.	98.	-	-	-	-
	mean	99.1	99.1	99.0	98.8	98.9	-	-	-	-
	max	100.	100.	100.	100.	100.	-	-	-	-
Mode S	**min**	-	80.	86.	85.	80.	77.	86.	85.	85.
	mean	-	98.7	98.5	98.1	98.3	98.5	97.8	98.4	97.8
	max	-	100.	100.	100.	100.	100.	100.	100.	100.

Table 4-4: IoI Frankfurt – reply efficiency

From the reply efficiency values presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. Mode C reply efficiency is slightly poorer than Mode A reply efficiency. This is due to the fact that a Mode C interrogation last longer than a Mode A signal and therefore overlapping of a Mode C interrogation is more likely.

2. Mode S reply efficiency is always below Mode A/C reply efficiency. This can be explained by the fact that on one hand Mode S transponders are more sensitive than Mode A/C transponders and, therefore, higher interrogation rates are seen by Mode S transponders. On the other hand, the occupancy time caused by the processing of

Mode S signals at an Mode S transponders lasts longer than the occupancy caused by Mode A/C signals at a Mode A/C transponder.

3. Mode A/C reply efficiency is only weakly affected by the scenario variations analysed. The deviation of the mean values is within 0.2%.
4. The variation of mean Mode S reply efficiency in the scenarios analysed is within 1%. The simulations performed predicted the lowest values (97.8%) for the scenarios with a full Mode S interrogator and transponder environment (scenario A07 and A09). The best values (98.7%) were achieved for a mixed MSSR/Mode S interrogator environment with an equally shared Mode A/C and Mode S transponder environment (scenario A02).
5. An increase of the number of ACAS interrogators (scenario A03/A05 and scenario A07/A09) will reduce mean Mode S reply efficiency by not more than 0.2%.
6. A transition from autonomous operated Mode S stations (scenario A08) to an operation in clusters (scenario A06) within a mixed MSSR/Mode S interrogator environment will slightly improve mean Mode S reply efficiency by 0.1% in average.
7. In a scenario which takes into account military interrogators, it has to be expected that mean reply efficiency is about 2-3% below the values provided in the table above.

Beside fruit, which is reflected in the interrogator receiver utilisation (see section 4.3.1), synchronous garbling is a further interference mechanism affecting reception and decoding of replies. Especially Mode A/C interrogators are susceptible to synchronous garbling, since no provision is made to avoid concurrent reply generation by transponders at similar range simultaneously illuminated by an interrogator’s main beam. A performance parameter taking into account both interference effects, fruit as well as synchronous garbling, is the so called decode efficiency (DE). The decode efficiency denotes the percentage of ToI-replies which are correctly received, decoded, and evaluated by an IoI.

In the scenario A01, the selected IoIs were interrogating Mode A and Mode C. In the scenarios A02 to A09, the selected IoIs were modelled as Mode S stations eliciting Mode A/C replies from aircraft fitted with Mode A/C transponders and responses in the Mode S formats DF4 and DF21 from Mode S transponder equipped aircraft. During simulation the reception and decoding of replies by the IoIs were monitored and such the decode efficiency for the particular interrogators was obtained. Since a Mode A reply equals a Mode C reply, as far as signal structure is concerned, a combined decode efficiency for both Modes was evaluated. Within Table 4-5 the values for decode efficiency are provided obtained by simulation for the IoI Frankfurt.

Scenario	A01	A02	A03	A04	A05	A06	A07	A08	A09
Mode A/C	93.	94.	93.	94.	93.	-	-	-	-
DF4	-	97.	99.	99.	98.	99.	99.	99.	99.
DF21	-	95.	98.	98.	98.	98.	99.	98.	99.

Table 4-5: IoI Frankfurt – decode efficiency

From the decode efficiency presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. In all scenarios analysed, Mode A/C decode efficiency is about 5% below Mode S decode efficiency. Thereby, synchronous garbling is the main reason for the loss of Mode A/C replies. By contrast, Mode S avoids synchronous garbling by means of interrogation scheduling which is reflected in the higher decode efficiency.
2. Mode S decode efficiency is 2-3% lower in a scenario with an equally shared Mode A/C and Mode S transponder environment (scenario A02) than in the other scenarios analysed. Obviously, this reflects the high downlink signal load in scenario A02 already indicated by the interrogator receiver utilisation (see 4.3.1).
3. The Mode S decode efficiency is nearly unaffected by the variations analysed in scenarios with a predominated or a full Mode S transponder environment (scenario A03 to A09). It should be noted that a deviation of 1% is still within range of mathematical precision with which decode efficiency values were derived by the simulation.
4. Studies previously conducted revealed that the activity of military interrogators can reduce decode efficiency provided in the table above by 2-3%.

To quantify the success of a complete MSSR and Mode S surveillance process, performed during an antenna sweep across a target, parameters are used termed code detection probability (PC) and Mode S detection probability (PS), respectively. The code and Mode S detection probability denotes the average number of transponders for which an IoI successfully obtained the requested Code A, Code C, and Mode S data during a single antenna revolution. In the simulation model, Code A was detected by an interrogator as soon as two Mode A replies were properly decoded. For Code C detection the same criterion was applied. Table 4-6 lists the values achieved for Code A, Code C, and Mode S detection at the IoI Frankfurt for the in the scenarios analysed.

Scenario	A01	A02	A03	A04	A05	A06	A07	A08	A09
Code A	97.	97.	95.	96.	97.	-	-	-	-
Code C	97.	98.	97.	97.	97.	-	-	-	-
UF4/DF4	-	100.	100.	100.	100.	100.	100.	100.	100.
UF5/DF21	-	100.	100.	100.	100.	100.	100.	100.	100.

Table 4-6: IoI Frankfurt – Code A/C and Mode S detection

From the detection values presented above, the following conclusions can be drawn:

1. In all scenarios analysed, the Mode S detection is 100%, an effect that can be explained by the fact that Mode S avoids synchronous garbling by means of interrogation scheduling and, furthermore, in case of failure, the re-interrogation function can be invoked.

2. The Code A/C detection values obtained for the scenarios analysed vary within the range of the statistical precision with which the probabilities could be derived from the simulation. Therefore, it has to be concluded that the scenario variations analysed have no significant impact on Code A/C detection.

3. Although reply efficiency and decode efficiency show some variations for the scenarios analysed, these variation are nearly not reflected in code and Mode S detection. This can be explained by the fact that the failure of a single interrogation/reply interaction can be compensated in case of Code A/C detection by the transmission of more than required interrogations during an antenna dwell and in case of Mode S detection by the re-interrogation function.

4. If military interrogators are taken into account, the Code A/C detection is reduced by about 1%. Mode S detection is not affected. However, it should be noted that the Mode S re-interrogation rate is slightly increased.

4.4 Summary of conclusions

1. The ACAS interference limiting algorithm meets the 2% limit in all scenarios analysed.
2. In a predominated Mode S transponder environment and in a full Mode S transponder environment, the ACAS contribution to the overall transponder utilisation accounts for about 30%-40%.
3. The overall transponder utilisation is increased at least by a factor of two if military interrogators are taken into account.
4. A transition from a mixed MSSR/Mode S interrogator environment to a full Mode S interrogator environment will reduce interrogator receiver utilisation by about 10% relative to mixed MSSR/Mode S interrogator environment.
5. A transition from an equally shared Mode A/C and Mode S transponder environment to a predominated Mode S transponder environment will reduce interrogator receiver utilisation by about 40% relative to equally shared Mode A/C and Mode S transponder environment.
6. If military interrogators are taken into consideration, interrogator receiver utilisation will be more than doubled
7. In all scenarios analysed, Mode A/C decode efficiency is about 5% below Mode S decode efficiency. Thereby, synchronous garbling is the main reason for the loss of Mode A/C replies.
8. Mode S decode efficiency is 2-3% lower in a scenario with an equally shared Mode A/C and Mode S transponder environment than in the other scenarios analysed.
9. The activity of military interrogators can reduce decode efficiency by 2-3%.
10. In all scenarios analysed, the Mode S detection is 100%, an effect that can be explained by the fact that Mode S avoids synchronous garbling by means of interrogation scheduling and, furthermore, in case of failure, the re-interrogation function can be invoked.
11. Although reply efficiency and decode efficiency show some variations for the scenarios analysed, these variation are nearly not reflected in code and Mode S detection. This can be explained by the fact that the failure of a single interrogation/reply interaction can be compensated in case of Code A/C detection by the transmission of more than required interrogations during an antenna dwell and in case of Mode S detection by the re-interrogation function.

12. If military interrogators are taken into account, the Code A/C detection is reduced by about 1%. Mode S detection is not affected. However, it should be noted that the Mode S re-interrogation rate is slightly increased.

5. ACAS SURVEILLANCE PERFORMANCE

5.1 Objective of analysis

The issues discussed so far in the present report were dedicated to MSSR/Mode S surveillance performance and the effects of ACAS on it. By contrast, this section 5 will focus on the surveillance performance of ACAS itself.

Concerning ACAS surveillance performance, it is postulated that ACAS is capable of operating in most air traffic densities without any significant performance degradation. Although ACAS is able to operate up to a range of 30 NM, the required nominal surveillance range of ACAS is 14 NM. However, when operating in high density, the interference limiting function may reduce system range to approximately 5 NM, which is still adequate to provide enough surveillance performance. Furthermore, it is required that a track is established with a probability of at least 90% for aircraft within the surveillance range.

If an ACAS interrogator performs a surveillance process within a complex and dense environment, as represented by the environment 2005 described in section 2, each question and answer cycle will suffer various impacts. Thereby, the receiving and processing of ACAS interrogations by transponders as well as the receipt and evaluation of replies by an ACAS interrogator may be influenced.

In order to analyse ACAS surveillance performance in a complex scenario with a large number of interrogators and transponders spread unevenly over a large area on the ground and in the air, the model utilised for the investigations discussed in the previous sections was upgraded to obtain estimates for the reliability of ACAS surveillance processes in various scenarios. Section 5.2 introduces the analysis methodology. The results obtained by the investigations are presented in section 5.3.

5.2 Analysis methodology

In order to explore the performance of ACAS surveillance under various conditions, the same nine scenarios A01 to A09 were considered as analysed to determine MSSR/Mode S system performance. The scenarios were based on the environment 2005 described within section 2. The scenarios analysed varied with respect to the interrogator equipage of the SSR ground stations and the transponder equipage of civil and military aircraft. The scenarios considered are listed in Table 4-1.

To analyse ACAS system performance, four ACAS interrogators were chosen as Interrogators of Interest (IoI). Due to the fact that Frankfurt is the busiest area in Germany, the ACAS IoIs were picked out of the set of ACAS units dispersed within the coverage of the SSR site Frankfurt/Süd. The following Figure 5-1 shows the distribution of ACAS interrogators within the 100 NM surveillance volume of the SSR interrogator Frankfurt/Süd as assumed for the scenarios A01 to A04 and the positions of the four selected ACAS IoIs (ID-number: 209 (1499 ft), 260 (4199 ft), 300 (3301 ft), 386 (4902 ft).

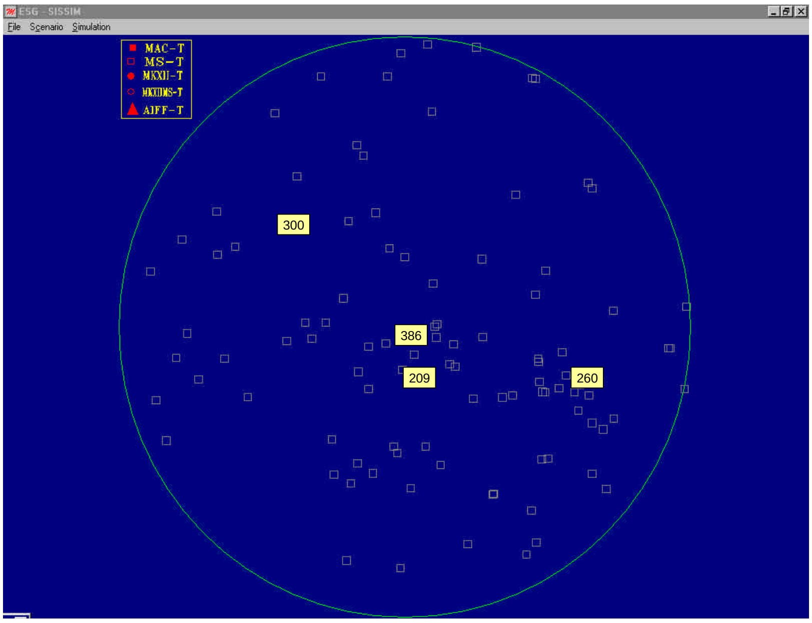


Figure 5-1: Location of ACAS IoIs within coverage of SSR site Frankfurt/Süd

The investigations were performed using the simulation programme SISSIM described in section 3. The same scenarios A01-A09 as described in section 4 were analysed.

5.3 Results

5.3.1 RF load on ACAS

In principal, the interfering impacts on an ACAS surveillance process in the scenarios analysed are the same as on an SSR surveillance process depicted by Figure 4-1. At the ToI, the impacts may consist of Mode A, Mode C, Mode A-only, Mode C-only, UF0, UF4, UF5, UF11, and UF16 interrogations. An ACAS IoI may be influenced by fruit consisting of Mode A, Mode C, Mode A-only, Mode C-only, DF0, DF4, DF11, and DF21 replies.

Since the four ACAS IoIs were chosen within the coverage of the SSR interrogator Frankfurt/Süd, the interrogation rates at the transponders and the utilisation of the transponders tracked by the ACAS interrogators are within range of the values predicted for the ToIs of the IoI Frankfurt. Because interrogation rates and transponder utilisation were already discussed in section 4.3.1 for the Frankfurt area, an extra evaluation of the parameters based on the sample of the transponders tracked by the ACAS IoIs is omitted and reference is made to section 4.3.1.

In order to shorten the description of the results, the following discussion will concentrate on the results obtained for IoI 300 and 386 only. However, it should be noted that the simulations performed predicted quite similar results for IoI 209 and IoI 260 and, in general, the conclusion drawn from the IoIs 300 and 386 are also valid for IoI 209 and IoI 260.

The fruit rates received by IoI 300 and IoI 386, which are affecting the surveillance processes in the scenarios under examination, are listed in the following Table 5-1. The fruit rates are separated into replies challenged by Mode A/C, Mode S, and ACAS interrogators. The rates are quoted in replies per second.

	IoI 300									IoI 386								
Scenario	**A01**	**A02**	**A03**	**A04**	**A05**	**A06**	**A07**	**A08**	**A09**	**A01**	**A02**	**A03**	**A04**	**A05**	**A06**	**A07**	**A08**	**A09**
	Mode A/C																	
Mode A	791	585	648	-	640	635	-	637	-	1144	776	750	-	746	746	-	746	-
Mode C	790	583	645	-	637	633	-	635	-	1142	774	747	-	744	744	-	741	-
	Mode S																	
Mode A-only	-	71	24	94	23	-	35	-	-	-	165	34	117	34	-	7	-	-
Mode C-only	-	71	24	94	23	-	35	-	-	-	165	34	117	34	-	7	-	-
DF4	-	24	38	116	36	22	126	44	131	-	30	58	155	58	41	177	67	179
DF11	45	45	70	70	68	78	75	80	79	80	79	152	152	152	169	166	169	169
DF21	-	24	38	116	36	22	126	44	131	-	31	58	155	58	41	177	67	179
	ACAS																	
Mode C-only	300	296	96	96	200	-	109	-	-	1954	1926	240	238	446	-	72	-	-
DF0	47	47	64	64	111	136	91	138	135	107	107	182	181	328	376	276	376	373

Table 5-1: ACAS IoIs 300 and 386 - fruit rates

From the fruit rates listed above the interrogator receiver utilisation (IRU), at the ACAS IoIs were derived. Within Figure 5-2 and Figure 5-3 the values obtained for IoI 300 and for IoI 386 are plotted.

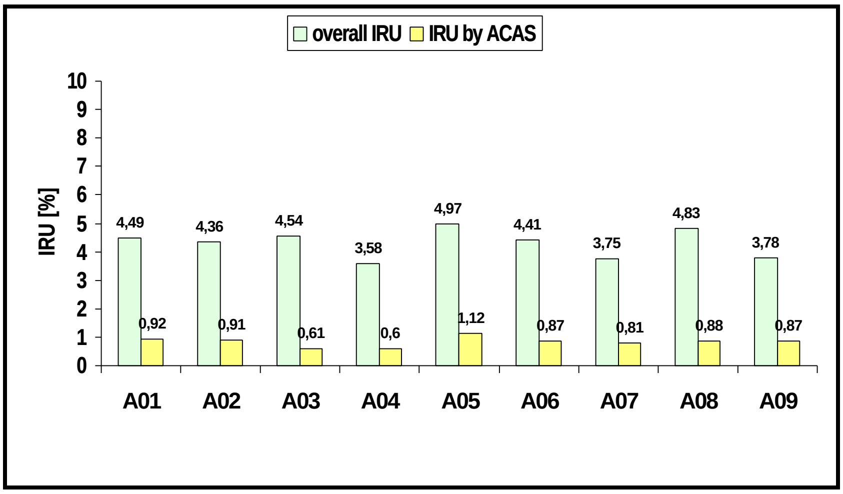


Figure 5-2: ACAS IoI 300 – interrogator receiver utilisation

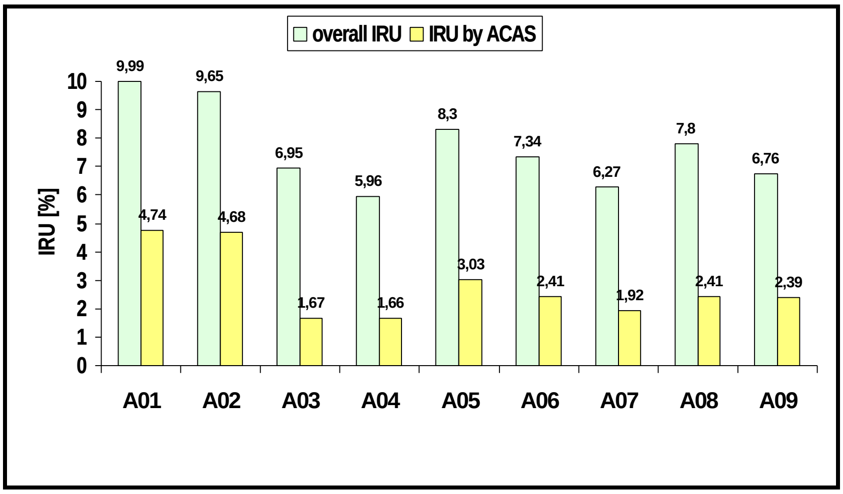


Figure 5-3: ACAS IoI 386 – interrogator receiver utilisation

From the interrogator receiver utilisation presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. IoI 386, deployed in close proximity to Frankfurt airport, is suffering more than twice the fruit seen by IoI 300, located at a distance of 52 NM from the airport.
2. In an equally shared Mode A/C and Mode S transponder environment (scenario A01, A02), more than half of the interrogator receiver utilisation is caused by ACAS at interrogators deployed close to the airport. At greater distances, the ACAS contribution is approximately 20%.

3. In a predominated Mode S transponder environment (scenario A03, A04, A05) and in a full Mode S transponder environment (scenario A06, A07, A08, A09), the ACAS portion of the overall interrogator receiver utilisation accounts for about 20-30%.
4. A transition from a full MSSR interrogator environment (scenario A01) to a mixed MSSR/Mode S interrogator environment (scenario A02) in an equally shared Mode A/C and Mode S transponder environment will reduce interrogator receiver utilisation by not more than 3% (relative to scenario A01).
5. A transition from a mixed MSSR/Mode S interrogator environment (scenario A03) to a full Mode S interrogator environment (scenario A04) in a predominated Mode S transponder environment will reduce interrogator receiver utilisation by about 20% (relative to scenario A03).
6. A transition from a mixed MSSR/Mode S interrogator environment (scenario A08) to a full Mode S interrogator environment (scenario A09) in a complete Mode S transponder environment will decrease interrogator receiver utilisation by about 20% (relative to scenario A08).
7. A transition from an equally shared Mode A/C and Mode S transponder environment (scenario A02) to a predominated Mode S transponder environment (scenario A03) in a constant mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation by about 30% (relative to scenario A02) in the vicinity of the airport. At greater range, interrogator receiver utilisation may be slightly raised by 4% (relative to scenario A02) due to the additional Mode S fruit produced by Mode S transponders.
8. An increase of the number of ACAS interrogators from 50% (scenario A03) to 75% (scenario A05) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will raise the interrogator receiver utilisation by 10-20% (relative to scenario A03).
9. An increase of the number of ACAS interrogators from 50% (scenario A07) to 75% (scenario A09) in a full Mode S transponder and interrogator environment will raise the interrogator receiver utilisation by not more than 10% (relative to scenario A07).
10. A transition from autonomous operated Mode S stations (scenario A08) to an operation in clusters (scenario A06) within a mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation by about 10% (relative to scenario A08).

11. A transition from a scenario without extended squitters (scenario A05) to a scenario with extended squitters (scenario B03, see section 7) will increase interrogator receiver utilisation by approximately 70% relative to the values obtained for the scenario without extended squitters.

5.3.2 ACAS surveillance performance

The following Figure 5-4 illustrates the density of ACAS units within the 100 NM surveillance volumes of the SSR site Frankfurt/Süd for the scenarios analysed. In addition to the actual density distribution (solid line) the corresponding curves (dotted lines) for an uniform in area and an uniform in range distribution are attached.

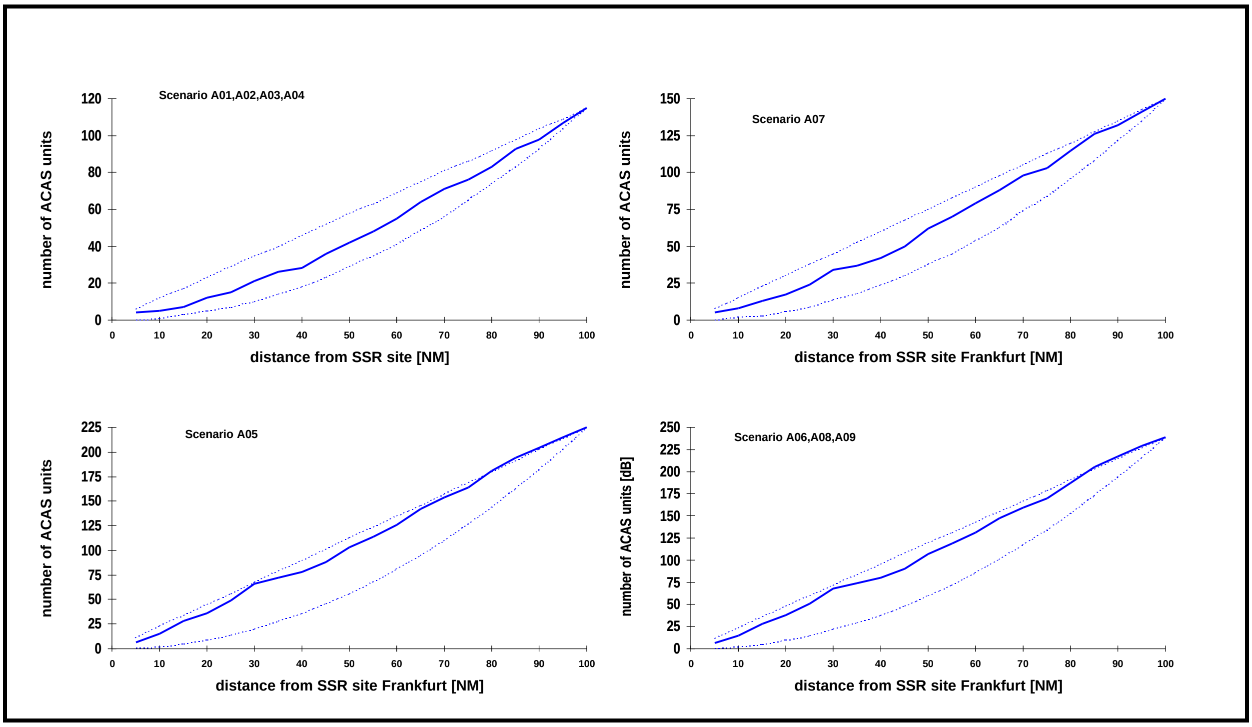


Figure 5-4: Scenarios A01 to A09 - density of ACAS interrogators

From the ACAS density distributions presented above, the following conclusions can be drawn:

1. The distribution of the ACAS units, deployed in the scenarios A01 to A04 and in scenario A07, is fairly between a uniform in area and a uniform in range distribution.
2. In the scenarios A05, A06, A08, and A09 the distribution of the ACAS interrogators tends rather to a uniform in range than to a uniform in area distribution.

On one hand, the objective of ACAS interference limiting is to reduce the overall ACAS interrogation rate and as a consequence the time transponders are occupied by ACAS signals. On the other hand, limiting Mode C and Mode S transmitter power, in order to reduce ACAS interrogation rates, affects the surveillance performance of ACAS units. In order to quantify the reduction of ACAS transmitter power by the application of interference limiting procedures, Figure 5-5 illustrates the Mode C and Mode S power reduction of the

ACAS interrogators within 100NM of the SSR site Frankfurt. The power reduction is plotted dependent on the range of the ACAS units from the SSR station.

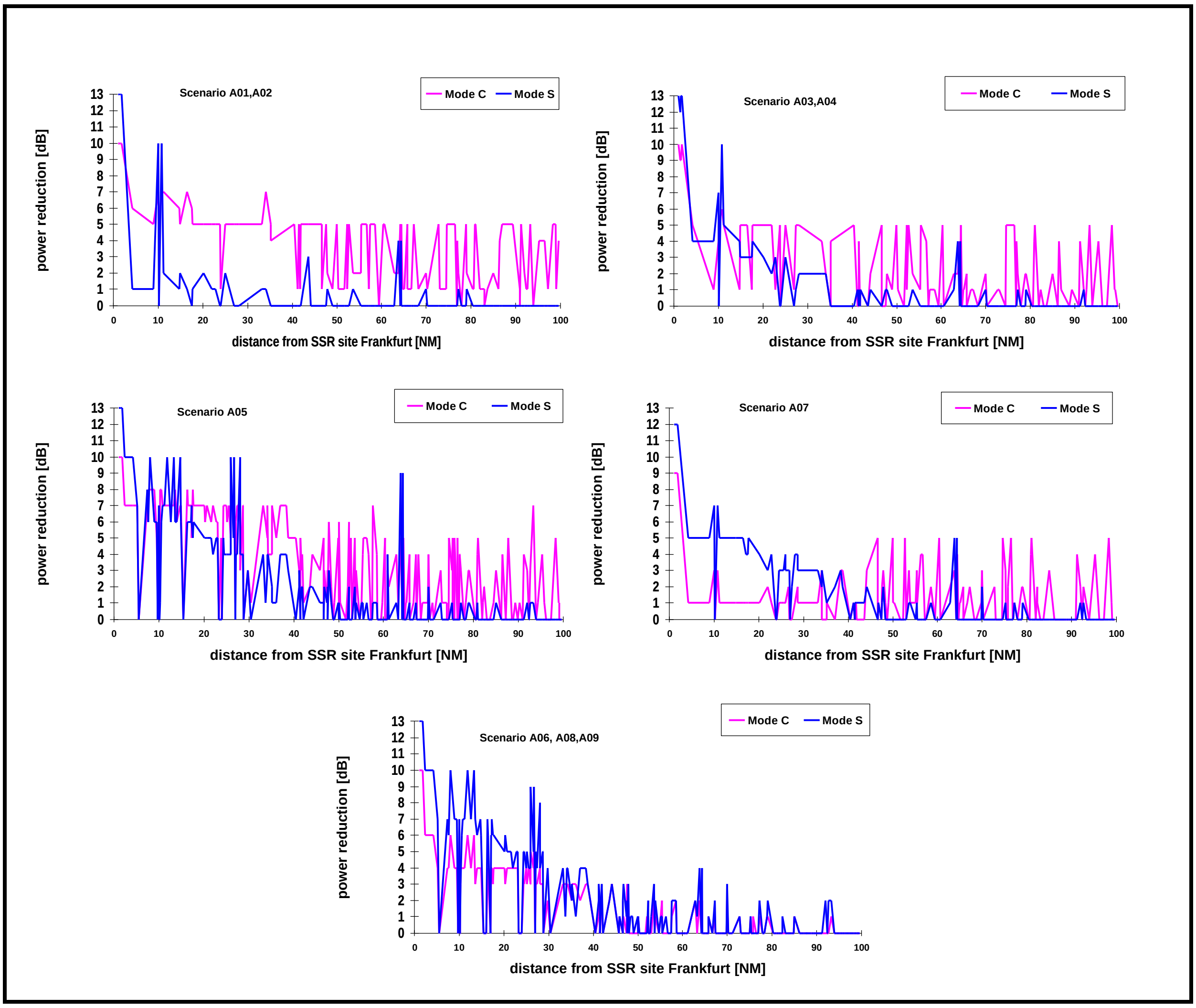


Figure 5-5: Scenarios A01 to A09 - ACAS power reduction

From the power reductions presented above, the following conclusions can be drawn:

1. In the scenarios under examination, four ACAS interrogators are assumed on the surface at Frankfurt airport. These ACAS units have to reduce Mode C power and Mode S power to the absolute permitted limit of 10 dB and 13 dB in all scenarios, except in scenario A07.

2. A transition from an equally shared Mode A/C and Mode S transponder environment (scenario A02) to a predominated Mode S transponder environment (scenario A03) will decrease the mean Mode C power reduction, computed across all ACAS units deployed within the 100 NM coverage of Frankfurt, from 3.6 dB to 2.3 dB. Concurrently, the mean

Mode S power reduction is raised from 0.9 dB to 1.2 dB. This effect can be explained by the fact that in a high Mode A/C transponder density (scenario A02) ACAS interrogators are mostly forced to select medium and long Mode C-only sequences resulting in high Mode S power limitations to satisfy the third interference limiting inequality. In an air environment dominated by Mode S transponders (scenario A03), ACAS units can restrict themselves to the usage of short and medium Mode C-only sequences. However, more Mode S transponders have to be tracked resulting in a higher Mode S power limitation in order to fulfil the first interference limiting inequality.

3. An enhancement of the number of ACAS interrogators from 50% (scenario A03) to 75% (scenario A05) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will increase the mean Mode C power reduction from 2.3 dB to 3.3 dB and the mean Mode S power reduction from 1.2 dB to 2.1 dB.

4. An enhancement of the number of ACAS interrogators from 50% (scenario A07) to 75% (scenario A09) in a full Mode S transponder and interrogator environment will increase the mean Mode S power reduction from 1.4 dB to 2.1 dB.

The ACAS IoIs were selected out of the surveillance area of the SSR interrogator Frankfurt/Süd. Hence, each of them is representing a point in the power reduction curves plotted above. In order to characterise the environments surrounding the selected ACAS IoIs in more detail the following Table 5-2 lists for IoI 300 and IoI 386 the number of aircraft within the nominal surveillance range, the number of ACAS units within 3NM, 6NM, and 30NM, the selected Mode C-sequence for the forward, right, left, aft, and omni antenna, the reduction of Mode C and Mode S power due to the interference limiting, the resulting effective surveillance range, and finally, the number of targets within the effective surveillance range (ToIs).

Scenario	IoI 300 A01 A02	IoI 300 A03 A04	IoI 300 A05	IoI 300 A07	IoI 300 A06 A08 A09	IoI 386 A01 A02	IoI 386 A03 A04	IoI 386 A05	IoI 386 A07	IoI 386 A06 A08 A09
Aircraft in nominal range:										
Mode A/C transponders	5	3	3	0	0	65	11	11	0	0
Mode S transponders	23	29	29	32	35	37	82	82	94	97
ACAS units within:										
3 NM	0	0	0	0	0	0	0	1	0	1
6 NM	0	0	0	0	0	0	0	4	1	4
30 NM	17	17	41	23	43	30	30	81	44	83
Mode C-sequence:										
Forward	Long	Long	Long	Short	Short	Long	Long	Long	Short	Short
Right	Medium	Medium	Medium	Short	Short	Long	Short	Short	Short	Short
Left	Short	Short	Short	Short	Short	Long	Medium	Medium	Short	Short
Aft	Short	Short	Short	Short	Short	Long	Short	Short	Short	Short
Omni	Long	Long	Long	Short	Short	Long	Long	Long	Short	Short
Power reduction:										
Mode C	5 dB	5 dB	6 dB	0 dB	1 dB	6 dB	5 dB	7 dB	1 dB	6 dB
Mode S	0 dB	0 dB	2 dB	0 dB	2 dB	1 dB	4 dB	10 dB	5 dB	10 dB
Effective range:										
Mode C	15.8NM	15.8NM	14.0NM	28.0NM	25.0NM	14.0NM	15.8NM	12.5NM	25.0NM	14.0NM
Mode S	39.6NM	39.6NM	31.4NM	39.6NM	31.4NM	35.3NM	25.0NM	12.5NM	22.3NM	12.5NM
Aircraft in effective range:										
Mode A/C transponders	1	0	0	0	0	38	6	2	0	0
Mode S transponders	23	29	16	32	20	27	47	12	49	15

Table 5-2: ACAS IoIs 300 and 386 - environment parameters

From the environmental parameters listed above the following conclusion can be drawn:

1. A transition from an equally shared Mode A/C and Mode S transponder environment (scenario A02) to a predominated Mode S transponder environment (scenario A03) will reduce the Mode A/C transponders and increases the number of Mode S transponders within the surveillance range. As a consequence more often the short and medium Mode C-sequence can be selected by the ACAS interrogators and the Mode C interrogation can be transmitted at higher power. On the other hand Mode S power has to be reduced to a higher level resulting in a reduction of the effective Mode S range.
2. An enhancement of the number of ACAS interrogators from 50% (scenario A03) to 75% (scenario A05) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will impose a higher power reduction on the ACAS interrogators decreasing the effective surveillance range.
3. Also, an enhancement of the number of ACAS interrogators from 50% (scenario A07) to 75% (scenario A09) in a full Mode S (100%) transponder and interrogator environment will force the ACAS interrogators to a higher power reduction.

In order to quantify the success of a ACAS surveillance processes, the round trip reliability (RTR) was evaluated for the ACAS IoIs under consideration. The round trip reliability denotes the percentage of interrogation-reply interactions initiated by an interrogator which are successfully completed. The values predicted by the simulations performed are illustrated in Figure 5-6 for IoI 300 and in Figure 5-7 for IoI 386.

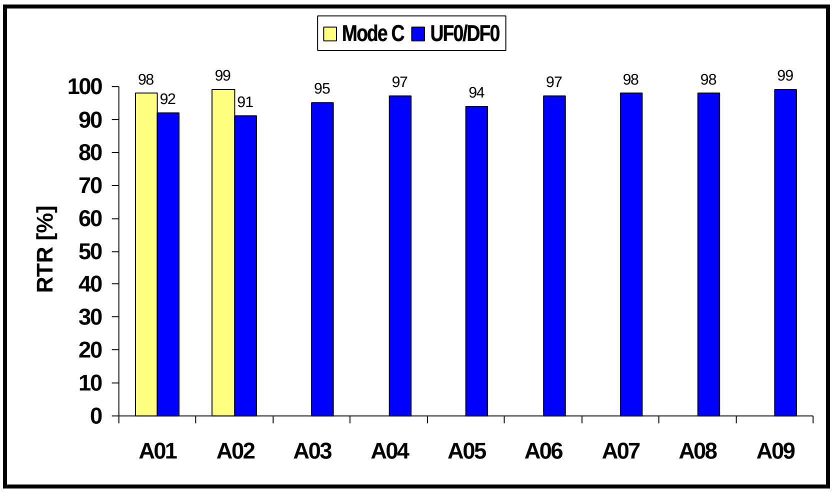


Figure 5-6: ACAS IoI 300 – round trip reliability

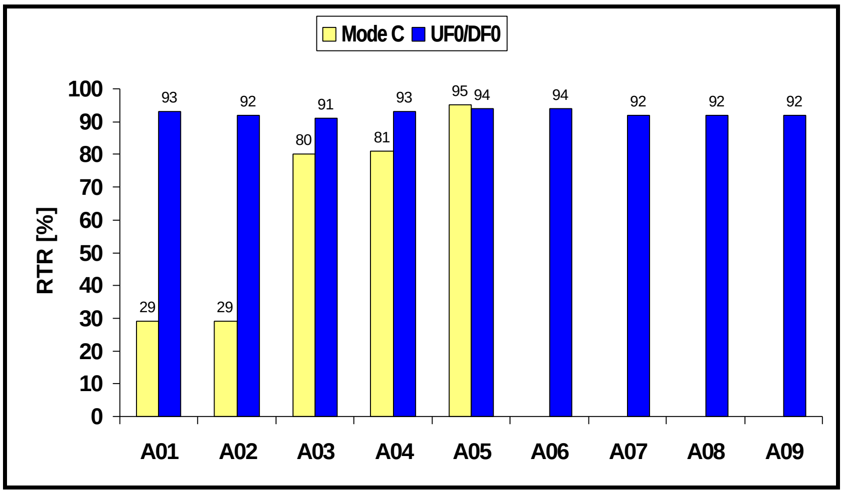


Figure 5-7: ACAS IoI 386 – round trip reliability

Care must be taken in drawing conclusions from the figures above. Firstly, it should be noted that due to the small sample of transponders tracked by the ACAS IoIs, the numbers quoted in the diagram are of lower confidence. Secondly, the values provided for the various scenarios are based on different sample sizes of ToIs interrogated by the ACAS IoIs. Therefore, a direct comparison of the round trip reliability values is actually not feasible. Nevertheless, from the results achieved the following statements can be concluded for a pure civil interrogator environment:

1. In an equally shared Mode A/C and Mode S transponder environment (scenario A01, A02), Mode C round trip reliability might be quite low. Thereby, synchronous garbling is the driving factor.

2. A transition from an equally shared Mode A/C and Mode S transponder environment (scenario A02) to a predominated Mode S (90%) transponder environment (scenario A03) in a constant mixed MSSR/Mode S interrogator environment can improve Mode A/C surveillance significantly due to the reduction of garbling.
3. A transition from a full MSSR interrogator environment (scenario A01) to a mixed MSSR/Mode S interrogator environment (scenario A02) in an equally shared Mode A/C (50%) and Mode S (50%) transponder environment has nearly no effect on ACAS surveillance.
4. Also, a transition from a mixed MSSR/Mode S interrogator environment (scenario A03) to a full Mode S interrogator environment (scenario A04) in a predominated Mode S transponder environment as well as in a full Mode S transponder environment (scenario A08, A09 does not significantly affect ACAS surveillance performance.

5.4 Summary of conclusions

1. ACAS interrogators deployed in close proximity to Frankfurt airport are suffering more than twice the fruit seen by interrogators at greater distances.
2. In an equally shared Mode A/C and Mode S transponder environment, more than half of the interrogator receiver utilisation is caused by ACAS at interrogators deployed close to the airport. At greater distances, the ACAS contribution is approximately 20%.
3. In a predominated Mode S transponder environment and in a full Mode S transponder environment, the ACAS portion of the overall interrogator receiver utilisation accounts for about 20-30%.
4. An increase of the number of ACAS interrogators from 50% to 75% in a full Mode S transponder and interrogator environment will raise the interrogator receiver utilisation by not more than 10% (relative to the 50% ACAS deployment).
5. A transition from autonomous operated Mode S stations to an operation in clusters within a mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation by about 10% (relative to the autonomous scenario).
6. ACAS interrogators on the surface at Frankfurt airport have to reduce Mode C power and Mode S power to the absolute permitted limit of 10 dB and 13 dB.
7. A transition from an equally shared Mode A/C and Mode S transponder environment to a predominated Mode S transponder environment will decrease the Mode C power reduction. Concurrently, the Mode S power reduction is raised.
8. In an equally shared Mode A/C and Mode S transponder environment Mode C round trip reliability can be quite low. Thereby, synchronous garbling is the driving factor.
9. A transition from an equally shared Mode A/C and Mode S transponder environment to a predominated Mode S (90%) transponder environment can improve Mode A/C surveillance significantly due to the reduction of garbling.

6. IMPACT OF ACAS ON MSSR/MODE S PERFORMANCE IN CASE OF HYBRID SURVEILLANCE

6.1 Objective of analysis

Mode S transponders generate an unsolicited reply in the Mode S downlink format DF11 once per second known as "Mode S squitter". The squitter contains the unique Mode S address of the aircraft and is utilised by ACAS interrogators for the acquisition of Mode S transponders. For the future, an expansion of the squitter technique is intended by introducing so called Mode S Extended Squitters. Mode S Extended Squitters shall be used to broadcast aircraft-derived data to airborne and ground users.

The Mode S downlink format DF17 has been defined for the Extended Squitter. The duration of the Extended Squitter signal is 120 µs including a data block of 112 Bits. Dependent on the information coded in the data block, five types of Extended Squitters are distinguished:

- airborne position squitter,
- surface position squitter,
- aircraft identification squitter,
- airborne velocity squitter, and
- event-driven squitter.

The transmission rate of the Extended Squitter is determined by the status of the aircraft. When an aircraft is airborne, the airborne position and the airborne velocity squitter are each transmitted pseudo randomly twice per second, while the aircraft identification squitter is generated pseudo randomly once every 5 seconds (. On surface, the surface position squitter is transmitted pseudo randomly twice per second when the aircraft is moving and once per 5 seconds when the aircraft is stationary. On ground, the aircraft identification squitter is transmitted pseudo randomly once every 5 seconds when the aircraft is moving and once every 10 seconds when the aircraft is stationary.

The introduction of Mode S Extended Squitter provides further means to reduce ACAS interrogation rates by a new ACAS surveillance technique termed ACAS Hybrid Surveillance. The purpose of ACAS Hybrid Surveillance is to incorporate passively received data transferred via Mode S Extended Squitter while at the same time maintaining the independence of ACAS as an active surveillance system.

The approach to achieve this goal is to utilise active interrogations for an initial validation of the data received via Mode S Extended Squitter. Initial validation is initiated as soon as track initiation is indicated by the receipt of an Extended Squitter with a 24-bit address that is not yet in the track file. Initial validation is performed by transmitting a selective UF0 interrogation, which challenges a DF0 or DF16 reply. The reply provides aircraft speed and altitude. These data are compared with the data contained in the Extended Squitter. Dependent on the result of the comparison a target is put into a monitoring or a full active surveillance state in the following way:

- If the Extended Squitter information does not agree with the data obtained via the active interrogation, the aircraft is put into full active surveillance. In this case the target is interrogated in the format UF0 each second and further Extended Squitters from this aircraft are ignored.
- If the Extended Squitter information agrees with the data obtained via the initial validation interrogation, the aircraft is declared to be in a monitoring state. In this case the Extended Squitters are evaluated continuously and an active interrogation is made every 10 seconds to validate the Extended Squitter data. Any detected difference will results in a full active surveillance of the aircraft.

The generation of Extended Squitters by Mode S transponders imposes additional impacts on the SSR downlink channel. Furthermore, due to transponder suppression during squitter transmission and recovery, a degradation of transponder availability has to be expected.

To demonstrate the effects of Extended Squitter activities on the SSR surveillance performance, investigations were performed for various scenarios. In section 6.2 an overview of the scenarios analysed is provided. The results of the investigations are presented in section 6.3.

6.2 Analysis methodology

In order to explore the effects of ACAS Hybrid surveillance on MSSR/Mode S system performance under various conditions, five scenarios were analysed in detail. The scenarios considered were based on the environment 2005 described within section 2. The scenarios varied with respect to the interrogator equipment of ground stations as well as with respect to the transponder fitting of civil and military aircraft. The characteristics assumed for the five scenarios under examination are listed in the following Table 6-1 in terms of number and percentage of:

MS-I: civil ground stations equipped with a MSSR/Mode S interrogator,
MAC-I: civil ground stations equipped with a MSSR/Mode A/C interrogator,
ACAS-I: civil Mode S transponder-equipped aircraft with an ACAS interrogator,
ACAS-HS civil ACAS-equipped aircraft applying Hybrid Surveillance
MS-T: civil aircraft equipped with a Mode S transponder,
MAC-T: civil aircraft equipped with a Mode A/C transponder,
MKXIIMS-T: military aircraft equipped with a Mode S capable transponder, and
MKXII-T: military aircraft equipped with a non-Mode S capable transponder.

Scenario	***Number/percentage of***															
	MS-I		***MAC-I***		***ACAS-I***		***ACAS-HS***		***MS-T***		***MAC-T***		***MKXII-T***		***MKXIIMS-T***	
B01	0	0%	49	100%	392	100%	78	20%	409	50%	408	50%	41	28%	104	72%
B02	12	24%	37	76%	392	100%	78	20%	409	50%	408	50%	41	28%	104	72%
B03	12	24%	37	76%	528	75%	106	20%	736	90%	81	10%	41	28%	104	72%
B04	12	24%	37	76%	528	75%	422	80%	736	90%	81	10%	41	28%	104	72%
B05	49	100%	0	0%	528	75%	422	80%	736	90%	81	10%	41	28%	104	72%

Table 6-1: Scenarios B01-B05[2]

It should be noted that military interrogators were not included in the scenarios B01 to B05. Furthermore, it should be borne in mind that all Mode S capable transponders transmitted Extended Squitters in the scenarios B01 to B05.

For the analysis performed, the ASR sites at Frankfurt/Süd, München, and Teufelsberg as well as the long range radars at Neunkirchen and Nordholz were chosen as Interrogators of Interest (IoI). Regarding the ASR stations Frankfurt, München, and Teufelsberg, all transponders within a surveillance range of 100 NM of the IoI were defined as Transponders of Interest (ToIs). Concerning the long range systems Neunkirchen and Nordholz, all transponders within a coverage of 150 NM of the respective site were regarded as ToIs. The

[2] A removable table defining the scenarios B01-B05 is provided in Annex B to be used as a cross reference list for the following discussion of results.

selected IoIs along with their ToIs were considered as representatives of the SSR system surveillance performance had to be explored for.

Due to the fact that scenario B01 represented a pure Mode A/C interrogator environment, in the simulation performed the selected IoIs were also modelled as MSSR stations performing surveillance of both Mode A/C and Mode S transponders by means of Mode A/C interrogations. In the scenarios B02 to B05, the selected IoIs were part of the SSR sites equipped with a Mode S interrogator.

It should be noted that scenario B03, defined in the Table 6-1, differs from scenario A05, discussed in section 4 and 5, only with respect to 106 ACAS interrogators applying Hybrid Surveillance techniques. Therefore, these two scenarios establish the link between the results presented in section 4 an 5 and the analysis discussed in the present and the following section.

The investigations for the scenarios B01 to B05 were conducted using the simulation programme SISSIM described in section 3. For each scenario a simulation run was conducted. Each run was executed five times with different initial conditions.

6.3 Results

6.3.1 ACAS contribution to RF load

The following Figure 6-1 illustrates the various impacts on a SSR surveillance process between an IoI and a ToI that can occur in the scenarios B01 to B05. The diagram depicts the different types of interfering interrogations at the ToIs caused by Mode A/C (MAC-I), Mode S (MS-I), and ACAS (ACAS-I) interrogators. The diagram also shows the various types of interfering replies at an IoI produced by civil Mode A/C transponders (MAC-T), civil Mode S transponders (MS-T), military non-Mode S capable transponders (MKXII-T), and military Mode S capable transponders (MKXIIMS-T). It should be noted that Extended Squitters, generated by Mode S capable transponders in the downlink format DF17, are also taken into account.

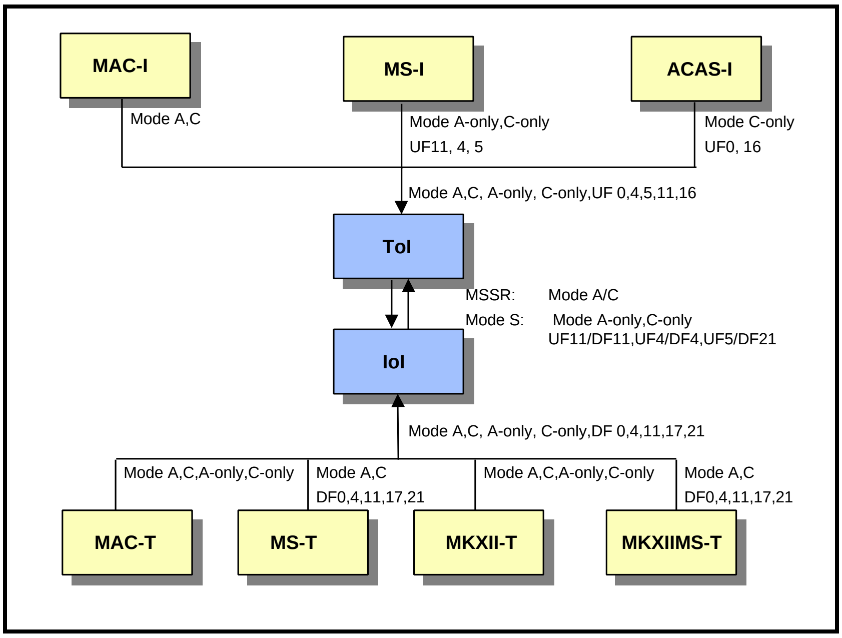


Figure 6-1: Scenario B01 to B05 - impacts on MSSR/Mode S surveillance

Concerning interfering interrogations, the simulations conducted for the scenario B01 to B05 predicted the long term mean rates of the main beam and side lobe signals received by each ToI. The following Table 6-2 comprises minimum, mean, and maximum values of the main beam and side lobe interrogation rates based upon the individual rates at all ToIs within the coverage of the IoI Frankfurt. The rates, quoted in interrogations per second, are listed for the various Modes and Mode S formats separately. The rates are also grouped with respect to the interrogator type originating the respective signals.

Scenario		Main beam rates B01	B02	B03	B04	B05	Side lobe rates B01	B02	B03	B04	B05
		Mode A/C									
Mode A	**min**	2	1	1	1	-	0	0	0	0	-
	mean	12	8	8	8	-	35	15	21	21	-
	max	27	20	20	20	-	358	123	179	179	-
Mode C	**min**	2	1	1	1	-	0	0	0	0	-
	mean	12	8	8	8	-	35	15	21	21	-
	max	26	20	20	20	-	358	123	179	179	-
		Mode S									
Mode A-only	**min**	-	1	1	1	2	-	0	0	0	0
	mean	-	3	3	3	10	-	10	13	13	24
	max	-	5	5	5	23	-	117	117	117	181
Mode C-only	**min**	-	1	1	1	2	-	0	0	0	0
	mean	-	3	3	3	10	-	10	13	13	24
	max	-	5	5	5	23	-	117	117	117	181
UF4	**min**	-	0	1	1	2	-	0	0	0	0
	mean	-	2	4	4	12	-	7	16	16	26
	max	-	7	9	9	30		84	136	136	202
UF5	**min**	-	0	1	1	1	-	0	0	0	0
	mean	-	2	4	4	12	-	7	16	16	26
	max	-	7	9	9	30	-	85	136	136	202
UF11	**min**	-	3	3	3	4	-	0	0	0	0
	mean	-	5	5	5	20	-	19	26	26	48
	max	-	11	11	11	45		233	233	233	362
		ACAS									
Mode C-only	**min**	0	0	1	1	5	0	0	0	0	0
	mean	16	16	29	29	29	8	8	8	7	7
	max	81	81	113	113	99	148	148	59	59	59
UF0	**min**	0	0	1	0	0	-	-	-	-	-
	mean	21	21	40	28	28	-	-	-	-	-
	max	60	60	123	99	99	-	-	-	-	-
UF16	**min**	0	0	1	1	1	-	-	-	-	-
	mean	3	3	5	5	5	-	-	-	-	-
	max	6	6	10	10	10	-	-	-	-	-

Table 6-2: IoI Frankfurt - interrogation rates

Within Figure 6-2 the overall transponder utilisation at the ToIs of the IoI Frankfurt is pictured versus the distance of the ToIs from the IoI. In addition to the overall transponder utilisation, the transponder utilisation caused by ACAS activities is inserted separately. The utilisation by ACAS comprises occupancy by interrogations from other ACAS units as well as the mutual suppression by the onboard ACAS interrogator.

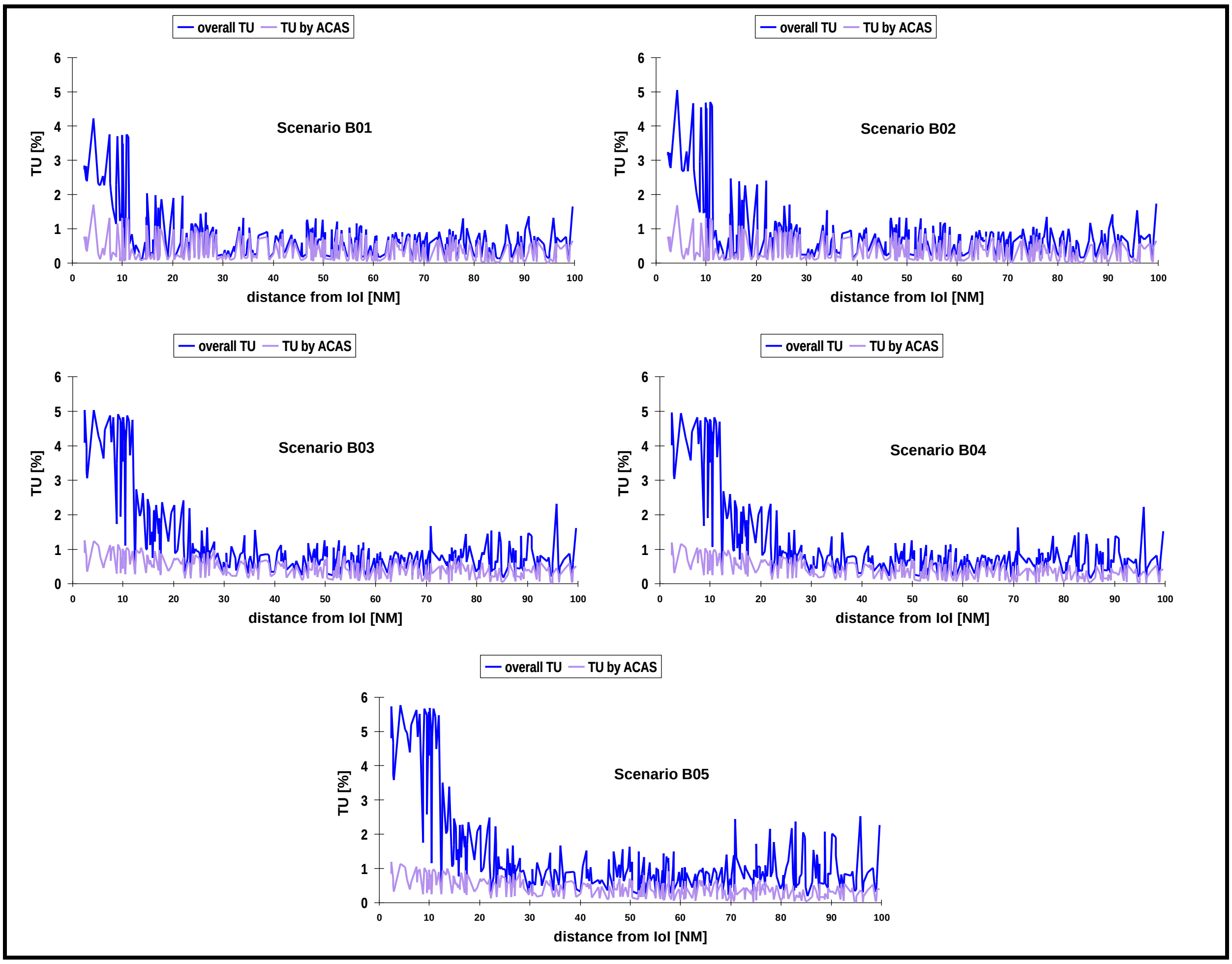


Figure 6-2: IoI Frankfurt - transponder utilisation

The following Figure 6-3 and Figure 6-4 provide statistics of the overall transponder utilisation as well as of the utilisation caused by ACAS. for transponders. Minimum, mean, and maximum values are provided for the IoI at Frankfurt based on the sample of all ToIs deployed within the surveillance area.

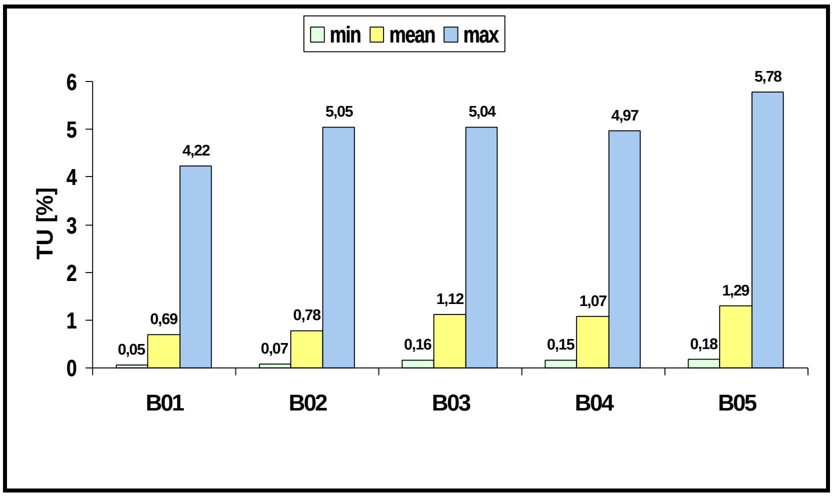


Figure 6-3: IoI Frankfurt - statistics of overall transponder utilisation

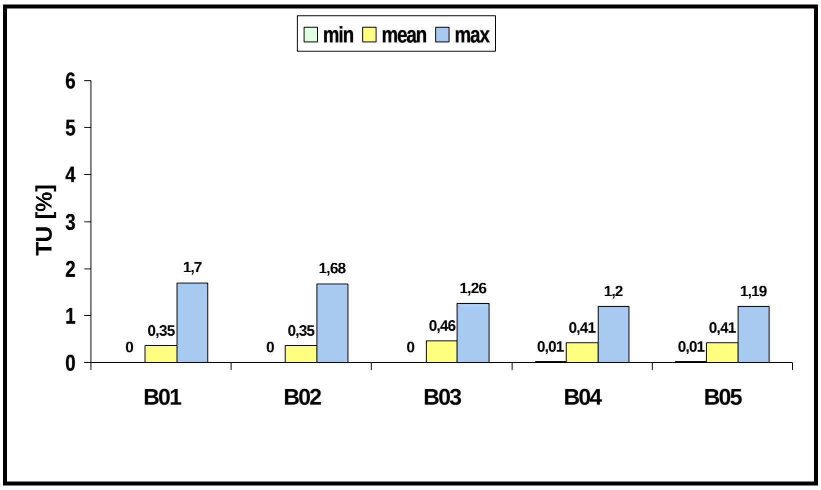


Figure 6-4: IoI Frankfurt - statistics of ACAS transponder utilisation

Concerning transponder utilisation, the following conclusions can be drawn for a pure civil interrogator environment:

1. In all scenarios, the peak transponder utilisation is achieved in close proximity to the airport.
2. In an equally shared Mode A/C and Mode S transponder environment (scenario B01, B02), transponder utilisation in the vicinity of Frankfurt airport is slightly below 2% but it nearly scores the limit imposed on ACAS.
3. In an equally shared Mode A/C and Mode S transponder environment (scenario B01, B02), approximately half of the transponder utilisation is caused by ACAS in average.

4. In a predominated Mode S transponder environment (scenario B03-B05), the peak transponder utilisation in the vicinity of Frankfurt airport exceeds 1% but the 2% limit imposed on ACAS is met.
5. In a predominated Mode S transponder environment (scenario B03-B05), the ACAS portion of the mean transponder utilisation accounts for about 30%-40%.
6. A transition from a scenario where all ACAS interrogators use conventional surveillance procedures (scenario A05, s. 4.3.1) to a scenario where 20% of the ACAS interrogators apply Hybrid Surveillance techniques (scenario B03) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will slightly increase the mean overall transponder utilisation from 1,08% to 1.12%, i.e. by 4% relative to scenario A05, although the utilisation caused by ACAS is reduced. The increase is caused by the transmission of extended squitters suppressing Mode S transponders additionally. Since the simulations performed indicate an increase of the overall transponder utilisation, it has to be concluded that the additional suppression by extended squitter transmission overbalances the reduction of transponder utilisation accomplished by the lower number of active tracks due to Hybrid Surveillance.
7. A transition from a full MSSR interrogator environment (scenario B01) to a mixed MSSR/Mode S interrogator environment (scenario B02) in an equally shared Mode A/C and Mode S transponder environment will increase the mean transponder utilisation from 0.69% to 0.78%, i.e. by roughly 15% relative to scenario B01.
8. A transition from a mixed MSSR/Mode S interrogator environment (scenario B04) to a full Mode S interrogator environment (scenario B05) in a predominated Mode S transponder environment will raise mean transponder utilisation from 1.07% to 1.29%, i.e. by 20% relative to scenario B04.
9. An increase of the number of ACAS interrogators using Hybrid Surveillance from 20% (scenario B03) to 80% (scenario B04) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will reduce mean transponder utilisation from 1.12% t0 1.07%, i.e. by approximately 5% relative to scenario B03.

The various types of interfering replies at an IoI are pictured within Figure 6-1. Concerning these interfering replies, the simulations performed predicted the long term fruit rates (FR) at the selected IoIs. Table 6-3 contains the fruit rates received by the IoI Frankfurt. The fruit rates, quoted in replies per second, are listed for the various Modes and Mode S formats separately. Additionally, the rates are grouped with respect to the originating interrogator type.

Scenario	B01	B02	B03	B04	B05
	Mode A/C				
Mode A	596	130	178	178	-
Mode C	594	128	175	175	-
Mode A-only	-	213	55	55	67
Mode C-only	-	213	55	55	67
DF4	-	43	74	74	95
DF11	10	11	29	28	28
DF17	88	94	172	172	172
DF21	-	44	74	74	95
Mode C-only	1399	1391	145	145	144
DF0	25	26	95	79	78

Table 6-3: IoI Frankfurt - fruit rates

From the fruit rates listed above, the interrogator receiver utilisation was derived. Within Figure 6-5 the values obtained are plotted for the IoI Frankfurt. The figure shows the total interrogator receiver utilisation caused by the complete fruit as well as the utilisation by ACAS signals only.

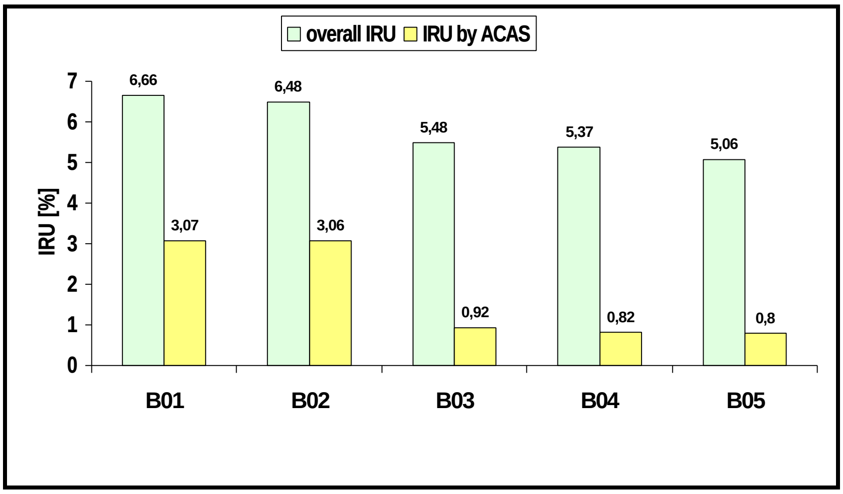


Figure 6-5: IoI Frankfurt – interrogator receiver utilisation

From the interrogator receiver utilisation listed above, the following conclusions can be drawn for a pure civil interrogator environment:

1. In an equally shared Mode A/C and Mode S transponder environment (scenario B01, B02), nearly half of the interrogator receiver utilisation is caused by ACAS.
2. In a predominated Mode S transponder environment (scenario B03, B04, B05), the ACAS contribution to the overall interrogator receiver utilisation accounts for about 15%.
3. A transition from a scenario where all ACAS interrogators use conventional surveillance procedures (scenario A05) to a scenario where 20% of the ACAS interrogators apply

Hybrid Surveillance techniques (scenario B03) in a predominated Mode S transponder and in a mixed MSSR/Mode S interrogator environment will decrease interrogator receiver utilisation caused by ACAS from 0.96% to 0.92%, resulting from a reduction of DF0 replies, which accounts for about 5% relative to scenario A05.

4. A transition from a full MSSR interrogator environment (scenario B01) to a mixed MSSR/Mode S interrogator environment (scenario B02) in an equally shared Mode A/C and Mode S transponder environment will reduce interrogator receiver utilisation from 6.66% to 6.48%, i.e. by 3% relative to scenario B01.

5. A transition from a mixed MSSR/Mode S interrogator environment (scenario B04) to a full Mode S interrogator environment (scenario B05) in a predominated Mode S transponder environment will decrease interrogator receiver utilisation from 5.37% to 5.06%, i.e. by approximately 5% relative to scenario B04.

6. An increase of the number of ACAS interrogators using Hybrid Surveillance from 20% (scenario B03) to 80% (scenario B04) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will reduce interrogator receiver utilisation from 5.48% to 5.37%, i.e. by about 2% relative to scenario B03.

6.3.2 MSSR/Mode S surveillance performance

In scenario B01, the IoIs used Mode A and Mode C signals to interrogate their ToIs. In the scenarios B02 to B05, Mode A/C transponders were tracked by the IoIs using Mode A-only and Mode C-only interrogations. Surveillance of Mode S capable transponders was accomplished by transmitting interrogations of the Mode S uplink formats UF4 and UF5. Statistical data for reply efficiency in the Modes and formats used are listed in the following Table 6-4 for the IoI Frankfurt. Thereby, minimum, mean, and maximum reply efficiency for Mode A-only and Mode C-only is based on the sample of the Mode A/C ToIs and the corresponding data for the Mode S reply efficiency are derived from the set of Mode S capable ToIs. Since there is no difference between the signal structure of an UF4 and an UF5 interrogation, a common Mode S reply efficiency is provided

IoI		B01	B02	B03	B04	B05
Mode A-only	**min**	90.	90.	97.	99.	93.
	mean	99.1	99.3	99.2	99.2	99.2
	max	100.	100.	100.	100.	100.
Mode C-only	**min**	90.	94.	91.	91.	91.
	mean	99.1	99.1	98.9	99.0	98.7
	max	100.	100.	100.	100.	100.
Mode S	**min**	-	84.	86.	86.	85.
	mean	-	98.5	98.2	98.3	97.8
	max	-	100.	100.	100.	100.

Table 6-4: IoI Frankfurt – reply efficiency

From the reply efficiency presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. Mode C reply efficiency is slightly poorer than Mode A reply efficiency. This is due to fact that a Mode C interrogation lasts longer than a Mode A signal and therefore overlapping of a Mode C interrogation is more likely.
2. Mode S reply efficiency is always below Mode A/C reply efficiency. This has to be traced back to the fact that on one hand Mode S transponder are more sensitive than a Mode A/C transponder, therefore higher interrogation rates are received, and that on the other hand the occupancy time caused by the processing of Mode S signals last longer than the occupancy by Mode A/C signals.
3. Mode A/C reply efficiency is only weakly affected by the scenario variations analysed.
4. The variation of mean Mode S reply efficiency is within 0.7%. The simulations performed predicted the lowest value (97.8%) for the scenario with a full Mode S interrogator and transponder environment (scenario B05). The best value (98.6%) was achieved for a

mixed MSSR/Mode S interrogator environment with an equally shared Mode A/C Mode S transponder environment (scenario B02).

5. A transition from a scenario where all ACAS use conventional surveillance (scenario A05, s. 4.3.2) to a scenario where 20% of the ACAS interrogators apply Hybrid Surveillance techniques (scenario B03) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will have nearly no effect on reply efficiency.
6. An enhancement of the number of ACAS interrogators using Hybrid Surveillance from 20% (scenario B03) to 80% (scenario B04) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will only marginally affect reply efficiency.

In scenario B01, the selected IoIs were interrogating Mode A and Mode C. In the scenarios B02 to B05, the IoIs were modelled as Mode S stations eliciting Mode A/C replies from aircraft fitted with Mode A/C transponders and responses in the Mode S formats DF4 and DF21 from Mode S transponder equipped aircraft. Within Table 6-5 the values for decode efficiency obtained by simulation are provided.

IoI	**B01**	**B02**	**B03**	**B04**	**B05**
Mode A/C	92.	93.	92.	92.	92.
DF4	-	97.	98.	98.	98.
DF21	-	95.	97.	98.	98.

Table 6-5: IoI Frankfurt – decode efficiency

From the decode efficiency presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. In all scenarios analysed, Mode A/C decode efficiency is about 4-6% below Mode S decode efficiency. Thereby, synchronous garbling is the main reason for the loss of Mode A/C replies. By contrast, Mode S avoids synchronous garbling by means of interrogation scheduling which is reflected in the higher decode efficiency.
2. Mode S decode efficiency is 1-2% lower in a scenario with an equally shared Mode A/C and Mode S transponder environment (scenario B02) than in other scenarios analysed. Obviously, this reflects the high downlink signal load in scenario B02 already indicated by the interrogator receiver utilisation.
3. The Mode S decode efficiency in scenarios with a predominated Mode S transponder environment (scenario B03 to B05) is of the same magnitude.

To quantify the success of a complete surveillance process, performed during an antenna sweep of the IoI across a ToI, Code A, Code C, and Mode S detection probabilities were evaluated. Table 6-6 depicts the values achieved for the IoI Frankfurt in the scenarios analysed.

IoI	B01	B02	B03	B04	B05
Code A	97.	97.	96.	96.	96.
Code C	97.	98.	97.	98.	97.
UF4/DF4		100.	100.	100.	100.
UF5/DF21		100.	100.	100.	100.

Table 6-6: IoI Frankfurt – Code A/C and Mode S detection

From the detection values presented above, the following conclusions can be drawn for a pure civil interrogator environment:

1. In all scenarios analysed, Mode S detection is 100%. This can be explained by the fact that Mode S avoids synchronous garbling by means of interrogation scheduling and furthermore, that in case of failure, the re-interrogation function is invoked.
2. The Code A/C detection values obtained for the scenarios analysed vary within the statistical precision with which the probabilities could be derived from the simulation. Therefore, it has to be concluded that the scenario variations analysed have no significant impact on Code A/C detection.

6.4 Summary of conclusions

In the environment simulated, ACAS Hybrid Surveillance affects the performance of ground interrogators only slightly. However, in increasing traffic densities the ground environment will benefit to lower interference levels.

7. ACAS SURVEILLANCE PERFORMANCE IN CASE OF HYBRID SURVEILLANCE

7.1 Objective of analysis

In the previous section, MSSR/Mode S surveillance performance and the effects of ACAS on it were explored in scenarios that assumed the application of ACAS Hybrid Surveillance techniques. By contrast, the current section will address the issue of ACAS surveillance performance in environments where ACAS Hybrid Surveillance is used.

The purpose of Hybrid Surveillance is to allow ACAS to take advantage of the passive surveillance provided by Extended Squitters to reduce interrogation rates while at the same time preserving ACAS independence from the information transferred via Extended Squitter. The approach to achieve this goal is to use active surveillance interrogations to validate the data received via Extended Squitter or to utilise the actively requested data in case of incorrect or missing Extended Squitter information.

Also when Hybrid Surveillance techniques are applied, it is required that ACAS is capable of operating in all air traffic densities without any significant performance degradation within a nominal surveillance range of 14 NM. Only in high density areas, the interference limiting function should reduce system range to at most 5 NM, which is still adequate to provide enough surveillance performance.

If an ACAS interrogator performs a surveillance process within a dense environment, as represented by the environment 2005 described in section 2, each question and answer cycle will suffer various impacts. Thereby, the receiving and processing of ACAS interrogations by transponders as well as the receipt and evaluation of replies by an ACAS interrogator may be influenced. Nevertheless, it is required that a track is established with a probability of at least 90% for aircraft within the surveillance range.

In order to analyse ACAS surveillance performance with regard to the requirements addressed above in scenarios where Hybrid Surveillance is applied, the model utilised for the investigations discussed in the previous sections was upgraded to obtain estimates for the reliability of ACAS surveillance processes. Section 7.2 introduces the analysis methodology used. The results achieved obtained are presented in section 7.3.

7.2 Analysis methodology

In order to explore the ACAS surveillance performance if ACAS Hybrid Surveillance techniques are applied, the same five scenarios B01 to B05 were considered as analysed to determine MSSR/Mode S surveillance performance. The scenarios, based on the environment 2005 described within section 2, varied with respect to the interrogator equipage of the SSR ground stations and the transponder equipage of civil and military aircraft. The scenarios considered are listed in Table 6-1.

To analyse ACAS system performance, the same four ACAS interrogators ID-number: 209 (1499 ft), 260 (4199 ft), 300 (3301 ft), 386 (4902 ft)) were chosen as Interrogators of Interest (IoIs) that were already considered in section 5. The locations of the ACAS IoIs selected within the coverage of the SSR site Frankfurt/Süd is depicted by Figure 5-1 in section 5.2. It should be pointed out that IoI 209 and 260 applied Hybrid Surveillance techniques in all scenarios B01 to B05, while IoI 300 used Hybrid Surveillance in the scenarios B03 to B04 and IoI 386 in the scenarios B04 and B05.

The investigations were performed using the simulation programme SISSIM described in section 3. For each scenario B01 to B05 a simulation run was conducted. Each run was executed five times with different initial conditions.

7.3 Results

7.3.1 RF load on ACAS

The interfering impacts on an ACAS surveillance process in the scenarios under consideration are the same as on an SSR surveillance process depicted by Figure 6-1. At the ToI the impacts consist of Mode A, Mode C, Mode A-only, Mode C-only, UF0, UF4, UF5, UF11, and UF16 interrogations. An ACAS IoI is influenced by fruit consisting of Mode A, Mode C, Mode A-only, Mode C-only, DF0, DF4, DF11, DF21, and DF17 replies.

Since the four ACAS IoIs were located within the coverage of the SSR interrogator at Frankfurt, the interrogation rates at the transponders and the utilisation of the transponders tracked by the ACAS interrogators are within range of the values predicted for the ToIs of the IoI Frankfurt/Süd. Because these quantities were already discussed in section 6.3.1 an extra evaluation of interrogation rates and transponder utilisation for ToIs of the ACAS IoIs is omitted. Instead reference is made to section 6.3.1.

The fruit rates received by the ACAS IoIs 300 and 386, which are affecting the surveillance processes in the scenarios under examination, are listed in the following Table 7-1. The fruit rates are separated into replies challenged by Mode A/C, Mode S, and ACAS interrogators. The rates are quoted in replies per second.

	IoI 300					IoI 386				
Scenario	**B01**	**B02**	**B03**	**B04**	**B05**	**B01**	**B02**	**B03**	**B04**	**B05**
	Mode A/C									
Mode A	789	590	647	625	-	1134	768	745	781	-
Mode C	787	589	644	622	-	1133	766	742	777	-
	Mode S									
Mode A-only	-	68	23	24	93	-	165	34	36	122
Mode C-only	-	68	23	24	93	-	165	34	34	122
DF4	-	23	39	38	111	-	30	58	59	161
DF11	43	42	67	65	65	59	59	110	115	114
DF17	185	185	292	279	279	293	293	514	534	534
DF21	-	23	39	38	112	-	30	58	60	161
	ACAS									
Mode C-only	434	432	204	199	199	2045	2029	445	477	475
DF0	60	60	117	69	69	123	123	300	257	254

Table 7-1: ACAS IoIs 300 and 386 - fruit rates

From the fruit rates listed above, the interrogator receiver utilisation at the four ACAS IoIs was derived. Within Figure 7-1 and Figure 7-2 the interrogator receiver utilisation is plotted for the ACAS IoIs 300 and 386.

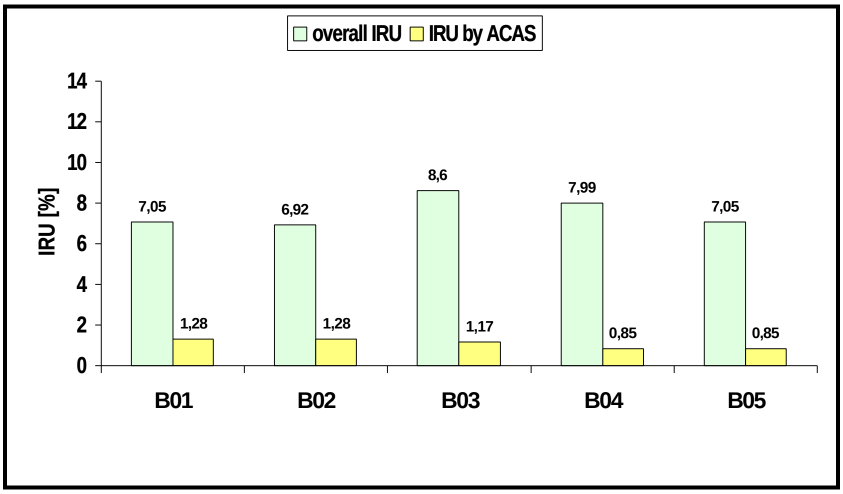


Figure 7-1: ACAS IoI 300 – interrogator receiver utilisation

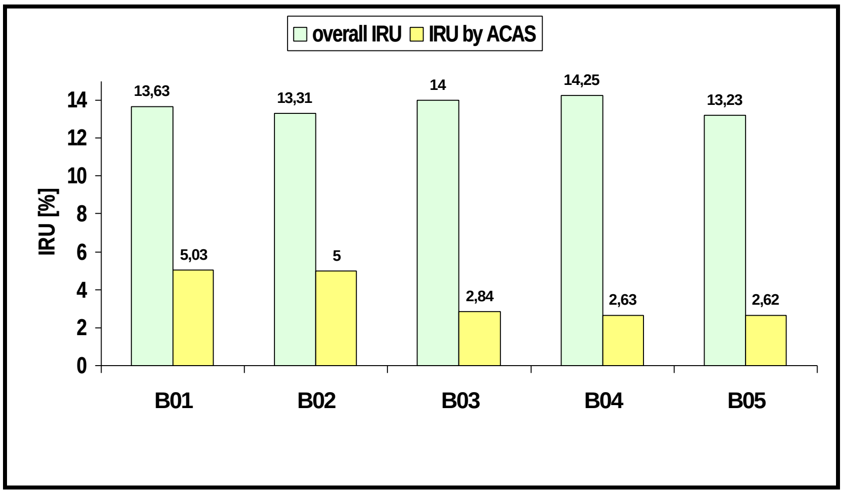


Figure 7-2: ACAS IoI 386 – interrogator receiver utilisation

From the interrogator receiver utilisation listed above, the following conclusions can be drawn:

1. In an equally shared Mode A/C and Mode S transponder environment (scenario B01, B02), more than 30% of the interrogator receiver utilisation is caused by ACAS at interrogators deployed close to the airport. At greater distances, ACAS contributes about 20%.

2. In a predominated Mode S transponder environment (scenario B03, B04, B05), the ACAS contribution to the overall interrogator receiver utilisation accounts for 10-20%.

3. A transition from a full MSSR interrogator environment (scenario B01) to a mixed MSSR/Mode S interrogator environment (scenario B02) in an equally shared Mode A/C and Mode S transponder environment will reduce interrogator receiver utilisation by roughly 2% (relative to scenario B01).

4. A transition from a mixed MSSR/Mode S interrogator environment (scenario B04) to a full Mode S interrogator environment (scenario B05) in a predominated Mode S transponder environment will reduce interrogator receiver utilisation by about 10% (relative to scenario B04).

5. An increase of the number of ACAS interrogators using Hybrid Surveillance from 20% (scenario B03) to 80% (scenario B04) in a predominated Mode S (90%) transponder and a mixed MSSR/Mode S interrogator environment will normally decrease interrogator receiver utilisation at ACAS IoI by approximately 5% (relative to scenario B03). The increase of nearly 2% (relative to scenario B03), noted for IoI 386, has to be traced back to the fact that IoI 386 is deployed in an area where the signal load on the SSR uplink channel is reduced above-average due to the usage of Hybrid Surveillance. As a consequence reply efficiency and, therewith, reply rates, fruit rates and interrogator receiver utilisation are increased.

7.3.2 ACAS surveillance performance

The following Figure 7-3 illustrates the density of ACAS units within the 100 NM surveillance volumes of the SSR site at Frankfurt for scenarios investigated. In addition to the actual density distribution (solid line) the corresponding curves (dotted lines) for an uniform in area and an uniform in range distribution are attached

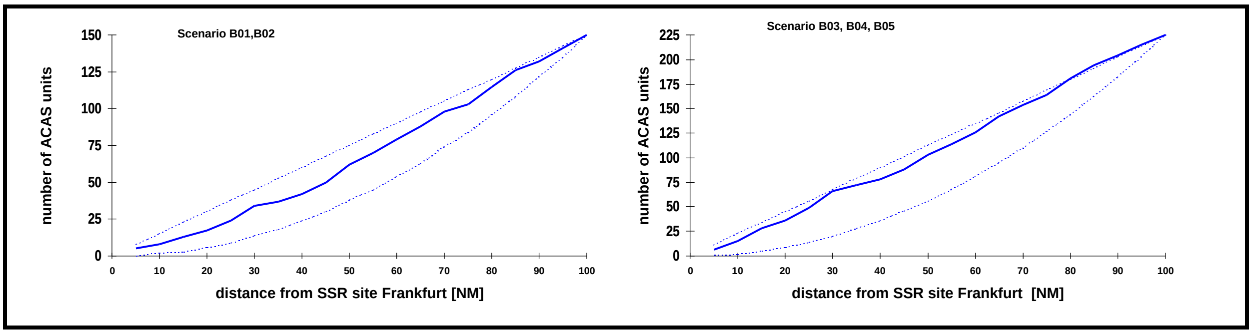


Figure 7-3: Scenario B01 to B05 – ACAS density

From the ACAS density distributions presented above, the following conclusions can be drawn:

1. The distribution of the ACAS units, deployed in the scenarios B01 and B02, is fairly between a uniform in area and a uniform in range distribution.
2. In the scenarios B03, B04 and B05 the distribution of the ACAS interrogators tends rather to a uniform in range than to a uniform in area distribution.

Figure 7-4 illustrates the Mode C and Mode S power limitation of the ACAS interrogators within 100 NM of the SSR site Frankfurt. The power reduction is plotted dependent on the range of the ACAS units from the SSR station.

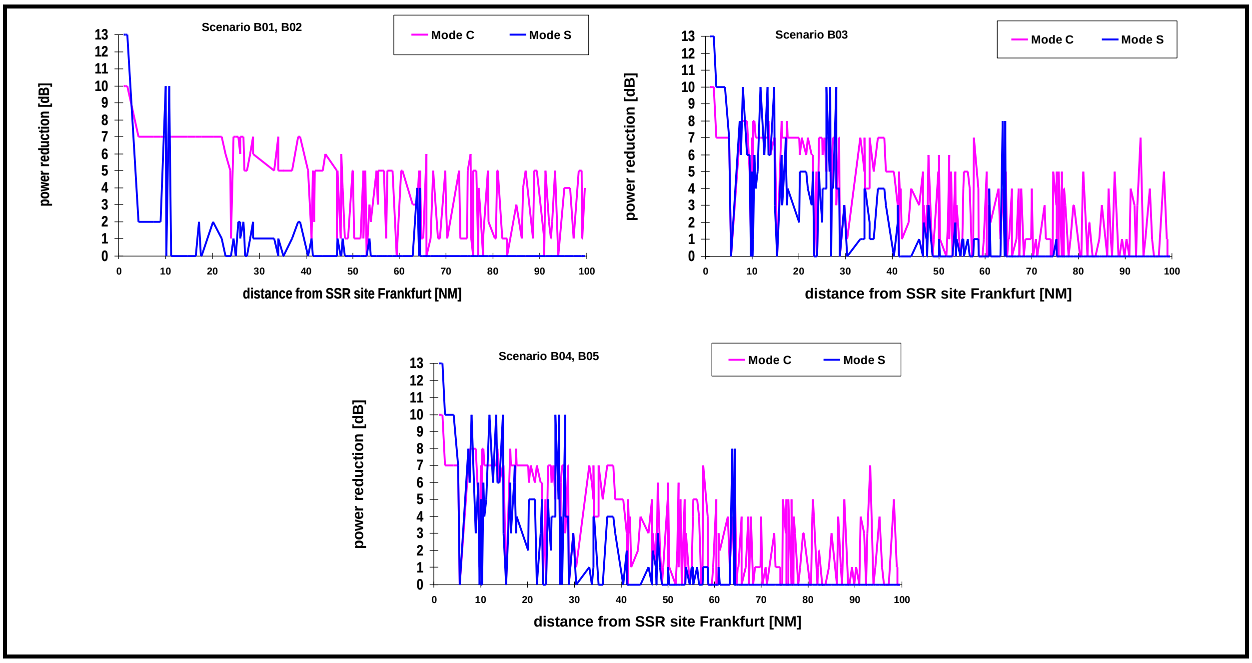


Figure 7-4: Scenario B01 to B05 – ACAS power reduction

From the power reductions presented above, the following conclusions can be drawn:

1. In the scenarios under examination, four ACAS interrogators are assumed on the surface at Frankfurt airport. These ACAS units have to reduce Mode C power and Mode S power to the absolute permitted limit of 10 dB and 13 dB in all scenarios.

2. A transition from a scenario where all ACAS use conventional surveillance (scenario A05) to a scenario where 20% of the ACAS interrogators apply Hybrid Surveillance techniques (scenario B03) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will decrease the mean Mode S power reduction, computed across all ACAS units deployed within the 100 NM coverage of Frankfurt, from 2.1 dB to 1.8 dB. Mode C power reduction is not affected.

3. An enhancement of the number of ACAS interrogators using Hybrid Surveillance from 20% (scenario B03) to 80% (scenario B04) in a predominated Mode S transponder and a mixed MSSR/Mode S interrogator environment will slightly decrease the mean Mode S power reduction from 1.8 dB to 1.7 dB.

The ACAS IoIs selected for the performance analysis were all located within the surveillance range of the SSR interrogator at Frankfurt. Hence, each of them is representing a point in the curves plotted above. In order to characterise the environments surrounding the selected ACAS IoIs in more detail, the following Table 7-2 lists for IoI 300 and IoI 386 the number of aircraft within the nominal surveillance range, the number of ACAS units within 3NM, 6NM, and 30NM, the selected Mode C-sequence for the forward, right, left, aft, and omni antenna, the reduction of Mode C and Mode S power due to interference limiting, the resulting effective surveillance range, and finally, the number of targets within the effective surveillance range (ToIs).

Scenario	**IoI 300**			**IoI 386**		
	B01 B02	**B03**	**B04 B05**	**B01 B02**	**B03**	**B04 B05**
Aircraft within nominal range:						
Mode A/C transponders	5	3	3	65	11	11
Mode S transponders	23	27	27	37	82	60
ACAS units within:						
3 NM	0	0	0	0	1	1
6 NM	0	0	0	1	4	4
30 NM	23	41	41	44	81	81
Mode C-sequence:						
Forward	Long	Long	Long	Long	Long	Long
Right	Medium	Medium	Medium	Long	Short	Short
Left	Short	Short	Short	Long	Medium	Medium
Aft	Short	Short	Short	Long	Short	Short
Omni	Long	Long	Long	Long	Long	Long
Power reduction:						
Mode C	5 dB	6 dB	6 dB	7 dB	7 dB	7 dB
Mode S	0 dB	0 dB	0 dB	2 dB	10 dB	10 dB
Effective range:						
Mode C	15.8 NM	14.0 NM	14.0 NM	12.5 NM	12.5 NM	12.5 NM
Mode S	39.6 NM	39.6 NM	39.6 NM	31.4 NM	12.5 NM	12.5 NM
Aircraft within effective range:						
Mode A/C transponders	1	0	0	32	2	2
Mode S transponders	23	27	27	23	12	6

Table 7-2: ACAS IoIs 300 and 386 - environment parameters

From the environmental parameters listed above the following conclusion can be drawn:

- A transition from conventional ACAS surveillance to ACAS Hybrid Surveillance techniques (scenario A05/B03 for IoI 300) and (scenario B03/B04 for IoI 386) will lower the number of Mode S transponders to be tracked. As a consequence more Mode S power is available and thus the effective Mode S range might be increased.

In order to quantify the success of an ACAS surveillance process, the round trip reliability was evaluated for the ACAS IoIs under consideration. The values predicted for the IoIs 300 and 386 by the simulations performed are shown in Figure 7-6.

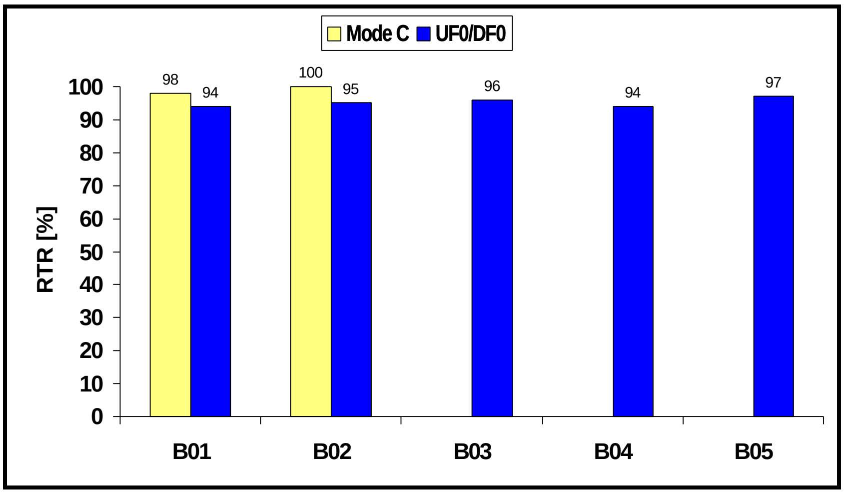


Figure 7-5:ACAS IoI 300 – round trip reliability

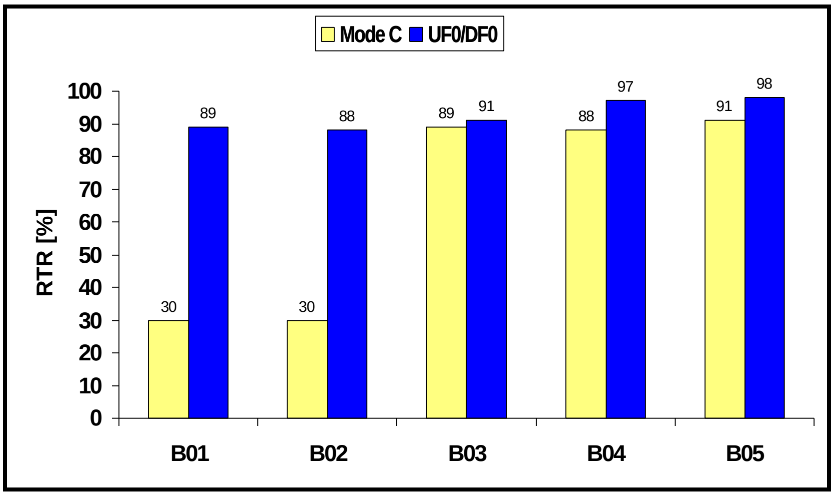


Figure 7-6: ACAS IoI 386 - round trip reliability

Care must be taken in drawing conclusions from the figures above. Firstly, it should be noted that due to the small sample of transponders tracked by the ACAS IoIs, the numbers quoted in the diagram are of lower confidence. Secondly, the values provided for the various scenarios are based on different sample sizes of ToIs interrogated by the ACAS IoIs. Therefore, a direct comparison of the round trip reliability values is actually not feasible. Nevertheless, from the results achieved the following statements can be concluded for a pure civil interrogator environment:

1. In an equally shared Mode A/C and Mode S transponder environment (scenario B01, B02), Mode C round trip reliability might be quite low. Thereby, synchronous garbling is the driving factor.
2. A transition from a scenario with conventional ACAS surveillance (scenario A05) to a scenario with Extended Squitter transmissions and ACAS Hybrid Surveillance techniques

(scenario B03) can reduce Mode C and Mode S round trip reliability up to 5% (see IoI 386).

3. A transition from a full MSSR interrogator environment (scenario B01) to a mixed MSSR/Mode S interrogator environment (scenario B02) in an equally shared Mode A/C and Mode S transponder environment will only marginally affect round trip reliability. The deviations predicted are within range of precision with which round trip reliability is obtained by the simulations performed.
4. Also, a transition from a mixed MSSR/Mode S interrogator environment (scenario B04) to a full Mode S interrogator environment (scenario B05) in a predominated Mode S transponder environment will slightly affect ACAS round trip reliability.

7.4 Summary of conclusions

The application of ACAS Hybrid Surveillance will stabilise the surveillance range of ACAS equipped aircraft making it, to some extend, independent of most aircraft densities. In particular, in the vicinity of major airports power and surveillance range reduction will become effective later compared with normal ACAS operation.

8. REFERENCES

[1] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting and Hybrid Surveillance
Scenario Description
Doc. No: 1DFS-BT-0001, Issued: 31.01.2001, Issue No: 1.0

[2] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting and Hybrid Surveillance
Modellbeschreibung
Dok.-Nr.: 1DFS-BT-0002, Ausgabedatum: 16.02.2001, Ausgabe-Nr.: 1.0

[3] ICAO
International Standards and Recommended Practices
Aeronautical Telecommunications,
Annex 10 to the convention on international civil aviation
Volume IV, surveillance radar and collision avoidance systems
Second Edition of volume IV, July 1998, Amendment 74

[4] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting and Mode S Extended Squitter
Final Report
Doc. No: 1AN5-BT-0003, Issued: 05.06.1996, Issue No: 1.0

[5] ESG Elektroniksystem- und Logistik-GmbH
Einfluss von Mk XII Mode 4 auf das SSR-System der zivilen Flugsicherung im Szenario 2003
Ergebnisbericht
Doc. No.: 4MOD-BT-0002, Issued: 30.07.2001, Issue No: 1.0

9. Annexes

Annex A: WP5-Electromagnetic environmental effects of and on ACAS (when those systems are operated in clusters)

Annex B: SIEM Modeling results

ACAS PROGRAMME

ACASA PROJECT

Annex A to

Work Package 5

Final report on

Electromagnetic Environmental Effects of, and on, ACAS

Edition 1.0
March 2002

Annex A to Work Package 5

Final Report on Electromagnetic Environmental Effects of, and on, ACAS

Version 1.1, March 2002

TABLE OF CONTENTS

List of Tables

Table of Abbreviations

ACAS	Airborne Collision Avoidance System
ASR	Airfield Surveillance Radar
ATC	Air Traffic Control
DB	Decibel
DBm	Decibel (with reference to 1mWatt)
DE	Decode Efficiency
DF	Mode S Downlink Format
DFS	Deutsche Flugsicherung GmbH
ESG	Elektroniksystem- und Logistik-GmbH
Fruit	Friendly replies unsynchronised in time
FR	Fruit Rate
Ft	Feet
Hz	Hertz
I	Interrogator
ICAO	International Civil Aviation Organisation
IFF	Identification Friend or Foe
ILI	Interference Limiting Inequality
ILP	Interference Limiting Procedure
IoI	Interrogator of Interest
IRU	Interrogator Receiver Utilisation
MB	Main Beam
MHz	Megahertz
Mk	Mark
MS	Mode S
s	Microsecond
Ms	Millisecond
MSSR	Monopulse Secondary Surveillance Radar
NM	Nautical miles
PC	Personal Computer
RE	Reply Efficiency
RF	Radio Frequency
RTR	Round Trip Reliability
S	Seconds
SICASP	Secondary Surveillance Radar Improvement and Collision Avoidance Systems Panel
SISEVA	SSR IFF System Evaluator
SISSIM	SSR IFF System Simulator
SL	Side Lobe
SSR	Secondary Surveillance Radar
T	Transponder
TCAS	Traffic alert and Collision Avoidance System
ToI	Transponder of Interest
TU	Transponder Utilisation
UF	Mode S Uplink Format
UK	United Kingdom
US	United States of America

WP-5

Electromagnetic environmental effects of and on ACAS

This paper is a study on the Electromagnetic environmental effects of and on ACAS, in particular when those systems are operated in clusters.

1. Introduction

To support save air traffic operation, Airborne Collision Avoidance Systems (ACAS) have been standardised by ICAO. The Traffic Alert and Collision Avoidance System (TCAS) is the implementation available today. TCAS systems are divided in TCAS I, which is mainly operated by commuter aircraft, helicopter and general aviation, and TCAS II, which is foreseen for commercial air transport aircraft. While TCAS I supports “see and avoid” with the capability to generate Traffic Advisories, TCAS II is additionally capable of generating automatic Resolution Advisories against potential threat aircraft. TCAS II (Version 7) is compliant with ICAO ACAS II standards. Regional and global mandates have been published to equip aircraft with ACAS II. Since some authorities allow the local operation of TCAS I equipment, ICAO has amended international standards to ensure save operation of ACAS for international traffic. These amendments limit the interference generated by TCAS I (ACAS I) in particular, to protect sufficient surveillance for ACAS and ground surveillance systems. This report is dealing with ICAO systems (ACAS), thus discussing various aspects of their behaviour in the European environment. ACAS I is not foreseen to be operated in this airspace. However, industry is advertising products and therefore some of the important aspects were investigated and are discussed in this report. When the report is referring to ICAO compliant equipment, the acronym “ACAS” has been used, while special implementations are named “TCAS”.

The Airborne Collision Avoidance Systems ACAS II and the Traffic Alert and Collision Avoidance System TCAS I are co-operative surveillance systems including an interrogator and a Mode S transponder on board of an aircraft. ACAS II as well as TCAS I interrogators tracks both Mode A/C and Mode S transponder-equipped aircraft in their vicinity.

ACAS II interrogators accomplish tracking by two entirely separate techniques. Mode A/C transponders are controlled via Mode C-only interrogations. Mode S transponders are acquired passively by listening for Mode S squitters. Surveillance is performed by directly addressed UF0 Mode S interrogations challenging DF0 replies. If collision threat is detected by the system, vertical resolution advisories are computed and exchanged via Mode S data link.

TCAS I interrogators make use of conventional Mode C interrogations for surveillance of Mode A/C and Mode S transponders. Thereby, an option is to transmit the Mode C interrogations in sequences using whisper-shout techniques.

Due to the involvement of the SSR transponder in the collision avoidance system, ACAS II and TCAS I units interrogate at the SSR uplink frequency 1030 MHz and detect replies on the SSR downlink frequency 1090 MHz. Due to the utilisation of the SSR channels by ACAS II and TCAS I, SSR system performance may be degraded by ACAS/TCAS operations. In order to minimise the impact of ACAS/TCAS upon the SSR system, ACAS II as well as TCAS I interrogators are obliged to limit their interrogation rates and their transmitter power by implementing so-called interference limiting procedures (ILP). These procedures are expected to ensure a transponder utilisation by ACAS II and TCAS I not exceeding 2%.

Investigations previously performed in the framework of the study “ACAS interference limiting and Hybrid Surveillance” (see [3]) revealed that the procedures currently proposed in ICAO Annex 10 ([4]) satisfy the criteria imposed on ACAS under normal conditions. However, although the algorithms are effective in reducing the ACAS interrogation rates, in some scenarios analysed the design limits were nearly reached.

Several problems have been uncovered especially close to airports, where higher than expected interrogation rates and transponder utilisation were observed. Therefore, to analyse the effectiveness of the interference limiting algorithms under more severe conditions, especially if a higher number of ACAS/TCAS units is operated in clusters, additional investigations were required. Thereby, the primary goal was to explore in more detail the following three aspects:

- impact of ACAS/TCAS clustering on MSSR/Mode S system performance,
- ACAS II surveillance performance, and
- TCAS I surveillance performance.

For that purpose, simulation runs were conducted utilising a programme which includes models for processing of interrogations by transponders and for decoding and evaluation of replies by interrogators that are based on measurements.

The results obtained are documented in this report. The report has to be considered as an attachment to [3], where the results of the above mentioned study “ACAS interference limiting and Hybrid Surveillance” are described. Scenarios and models, mentioned but not separately discussed in this report, are documented in [1] and [2], respectively.

The report is structured into 6 sections. Following this introductory section, in section 2 the scenarios considered in the study are detailed. Section 3 is dealing with some additional aspects concerning the simulation model SISSIM, which was already used for the previous study and which is documented in [2] in detail. Section 4 describes the analysis performed to explore the impact of TCAS I and ACAS II on the MSSR/Mode S system performance in the scenarios defined. Based on the same scenarios, Section 5 explores the ACAS II surveillance performance. Surveillance aspects regarding TCAS I are discussed in section 6.

2. Scenarios

The goal of the analysis, documented in the present report, was to explore effects of clustered ACAS/TCAS interrogators in the vicinity of Frankfurt airport upon the MSSR/Mode S, ACAS II, and TCAS I surveillance performance. In order to achieve this goal, three scenarios, denoted by C01, C02, and C03, were analysed in detail. The three scenarios under examination were defined on the basis of scenario A05 discussed in [3].

Scenario A05 consisted of

37	MSSR (Mode A/C) interrogators
12	Mode S interrogators
528	ACAS II interrogators
81	civil Mode A/C transponders
736	civil Mode S transponders
41	military non-Mode S capable transponders
104	military Mode S capable transponders

A more detailed description of scenario A05, including the technical and operational data used for the analysis, is provided in [1].

The three scenarios C01, C02, and C03 defined for the analysis differed from scenario A05 with respect to additional numbers of aircraft equipped with ACAS/TCAS interrogators and Mode S transponders. Beside the interrogators and transponders deployed in scenario A05, the three scenarios under examination included in detail:

scenario C01: 5 additional aircraft deployed in one cluster at Frankfurt/Kreuz (motorway junction),
each equipped with an ACAS II interrogator and a Mode S transponder.

scenario C02: 36 additional aircraft
5 at Frankfurt/Kreuz (the same as in scenario C01),
18 clustered at Frankfurt/Waldstadion (stadium),
13 clustered at Frankfurt/Messe (fairgrounds),
each equipped with an ACAS II interrogator and a Mode S transponder.

scenario C03: 36 clustered aircraft (the same as in scenario C02),
each equipped with an TCAS I interrogator and a Mode S transponder.

It should be noted that the three scenarios considered in the present study included no military interrogators. Furthermore, it should be pointed out that the 12 Mode S interrogators were supposed to be operated as autonomous Mode S sites without any clustering.

Since Frankfurt has been defined as the area of interest, the ASR sites Frankfurt/Süd and Frankfurt/Nord were chosen as Interrogators of Interest (IoI) for the analysis of MSSR/Mode S system performance. Thereby, Frankfurt/Süd, referenced in the scenario data base by index 15, was modelled as a MSSR/Mode S station, while Frankfurt/Nord, index 9, was assumed to be operated as a MSSR/Mode A/C interrogator. For the ASR sites Frankfurt/Süd, all transponders within a surveillance range of 100 NM were defined as Transponders of Interest (ToIs). Concerning Frankfurt/Nord, all transponders within a coverage of 60 NM were regarded as ToIs. The selected IoIs along with their ToIs formed the sample of the SSR system, the performance had to be explored for. It should be noted, although the transponders within the surveillance range were considered as ToIs only, the signal load was produced by all interrogators and transponders deployed in the scenario.

In order to investigate the surveillance performance of ACAS II, the aircraft referenced in the scenario data base by the indices 1048 and 1049 were chosen as ACAS II IoIs. Thereby, IoI 1048 represented an overflight at an altitude of 15.000 ft and at a distance of 6.3 NM from the SSR site Frankfurt/Süd. IoI 1049, at a height of 5.000 ft and a distance of 5.2 NM, was regarded as an approach for landing at Frankfurt airport.

For the analysis of TCAS I surveillance performance, the aircraft with the index 1014 was selected as IoI. IoI 1014 is one of the 5 aircraft at Frankfurt/Kreuz added to the scenario.

The following Figure 2-1 depicts the locations of the selected SSR IoIs Frankfurt/Süd (IoI 15) and Frankfurt/Nord (IoI 9) as well as of the ACAS II IoIs 1048 and 1049 and the TCAS I IoI 1014.

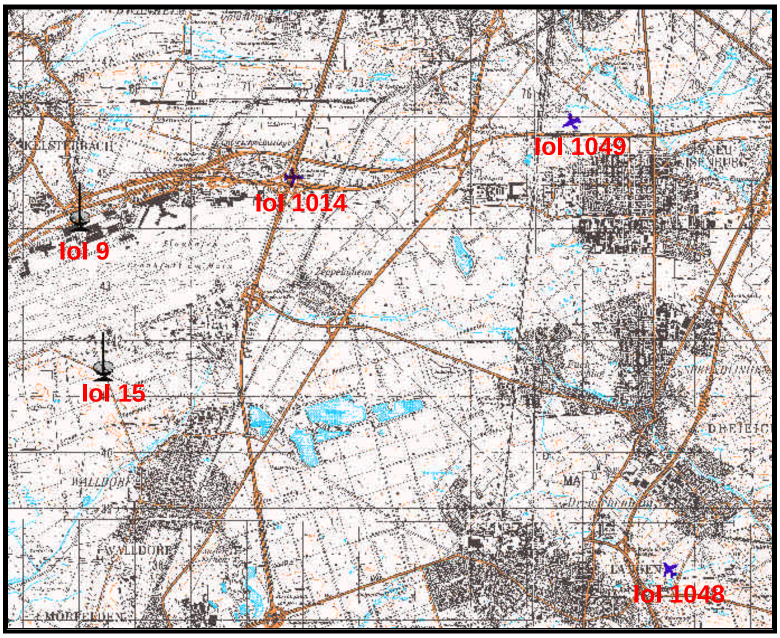


Figure 2-1: Location of IoIs

3. Simulation Model

The investigations documented in the present report were conducted using the simulation programme SISSIM described in [2]. In addition to the functionality specified in [2], the version of the programme used included a model for TCAS I interrogators. The TCAS I interrogator model was developed and implemented specifically for the analysis detailed in the present report. The model is based on the specifications documented in [4]. However, ICAO standards do not define implementation standards. Therefore, the model used can be considered as one possible implementation of the corresponding ICAO specification.

The most important assumptions made relating to the TCAS I model are listed in the remaining part of this section.

<u>Antenna system of a TCAS I interrogator</u>

1. The antenna system of a TCAS I interrogator consists of a directional antenna mounted on the top of the aircraft and an omni-directional antenna on the bottom.
2. The directional antenna generates beams that point in the forward, aft, left, and right directions. The directional antenna has a 3 dB beam width in azimuth of 90±10°.

<u>Surveillance of Mode A/C and Mode S Transponders</u>

1. A TCAS I interrogator uses Mode C interrogation for surveillance of both Mode A/C and Mode S transponder equipped aircraft.
2. The Mode C interrogations are transmitted in sequences using whisper-shout techniques. The sequences are determined in the same way as the high density whisper/shout sequences defined for an ACAS II interrogator (see [2]).
3. All interrogations in a sequence are transmitted within a single surveillance update interval of one second.
4. Each of the interrogations in the sequence, other than the one at lowest power, is preceded by a suppression transmission, where the first pulse of the interrogation serves as the second pulse of the suppression transmission. The suppression transmission pulse begins at a time 2 μs before the first pulse of the interrogation. The suppression pulse is transmitted at a power level lower than the accompanying interrogation.
5. The time interval between successive interrogations within a sequence is 1 ms.
6. The maximum radiated power for an interrogation is 52 dBm.

Interference Control

1. TCAS I monitors the Mode A/C reply rate (*RR*) of the own transponder.
2. TCAS I counts the number of ACAS II interrogators in the vicinity (*NTA*). The count is obtained by monitoring ACAS broadcast (UF16).
3. Implementation of Interference Limiting Procedure:
   The number of whisper-shout interrogations is reduced (in the order defined in [4]) such that the inequality

$$\sum_{k=1}^{83} Pa_k < f(NTA, RR)$$

   is satisfied. Thereby, Pa_k denotes the peak power radiated from the antenna in all directions of the pulse having the largest amplitude in the group of pulses comprising a single interrogation during the k-th Mode C interrogation in a sequence [W]. The function *f* is defined by the following table.

NTA	***f(NTA,RR)***	
	if RR£240	***if RR>240***
0	250	118
1	250	113
2	250	108
3	250	103
4	250	98
5	250	94
6	250	89
7	250	84
8	250	79
9	250	74
10	245	70
11	228	65
12	210	60
13	193	55
14	175	50
15	158	45
16	144	41
17	126	36
18	109	31
19	91	26
20	74	21
21	60	17
≥22	42	12

Table 3-1: TCAS I permitted power budget [W]

Decoding of replies

The decoding of replies by ACAS II and TCAS I receivers was modelled using the detection curves derived by DFS during a measurement campaign at the MSS/Mode S test station Götzenhain. Thus, TCAS I decoder were modelled in the same way as a MSSR/Mode S decoder implying a better performance than may be derived with an actual implementation.

4. Impact of ACAS on MSSR/Mode S Performance

4.1 Objective of analysis

The Airborne Collision Avoidance System ACAS II is designed to provide surveillance of both Mode A/C and Mode S transponder equipped aircraft. Mode A/C aircraft are tracked by using Whisper/Shout sequences consisting of Mode C-only all-call interrogations. A sequence is transmitted once per second. Mode S transponders are acquired passively by monitoring the Mode S squitter regularly transmitted by a transponder each second. Tracking is then accomplished using directly addressed interrogations of the Mode S uplink format UF0 which are challenging replies in the Mode S downlink format DF0.

The Traffic Alert and Collision Avoidance System TCAS I is able to provide surveillance of Mode A/C and Mode S transponders. Both are tracked by using conventional Mode C interrogations, which are transmitted in sequences applying whisper-shout techniques.

Since ACAS II as well as TCAS I are using the SSR frequencies 1030 MHz (uplink) and 1090 MHz (downlink), ACAS interrogations and replies may cause impacts upon the SSR air traffic control system. On the downlink, replies generated in response to ACAS interrogations may interfere with replies challenged by SSR interrogators. On the uplink, two interference mechanisms have to be distinguished. Firstly, a transponder on-board of an ACAS equipped aircraft is suppressed during each own ACAS interrogation. Secondly, a transponder may be taken off the air by processing interrogations originating from other ACAS aircraft. Both effects result in a reduction of the transponder availability and, as a consequence, in a potential degradation of SSR system performance.

In order to limit the impact upon the SSR system, all ACAS II and TCAS I units are obliged to control their interrogation rates and transmitter power by the implementation of so called interference limiting procedures (ILP).

For TCAS I, the interference limiting algorithm is based on one interference limiting inequality (see [4]), which takes into account the number of ACAS II interrogators in the vicinity and the Mode A/C reply rate of the own transponder. The count of the number of ACAS II units is obtained by monitoring ACAS broadcasts (UF16). The goal of the ILP is to limit the interrogation power of each TCAS I interrogator such that the defined interference limiting inequality is satisfied.

The interference limiting procedure for ACAS II is based on three interference limiting inequalities (ILI). If at least one of these inequalities is not satisfied, an ACAS II interrogator adjusts its interrogation rate and transmitter power such that the three inequalities become true.

The aim of the interference limiting algorithms for ACAS II as well as for TCAS I is to minimise their impact on the SSR system and to ensure a transponder utilisation by ACAS II and TCAS I not exceeding 2%. Thereby, the 2% limit comprises interrogations from other ACAS interrogators as well as the mutual suppression caused by the own ACAS interrogator.

In order to analyse the effectiveness of the ACAS interference limiting procedures in the scenarios C01, C02, and C03 defined in section 2, a simulation run was conducted for each scenario. Each run was executed several times with different initial conditions for antenna pointing angles, transmission start times, etc., in order to exclude statistical correlation as far as possible.

4.2 Results

The simulations performed modelled the IoI Frankfurt/Nord as a MSSR station performing surveillance for both Mode A/C and Mode S transponders by means of Mode A/C interrogations.

By contrast, the IoI Frankfurt/Süd was assumed as a Mode S station and was modelled in compliance with the multisite acquisition protocol. Multisite acquisition is determined by the transmission of a Mode S only all-call interrogation in the uplink format UF11 and of a Mode A/C-only all-call interrogation during each all-call period. During the Mode S periods, acquired Mode S transponders are tracked by selective interrogations. Therefore, the IoI Frankfurt/Süd, as well as each other Mode S interrogator in the scenario, was interrogating Mode A/C transponders in Mode A/C-only all-call and was tracking Mode S transponders via a cycle of Mode S transactions consisting of UF11/DF11, UF4/DF4, and UF5/DF21. When simulation started, each Mode S interrogator was assumed to have already acquired all Mode S transponders within its surveillance volume. Thus, a steady state condition could be monitored during the whole simulation. The Mode S surveillance was modelled such that each of the two transactions (UF4/DF4 and UF5/DF21) was performed for all Mode S transponders during each antenna sweep. In case of failure, a transaction was repeated up to a maximum of two re-interrogations.

Due to the fact that many interrogators and transponders are deployed in the scenarios under consideration, each surveillance process performed by an IoI for a ToI was potentially affected by multiple interference impacts. The following Figure 4-1 illustrates the various impacts on a MSSR/Mode S surveillance process that are applying within the three scenarios under examination. The diagram depicts the different types of interfering interrogations at the ToIs caused by Mode A/C (MAC-I), Mode S (MS-I), ACAS II (ACASII-I), and TCAS I (TCASI-I) interrogators. The diagram also indicates the various types of interfering replies at an IoI produced by civil Mode A/C transponders (MAC-T), civil Mode S transponders (MS-T), military non-Mode S capable transponders (MKXII-T), and military Mode S capable transponders (MKXIIMS-T). It should be noted that the impact of TCAS I interrogators is applicable for scenario C03 only.

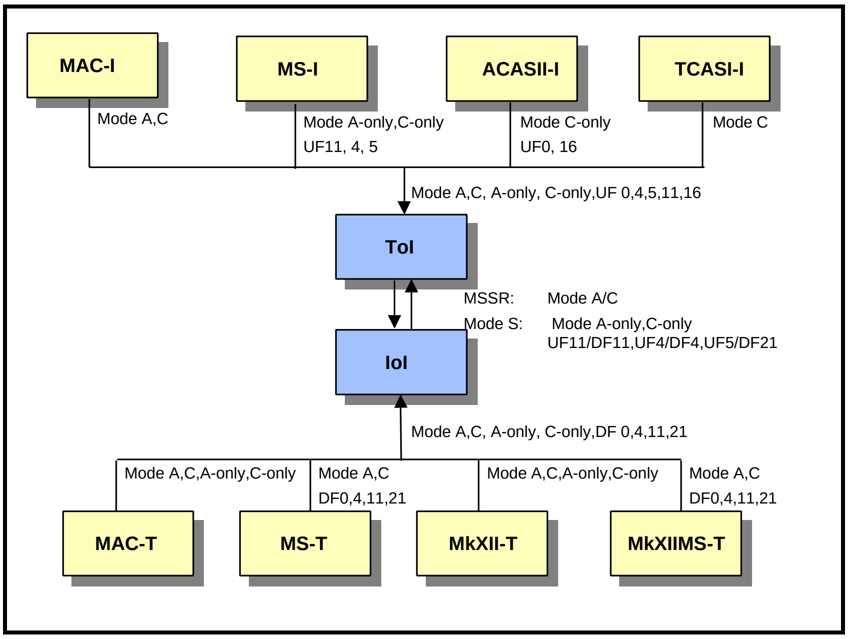


Figure 4-1: Impacts on MSSR/Mode S surveillance

4.2.1 Interrogation rates

Concerning the interfering interrogations at transponders, the simulation runs conducted for the scenarios under examination predicted the long term mean rates of main beam (MBIR) and side lobe (SLIR) signals received by each ToI. Since the range of the IoI Frankfurt/Süd is 100 NM, while Frankfurt/Nord covers only 60 NM, the ToIs of Frankfurt/Nord form a subset of the ToIs of Frankfurt/Süd. Therefore, an evaluation of the interrogation rates was restricted to the sample of the Frankfurt/Süd ToIs. The following Table 4-1 comprises minimum, mean, and maximum values of the main beam and side lobe interrogation rates based upon the individual rates obtained for the ToIs of the IoI Frankfurt/Süd. The rates are quoted in interrogations per second and are listed for the various Modes and Mode S formats separately. The rates are grouped with respect to the interrogator types originating the respective signals. For comparison purposes, the interrogation rates achieved for scenario A05, which are documented in [3], are also inserted.

Scenario		A05		C01		C02		C03	
		MBIR	SLIR	MBIR	SLIR	MBIR	SLIR	MBIR	SLIR
		Mode A/C							
Mode A	**min**	1	0	1	0	1	0	1	0
	mean	8	21	8	23	8	31	8	31
	max	20	179	20	179	20	179	20	179
Mode C	**min**	1	0	1	0	1	0	1	0
	mean	8	21	8	23	8	31	8	31
	max	20	179	20	179	20	179	20	179
		Mode S							
Mode A-only	**min**	1	0	1	0	1	0	1	0
	mean	3	13	3	15	2	21	2	21
	max	5	117	5	117	5	117	5	117
Mode C-only	**min**	1	0	1	0	1	0	1	0
	mean	3	13	3	15	2	21	2	21
	max	5	117	5	117	5	117	5	117
UF11	**min**	3	0	3	0	3	0	3	0
	mean	5	26	5	29	5	42	5	42
	max	11	233	11	234	11	234	11	234
UF4	**min**	1	0	1	0	1	0	1	0
	mean	4	16	4	18	4	28	4	28
	max	9	136	9	138	11	154	10	155
UF5	**min**	1	0	1	0	1	0	1	0
	mean	4	16	4	18	4	28	4	29
	max	9	136	9	139	12	155	11	159
		ACAS							
Mode C-only	**min**	2	0	1	0	2	0	1	0
	mean	29	7	32	9	71	62	36	9
	max	113	59	157	92	440	592	117	59
UF0	**min**	1	-	1	-	1	-	1	-
	mean	42	-	46	-	182	-	62	-
	max	117	-	174	-	1427	-	240	-
UF16	**min**	1	-	1	-	1	-	1	-
	mean	5	-	6	-	8	-	6	-
	max	10	-	11	-	15	-	11	-
Mode C	**min**	-	-	-	-	-	-	1	0
	mean	-	-	-	-	-	-	17	34
	max	-	-	-	-	-	-	184	396

Table 4-1: Interrogation rates

Concerning the variation of the interrogations rates listed in the table above, it can be stated:

1. The Mode A/C interrogation rates produced by the MSSR/Mode A/C interrogators as well as the Mode A/C-only rates and the UF11 rates induced by Mode S interrogators are the same for all scenarios analysed.
2. The UF4 and UF5 rates are slightly increased when additional Mode S transponder equipped aircraft are incorporated (scenario C01 and scenario C02). Selective interrogations generated by Mode S stations for the transponders added are the reason for higher rates.

3. The Mode C-only rates induced by ACAS are increased as the density of ACAS II aircraft rises (scenario C01 and scenario C02). The Mode C-only rates are significantly reduced when the clustered 36 ACAS II units additionally assumed are replaced by TCAS I interrogators (scenario C03). However, concurrently a quite high Mode C rate is achieved.

4. UF0 and UF16 rates are increased if the number of ACAS II interrogators is raised. A tremendous increase of the UF0 rates is predicted, if the 36 clustered ACAS II units are taken into account (scenario C02). Each of these ACAS II units is interrogating each other aircraft added once per second, which implicates the observed huge rate.

   The UF0 rates are decreased when the 36 ACAS II interrogators are replaced by TCAS I interrogators (scenario C03). However, the additional Mode S transponder equipped aircraft are selectively interrogated by ACAS II units and therefore, the UF0 rates are still higher than in scenario A05.

5. If the 36 aircraft added are TCAS I equipped instead of ACAS II (scenario C03), fairly high Mode C interrogation rates are induced additionally.

4.2.2 Transponder utilisation

Interrogations received are processed and, where applicable, are replied by a transponder. During processing and reply transmission, a transponder is occupied making it unavailable for the access of other sensors. The receiver internal processes were modelled based on measurements on real equipment and thus, the time periods the ToIs were unavailable during simulation could be recorded. From these data, a performance parameter was derived termed transponder utilisation (TU). The transponder utilisation denotes the percentage of time a transponder is occupied by the main beam and side lobe interrogations received.

Within Figure 4-2 to Figure 4-5 the overall transponder utilisation at the ToIs of the IoI Frankfurt/Süd is pictured versus the distance of the ToIs from the IoI. In addition to the overall transponder utilisation, the transponder utilisation caused by ACAS activities is inserted separately. The utilisation by ACAS comprises occupancy by interrogations from other ACAS units as well as mutual suppression by the on-board ACAS interrogator.

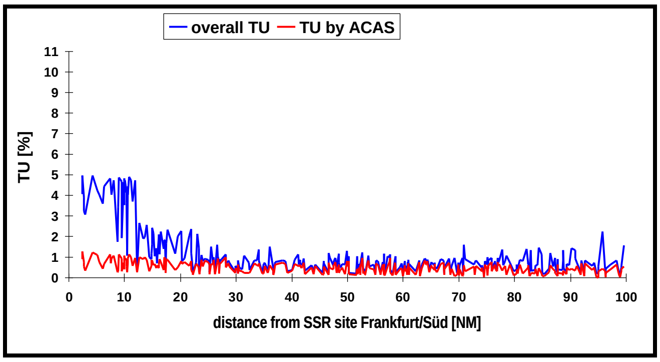


Figure 4-2: Scenario A05 – transponder utilisation

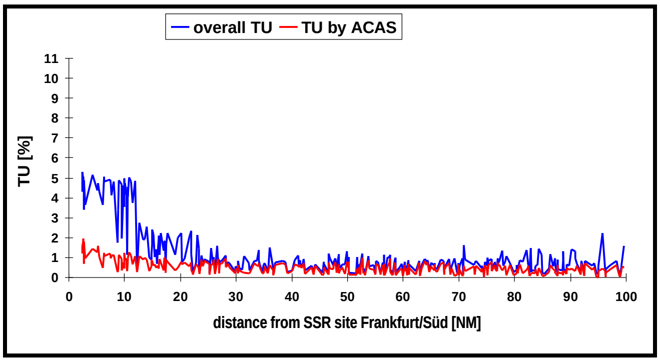


Figure 4-3: Scenario C01 - transponder utilisation

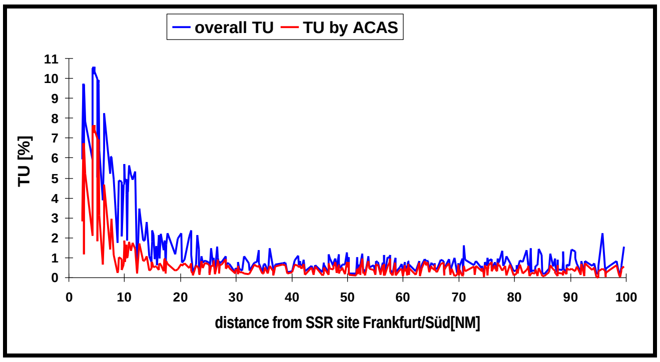


Figure 4-4: Scenario C02 - transponder utilisation

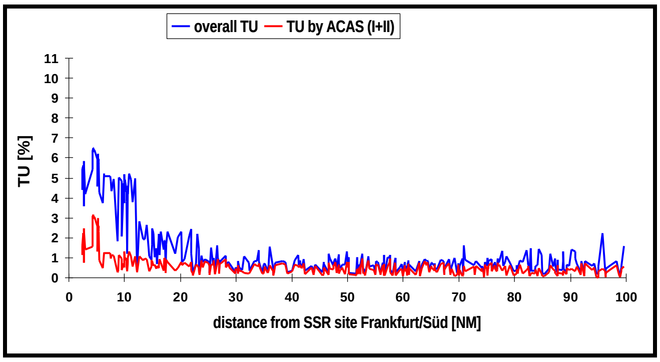


Figure 4-5: Scenario C03 - transponder utilisation

The following Table 4-2 summarises the overall transponder utilisation as well as the utilisation caused by ACAS for the transponders deployed within the surveillance area of the IoI Frankfurt/Süd. Minimum, mean, and maximum values are provided which are calculated across the sample of all ToIs.

Scenario		A05	C01	C02	C03
Overall TU	**min**	0.16	0.16	0.16	0.16
	m	1.08	1.16	2.04	1.60
	max	4.98	5.28	10.60	6.48
ACAS TU	**min**	0.00	0.01	0.01	0.01
	m	0.48	0.51	1.20	0.71
	max	1.26	1.97	7.68	3.15

Table 4-2: Statistics of transponder utilisation

With respect to the utilisation of transponders within the Frankfurt area in the scenarios under consideration, the following conclusions can be drawn:

1. In each scenario analysed, the highest transponder utilisation is achieved in close proximity to the airport.
2. In scenario A05, the ACAS contribution to the overall transponder utilisation in the vicinity of Frankfurt airport is well below 2%.
3. In scenario C01, where only 5 lustered ACAS II interrogators are deployed near Frankfurt airport, the transponder utilisation achieves already the 2% limit imposed on ACAS.
4. In scenario C02, where 36 ACAS II units are added, compared with scenario A05, the maximum transponder utilisation caused by ACAS is raised to 7.7% contributing more than 70% to the peak overall transponder utilisation of 10.6%. Moreover, the 2% criterion is not satisfied by almost all transponders within a range of 8 NM to the airport.
5. Substituting the 36 ACAS II units in scenario C02 by TCAS I interrogators (scenario C03) reduces the maximum ACAS transponder utilisation to 3.1%. However, there is still a remarkable number of transponders within 5.5 NM to the airport suffering a utilisation by ACAS of significantly more than 2%.

4.2.3 Reply efficiency

When an interrogation arrives at a ToI during transponder occupancy, the interrogation will fail. An interrogation may also fail if it overlaps and interferes with an interrogation of another interrogator. A parameter quantifying the success of interrogations is the so called reply efficiency (RE). The reply efficiency denotes the percentage of interrogations that are successfully received, processed, and replied to by a transponder in the presence of interfering signals. In the scenarios considered, the IoI Frankfurt/Nord used Mode A and Mode C signals to track its ToIs, while the IoI Frankfurt/Süd controlled Mode A/C transponders by using Mode A-only and Mode C-only interrogations and Mode S capable transponders by transmitting interrogations of the Mode S uplink formats UF4 and UF5. An evaluation of the reply efficiency for the Modes A and C and for the Mode S formats used by the IoIs is provided within the following Table 4-3. The table depicts the worst (minimum) and the best (maximum) reply efficiency found among the set of ToIs of the IoI Frankfurt/Süd. Additionally, the mean values, calculated across all ToIs in cover are inserted.

Scenario		A05	C01	C02	C03
Mode A	**min**	92.	85.	80.	85.
	m	98.7	98.3	96.9	97.6
	max	100.	100.	100.	100.
Mode C	**min**	90.	86.	74.	86.
	m	98.5	97.9	96.1	97.2
	max	100.	100.	100.	100.
Mode S	**min**	87.	85.	74.	77.
	m	98.3	98.1	96.3	97.2
	max	100.	100.	100.	100.

Table 4-3: Reply efficiency

The following Figure 4-6 illustrates the variation of the mean reply efficiency for Mode A, Mode C, and Mode S interrogations for the scenarios analysed.

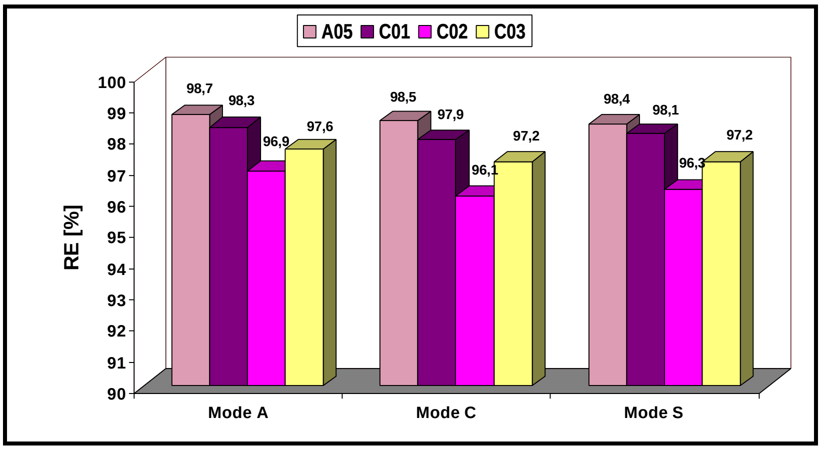


Figure 4-6: Mean reply efficiency

A comparison of the reply efficiency values predicted by the simulations performed for the scenarios C01, C02, and C03 with the values achieved for scenario A05 indicates:

1. In scenario C01, the activity of the clustered 5 ACAS II interrogators decreases reply efficiency for Mode A/C and Mode S interrogations by about 0.5% in average. The worst case obtained was a reduction of 7% (Mode A).
2. In scenario C02, where 36 clustered ACAS II units were taken into consideration, mean reply efficiency is reduced by about 2%. The highest decrease observed was 16% (Mode C).
3. In scenario C03, where the 36 clustered aircraft were equipped with TCAS I units, the mean reply efficiency is decreased by about 1%. The peak drop achieved was 10% (Mode S).

4.2.4 Fruit rates

The various types of replies that can interfere with a wanted reply at an IoI are pictured within Figure 4-1. Concerning the quantity of interfering replies, the simulations conducted predicted the long term fruit rates (FR) at the IoIs Frankfurt/Süd and Frankfurt/Nord. Table 4-4 quantifies the fruit rates received by the IoIs considered. The fruit rates, quoted in replies per second, are listed for the various Modes and Mode S formats separately.

IoI	Frankfurt/Süd				Frankfurt/Nord		
Scenario	**A05**	**C01**	**C02**	**C03**	**C01**	**C02**	**C03**
	Mode A/C				**Mode A/C**		
Mode A	167	201	255	262	559	614	621
Mode C	164	198	246	262	558	607	621
	Mode S				**Mode S**		
Mode A-only	55	55	55	55	7	7	7
Mode C-only	55	55	55	55	7	7	7
DF11	75	83	108	109	74	105	105
DF4	74	77	89	91	16	28	28
DF21	70	77	90	94	16	28	29
	ACAS				**ACAS**		
Mode C-only	147	205	453	157	231	485	185
DF0	102	169	1337	217	162	1336	219
Mode C (TCAS I)	-	-	-	7719	-	-	7721

Table 4-4: Fruit rates

Concerning the variation of the fruit rates listed in the table above, it can be stated:

1. Although the Mode A/C interrogation rates are the same in all scenarios analysed, the Mode A/C fruit rates are increased when the density of aircraft rises. This increase is induced by replies of the additional transponders. The Mode A/C fruit rate is increased as well when the clustered ACAS II units are replaced by TCAS I interrogators. This effect can be explained by the improved Mode A/C reply efficiency in scenario C03 resulting in higher reply rates.

2. As expected, the Mode A/C only fruit rates are the same for all scenarios analysed, since the additional transponders in the scenarios C01, C02, and C03 are all Mode S capable and do not reply to Mode A/C-only all-call interrogations.

3. Mode S fruit in the formats DF4 and DF21 is increased when the additional Mode S transponder equipped aircraft are taken into account. Due to the improved reply efficiency, DF4 and DF21 rates are further raised, if the aircraft added are TCAS I equipped. Due to the transmission of squitters, DF11 fruit is increased as the number of Mode S transponders is raised.

4. The Mode C-only rates and the DF0 rates induced by ACAS II are increased when the ACAS II density rises. A tremendous increase of the DF0 rates is predicted for scenario C02 reflecting the significant increase of UF0 interrogation rates.

5. If TCAS I equipage is assumed for the 36 aircraft added, Mode C-only and UF0 fruit is considerably reduced compared with scenario C02. However, a very huge rate of extra Mode C fruit is achieved.

4.2.5 Interrogator receiver utilisation

From the fruit rates listed above, a performance parameter was derived that provides a measure for the total signal load at an interrogator. This parameter, termed interrogator receiver utilisation (IRU), takes into account the disparity between the length of Mode A/C and Mode S replies and denotes the percentage of time reply signals present at the receiver of an interrogator. Within Figure 4-7 the interrogator receiver utilisation for the two IoIs analysed is plotted. The figure shows the interrogator receiver utilisation caused by ACAS signals only and, as an add on, the additional utilisation induced by ground based systems. The sum of both represents the overall interrogator receiver utilisation.

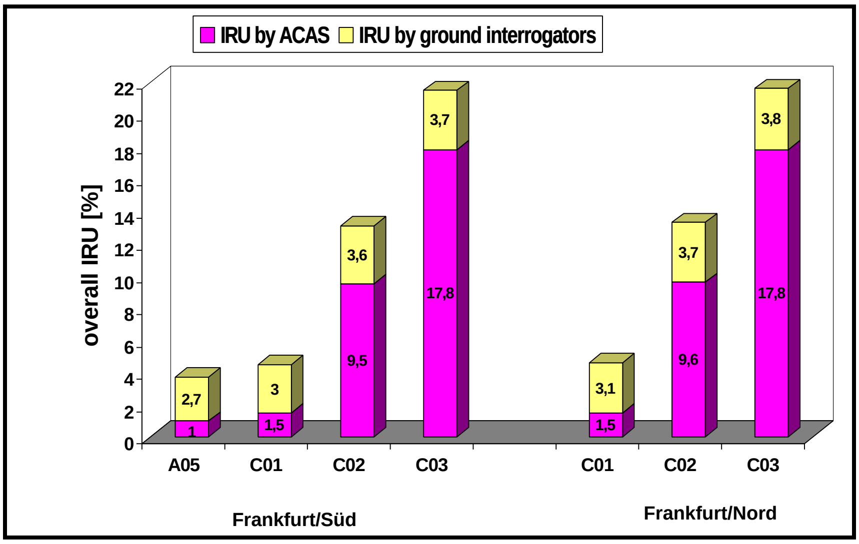


Figure 4-7: Interrogator receiver utilisation

Concerning interrogator receiver utilisation, the figure above yields:

1. Assuming additionally 5 ACAS II units clustered in close proximity to Frankfurt airport slightly increases interrogator receiver utilisation.
2. Adding 36 ACAS II units increases interrogator receiver utilisation significantly. In this case, the utilisation caused by ACAS II is raised by a factor of more than six.
3. Furthermore, interrogator receiver utilisation caused by ACAS is nearly doubled if the clustered 36 ACAS II interrogators are replaced by TCAS I units.
4. The interrogator receiver utilisation caused by ground interrogators is only slightly affected by the scenario variations analysed. The moderate increase obtained for the scenarios C01, C02, and C02 is due to replies of the transponders added and slightly increased re-interrogation rates of the Mode S stations.

4.2.6 Decode efficiency

Beside asynchronous fruit, which is reflected in the interrogator receiver utilisation, synchronous garbling is a further interference mechanism affecting reception and decoding of replies. Especially Mode A/C interrogators are susceptible to synchronous garbling since no provision is made to avoid concurrent reply generation by transponders at similar range simultaneously illuminated by an interrogator's main beam. A performance parameter taking into account both interference effects, asynchronous fruit as well as synchronous garbling, is the so called decode efficiency (DE) of a ground interrogator. The decode efficiency denotes the percentage of all ToI-replies which are correctly received, decoded, and evaluated. In the scenarios explored, the IoI Frankfurt/Nord was interrogating Mode A and Mode C, while the IoI Frankfurt/Süd was modelled as Mode S stations eliciting Mode A/C-only replies from aircraft fitted with Mode A/C transponders and responses in the Mode S formats DF4 and DF21 from Mode S transponder equipped aircraft.

During simulation, the reception and decoding of replies by the IoIs were monitored and such the decode efficiency was obtained. Since a Mode A reply equals a Mode C reply, as far as signal structure is concerned, a combined decode efficiency for both Modes was evaluated. By contrast, decode efficiency for DF4 and DF21 replies was recorded separately, because these signals differ with respect to message length. Within Figure 4-8 and Figure 4-9 the values for decode efficiency obtained by simulation are provided for the IoIs Frankfurt/Süd and Frankfurt/Nord.

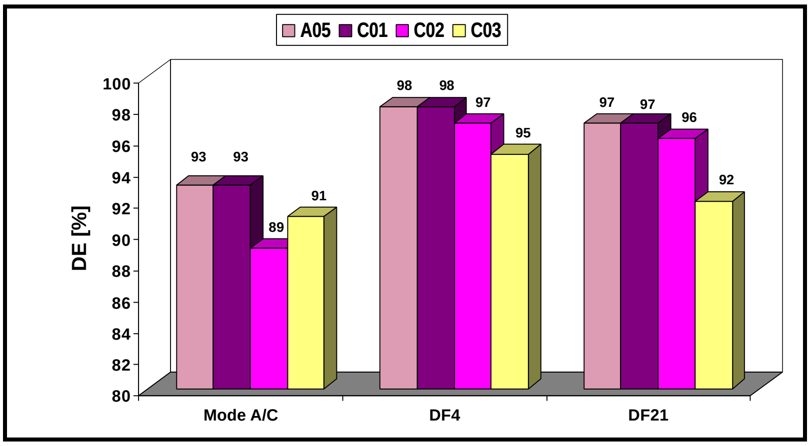


Figure 4-8: IoI Frankfurt/Süd - decode efficiency

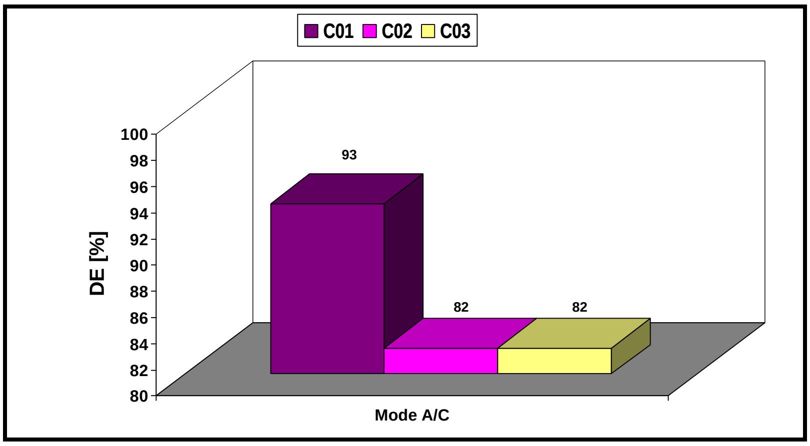


Figure 4-9: IoI Frankfurt/Nord – decode efficiency

From the decode efficiency values achieved, the following conclusions can be drawn:

1. The deployment of 5 clustered ACAS II units at Frankfurt/Kreuz has nearly no impact on decode efficiency of the SSR sites at Frankfurt.
2. Adding a total of 36 ACAS II interrogators (scenario C02) reduces decode efficiency for Mode A/C replies significantly. The simulation performed predicted a reduction of 3% for Frankfurt/Süd and even 11% for Frankfurt/Nord. The considerable reduction at the IoI Frankfurt/Nord is mainly caused by the additional aircraft which are deployed in three clusters resulting in a large number of garbling situations. The decoding of Mode S replies is less affected. This reduction is within 1%.
3. Replacing the ACAS II interrogators of the 36 clustered aircraft by a TCAS I unit (scenario C03), improves Mode A/C decoding at the IoI Frankfurt/Süd by 2% compared with scenario C02. On the other hand, decode efficiency for short Mode S replies is reduced by 2%, for long replies by 4%.

   These effects observed can be explained as follows. The decoder model applied for the IoIs is based on measurements performed by DFS at the test station Götzenhain. These measurements revealed that, in case of interference, a Mode S signal has a more severe impact on a wanted Mode A/C reply than a Mode A/C signal. By contrast, decoding of a Mode S replies is much more affected by Mode A/C signals than by Mode S signals. Bearing this in mind, together with the fact that fruit is dominated by DF0 replies in scenario C02 and by Mode C signals in scenario C03, gives the rationale behind the effect that Mode A/C decoding is more affected in scenario C02, while Mode S decoding is suffering more in scenario C03.

4.2.7 Round trip reliability

In order to quantify the success of a complete single interrogation/reply interaction, the round trip reliability was evaluated for the IoIs under consideration. The round trip reliability denotes the relative frequency of interrogations that are successfully received, processed, and replied by the ToIs and where the corresponding replies are correctly decoded and evaluated by the IoI. The following Figure 4-10 and Figure 4-11 illustrate the values obtained by simulation for the IoIs Frankfurt/Süd and Frankfurt/Nord.

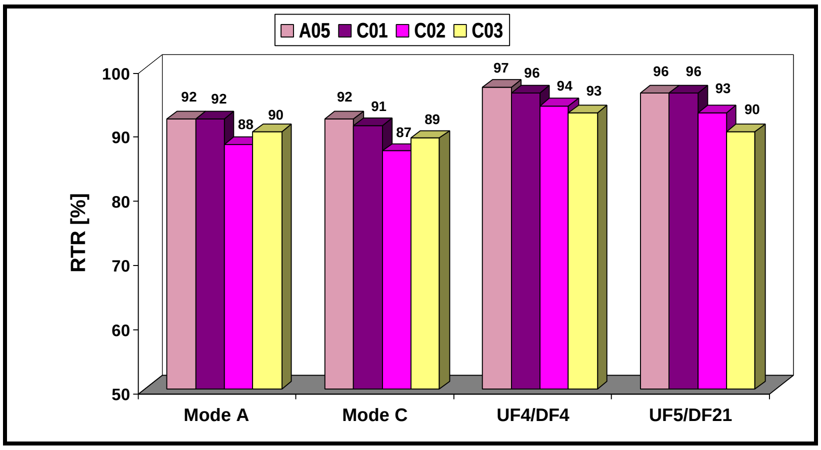


Figure 4-10: IoI Frankfurt/Süd – mean round trip reliability

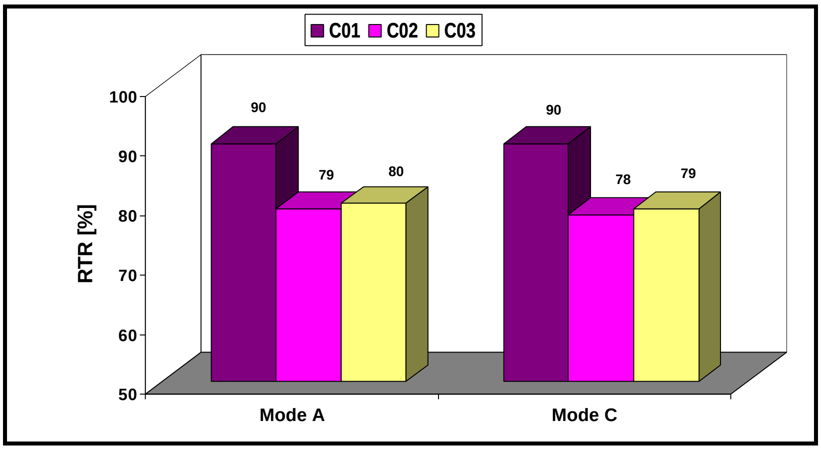


Figure 4-11: IoI Frankfurt/Nord – mean round trip reliability

Generally, the round trip reliability values provided above reflect the variations already realised for reply efficiency and decode efficiency. Moreover, the following conclusion can be drawn:

1. There is only a slight impact on the success of a single interrogation/reply interaction performed by the two IoIs, if the 5 ACAS II interrogators deployed at Frankfurt/Kreuz are taken into account.

2. Especially at IoI Frankfurt/Nord, round trip reliability for Mode A/C interactions is reduced considerably, if the 36 clustered units are ACAS II.

3. Replacing the ACAS II units on board of the 36 clustered aircraft by TCAS I interrogators induces a slight improvement of Mode A/C round trip reliability while the probability of success for Mode S transactions is further decreased.

4.2.8 Code detection probability

The parameters used in the simulation model to quantify the success of a complete MSSR and Mode S surveillance process, performed during an antenna sweep across a target, are termed code detection probability and Mode S detection probability, respectively. The Code A/C detection probability denotes the probability that a target position report with correct Code A/C data is produced for a transponder during a scan. In the model, the assumption was made that Code A is detected by an interrogator as soon as two Mode A replies were properly decoded. For Code C detection, the same criterion was applied. The Mode S detection denotes the probability that a Mode S transaction for a Mode S transponder is successfully completed during one single scan.

The simulations performed predicted Code A/C and Mode S detection probability for each ToI. Within the following Figure 4-12 and Figure 4-13, the corresponding distributions derived from the set of ToIs are presented for the scenarios C01, C02, and C03. Thereby, on the x-axis intervals for Code/Mode S detection are marked and on the ordinate the relative frequency of ToIs is provided falling within the respective interval.

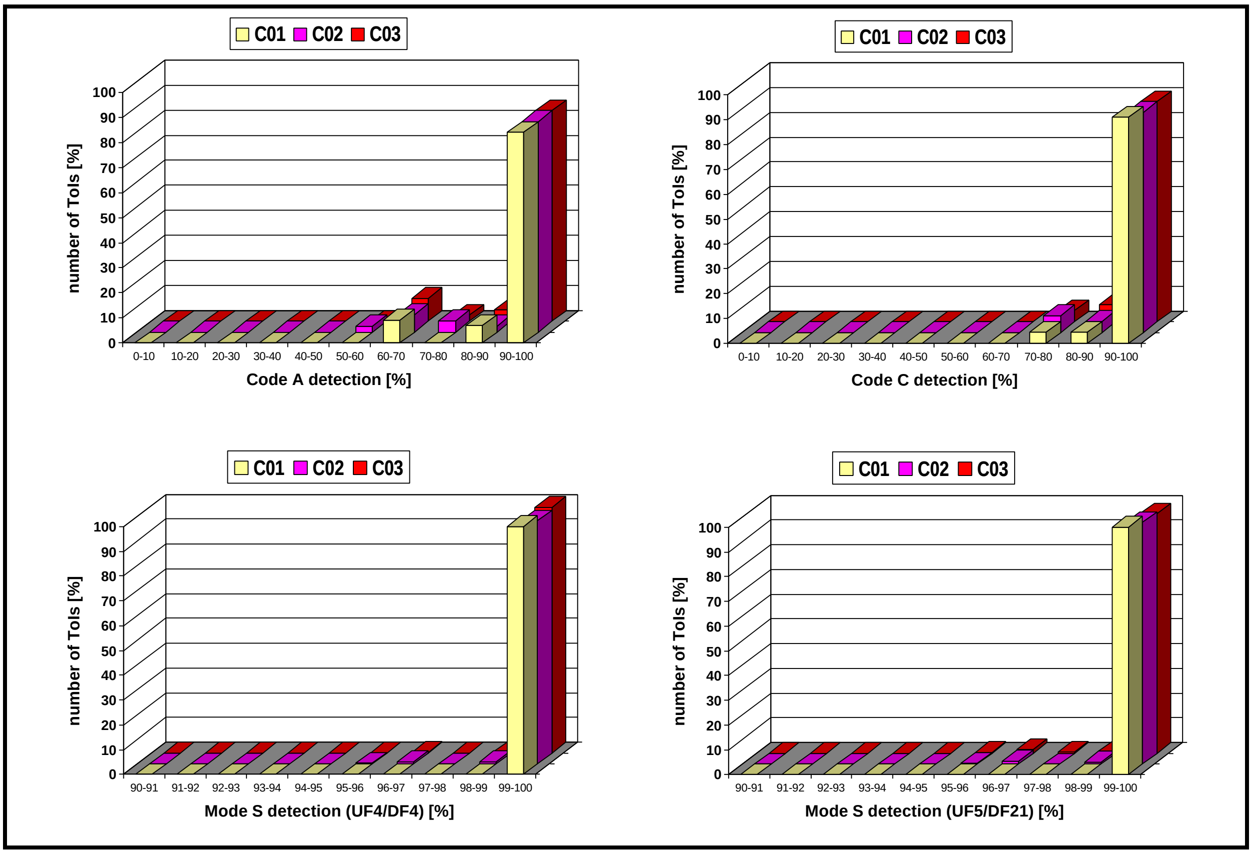


Figure 4-12: IoI Frankfurt/Süd – distribution of Code A/C and Mode S detection

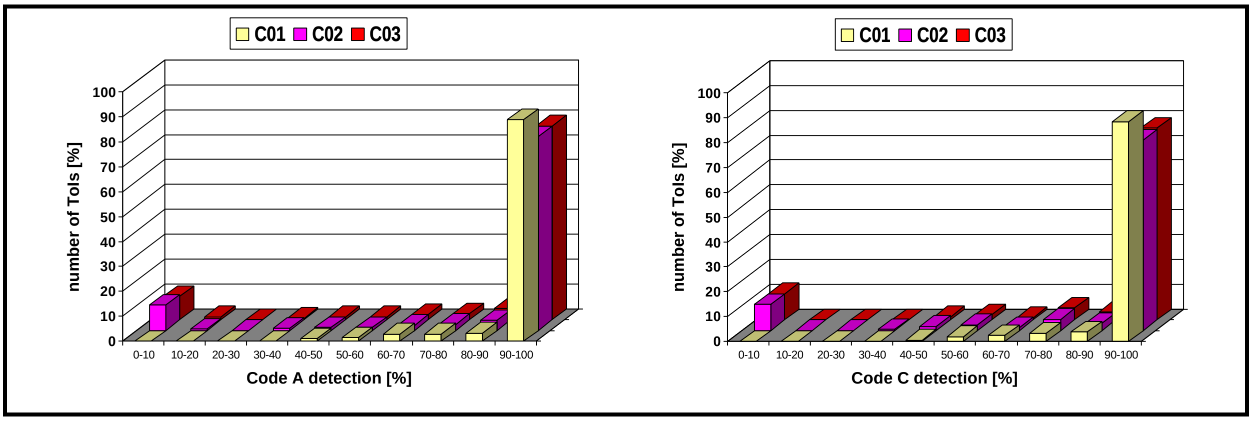


Figure 4-13: IoI Frankfurt/Nord – distribution of Code A/C detection

Based on the simulation results achieved and with respect to the distributions provided in the figures above, the following conclusions can be drawn regarding Code and Mode S detection:

1. The impact upon Code A/C detection is quite low, if only the 5 ACAS II interrogators deployed in a cluster at Frankfurt/Kreuz are taken into consideration. The deviation of mean values calculated across the sample of the Mode A/C ToIs of the IoI Frankfurt/Süd is within 1%.

2. Code A/C detection is slightly further reduced at IoI Frankfurt/Süd, if the 36 clustered ACAS II units are added. The mean value, calculated across all Mode A/C ToIs, is dropped by 1% for Mode A and by 2% for Mode C. Comparing scenarios C02 and C03, the situation is slightly improved, if the clustered aircraft are assumed to be TCAS I equipped.

   Code A/C detection is significantly decreased at IoI Frankfurt/Nord when scenario C01 is replaced by scenario C02. The mean values are reduced by 11% for Mode A and by 12% for Mode C. The decrease is mainly caused by the transponders added. These transponders are deployed in dense clusters and therefore most of their replies are garbled. These transponders establish the column for the interval 0-10% in the distributions above. Equipping the additional clustered aircraft with TCAS I units does not change the situation.

3. Mode S detection is slightly affected by the scenario variations analysed.

   In scenario C01, Mode S detection probability is equal to 100% for 98% of the ToIs. The minimum detection probability obtained among the remaining 2% of ToIs was 99.2%.

   In scenario C02, the relative frequency of ToIs with a probability equal to 100% is decreased to 89%. The minimum Mode S detection probability found among the remaining 11% of ToIs was 95%.

   For scenario C03, the simulation predicted a probability of 100% for 88% of the ToIs. The minimum detection probability obtained was again 95%.

4.3 Summary and conclusions on MSSR/Mode S surveillance performance

1. In the scenario chosen, the UF0 interrogation rate induced by ACAS will be increased by a factor of eight, if 36 additional ACAS II equipped aircraft are deployed in clusters close to Frankfurt airport. If the 36 aircraft are TCAS I equipped, extra Mode C interrogation rates are induced which are up to three times higher than the rates generated by the ground stations.

2. In each scenario analysed, the highest transponder utilisation is achieved in close proximity to the airport. If 5 ACAS II interrogators are deployed in a cluster near Frankfurt airport, the transponder utilisation achieves the 2% limit imposed on ACAS. If 36 clustered ACAS II units are added, the maximum transponder utilisation caused by ACAS is raised to 7.7% and the 2% criterion is not satisfied by almost all transponders within a range of 8 NM to the airport. If these 36 aircraft are TCAS I equipped, a peak transponder utilisation of 3.2% is achieved and most of the transponders within 5.5 NM to the airport suffering a utilisation by ACAS of more than 2%.

3. Mode C-only and DF0 fruit induced by ACAS is increased as the ACAS II density rises. A tremendous increase of the DF0 rates by a factor of thirteen is predicted if the clustered 36 ACAS II units are taken into account. If TCAS I equipage is assumed for these 36 aircraft, extra Mode C fruit is induced which is fifteen times higher than the Mode C fruit generated by the ground stations.

4. Assuming 5 ACAS II units clustered in the vicinity of Frankfurt airport, interrogator receiver utilisation increases slightly. Adding 36 clustered ACAS II units increases interrogator receiver utilisation by a factor of three. In this case, the utilisation caused by ACAS is raised by a factor of more than six. Interrogator receiver utilisation caused by ACAS is doubled once more, if the clustered 36 ACAS II interrogators are replaced by TCAS I units.

5. The deployment of 5 ACAS II units at Frankfurt/Kreuz has nearly no impact on decode efficiency of the SSR site Frankfurt/Süd. Adding 36 ACAS II interrogators reduces decode efficiency for Mode A/C by 3% at Frankfurt/Süd and by 11% at Frankfurt/Nord. Replacing the ACAS II interrogators of the 36 clustered aircraft by a TCAS I unit reduces decode efficiency for short Mode S replies by 2%, for long replies even by 4%.

6. The impact upon Code A/C detection is quite low if the 5 ACAS II interrogators deployed at Frankfurt/Kreuz are taken into consideration. The deviation of mean values is within 1%. Code A/C detection is also weakly reduced at IoI Frankfurt/Süd, if the 36 ACAS II units are added. However, Code A/C detection is significantly decreased, in average by 11%, at IoI Frankfurt/Nord. Mode S detection is suffering most if these 36 aircraft are assumed to be TCAS I equipped.

5. ACAS II Surveillance Performance

5.1 Objective of analysis

The preceding section was dedicated to the analysis of MSSR/Mode S surveillance performance and the effects of TCAS I and ACAS II on it. By contrast, the current section will focus on the surveillance performance of ACAS II.

Concerning ACAS II surveillance performance, it is postulated that ACAS II is capable of operating in most air traffic densities without any significant performance degradation. Although ACAS II is able to operate up to a range of 30 NM, the required nominal surveillance range of ACAS II is 14 NM. However, when operating in high densities, the interference limiting function may reduce system range to approximately 5 NM, which is still adequate to provide enough surveillance performance. Furthermore, it is required that a track is established with a probability of at least 90% for aircraft within the surveillance range.

If an ACAS II interrogator performs a surveillance process within a complex and dense environment, each question and answer cycle will suffer various impacts. Thereby, the receiving and processing of ACAS interrogations by transponders as well as the receipt and evaluation of replies by an ACAS interrogator may be influenced.

In order to analyse ACAS II surveillance performance in the scenarios C01, C02, and C03, defined in section 2, performance parameters for the selected ACAS II IoIs 1048 and 1049 (see section 2) were evaluated. The values for the parameters were obtained by the simulation runs performed for the scenarios defined.

5.2 Results

The following Figure 5-1 illustrates the density of ACAS II units within a range of 50 NM from the SSR site Frankfurt/Süd for the scenarios C01 and C02. In addition to the actual density distribution (solid line), the corresponding curves for an uniform in area (dotted line) and an uniform in range (broken line) distribution are attached. Obviously, ACAS II density in the Frankfurt area is close to an uniform in range distribution in case of scenario C01. In scenario C02, the density exceeds the uniform in range distribution considerably, especially within a range of 40 NM. At a distance greater than 50 NM, ACAS II density is again close to a uniform in range distribution.

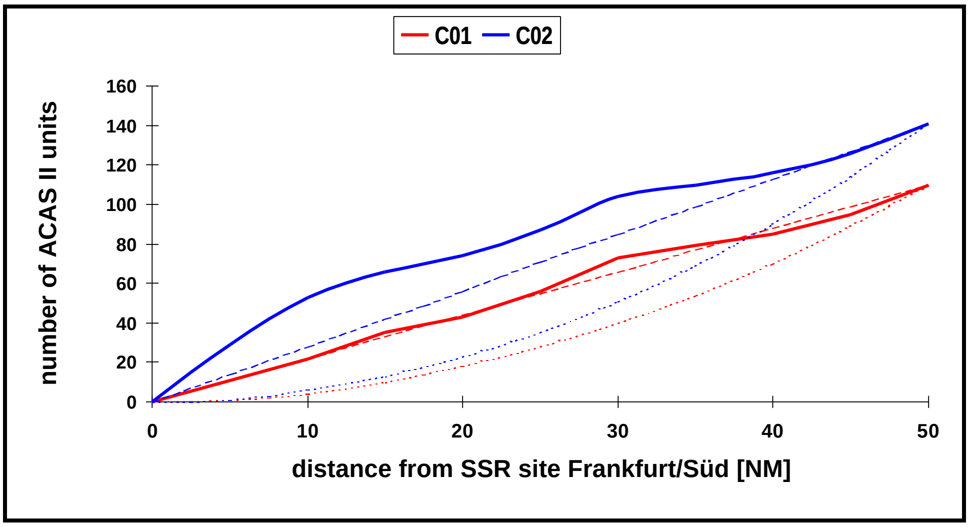


Figure 5-1: Density of ACAS II units in the scenarios C01 and C02

5.2.1 ACAS II interrogation power reduction

On one hand, the objective of ACAS interference limiting is to reduce the overall ACAS interrogation rate and as a consequence to shorten the portion of time transponders are occupied by ACAS signals. On the other hand, decreasing Mode C and Mode S transmitter power, in order to reduce ACAS interrogation rates, affects the surveillance performance of ACAS II interrogators. In order to quantify the reduction of ACAS transmitter power by the implementation of interference limiting procedures, Figure 5-2 to Figure 5-5 illustrate the Mode C and Mode S power limitation of the ACAS II interrogators which are within 100 NM of the SSR site Frankfurt/Süd and which are at an altitude not exceeding 18.000 ft. The power reduction is plotted dependent on the range of the ACAS II units from the SSR station for the scenarios A05, C01, C02, and C03.

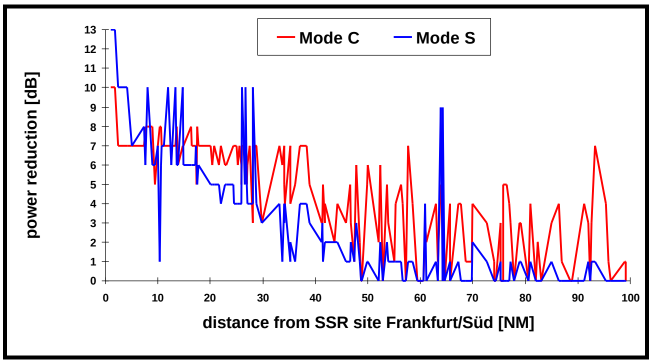


Figure 5-2:Scenario A05 – ACAS power reduction

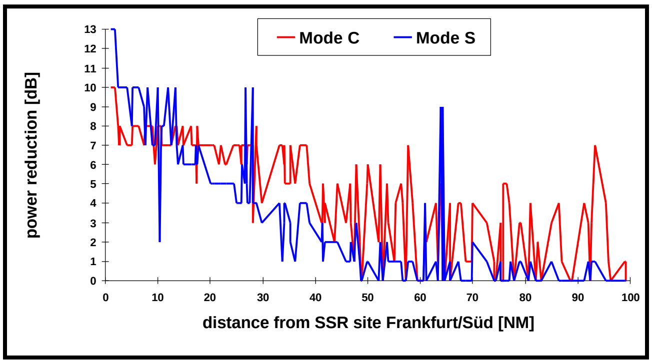


Figure 5-3: Scenario C01 – ACAS power reduction

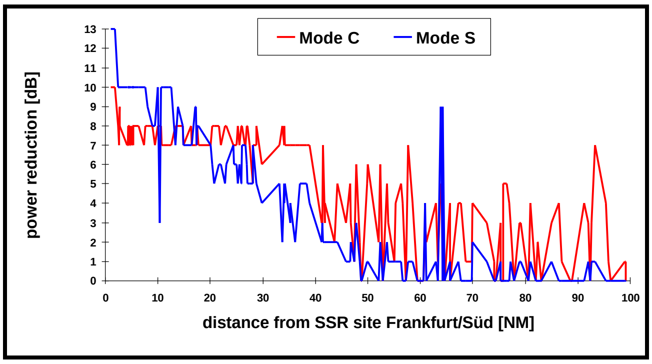


Figure 5-4: Scenario C02 – ACAS power reduction

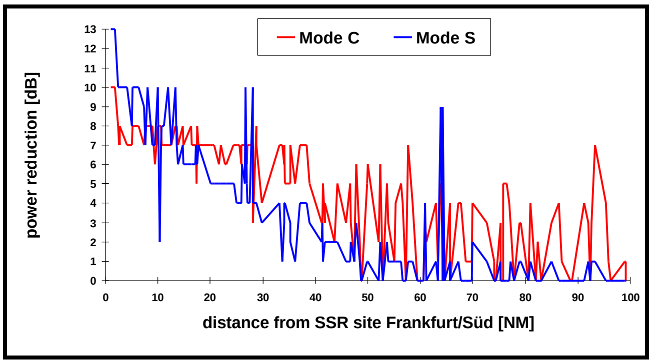


Figure 5-5: Scenario C03 – ACAS power reduction

The following Table 5-1 depicts the mean Mode C and Mode S power reduction calculated across all ACAS II units that are within 100 NM and at an altitude not greater than 18.000 ft for the scenarios considered.

Scenario	A05	C01	C02	C03
Mode C	4.36	4.63	5.39	4.49
Mode S	3.09	3.48	4.88	3.36

Table 5-1: Mean power reduction

Concerning power reduction, the data pictured and tabulated above indicate:

1. In the scenarios under examination, four ACAS interrogators are assumed on the surface at Frankfurt airport. These ACAS units have to reduce Mode C power and Mode S power to the absolute permitted limit of 10 dB and 13 dB, respectively.
2. If the 5 ACAS II units at Frankfurt/Kreuz are taken into consideration (scenario C01), power reduction is only slightly increased for other ACAS interrogators. The Mode C power reduction is between 7-8 dB within a range of 18 NM to the SSR site Frankfurt/Süd. Mode S power has to be reduced by most of the ACAS units deployed within 13 NM of Frankfurt/Süd by more than 7 dB.
3. Adding the set of 36 ACAS II units (scenario C02), the surveillance range of ACAS II interrogators in the vicinity of the airport is affected more severely. All ACAS II units within a range of 30 NM to Frankfurt/Süd have to reduce Mode C power by 7-8 dB. Mode S power reduction is above 7 dB at most of the ACAS units within a range of 20 NM of Frankfurt/Süd.

   It should be noted that at a distance of 27 NM two interrogators are located which are obliged to transmit at higher power in scenario C02 than in scenario C01. This is due to the fact that special conditions defined in [4] for the calculation of the parameter α apply. These conditions result in α=1.0 for scenario C02 while α=0.5 in scenario C01.
4. When the ACAS II interrogators on board of the 36 aircraft added are replaced by TCAS I units (scenario C03), the remaining ACAS II interrogators in the Frankfurt area are allowed to transmit surveillance interrogations at higher power again. The Mode C power reduction is between 7-8 dB within a range of 18 NM to Frankfurt/Süd. Mode S power has to be reduced by most of the ACAS units deployed within 13 NM by more than 7 dB. Although power reduction in scenario C03 is similar to the reduction in scenario A05, the calculated mean values indicate that the ACAS II interrogators have to reduce somewhat more power in scenario C03 than in scenario A05. This is due to the additional Mode S transponders that are tracked by the ACAS II interrogators.

5.2.2 Surveillance performance parameters for two selected aircraft

The ACAS IoIs 1048 and 1049 selected for the performance analysis are both located within the surveillance volume of the SSR interrogator at Frankfurt/Süd. Hence, each of them is representing a point in the power reduction curves plotted above. In order to characterise the environments surrounding the selected ACAS IoIs in more detail, the following Table 5-2 lists for each interrogator the important parameters: number of aircraft within the nominal surveillance range, number of ACAS II units within 3NM, 6NM, and 30NM, selected Mode C-sequence for the forward, right, left, aft, and omni antenna, reduction of Mode C and Mode S power due to the interference limiting algorithm, resulting effective surveillance range, and finally, number of targets remaining within the reduced surveillance range (ToIs).

IoI	**1048**			**1049**		
Scenario	**C01**	**C02**	**C03**	**C01**	**C02**	**C03**
Aircraft in nominal range:						
Mode A/C transponders	8	8	8	8	8	8
Mode S transponders	14	14	14	83	114	114
ACAS II units within:						
3 NM	0	0	0	5	33	0
6 NM	11	29	6	8	39	3
30 NM	85	116	80	84	115	79
Mode C-sequence:						
Forward	Medium	Medium	Medium	Medium	Medium	Medium
Right	Long	Long	Long	Medium	Medium	Medium
Left	Medium	Medium	Medium	Short	Short	Short
Aft	Short	Short	Short	Medium	Medium	Medium
Omni	Long	Long	Long	Medium	Medium	Medium
Power reduction:						
Mode C	8 dB	8 dB	8 dB	8 dB	8 dB	7 dB
Mode S	10 dB	10 dB	2 dB	10 dB	10 dB	10 dB
Effective range:						
Mode C	11.2 NM	11.2 NM	11.2 NM	11.2 NM	11.2 NM	12.5 NM
Mode S	12.5 NM	12.5 NM	31.4 NM	12.5 NM	12.5 NM	12.5 NM
Aircraft in effective range:						
Mode A/C transponders	1	1	1	3	3	3
Mode S transponders	1	1	5	24	55	55

Table 5-2: ACAS II IoIs - environmental parameters

It should be noted that IoI 1048 is deployed at an altitude of 15.000 ft. Therefore, the low flying aircraft additionally assumed around Frankfurt airport are all outside the relative altitude boundary of ±10.000 ft and thus, these transponders are not intended to be interrogated and tracked by the ACAS IoI.

5.2.3 Fruit rates (for the selected aircraft)

In general, the interfering impacts on an ACAS surveillance process in the scenarios considered are the same as on an SSR surveillance process, which are depicted by Figure 4-1. At the ToI, the impacts consist of Mode A, Mode C, Mode A-only, Mode C-only, UF0, UF4, UF5, UF11, and UF16 interrogations. An ACAS IoI is influenced by fruit consisting of Mode A, Mode C, Mode A-only, Mode C-only, DF0, DF4, DF11, and DF21 replies.

Since the two ACAS IoIs are located within the coverage of the SSR interrogator Frankfurt/Süd, interrogation rates, transponder utilisation, and reply efficiency at the transponders tracked by the ACAS IoIs are within range of the values predicted for the ToIs of the IoI Frankfurt/Süd. Since these parameters were already analysed in section 4, a further discussion can be omitted.

The fruit rates received by the two ACAS IoIs, which are affecting the surveillance processes in the scenarios under examination, are listed in the following Table 5-3. The fruit rates are separated into Mode A/C replies challenged by Mode A/C interrogators, Mode A/C-only, DF4, DF11, and DF21 replies induced by Mode S interrogators, and Mode C-only, DF0, and Mode C replies elicited by ACAS II and TCAS I interrogators. The fruit rates provided are quoted in replies per second.

IoI	1048			1049		
Scenario	C01	C02	C03	C01	C02	C03
	Mode A/C					
Mode A	822	763	873	846	834	843
Mode C	818	755	873	840	824	843
	Mode S					
Mode A-only	37	29	35	35	34	34
Mode C-only	37	29	35	35	34	34
DF4	64	69	77	63	73	74
DF21	65	69	78	63	73	75
DF11	167	187	198	166	192	192
	ACAS					
Mode C-only	519	743	479	585	787	455
DF0	410	1553	455	408	1530	431
Mode C (TCAS I)	-	-	7717	-	-	7539

Table 5-3: ACAS II IoIs - fruit rates

With respect to the fruit rates received by the ACAS IoIs within the scenarios analysed, the following conclusions can be drawn:

1. Although Mode A/C interrogation rates are the same in the scenarios C01, C02, and C03, the Mode A/C fruit rates are decreased when in addition to the 5 ACAS II units at Frankfurt/Kreuz the 31 ACAS II interrogators at Frankfurt/Messe and Frankfurt/ Waldstadion are also taken into account (scenario C02). To understand this result two contrary effects have to be borne in mind. On one hand, the transponders added in scenario C02 are producing extra fruit. On the other hand, the results discussed in section 4 revealed that reply efficiency is significantly decreased when transitioning from scenario C01 to C02 which results in a reduction of reply rates. This effect overbalances the first one.

   If the clustered 36 ACAS II units are replaced by ACAS I interrogators, reply efficiency is improved inducing much higher Mode A/C fruit rates.

2. Although the Mode A/C-only interrogations rates are invariant and the additional transponders assumed for the scenarios C02 and C03 are all Mode S capable and are not replying to Mode A/C-only all-call interrogations, the Mode A/C only fruit rates are varying. The variation again reflects the alteration of reply efficiency. Thereby, it will be seen that the transponders producing the fruit at the IoI 1048 are more affected than the transponders inducing the fruit at the IoI 1049.

3. The Mode S fruit rates in the formats DF4 and DF21 are increased when transitioning from scenarios C01 to scenario C02. This is a consequence of the higher interrogation rates in these formats induced by the additional transponders. The fruit rates in the format DF11 are increased due to the squitters generated by the Mode S transponders added.

4. The Mode C-only rates and the DF0 rates caused by ACAS II are raised in scenario C02 due to the clustered ACAS II units. It should be noted that a tremendous increase of the DF0 rates is predicted for scenario C02 reflecting the significant increase of the UF0 interrogation rates.

5. When the aircraft in the clusters are equipped with TCAS I interrogators instead of ACAS II units, Mode C-only and UF0 fruit is considerably reduced. However, a very huge rate of additional Mode C fruit is achieved in this case.

5.2.4 Interrogator receiver utilisation (for the selected aircraft)

Based on the fruit rates listed above, the interrogator receiver utilisation (IRU) at the two ACAS IoIs was derived. The interrogator receiver utilisation denotes the percentage of time reply signals are present at the receiver of an interrogator. Within Figure 5-6 the interrogator, receiver utilisation is plotted for the ACAS IoIs analysed.

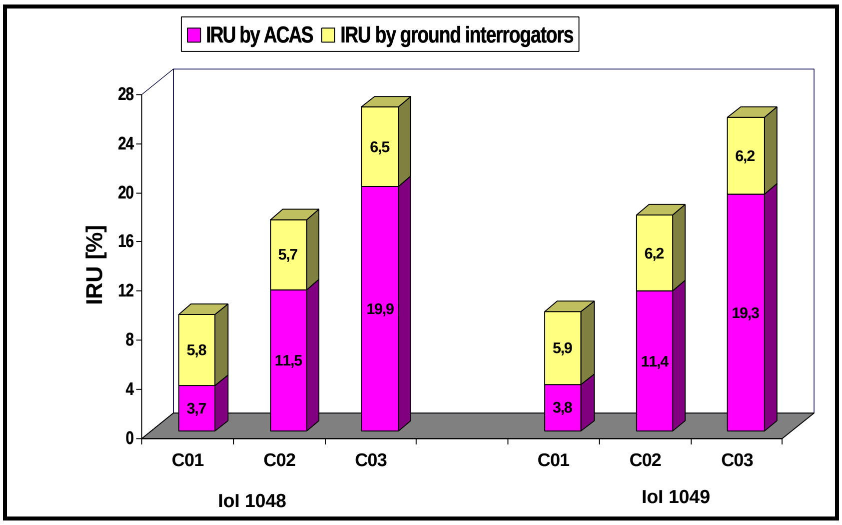


Figure 5-6: ACAS II IoIs - interrogator receiver utilisation

With respect to interrogator receiver utilisation, the following conclusions can be drawn:

1. Interrogator receiver utilisation is nearly doubled if in addition to the 5 ACAS II interrogators at Frankfurt/Kreuz the 31 ACAS II units at Frankfurt/Waldstadion and Frankfurt/Messe are added as well.
2. Interrogator receiver utilisation at the two ACAS II IoIs analysed is further raised, when the 36 aircraft added are TCAS I equipped instead of ACAS II.
3. The significant variation of interrogator receiver utilisation for the three scenarios analysed has mainly caused by ACAS. The contribution of ground stations varies only weakly.

5.2.5 Decode efficiency (for the selected aircraft)

The selected ACAS II IoIs elicited Mode C replies from aircraft fitted with Mode A/C transponders and DF0 replies from Mode S transponder equipped aircraft. During simulation, the reception and decoding of replies by the IoIs were observed and such the decode efficiency for the particular interrogators was obtained. Within Figure 5-7 the values achieved by simulation are plotted.

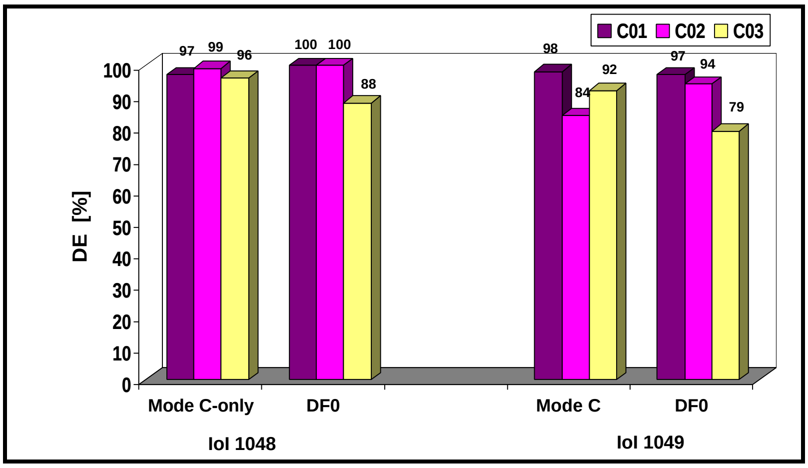


Figure 5-7: ACAS II IoIs - decode efficiency

Concerning decode efficiency of the ACAS II IoIs under consideration, it can be concluded:

1. In case of IoI 1048, decode efficiency for Mode C-only replies is only weakly affected by the scenario variations analysed.

   Decode efficiency for Mode S replies is considerably reduced when the ACAS II interrogators on board of the 36 clustered aircraft are substituted by TCAS I units. This is a consequence of the huge Mode C fruit rates and the resulting high interrogator receiver utilisation.

   Concerning IoI 1048 it has to be noted that only one Mode A/C and one Mode S transponder are tracked. Therefore, the sample of trials the decode efficiency provided above is based upon is quite low and the values provided are not indicative of confidence in the absolute accuracy of these values, but rather to demonstrate the magnitude of changes.

2. At IoI 1049, decode efficiency for Mode C-only and for DF0 replies is significantly decreased, if the 31 ACAS II units are added (scenario C02).

   Replacing the ACAS II interrogators of the 36 clustered aircraft by an TCAS I unit, improves decoding of Mode C replies while Mode S decoding is further reduced. These are the same effects that were already realised for the IoI Frankfurt/Süd and that can be explained as follows: A Mode S signal has more impact on a wanted Mode C reply than a Mode A/C signal. By contrast, decoding of a Mode S reply is much more affected by Mode A/C interference signals than by Mode S replies. In scenario C02, fruit is dominated by DF0 replies produced in response to the interrogations of the additional ACAS II interrogators while Mode C fruit, induced by the TCAS I units, is the dominating factor in scenario C03. Thus, Mode C decoding is more affected in scenario C02 while Mode S decoding is suffering more in scenario C03.

5.2.6 Round trip reliability (for the selected aircraft)

In each scenario analysed, IoI 1048 had 8 Mode A/C transponders and 14 Mode S transponders within its full surveillance range of 33.3 NM. The range of 33.3 NM is the maximum distance to receive acquisition squitters from Mode S transponders. The following Figure 5-8 illustrates the distribution of the 22 transponders within the full range of 33.3 NM around the IoI 1048.

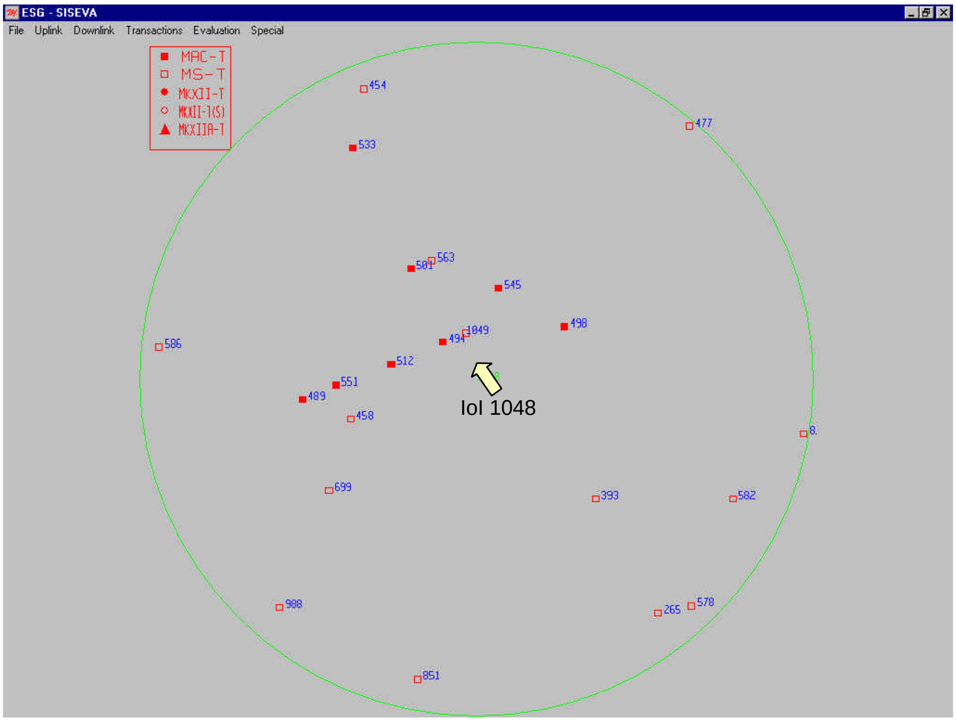


Figure 5-8: ACAS II IoI 1048 - target distribution

Due to a Mode C power reduction of 8 dB and a Mode S power reduction of 10 dB, only one Mode A/C transponder (ToI 494) and one Mode S transponder (ToI 1049) remain within the reduced surveillance volume. Both transponders are located in the forward sector of the ACAS interrogator, ToI 1049 at a distance of 4.7 NM and ToI 494 at 5.0 NM.

The Mode A/C transponder 494 receives only one Mode C-only interrogation during each surveillance cycle. The probabilities that this interrogation is replied by the transponder and that the corresponding reply is successfully decoded by the interrogator, as obtained by the simulations performed for the scenarios C01, C02, and C03, are provided by the following Figure 5-9. The Mode S ToI 1049 is interrogated once every 5 seconds. The probability for the success of the UF0/DF0 transactions is also depicted in Figure 5-9.

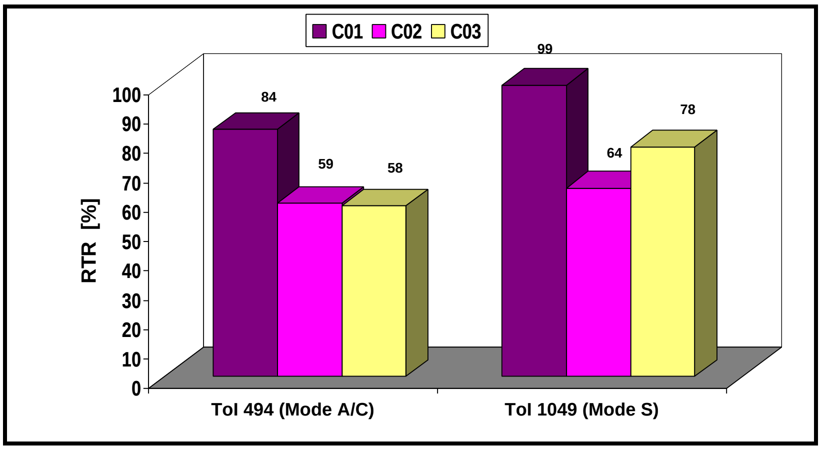


Figure 5-9: ACAS II IoI 1048 – round trip reliability

The following conclusions can be drawn with respect to the round trip reliability values achieved for the two ToIs of the IoI 1048:

1. Since only one interrogation of each Mode C-sequence is received by ToI 494, it should be noted that round trip reliability is identical with the probability that at least one successful interrogation reply cycle is performed during a one second surveillance period.

2. The figure indicates that the round trip reliability for both ToIs is significantly decreased by the activity of the clustered 31 ACAS II units assumed in scenario C02. Since Figure 5-7 indicates that Mode C-only as well as DF0 decode efficiency is only slightly affected at IoI 1048 when scenario C01 is replaced by scenario C02, the reduction of round trip reliability has to be attributed to a reduced reply efficiency. In deed, a more detailed analysis revealed that both ToIs are suffering a quite high signal load in scenario C02 and C03. This load considerably reduces the ability of the transponders to reply to interrogations of the ACAS II IoI.

3. Concerning specific Mode S transponders, i.e. ToI 1049, round trip reliability is significantly improved if the ACAS II units are substituted by TCAS I interrogators, although, as illustrated by Figure 5-7, decode efficiency for DF0 replies is decreased. This is due to the fact that reply efficiency is considerably improved in scenario C03, an effect which has been realised for the majority of transponders deployed in the Frankfurt area (see section 4).

The second ACAS IoI under consideration, IoI 1049, has 8 Mode A/C and 83 Mode S transponders in its nominal surveillance volume in scenario C01. Since all 31 aircraft added in scenario C02 and C03 are potential threats for IoI 1049 due to similar altitudes, the number of Mode S ToIs within the nominal range is increased to a total of 114. The following Figure 5-10 illustrates the transponders within the 33.3 NM range of the IoI 1049.

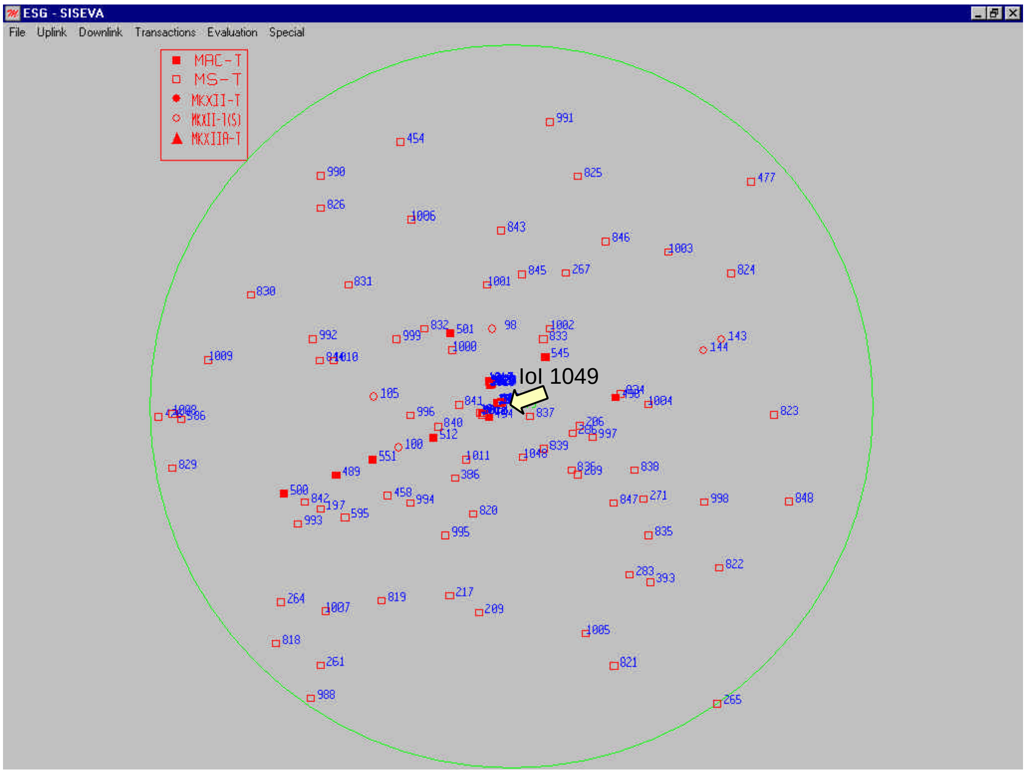


Figure 5-10: ACAS II IoI 1049 - target distribution

In scenario C01, IoI 1049 is obliged by the interference limiting algorithm to reduce Mode C power by 8 dB and Mode S power by 10 dB. Thus, the number of ToIs is reduce to 3 Mode A/C and 24 Mode S transponders. IoI 1049 has to reduce Mode C power by 8 dB in scenario C02 and by 7 dB in scenario C03. Mode S power is reduced by 10 dB in both scenarios. The power reductions result in a total of 3 Mode A/C and 55 Mode S ToIs for the scenarios C02 and C03. It should be noted that the 24 Mode S ToIs of scenario C01 are a subset of the 55 Mode S ToIs within scenario C02 and C03.

The following Figure 5-11 depicts the round trip reliability obtained by simulation for the interactions performed by IoI 1049 for the 3 Mode A/C ToIs within the scenarios C01, C02, and C03. Figure 5-12 shows the probability for at least one successful Mode C interaction during a one second surveillance update period, which takes into account the number of Mode C-only interrogations received by the ToIs during a single whisper/shout sequence.

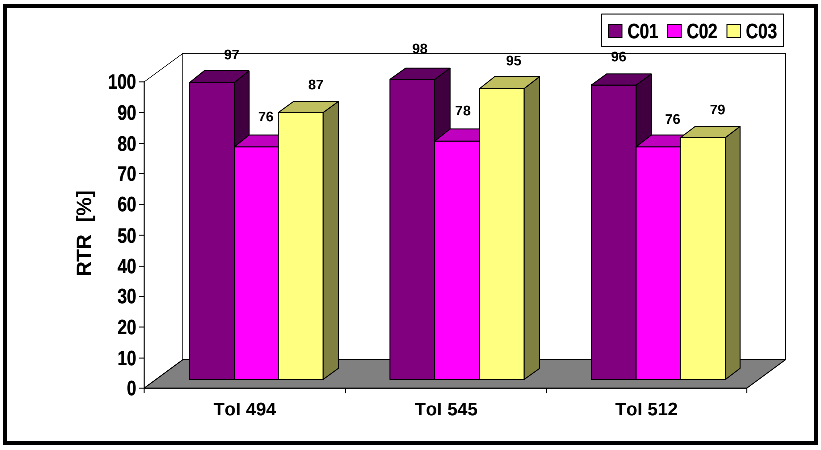


Figure 5-11: ACAS II IoI 1049 – round trip reliability for Mode A/C ToIs

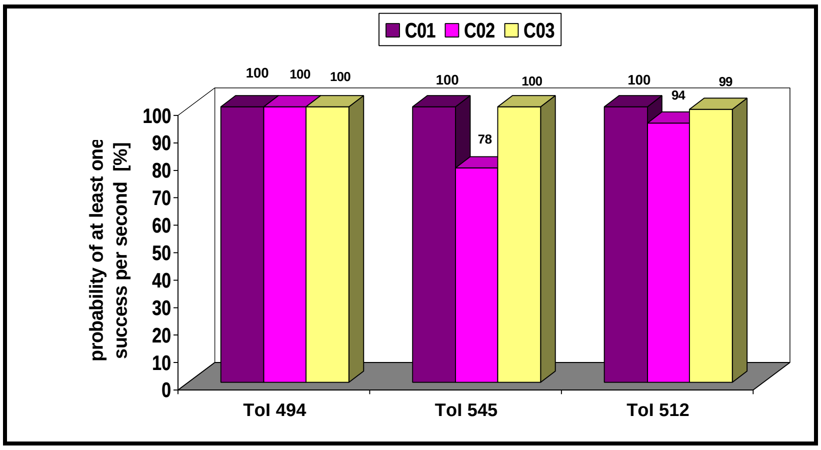


Figure 5-12: ACAS II IoI 1049 – probability for at least one success per second

With respect to the Mode A/C surveillance performance of the IoI 1049, the following conclusions can be drawn from the values provided in the figures above:

1. Round trip reliability for the three Mode A/C ToIs is considerably reduced by the activity of the clustered 31 ACAS II units assumed in scenario C02. This is a consequence of the reduced reply efficiency (see section 4) and the reduced decode efficiency (see Figure 5-7).

2. Substituting the ACAS II interrogators on board of these aircraft by a TCAS I interrogator improves round trip reliability for the three Mode A/C targets. This effect is caused by an improvement of both reply efficiency (see section 4) and decode efficiency (see Figure 5-7).

3. The variation of the probabilities for achieving at least one successful interrogation/reply interaction during a one second surveillance interval reflects the variation of the round trip reliability.

The following Figure 5-13 shows the round trip reliability for those 24 Mode S ToIs which are tracked by the IoI 1049 in scenario C01. Additionally, the values achieved for just these 24 ToIs in scenario C02 are inserted. In the figure, the ToIs are equally spaced on the x-axis but sorted with respect to the distance from the ACAS II IoI 1049.

Figure 5-13: ACAS II IoI 1049 – round trip reliability for Mode S ToIs (scenario C01 and C02)

Figure 5-14 illustrates the round trip reliability values obtained for all 55 Mode S ToIs tracked by IoI 1049 in scenario C02 and C03.

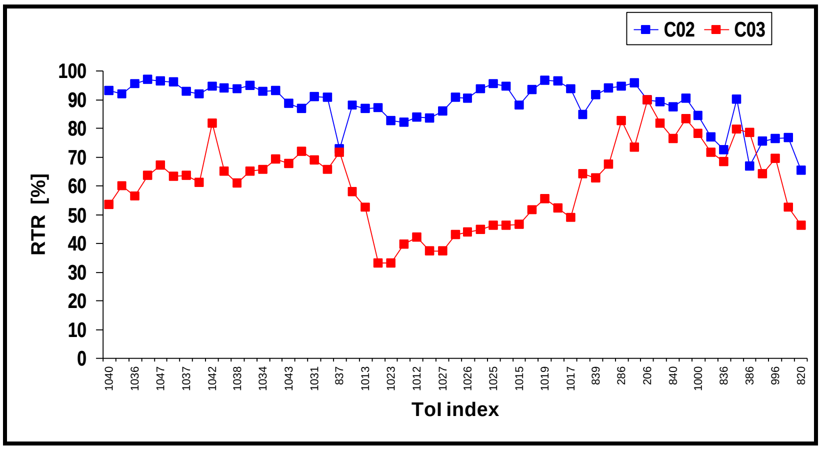


Figure 5-14: ACAS II IoI 1049 – round trip reliability for Mode S ToIs (scenario C02 and C03)

Concerning Mode S surveillance performance of the IoI 1049, the following conclusions can be drawn from the figures above:

1. Generally, round trip reliability for Mode S transactions is reduced by the activity of the clustered 31 ACAS II units in scenario C02. The mean value, calculated across the 24 ToIs, is decreased from 90% to 84%. The reduction is a consequence of a reduced reply efficiency (see section 4) and a reduced decode efficiency (see Figure 5-7).

2. Round trip reliability is significantly decreased when the 36 ACAS II interrogators are substituted by TCAS I units. The average across all 55 ToIs is reduced from 89% in scenario C02 to 61% in scenario C03. Thereby, especially the round trip reliability for the ToIs deployed at Frankfurt/Waldstadion and Frankfurt/Messe is significantly affected Primarily, the reason for the reduction is the drop of decode efficiency from 94% to 79% (see Figure 5-7) caused by the huge Mode C fruit produced in response to TCAS I interrogations. However, although the results discussed in section 4 revealed that in general reply efficiency in scenario C03 is higher than in scenario C02, the additional transponders deployed in the three clusters at Frankfurt/Kreuz, Frankfurt/Messe, and Frankfurt/Waldstadion show another trend. These transponders are all equipped with an TCAS I interrogator in scenario C03. The TCAS I interrogators use Mode C interrogations which are received and replied by each of the transponders added. Therefore, the loading at these transponders is increased above average and, as a consequence, reply efficiency for the interrogations of IoI 1049 is significantly decreased from 95% to 73%.

5.3 Summary and conclusions on ACAS II surveillance performance

1. If 5 clustered ACAS II units are taken into consideration close to Frankfurt airport, power reduction of the ACAS interrogators is only slightly affected. Adding a set of 36 ACAS II units, the surveillance range of ACAS II interrogators in the vicinity of the airport is considerably reduced. When the ACAS II interrogators on board of the 36 aircraft added are replaced by TCAS I units, the remaining ACAS II interrogators in the Frankfurt area are allowed to transmit surveillance interrogations at higher power.
2. The simulations performed indicated two cases where ACAS interrogators were transmitting at higher power in the denser environment. A more detailed analysis revealed that this is caused by the fact that special conditions defined in [4] for the calculation of the parameter α apply in these cases. A further discussion of this effect is recommended.
3. At the ACAS IoIs analysed, Mode C-only fruit is raised by about 40% and DF0 fruit by a factor of nearly four if 36 clustered ACAS II units are assumed. When these aircraft are equipped with TCAS I interrogators, a very huge rate of additional Mode C fruit is achieved which is nearly nine times higher than the rates produced by ground stations.
4. Interrogator receiver utilisation is nearly doubled if the 36 ACAS II in clusters are added. Interrogator receiver utilisation at the two ACAS II IoIs analysed is further raised, when these 36 aircraft are TCAS I equipped (instead of ACAS II).
5. Decode efficiency for Mode C-only and for DF0 replies is significantly decreased, if the 36 ACAS II units are taken into consideration. Replacing the ACAS II interrogators of the 36 aircraft in clusters by a TCAS I unit reduces Mode S decoding additionally.
6. Round trip reliability for Mode A/C ToIs is considerably reduced by the activity of the 36 clustered ACAS II units assumed. Moreover, round trip reliability for Mode S transactions is also reduced if the 36 ACAS II units are taken into account. Round trip reliability is significantly decreased when the 36 ACAS II interrogators are substituted by TCAS I units.

6. TCAS I Surveillance Performance

6.1 Objective of analysis

The objective of the preceding section was to explore the surveillance performance of ACAS II interrogators in the scenarios C01, C02, and C03. Within this section, performance aspects concerning TCAS I will be discussed.

The Airborne Collision Avoidance System TCAS I is designed to provided surveillance of nearby transponder equipped aircraft and to indicate to the flight crew the approximate position of close aircraft as an aid to visual acquisition. TCAS I is operated using Mode C interrogations to track both Mode A/C and Mode S transponders. Due to interference limiting, the maximum surveillance range of an TCAS I interrogator is generally about 8 NM.

If a TCAS I interrogator performs a surveillance process within a complex and dense environment, each question and answer cycle will suffer various impacts. Thereby, the receiving and processing of ACAS interrogations by transponders as well as the receipt and evaluation of replies by a TCAS I interrogator may be influenced.

In order to quantify TCAS I surveillance performance in scenario C03, defined in section 2, performance parameters for the selected TCAS I IoI 1014 (see section 2) were evaluated. The values for the parameters were obtained by the simulation runs performed.

6.2 Results

Although a maximum transmitter power of 52 dBm was assumed for the TCAS I interrogators deployed in scenario C03, the interference limiting algorithm implemented in the simulation model allows only a peak effective radiated power not exceeding 44 dBm in any case. Assuming a Mode A/C transponder sensitivity of –75 dBm, an effective radiated power of 44 dBm results in a maximum surveillance range of 7.9 NM.

Within the nominal range of 7.9 NM around the selected IoI 1014, a total of 77 targets are located. The following Figure 6-1 illustrates the distribution of these targets. It should be noted that the clustered aircraft at Frankfurt/Kreuz, Frankfurt/Waldstadion, and Frankfurt/Messe as well as the aircraft on the surface at Frankfurt airport are within the surveillance volume of IoI 1014. The transponders on ground respond to interrogations and the squitters generated by these transponders contribute to the fruit rates.

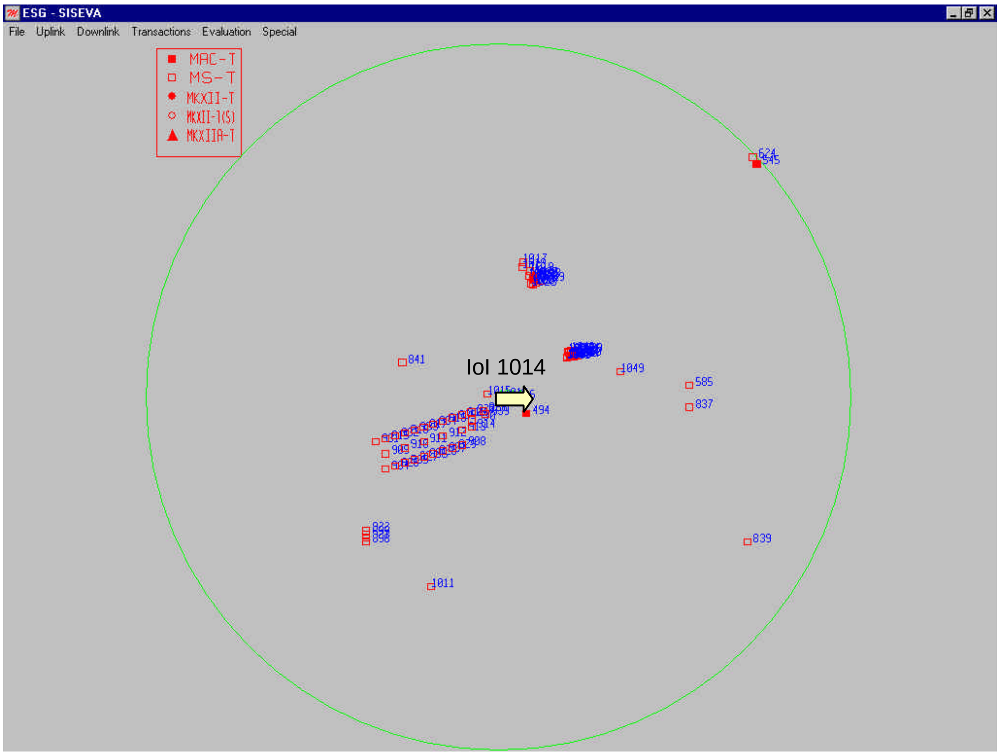


Figure 6-1: TCAS I IoI 1014 - target distribution

All TCAS I interrogators included in scenario C03 reduce transmitter output power by 15 dB relative to the peak power of 52 dBm. Thus, a maximum radiated power of 37 dBm is achieved and, as a consequence, only the first 24 Mode C interrogation of a Whisper/shout sequence consisting of 83 interrogations are transmitted. For Mode S transponders with a sensitivity of –78 dBm, the power reduction of the TCAS I units results in a surveillance range of 4.7 NM in the forward sector, 3 NM in the right and left sector, and 1.9 NM in the aft sector. In case of a Mode A/C transponder with a sensitivity of –75 dBm, the surveillance range is reduced to 3.3 NM in the forward beam, 2.1 NM in the right and left beam, and 1.3 NM in the aft beam.

Within the reduced surveillance volume of IoI 1014, a total of 68 transponders are located that receive Mode C interrogation transmitted by the IoI. The set of 68 ToIs consists of 2 Mode A/C transponders and 66 Mode S transponders.

The simulations performed indicate that during each surveillance cycle, i.e. once per second, a ToI received between 1 and 11 Mode C interrogations transmitted by the IoI. The number of interrogations received depends on the location of the transponder and its distance from the IoI. The variation is caused by the whisper/shout technique applied by TCAS I interrogators in conjunction with the side lobe suppression method realised via the S1-pulse preceding the Mode C interrogations. During simulation, each ToI was able to reply to 90% of the interrogations of interest in average. Thus, a total of nearly 160000 replies arrived at the IoI during simulation. However, since the majority of replies was garbled, the IoI was able to correctly decode only 4.7 % of the signals received.

The low decode efficiency of the IoI implies a low probability of success for a single interrogation/reply interaction. The round trip reliability values predicted for the 68 ToIs are pictured within the following Figure 6-2. The round trip reliability is depicted dependant on the transponder index. Thereby, the ToIs are equally spaced on the x-axis but sorted with respect to the distance from the TCAS I IoI.

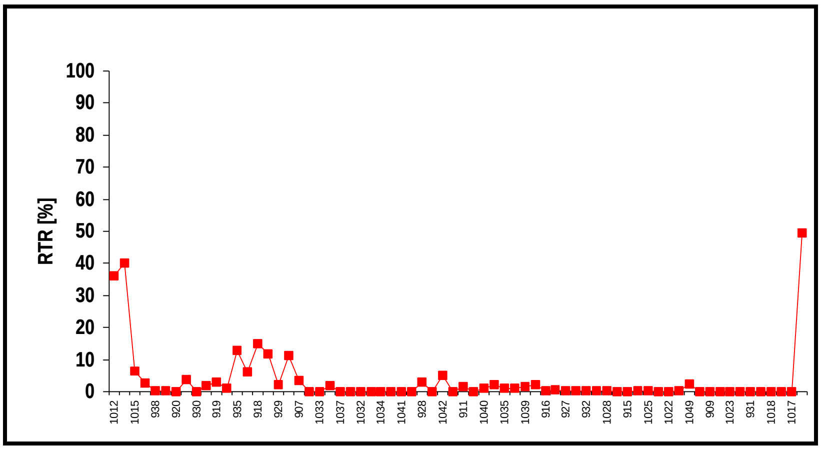


Figure 6-2: TCAS I IoI 1014 – round trip reliability

The figure above demonstrates that a round trip reliability of 50% is obtained only for one ToI, located at a range of 4.3 NM. Two ToIs, very close to the IoI, achieve a round trip reliability of about 40% and the probability of successfully completing a singe interrogation/reply transaction is below 20% for the remaining targets.

At a first view, the results discussed above seem worst. However, it has to be borne in mind that a TCAS I interrogator requires not all interrogations transmitted within a surveillance cycle to be replied and decoded. Therefore, the following Figure 6-3 provides for each of the 68 ToIs the probability that at least one interrogation/reply transaction was successful during a one second surveillance interval.

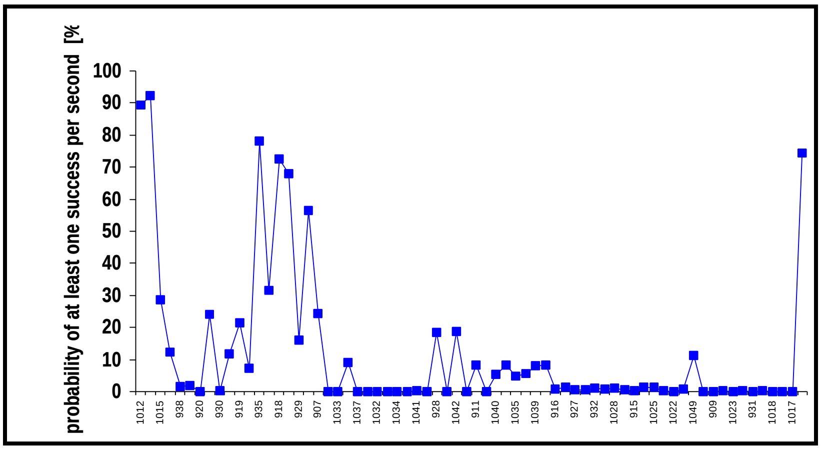


Figure 6-3: TCAS I IoI 1014 – code detection probability

The figure indicates that the probability of correctly decoding at least one valid reply during a one second surveillance interval is above 50% for 7 of the 68 ToIs (10%). On the other hand, the probability is equal to zero for 21 ToIs (31%), which means that these ToIs are never seen by the TCAS I interrogator. For the remaining 30 ToIs, the probability is somewhere between 0.2% and 30%. Thereby, a probability of 0.2% can be interpreted such that the IoI gets an altitude information of the target only every 500s in average. A probability of 30% means an update every three seconds.

6.3 Summary and conclusions on TCAS I surveillance performance

1. Since the majority of replies requested by the TCAS I IoI analysed were garbled, a decode efficiency of only 4.7 % was predicted by the simulations performed.
2. The probability of correctly decoding at least one valid reply during a one second surveillance interval was above 50% for 10% of the ToIs. The probability was equal to zero for 31% of the ToIs. For the remaining portion of ToIs the probability was somewhere between 0.2% and 30%.

7. References

[1] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting and Hybrid Surveillance
Scenario Description
Doc. No: 1DFS-BT-0001, Issued: 04.05.2001, Issue No: 1.0

[2] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting und Hybrid Surveillance
Modellbeschreibung
Dok.-Nr.: 1DFS-BT-0002, Ausgabedatum: 04.05.2001, Ausgabe-Nr.: 1.0

[3] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting and Hybrid Surveillance
Final Report
Doc. No: 1DFS-BT-0004, Issued: 27.07.2001, Issue No: 1.0

[4] ICAO
International Standards and Recommended Practices
Aeronautical Telecommunications,
Annex 10 to the convention on international civil aviation
Volume IV, surveillance radar and collision avoidance systems
Second Edition of volume IV, July 1998, Amendment 74

[5] ESG Elektroniksystem- und Logistik-GmbH
ACAS Interference Limiting and Mode S Extended Squitter
Final Report
Doc. No: 1AN5-BT-0003, Issued: 05.06.1996, Issue No: 1.0

ACAS PROGRAMME

ACASA PROJECT

Annex B to

Work Package 5

Final report on
Electromagnetic Environmental Effects of, and on, ACAS

Edition 1.0
March 2002

Annex B to Work package 5

Final Report on Electromagnetic Environmental Effects of, and on ACAS

Version 1.1, March 2002

TABLE OF CONTENTS

List of Tables

Page

WP5.2 Report

The electromagnetic environmental effects of ACAS II.

(SIEM Modelling Results)

Prepared by Andrew Peaty and David Bowen

1 Introduction

WP5 of the ACASA project involves the modelling of the RF environment to assess the impact of ACAS II, both with and without hybrid surveillance on the performance of SSR and ACAS.

Both ESG and QinetiQ have carried out modelling of the RF environment to investigate the impact of these techniques.

The Airborne Collision Avoidance System ACAS II is a co-operative surveillance and communication system including an ACAS interrogator and a Mode S transponder on board of an aircraft. The ACAS interrogator tracks both Mode A/C and Mode S transponder equipped aircraft in its vicinity. This is accomplished using two entirely separate techniques. Mode A/C transponders are tracked via Mode C-only interrogations. Mode S transponders are acquired passively by listening for Mode S squitters. Tracking is then performed by directly addressed UF0 Mode S interrogations challenging DF0 replies. If a collision threat is detected by the system, vertical resolution advisories are computed and exchanged via Mode S data link.

Since measurements performed on the SSR uplink channel revealed that the implemented interference limiting algorithms do not satisfy the criteria imposed upon ACAS, the responsible ICAO Panel (SICASP) modified these algorithms. A compromise was necessary between interference limiting on the one hand and ACAS surveillance performance on the other. Validation of this compromise, as well as validation of improved concepts, is still required to provide the desired reduction in the overall ACAS interrogation rates while maintaining sufficient surveillance performance for collision avoidance. The current concepts include modifications of the Interference Limiting Algorithms and the application of a more passive surveillance technique called "Hybrid Surveillance", based on Mode S Extended Squitter techniques.

Hybrid surveillance will improve ACAS surveillance performance while the effect on ATC processes and radio load may be minimised. The goal set by SICASP limiting the radio load due to ACAS (2% additional load) is still not completely met, especially in the vicinity of airports. Therefore, further investigations concerning the Interference Limiting Algorithms and their implementation environment show how the overall environment for all participants will be affected by using these techniques.

In order to evaluate the various concepts, detailed investigations are necessary concerning the following aspects:

- Influence of ACAS and its Interference Limiting Procedures on ATC performance
- ACAS Surveillance Performance

The major part of the work was carried out by ESG of Munich on behalf of DFS. QinetiQ carried out a subset of the ESG modelling to act as a validation agent for this work.

This paper reports the QinetiQ work, and compares the findings with those from the ESG modelling.

1.1 Overview of SIEM

Introduction and History of the Model

As numbers of IFF/SSR interrogators and transponders have progressively increased, and various new types of IFF/SSR systems are being developed, it is important that ATC operations are not compromised by the increasing levels of interference at the 1030 and 1090 MHz frequencies.

In the UK, the National IFF/SSR Policy Board is responsible for safeguarding the civil SSR environment by approving the operation of IFF/SSR interrogators. To assist in this approval process the SSR/IFF Environment Model (SIEM) was procured to calculate levels of mutual interference and probable effects on radar detection performance. Since its initial procurement in 1989, considerable enhancements of the SIEM have been made in order to extend its capability, particularly with regard to Mode S, TCAS and ADS-B.

Version 21b of SIEM software is currently in use. It was compiled using version 6.5 of the DIGITAL FORTRAN 77 compiler and run on a dual processor DIGITAL ALPHA server computer using version 7.1 of the Open Virtual Memory System (Open VMS) operating system.

The SIEM computer model uses statistical techniques to calculate the performance of individual Mode A/C and Mode S radars (including airborne Mode S interrogators such as ACAS II and certain TCAS I equipments) in simulations representing static snapshots of the SSR/IFF environment.

SIEM generates information on all the IFF/SSR, TCAS and Mode S interrogations that are present in the environment. The response of each transponder to the interrogations is modelled, including all the factors affecting a transponder's likelihood of receiving, correctly decoding and replying to an interrogation.

The SIEM model calculates various characteristics of the environment (such as transponder occupancy and 'fruit' rates), which leads to the calculation of the probability of each aircraft being detected by a radar of interest. Usually, the particular concern is the degradation in performance to one radar caused by the introduction into the environment of other radars or other systems such as TCAS and Extended Squitter.

Input to SIEM

The simulations consist of a scenario including radar interrogators (with associated equipment and antenna details), aircraft targets (with associated transponder types) and, if required, details of any Mode S Data Link applications.

The interrogator records include details of radar positions and the equipment associated with these radars. Examples are: the antenna radiation patterns; PRF; transmitter power; receiver sensitivity; minimum and maximum operational range; interrogation interlace (Modes 1, 2, 3/A, C, 4, etc, all Mode S formats, including SLMs and ELMs); and reply decoder and correlator characteristics. The only limit on the number of radars and transponder-carrying aircraft that can be modelled is the simulation time. A selected radar is analysed for its performance while other radars and aircraft contribute interference to the environment of that radar, possibly compromising its performance.

In addition to details of the radar interrogators and aircraft transponders, details of the elevation, roughness, slope and electrical attributes of the terrain can be input if required. These latter parameters enable allowance to be made for the effects of multipath, terrain screening and diffraction.

As an example, SIEM requires the input of the following parameters for interrogators:

- Site location
- Site height
- Antenna height
- Maximum operating range
- PRF
- Transmitter power
- Cable loss
- Receiver sensitivity
- Operating Mode (Mode S or Mode A/C)
- Interrogator tilt angle
- Interrogator scan period
- Definition of whisper shout (if appropriate)
- Mode S lockout behaviour (if appropriate)

The aircraft and transponder records contain details of the number of aircraft with the height, bearing, ground speed and vertical rate of each aircraft. Details of the equipment fitted to these aircraft, i.e. transponder operational parameters, are also included.

The aircraft scenario is a ‘snapshot’, which is usually determined from radar recordings with some extrapolation of numbers for future environments. Aircraft equipment may include TCAS (which also has interrogator characteristics), Extended Squitter and Mode S Enhanced Surveillance capability.

Details of the Mode S Data Link applications include types of Mode S format, rates, how many radars in a networked cluster, with a particular II code, sending an application etc.

Ground radar equipment (and airborne TCAS) specification includes characteristics such as position, antenna beam shape, interrogation power, interrogation rate, interrogation modes etc. Hence interrogators may include various types of SSR/IFF systems and various levels of Mode S functionality.

SIEM Output

In the SIEM computer model, statistical techniques are used to calculate levels of mutual interference in scenarios representing static snapshots of the SSR/IFF environment. Mean interrogation and FRUIT rates, and the "availability" of transponders are derived. Transponder availability represents the probability that interrogations will be recognised by the transponder. The model calculates the number of interrogations of each type and suppressions, both external and internal, that the transponder is experiencing. For each of these activities a defined duration is set within the model (for example 35 s for a suppression), and so the total occupancy of the transponder can be calculated.

The SIEM program models reply processing by ground radars using simple statistically based estimates of the probability of decoding a reply when zero, one, or more than one SSR Mode A/C or IFF MkXA FRUIT replies interfere with the wanted reply. Modern UK NATS radars suppress decoding (for the duration of the pulse train) following detection of a downlink Mode S message preamble. The program therefore reduces the probability of decode to zero when a Mode S FRUIT, received via the main-beam or a sidelobe, overlaps the wanted reply. Given the FRUIT rates, therefore, the probability of correctly decoding any given reply can be obtained.

The behaviour of the radar plot extractor is also modelled. For each interrogation made as the main-lobe of the radar antenna sweeps across the target, the probability of obtaining a correctly decoded reply is determined. The probability of obtaining a sufficient number of correctly decoded replies to reach, or exceed, the minimum detection threshold of the correlator for plot detection, track initiation, track updating and code validation is then calculated.

In summary SIEM produces various statistical outputs, including the following;

- Mean interrogation rates, including sidelobe suppressions, at each target.
- Mean transponder availability of a particular transponder to a specific interrogator and for specific types of interrogation, e.g. Mode A/C, Mode S short format and Mode S long format.
- Mean reply rates from each target.
- Mean FRUIT rates at each interrogator for each mode of reply, in main beam and sidelobes, for specific azimuth sectors.
- Reply decode probability. The probability that a reply at a specified SSR mode from a specified target will be correctly decoded in the presence of FRUIT.
- Round trip probability. The probability that a specified interrogation will be replied to and the reply correctly decoded.
- Plot detection probability. The probability of Mode A/C code validation.

Validation of SIEM

In 1992 an independent validation of the SIEM was carried out. The validation comprised a comparison of SIEM derived data with airborne measured information, collected by way of an aircraft SSR/IFF monitoring system. The report produced on behalf of UK NATS by DTS (UK) Ltd in June 1992 concluded: "*SIEM data, when compared with data achieved by airborne measurement, offers a good match and, therefore provides realistic predictions of the SSR/IFF Environment in terms of Mode 1,2,3/A and C interrogation levels*".

Further validation was carried out in 1995, when the model was used in simulations also modelled by the US (Joint Spectrum Centre) and Germany (ESG) who both operate similar models. The results of simulations carried out on defined scenarios were found to be within an acceptable range of error between all three models for the purposes of assessing the impact of IFF Mode 4 on the civil SSR system.

1.2 The Scenarios modelled

A subset of the scenarios modelled by ESG were agreed between QinetiQ and DFS as providing a reasonable cross section of the scenarios and giving sufficient data to compare both absolute results as well as trends between the different equipment configurations reflected across the scenarios.

In order to evaluate the system performance of MSSR/Mode S and ACAS, for both normal ACAS operation and with the introduction of hybrid surveillance, a number of scenarios were developed. These scenarios vary with respect to the interrogator equipage of the SSR ground stations and the transponder equipage of civil and military aircraft. The tables below represent the full set of ESG scenarios, the first table showing the 'A' scenarios with standard ACAS performance and the second table representing the 'B' scenarios where hybrid surveillance has been introduced:

Scenario	*Number of*						
	MS-I	*MAC-I*	*ACAS-I*	*MS-T*	*MAC-T*	*MKXII-T*	*MKXIIS-T*
A1	0	49	353	409	408	41	104
A2	12	37	353	409	408	41	104
A3	12	37	353	736	81	41	104
A4	49	-	353	736	81	41	104
A5	12	37	528	736	81	41	104
A6	12	37	528	736	81	41	104
A7	49	-	392	817	-	41	104
A8	12	37	586	817	-	-	145
A9	49	-	586	817	-	-	145

Table 1-1: Scenarios for analysis of MSSR/Mode S and ACS performance taking into account current ACAS operation

Scenario	*Number of*							
	MS-I	*MAC-I*	*ACAS-I*	*ACAS-HS*	*MS-T*	*MAC-T*	*MKXII-T*	*MKXIIS-T*
B01	0	49	392	78	409	408	41	104
B02	12	37	392	78	409	408	41	104
B03	0	49	528	106	736	81	41	104
B04	12	37	528	422	736	81	41	104
B05	49	0	528	422	736	81	41	104

Table 1-2: Scenarios for analysis of MSSR/Mode S and ACS performance taking into account ACAS Hybrid Surveillance

MS-I: civil ground stations equipped with MSSR/Mode S interrogator,
MAC-I: civil ground stations equipped with MSSR/Mode A/C interrogator,
ACAS-I: civil aircraft equipped with ACAS interrogator,
ACAS-HS civil aircraft equipped with ACAS interrogator using Hybrid Surveillance,
MS-T: civil aircraft equipped with Mode S transponder,

MAC-T: civil aircraft equipped with Mode A/C transponder,
MKXIIS-T: military aircraft equipped with Mode S capable transponder,
MKXII-T: military aircraft equipped with non Mode S capable transponder.

The highlighted scenarios (A01, A02, A09, B01 and B05) indicate those scenarios modelled by

QinetiQ, using the SIEM model, in order to compare and validate the results.

One difference that should be noted between the scenarios is that the QinetiQ scenarios all included the presence of extended squitter from Mode S aircraft, but it is understood that the A01-09 scenarios in the ESG modelling did not. The level of impact of this is not thought to be significant.

2 Method

2.1 Hybrid Surveillance and SIEM

Because of the nature of the SIEM model it is not possible to simulate the RF aspects of hybrid surveillance accurately without a major modification to the model and this is not consistent with the time-scale of this project. However, because of the stochastic nature of the SIEM modelling process as described above, it is possible to use a method of representing the different modes of active interrogation carried out within a hybrid surveillance environment. This involved the development of a spreadsheet which is intended to calculate the reply frequency of a set of Mode S transponders against a subset of TCAS interrogators. The hybrid surveillance technique is detailed in 4.5.1.3 in Annex 10 Volume 4 SARPs on Aeronautical Telecommunications.

Briefly, the SARPs detail when it is possible for an ACAS interrogator to rely on passive surveillance, to interrogate every ten seconds and use passive surveillance, or to resume 'normal' interrogations at a rate of one a second. Using this it is obvious that each interrogator-transponder pair can operate at 0, 0.1 or 1 interrogations per second, but that the same interrogator may be using different rates for different transponders and transponders may be replying at different rates to separate interrogators.

In the SIEM model, ACAS is simulated using the Mode S applications method, which enables up to ten applications to be associated with each interrogator or transponder. If an interrogator Mode S application matches the transponders, that interaction is simulated. Modelling the scenario exactly using these methods would not be possible. An alternative method is to assign each interrogator with a Mode S application corresponding to a rate of reply of 0, 0.1 or 1. All Mode S transponders will have all three applications and so will be able to pair up with every interrogator in range.

To decide which interrogator type to give to each Mode S aircraft a heuristic method is used. The spreadsheet consists of two sheets, the first contains a list of Platform Name, Latitude, Longitude, Altitude/Antenna height (m), Bearing (degrees), Ground speed (M/s) and Vertical Rate (m/s) for all Mode S transponders. The second is a table where the header row is a list of all ACAS interrogators. The macro then prepares a table of these interrogators against all the transponders with the calculated interrogation-reply rate for each pair according to the hybrid model. The table entry was left blank if the interrogator-transponder pair were out of range (14NM). For each interrogator the number of interrogations per second were summed and the average taken. The interrogators were ordered by their average, and thresholds were set to define the interrogator as a 1, 0.1 or 0 replies/sec type. The aim was to assign to each interrogator its closest match, whilst keeping the overall rate of replies for the whole as close as possible to the total predicted.

This approach, while not accurately matching the detail of the true hybrid surveillance ACAS operation, should give a stochastically equivalent result in terms of RF impact.

2.2 Model Input Variations

The ESG model does have the same range of input parameters as SIEM. As a result there were a number of parameters that were not provided by ESG as part of the scenario descriptions. Where this was the case, the values were derived from similar objects currently modelled by SIEM.

3. Results and Discussion

There are certain aspects of the results that are different between the ESG results and the QinetiQ SIEM results presented here. The ESG results, whilst including the effect of all aircraft and interrogators in the model, only show the results for aircraft ‘under control’ of the Interrogator of Interest (IoI), Frankfurt. Consequently the results for aircraft on the ground or military aircraft are not shown. The SIEM results show all aircraft in the scenario, and so caution should be exercised when trying to evaluate aircraft against aircraft results. Also, the maximum values from the SIEM model may refer to aircraft not ‘under the control’ of the IoI, so comparisons between these may not be valid.

3.1 Transponder Utilisation.

<u>Derivation</u>

This was derived from the SIEM-produced Transponder Availability. SIEM TA is a measure of whether the transponder is available to reply to an interrogation and includes factors such-as :

1. Transponder is already replying or is in dead-time after doing so;
2. Transponder has been suppressed having received P1-P2 suppression pair;
3. Transponder has self-suppressed to protect against other aircraft system transmissions.

As transponder utilisation is based solely on the effect of interrogations in main and side beams, we removed the effect of the transponder self-suppression (a fixed level in the SIEM model).

SIEM does not output a breakdown of the causes transponder utilisation, so no values are available for the specific transponder utilisation due to ACAS.

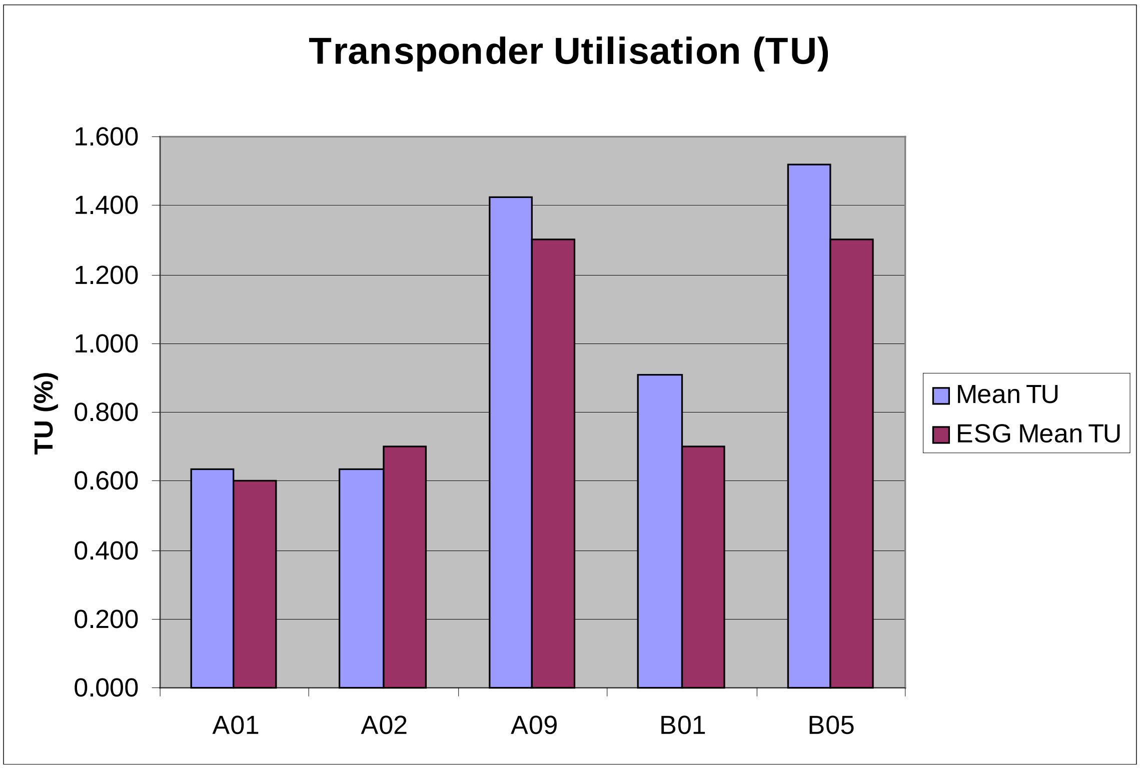


Figure 3.1

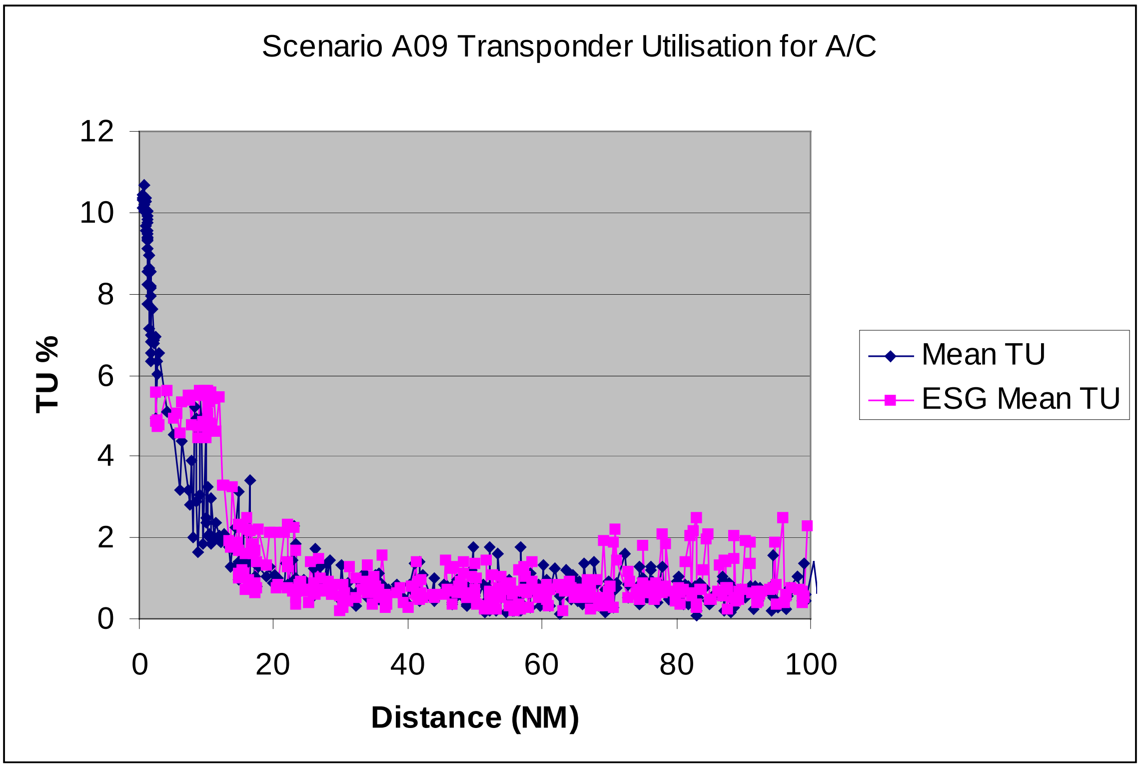


Figure 3.2

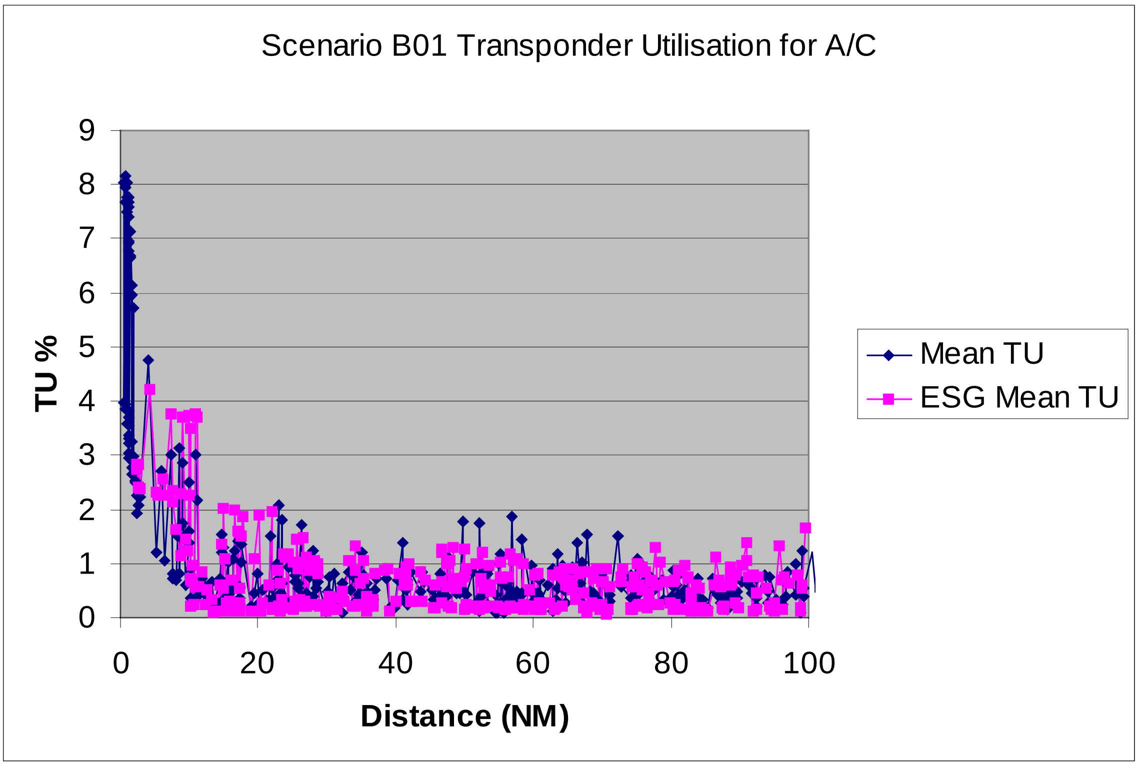


Figure 3.3

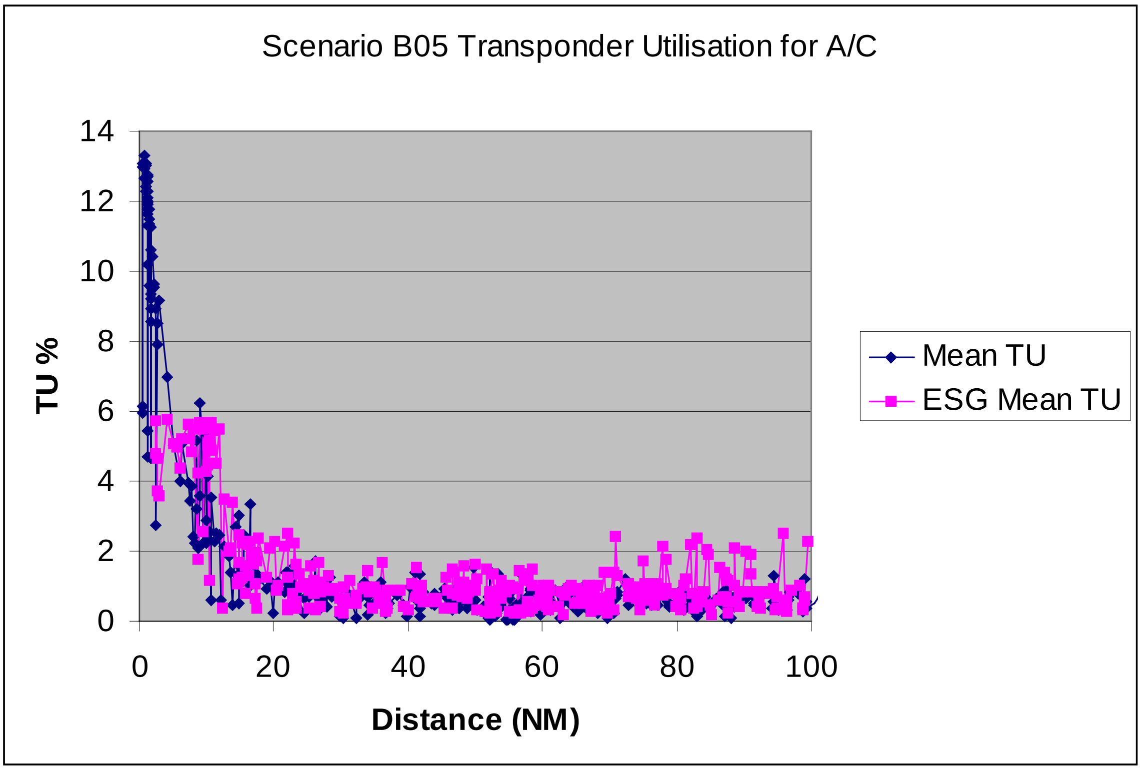


Figure 3.4

Comments on Results

The average transponder utilisation results match well considering the difference in the models. The SIEM results generally show higher utilisation than the ESG results. One possible explanation for this is the effect of the aircraft with high utilisation on the ground, which are not included in the ESG results.

With respect to the transponder utilisation verses range results for the Frankfurt interrogator, there is some agreement between SIEM and the ESG results, with the trends being generally similar. The ESG transponder utilisation value appears to be generally greater than the SIEM result within 20NM and beyond 80NM. Overall, considering the differences in modelling and calculations, the results are comparable.

3.2 Interrogator Utilisation

Derivation

Once again, SIEM does not produce a value directly comparable to interrogator utilisation. We took the FRUIT rate and, assuming no overlap of FRUIT, calculated the effect this would have on the IoI. In order to compare this method of calculation to the ESG results, we took the ESG FRUIT rates (for A01-9) and performed the same process, and this is shown in the tables below.

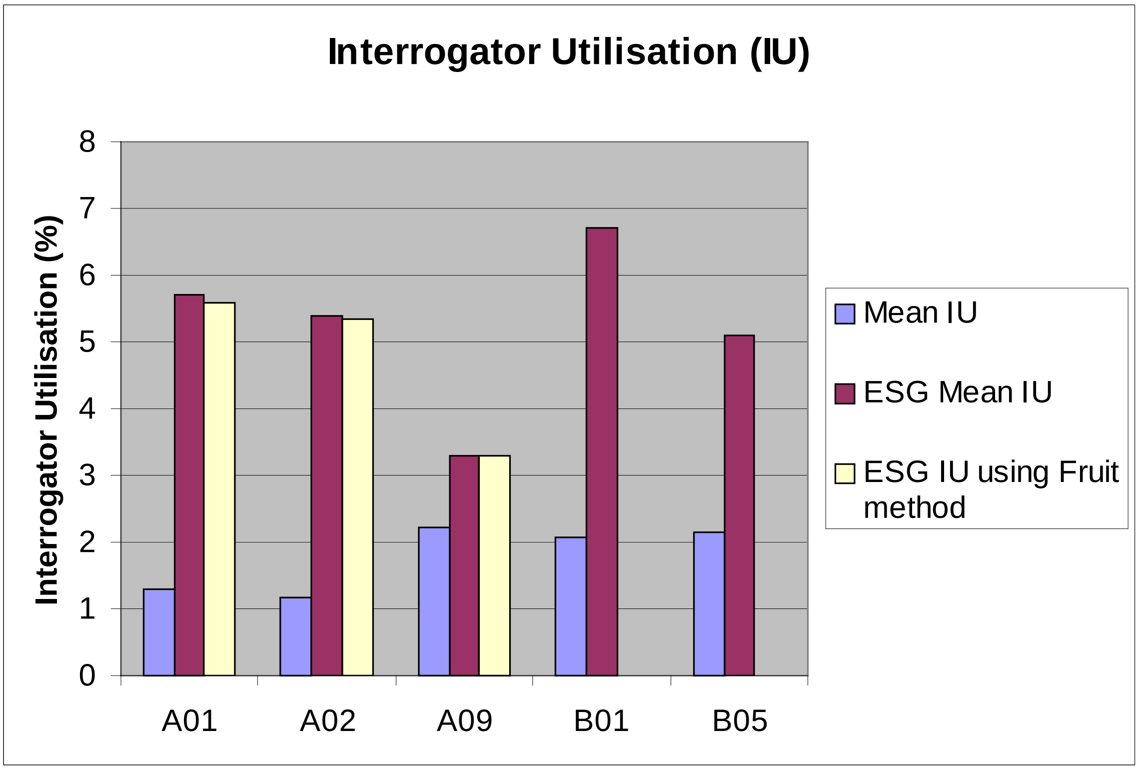


Figure 3.5

Comments on Results

The interrogator utilisation results show considerable differences, with the SIEM results being significantly lower than the ESG results. The estimation of interrogator utilisation using FRUIT from ESG gives results that are similar to the ESG interrogator utilisation results. This indicates that the ESG results do not allow for the processing time of synchronous (wanted) replies.

For an ATCRBS environment (scenario A01) the interrogator utilisation for synchronous (wanted) replies can be calculated at around 2.5% interrogator utilisation (given the PRF and number of aircraft across the beam).

Similarly for a Mode S environment (scenario A09) the interrogator utilisation for synchronous (wanted) replies, taking into account both all-call and addressed interrogations should be around 1.4%.

This gives an estimated interrogator utilisation for scenario A01of 3.8% and for scenario A09 of 3.6%

These figures are closer to the ESG results, but this raises the question as to whether the ESG interrogator utilisation results take these wanted interrogations into account. The ESG results for total interrogator utilisation are only very slightly higher than the results taking into account only the FRUIT calculation.

3.3 Mode A/C and Mode S detection.

Derivation

This was derived from the SIEM round trip reliability using the number of hits across the beam and the respective interrogator interlace pattern. The probability of having the required number of specified replies was calculated using a binomial distribution.

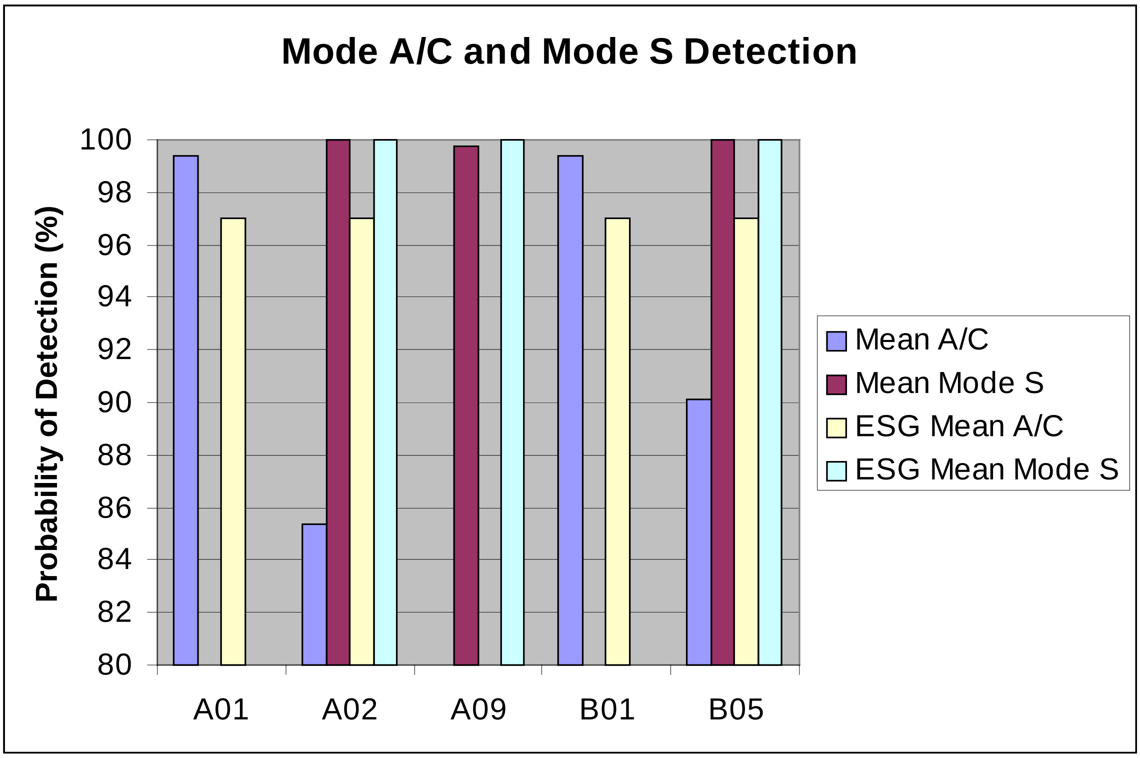


Figure 3.6

Comments on Results

The Mode S values match quite well in that all of them are quite close to 100%. However, it is difficult to draw too many conclusions from this. Mode A/C code detection results are more disparate. The potential differences in main beam modelling between the ESG model and SIEM could cause this effect. Further work would be required to match the models up more precisely.

If you remove the transponders with too few hits across the beam to return a valid Mode A/C, the detection rate for scenario A01 goes from 85.4% to 93.5%, and for scenario B05 from 90.2% to 91.5%. It is not known whether the ESG results include transponders that replied but could not return a valid Mode A/C due to having too few replies across the beam.

3.4 Decode Efficiency

Derivation

This is calculated directly by SIEM.

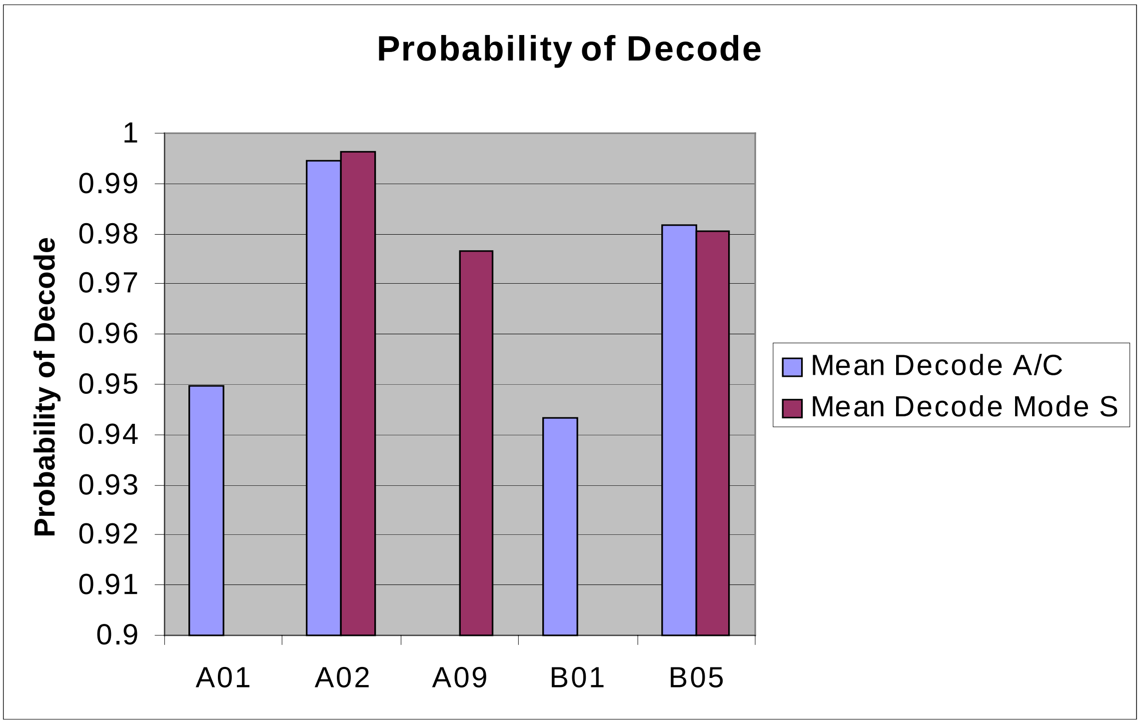


Figure 3.7

Comments on Results

Between scenarios A02 and A09, an increase in the Mode S equipage and ground-stations, there is a decrease in Probability of Decode. This is opposite to the trend in the ESG results for the same scenarios. These differing results are consistent with the differences in Interrogator Utilisation shown in section 3.2.

3.5 ACAS Power Reduction.

Derivation

This is calculated directly by SIEM.

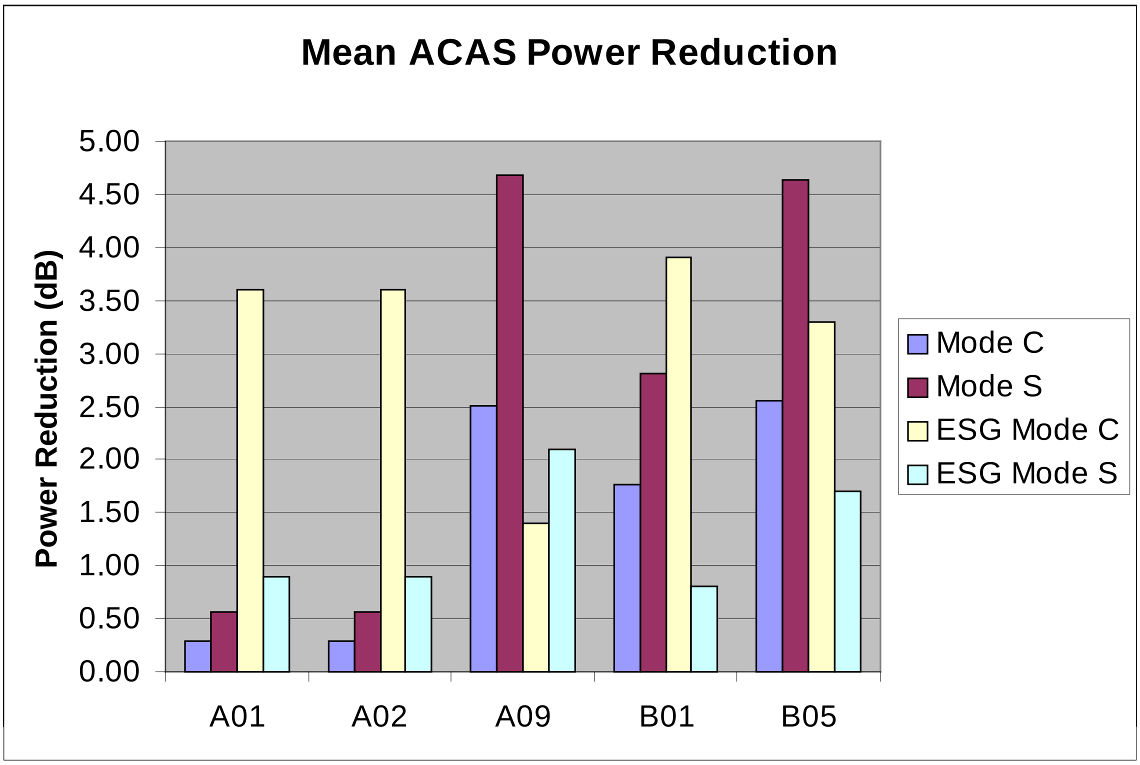


Figure 3.8

Comments on Results

There is little correlation between the SIEM and ESG ACAS power reduction results. Only scenario A09 shows any signs of similarity where, although the average differs, the detailed results show very similar trends. It is possible that the order in which the interference limiting inequalities are applied will have an effect, and there is little guidance as to how these should be applied. This may account for why the ESG results have a higher Mode C power reduction compared to the SIEM results for scenarios with ATCRBS transponders (i.e. excluding scenario A09), whereas the SIEM results tend to have higher Mode S power reduction. Further work is required before this can be satisfactorily answered.

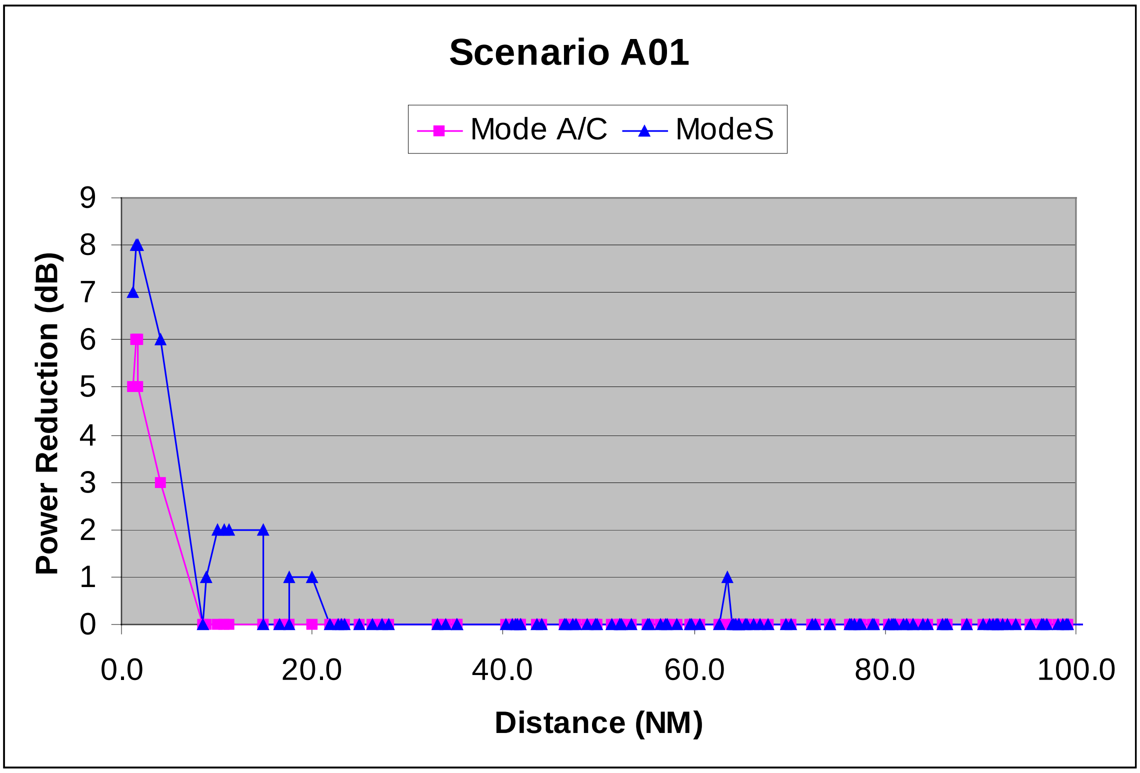


Figure 3.9

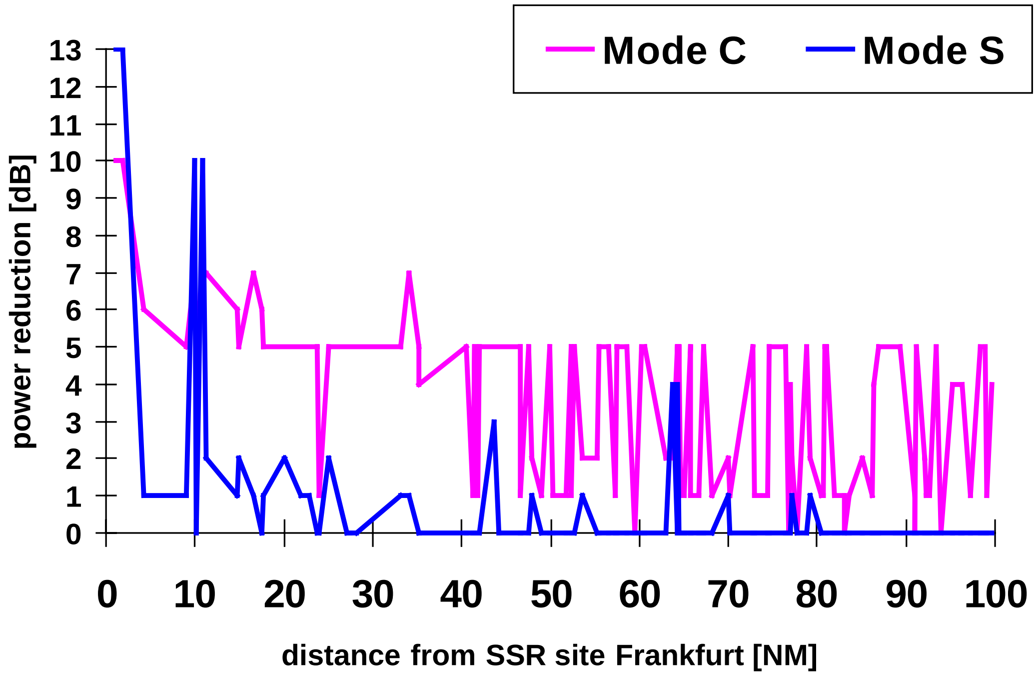


Figure 3.10 – ESG Results

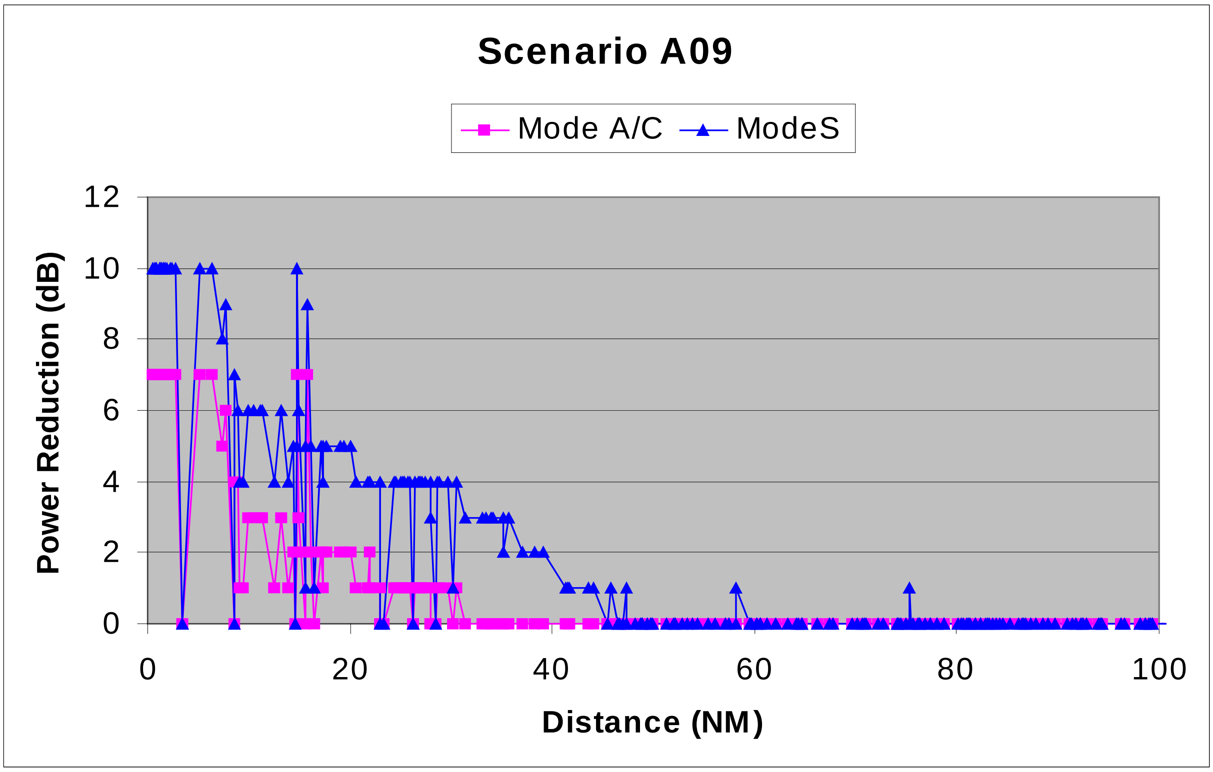


Figure 3.11

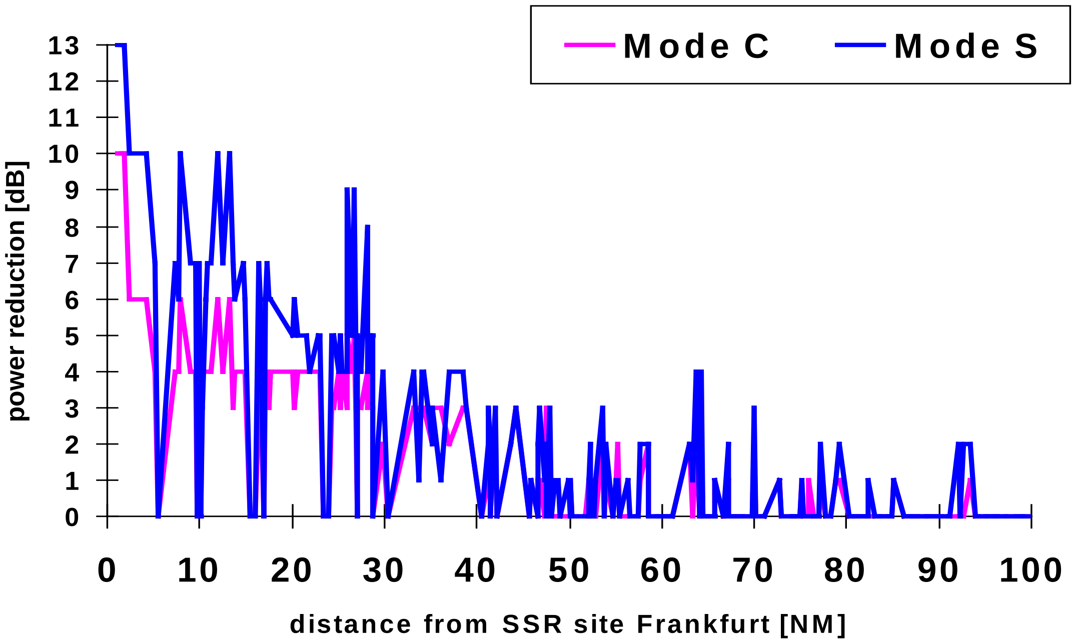


Figure 3.12 – ESG Results

4. Conclusions

The results presented above do not show a clear correlation between the QinetiQ and ESG modelling results. A number of significant variations can be seen and, although potential explanations can be offered for each of these, further investigation would clearly be required to understand fully the source of these differences.

Although the simplest set of results, that of Transponder Utilisation, show reasonable agreement, the results differ more as we consider the downlink aspects of the modelling.

Neither set of modelling shows any clear benefits in terms of RF impact from introducing Hybrid Surveillance. A reduction in the levels of Mode A/C FRUIT is clearly a more important factor in improving the RF environment.

The order in which the ACAS interference limiting algorithms are applied warrants further investigation, as it seems this may have a significant impact in the nature of any power reductions that are applied to an ACAS unit.