EUROPEAN ORGANISATION
FOR THE SAFETY OF AIR NAVIGATION

EUROCONTROL

# ACASA PROJECT

## Updated Work Package 5 -
## Final Report on
## Electromagnetic Environmental Effects of, and on, ACAS

**ACAS-09-094**


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**Abstract**


The 2002 Airborne Collision Avoidance Systems Analysis (ACASA) was conducted to support the implementation of ACAS II in European airspace. The Work Package 5 of the study reported on the electromagnetic environmental effects of and on ACAS.

Because of discussions on the use of ACAS I systems in European airspace the scope of the analysis was expanded in WP 5.1. The analysis confirmed the doubts in surveillance performance of these devices and the concerns with respect to additional load on the electromagnetic environment. This WP 5.1 report has been updated in 2009 with up to date measurements to provide a current picture of electromagnetic environmental issues to be expected for 2015.

In general, results from the 2002 analysis have been confirmed with a trend to even worse results due to higher traffic densities.



**Keywords**

| | | | |
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| TCAS | RA | ACASA | Transponder |
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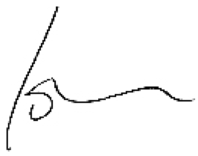
| Mode S & ACAS Programme Manager |  John Law | 4 August 2009 |
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# WP-5

# Electromagnetic environmental effects of and on ACAS

## UPDATED August 2009

Prepared by Dr. Roland Mallwitz (DFS)

This paper updates the results of the 2002 study on the Electromagnetic environmental effects of and on ACAS, in particular when those systems are operated in clusters.

# Table of Content

# 1. Introduction

To support safe 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 safe 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 7 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. Section 7 covers an update of the report discussing 2015 air traffic scenarios.

## 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.

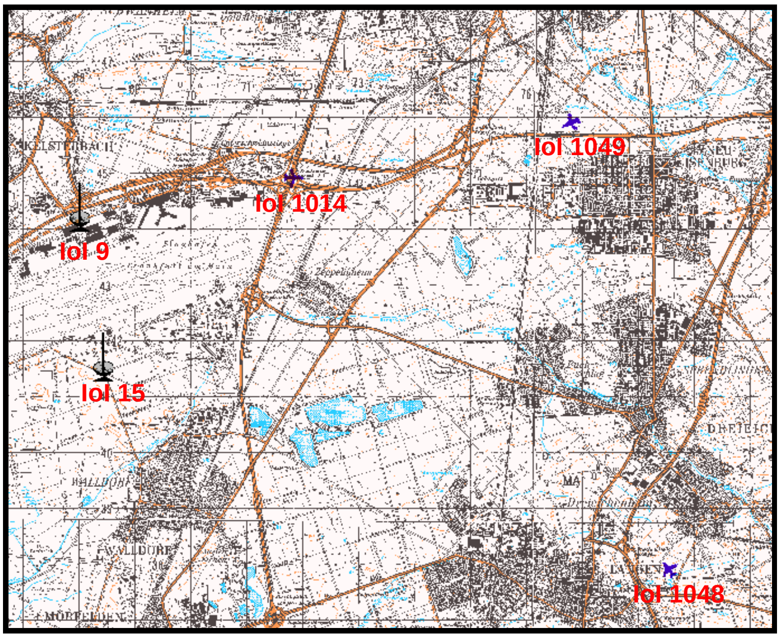


Figure 2-1: Location of IoIs

# 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.

Antenna system of a TCAS I interrogator

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°.

Surveillance of Mode A/C and Mode S Transponders

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.

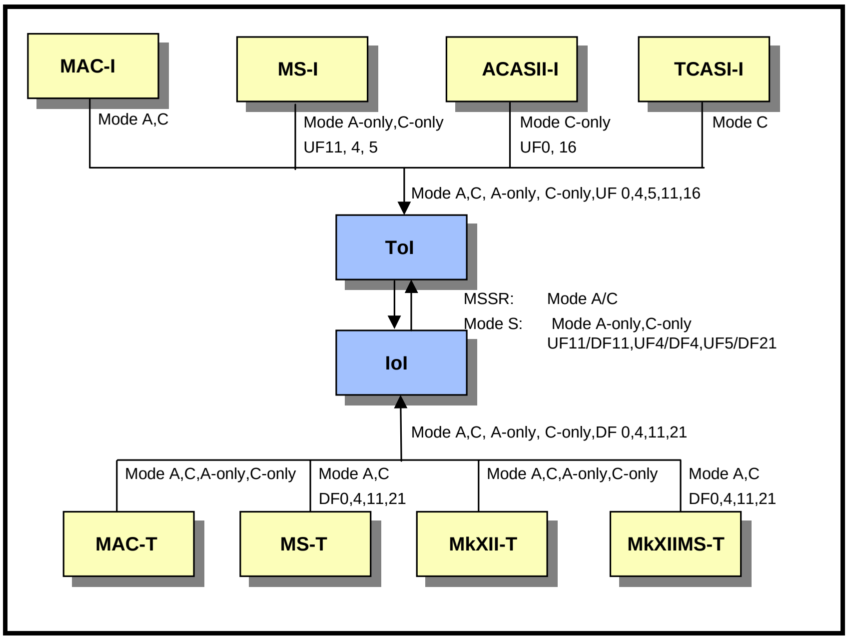


Figure 4-1: Impacts on MSSR/Mode S surveillance

### 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.

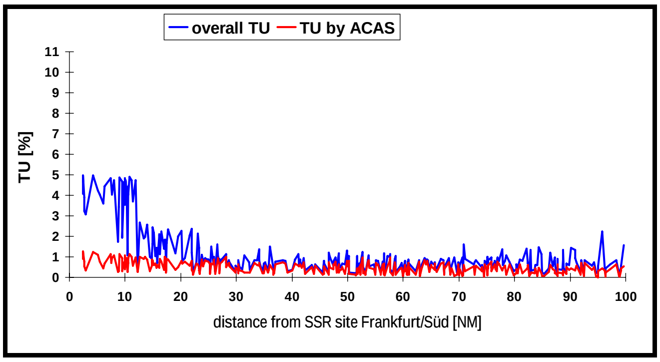


Figure 4-2: Scenario A05 – transponder utilisation

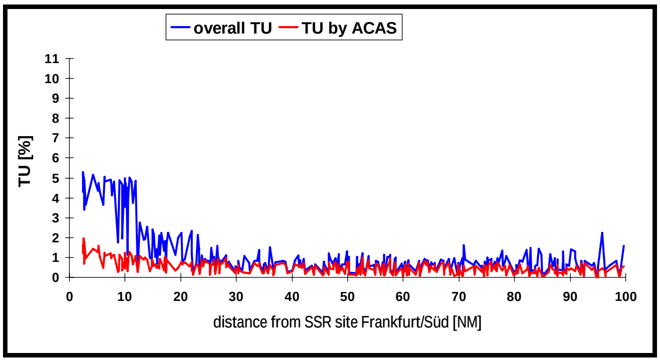


Figure 4-3: Scenario C01 - transponder utilisation

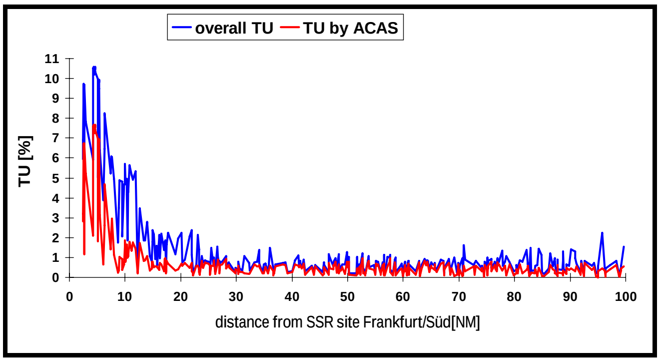


Figure 4-4: Scenario C02 - transponder utilisation

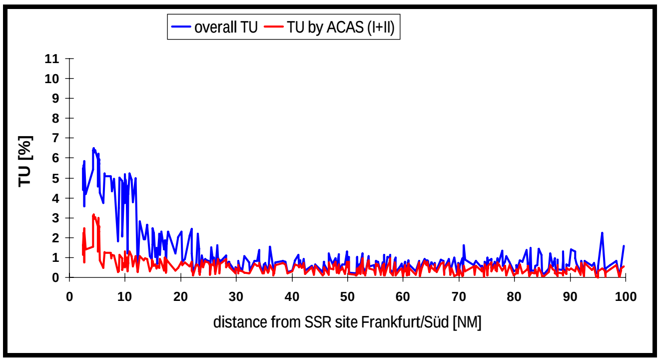


Figure 4-5: Scenario C03 - transponder utilisation

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 |
| | $\mu$ | 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 |
| | $\mu$ | 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 clustered 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. |
| | μ | 98.7 | 98.3 | 96.9 | 97.6 |
| | **max** | 100. | 100. | 100. | 100. |
| **Mode C** | **min** | 90. | 86. | 74. | 86. |
| | μ | 98.5 | 97.9 | 96.1 | 97.2 |
| | **max** | 100. | 100. | 100. | 100. |
| **Mode S** | **min** | 87. | 85. | 74. | 77. |
| | μ | 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.

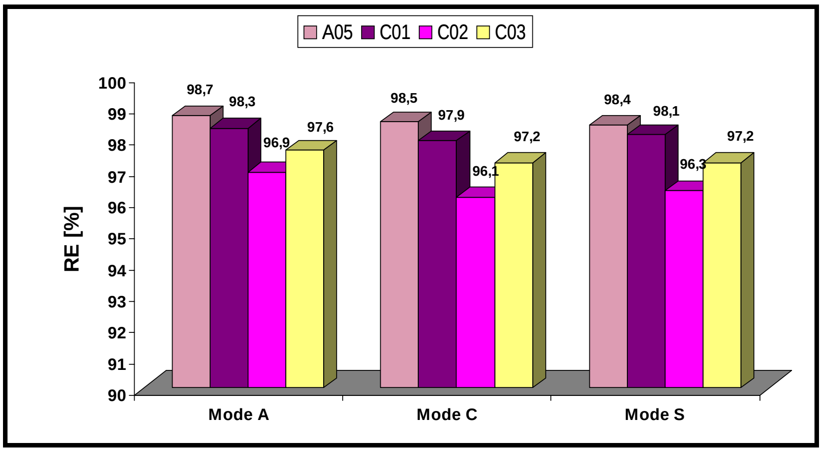


Figure 4-6: Mean reply efficiency

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.

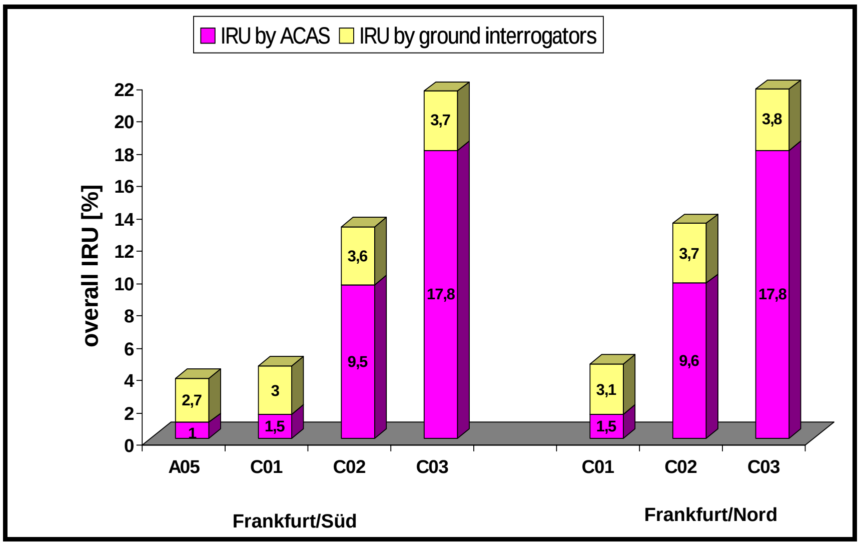


Figure 4-7: Interrogator receiver utilisation

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.

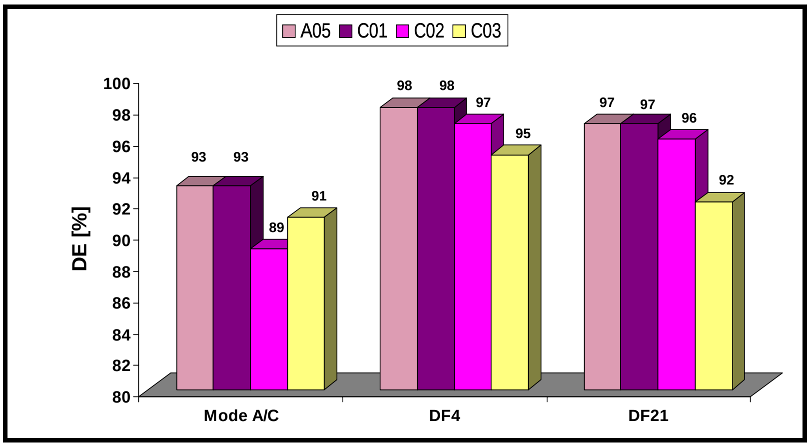


Figure 4-8: IoI Frankfurt/Süd - decode efficiency

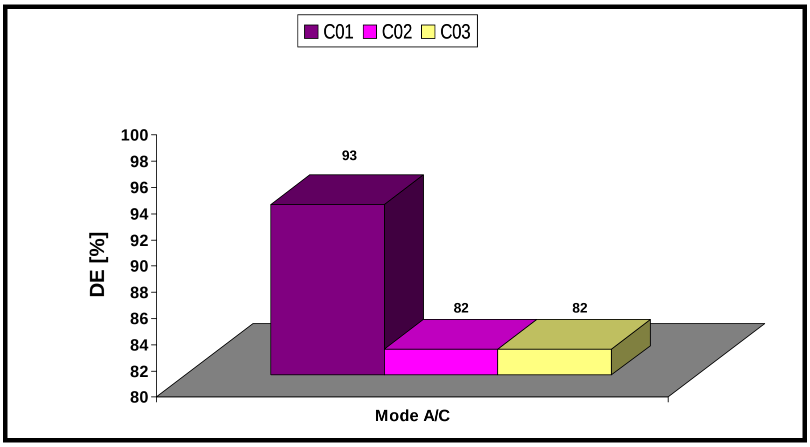


Figure 4-9: IoI Frankfurt/Nord – decode efficiency

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.

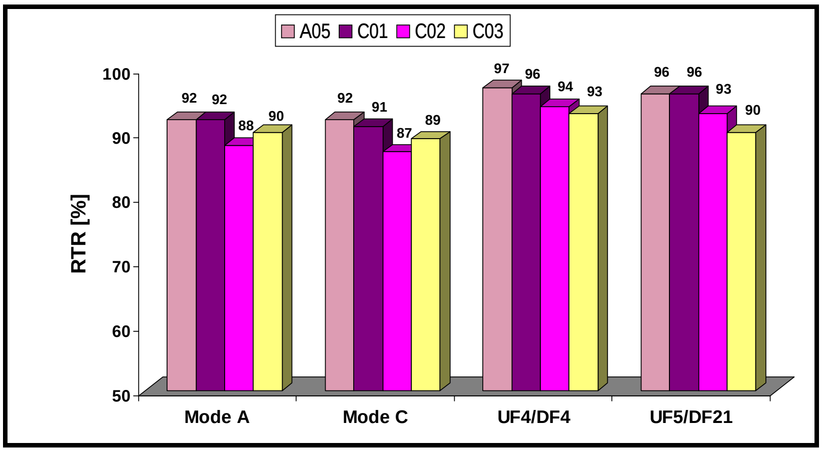


Figure 4-10: IoI Frankfurt/Süd – mean round trip reliability

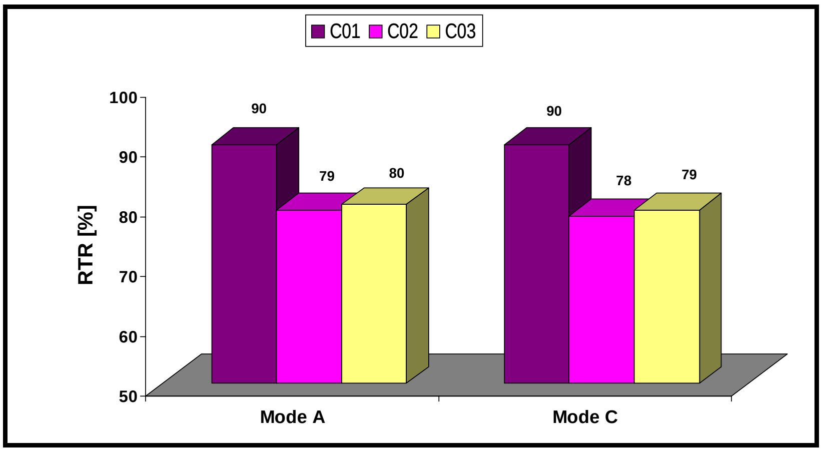


Figure 4-11: IoI Frankfurt/Nord – mean round trip reliability

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.

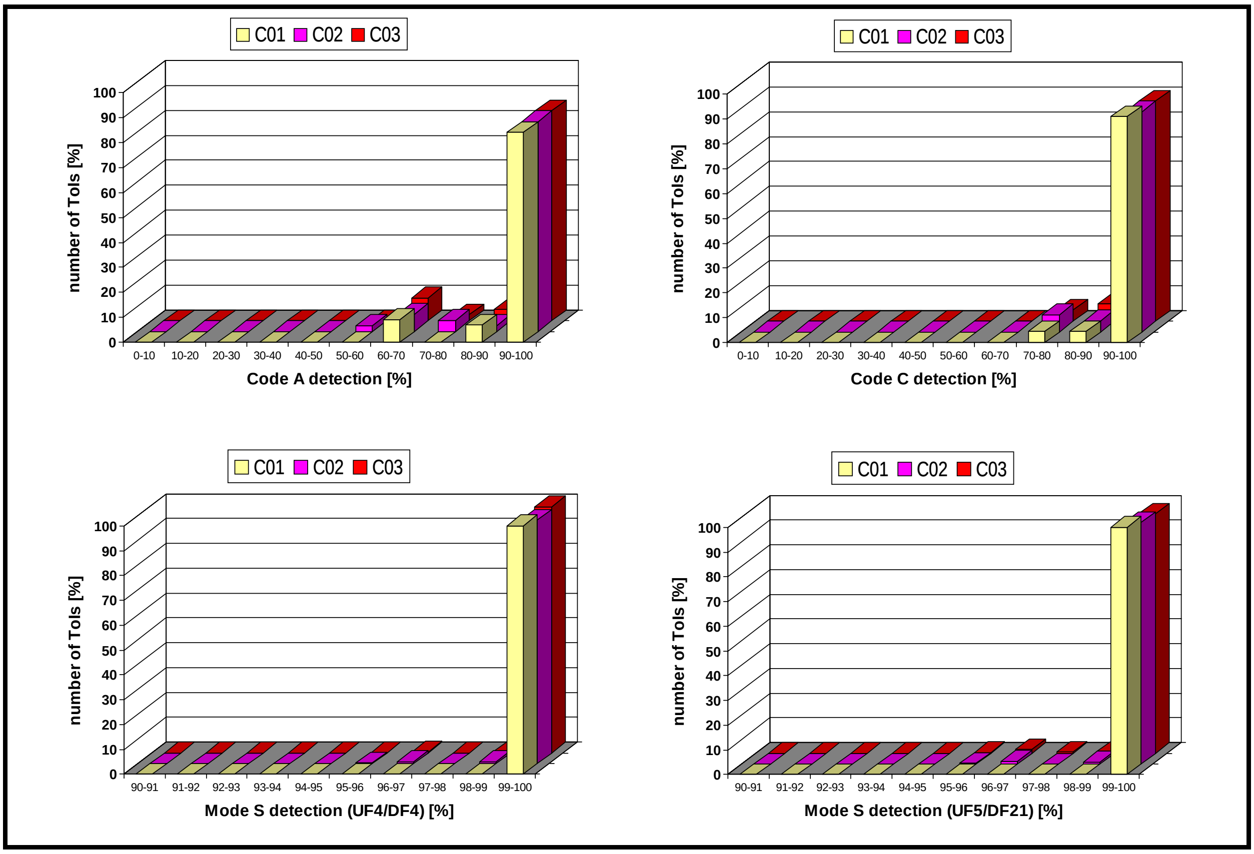


Figure 4-12: IoI Frankfurt/Süd – distribution of Code A/C and Mode S detection

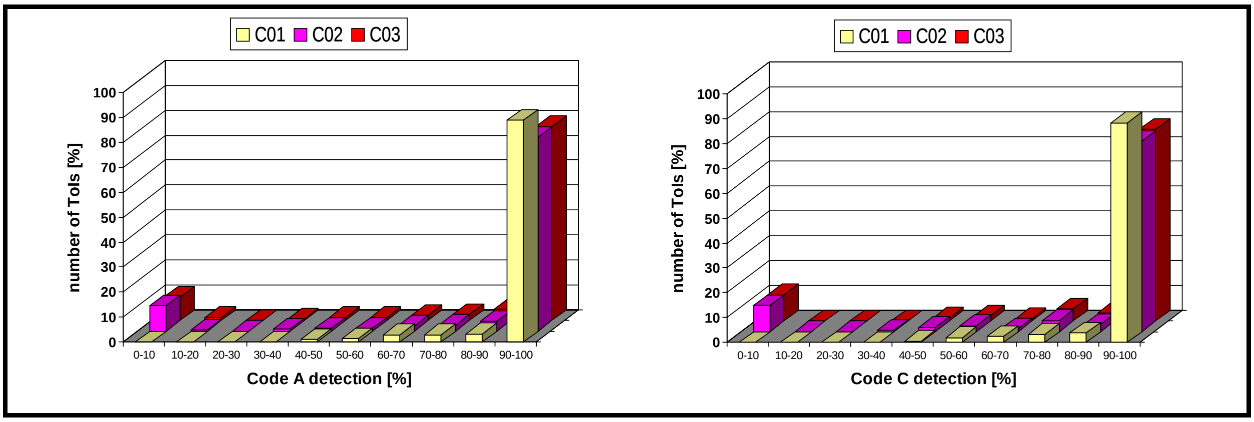


Figure 4-13: IoI Frankfurt/Nord – distribution of Code A/C detection

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.

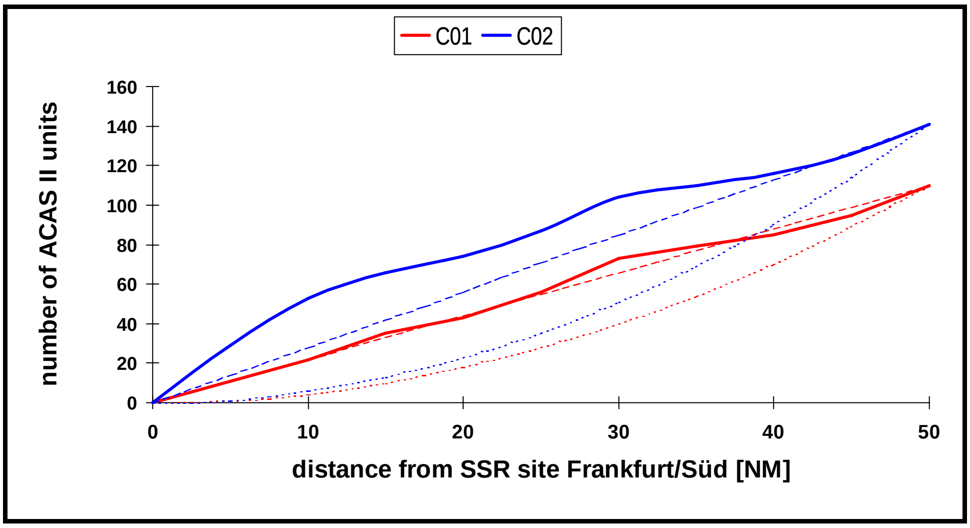


Figure 5-1: Density of ACAS II units in the scenarios C01 and C02

### 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.

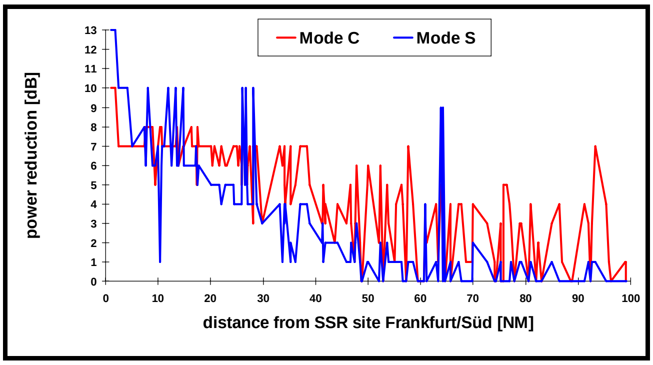


Figure 5-2: Scenario A05 – ACAS power reduction

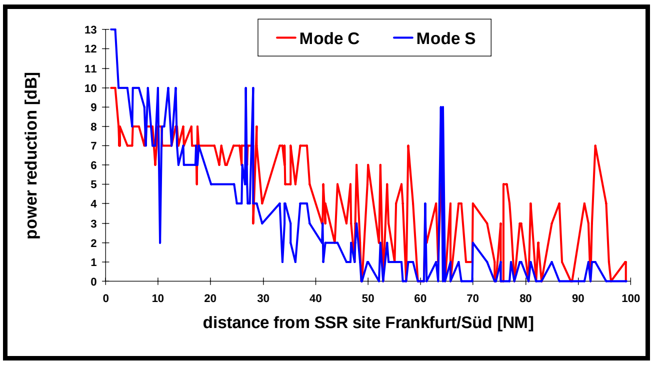


Figure 5-3: Scenario C01 – ACAS power reduction

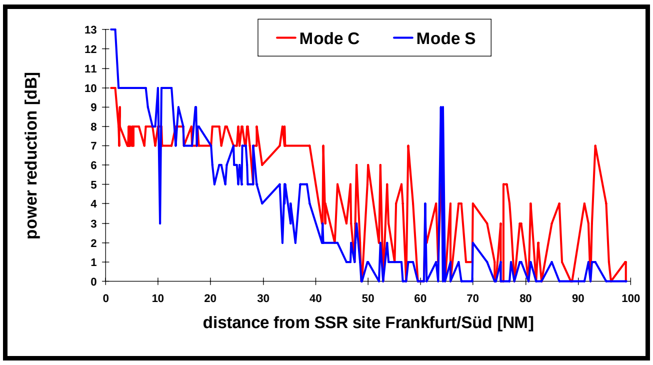


Figure 5-4: Scenario C02 – ACAS power reduction

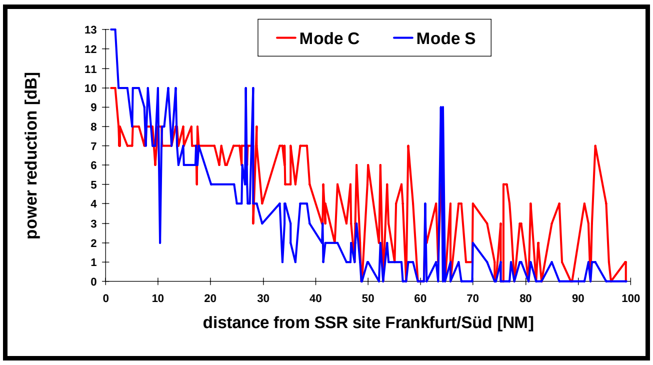


Figure 5-5: Scenario C03 – ACAS power reduction

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 $\alpha$ apply. These conditions result in $\alpha$=1.0 for scenario C02 while $\alpha$=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.

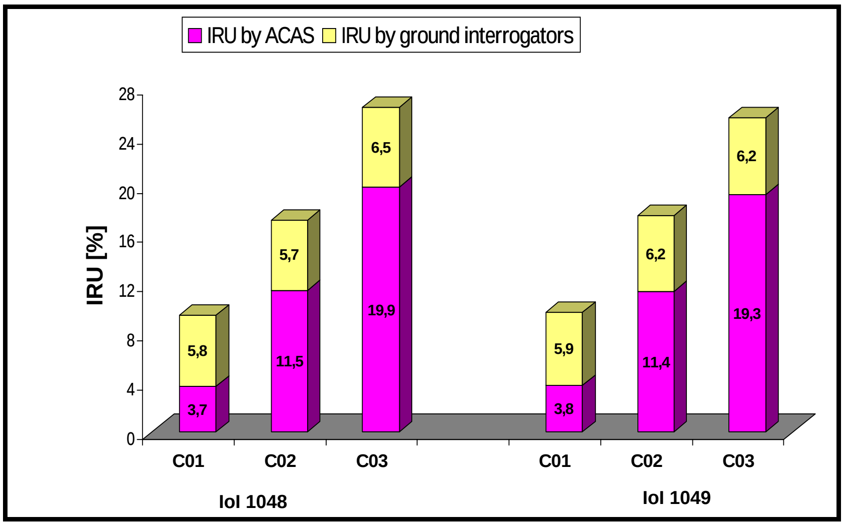


Figure 5-6: ACAS II IoIs - interrogator receiver utilisation

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.

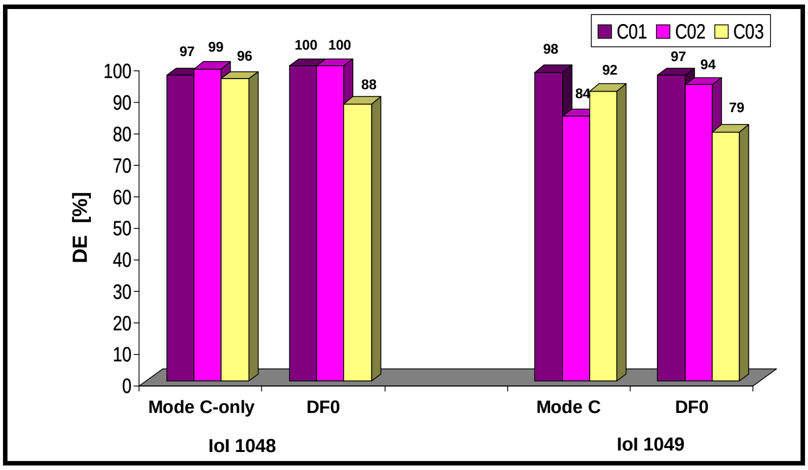


Figure 5-7: ACAS II IoIs - decode efficiency

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.

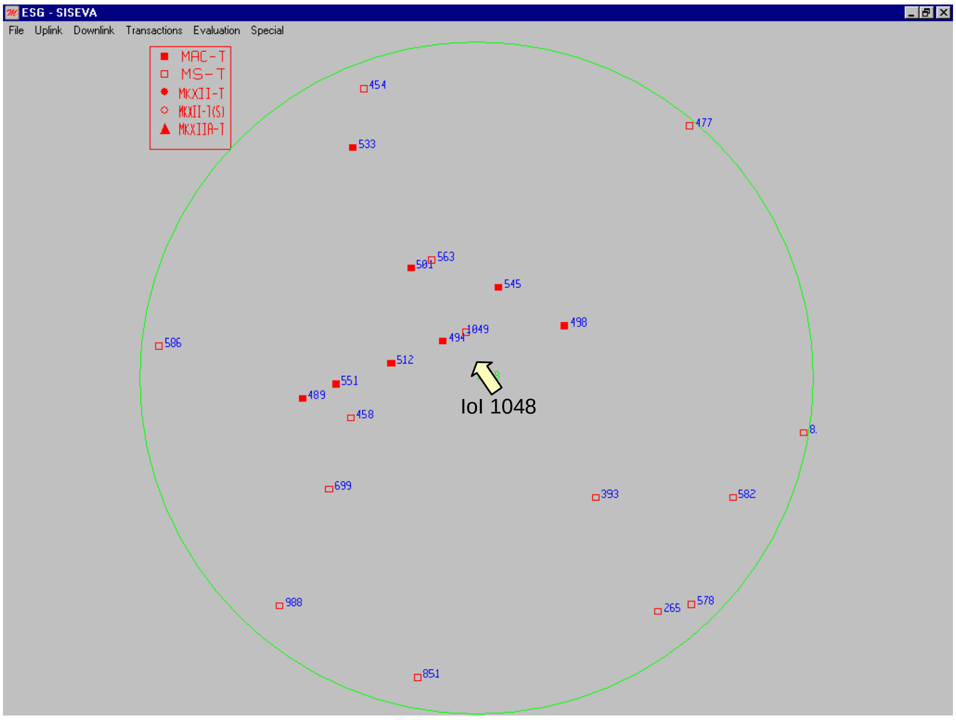


Figure 5-8: ACAS II IoI 1048 - target distribution

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.

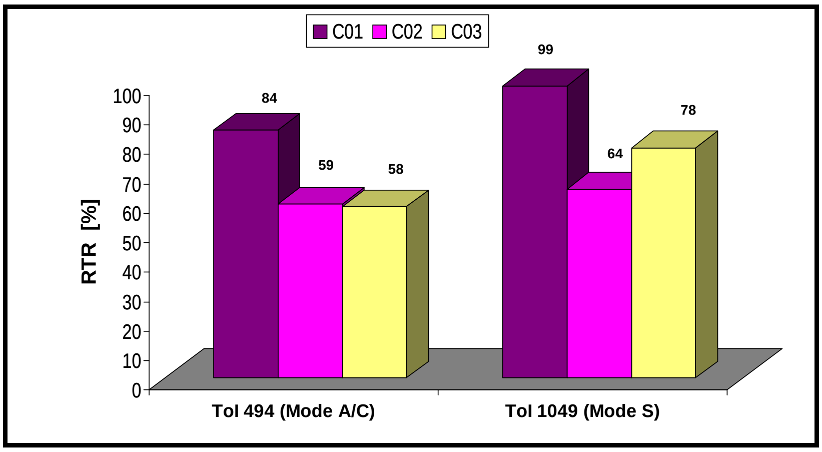


Figure 5-9: ACAS II IoI 1048 – round trip reliability

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.

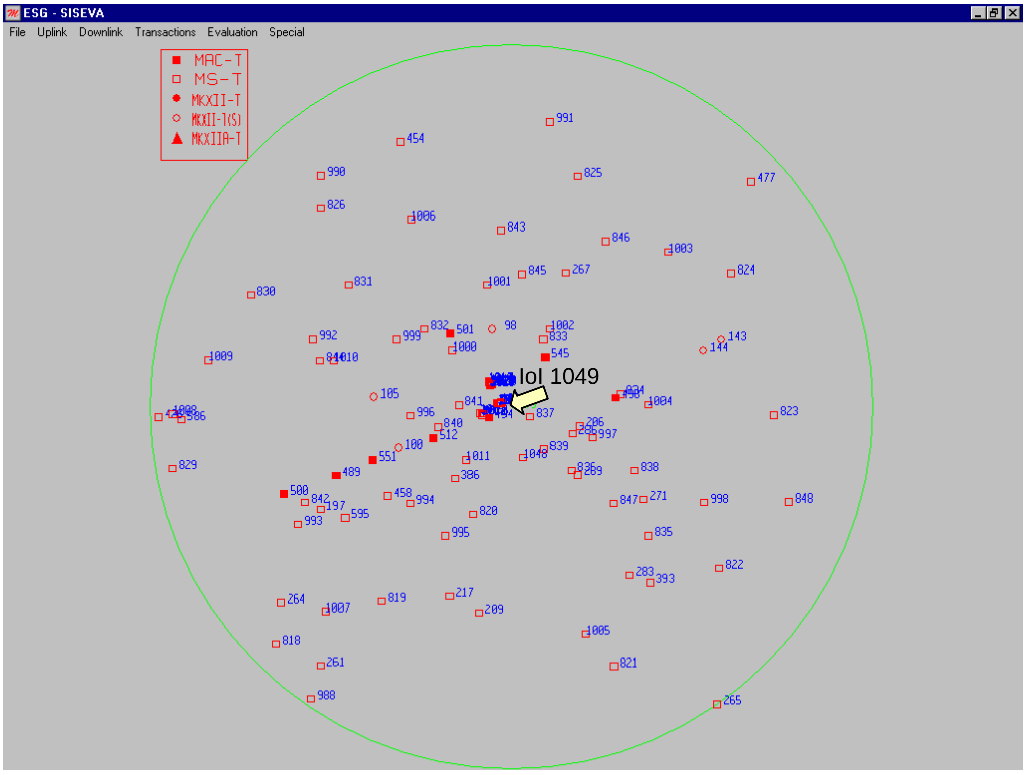


Figure 5-10: ACAS II IoI 1049 - target distribution

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.

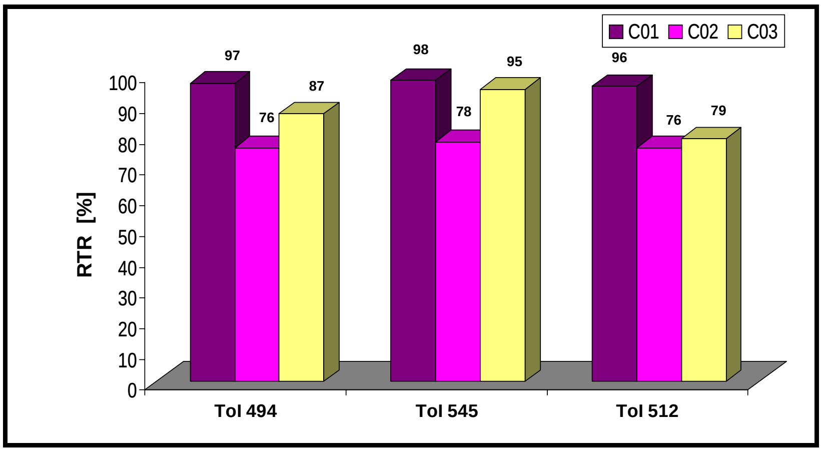


Figure 5-11: ACAS II IoI 1049 – round trip reliability for Mode A/C ToIs

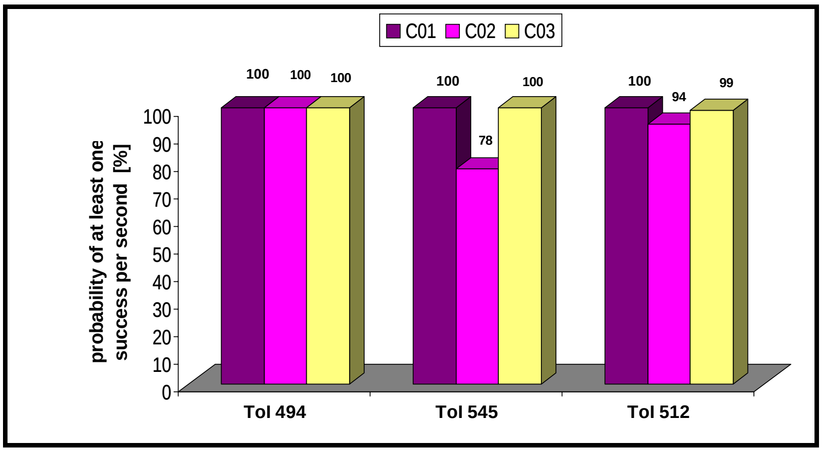


Figure 5-12: ACAS II IoI 1049 – probability for at least one success per second

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 TorIs 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.

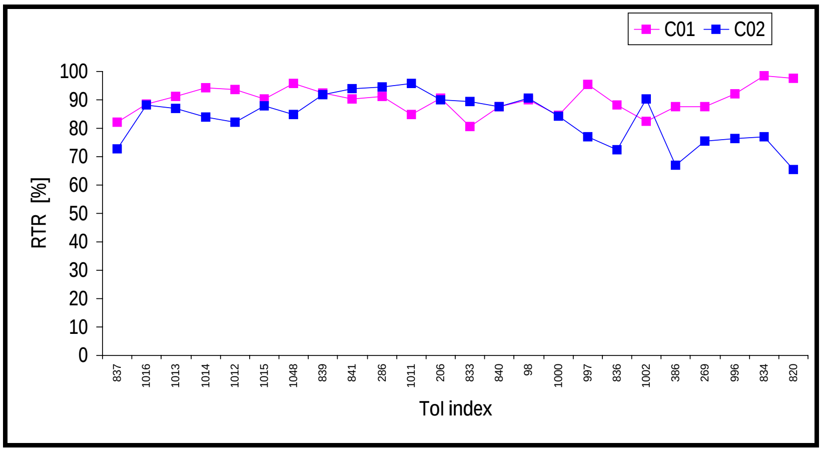


Figure 5-13: ACAS II IoI 1049 – round trip reliability for Mode S ToIs (scenario C01 and C02)

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.

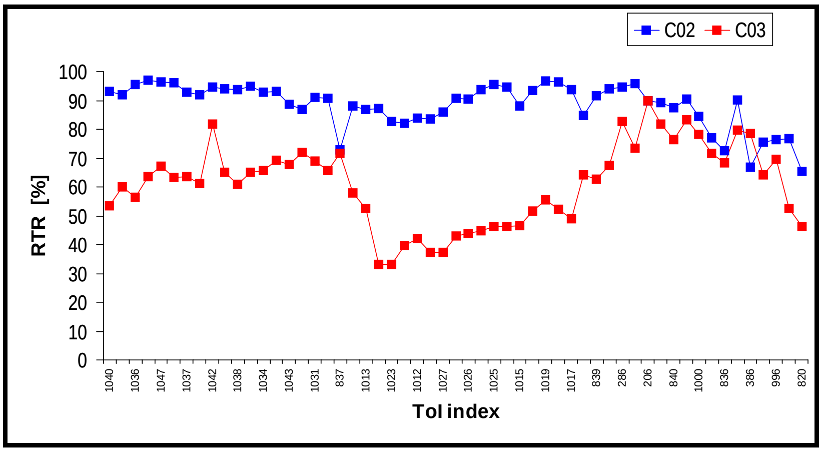


Figure 5-14: ACAS II IoI 1049 – round trip reliability for Mode S ToIs (scenario C02 and C03)

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 $\alpha$ 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.

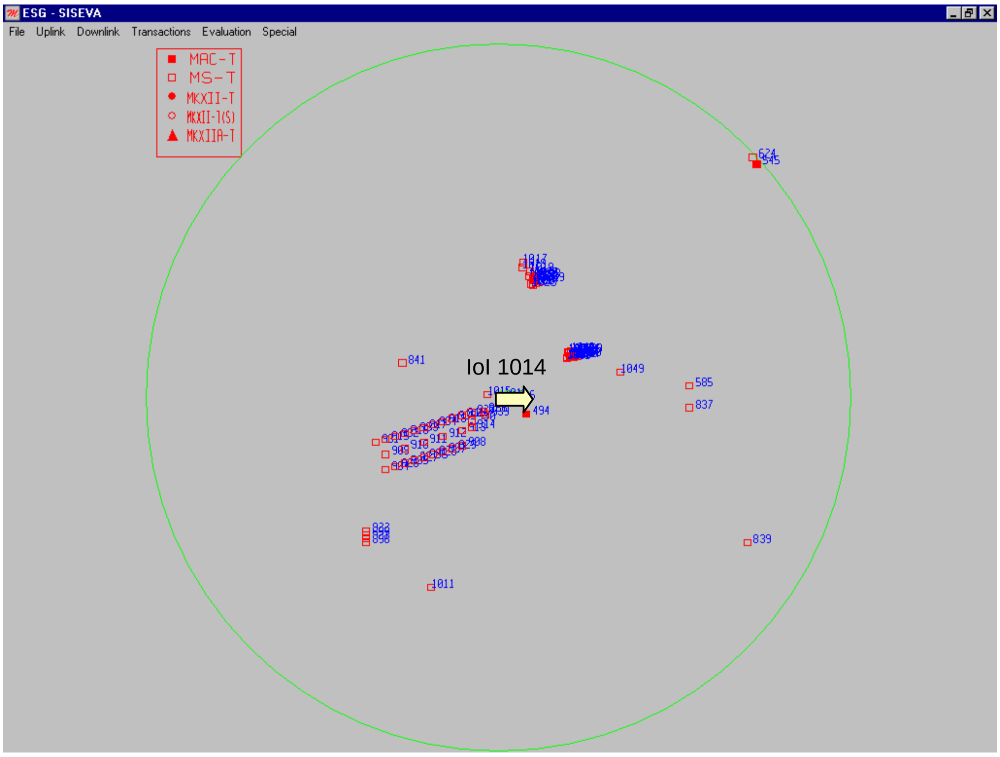


Figure 6-1: TCAS I IoI 1014 - target distribution

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.

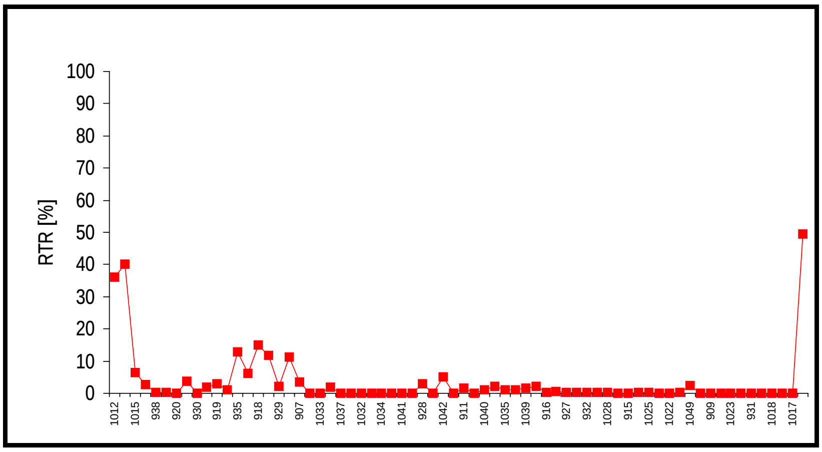


Figure 6-2: TCAS I IoI 1014 – round trip reliability

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.

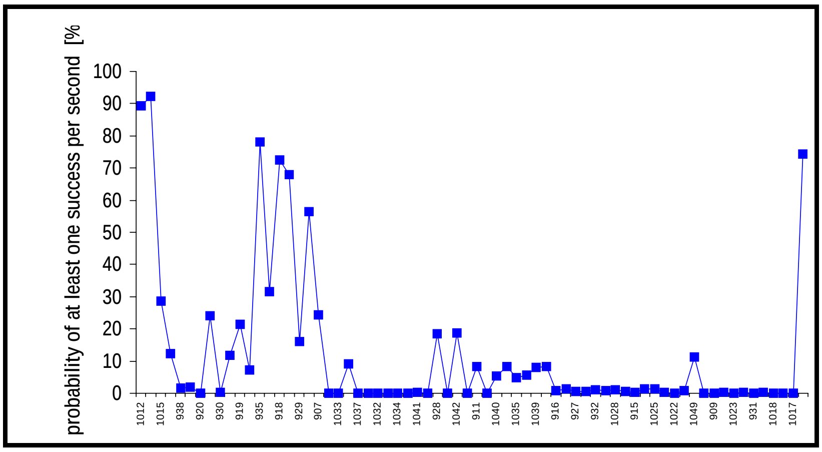


Figure 6-3: TCAS I IoI 1014 – code detection probability

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. Analysis Update Using a 2015 Traffic Scenario

The analysis documented in the previous chapters was updated as 2015 got a date which was used in several new RF reports [10]. In addition, industry marketed more and more equipment to support General Aviation pilots in their “see and avoid”-task. However, those companies did not take into account ICAO’s advice [6], but implemented either ACAS II interference limiting (“ACAS like”) or stayed with TCAS I interference limiting.

For the analysis update the same models, scenarios and the same environment were used as the previous simulations. Only the traffic density was adapted according to current forecasts. The scenarios used were again

- A05 – reference scenario without any ACAS/TCAS cluster,
- C02 – scenario with 36 clustered CAS equipped aircraft using ACAS II interference limiting algorithms (“ACAS like”),
- C03 - scenario with 36 clustered CAS equipped aircraft using TCAS I interference limiting.

More detailed results may be obtained from [7], [8] and [9].

## 7.1 Interrogation Rates

To quantify the uplink signal load at the ToIs within the coverage of the Frankfurt IoIs in the scenario 2015, the long term mean rates of the main beam (MBIR) and side lobe (SLIR) interrogations received by each ToI have been determined. The following Table 7-1 comprises minimum, mean, and maximum values of these rates. As in the previous chapters the statistical data are calculated upon the individual rates at all ToIs within the coverage of the IoI Frankfurt/South. The rates are quoted in interrogations per second and are listed for the various Modes and Mode S formats separately.

Concerning the variation of the interrogation rates it can be stated:

1. Mode A and C interrogation rates produced by civil MSSR/Mode A/C and military interrogators as well as the Mode A/C-only rates and the Mode S all-call rates induced by Mode S interrogators are in the same order as for the previous simulation runs performed. Slight variations are caused by the larger sample size of ToIs.
2. Mode S interrogation rates are slightly increased. Selective interrogations generated by Mode S stations for the higher transponder density are the reason for the higher rates.
3. Mode C-only rates induced by ACAS are increased as the density of ACAS II aircraft raises. Mode C-only rates are significantly reduced when the clustered “ACAS like” units are replaced by TCAS I interrogators. This change, of course, induces fairly high Mode C interrogation rates.

4. UF0 and UF16 rates are increased, if the number of “ACAS like” interrogators is raised. A tremendous increase of the UF0 rates has to be expected for clustered “ACAS like” interrogators. Each of these units is interrogating all other aircraft in the cluster once per second, which implicates the observed huge rate.
5. The UF0 rates are decreased when the “ACAS like” interrogators are replaced by TCAS I interrogators. However, the additional Mode S transponder equipped aircraft are selectively interrogated in Mode S and therefore, the UF0 rates are still higher than in the scenario without ACAS clusters.

| | | no ACAS/TCAS clusters | | ACAS II clusters | | TCAS I clusters | |
|---|---|---|---|---|---|---|---|
| | | MBIR | SLIR | MBIR | SLIR | MBIR | SLIR |
| | | **Mode A, C** | | | | | |
| **Mode A** | min | 7 | 0 | 6 | 0 | 6 | 0 |
| | mean | 48 | 263 | 47 | 282 | 47 | 283 |
| | max | 96 | 739 | 97 | 756 | 98 | 758 |
| **Mode C** | min | 3 | 0 | 3 | 0 | 3 | 0 |
| | mean | 28 | 53 | 27 | 58 | 27 | 58 |
| | max | 63 | 267 | 64 | 267 | 64 | 267 |
| | | **Mode S** | | | | | |
| **Mode A-only** | min | 1 | 0 | 1 | 0 | 1 | 0 |
| | mean | 5 | 10 | 5 | 14 | 5 | 14 |
| | max | 14 | 112 | 14 | 112 | 14 | 112 |
| **Mode C-only** | min | 1 | 0 | 1 | 0 | 1 | 0 |
| | mean | 5 | 10 | 5 | 14 | 5 | 14 |
| | max | 14 | 112 | 14 | 112 | 14 | 112 |
| **UF11** | min | 2 | 0 | 2 | 0 | 2 | 9 |
| | mean | 11 | 21 | 10 | 29 | 10 | 29 |
| | max | 28 | 224 | 28 | 224 | 28 | 224 |
| **UF4** | min | 1 | 0 | 1 | 0 | 1 | 0 |
| | mean | 9 | 14 | 9 | 24 | 9 | 23 |
| | max | 24 | 154 | 25 | 184 | 25 | 178 |
| **UF5** | min | 1 | 0 | 1 | 0 | 1 | 0 |
| | mean | 9 | 14 | 10 | 25 | 9 | 24 |
| | max | 26 | 158 | 27 | 194 | 27 | 186 |
| | | **ACAS** | | | | | |
| **Mode C-only** | min | 5 | 0 | 5 | 0 | 5 | 0 |
| | mean | 28 | 0 | 42 | 0 | 28 | 0 |
| | max | 74 | 0 | 216 | 0 | 49 | 0 |
| **UF0** | min | 1 | - | 1 | - | 1 | - |
| | mean | 34 | - | 136 | - | 57 | - |
| | max | 99 | - | 1503 | - | 386 | - |
| **UF16** | min | 1 | - | 1 | - | 1 | - |
| | mean | 5 | - | 7 | - | 5 | - |
| | max | 10 | - | 14 | - | 9 | - |
| **Mode C** | min | - | - | - | - | 0 | 0 |
| | mean | - | - | - | - | 13 | 26 |
| | max | - | - | - | - | 150 | 315 |

Table 7-1: Statistics of Interrogation Rates

## 7.2 Transponder Utilisation

Interrogations received by a transponder are processed and, if applicable, replied. During processing and reply transmission, a transponder is unavailable for the access by other sensors. The time periods of unavailability during simulation were recorded for each ToI separately. From these data the performance parameter overall transponder utilisation (OTU) is derived. The overall transponder utilisation denotes the percentage of time a transponder is occupied by processing the main beam and side lobe interrogations received.

Within the following Figure 7-1 to Figure 7-2 the overall transponder utilisation as well as the utilisation caused by ACAS/TCAS at the ToIs of the IoI Frankfurt/South is displayed versus the distance of the ToIs from this ground based IoI.

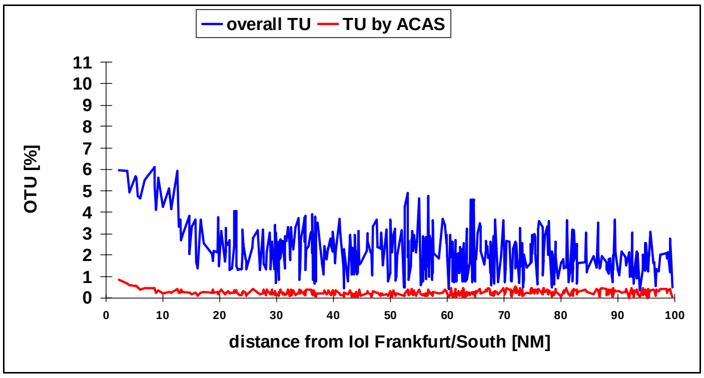


Figure 7-1: Transponder Utilisation without ACAS/TCAS clusters

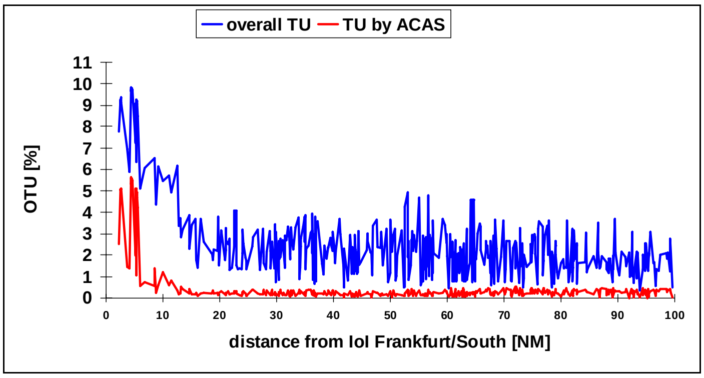


Figure 7-2: Transponder Utilisation in the presence of ACAS II clusters

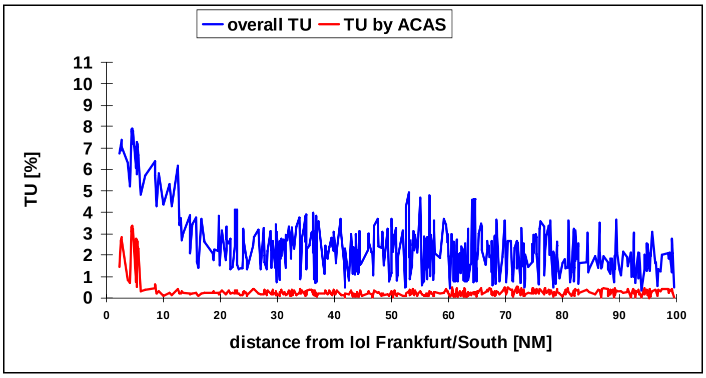


Figure 7-3: Transponder Utilisation in the presence of TCAS I clusters

The transponder utilisation caused by ACAS stays around 1% in the absence of any airborne cluster. In the presence of an “ACAS like” cluster the maximum peaks close to 6%. If the cluster is TCAS I equipped the maximum reaches still 3.4%. The previous studies showed that a number of 3 aircraft with ACAS II or TCAS I in close proximity to each other can already violate the 2% criterion. Although this is validated currently only for the vicinity of airports (where the aircraft density is higher) results from other studies indicate that the results may yield for any airspace.

With respect to the utilisation of transponders within the Frankfurt area in the three investigation cases, the following conclusions can be drawn:

1. In each case, the highest transponder utilisation is achieved in close proximity to the airport.
2. Without any ACAS/TCAS cluster, the ACAS contribution to the overall transponder utilisation in the vicinity of Frankfurt airport is with about 1% maximum well below 2%.
3. If clustered ACAS II units are added, the maximum transponder utilisation caused by ACAS is raised to nearly 6%. Moreover, the 2% criterion is not satisfied by almost all transponders within a range of 6 NM to the airport.
4. Substituting the 36 ACAS II units with TCAS I interrogators reduces (compared to scenario C02) the maximum ACAS transponder utilisation to 3.4%. However, there are still a remarkable number of transponders within 6 NM to the airport suffering an utilisation of more than 2%.

### 7.3 Fruit Rates

The various types of interfering replies at an IoI are pictured within Figure 4-1. Concerning these interfering replies, the simulation runs provided the long term fruit rates (FR) at the selected IoIs. Table 7-2 quantifies the fruit rates received by the IoIs for the three investigation cases. The fruit rates, quoted in replies per second, are listed for the various Modes and Mode S formats separately. The fruit rates are based on a receiver sensitivity of –89 dBm.

| | no ACAS/TCAS clusters | ACAS II clusters | TCAS I clusters |
|---|---|---|---|
| **Mode A** | 10274 | 11614 | 11814 |
| **Mode C** | 5233 | 5533 | 23910 |
| **Mode A-only** | 0 | 0 | 0 |
| **Mode C-only** | 0 | 0 | 0 |
| **DF0** | 233 | 1603 | 495 |
| **DF4** | 104 | 109 | 109 |
| **DF11** | 744 | 782 | 785 |
| **DF17** | 858 | 1009 | 1009 |
| **DF21** | 105 | 110 | 110 |

Table 7-2: Fruit Rates

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

1. Although the Mode A interrogation rates are the same in all scenarios analysed, the Mode A fruit rates are increased when the density of aircraft rises. This increase is induced by replies of the additional transponders.
2. Mode S fruit caused by ground interrogators is slightly increased in an environment with a higher Mode S equipped aircraft density.
3. Due to the transmission of squitters, DF11 and DF17 fruit is increased as the number of Mode S transponders is raised.
4. A tremendous increase of the DF0 rates has to be expected, if the clustered aircraft are equipped with an ACAS II interrogator.
5. If TCAS I equipage is assumed for the clustered aircraft, UF0 fruit is considerably reduced again against scenario C02. However, the presence of clustered TCAS I aircraft results in a very huge Mode C fruit rate.

### 7.4 Interrogator Receiver Utilisation

From the fruit rates, discussed in the previous section, 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 of the signal length of Mode A/C and Mode S replies. The IRU denotes the percentage of time reply signals are present at the receiver of an interrogator. Within Figure 7-4 the interrogator receiver utilisation for the IoIs Frankfurt/South and Frankfurt/North is plotted.

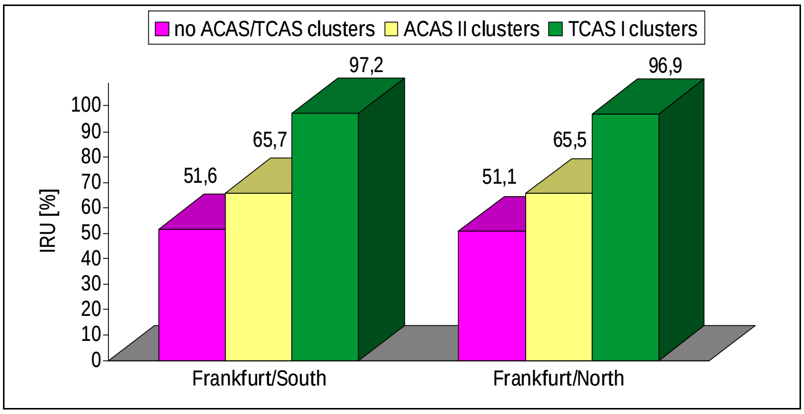


Figure 7-4: Interrogator Receiver Utilisation

Concerning interrogator receiver utilisation, the figure above yields:

1. The clustered 36 ACAS II units increases interrogator receiver utilisation by 14%.
2. The Interrogator receiver utilisation is nearly doubled, if clustered TCAS I interrogators are inserted in the scenario.

## 7.5 Decode Efficiency

Asynchronous fruit, which is reflected in the interrogator receiver utilisation, is an interference mechanism, which affects the reception and decoding of replies. A performance parameter taking into account this interference effect is the 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 explored, the IoI Frankfurt/North was interrogating Mode A and Mode C, while the IoI Frankfurt/South was modelled as Mode S station 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 7-5 the values for decode efficiency obtained by simulation are provided for the two IoIs.

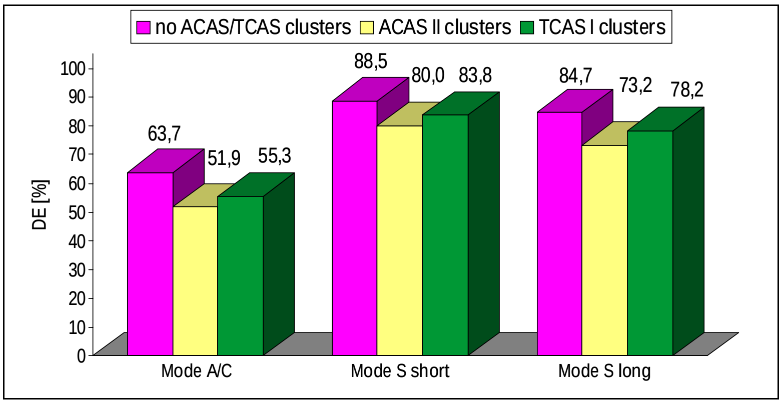


Figure 7-5: Decode Efficiency

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

1. The clustered ACAS II interrogators reduce the decode efficiency for Mode A/C replies by 12%, for Mode S replies by about 10%.
2. Replacing the ACAS II interrogators of the clustered aircraft with TCAS I units improves Mode A/C decoding by 4%, decode efficiency for Mode S replies is increased by 4-5%. Nevertheless, decode efficiency is reduced compared to the reference scenario by 5 to 6%.

### 7.6 Code A/C and Mode S Detection

The parameters used 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. Table 7-3 lists the minimum, mean, and maximum values derived for Code A/C and Mode S detection for the three investigation cases. The mean values are additionally plotted in Figure 7-6.

| | | **no ACAS cluster** | **ACAS II cluster** | **TCAS I cluster** |
|---|---|---|---|---|
| **PCA** | min | 0.0 | 0.0 | 0,0 |
| | mean | 76.5 | 63.3 | 67,5 |
| | max | 100 | 97.0 | 99,0 |
| **PCC** | min | 0.0 | 0.0 | 0,0 |
| | mean | 76.3 | 63.2 | 67,2 |
| | max | 100 | 96.0 | 99,0 |
| **PS(UF4/DF4)** | min | 90.0 | 88.0 | 88,0 |
| | mean | 99.5 | 98.5 | 99,1 |
| | max | 100 | 100 | 100 |
| **PS(UF5/DF21)** | min | 83.0 | 80.0 | 85,0 |
| | mean | 99.2 | 96.6 | 98,1 |
| | max | 100 | 100 | 100 |

Table 7-3: Statistics of Code A/C and Mode S Detection

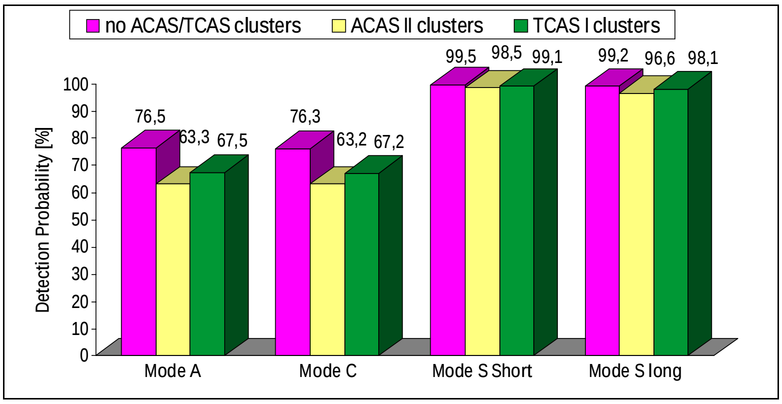


Figure 7-6: Code A/C and Mode S Detection

Based on the simulation results above, the following conclusions can be drawn regarding Code A/C and Mode S detection:

1. Mean Code A/C detection is reduced by 13% in the presence of clustered ACAS II units. The reduction accounts for 9% in case of clustered TCAS I interrogators.
2. Mean Mode S detection is reduced by 1-2% in case of clustered ACAS II interrogators. It is decreased even less in case of clustered TCAS I units.

### 7.7 Summary and Conclusions

In general, results from a previous analysis are confirmed.

1. The highest transponder utilisation is achieved in close proximity to the airport.
2. Previous studies showed that a number of 3 aircraft with ACAS II or TCAS I in close proximity to each other can violate the 2% criterion.
3. In the scenario 2015 the mean UF0 interrogation rate induced by ACAS at transponders controlled by the SSR sites Frankfurt/North and Frankfurt/South is increased by a factor of four, if 36 ACAS II equipped aircraft are deployed in clusters close to Frankfurt airport.
4. If these aircraft are TCAS I equipped, extra Mode C interrogation rates are induced which are even higher than the Mode C rates generated by all ground stations.
5. If clustered ACAS II units are added, the maximum transponder utilisation caused by ACAS is raised to nearly 6% and the 2% criterion is not satisfied by almost all transponders within a range of 6 NM to the airport.
6. If the clustered aircraft are TCAS I equipped, the ACAS/TCAS generated peak transponder utilisation is raised to 3.4% and most of the transponders within 6 NM to the airport are suffering an utilisation caused by ACAS/TCAS of more than 2%.
7. DF0 fruit is increased as the ACAS II density raises. A tremendous increase by a factor of seven is predicted in the presence of clustered ACAS II units.

8. If TCAS I equipage is assumed for the clustered aircraft, the extra induced Mode C fruit is four times higher than the Mode C fruit initiated by ground stations.
9. Adding clustered ACAS II units increases interrogator receiver utilisation by 15%.
10. Interrogator receiver utilisation is nearly doubled in case of clustered TCAS I.
11. Mean Code A/C detection is reduced by 13%, when clustered ACAS II units are added. The reduction accounts for 9%, in case of clustered TCAS I.

In general, results from a previous analysis are confirmed, but the e.g. Mode C fruit rates are three times higher in a TCAS I cluster scenario because of a higher traffic density estimated for a 2015 scenario.

The majority of replies to TCAS I interrogations are garbled. Therefore, a decode efficiency of less than 4.7 % can be expected. In addition, the probability of correctly decoding at least one valid reply during a one second surveillance interval was for TCAS I above 50% only for 10% of the ToIs. The probability was equal to zero for 31% of the ToIs. These results may be interpreted as best case performance for TCAS I in a high density environment in the near future.

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# 9. Annexes

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# 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 |
| $\mu$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 |