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Work Package 7

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Abstract

The objective of this study was to provide the ability to instigate automatic monitoring for all types of Mode S information that relate to ACAS

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List of Acronyms

ACAS	Airborne Collision Avoidance System
ACASA	Airborne Collision Avoidance Systems Analysis
ASMT	Automatic Safety Monitoring Tool
ASTERIX	All-purpose STructured Eurocontrol Radar Information eXchange (a radar data format)
ATC	Air Traffic Control
CENA	Centre d'Etudes de la Navigation Aérienne
CPA	Closest Point of Approach
EEC	EUROCONTROL Experimental Centre
FL	Flight Level
HMD	Horizontal Miss Distance
HRA	Horizontal Resolution Advisory
ICAO	International Civil Aviation Organisation
MADREC	MADAP Records (a radar data format)
MUAC	Maastricht Upper Airspace Centre
MOPS	Minimum Operational Performance Standard
NM	Nautical Miles
NMAC	Near Mid Air Collision
OSCAR	Off-line Simulator for Collision Advisory Resolution
POEMS	Pre-Operational Experimental Mode S system.
RA	Resolution Advisory
RDPS	Radar Data Processing System
SARPS	Standard and Recommended Practices
SICASP	SSR Improvements and Collision Avoidance Systems Panel
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TEN	Trans European Networks
UK NATS	UK National Air Traffic Services
VMD	Vertical Miss Distance
WINTSAR	WINdows Tool for Selective ASTERIX Recording

1 Introduction

1.1 Background and context

1.1.1 The Airborne Collision Avoidance System (ACAS) has been defined by the International Civil Aviation Organisation (ICAO). It uses Mode S signals to perform surveillance, to co-ordinate resolution advisories (RAs) between aircraft, and also to report RAs to the ground.

1.1.2 The correct functioning of the Mode S is essential to ACAS operations. This needs to be monitored. In addition, monitoring of resolution advisories allows assessment of whether ACAS continues to provide its expected safety benefits.

1.2 ACASA project

1.2.1 The TEN ('Trans European Network') / ACASA ('Airborne Collision Avoidance Systems Analysis') project investigates several areas related to ACAS II operations in Europe [WP001].

1.2.2 The ACASA/WP7 ('Work Package') developed equipment for monitoring ACAS related Mode S signals, and analysed results from such equipment.

1.2.3 The ACASA partners involved in this study were:

CENA ('Centre d'Etudes de la Navigation Aérienne') and Sofreavia: responsible for investigating RA data collected by Mode S.

DFS: responsible for developing the requirements and specification of a radio field monitor for ACAS and SSR.

EEC (EUROCONTROL Experimental Centre): responsible for developing operational equipment to automatically record RA and environmental data when an RA is detected by Mode S.

QinetiQ: responsible for recording and analysing Mode S parameters that have an impact on ACAS.

UK National Air Traffic services (UK NATS) gave permission to use their Mode S data.

1.3 Objective

1.3.1 The objective of this study was to provide the ability to instigate automatic monitoring for all types of Mode S information that relate to ACAS

1.4 Work Breakdown

1.4.1 Originally 5 tasks were foreseen:

WP7.1: Automate Mode S RA operational reporting

WP7.2: RA monitoring with POEMS (Pre operational Experimental Mode S System)

WP7.3: Perform monitoring of ACAS related radar replies

WP7.4: Performance monitoring of ACAS related 1030 and 1090 signals

WP7.5: Analysis of RAs and other data

WP7.6: Co-ordination between tasks and synthesis

1.4.2 During the course of the ACASA project, the first two tasks were merged.

1.5 Structure of the document

1.5.1 Three studies and one software development planned for WP7 of the ACASA project have been completed. This final report summarises the main results and briefly describes the software.

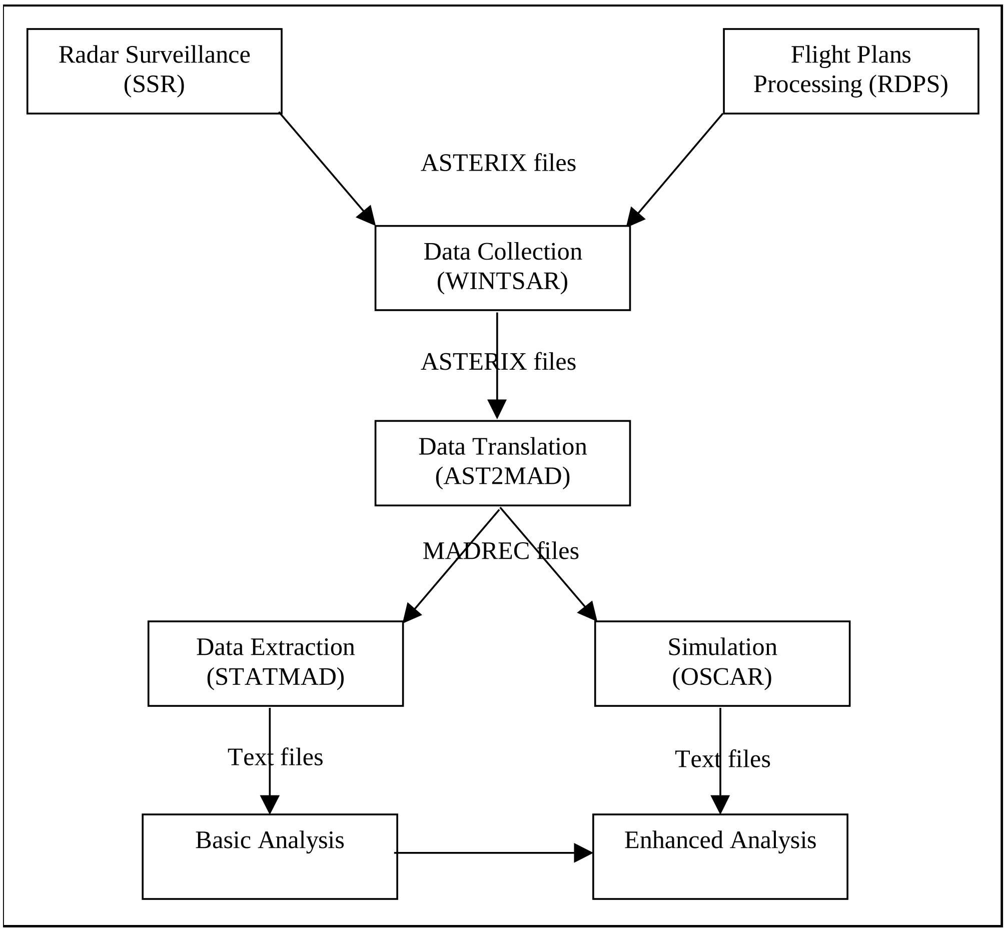
1.5.2 The analysis of RA recordings is reported in section 2. The third section presents the software to perform automatic recording of RAs. Section 4 contains the results of monitoring some (non RA) Mode S parameters that are relevant to ACAS. Section 5 discusses the requirements for a radio field monitor for ACAS and SSR. This report ends with some concluding remarks about the studies and includes some recommendations.

2 Mode S ACAS Events Analysis.

This section summarises the CENA/Sofreavia analysis of the RAs detected by Mode S between November 1996 and October 1997 [WP060D].

2.1 Data Collection Method

2.1.1 The following figure summarises the operations and tools used to collect and analyse the ACAS events provided by a Mode S station.



2.1.2 Mode S, SSR and flight plan data were captured from one minute before to one minute after an RA by WINTSAR (WINdows Tool for Selective ASTERIX Recording) - a tool for recording radar data transmissions in order to assist the experimentation and pre-operational installation of Mode S.

2.1.3 The captured data was in the ASTERIX (All-purpose STructured Eurocontrol Radar Information eXchange) format. However, the analysis tools all worked with MADREC (MADAP RECording) format. A small tool was built to convert the data between the two formats (AST2MAD).

2.1.4 Each MADREC radar file was processed by a local software tool called *statmad*. The data was extracted and entered into an Access database. In addition, the tool computed some basic statistics about the traffic found in the radar file.

2.1.5 The raw data transferred into the database provided the material for a basic analysis of the ACAS events. For a deeper analysis, the necessary data was researched by replaying each ACAS event with the OSCAR (Off-line Simulator for Collision Advisory Resolution) test-bench.

2.1.6 OSCAR was used to detect the potential threats surrounding the TCAS aircraft. It was possible to check if the threat could have triggered the event and to try to reproduce what was the course of the events when the resolution advisory was issued.

2.1.7 After all these analyses, final statistics and reporting were made.

2.2 Summary of Results

2.2.1 1109 ACAS automatic reports were collected from 343 events. Amongst these a significant number of wrong messages were either transmitted by aircraft or "created" by the pre-operational chain of acquisition of Mode S data[1]. Despite these problems 303 events were analysed.

2.2.2 The analysis confirmed that events are concentrated in high-density areas.

2.2.3 In 210 encounters the potential threat was identified and a deeper analysis performed[2]. 1000ft level-offs were two thirds of them. Only two thirds of pilots followed their RAs, and the deviations entailed were acceptable on average (428 ft), although many of them (40%) may still be a source of concern for controllers.

2.2.4 Automatic reports do not provide information about the context of each event. It would have been useful to assess the proportion of visual acquisition and the necessity of each event. This information can be found in pilot and controller reports; unfortunately too few are correlated to a Mode S event.

2.2.5 Results from pilot and controller reports are considerably different from automatic reports, mainly because humans report events that they consider important from their perspective. Nevertheless they provide an essential source of information when analysing puzzling or worrying events. They also highlight how people perceive TCAS and those situations having the greatest impact on their work. Human and automatic reports are complementary tools for ACAS studies.

[1] Subsequently work has been undertaken to improve the Mode S chain of acquisition.

[2] Mode S information from TCAS v6.04a does not allow the direct identification of the intruder. This is not the case with v7.0 format.

3 Automatic Safety Monitoring Tool – Mode S extention.

This section summarises the software developed by the EEC to record RAs and some Mode S equipment problems related to ACAS [WP174D].

3.1 Context

3.1.1 The aim of this work was to provide a tool that would let states easily monitor ACAS RAs using Mode S.

3.1.2 The experience of the ACAS Mode S events analysis was used to develop a set of requirements for such a tool. Various existing tools were examined for their suitability to be adapted for this work. The Automatic Safety Monitoring Tool (ASMT) was chosen because it already provided much of the desired operational functionality.

3.1.3 The ASMT already provided the following capabilities for the Maastricht Upper Airspace Centre (MUAC):

Automatic recording of proximity occurrences

24hr per day on-line operation

generate alerts to supervisors and occurrence investigators

perform local occurrence storage to allow further safety analysis

3.1.4 It was developed to the requirements of operational ATC staff. Furthermore, it was already being adapted for other operational centres and other safety occurrences (such as altitude bust and runway incursions) as well as separation monitoring.

3.2 New functionalities

3.2.1 Several new functions were added to process ACAS related Mode S data:

3.2.2 Interfaces were developed to standard ASTERIX Mode S track data. ASMT extracts RA information, and creates new RAs based on the Mode S information about aircraft involved.

3.2.3 All flight plans and surveillance data is collected for aircraft involved in the RA, or in the proximity, from a few minutes before the RA until a few minutes afterwards. The data integrity of all data used for detection is also examined.

3.2.4 The ASMT classifies each detected RA according to the aircraft involved, the geometry of the occurrence, the severity and the airspace involved. Using this classification, the ASMT examines each new RA with a set of criteria to determine if it represents a case of interest to the user.

3.2.5 The ASMT provides alerts for users and an interface to examine cases in detail. An interface to provide statistics from a series of alerts is being planned.

3.2.6 In addition to these RA capabilities, the ASMT also checks the surveillance data for several Mode S reporting errors from aircraft:

Mode S addresses inconsistencies

Mode S format errors

Erroneous reporting of altitude in 25ft format

Gilham code errors (which led to the British Airways and Korean Airlines incident).

3.3 Testing and operation

3.3.1 24 hours of radar recordings were used to check the functioning of the ASMT. In September 2001 it was put into Gatwick for further technical testing. Based on the results from this trial, the interface will be revised.

3.3.2 The ACAS functionality has been requested by Maastricht when they get their Mode S feed in 2002.

3.3.3 For other sites, ASMT RA monitoring can be made available with or without separation monitoring.

4 Detecting Anomalies in Mode S Parameters.

This section summarises the QinetiQ report on detecting anomalies in Mode S parameters that relate to ACAS operation [WP143D].

4.1 Objectives

4.1.1 The objectives of this work were:

To collect representative samples of aircraft data

To decode aircraft parameters that relate to ACAS operation

To detect anomalies in the decoded data that may have an impact on ACAS operation, and to estimate their frequency.

4.2 Method and Results

4.2.1 14 days recordings of Mode S data were made during year 2000 using the UK NATS experimental Mode S ground station. 3243 different aircraft were observed.

4.2.2 The recordings were analysed for the following anomalies:

Illegal aircraft addresses

Duplicate aircraft addresses

Flight status

ACAS and Data Link Capability Reporting

Altitude Reporting

Incorrect Broadcast Protocol

4.2.3 Only two instances of 'illegal' addresses, which may disrupt Mode S operation, were identified. This represents less than 0.1% of the observed population. Another 0.3% of the addresses were observed to be suspect – not belonging to a recognised national block allocation.

4.2.4 Other than the 'illegal' addressing noted above, the analysis has provided no evidence of the presence of duplicate aircraft addresses in the aircraft population. However, a more rigorous monitoring capability would be required in order to obtain more definite results.

4.2.5 Occurrences have been identified of aircraft reporting a flight status 'on the ground' when airborne. ACAS will not generate RAs against these aircraft even when they are on a collision course.

4.2.6 Although a number of anomalies were observed in the 'data link capability report', none of them related directly to ACAS.

4.2.7 Approximately 93% of Mode S equipped aircraft claim altitude reporting to 25ft resolution. A small proportion of these may only actually report altitude in 100ft steps. This has serious consequences for the ACAS vertical tracking process that has led to false TAs and false RAs.

4.3 Next Steps

4.3.1 A number of anomalies have been identified in this report which required follow up with avionics manufacturers, airlines and ATC authorities.

4.3.2 A sufficient number of anomalies have been identified in aircraft installation to indicate that an ongoing programme of monitoring may be desirable. This would suggest the development of a more automated system than is currently employed[3].

[3] As a result of this observation, a number of additional tests were incorporated into the ASMT monitoring requirements. Nevertheless, several of the parameters will require automatic monitoring support from other tools.

5 Parallel recording of ACAS related 1030 and 1090 MHz signals.

This section summarises the DFS report on the design of a radio field monitor for ACAS and SSR [WP150D].

5.1 Objectives

5.1.1 The aim of this work was to design portable monitoring equipment that could:

Measure radio field loads on both interrogator and response channels for Mode S.

Measure equipage of ACAS II and Mode S

Assess compliance of individual ACAS II and Mode S units on both interrogator and response channels.

5.1.2 The first of these features will check whether or not the radio frequency (RF) environment is kept within ICAO suggested limits.

5.1.3 The third feature will allow new types of compliance monitoring of transponders and ACAS units. E.g. of the whisper shout sequence.

5.1.4 The design was to consider a range of different methods for measuring and recording the data, as well as the evaluations that could and should be performed with the equipment. Costs were to be considered in any tradeoffs that had to be made.

5.2 Outcome

5.2.1 The chosen solution met all the objectives and allowed scope for further development.

5.2.2 DFS will be developing equipment according to this design, which should become operational towards the end of 2003.

6 Conclusions

6.1 Mode S monitoring study

6.1.1 Automatic monitoring allows the unbiased recording of the location, timing and nature of ACAS RAs. Importantly it allows experts to assess the rate of pilot response and the extent of disruption to ATC.

6.1.2 However, automatic monitoring does not provide information about the context of each event. Therefore it should be seen as complementary to a human reporting system.

6.2 Mode S Monitoring Equipment

6.2.1 The Automatic Safety Monitoring Tool (ASMT) has been further developed as an operational tool to monitor Mode S for RAs.

6.2.2 In addition it can detect several Mode S reporting errors from aircraft. The system is undergoing technical trials with UK NATS and will become operational in Maastricht.

6.3 Study of other Mode S parameters

6.3.1 A number of anomalies have been identified which required follow up with avionics manufacturers, airlines and ATC authorities.

6.3.2 The number of anomalies is sufficient to indicate that an ongoing programme of monitoring would be desirable

6.4 Operational Field Monitor Design

6.4.1 A design has been prepared for equipment that can check whether or not the radio frequency (RF) environment is kept within ICAO suggested limits, and also monitor the compliance of communications between different Mode S devices (e.g. two ACAS units).

6.4.2 DFS will be developing equipment according to this design.

7 Recommendations

7.1.1 States with access to Mode S data should consider automatically monitoring ACAS RAs in their airspace.

7.1.2 States should monitor their Mode S data for anomalies.

8 References

8.1 ACASA references

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[WP060D] ACASA/WP7.5/060D – 'Final Results for the Mode S ACAS Events Analysis' CENA, Version 2.0, 15 October 1999.

[WP143D] ACASA/WP7.3/143D – 'Mode S Monitoring for ACASA – Final Report' QinetiQ, Version 1.0, 21 November 2000.

[WP150D] ACASA/WP7.3/150D – 'Parallel monitoring of ACAS related 1030 and 1090 signals' DFS, Version 1.2f, 23 July 2001.

[WP174D] ACASA/WP7.1/174D – 'Automatic Safety Monitoring Tool WP7 ASMT Mode S Monitoring Final Report' EEC, Version 1.0, 1 August 2001.

9 Annexes

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Annex B: Mode S Monitoring for ACASA
Annex C: Parallel monitoring of ACAS Related 1030 and 1090 signals
Annex D: Automatic Safety Monitoring Tool -WP7 ASMT Mode S Monitoring

ACAS PROGRAMME

ACASA PROJECT

Annex A to

Work Package 7

Final results for the
Mode S ACAS Events Analysis

Edition 1.0
March 2002

Annex A to Work Package 7

Final Results for the Mode S ACAS Events Analysis

Version 1.1, March 2002

WP-7.5

Final Results for the Mode S ACAS Events Analysis

Prepared byChristian Aveneau & Dominique Martinon

Summary

This report describes the results of an analysis of the ACAS events recording during one year from November 1996 to October 1997, from the mode S radar station of Orly.

A description of the contents of recorded information and of the ways used to collect them precedes the presentation of the results.

The contents of the recorded information allow a basic analysis concerning the conditions when the events take place and the sequence of advisories occurring on-board.

Then, a deeper analysis was performed by replaying the events where a potential threat existed and looking at each simulation to deduct indicators about the conflict configuration, the reaction to the TCAS advisories and the impact on ATC.

Finally, with an analysis of a continuous record during one week, this report evaluates more precisely the current amount of aircraft equipped with TCAS, and the number of events that they produce in a unit of volume equal to the mode S radar coverage of Orly.

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1. Introduction

TCAS II is currently the only implementation of the standards for an Airborne Collision Avoidance System (ACAS) providing vertical resolution advisories to pilots (indicated by the type number II). Its use as well as the regulations encouraging the carriage of an ACAS II keep on spreading.

On 19 June 1997, the Air Navigation Commission (ANC) presented an amendment to the Annex 6 published by the International Civil Aviation Organisation, who aimed at making compulsory the carriage of an ACAS II by its member states.

Since the first American mandate, the number of equipped aircraft kept increasing. France, as well as other European countries, became rapidly interested in acquiring the capacity for a mode S ground station to download the resolution advisories issued onboard the TCAS-equipped aircraft.

This report is the conclusion of a whole year of data collection, made by the Orly mode S station.

For a better understanding of the following chapters, some terms must be clarified:

Report: a resolution advisory piece of information automatically retrieved by a mode S ground station.

Event: a sequence of resolution advisory issued on a TCAS aircraft, triggered by one or more threat aircraft, and closed by a ‘Clear of Conflict’ advisory.

Encounter: a conflict situation involving two or more aircraft in which one aircraft at least is subject to an event and the other one(s) is(are) the threat(s).

2. ACAS information collection and analysis

2.1 TCAS air-ground information exchange

A TCAS-equipped aircraft carries inevitably a Mode S transponder enabling it to communicate with ground stations and other aircraft. TCAS information available on ground via the Mode S transponder belong to two types:

status of the airborne ACAS system (existence and configuration) ;

resolution advisories issued on board.

When replying to surveillance interrogations, the Mode S transponder indicates ACAS capabilities on board. Three cases can occur:

No on-board ACAS;

ACAS with resolution capability inhibited; and

ACAS with vertical-only resolution capability.

As soon as TCAS II issues a resolution advisory, it transmits the related data to the Mode S transponder. When a ground station interrogates the latter, its reply will indicate that a resolution advisory is available. The ground station can then request the content of the resolution advisory (the report), which is made up of different data according to the TCAS II version.

Version 6.04a is the current airborne TCAS II version. It is not fully compliant with ACAS standards enacted by ICAO. By the year 2000, version 7.0 will be available on the market and will be mandatory on all aircraft liable to be TCAS equipped and will be compliant with ACAS standards.

The main difference between both versions is that version 7.0 provides data on the threat triggering an advisory. As this feature does not exist in version 6.04a, the threat must be identified with another source of data.

2.2 Means of collection

2.2.1 Sources of data

2.2.1.1 Mode S ground stations

To collect the resolution advisory reports, which are issued on board TCAS, equipped aircraft, two mode S experimental radars existed in France at the time of the study. They were located at Orly and Rouen. They could be used for numerous Mode S and/or data-link experiments, and could not be wholly dedicated to ACAS data collection. Furthermore, they were not always active (maintenance, upgrades, failures…).

The ground stations can provide tracks for Mode S equipped aircraft as well as receive and store resolution advisory reports.

2.2.1.2 Monopulse Secondary Surveillance Radars (SSR)

A Mode S radar detects only aircraft equipped with Mode S transponders. As the majority of TCAS encounters include a non-Mode S aircraft, recording one or several SSRs (Boulogne, Palaiseau, Avranches…) allows the reconstruction of the whole air traffic picture on the coverage of the involved Mode S radar.

The SSRs can provide tracks for Mode A/C equipped aircraft.

2.2.1.3 French Radar Data Processing Systems (RDPS)

The French Radar Data Processing Systems distribute their data to servers (called IMAGE servers) allowing to see the traffic in real time over the whole territory. These information include flight plan data. The tracks are refreshed every 200 seconds.

The RDPSs can provide flight plan data for all aircraft.

2.2.2 Collection tool: WINTSAR

2.2.2.1 History

As early as 1994, STNA (Service Technique de la Navigation Aérienne = Technical Department of Air Navigation) had studied and presented a system enabling the collecting of ACAS resolution advisories transmitted by aircraft within the coverage of the Orly experimental Mode S experimental ground station. Despite its lack of reliability, it enabled CENA to analyse some collected events [1].

In 1996, STNA developed a tool for recording radar data transmissions in order to ease the experimentation and pre-operational installation of Mode S. This tool was named WINTSAR (WINdows Tool for Selective ASTERIX Recording) and is now CENA’s provider of collected ACAS events.

2.2.2.2 Purpose

This system allows the recording of data (tracks, resolution advisories, active military areas…) into ASTERIX (All-purpose STructured Eurocontrol Radar Information eXchange) format. They are recorded during a time window centred on the instant where a resolution advisory was reported.

2.2.2.3 System architecture

The system is built around a configurable input system, made up of a PC under Windows OS, equipped with an X25 network board.

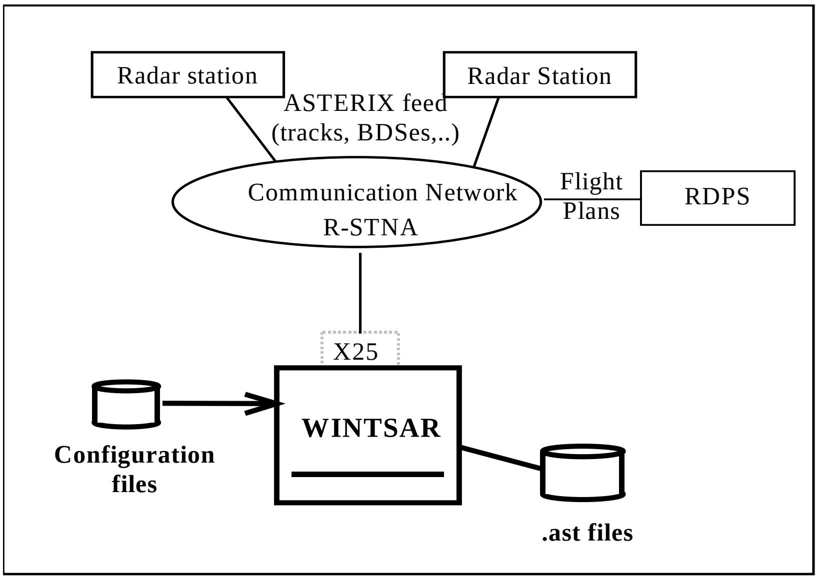

Fig. 2.1 *WINTSAR environment*

Simply said, the input system receives a flow of ASTERIX messages through an X25.3 interface and performs a first filtering on the X25 addresses and sub-addresses, and on the ASTERIX category number. The ASTERIX messages retained after this stage are temporarily recorded in a circular buffer.

When an ACAS resolution advisory is detected in the flow of entering message, the system creates a file of ASTERIX messages covering 60 seconds before and after the date of the alert. At the end, the system computes some statistics about the alert and writes them in a text file.

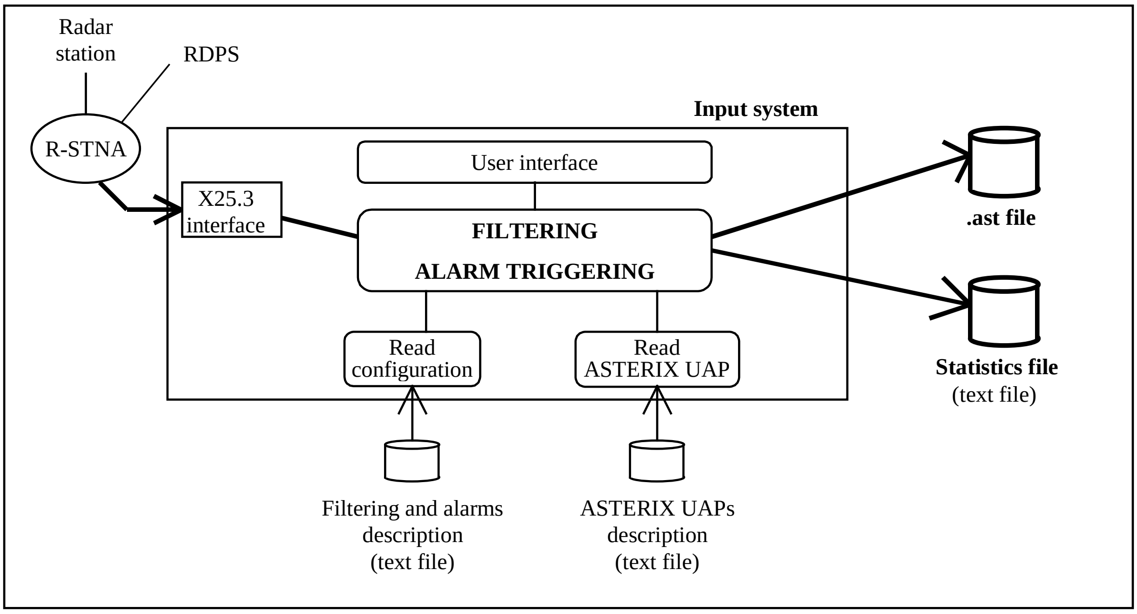

Fig. 2.2 *ASTERIX input system*

Fig. 2.2 illustrates how the input system works. It requires two configuration files (text files):

One gives the definition of the supported ASTERIX categories;

Another one includes the addresses to be filtered and the alarm conditions that trigger a recording.

The whole thing is supervised through a user interface under Windows.

2.2.2.4 ASTERIX files

These files contain the recordings of several radars, among which at least one Mode S radar. The radar information collected in ASTERIX files primarily contains 4 categories of ASTERIX recordings: categories 1, 2, 3 and 16.

Categories 1 and 2 were processed according to their specification in the Eurocontrol document defining the ASTERIX format [2].

Category 3 is not defined in the Eurocontrol document. It was defined locally, to receive the information on flight plans coming from the French RDPSes.

Category 16 has an item (I016/260: ACAS Resolution Advisory Report) giving the nature of the resolution advisory. This item was not processed as per document [2], because the latter refers to the data format based on ICAO ACAS standards and, at the moment of the study, no collision avoidance system complies with these standards. It was processed according to the current data format used by collision avoidance systems.

2.3 Means of analysis

2.3.1 ASTERIX format decoding tool

The WINTSAR system simultaneously records the advisory reports provided by one of both radars, the tracks provided by standard SSR radars and flight plan information. All these data are bundled in a single file in ASTERIX format. CENA uses the locally developed software called *ast2mad* to split each kind of information into a corresponding file in MADREC format.

Among the flight plan data, we extract the following items:

Mode A code;

time of day;

(X, Y) co-ordinates;

type of aircraft;

departure airfield;

arrival airfield;

aircraft registration.

The first three items allow for a quick correlation. Thus, the tool can link the SSR trajectories with the flight plan data. The last four items are supplementary data, the storage of which required an adaptation of the MADREC format.

2.3.2 Statistics tool

Each MADREC radar file can be processed by a locally developed software called *statmad*. The data are extracted and organised in a convenient order, so as to be easily entered into an Access database. In addition, the tool computes some basic statistics about the traffic found in the radar file.

The raw data transferred into the database provide the material for a basic analysis of the ACAS events.

2.3.3 Simulation tool : OSCAR

For a deeper analysis, the necessary data must be researched by trying to replay each ACAS event.

2.3.3.1 Presentation

The OSCAR (Off-line Simulator for Collision Advisory Resolution) test-bench is a set of integrated tools to prepare, execute and analyse ACAS conflicts. It includes an implementation of the TCAS II logic version 6.0, 6.04a and 7.0 conformed to the MOPS.

The purpose of the OSCAR test-bench is to perform ACAS studies from real or artificial data in order to:

Analyse the interference between ATC and the ACAS system;

Identify potential ACAS issues and evaluate ACAS logic improvements;

Perform safety studies.

The OSCAR test-bench is composed of separated sub-systems allowing the preparation, the execution and the analysis of scenarios. The OSCAR test-bench sub-systems share input/output files.

<u>Notes</u>: A *scenario* is a set of related or not encounters whose aircraft have been equipped with some TCAS logic and some pilot response model including the standard pilot model conformed to the ACAS SARPS.

An *encounter* is a potential conflict situation involving two or more aircraft. A *real encounter* is an encounter issued from radar recording treatment; an *artificial encounter* is an encounter defined by the user.

2.3.3.2 Real encounter generation

The Real Encounter Generator of the OSCAR test-bench allows to extract potential conflicts (involving two or more aircraft) from radar data recordings in the MADREC format.

The Real Encounter Generator includes a pair-wise conflict detection algorithm based on:

A geographical test which detects aircraft in proximity within a range of 30 NM and an altitude band of +/- 8000 feet; and then,

A TA simplified logic which includes an horizontal test using TAU and DMOD like parameters and a vertical test (much larger than TCAS) with a ZTHR like parameter. For instance, the previous parameters are respectively set to 48 seconds (TAU), 5 NM (DMOD) and 2500 feet (ZTHR) above FL290.

The next step of the Real Encounter Generator consists in the fusion of pairs of aircraft in conflict within encounters.

The Real Encounter Generator also includes smoothing and interpolation algorithms in order to generate trajectories with one-second update rate (as required by the TCAS II logic).

2.3.3.3 Scenario creation, execution and analysis

The OSCAR test bench allows to interactively create scenario files where aircraft potentially in conflict within encounters are equipped with:

The SSR and ADC equipment;

The type and release of the possible ACAS equipment; and

The pilot response model to be applied when RA occurs.

Apart from the OSCAR test-bench, scripts are also available to automatically create OSCAR scenario files from a set of encounters.

The execution of a scenario by the OSCAR test bench means:

Off-line simulation of each encounter of the scenario including for each ACAS equipped aircraft: the performance of the ACAS computations and co-ordination mechanism, as well as, the simulation of the pilot response to the RA issued by the ACAS logic.

Recording of the simulation results for analysis. The scenario results file includes the history of the each ACAS events, the possible ACAS co-ordination messages and the modification of the initial aircraft trajectories when RAs are issued.

The OSCAR test-bench includes a set of facilities to display the encounters and scenarios, to replay the encounters and to visualise the scenario results in a graphical and textual way.

Apart from the OSCAR test-bench, scripts are also available to extract statistics from a set of OSCAR scenario results files.

2.3.3.4 Use of OSCAR in the data analysis

The Real Encounter Generator was used to detect the potential threats surrounding the TCAS aircraft. When at least one was found, a scenario file was created. With it, it was possible to check if the threat could have triggered the event and to try and reproduce what was the course of the events when the resolution advisory was issued.

2.4 Conclusion

The following figure sums up the operations and tools required to collect and analyse the ACAS events provided by a mode S station.

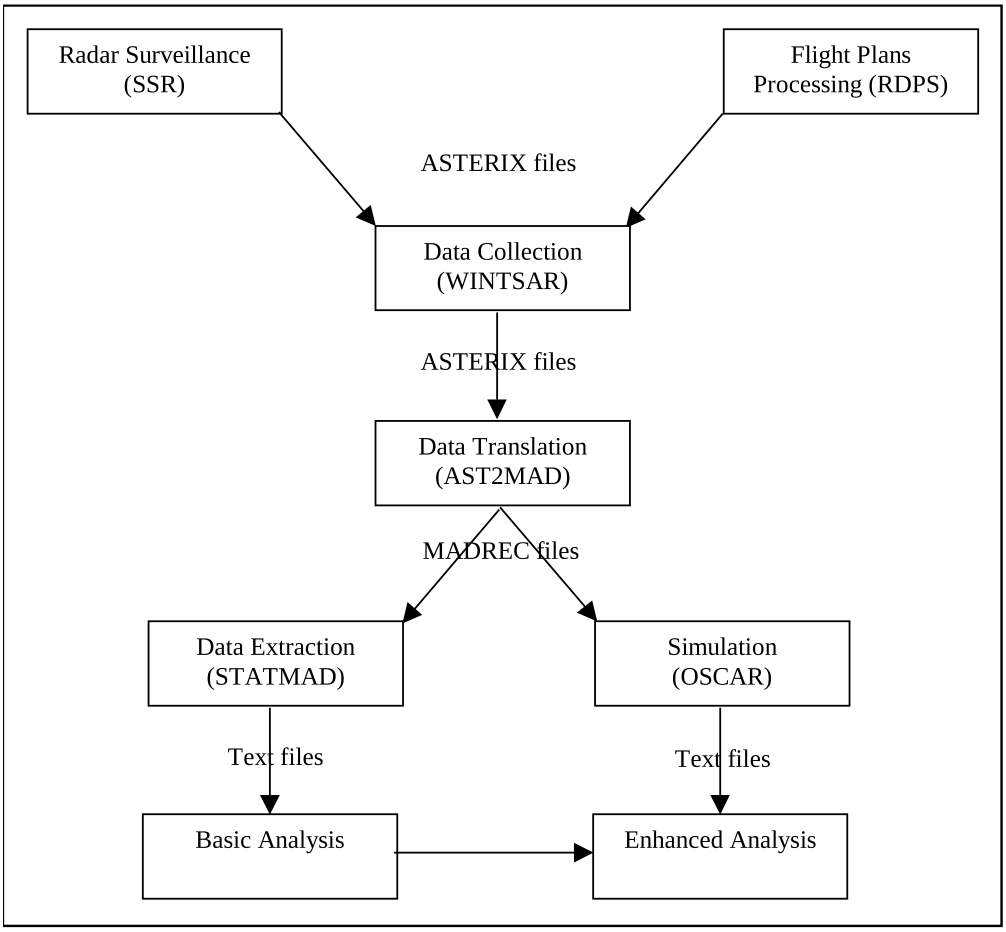

Fig. 2.3 *Collection and analysis process summary*

3. Validity of the collected data

3.1 Introduction

The WINTSAR chain of acquisition (described in chapter 2) provided CENA with a data file each time an ACAS event occurred on an aircraft within the range of the Mode S station. Each file contained one or several events, each described by the series of advisory reports that happened to a single aircraft.

WINTSAR recorded 1109 reports, distributed in 321 files. The majority of them contained only one event. However:

19 files contained two events, which were co-ordinated. Both aircraft were TCAS-equipped and each aircraft was seen as a threat by the other, so the TCAS units communicated to produce a co-ordinated response.

1 file contained two unrelated events that happened in the same period. The events occurred in remote areas and have nothing in common. It is purely coincidental that they happened simultaneously.

1 file contained two co-ordinated events *as well as* one unrelated

Overall, the sample is made up of **343 events**, among which **40 are co-ordinated**.

The scope of the current chapter is a first glance at the data sample, with a critical eye towards the quantity of collected events and the reliability of the reports. The analysis cover the reports received over a year between 22 October 1996 (operational start-up of WINTSAR) and 23 October 1997.

3.2 Quantitative aspect

3.2.1 Number of aircraft

245 different aircraft (single Mode S address) have contributed to the sample of events.

The following illustration gives the distribution of aircraft according to the number of events they went through. It reveals that a great majority of aircraft has only one event. Only one of them has a suspiciously high number of events: 37. The on-board equipment is probably the problem here.

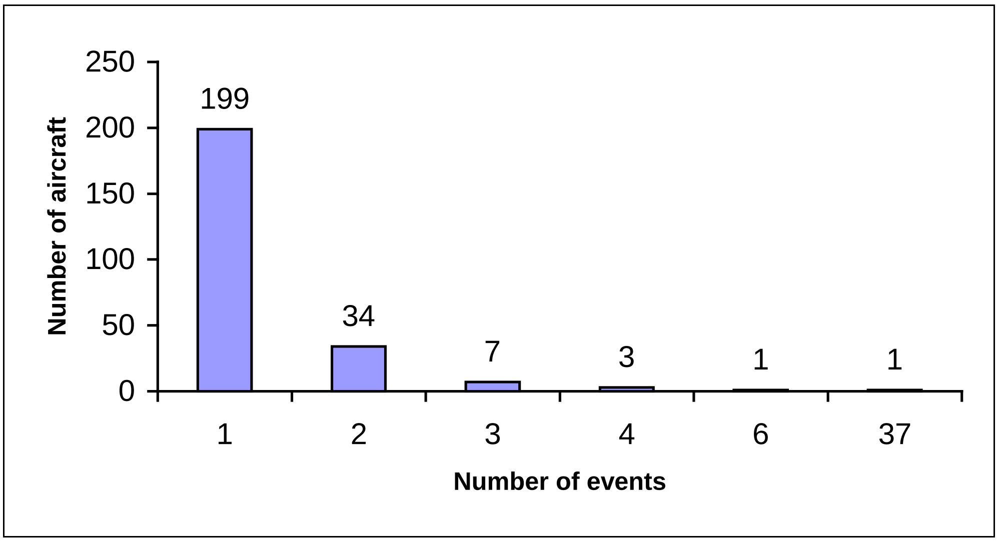

Fig. 3.1 *Number of aircraft having n events over one year*

3.2.2 Number of collected events

With 343 events over a year, the average number of events approaches one per day. This being only in the coverage of the Orly station (nearly corresponding to the radar coverage of the Paris ACC), the number could appear as rather large. However, all the alerts that may occur in the area are not collected by WINTSAR.

Indeed, the whole system enabling Mode S data collection is not always available for the sole purpose of recording TCAS alerts. Among others, data-link experiments consumed part of the overall working time of the system. That is why the collection of TCAS alerts was operational only 66 % of the time.

This availability is not uniform and the monthly distribution thereof is shown below:

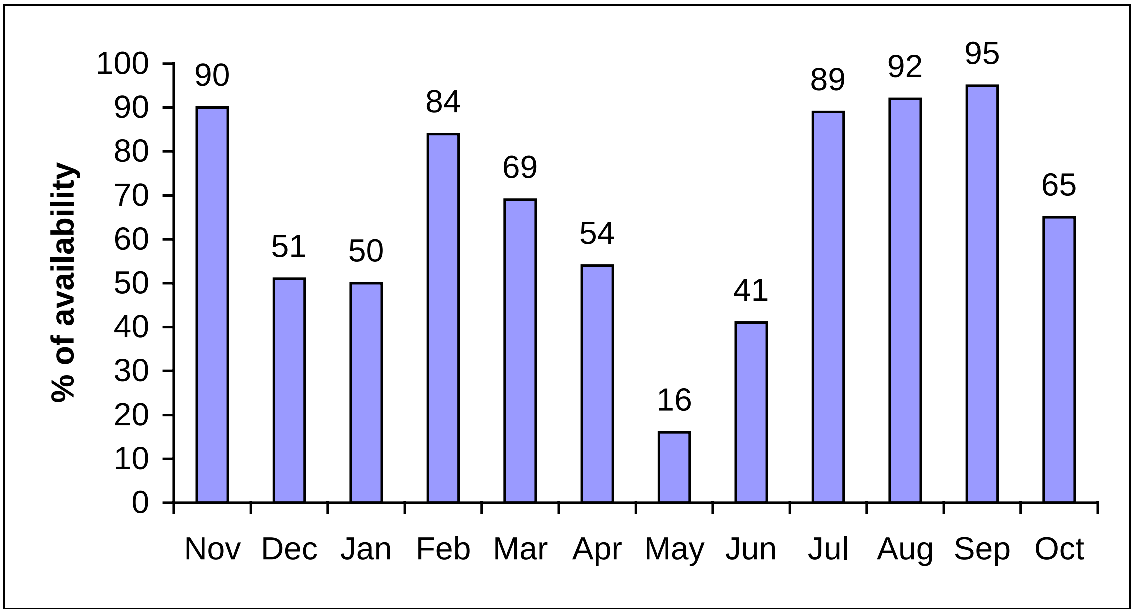

Fig. 3.2 *Monthly availability of the collection system*

Fortunately, during the high level of traffic months of July, August and September, the system was available 92 % of the time. May is a special month with only 16 % availability: as no event was collected in May, we will not take this month into account for the rest of the study. Without May, the average availability is 70%.

Had the system reached an availability rate of 100 %, CENA would have collected an extrapolated number of 492 events, that is an average of 45 events per month or 3 events every 2 days.

So, although the data collection was not continuous, we can estimate that we captured 70% of the events having occurred in the Orly coverage. Moreover, 343 events make a statistically significant sample.

3.2.3 Number of reports per event

Standards for ACAS II specify a resolution advisory report must be transmitted by the Mode S transponder when requested by the mode S radar, as long as the resolution advisory is presented onboard and 18 seconds thereafter.

Orly mode S radar antenna has an 8-second rotating cycle, so the number of received resolution advisory reports should be at least 2, when a single and short-duration RA is issued. If only one report is sent, it is the sign that the advisory was not maintained available for collecting long enough.

The observation of real events during previous studies (operational evaluation of TCAS essentially) pinpointed that the majority of events have an average duration of 25 seconds. Taking into account the 18-second persistence of the last RA we should observe an average of 5 reports per event. Here is what is really reported:

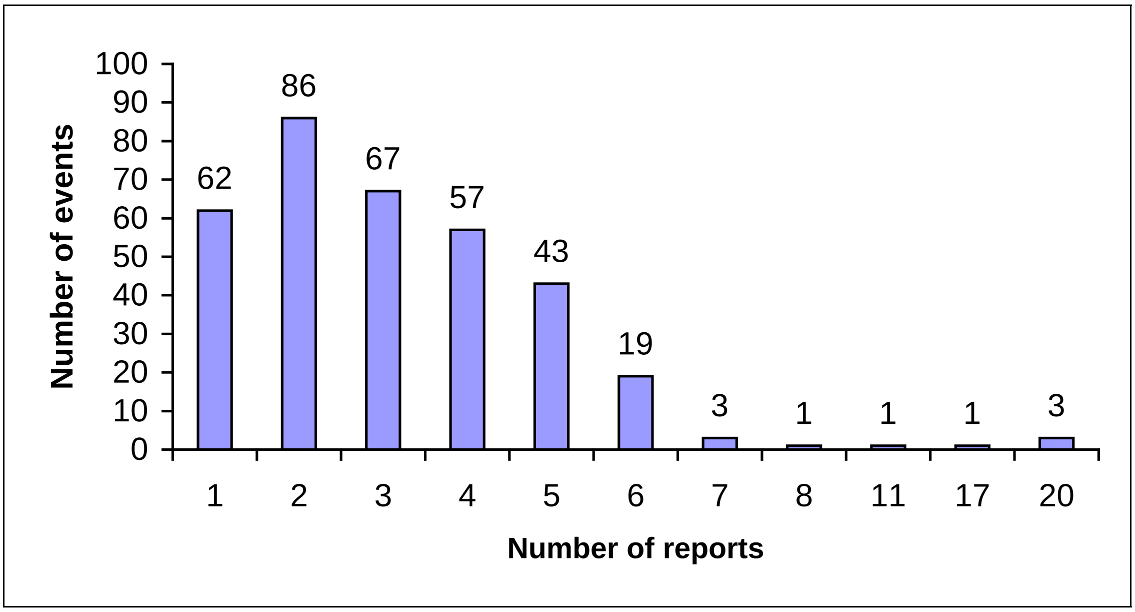

Fig. 3.3 *Number of events having n reports*

62 out of 343 events had only one report collected. This means that 17.8 % of the events are incompletely reported.

31 out of 245 aircraft were involved in the 62 single-report events. 24 of these aircraft were only involved in single-report events so one is entitled to believe that the airborne equipment of these aircraft (9.8 %) was (at least partially) malfunctioning.

6 out of 343 events had more than 7 reports collected (alert duration superior to one minute)

4 aircraft out of 245 produced these 6 events. As 3 of them also had another event within the average RA duration and since we have only one event for the fourth aircraft, we can not be conclusive as regards the possibility of malfunction.

For aircraft involved in such events, this casts a doubt on the correct behaviour of their surveillance/reporting equipment. The chain of acquisition can also be questioned since an antenna turn can be lost if the ACAS information download is not made in the same turn the RA is detected.

3.3 Qualitative aspect

The examination of the content of the reports revealed two categories of suspicious data:

events with unknown advisories;

events with inconsistent advisories.

3.3.1 Events with unknown advisories

Each advisory report contains a field, which must be filled with a non-zero number for it to be interpreted as a known type of RA. When the field is empty, the resolution advisory that has been issued remains unknown to us.

This is obviously the result of a flaw in the data collection chain.

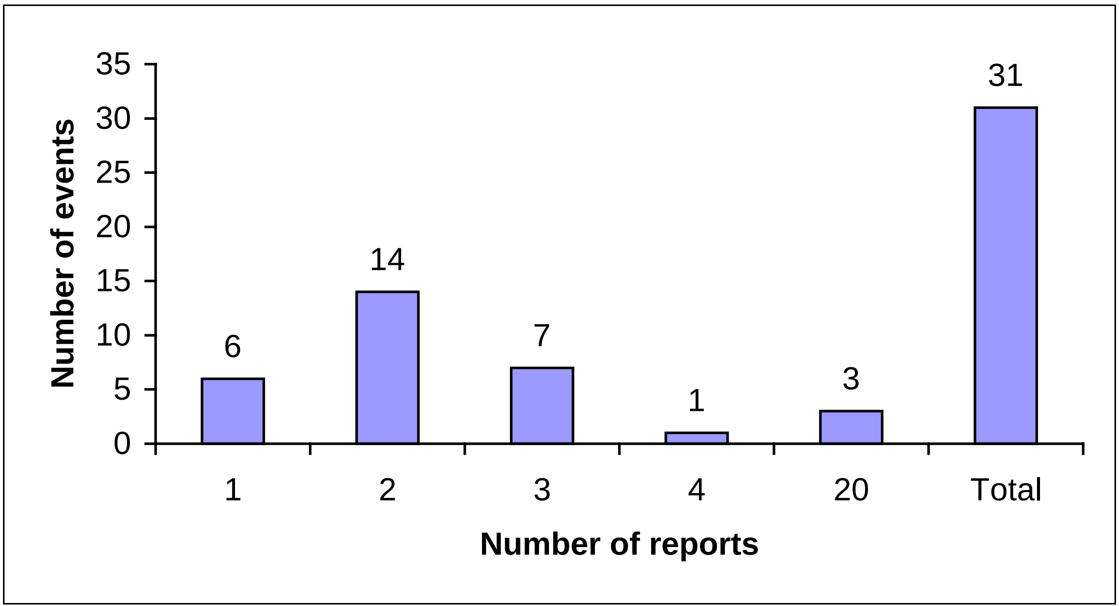

Fig. 3.4 *Number of events having n empty reports*

31 out of 343 events were made up of empty reports. In addition, 25 other events had a mix of empty reports and valid reports.

24 out of 245 aircraft were involved in the 31 empty events. 16 of these aircraft were only involved in empty events. For 2 of them, they had more than one empty event, which indicates a high probability of on-board problem. But for the 14 remaining, we can not tell for sure that the problem comes from the airborne side of the collection chain.

3.3.2 Events with inconsistent advisories

Two sub-categories of reports are considered as inconsistent:

> The resolution advisory report offers the possibility to encode horizontal resolution advisories, since originally there were plans for developing ACAS III equipment (giving horizontal advisories). No such TCAS unit existing at the time of this study, a report should not contain a horizontal manoeuvre;
>
> When the TCAS unit must avoid two threats, it issues two resolution advisories at the same time (composite advisories). However, these vertical advisories are never contradictory (e.g.: Climb and Descend can never occur). A report should not contain simultaneously two contradictory advisories.

The problem probably lies onboard, in a wrong encoding of the advisory on the transponder, or even in the TCAS unit itself.

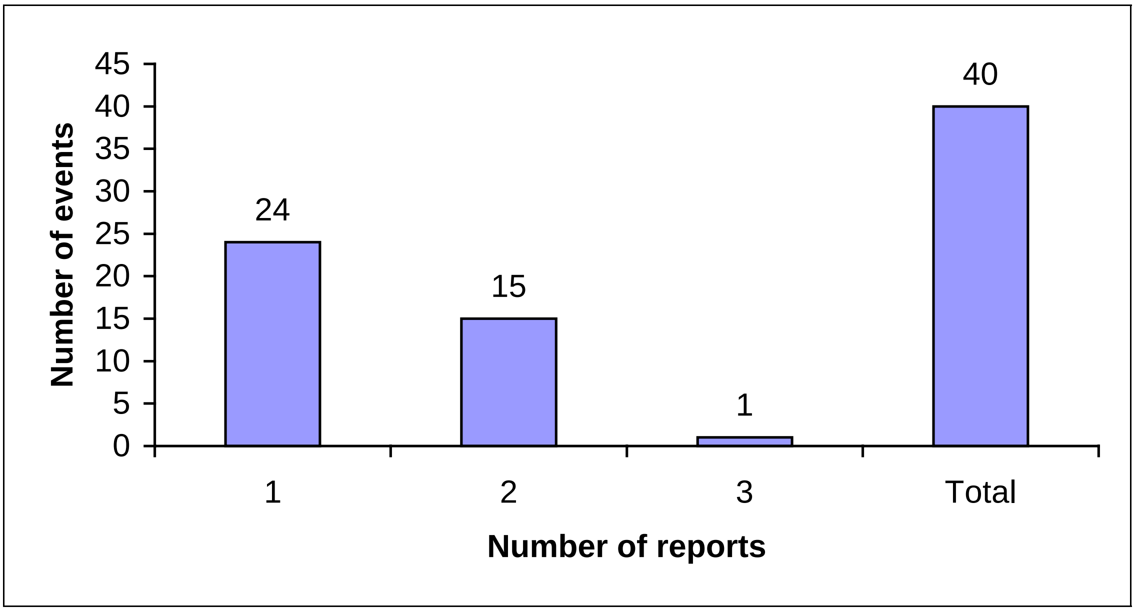

Fig. 3.5 *Number of events having n inconsistent advisories*

40 out of 343 events were made up of inconsistent reports. Contrary to section 3.3.1, there are no events where a mix of inconsistent reports and valid reports is present.

2 out of 245 aircraft were involved in these 40 events. These aircraft were not involved in other events so it seems that their airborne equipment is always sending a wrong advisory and needs being checked.

One of them is precisely the aircraft identified as suspicious in section 3.2.1, for having had 37 events.

3.4 Conclusion

The following table sums up the different types of events according to the quality of the contents of their reports. Figures between parentheses represent the number of co-ordinated event for this category

Number of reports	1	2	3	4	5	6	7	8	11	17	20+	Total
Events with only empty reports	6	14	7	1	0	0	0	0	0	0	3	31 (4)
Events with only inconsistent reports	24	15	1	0	0	0	0	0	0	0	0	40
Events with both valid and abnormal reports	0	2	6	8	7	2	0	0	0	0	0	25 (2)
Events with only valid reports	32	55	53	48	36	17	3	1	1	1	0	247 (34)
Total	62	86	67	57	43	19	3	1	1	1	3	343

Tab. 3.1 *Quality of the collected events*

Overall, 71 events (20.7%) were made up of abnormal reports. With 32 events that have incomplete series of reports, we have only 215 events (62.7%) left which match perfectly with the expected pattern.

This reminds us that we are working with an experimental hardware in a real environment, so the conditions are far from perfect.

The first reaction in front of abnormal events is naturally to discard them. For the inconsistent events, this is not a problem since all of them occurred to only two aircraft, which never had valid or event partly valid events. In the case of the empty events, some related aircraft had also valid or partly valid events. As section 4.5.4 shows, many events occurred with identifiable threats around, and a part of them could be replayed in simulation. As it is impossible to tell if an empty event is a TCAS malfunction or not, we will not discard them.

Consequently, only **the events with inconsistent reports will no be considered in the following pages.**

4. Basic analysis of the events

4.1 Introduction

Going through the 343 events provided by WINTSAR (cf. chapter 2) revealed some imperfections in the data sample (cf. chapter 3). Consequently, the most suspicious events were discarded and the study goes on with 303 events.

The scope of the current chapter is the characterisation of the events. It will be done firstly by pinpointing where and when the events have occurred, secondly by describing the sequence of resolution advisories making up an event, and finally by looking in the vicinity of the TCAS aircraft for threats liable to have triggered the event

4.2 Spatial position

4.2.1 Geographical distribution

The following map gives the location of each event:

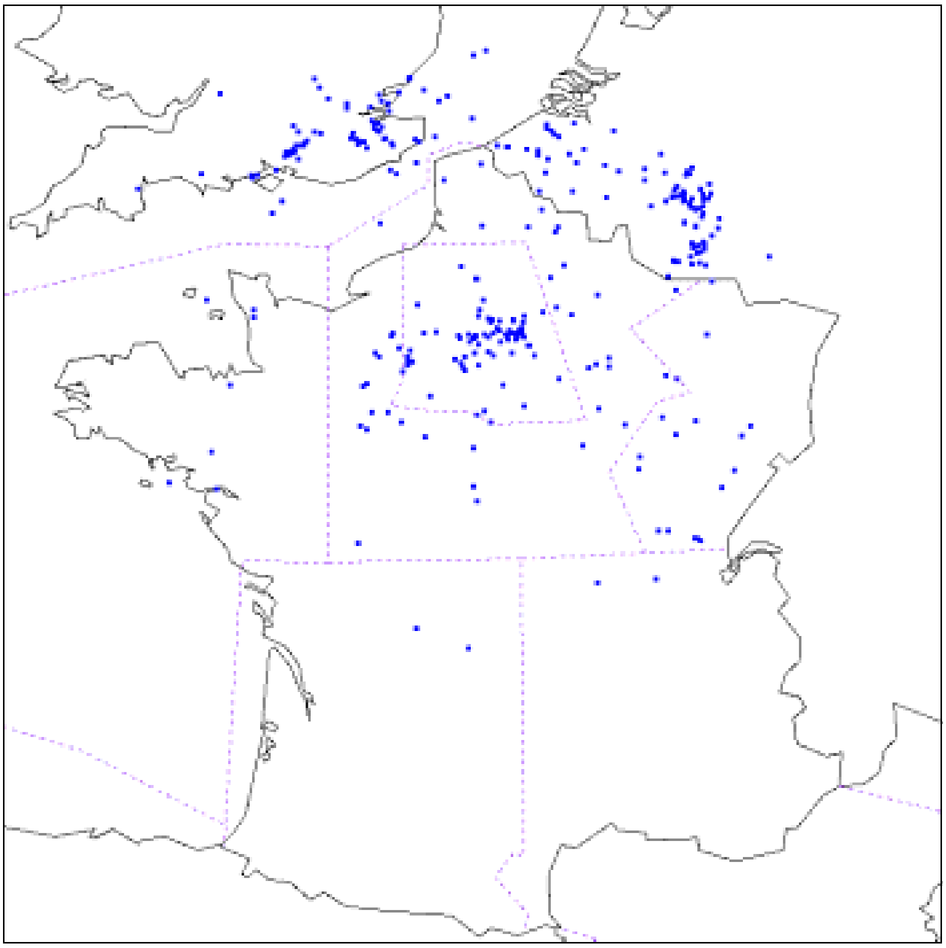

Fig. 4.1 *Geographical distribution of events*

The three main sources of events are the Paris TMA, the southern London area and the Düsseldorf area. Of course, this pattern corresponds with the higher traffic density areas.

More precisely, there are 148 events in France, 71 events in Great Britain and 84 events in Belgium/Germany.

4.2.2 Altitude distribution

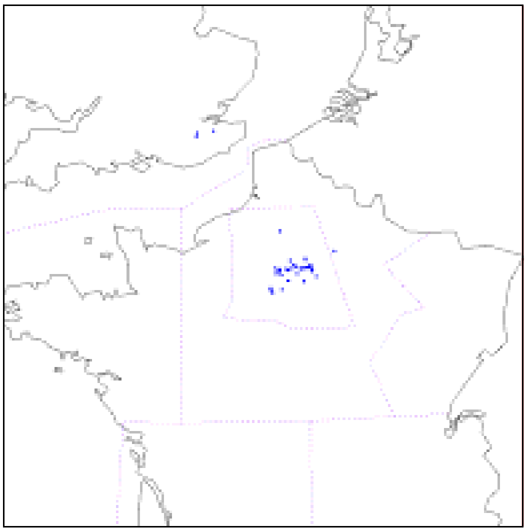

Fig. 4.2a *Events below FL100*

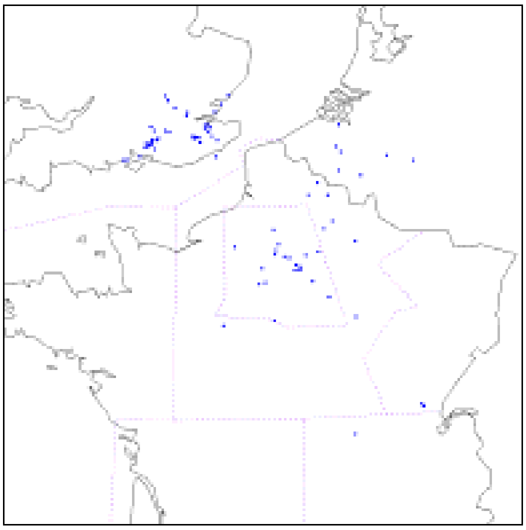

Fig. 4.2b *Events between FL100 and 200*

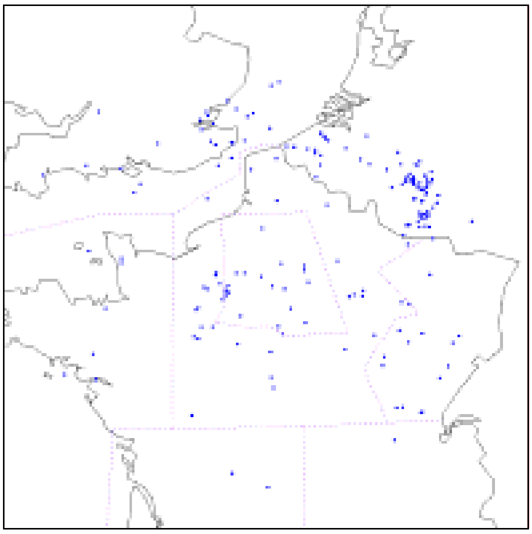

Fig. 4.2c *Events above FL200*

Illustrations 4.2a, 4.2b and 4.2c help to understand the following histograms about the distribution according to altitude layers.

Indeed, the first map shows the events occurring to aircraft in airport circuits. The middle map shows the events occurring with aircraft, mainly in evolution (arriving or departing from TMAs). The last map deals with events occurring to aircraft transiting at high altitudes

Incidentally, the maps give a rough idea of the radar coverage according to altitude.

To represent more precisely the distribution of events along altitude layers, we chose to divide the airspace into 50 FL-wide bands. As the nature of the flights is different in each overflown territory, the distribution was computed within each "country".

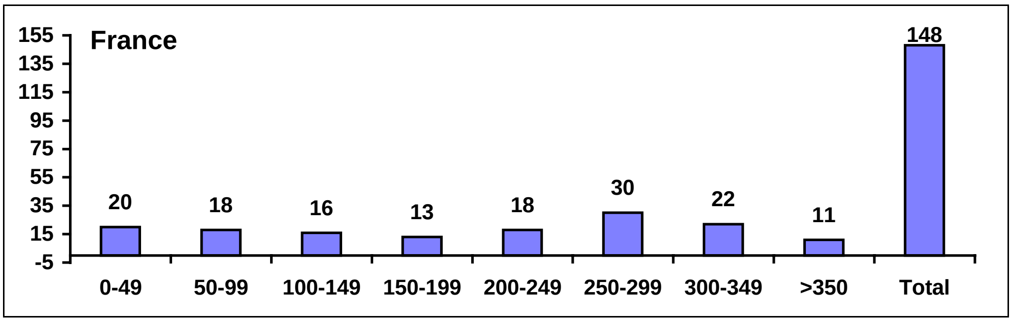

Fig. 4.3a *Altitude distribution over France*

For France, the distribution roughly shows as much events in TMA airspace than in transit airspace. There is only one difference vis-à-vis what was observed in the French operational evaluation: there is no peak above FL 300.

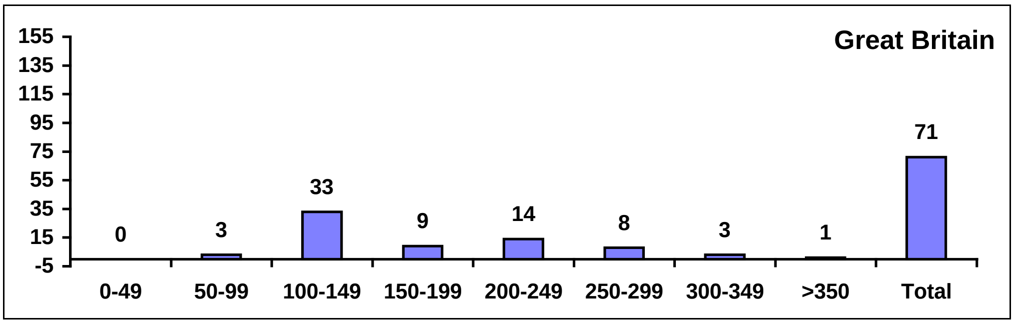

Fig. 4.3b *Altitude distribution over Great Britain*

For Great Britain, a high number of events occur in the layer 100-149. Since the radar detection below FL100 is weak, we can imagine that the numeric preponderance of events below FL150 is even more important. It is the sign of the intense activity of London TMA.

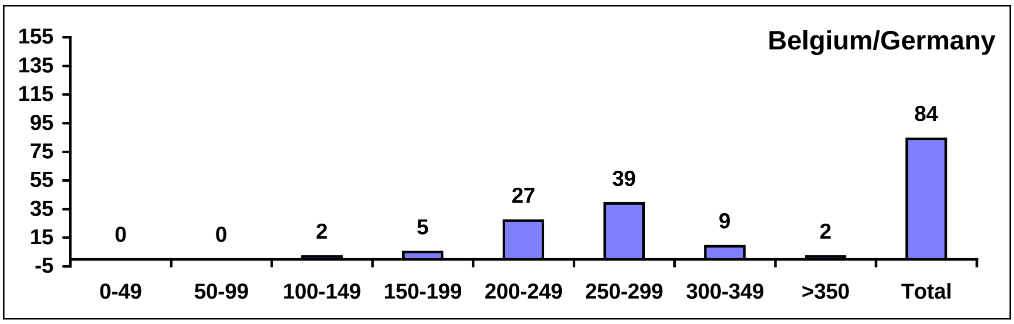

Fig. 4.3c *Altitude distribution over Belgium/Germany*

For Belgium/Germany, on the contrary, the events are almost all located above FL200. As Fig 3.6 shows, they are concentrated over the region of Düsseldorf, where numerous high altitude routes cross each other (both North-South and East-West).

4.3 Temporal position

4.3.1 Monthly distribution

As we already noticed in section 3.2.2, during the month of May, the collection system had an exceptionally low rate of availability (16%), which is a good reason why no event was collected in May. Consequently, this month will not be considered in the following paragraphs.

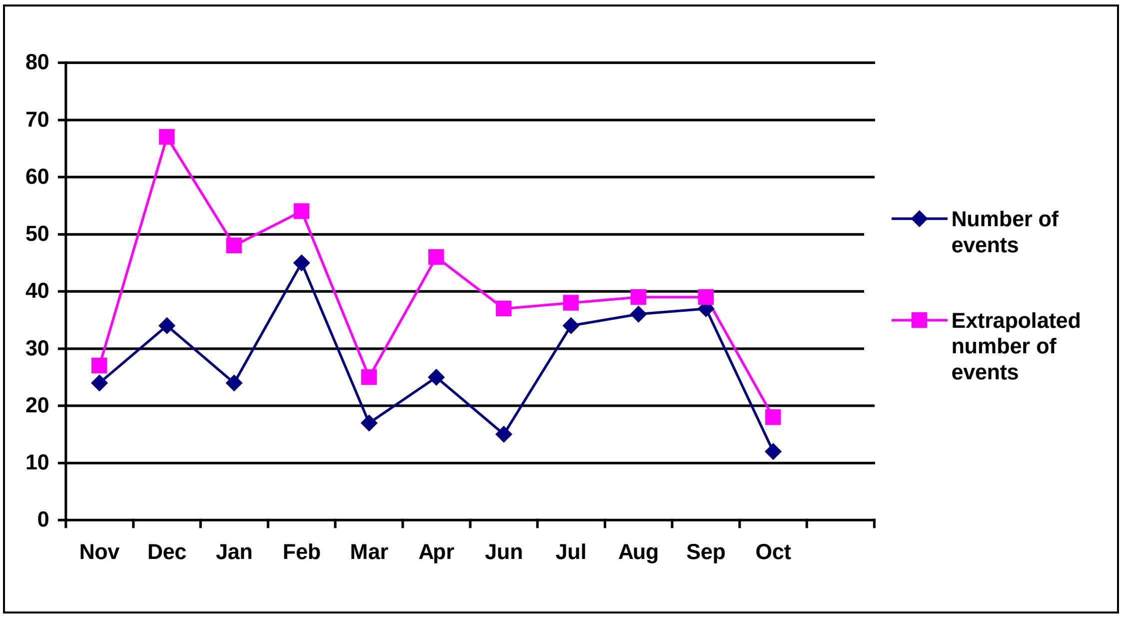

Fig. 4.4 *Monthly distribution of events*

The majority of events were collected over 4 months (February, July, August and September), that match with the highest availability rates. The curve representing the number of extrapolated events is difficult to link to the traffic density observed in the area. For example the rise in density from April to July is not reflected, and the month of October, which was the peak of traffic in 1997 has yielded the least events.

Obviously, the random aspect of the unavailability of the collection system, added to the relatively low number of events in a month, does not permit to capture a distribution of events matching the expected proportionality with the traffic density.

For an availability rate of 100 %, we could have received 3 events every 2 days. As computed in chapter 6, the proportion of TCAS equipped aircraft at the time of the study was 22 %. With an entirely equipped fleet, we can extrapolate that at least 13 events would occur every 2 days.

4.3.2 Daily distribution

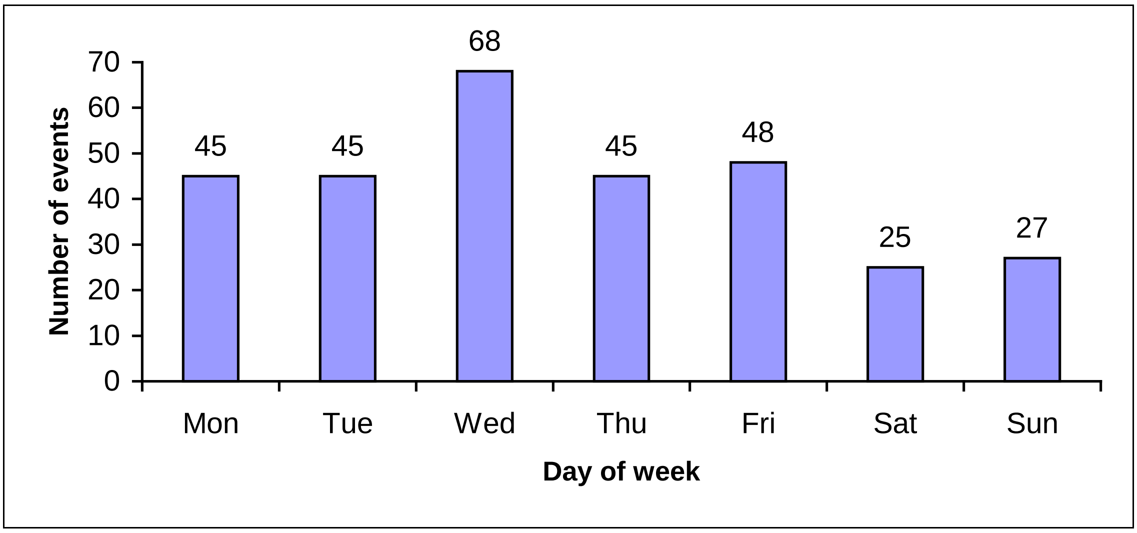

Fig. 4.5 *Daily distribution of events*

During the 5 working days, the number of events is equally distributed, except for an unexplainable peak on Wednesday. During the weekend, the number of events per day is halved.

This difference can not be linked to the level of traffic, which is in fact quite the same for each day of the week. However, the nature of the traffic is different (less business transit and more charters) and no military aircraft are flying during the weekend.

4.3.3 Hourly distribution

To examine this distribution, the day was sliced into 4-hour portions, which is convenient because it matches the daily peaks of operational activity.

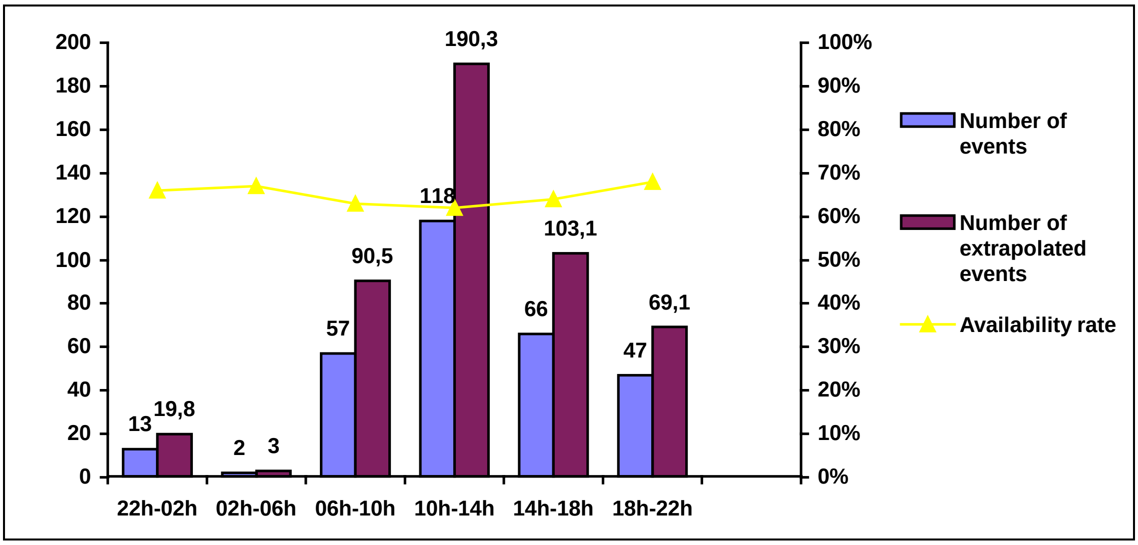

Fig. 4.6 *Hourly distribution of events (local time)*

First, we can see that the availability rate of the collection system is roughly constant: the impossibility to collect events is not linked to a specific period of day. Thus, the form of the hourly distribution of event curve is unaffected by the availability rate.

While, as expected, the level of events is very low during the night, the moment when the peak of events is higher corresponds to the period between 10 and 14 o'clock. 37 % of the events occur during this slice which is surprising because it is not a period of high activity compared to the previous period, between 06 and 10 o clock (at least in TMAs).

4.4 RA qualification

4.4.1 Event duration

Fig. 3.3 gives the number of events having a given number of reports. Since a report represents an antenna turn (8 seconds), the Figure also shows the distribution of events according to their maximum duration.

A majority of events last less than 24 seconds. Only 2.6 % last more than 48 seconds. The measured average duration of an event is 27.7 seconds. The real duration of an event is its measured duration plus 4 seconds (average delay between the availability of first RA and the effective download) minus 16 seconds (the last advisory is available 18 seconds after the event has ended, that is two antenna turns on average).

So, **the real average duration of an event is 15.7 seconds**. However this figure should be taken carefully since there is a lot of single-report events in the sample. It is quite possible that some events lack one report, if the ground station happen to not download the advisory in the same turn as it was detected.

4.4.2 RA types

The first advisory of each event was taken into account to represent the distribution of RA types shown below.

The types of advisory are:

Cl: Climb	Des: Descend
DDes: Don't Descend	DCl: Don't Climb
LD5: Limit Descent at 500 ft/min	LC5: Limit Climb at 500 ft/min
LD1: Limit Descent at 1000 ft/min	LC1: Limit Climb at 1000 ft/min
LD2: Limit Descent at 2000 ft/min	LD2 Limit Climb at 2000 ft/min

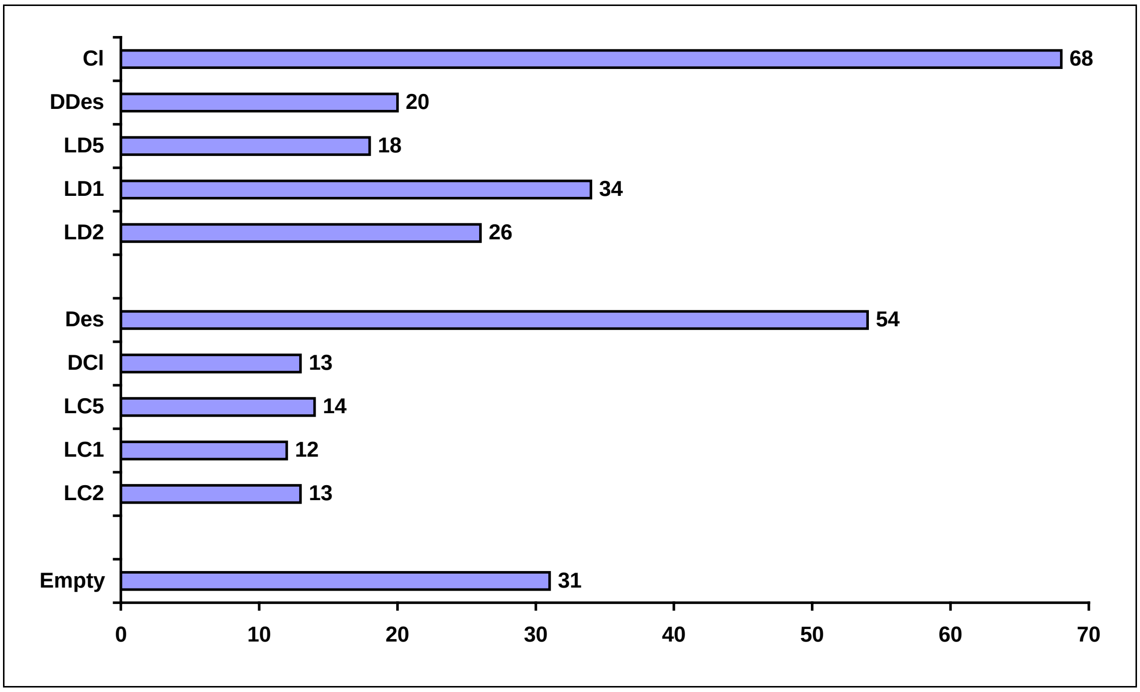

Fig. 4.7 *Distribution of events by type of first report*

There is a preponderance (61 %) of «upwards» advisories compared to «downwards» advisories, which is difficult to explain.

4.4.3 RA modifications

In 175 events, only one resolution advisory was issued. Out of the 128 remaining, 100 had 2 successive advisories, 27 had 3 successive advisories and 1 had 4 successive advisories.

The following figure is based on the transition between the first and second RA and shows the way TCAS modified its advisories to take into account the changes in conflict geometry.

Weakening means that the second RA weakens the constraint on the pilot (e.g. LC5 after DCl).

Strengthening means that the second RA strengthens the constraint on the pilot (e.g. Des after DCl).

Reversal means that the second RA changes the sense of the constraint on the pilot (e.g. Cl after LC1).

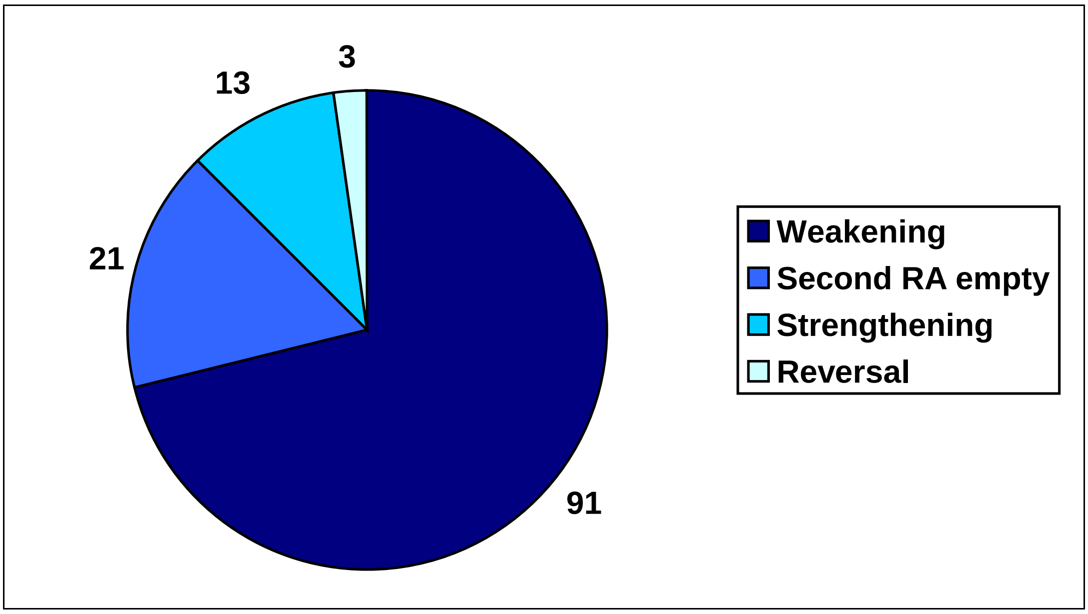

Fig. 4.8 *RA alterations during the event*

As expected, the cases where TCAS has to reverse the direction of resolution (e.g.: Climb then Descend) are scarce (0.9%). Few advisories need to be strengthened (3.8%), from which we can anticipate that pilots usually follow the resolutions. A later analysis of pilots' reactions will allow to check this explanation.

4.5 Potential threat identification

4.5.1 Method of identification

To simulate what happened to a TCAS equipped aircraft, we needed to identify the cause of the event. In TCAS version 6.04a, which is the current version in equipped aircraft, the advisory report does not include information on the threat that triggered the advisory. It will only become possible with TCAS version 7.

To overcome this lack, we used the SSR tracks provided with the reports. The OSCAR test bench allowed to make an automatic pre-selection of potential threats and to visualise their trajectory, thus enabling us to determine the best potential threat.

4.5.2 Causes of non-identification

In light of this, three causes of non-identification of the potential threat exist:

no SSR data : the monopulse recording in which the TCAS aircraft was tracked was not joined with the Mode S report ;

no aircraft eligible for threat: the actual threat does not appear on the radar. Two cases can be separated :

The TCAS aircraft is on the edge of the radar covering so the threat might be outside radar range ;

Other (undiscriminable) reasons: no real threat (TCAS malfunction), untracked aircraft...

4.5.3 Number of events with potential threat

The process of identification of the potential threat yielded the following figures:

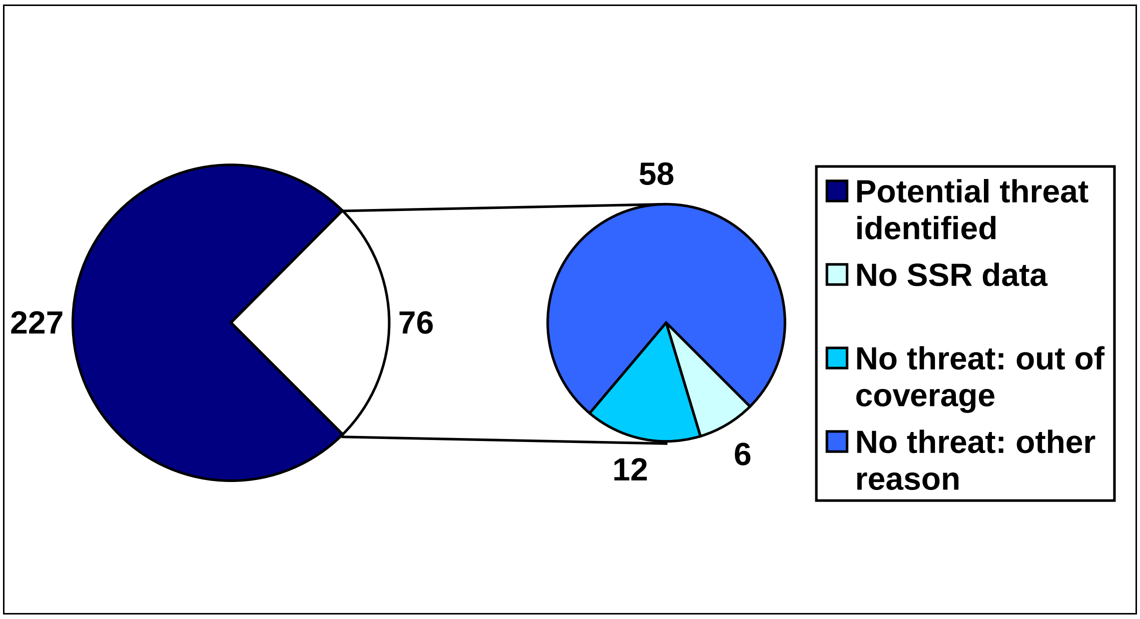

Fig. 4.9 *Classification of events according to potential threat identification*

25 % of the events don't have an identified threat. Among them 3 pairs of events were co-ordinated. That leaves 17 pairs of co-ordinated events, which can be simulated. Thus we are able to simulate 210 (227 – 17) encounters.

4.5.4 Correlation with suspicious data

	Events with only empty reports	Events with only inconsistent reports	Other events
Threat identified	14	2	213
Threat unidentified	17	38	59

Tab. 4.1 *Threat identification vs. validity of reports*

As shown in Table 4.1, the frequency of abnormal reports is far higher in events without identified threat (48 %) than in events with identified threat (7.0 %).

Moreover, only 18 events with identified threat are made of single reports whereas 44 events without identified threat fall under this category of incomplete events.

This tends to confirm that a large proportion of the events with suspicious reports is the result of some onboard malfunction.

5. Enhanced analysis of the events

5.1 Introduction

After reducing the number of studied events from 343 to 303 (cf. chapter 3), due to suspicious events, a basic analysis was conducted over the information yielded by the automatic mode S reports (cf. chapter 4). Going further required to examine the conditions in which an encounter triggered a sequence of RAs, and that meant finding a threat for each event.

The monoradar data allowing to find the trajectory of a threat aircraft were recorded in parallel with the Mode S radar data. Sometimes, they could not be recorded because the required radar was not available. When they could be recorded, it was sometimes impossible to confidently detect a threat in the vicinity of the TCAS aircraft.

The identification was possible in 227 events. As 34 events were co-ordinated, the aircraft in half of them are the threat for the other half (and vice-versa), the 227 events allow to form 210 encounters.

The scope of the current chapter is to examine the trajectories and results from simulations performed on the encounters. Some of the results required the intervention of an ATC expert, so they are subject to the limitations of a human's interpretations. We will also try and seek correlations between the events and human reports.

5.2 Characterisation of ACAS encounters

5.2.1 Operational geometry

Encounters can be classified according to their operational situation ATC-wise, i.e. the way the controllers have handled the pair of aircraft in an encounter. An ATC expert visualised all the encounters and defined six classes:

<u>1000-ft level-off</u>: ATC chose to separate the aircraft vertically by 1000 ft. The TCAS alert occurred either because the vertical closure speed is too high or because one of the pilots overshot its cleared FL.

<u>Radar horizontal separation</u>: the control chose to separate the aircraft horizontally. However, the resolution was not perfect since TCAS triggered.

<u>Unresolved</u>: the conflict was seemingly overlooked by ATC. It is not resolved in any plane and TCAS triggered. This class probably includes encounters where the separation is maintained by visual acquisition but we do not have this piece of information.

<u>Military threat</u>: the high performances of the military aircraft under military operations explain the triggering of TCAS.

Parallel approach: both aircraft are in parallel approach at Roissy.

Strategic segregation of airspace: this class deals with IFR-VFR conflicts.

The following table shows the number of encounters for each class:

1000-ft level-off	131
Unresolved	53
Radar horizontal separation	12
Military threat	8
Parallel approach	4
Strategic segregation of airspace	2

Tab. 5.1 *Distribution of encounters according to operational situation*

One can note a majority of level-offs (62%). All the events with military threat occurred over French territory.

5.2.2 Conflict geometry

The vertical tendencies of aircraft were classified into 5 categories: climbing, descending, levelling off in descent, levelling off in climb and steady.

The following table crosses the vertical tendency of the own aircraft (arbitrarily chosen in case of a co-ordinated event where both aircraft are TCAS equipped) with the vertical tendency of the threat aircraft.

Threat / Own	Climb	Descent	Level-off in descent	Level-off in climb.	Steady	Total
Climb	5	2	4	1	17	**29**
Descent	8	5		4	10	**27**
Level off in descent.	1	1		30	40	**72**
Level-off in climb.	1	3	23		13	**40**
Steady	4	9	6	15	8	**42**
Total	**19**	**20**	**33**	**50**	**88**	**210**

Tab. 5.2 *Vertical tendencies of aircraft*

The TCAS aircraft:
- is level in 20% of the encounters
- is levelling-off in 53% of the encounters
- is climbing/descending in 27% of the encounters

The threat aircraft:
- Is level in 42% of the encounters
- Is levelling-off in 40% of the encounters
- Is climbing/descending in 18% of the encounters

The geometries can be summed up in 4 categories, materialised by cells of different colours in Tab. 5.2, and can be compared with the results obtained during the French operational evaluation in 1996 [3] performed through the analysis of pilots/controllers reports.

	Operational evaluation	Mode S data
One aircraft steady, other aircraft climbing/descending	38%	19%
At least one aircraft levelling-off	21%	67%
Both aircraft climbing/descending	17%	10%
Both aircraft steady	24%	4%

Tab. 5.3 *Conflict geometries in the operational evaluation and in mode S data*

The results are completely different. This highlights some biases in the decision process of pilots/controllers on what to report. Geometries with steady aircraft are favoured: a level aircraft deviating from its clearance can be very disturbing. Geometries with level-offs are neglected.

5.2.3 Simulated RA types

Each event with an identified threat was replayed in the OSCAR test-bench. The first RA of the sequence obtained in the simulation is accounted for in Fig. 5.1.

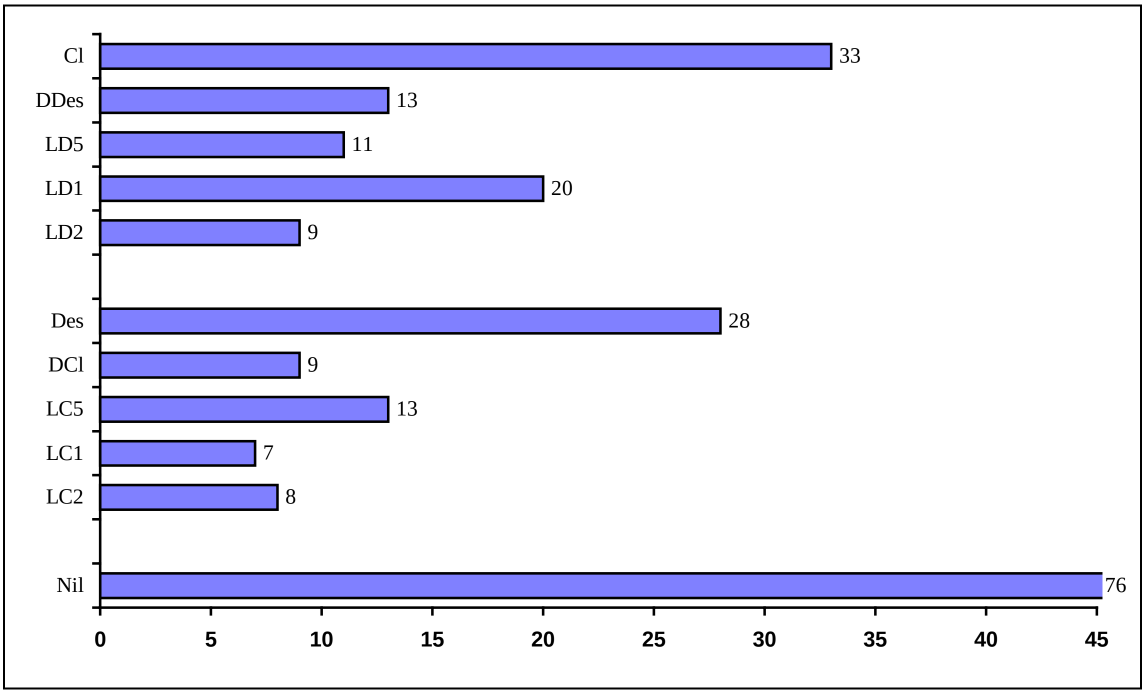

Fig. 5.1 *Distribution of simulated first RAs*

33 % of the replayed situations did not produce a resolution advisory. Either the threat was not the one responsible for the reported sequence (but no other visible aircraft could be) or the lack of accuracy of the radar data combined with the high sensibility of the TCAS logic to the conflict geometry are to blame for this lack of response.

57 % of the orders is upward oriented. This result seems to manifest a yet unexplained preference for upward instructions.

Fig 5.2 follows the same principle as Fig. 5.1 but with the originally reported RAs.

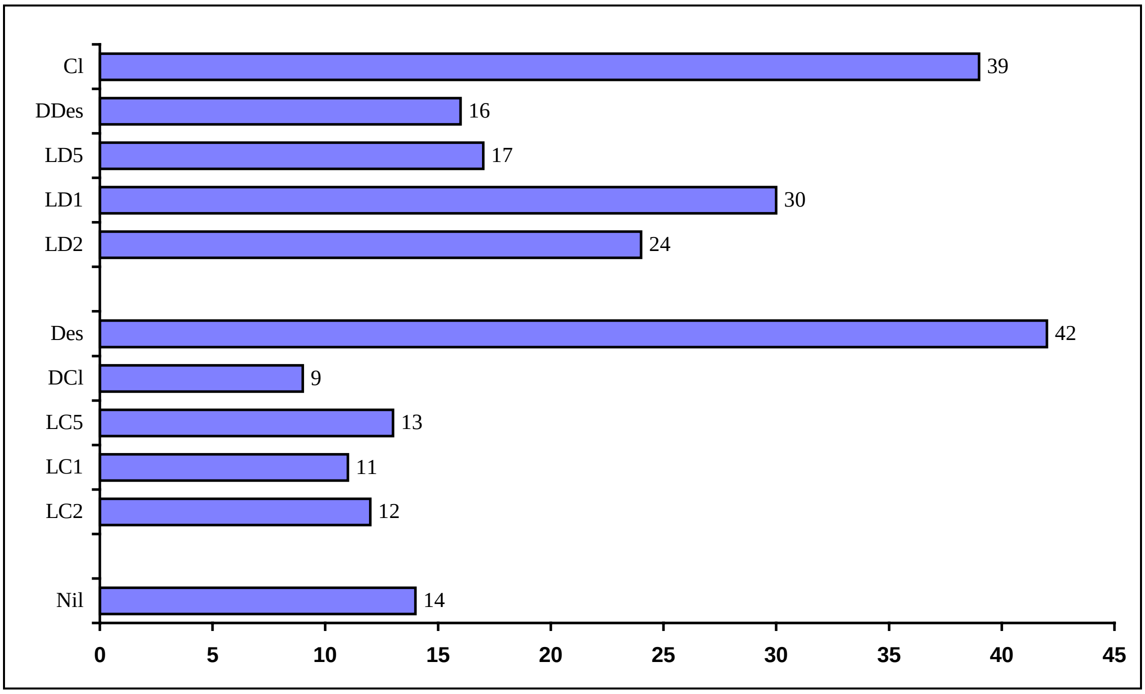

Fig. 5.2 *Distribution of reported first RAs*

The upwards preference of the logic was also present in the collected data, as the number of upwards instructions represents 59 % of the first RAs.

The two distributions are very similar in the downward instructions. The upwards instructions and also the Descend instruction are more numerous in the reported than in the simulated advisories. The difference seems to come from the set of replayed events were no advisory occurred.

An event by event comparison of the reported and the simulated first advisories is summarised below:

Reported and simulated first RAs are:	Identical	Of same sense	Of opposite sense	Not comparable
Number of events	80	60	4	83

Tab. 5.4 *Correlation between reported and simulated first RAs*

The correlation is fairly good. The slight difference between the RAs in the second column might have two causes:

the lack of accuracy of radar data;

the reported RA is not the real first one but a following one, due to the delay which may exist between onboard issuance of an RA and ground downloading of the BDS content.

5.2.4 Pilots' reactions

When a TCAS alert occurs, the pilot can choose to react or not. The reaction can be appropriate (the pilot follows the RA) or not. Therefore, we have three categories of pilots:

Category A: Those whose reaction complied with the RA

Category B: Those whose reaction did not comply with the RA.

Category C: Those who ignored the RA.

Note: Some RAs do not require a manoeuvre (e.g. Limit Climb RAs when the aircraft is not climbing). If the pilot does not alter the aircraft course, he is considered as Category A

Among the 227 events with a threat, the pilot's reaction was the following:

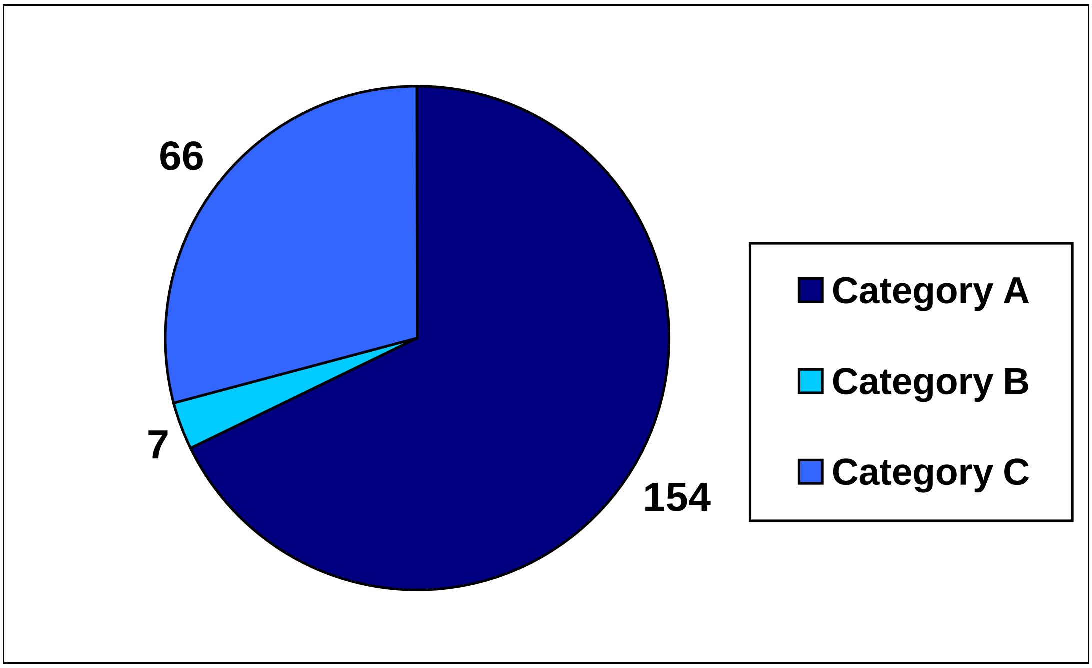

Fig. 5.3 *Pilots' reactions to resolution advisories*

2 pilots out of three follow the RA. In the following sections, we try to find an explanation to why pilots happen not to react.

5.2.4.1 Relation with operational geometry

Geometry	1000-ft level-off	Unresolved	Radar horizontal separation	Military threat	Parallel approach	Strategic segregation of airspace

Cat A	99	38	10	5	1	1
Cat B	5	2	0	0	0	0
Cat C	37	17	5	3	3	1

Tab. 5.5 *Pilots' reactions according to operational geometry*

During 1000-ft level-offs, radar horizontal separations and parallel approaches, the pilots are informed by ATC or may expect an alert on the basis of their experience with those kinds of operational situations. Also when the controller gave a traffic information, the pilot may manage a visual acquisition of the threat. These reasons should explain the high level of not followed RAs during those geometries.

When the conflict has been overlooked by ATC, the number of not followed RAs reaches 30%. This bad performance is difficult to explain except by the lack of confidence of the pilot in its TCAS compared with ATC.

The worst behaviour (moving but without complying with TCAS instructions) is fortunately rare and limited to two operational geometries. They are probably the mark of pilot's confusion in front of conflicting ATC and TCAS instructions.

5.2.4.2 Relation with reported RA types

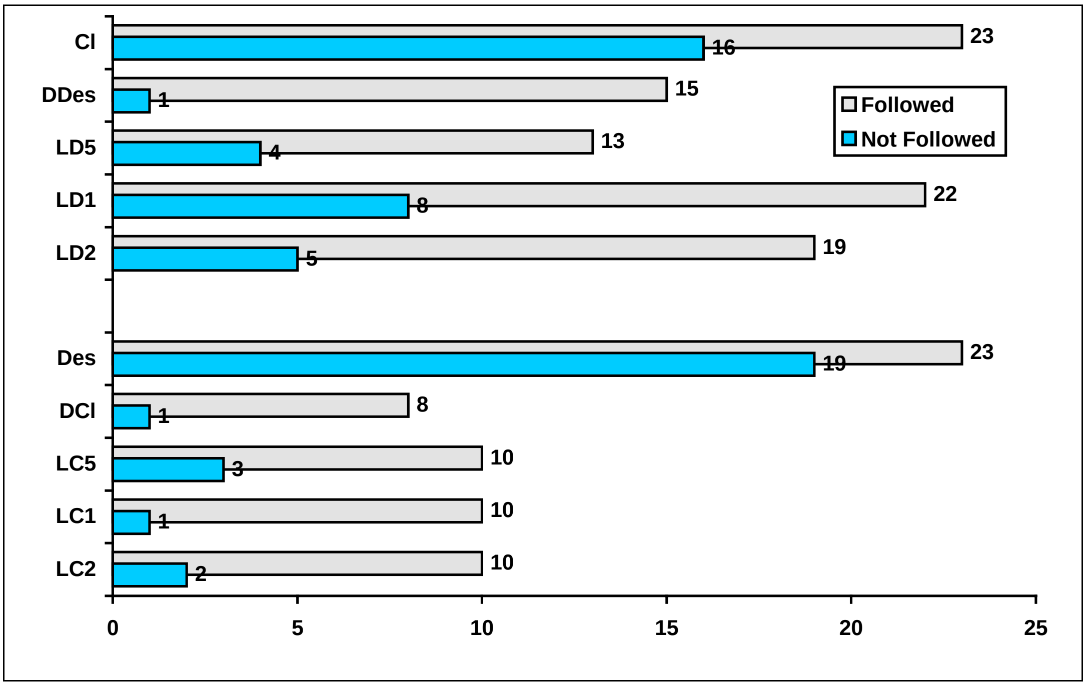

Fig. 5.4 *Pilot's reaction according to reported RA type*

<u>Note</u>: In Fig. 5.6, Category B and C have been merged in 'not followed', for simplicity's sake. As some events didn't produce RAs when replayed, the total of events is less than 227.

The straight RAs (Climb and Descend) are less followed than the less constraining ones, which is not surprising since they require less effort and stress from the pilot.

Nonetheless, such a behaviour, also highlighted in [4] is a source of degradation of overall TCAS performance and thus, a safety concern.

5.2.5 Vertical deviation

The deviation is computed by drawing a rectangular box, whose one of the diagonal starts on the point where the aircraft alters its flight profile to follow the RA, and ends on the point where it resumes its previous trajectory.

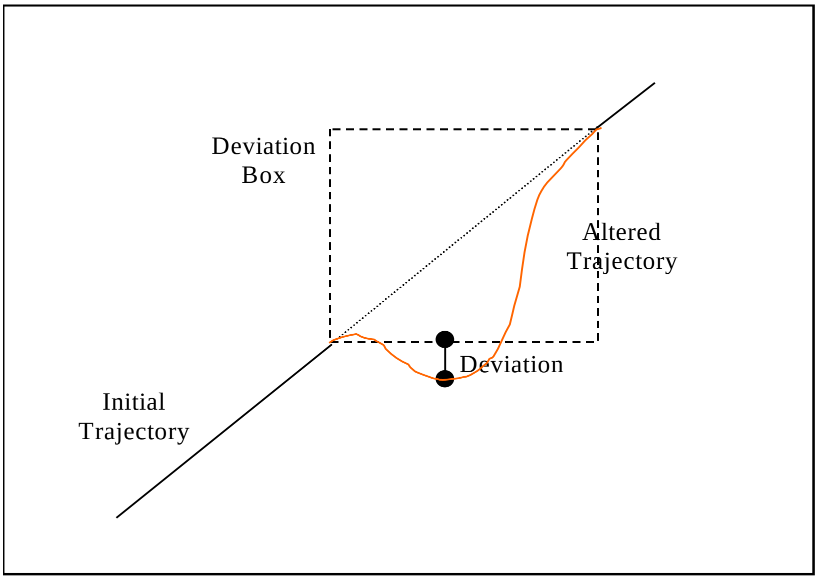

Fig. 5.5 *Deviation measure*

If the trajectory between these two points stays inside the box, there is no deviation. Otherwise, the greatest distance between the part of the trajectory that is outside the box and the nearest point of the box is the measured deviation. The deviation given by this method is the most significant from the ATC standpoint.

The results gave three kinds of deviation:

No deviations: the deviation box could not be built because the aircraft did not alter its trajectory. 69 events were in this case;

Zero deviations: the aircraft did not move outside of the box. 101 events were in this case;

Positive deviations: the distribution of events with positive deviations is presented in Fig. 5.4, by bands of 100 feet of deviation.

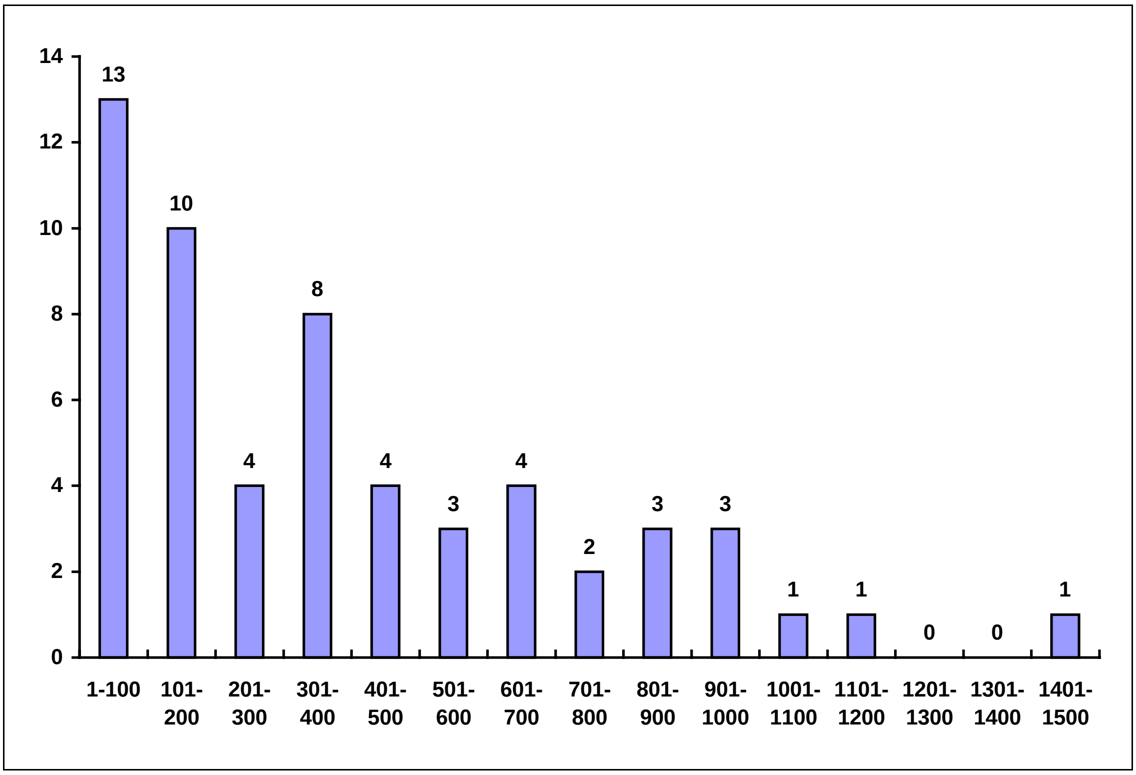

Fig. 5.6 *Distribution of events according to deviation band*

A majority of events do not induce deviations. For those who do, the events with a deviation greater than 600 ft are few (15). However, they can be very disruptive for ATC.

The average deviation (computed with only positive deviations) is 428 ft. It is much better than the deviation computed in the ACAS operational monitoring for 1996 [5], which was 643 ft. The 215-foot difference may well be the consequence of an over-representation of high deviation events in controller reports, as they are more disturbed by this kind of event.

5.2.5.1 Relation with operational geometry

Geometry	1000-ft level-offs	Unresolved	Radar horizontal separation	Military threat	Parallel Approach	Strategic segregation of airspace
Minimum deviation	60	150	100	100	975	N/A
Maximum deviation	966	1180	870	1492	975	N/A
Average deviation	333	549	436	564	975	N/A

Tab. 5.6 *Deviation and operational geometries*

Only one event of parallel approach is accounted for in Tab. 5.6, so the average deviation is not significant for this operational geometry.

1000-ft level-off geometries lead to low deviations since the RA is often just a limitation of the vertical rate when the TCAS aircraft is the one levelling-off or the Clear of Conflict is quickly issued when the threat aircraft is the one levelling off.

Military threat geometries provide the highest average deviation and the highest maximum deviation of the whole sample.

5.2.5.2 Relation with reported RA types

Type	Cl	DDes	LD2	LD1	LD5	Des	DCl	LC2	LC1	LC5
Minimum deviation	75	60	142	175	575	90	75	100	100	75
Maximum deviation	1492	1000	480	175	575	863	500	374	1100	100
Average deviation	633	458	280	175	575	310	288	237	467	88

Tab. 5.7 *Deviation and types of RA*

In general, the deviation is all the smaller than the RA is less constraining, which is not surprising. As there are few data for each RA type, a single exceptional deviation can easily influence the average, which explains the outstanding figures for LD5 and LC1.

The upward instructions seem to generate higher deviations than the downward ones. The pilot is more easily climbing to avoid a threat than descending. Maybe because, when the threat is above, he is more confident that he will be able to see it though the cockpit windshield?

5.2.5.3 Relation with pilot’s reactions

Category A pilots (who follow the RA) achieve an average deviation of 444 ft.

Category B pilots achieve a lower average deviation: 212 ft. These pilots react to the RA but not strongly enough to achieve the required vertical speed, so they don’t climb or descend as much as Category A pilots.

Category C pilots don’t deviate from their trajectory.

5.2.6 Compatibility with ATC

To determine whether a TCAS instruction is compatible with ATC, we looked at the vertical trajectory of the TCAS aircraft. If the alert did not change the vertical profile of the aircraft, it was deemed as compatible.

For the 57 unresolved events, the compatibility could not be estimated since ATC is supposed not to have influenced the trajectory.

Among the 170 events where ATC was involved, 103 (60%) had an ATC compatible TCAS alert and 67 (40%) a not compatible TCAS alert.

Note: (in)compatibility with ATC is not an indication of whether an event is necessary or not from a safety standpoint.

5.2.6.1 Relation with operational geometry

Operational geometry	1000-ft level-offs	Radar horizontal separation	Military threat	Parallel Approach	Strategic segregation of airspace
Compatible	91	7	2	0	2
Not compatible	50	8	6	4	0

Tab. 5.8 *ATC compatibility of operational geometries*

This high percentage of incompatible level-offs (65%) was anticipated since level-offs are known to be the main situation where ATC disturbing alerts occur.

When a military threat was present, 2 (25%) alerts were compatible and 6 (75%) were not compatible. The high performance of military aircraft often compels TCAS to issue long lasting alerts (leading to high deviations) or to reverse the manoeuvre direction.

During parallel approaches, no event was compatible since the pilot wants to land and TCAS can only offer upward instructions, so close to the ground.

5.2.6.2 Relation with reported RA types

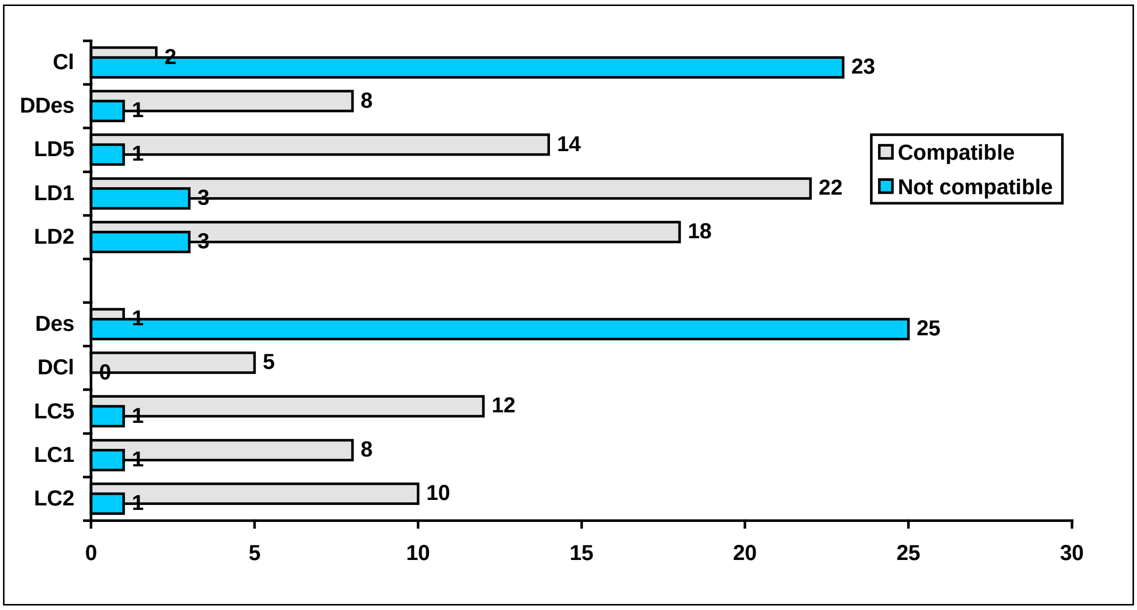

Fig. 5.7 *ATC Compatibility according to reported RA type*

The negative resolution advisories (Limit … or Don't…) are far more compatible (87%) with ATC than the positive resolution advisories (11%). A negative advisory is far less constraining than a positive one, since it may already be respected by the aircraft at the time of issuance. Hence the better compatibility.

5.2.6.3 Relation with pilots' reactions

ATC Compatible?	No	Yes
Cat A	29	87
Cat B	3	2
Cat C	37	14

Tab. 5.9 *ATC compatibility and pilot's reaction*

The pilots react and follow far more easily the RA when it is compatible with ATC.

5.3 Correlation with human reports

5.3.1 ACAS monitoring reports

When TCAS became mandatory in the United States, many long-range aircraft from European fleets were equipped. European airspace authorities took advantage of this situation by starting an evaluation programme of TCAS, to assess its impact on safety and on ATC. Controllers and pilots were asked to fill in a report form after significant events. Now that the evaluation is finished, the report process has continued, but with the goal of monitoring the implementation of ACAS in Europe.

5.3.1.1 Quantity of correlated reports

We examined the collected Mode S events and matched them when possible with pilots and controllers reports.

Month	Mode S events	ACAS reports	Correlated events
Nov	24	2	1
Dec	34	5	2
Jan	24	9	1
Feb	45	9	1
Mar	17	10	1
Apr	25	7	1

May	0	9	0
Jun	15	10	0
Jul	34	14	3
Aug	36	6	4
Sep	37	12	3
Oct	12	9	2
Total	**303**	**93**	**19**

Tab. 5.10 *Monthly correlation of mode S events with pilots/controllers reports*

20 % of the reports could be correlated with a reported event. Such a low figure is understandable since the mode S station was not always available.

At least 66 % of the events are not reported by the pilots of the controllers. This was expected but we had no idea of the non-reporting level until now. In these cases, the pilot/controller probably didn't find the alert disturbing or unusual enough to file a report (or was too busy afterwards).

For the 19 correlated events, 14 resulted in corrective resolution advisories, requiring a trajectory change, which was performed by the pilot in 13 cases. Also 5 correlated events were without identified threat.

5.3.1.2 Comparison with operational geometry

Geometry	Number
1000-ft level-off	2 (13%)
Unresolved	8 (53%)
Radar horizontal separation	1 (7%)
Military threat	3 (20%)
Roissy parallel approach	1 (7%)

Tab. 5.11 *Correlated reports and operational geometry*

The distribution is very different from what it was for the Mode S events (cf. Tab. 4.1). As the decision to report is primarily based on the perception of the TCAS alert as a nuisance (at least for ATC) it is not surprising that the proportion of reports for 1000 ft level offs is far lower.

Conversely, the events involving military aircraft are 4 times more frequently reported than could be expected, should the number of reports be proportional to the number of events of the same type. Of course, such an alert is always disturbing for the pilot, who has not been warned of the military presence.

The unresolved cases make up the majority of reports because as their name implies, the conflicts have not been resolved by ATC.

5.3.2 Airprox reports

When a pilot thinks that a situation, in which its aircraft and another one were involved, was hazardous, he can file an 'air proximity' (airprox) report.

5.3.2.1 Quantity of correlated reports

We examined the collected Mode S events and matched them when possible with airprox reports. 9 airproxes could be correlated. For each of them, an ACAS monitoring report had also been filed. 3 airproxes corresponded to events without identified threats.

5.3.2.2 Comparison with operational geometry

Geometry	Number
Unresolved	1 (17%)
Military threat	4 (67%)
Roissy parallel approach	1 (17%)

Tab. 5.12 *Correlated airproxes and operational geometry*

Events involving military threat (called mixed airproxes) are the most significant here. But the data are not sufficient to speculate from this table.

5.4 Conclusion

The enhanced analysis of ACAS events was based on data acquired through ATC expert interpretation of raw situations. Being aware of this possible bias, the following results must be outlined:

The preponderance of level-off geometries (62%);

A good correlation between reported and simulated events;

Pilots usually follow the RAs. When they do not, it may be due to visual acquisition of the threat, but we can't estimate the proportion of visual acquisition, for lack of data;

Less important vertical deviations than in operational evaluation/monitoring of TCAS done through pilots/controllers reports;

A fair share of non ATC compatible events (40%), mainly due to level-offs. Comparing the compatibility with the necessity of the events would have been interesting, but the context information needed to assess the necessity of an event was not available.

The results obtained through automatic ACAS reports are significantly different from the results obtained through human ACAS reports during the operational evaluation/monitoring of ACAS mainly because humans report events which they consider important from their perspective.

6. Complementary study: analysis of a full week of recordings

6.1 Introduction

As the chain of acquisition of ACAS reports was, first, only recording data after being triggered by the presence of a presence-of-RA bit onboard and second, had not a continuous activity, we wished to perform a continuous recording over a short period.

A week seemed ideal to get a statistically significant sample without mobilising too many storing resources. September was chosen because it's one of the busiest months as regards air traffic. The week for which we could have a continuous recording goes from Monday 15 September to Monday 22 September 1997.

The goal of the continuous recording is not to re-do the analyses of the former chapters but to get reliable figures about heretofore unknown or roughly estimated parameters, placing the TCAS aircraft in context with the rest of the fleet.

6.2 Methodological details

6.2.1 Mode S station recording

During this week, all the information coming from the Mode S radar of Orly were recorded. They were stored in ASTERIX format files and represent 218 Mb. The total recording time was 169h 29mn 14s, that is a bit more than a week.

As described in section 2.1, each TCAS equipped aircraft transmits information about its ACAS configuration to the ground. This feature allowed to count the flight time of the TCAS-equipped aircraft for each configuration:

No ACAS: the aircraft is not equipped;

ACAS in stand-by mode: no advisories are generated;

ACAS in TA-only mode: TCAS only issues traffic advisories;

ACAS in standard mode: TCAS can issue traffic advisories and resolution advisories.

Unfortunately, the information necessary to discriminate between the case where TCAS is in stand-by mode and the case where TCAS is not present do not exist in the ASTERIX format used.

6.2.2 SSR stations recordings

The Mode S radar only detects Mode S-equipped aircraft. Getting the complete information about the traffic flying in the Mode S radar coverage required the recording of the SSR radars of Avranches, Palaiseau and Nevers.

The following map shows how the coverage of all those radars overlap.

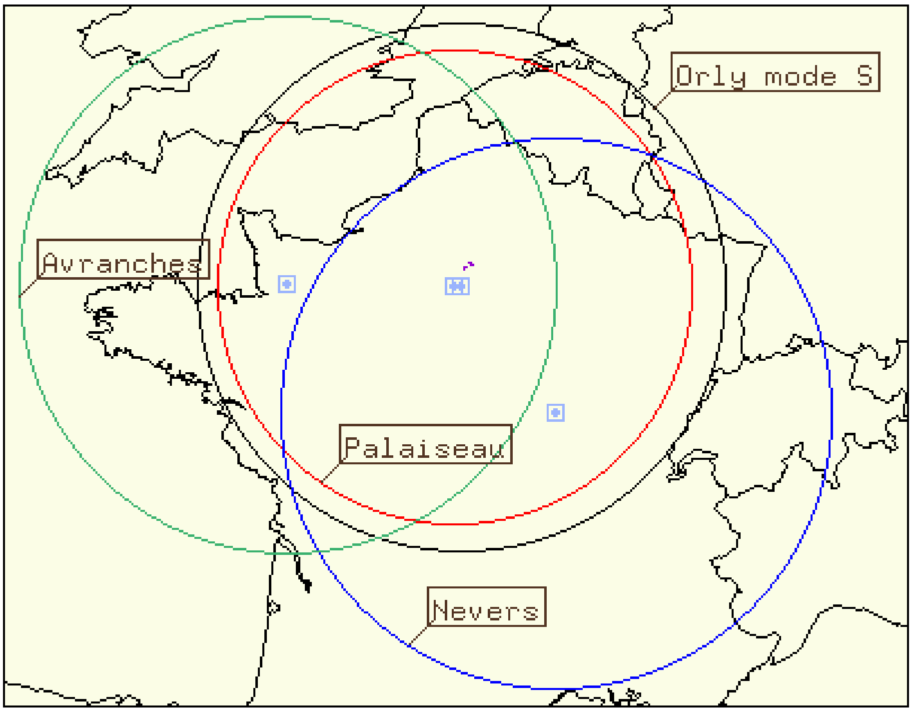

Fig. 5.1: Overlap of radar coverages

There exists a section of ring covered by the Orly mode S radar that is not covered by an SSR. Located in the northeast quadrant, it represents 4 % of the total mode S radar coverage. In the following analyses, corrections will be made to take this blind spot into account.

6.3 Quantitative analysis

6.3.1 The TCAS-equipped fleet

The recording period allowed to perform the following study on 1610 different TCAS equipped aircraft, from 67 different countries.

The following table presents the number of TCAS-equipped aircraft for the most equipped countries.

United States	331	Italy	20
Germany	240	Denmark	19
United Kingdom	220	Turkey	18
France	140	United Arab Emirates	16
Switzerland	63	Saudi Arabia	15
Netherlands	61	Malaysia	13
Canada	45	Brazil	13
Belgium	30	Australia	13
Singapore	27	Ireland	13
Japan	24	South Korea	12
Spain	24	South Africa	12
China	23	Sweden	11
Austria	23	Unknown	11
Israel	21		

Tab. 6.1 *Number of TCAS aircraft per country*

6.3.2 Total flight time

For technical reasons, we couldn’t record the SSRs simultaneously with the Orly mode S radar recording. The SSR data were recorded the following week, over 4 days, from 26 to 29 September 1997, yielding a continuous recording duration of 96 hours.

The cumulated flight hours of all aircraft give an average of 3984 flight hours per day. Extrapolated to a week (169h 29 m 14s), the total flight time is 27.500 flight hours.

6.3.3 Number of movements

During the recording period, 26.569 movements of mode S aircraft occurred, in 15.564 flight hours. Assuming that the mode S equipped aircraft don’t fly more (or less) than the others, the extrapolation of the number of movements for 27.500 flight hours is 50.168, that is 7.166 movements per day.

Statistics for the Northern French ACC indicate 5016 movements per day. The difference with our own figure comes from the 1970 movements over the Belgium/Luxembourg territories, some movements controlled by other French ACCs and some movements in the United Kingdom. Also, an aircraft flying over France then Belgium was accounted as a single movement.

Over 50.168 movements, there were 26.569 movements of mode S equipped aircraft, that is 53 %, and as 10.387 movements are made by TCAS-equipped aircraft, **the TCAS equipage rate of the fleet is 22 %**.

Over 10.837 movements of TCAS equipped aircraft, 97 are in ‘stand-by’ mode or in ‘traffic advisory only’ mode.

6.3.4 Duration of a flight

Overall, there were 5829 flight hours of TCAS equipped aircraft, distributed as follows:

862 flight hours in ‘stand by’ mode (15%);
128 flight hours in ‘traffic advisory only’ mode (2%); and
4839 flight hours in ‘resolution advisory’ mode (83%).

Inside the Orly radar coverage, each TCAS-equipped movement fly an average time of 33 minutes, distributed as:

5 minutes in ‘stand-by’ mode;
1 minute in ‘traffic advisory only’ mode; and
27 minutes in ‘resolution advisory’mode.

Here is a summary of the different types of flight hours computed in the recordings:

Mode S equipped aircraft	TCAS equipped	5829	21%
	Others	3768	14%
Other aircraft		17903	65%
Total flight time		27500	100%

Tab. 6.2 *Flight hours summary*

6.3.5 ACAS events

Over one week, 12 ACAS events occurred. However 2 events came from the same aircraft and contained erroneous resolution advisories. They won’t be considered in the future. After being processed by OSCAR, only 7 events revealed a potential threat in the vicinity of TCAS aircraft.

The 10 valid events occurred within a 169 h 29 mn 14 s period and for 10837 movements of TCAS equipped aircraft. The average time between two events is then 17 h and 1084 movements of TCAS equipped aircraft happen on average between two events.

One event occurs every 583 flight hours. In 1996, the figure computed by Air Inter Europe, during a one-year single-aircraft TCAS evaluation, was one event every 175 flight hours. The large difference between the two results is probably explained by the greater-than-average number of vertical manoeuvres made by a short-range aircraft, which make it more liable to conflicts with other flights.

Out of the 7 events with identified threat, 5 are 1000-ft level-offs, between FL180 and FL310. One of the 5 level-offs is co-ordinated.

6.4 Conclusion

The analysis of a week of traffic, recorded continuously by the Orly mode S station allowed to measure a number of parameters, the most significant of which are:

At the time of the study, the TCAS equipped aircraft represented 22 % of the fleet and belonged to 67 countries.

One TCAS event occurs every 580 flight hours

One TCAS event occurs every 17 hours, that is 2.8 events every 2 days, which is in line with the result obtained in the main study (cf. section 3.2.2).

7. Conclusion

The sample of data collected through WINTSAR gathered 1109 ACAS automatic reports, making up 343 events, sent by 245 different aircraft and distributed over 321 files.

The validity analysis of the data showed that a significant number of wrong messages are either transmitted by aircraft or “created” by the chain of acquisition of mode S data. Also, the chain of acquisition was unfortunately not working continuously, thus requiring to extrapolate received data. Of course, these flaws are not surprising, for a system which is still in pre-operational status.

Despite them, it was possible to perform a basic analysis on 303 events, confirming that events occur mainly in high-density areas. Surprisingly, events occur more often between 10 and 14 o’clock. Overall 3 events occur every 2 days, and if the fleet was fully equipped, this number would raise to at least 13 events. Upward advisories are more numerous than downward advisories, because the geometries of aircraft favour the upward sense.

Identification of potential threat in 227 events led to an deeper analysis of them and the 210 encounters they form. 1000 feet level-offs make the bulk of them. Pilots who did not follow the RAs were the minority and the deviations entailed by complying with TCAS instructions are acceptable on average (428 ft), although many of them (40%) may still be a source of concern for controllers.

The main regret and limitation of the current report is that the automatic reports do not provide information about the context of each event. Among others, it would have been useful to assess the proportion of visual acquisition and the necessity of each event, safety-wise. This kind of information can be found in pilots and controllers reports. Unfortunately, too few reports are correlated to a mode S event.

The operational evaluation of TCAS ([3] and [6]) was based on human reports. The results obtained through their analysis were significantly different than the automatic reports based results described in this report mainly because humans report events which they consider important from their perspective.

However, it does not mean that human reporting can be discontinued in favour of automatic reporting. Apart from being an essential source of information when thoroughly analysing a puzzling or worrying event, pilots’ and controllers’ reports highlight how these people perceive TCAS and what are the situations which have the greatest impact on them and their work. Human and automatic reports are complementary tools for ACAS studies.

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Abbreviations

ACAS	Airborne Collision Avoidance System
ACC	Area Control Centre
ANC	Air Navigation Commission
ASTERIX	All purpose Structured Eurocontrol Radar Information eXchange
CENA	Centre d'Etudes de la Navigation Aérienne
ICAO	International Civil Aviation Organisation
MADREC	Maastricht Data RECording
OSCAR	Off-line Simulator for Collision Avoidance Resolution
PC	Personal Computer
RA	Resolution Advisory
RADAR	RAdio Detection And Ranging
RDPS	Radar Data Processing System
SSR	Secondary Surveillance Radar
STNA	Service Technique de la Navigation Aérienne
TA	Traffic Advisory
TCAS	Traffic alert and Collision Avoidance System
TMA	TerMinal control Area
WINTSAR	WINdows Tool for Selective ASTERIX Recording

ACAS PROGRAMME

ACASA PROJECT

Annex B to

Work Package 7

Final report on
Mode S Monitoring for ACASA

Edition 1.0
March 2002

Annex B to Work Package 7

Final Report for the Mode S Monitoring for ACASA

Version 1.1, March 2002

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ACASA
WP – 7.3
Mode S Monitoring for ACASA – Final Report

Mike Sharples and Yvonne Etem, DERA Malvern

1 Introduction

1.1 This report details an extended Mode S monitoring exercise carried out at DERA Malvern, using the NATS experimental Mode S groundstation, in support of the ACAS project. It follows on from an earlier interim report ACASA/WP7.3/1 issued in December 1999.

1.2 The monitoring exercise for this latest report has made use of data recordings made over a period from 7 January 2000 to 16 August 2000 inclusive. Over this period, recordings were collected on 14 separate days. Many of these recordings were made on behalf of NATS for other purposes, but contained the required information to support this ACASA study.

1.3 As with the interim report, no development of either the hardware or software of the Mode S ground facility was carried out. All analysis has been achieved using information extracted from aircraft during the normal target acquisition process. However, due to less stringent time constraints on this occasion, significantly more data has been collected and this has been subjected to more detailed analysis.

2 Objectives

2.1 The principal objectives of this exercise were:

To collect representative samples of aircraft data on a number of different days, over several hours, at different times of day;

To decode aircraft parameters that relate to ACAS operation;

To detect anomalies in the decoded data that may have an impact on ACAS operation;

To estimate the frequency of occurrence of anomalies in the decoded data.

2.2 The emphasis of the analysis was not to identify individual aircraft providing anomalous data, but rather to identify the type and probability of such occurrences.

3 Experimental configuration

3.1 Recordings were made using the NATS' Mode S ground station at DERA Malvern. The data collection was performed by a component of this experimental configuration known as the Private Specific Services Entity (PSSE). This is a PC based element which controls the data link activity of the ground station and which maintains a record of *Target Acquisition* and *Target Relinquish* reports generated by the ground station.

3.2 The *Target Acquisition* reports contain capability and identity information from each aircraft acquired by the ground station and this is the key information which has been used as the basis of all subsequent analysis. The following information is contained in each *Target Acquisition* report:

Time of acquisition;

Target Address;

Surveillance position (range; azimuth; altitude);

Mode A code;

Transponder capability;

BDS 1,0 (data link capability report);

BDS 2,0 (aircraft identification).

3.3 The *Target Acquisition* reports from the PSSE were recorded as text files from where they could be transferred to another PC. Here the recordings were imported into Microsoft Excel, where the analysis was carried out.

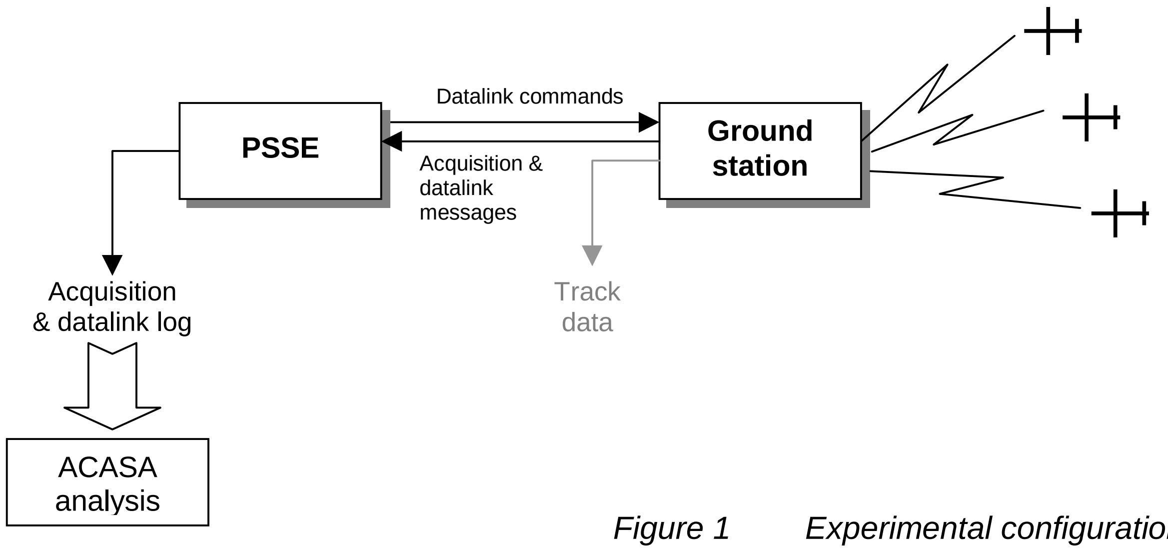

Figure 1 Experimental configuration

4 Data recordings

4.1 The following table summarises the data recordings used in this analysis.

	Date	Total number of unique aircraft observed
1	7 Jan 2000	712
2	21 Jan 2000	714
3	2 Feb 2000	841
4	3 Feb 2000	1048
5	8 Feb 2000	620
6	11 Feb 2000	732
7	14 Feb 2000	596
8	21 Feb 2000	737
9	28 Feb 2000	789
10	6 Mar 2000	870
11	10 May 2000	861
12	16 May 2000	1046
13	1 Aug 2000	1188
14	16 Aug 2000	1153
Total aircraft observations		**11907**
Overall sample size		**3243**

Table 1 Summary of recordings used in analysis

4.2 The table indicates that the data sample used for this latest analysis was extensive. However, it must be recognised that air traffic observed from a single station cannot be considered as a complete cross section of the aircraft population. The aircraft of some national authorities and of some airlines will never pass within the coverage of the Malvern radar.

5 Analysis

5.1 The recordings have been analysed in the following areas:

- Illegal Aircraft Address;
- Duplicate Aircraft Address;
- Flight status;
- ACAS & Data Link Capability Reporting;
- Altitude Reporting;
- Incorrect Broadcast Protocol.

5.2 The analysis has been carried out using Microsoft Excel. Existing Excel features such as the sort and filter functions were used extensively, and it was also necessary to develop specific Visual Basic procedures to perform more complex manipulations of the data.

5.3 Each of these analysis categories is fully explained and reported in the following sections of this report.

6 'Illegal' Aircraft Address

6.1 Aircraft responding to Mode S interrogation must necessarily provide a unique 24 bit aircraft address. These addresses have been allocated in blocks based upon nationality of registration. All aircraft addresses were checked for 'legality' in the following respects:

The presence of targets using the addresses 000000 or FFFFFF;

The presence of targets using addresses which did not fall within known block allocations for national registration.

6.2 Targets using 000000 or FFFFFF represent a serious breach of Mode S operating practice because these addresses will cause conflict with normal Mode S protocols. Such breaches were regularly observed by the Malvern facility in the early 1990's when Mode S transponder installation on commercial aircraft first became widespread. Had this situation continued, it would have represented a serious detriment to the operation of ACAS and Mode S Surveillance.

6.3 The current analysis has found two examples of address 000000[1] but no examples of address FFFFFF. This represents less than 0.1% of the observed population. The finding confirms a more general observation over recent years that the problem has now been reduced to a minimal level. However, the problem does still exists and therefore is a cause for concern.

6.4 The use of aircraft addresses outside known national block allocations does not itself create a problem for ACAS or Mode S. However, it does give cause for concern that some address allocation is not being properly regulated and so the potential for duplication of addresses exists.

6.5 The data sample used for this report indicated an occurrence of 'suspect' addresses at a rate of approximately 0.3%. One of the addresses was FFFFFC, which is clearly suspicious. Others appear to belong to definite but unrecognised block allocations, some even showing sequential numbering. The complete list of suspect addresses is as follows:-

Suspect aircraft addresses
05AD70
511001
89908A (see footnote[2])
8BFAB0
9754C3, 9754C5, 9754C6, 9754C8
CCA104
FFFFFC

Table 2 Suspect aircraft addresses

[1] From observations on 08 Feb 2000 and 10 May 2000 respectively. These are believed to be different aircraft based upon a difference in altitude reporting capability.
[2] This address may be an ICAO temporary allocation.

7 Duplicate addresses

7.1 The Malvern radar facility does not permit two or more targets with identical addresses to be tracked simultaneously. Therefore it would not be possible to observe the acquisition of a duplicate target until the original target was relinquished. The following techniques were employed to establish the existence of aircraft addresses duplicated on different airframes:-

> Comparison of the time and position of *Target Acquisition* reports with duplicate addresses;
>
> Comparison of reported aircraft capability within *Target Acquisition* reports with duplicate addresses.

7.2 This analysis was applied to one of the largest of the collected data samples, namely 1 August 2000 (see Table 1). In the absence of any positive indication of a potential problem, the analysis was not continued through the remaining data samples.

7.3 As stated in 7.1, a duplicate *Target Acquisition* cannot be observed (with the Malvern system) until the original target has been relinquished. However, a comparison of the time and position of *Target Acquisition* reports does indicate a probability that the two sequential, duplicate *Target Acquisitions* cannot be attributed to the same aircraft. The validity of this technique was confirmed by positive identification of several potential duplicate addresses. However, in all cases, through a further check of relative positions and Mode A code, it was possible to confirm that all of these cases were caused by temporary target acquisition via reflections off the Malvern Hills.

7.4 The comparison of reported aircraft capability was believed to offer another potential indicator of address duplication. Identically addressed *Target Acquisitions* with substantially different capability reports may indicate address duplication.

7.5 A large number of such cases were identified. However, in the majority of cases it was possible to confirm that the suspect aircraft was capable of changing its reported capability in mid flight. Reported changes in ACAS capability, Aircraft ID capability and even changes in Subnetwork Version[3] during flight were sufficiently frequent to eliminate any indication of a problem with duplicate addressing.

7.6 In conclusion, the analysis has provided no evidence of the presence of duplicate aircraft addresses in the aircraft population. It has given some positive indication that duplicate addressing is not occurring. However, the analysis has been far from conclusive. A more rigorous monitoring capability would be required in order to obtain more definite results. This would require changes to the Malvern radar facility, which were beyond the scope of this present study.

[3] The incorrect reporting of Subnetwork Version is an observed problem which is discussed later.

8 Flight status

8.1 The 3-bit FS field is extracted from a Mode S transponder that is interrogated for DF4, 5, 20 or 21 type replies. FS values of 1 or 3 indicate that the aircraft is on the ground and must not be provided by an aircraft in flight. FS values of 6 or 7 are unassigned and should not be provided by any aircraft.

8.2 No aircraft were observed reporting FS values of 6 or 7.

8.3 A total of five aircraft were observed reporting a FS value of 1. In three cases, these same aircraft were observed during the same flight with an FS value of 0. The transient nature of these occurrences would indicate a fault within the transponder logic rather than a fault in the 'grounded' sensor or its connection.

8.4 The CA field obtained from DF11 replies (representing transponder capability) was checked for all five aircraft. In four cases the value of CA was 1 indicating transponder installations pre-dating Amendment 71[4]. In one case, the CA value was seen to transit between 5 and 7, indicating a transponder installation to at least Amendment 71.

8.5 It should be noted that ACAS systems obtain Vertical Status information from the VS field of DF0 or DF16 (air-to-air) replies, which were not investigated here. However, it is likely that any error in FS would be also be reproduced in VS. Therefore any aircraft reporting FS incorrectly, particularly with regard to "in the air / on the ground" status, should be treated as a potential problem for ACAS.

8.6 Table 3 below summarises the anomalies in Flight Status reporting.

Aircraft Address	Reported transponder capability (CA)	Both FS=1 and FS=0 states observed for this address	FS change observed within a single flight	Date of FS=1 observation
40063F	1	✓	✓	16 Aug 2000
4006A5	1	✓	✗	1 Aug 2000
400843	5 / 7	✓	✓	21 Feb 2000
484014	1	✓	✓	6 Mar 2000
C04E7B	1	✗	✗	16 Aug 2000

Table 3 Aircraft reporting anomalous Flight Status

[4] Amendment 71 to the International Standards and Recommended Practices / Aeronautical Telecommunications / Annex 10 to the Convention on International Civil Aviation / Volume IV, March 1996.

9 ACAS & data link capability

9.1 The *Target Acquisition* report provides the complete contents of BDS 1,0, which is the “Data link capability report”. This report includes information on ACAS capability and current status.

9.2 In this analysis it was found that aircraft would commonly change their ACAS status during flight. Instances of ACAS being switched off were observed and also changes from ‘TA & RA’ operation to ‘TA only’.

9.3 In the cases of ACAS being switched off, aircraft became indistinguishable from ones which did not have ACAS fitted, i.e. both ‘bit 48’ and ‘bit 70’ would be set to zero. Hence it is not straightforward to gain a totally accurate picture of the proportion of ACAS equipped aircraft.

9.4 Table 4 summarises ACAS status based upon samples of over 1000 aircraft (as detailed in Table 1). The samples cover a period of over 6 months and so the variation in ACAS and ‘Change 7’[5] capability may actually indicate a trend.

9.5 The indication of ‘Change 7’ should show installation of both a ‘Change 7’ ACAS unit and a ‘Change 7’ compliant Mode S transponder. An installation level approaching 2% is actually higher than might be expected at the current time and there are grounds to suspect that the indicator may not reflect a true ‘Change 7’ capability. This could only be confirmed through inspection of RA reports generated by the aircraft or by contacting the aircraft operator. Such confirmation was beyond the scope of the current study.

Date of sample	Sample size	ACAS off or not fitted	ACAS TA only	ACAS Change 7	ACAS III
3 Feb 2000	1048	11.3%	0.7%	0.4%	0%
16 May 2000	1046	12.1%	2.1%	0.7%	0%
1 Aug 2000	1188	7.9%	0.8%	1.7%	0%
16 Aug 2000	1153	8.9%	0.6%	1.8%	0%

Table 4 Reported ACAS capability

9.6 Other aspects of the BDS 1,0 ‘Data link capability report’ have also been analysed. Although these do not relate directly to ACAS operation, certain anomalies have indicated that a proportion of aircraft may not be properly compliant to the ICAO SARPs requirements. This may therefore be of concern to ACAS performance, which is dependent upon accurate operation Mode S transponders.

9.7 A significant number (approximately 7%) of aircraft were providing unusual values in the ‘Subnetwork version number’ field. Normally this would be expected to contain 0, 1 or 2 to reflect compliance with a particular version of the Mode S Subnetwork SARPs. However various values between 6 and 118 were observed. In a small number of cases, these were observed to change in mid-flight.

[5] Installations compliant to Amendment 73 of the International Standards and Recommended Practices / Aeronautical Telecommunications / Annex 10 to the Convention on International Civil Aviation / Volume IV

9.8 In the majority of cases, the aircraft reporting these unusual values reported that they did not have Mode S Specific Services capability – a clear contradiction. As most of these targets were also reporting transponder capability (CA) to the older Amendment 69 standard, it is reasonable to conjecture that these are old installations which are contravening current ICAO SARPs requirements.

9.9 A small number of aircraft (approximately 1%) were found to be claiming ID reporting capability but were not reporting Aircraft ID. Notably, these were all reporting transponder capability (CA) to the Amendment 71 standard, indicating relatively recent installations.

10 Altitude reporting

10.1 Mode S altitude reporting can be provided in metres or feet. In the latter case, it may be reported in 25ft or 100ft intervals. The proportion of the aircraft population reporting 25ft capability was approximately 93%, based upon the largest data samples (greater than 1000 unique aircraft) used for this analysis.

10.2 Currently there is no mandate for aircraft to report height to 25ft intervals. However it is imperative that, if an aircraft states a 25ft reporting capability, the altitude reports are indeed provided with this stated resolution. If this is not the case, vertical tracking problems may be encountered by ACAS and other systems.

10.3 The analysis of *Target Acquisition* reports, which forms the basis of this report, allows the type of altitude reporting to be identified but would not normally facilitate checking the resolution of reported altitude against this claimed capability. However, approximately 10% of all observed aircraft currently demonstrate a problem of continuous broadcast announcement (discussed in the next section). The consequence of this is that the Malvern facility generates *Target Acquisition* reports for such aircraft at regular and frequent intervals, which in turn permits the monitoring of altitude over time. Hence, approximately 10% of the aircraft population could be monitored for true altitude reporting resolution.

10.4 The analysis raised suspicion about a significant number of aircraft – approximately 5% of the population that could be monitored in this way. This suspicion was based upon extended periods of level flight (in one case exceeding 40 minutes without a single deviation) or short periods of climb or descent that were observed to contain only 100ft multiples in every report. Although suspicious, this evidence is not conclusive because:

Many other aircraft in the data samples illustrated the ability to perform altitude keeping very accurately, with 25ft deviations occurring only occasionally.

A climb or descent involving few monitored points may demonstrate only 100ft intervals purely as a consequence of the probabilistic nature of random sampling.

10.5 Although inconclusive, the evidence is sufficient cause for concern to suggest a more rigorous investigation should be performed. Such an investigation could be carried out at Malvern based upon *track data* rather than *Target Acquisition* reports (see Figure 1) by making some relatively straightforward modifications to the system. This would allow all of the aircraft in coverage to be monitored instead of a small subset.

11 Incorrect broadcast protocol

11.1 Approximately 10% of the targets monitored were found to be continuously announcing *Downlink Broadcast* messages. This situation is unchanged since the interim report issued in December 1999.

11.2 The fault was characterised by a continuous presence of DR=4 or DR=5 in *Roll Call* replies, and in the presence of CA=7 in *All Call* replies throughout the period that the targets were in coverage. Normally, *Downlink Broadcast* messages should timeout after 18 seconds.

11.3 The nature of the problem observed would indicate a fault in transponder logic rather than the continuous existence of information requiring transmission. This is concluded from the fact that the DR value was seen to remain fixed at either 4 or 5 (usually 5), rather than alternating between these two values to indicate a new message to be downlinked.

11.4 The problem appeared to be almost exclusive to transponders operating to at least Amendment 71 standard[6], as indicated by the value of the CA field in *All Call* replies. Only one instance of a similar problem was observed with an older transponder installation[7] – and in this case the DR value was seen to alternate between 4 and 5 indicating that a different mechanism was responsible.

11.5 While this observed fault does not have a 'first order' impact on the operation of ACAS, there are two significant concerns. Firstly, any unnecessary Mode S interrogations and replies have a degrading effect on the RF environment. Secondly, any evidence that transponders are not fully compliant to the relevant SARPs is a matter of concern for systems that rely on the accurate operation of Mode S.

[6] Amendment 71 to the International Standards and Recommended Practices / Aeronautical Telecommunications / Annex 10 to the Convention on International Civil Aviation / Volume IV, March 1996
[7] An observed CA value of 1 indicating a transponder operating to Amendment 69 standard.

12 Conclusions

12.1 General

The traffic recordings analysed for this report represent a sample of 3243 aircraft. This is believed to be a significant proportion of the total, Mode S equipped, aircraft population. However, it must be recognised that air traffic observed from a single station cannot be considered as a complete cross section of the aircraft population. The aircraft of some national authorities and of some airlines will never pass within the coverage of the Malvern radar.

12.2 'Illegal' aircraft address

The allocation and control of aircraft unique 24-bit addressing now seems to be well regulated at an international level. Only two instances of 'illegal' addresses which may disrupt Mode S operation were identified. This represents less than 0.1% of the observed population.

Approximately 0.3% of addresses were observed to be 'suspect' in that they did not belong to recognised national block allocations. Although this does not represent a direct problem for Mode S or ACAS, any incidence of address allocation that is not properly regulated indicates a potential risk of address duplication.

12.3 Duplicate aircraft address

Other than the 'illegal' addressing noted above, the analysis has provided no evidence of the presence of duplicate aircraft addresses in the aircraft population. It has given some positive indication that duplicate addressing is not occurring. However, the analysis is far from being conclusive. A more rigorous monitoring capability would be required in order to obtain more definite results. This would require changes to the Malvern radar facility, which were beyond the scope of this present study.

12.4 Flight status

Occurrences have been identified of aircraft reporting a flight status (FS) 'on the ground' when airborne. It should be noted that ACAS systems obtain Vertical Status information from the VS field of DF0 or DF16 (air-to-air) replies, which were not investigated here. However, it is likely that any error in FS would be also be reproduced in VS. Therefore any aircraft reporting FS incorrectly, particularly with regard to "in the air / on the ground" status, should be treated as a potential problem for ACAS.

12.5 ACAS and data link capability

Analysis of the BDS 1,0 “Data link capability report” indicated approximately 90% of aircraft reporting ACAS II capability, with a small proportion (<2%) reporting ‘Change 7’ capability. No aircraft were reporting ACAS III capability. Anomalies were observed in the general usage of BDS 1,0, indicating a failure to be complaint with current SARPs in a significant number of cases (~7%). However these anomalies did not relate directly to ACAS.

The proportion of aircraft reporting ACAS ‘Change 7’ capability, although small, is still higher than might be expected at the current time. Therefore, there are grounds to suspect that this may not reflect a true ‘Change 7’ capability in all cases.

12.6 Altitude reporting

Approximately 93% of aircraft claim altitude reporting to 25ft resolution. However, there is some evidence that a very small proportion of these may only actually report altitude in 100ft steps – a potentially serious problem for any vertical tracking process. The evidence is not conclusive, but is sufficient to suggest further investigations are required.

12.7 Incorrect broadcast protocol

Approximately 10% of the targets monitored were found to be continuously announcing *Downlink Broadcast* messages. This situation is unchanged since the interim report issued in December 1999. While this observed fault does not have a ‘first order’ impact on the operation of ACAS, there are two significant concerns. Firstly, any unnecessary Mode S interrogations and replies have a degrading effect on the RF environment. Secondly, any evidence that transponders are not fully compliant to the relevant SARPs is a matter of concern for systems that rely on the accurate operation of Mode S.

13 Recommendations

13.1 A number of anomalies in aircraft installation have been identified in this report which may need to be pursued with avionics manufactures or airlines.

13.2 The number of aircraft reporting ACAS ‘Change 7’ capability is higher than might be expected at the current time (see 9.5). This may need to be pursued with operators or through monitoring of RA reports to ensure that ‘Change 7’ capability is fully supported in all cases.

13.3 Anomalies relating to illegal and ‘suspect’ aircraft addresses (Section 6) require the assistance of the ATC provider (NATS in this case) to be able to correlate target data (time of observation and Mode A code) to a flight number.

13.4 The analysis detailed in this report has made use of data available without modification to the Malvern radar facility. In the areas relating to duplicate aircraft addresses (Section 7) and altitude reporting (Section 10), far more conclusive evidence could be gathered from this facility through the provision of relatively straightforward changes to the system.

13.5 A sufficient number of anomalies have been identified in aircraft installation to indicate that an ongoing programme of monitoring may be desirable. This would suggest the development of a more automated system than is currently employed. This system could be designed to be completely stand-alone or to operate in conjunction with an existing facility such as the Malvern Mode S radar.

ACAS PROGRAMME

ACASA PROJECT

Annex C to

Work Package 7

Parallel monitoring of ACAS Related 1030 and 1090 signals

Edition 1.0
March 2002

Annex C to Work Package 7

Final Report on Parallel monitoring of ACAS related 1030 and 1090 signals

Version 1.1/1.2f, March 2002

WP-7.4

Parallel monitoring of ACAS related 1030 and 1090 signals

This paper includes the study on the implementation of a radio field monitor for ACAS and SSR as described in the ACASA workplan section 7.4. The version 1.2f of the study is the final version.

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1 Introduction

1.1 Problem Description

The amount of air traffic has been increasing in the past decades and all forecasts indicate that it will continue to do so in the future. The task of air traffic services is to provide the necessary air traffic control capacity at the existing high level of safety and to continuously examine all factors which could affect this capacity.
The high radio field loading results on the one hand from the large number of active ground-based interrogators (SSRs), of which only a few are operated by DFS and can thus be controlled directly by DFS, and, on the other hand, by the increasing number of airborne interrogators resulting from the introduction of the collision avoidance system TCAS/ACAS. Particularly in the case of high traffic density (such as in the Frankfurt area), the high radio field loading leads to a (potential) reduction in the detection probability. In other words, there is an increasing risk that an aircraft does not appear on the radar screen for a long period.
As long as ADS-B does not fulfil the performance requirements for a "sole means of surveillance" system, an independent location system must be provided. Experts in both Europe and the USA are therefore currently of the opinion that secondary radar cannot be completely dispensed with before the year 2015.
It is thus necessary to find a long-term solution to the above-mentioned problems in the area of the SSR infrastructure. The introduction of ADS-B does not reduce the load on the radio field in the SSR frequency band. In the meantime, it has become possible to reduce the radio field loading by introducing Mode S. DFS plans to provide a total of 11 Mode S systems by 2003. For the period until then, the detection probabilities close to the limit values which are currently observed, particularly in airspaces with high traffic densities, indicate that urgent action must be taken.
Measurements made in the past show peak loads in the SSR channels in some areas of the Federal Republic of Germany. A significant change in the loads, particularly in the vicinity of airports, is also expected as the result of the mandatory installation of ACAS II. Due to this obvious overlap and interdependence between ACAS and ground interrogators this study will not be limited to either of both systems but cover both. In order to determine the current status and to evaluate future developments, a system should be developed to permit determination and evaluation of the loads on both the interrogation and response channels. At the same time, the degree of equipment and/or the compliance with the specification should be analysed for both ACAS II and Mode S. For this reason, the aspects listed below should be discussed as part of a study on the implementation of such a system.

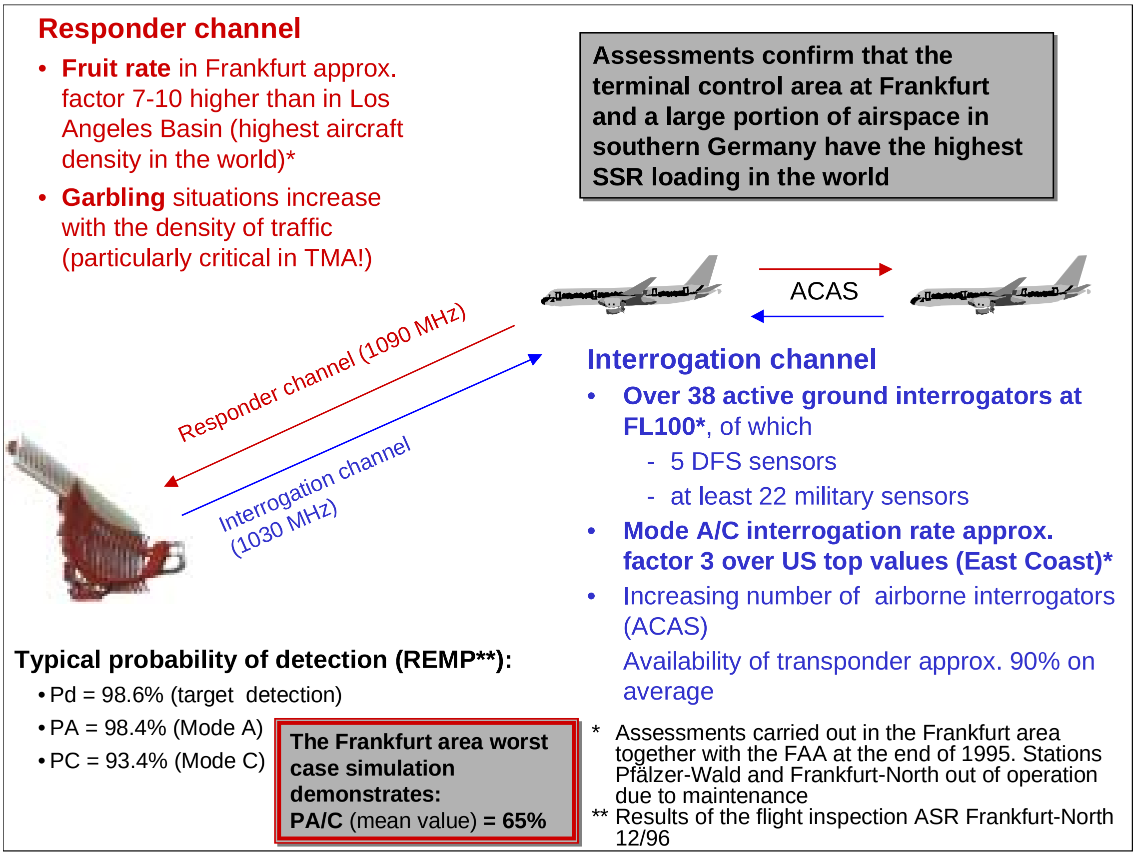

Fig. 1.1-1: Problems in today's system environment
(SSR radio field channel loading)

1.2 DFS Internal Task Description

The most recent examinations "Introduction of Mode S", under the management of a DFS working group and with participation by military representatives and the Federal Ministry of Transport, showed that solutions are needed urgently for both the small number of available SSR codes and, above all, the problem of high radio field loading.

A DFS internal coordination group with participation by military representatives discussed measures which were deemed appropriate for short-term and medium-term relief of the SSR radio field. In order to check the effectiveness and efficiency of these measures and to work out new measures, the coordination group drew up a set of tasks to be performed by an "SSR radio field monitor", which is outlined in Chapter 2.
This study on the implementation of an "SSR radio field monitor" system thus discusses the aspects which are relevant for performing these tasks.

Description of the necessary components and parameters of a system for:

measuring the SSR channels (without/with direction measurement),
determining the radio field loading (main and side lobes),
defining the airborne SSR equipment,
analysing the behaviour of ACAS II,

taking the following formats into account

Recognition:	**1030 MHz**	**1090 MHz**	**SSR/IFF**	**ACAS**
Mode 3A, C	Interrogation	Reply	x	(x)
Mode 1, 2, 4	Interrogation	Reply	x	
Suppressions	A, C, 1, 2, 3, 4, S, ACAS w/s	-	x	x
Mode S (short)	UF 0, 4, 5, 11	DF 0, 4, 5, 11	x	x
Mode S (long)	UF 16, 20, 21, 24	DF 16, 17, 20, 21, 24	x	x
Intermode	A/C/S, A-only, C-only	-	x	x

Decoding:	**1030 MHz**	**1090 MHz**	**SSR/IFF**	**ACAS**
Mode A, C	Main lobe	Frame	x	(x)
Mode 1, 2, 3	Main lobe	Frame	x	
Suppressions	P_2 , P_5	-	x	x
Mode 4	-	-	x	
Mode S (short) (0,4,5,11)	Format and telegram	Format and telegram	x	x
Mode S (long) (16,17,20,21)	Format and telegram	Format and telegram	x	x
Intermode (A/C/S, A-only, C-only)	Main and side lobes	-	x	x

From the table it is quite obvious, that most tasks are related to load contribution and surveillance performance of both grouns systems and ACAS. Only a few aspects are related to civil military coordination. But also these subjects influence ACAS surveillance performance to some extend.

1.3 Measuring concepts and recording methods

Possible measuring concepts and recording methods should be compared with each other:
online <-> offline evaluation
analogue <-> digital recording
evaluation levels (video, digital)
functional monitoring during measurement
correlation of the input data (selective interrogation / related reply)
possibility of modular / expandable design
correlation of the data with external sources

1.4 Evaluation methods

The following should be emphasised in the description of possible evaluation methods.

Which parameters and characteristic values must be determined?
Which results can be presented with these?
In which form can results be presented?
Which software is suitable?

1.5 Component availability, cost estimates and development costs

The following points would be of interest for the implementation of an SSR monitor.

How far can commercial components and systems be used as part of an SSR monitor?
Are any critical components (components which must be precisely specified or are difficult to manage) needed?
How many components which are in short supply and cause costs which could have a dominant effect on the financial costs of an SSR monitor need to be used?

1.6 Assessment of the implementation costs for industrial manufacture

As far as possible, statements on the development and manufacture of SSR monitors in the form of prototypes, together with the related costs, should be derived.

1.7 Suggestion for a measuring concept

During the processing period, the measuring concept developed in the course of the study should be presented to the customer and discussed with him in several meetings. This should include showing the possibilities and the limits (related to the costs) of the measuring technology, mode recognition, decoding and demodulation, and describing the achievement of modular design which meets the requirements as closely as possible.

2 A first overview of the problem

2.1 Radar field measurement

Today's secondary radar system SSR is used to monitor all flights in the controlled airspace when the aircraft are equipped with, or must be equipped with, transponders. Due to the ever-increasing traffic density, the requirement for installation of transponders is being extended more and more.

In order to achieve full and redundant coverage of the controlled airspace, the ranges of the ground radar systems overlap each other, which means that airborne transponders using the SSR technology are not only interrogated several times (10 to 50 times) each time the radar beam passes them, but are also interrogated by the beams of several ground radar systems.

If there are aircraft at the intersection point of two radar beams, the interrogations from two radar systems may arrive together in the transponder receiver, interfering with the recognition of the radar interrogations (of the mode). Similarly, the ground radar systems will receive not only the replies from the aircraft they have just interrogated, but also the replies resulting from interrogation by other ground radar systems. All of these replies may overlap each other and can, in extreme cases, make them unreadable.

The superimposition of interrogations and replies, and the amount of resulting interference, depends to a great degree on the strength of the received signals, i.e. on the amplitudes of the superimposed interrogations and replies.

An important feature of a radar field measurement system is thus the measurement of the amplitudes of the incoming signals which are to be measured. If this is done in a measuring station, the measured amplitudes are not necessarily identical to those which would be measured by a ground radar system or by an airborne transponder.

2.2 Measurement of the transponder accessibility

In order to compensate for the reflections which can affect interrogations in the vicinity of a radar system, and also to compensate for the restricted quality of radar antennas, the principle of blocking the transponders was introduced. If a transponder detects an (interference-free) interrogation in the main lobe of a radar (P2 pulse - 9dB weaker than the P_1 pulse), it replies and then blocks itself for the next 100 s so that it does not reply again to a reflected pulse (which arrives slightly later). Any interrogation from another radar which arrives during this period will thus be ignored. If the transponder detects an interrogation which comes from the side lobes of the radar antenna, rather than the main lobe, (P_2 P_1 pulse), it does not reply and blocks itself for the next 35 s, with the same effect. This so-called side-lobe suppression is effective in transponders which are less 20 NM from a radar and not in the main lobe. The blocking effect is therefore far greater in the side lobe than in the main lobe which may be, for example, only 4^0 wide. However, these so-called side-lobe suppression pulses P_1-P_2 can be measured at far greater distances. A further major feature of the radio field measurement will thus be the ability to calculate the transponder blocking times which result from interrogations and side-lobe suppression. Whether a transponder interprets a received SSR pulse group as a main interrogation, to which it must reply and then block itself for the next 100 s, or as a side-lobe signal, to which it does not reply and then blocks itself for 35 s, depends on the amplitude ratio of the received pulses P_1 - P_2. In this case, it is thus necessary to measure amplitude ratios and these are not necessarily identical to those which would be measured by the transponder of an aircraft in the controlled airspace.

2.3 Consequences of the combined civil-military use of secondary radar.

The secondary radar system SSR was originally a military development used for distinguishing friendly and enemy aircraft from each other (IFF). Its use was subsequently standardised for civil aviation by the ICAO. It goes without saying that the military aviation still uses these systems today, in some cases in a special manner, both for monitoring and for special mission-related purposes.

Some military radars are stationary (for example, ASR at aerodromes), while others are mobile installations on ground vehicles, ships and even aircraft. The so-called Modes 1 and 2 are used only by military users, and their basic blocking effect is similar to that of the Modes 3/A and C, which are also used by civil aviation. An exception to this is the military Mode 4, which uses relatively long interrogation sequences for more complex IFF tasks and data transfer and a very short reply, i.e. with signal formats which are completely different from those of the other modes.

A further, completely different aspect is related to Mode 4: the interrogation is not actually repeated (10 to 50 times) per beam passage, as in the Modes 1,2, 3/A and C, but is apparently a single (data) transaction and thus similar to the (civil) Mode S, even if several sequences are transmitted. For peacetime integration of civil and military air traffic control as in Germany, it is thus interesting to be able to make statements with respect to the total number of simultaneously active SSR interrogators in a given area and with respect to the resulting consequences – the transponder assignments.

2.4 The effects of single interrogations in the secondary radar

Generally, the quality of a radar surveillance system is apparently described by the probability with which a transponder replies to the interrogation by a radar, i.e. detects the interrogations and replies in a manner which the radar can recognise.

The still very common SSR radars with so-called wandering window detectors require a large number of replies per beam passage in order to carry out the correlation and a sufficiently accurate azimuth measurement. Interrogation is mostly executed in so-called interlace mode, i.e. alternating interrogation in Mode A, Mode C, Mode A and so on. The decisive factor for the momentary quality of a wandering window detector radar is thus the number of interrogations to which each aircraft transponder currently located in the main lobe replies during the short beam passage (about 30 ms). Each aircraft transponder can be detected and located only if it replies successfully to, for example, 5 of 9 interrogations.

This fact indicates that radio field measurements must be capable of displaying the frequency of events within very short periods of time, i.e. over only a few tens of milliseconds. Measuring the frequency of events over periods of 1 or 30 seconds will probably not provide results which are decisive for the surveillance quality. Radars with monopulse technology, which are being introduced to an increasing degree, measure the azimuth angle of a reply, relative to the vertical line of the antenna, with each pulse which is received. This, together with the direction decoder of the antenna, provides an azimuth accuracy of 0.01 degrees. Theoretically, only a single reply from each aircraft transponder currently located in the main lobe is needed in each beam passage; in practical applications, however, two or three successful replies, and thus the same number of interrogations, are necessary. The probability of successful replies must therefore be measured over similarly short periods of time if the momentary quality is to be assessed.

Basically, such a function can be executed by any radar analysis system, if it is installed. However, such a system cannot determine the reason for missing replies.

I do not know in detail how far the interrogation rates have actually been reduced in monopulse radars by the use of this possibility. This is particularly true for the side-lobe suppression.

The monopulse technology, and thus the reduction of the interrogation rates, is an important prerequisite for the addressed Mode S radar, which has been standardised by the ICAO for several years now. The reason for this is that the reduced rates for interrogations in Modes A and C result in free time intervals during which aircraft transponders can be addressed, i.e. interrogated individually with their address, and their replies, which are also addresses, can be received. Any missing addresses reply is detected by the Mode S radar, which can then usually repeat the interrogation within the same roll-call cycle. However, the Mode S radar cannot determine why the reply was not received.

The observation of events which occur within very short time periods is even more necessary for Mode S, particularly since the interrogations and replies are not only used for measurement of the azimuth and the distance, but contain, in addition to the altitude reporting, data transfer transactions in various Mode S formats. Such transactions represent one-time events, even if they sometimes have to be repeated.

The possibilities of the Mode S secondary radar system with respect to the controlled transfer of data such as the flight plan number, airborne data, automatically generated warnings and routine instructions, together with the necessity for these in modern air traffic control, were not recognised for a long time and were also displaced by widespread system concept proposals which, it was said, were equally powerful.

The fact that the radar field loading is reduced by the increasing introduction of the Mode S system is undisputed. However, the measurement of the causes of interference with the Mode S system requires particular attention and special procedures.

2.5 The effects of ACAS/TCAS collision avoidance systems

It is well known that the ACAS airborne collision avoidance system standardised by ICAO has a considerable effect on the radar field, since aircraft with this system transmit both conventional Mode C interrogations (whisper shout) and Mode S interrogations (formats UFO, UF16, UF17) and thus also initiate replies from the aircraft around them. The so-called whisper shout sequence, a string of Mode C interrogations transmitted with increasing intensity, imposes a load on the radar file which is 5.5 times as large as that caused by an addressed Mode S interrogation.

In general, there is no possibility in aircraft equipped with ACAS (or TCAS) of assessing the quality in any manner or of judging the causes for a reduction in the quality.
Depending on the number of aircraft with ACAS/TCAS and/or transponders within the operating range, so-called interference limiting procedures reduce the transmitter output power and the average transmission rate. The intensity steps and the number of pulse groups in a whisper shout sequence are also affected by these procedures. However, the number of addressed interrogations and replies in Mode S depends mainly on the number of aircraft in the vicinity of an aircraft equipped with ACAS/TCAS and also on whether they must just be detected and whether they are entering a critical distance.

As already concluded in Section 2.3, it is interesting for the purpose of monitoring the quality of air traffic surveillance to determine which aircraft with only conventional transponders reply to Mode C whisper shout interrogations and are then blocked and which aircraft with Mode S transponders (currently about 60% of the aircraft in the Frankfurt area) do not reply and thus do not block themselves, but must then be interrogated with their addresses. At the moment, about 40% of the aircraft in the Frankfurt area are equipped with ACAS/TCAS. The mandatory fitting of Mode S transponders and with ACAS/TCAS, which is planned for Europe (2000), will result in a dramatic increase in these numbers.

Airborne ACAS/TCAS II devices have smaller antenna apertures than radar sets. For this reason, they transmit whisper shout sequences in five sequential groups:

- at high power in a forward-pointing 90^0 sector with the top antenna (max +27dBW)

- at lower power in each of the 90^0 sectors to port and starboard with the top antenna

- at lower power in a rearward-pointing 90^0 sector with the top antenna

- at high power via the antenna under the aircraft with equal distribution in all directions (insofar as the antenna characteristic permits).

With the aid of the ACAS broadcasts transmitted at full power by all ACAS/TCAS devices at intervals of 8 to 10 seconds (Annex 10, Section 4.3.7.1.2.4), it is possible to measure the number of aircraft equipped with ACAS within reception range of a radio field monitor and to calculate from this how many whisper shout sequences or groups are transmitted by them. However, it is not possible to conclude how many transponders they reach and how these are allocated without knowledge of the traffic distribution.

3 Considerations which determine the complexity of the SSR monitor system

3.1 Load measurement

Section 1.1 of the DFS statement of the problem demands a monitor system with which the loading of both the SSR interrogation channel and the SSR reply channel can be determined and evaluated.

3.2 Measuring the degree of equipment and compliance with the standards

In addition, it must be possible to analyse the degree of equipment with ACAS II and Mode S and the compliance with the applicable specifications (and standards). Upon closer examination, it seems that it should be possible to determine the degree of equipment with the data of a Mode S radar, and it may even by possible to do it with this alone.

3.3 Initial conditions

The aspects to be discussed in the study, which are also stated in Section 1.1 of the problem description, describe the seriousness of the situation and the planned performance of the monitor system.

3.4 Correlation of interrogations and replies

Section 1.3 of the problem description mentions a correlation between the transmitted interrogations and the replies as a measuring concept which should be discussed. This can contribute considerably to detection of the correct function of the system, in particular for Mode S transponders and ACAS devices, i.e. to compliance with the above-mentioned Section 3.2. For transmission in the Mode S format, this can be done with the aid of the addresses, providing these can be recognised correctly. For all other modes, the correlation can be determined, if at all, only from the timing of the multiple interrogations and replies.

3.5 Recognition and decoding

In accordance with the table in Section 1.2 of the problem description, all principally possible modes (both military and civil) should be recognised and decoded. The specially formatted whisper shout interrogations from airborne ACAS devices should be added to this table, since they could otherwise be confused with Mode C interrogations

3.6 Best possible information about sources of significant interference

In addition to the above, the viewpoints of DFS which lie in the background of the problem description were discussed at a meeting at DFS on 28 January 1999. These apparently have the objective of obtaining comprehensive information not only on the current status of the SSR radio field loading and the accessibility of the aircraft transponders, but also on the sources of interference with the radar system of the air navigation services.

It is clear that these sources of interference can be of many different kinds which, at the moment, are absolutely unpredictable. For this reason, it appears advisable to present a short discussion of the possible sources at this point.

3.6.1 Legal overloading by the conventional SSR system itself

As long as aircraft with conventional transponders in controlled airspace demand non-addressed interrogations in modes 3/A and C by radars and by airborne ACAS devices, the radio field load and the blocking of transponders will remain unacceptably high for the purposes of air traffic control. Interference with the surveillance quality will manifest itself mainly in areas with high traffic densities and with many overlapping radar systems (civil and military). SSR monitors of the planned type are suitable for displaying the general, slowly developing deficit in the form of numbers, so that changes can be initiated.

3.6.2 Legal loading by ACAS

As measurements made in 1995 by the FAA and the Technical University of Braunschweig (Germany) have shown, the load on the SSR radio field resulting from airborne ACAS devices is considerable, particularly in areas where aircraft equipped with ACAS (to meet the mandatory requirement in the USA) are flying. This load effect will become most obvious in the approaches to large airports with high traffic densities. The possible introduction of mandatory equipment with fitting ACAS which is currently being discussed in the European countries will mean that this effect will be come apparent in the approaches to most airports.

SSR monitors should make the consequences of this slow development, which is also affected by political decisions, visible and predictable. For this reason, it seems reasonable to locate the SSR monitor stations in areas with large amounts of traffic, since the observation of this traffic will permit the detection of such slow developments.

Airborne ACAS devices are interrogators which are not under the control of air navigation services, but must still be technically compatible with the components of the air navigation service system with which they cooperate. This applies to an even greater degree to the transponders, particularly to the Mode S transponders whose complex functions are currently not fully utilised, due to the lack of Mode S radars capable of transmitting data and the lack of onboard integration. These functions can currently not even be tested correctly at the present time.
On the one hand, the standard defines requirements with respect to the acquisition, forming of traces, etc.; on the other hand, it demands compliance with radio field loads, speci-

fied as average values, which may be exceeded for short periods. The reconciliation of these relationships (and conflicts) is left to the manufacturers, who naturally find differing solutions.

It would certainly be desirable to be able to detect the short-term consequences of these manufacturer-specific solutions. However, it is difficult to interpret the situation from the outside. Providing the transactions in the interrogation and reply channels are in the Mode S format, i.e. with unambiguous addresses, and can be received and read correctly in the SSR monitor, it is possible to identify the participants. However, the interpretation and justification of the transaction demanded by the situation will probably require knowledge of where the participants are located.

This consideration speaks for a correlation of the data of an SSR monitor station with the data of Mode S radars which cover the same airspace as the SSR monitor station.

3.6.3 Irregular behaviour of ACAS and transponders

Irregular behaviour of airborne ACAS devices and transponders and of other airborne devices can also interfere with the SSR functions.
Typical examples of this, which have actually been observed, are:

- DME pulses in the frequency bands 1030 and 1090MHz (airborne and ground equipment).
- Transmission of squitters or all-call replies (DF 11) with high repetition rates in the presence of CW signals around 1030 MHz by, for example, badly keyed radar systems or other equipment.
- Use of the forbidden technical Mode S address 00000.
- Replies from conventional transponders to Mode S interrogations.

On radar systems, such irregularities are displayed only as so-called fruit. For this reason, they can only be detected in SSR monitors, but not necessary identified. In such case, the direct correlation of SSR monitor and radar location data cannot be used as an aid in determining the location of the interference source.

3.6.4 Military sources of signals in the SSR

Military radar systems and interrogators and their airborne transponders are subject to different regulations and are intended for different purposes. Measurements carried out by the FAA (1995) and examinations carried out by the Technical University of Braunschweig in cooperation with the Federal Ministry of Transport (BMV) and DFS (1990 to 1992) have shown that the number of active military interrogators is in most cases far higher than the number of civil radar systems.

The necessity for these interrogators, which are installed on the ground, in motor vehicles, in aircraft and in ships, is undisputed. However, they may not endanger the functions of radar surveillance in certain areas. The main task of military interrogators is the identification of friendly (and enemy) aircraft, but this is not accessible or useful to civil air navigation services, neither in Modes 1 and 2 nor in the cryptographical Mode 4. However, some radar system of civil air navigation services – such as in Canada – also interrogate in Mode 2.

In the case of military formation flights, only the transponders of the leading aircraft are active. This is done to avoid the synchronous overlapping of the replies from the closely spaced aircraft and, of course, any unnecessary fruit. This measure helps to reduce the load on the reply channel (downlink), whose radio field loading is increasing continuously.

At the second meeting on 16 March 1999, the interest of DFS in identifying and localising the sources of heavy loads on the SSR radio field and of strong interference with transponder accessibility was expressed more clearly than in the problem description.

Within certain limits, the number of sources which interrogate frequently per beam passage can be determined by the time-correlation of the detected interrogation modes. This should work for wandering-window detector radar systems with Mode 1 and 2 interrogations. It will probably not provide usable results in the case of monopulse radars, which interrogate far less frequently. This also applies to Mode 4 interrogators, which apparently interrogate only sporadically, and to Mode S interrogators, whose addressed interrogations can be received by the monitor only if the aircraft being interrogated happens to be on the connecting line between the interrogator and the monitor.

A universal solution for the identification of all sources which could possibly interfere with the secondary radar is feasible only with a network of monitors installed at suitable locations so that there is a high probability that such interrogations will be received and can then, for example with the aid of multilateration techniques, be distinguished from each other, i.e. identified.

Technical possibilities which are basically suitable for this are dealt with in Section 5.4.

4 Detection of signals

4.1 Antennas and their effects on the results

The signals received with an antenna in the frequency bands around 1030 and 1090 MHz from the radio field of the secondary radar possess a wide range of different amplitudes, pulse lengths and pulse intervals. These result from the various mode patterns and from the random order in which these patterns occur. In some cases, several signals overlap each other. The reflections of these pulses from objects at various distances from the receiving antenna cause, due to their delays, noticeable distortions at the trailing edges of the pulses and also fill in the gaps between the pulses.

With pulse lengths of 0.5 µs and 0.8 µs in the interrogation channel (1030 MHz) and 0.45 µs and 0,5 µs in the reply channel, the trailing edges of the pulses are distorted by reflected signals with an additional path distance of 150 to 240 m and more. Longer reflection paths cause reflected pulses which fill in the gaps between the actual pulses.

The success of usable measurements of this type depends decisively on the location and, in particular, on the characteristic of the receiving antenna. Measurements with simple, vertical dipole antennas, for example in Frankfurt, returned absolutely useless results, since these antennas receive too many ground reflections and thus apparently increase the number of interrogations and replies.

In contrast to this, very good results with little distortion were obtained in all environments which have been used until now (Braunschweig, Frankfurt and Cologne/Bonn) with antennas which have a low sensitivity at negative elevations. Antennas of this type (SEL) are similar to those used at DME ground stations and have, for example, 13 vertical dipoles arranged above each other with weighted feeds.

For various reasons, these possibilities cannot be used on board a measuring aircraft. It is not known whether and to which degree reflected signals could be measured and counted in such experiments, using a suitable receiver sensitivity (such as -70 or -76 dBm).

The diagrams of Mode C, A and 2 interrogations received on board an aircraft, which are shown on pages 10 and 11 of the FAA Report DOT/FAA/CT-TN 96/20 (Figs. 11,12,13), could give an indication of such effects, at least close to the ground (during this flight, no replies were measured during departure from Frankfurt).

4.2 Receiver technologies and their consequences

The statements in this section are based on methods and experimental experience, which have been published in the meantime, used and gained by the Technical University of Braunschweig (IEV) in the measurement of SSR signals, in particular of Mode S signals on the uplink and the downlink.

The results of these experiments can be used for the purposes of this study only because, in addition to the recognition of the pulse patterns, the voltage curves as a function of time which existed at the antenna or the receiver input were also recorded. This is not the case for measurements carried out by other people (FAA, Lincoln Lab); their results show only the statistics of the pulse patterns which were detected.

Initially, transponders (A/C) modified in 1985-88 were used for the uplink measurements. Later, receivers capable of executing both uplink and downlink measurements were developed. Logarithmic receivers were used for this since they reduce the dynamic range of the receiver signals which can be evaluated meaningfully from about -80 to -20 dBm, i.e. six orders of magnitude, to about two orders of magnitude by power. At the same time, they can still be calibrated so that the received power at the antenna can be calculated at any time from the output voltage of the receiver, something which is impossible with the pulse-regulated receivers commonly used in transponders.

A peculiarity of logarithmic receivers is that they steepen the edges of pulses, particularly the leading edges because – as already mentioned – the reflected signals already make the trailing edges less steep. The recovery time of a logarithmic receiver has very little effect on this.

In all methods which were used, therefore, the leading edges of the received pulses were used primarily for detection of a pulse and/or of a pulse pattern, i.e. a sequence of leading edges.

In addition to their bandwidth, the quality of logarithmic amplifiers in a receiver is described by their dynamic range and their signal-to-noise ratio. They are available for intermediate frequencies of 30, 60 and 160 MHz, which means that the incoming signal must be converted with the aid of a suitable noise-free oscillator to one of these frequencies. Logarithmic amplifiers are also available for the original frequency range around 1 GHz, which means that no additional mixing is needed in the receiver.

All known available logarithmic receivers have, in addition to the RF and IF inputs, a video output at which the rectified signal is available and an output which provides the RF or IF AC voltage with a greatly limited amplitude.

The video output which provides the steepened (DC voltage) pulses is important for the following consideration, while the limited IF output can be used only for phase measurement since its output voltage bears no relationship to the antenna voltage or power.

4.3 Principles of pulse detection for an SSR monitor

The term "pulse" is a technical construct which – if ever – is described by leading and trailing edges during defined rise and fall times and, above all, by its duration. The amplitude of a received pulse depends basically on the original radiated power, the characteristics of the transmitter and receiver antennas, their distance from each other, and the properties of the receiver. However, this is true only if there are no diversity effects in the radio field between the two antennas and no heterodyning with wanted or unwanted system-inherent signals.

The amplitude of the top of the pulse is normally described as flat. However, during reception, overshoots can occur after the leading edge and, theoretically, at the trailing edge due to settling effects. However, the latter are almost always hidden by reflections in practical applications.

The specified pulse duration or length, specified, for example, by ICAO, for secondary radar applications are not defined as the duration of the top of the pulse, but as the time between the 50% point on the leading edge and the 50% on the trailing edge.
These pulse durations specified by the ICAO and their tolerances for the various pulses are:

S, P1, P2, P3, P4 (short) : 0.8 µs +/- 0.1 µs on the uplink

F1, F2, all data pulses : 0.45 µs +/- 0.1 µs

Mode S : 0.5 µs +/- 0.1 µs on the downlink

In Mode 4, the pulse lengths of the interrogations are 0.5 µs and those of the replies are 0.45 µs. The tolerances are not known.

Receivers in conventional transponders check whether the received pulses are longer than 0.3 µs (so-called ditch-digger) in order to eliminate any shorter interference pulses. Such checks appear superfluous for measurements in ground stations, since such interference was practically never observed there.

Nevertheless, it seems highly advisable to follow the detection of the leading edge of a pulse with a check requiring a certain minimum pulse duration before the pulse is passed on for further evaluation.

On the basis of the tolerances for, for example, the pulses

S, P1, P2, P3, P4 (short) = 0.8 µs +/- 0.1 µs

a required pulse duration of, for example, at least 0.5 µs seems appropriate. However, the problem is defining the conditions which are to apply and how they are to be checked.
Part of the pulse duration already occurs during the leading edge, which is primarily determined by the transmitter of the pulse and is then also affected by the bandwidth, settling behaviour and dynamic compression of the receiver. Last but not least, the detection of a pulse edge depends on the selected method used for this, since measurement of the pulse duration can start only at the point in time where the edge of a pulse is detected.
The actual measurement of the minimum pulse duration can only be based on the assumption that the amplitude of its top is constant during the duration of the pulse, i.e. that it

remains within certain amplitude limits. This check is aided by the fact that logarithmic amplifiers are relatively insensitive during the period with the high amplitude of the pulse top, which means that receiver noise has little effect on this amplitude.

For measurement of the minimum pulse duration, it would be helpful to detect the trailing edge of the pulse. However, since this is rarely steep, and is often exponential, due to the sequence of reflected signals, it is normally not possible to detect a trailing edge, quite apart from finding a point at which the pulse can be regarded as terminated.
Due to these difficulties, earlier signal detection methods used a check which demanded a certain definable reduction in the pulse amplitude after the nominal end of the pulse (including the +/- tolerance). In the field tests carried out with this method, however, this check was disabled because it apparently prevented the detection of pulses in many cases.

If one first considers the pulse lengths in the interrogation channel of the various modes to be detected, it can be seen that these are all 0.8 µs +/- 0.1 µs long, except for the long P4 pulse in Mode S A/C/S - Allcall, the P6 pulse (Mode S) and the pulses in Mode 4, which are only 0.5 µs long and possibly also have a tolerance of +/- 0.1 µs. The difference in the durations of the valid 0.8 µs +/- 0.1 µs pulses and the 0.5 +/-0.1 µs pulses can thus legally be as little as 0.1 µs.

In view of the leading edges of the pulses observed at the video output of logarithmic receiver amplifiers, with a length of about 0.1 µs, and the trailing edges distorted by reflections, it seems impossible to distinguish Mode 4 interrogation pulses from the longer pulses of Modes 1, 2, 3/A and C or Mode S (P1, P2) with the aid of hard duration thresholds.

If one wanted to detect such small time differences of 0.1 µs by digital time measurement, i.e. by scanning and clocked insertion into readable memories or registers, the inherent error of this method of +/-1 clock cycle would demand clock frequencies far above 20 MHz, such as 30 MHz. This cannot be done at the present time with the highly integrated circuits available for such applications. Furthermore, the distortion of the trailing edges of the pulse by reflections makes such a method unsuitable.

Since, however, the pulse patterns of the many modes to be detected with the SSR monitor are very similar in many respects, it seems worthwhile to pursue the objective of pulse length distinction which could possibly be reached with the aid of other (perhaps analogue) techniques with "softer" decisions. Techniques of this type will be proposed in subsequent sections of the study, but have not yet been tested, since previous examinations have never had to be able to distinguish between the large number of modes demanded by the current problem description for this study.

4.4 Principles of pulse pattern detection for an SSR monitor

Only digital time measurement is suitable for the detection of the time sequence of detected pulses and comparison of these with the time patterns of the various modes. Due to the physically restricted possibilities of detecting individual pulses, as described above, the detection of legal time patterns must bear the brunt of the task of identifying the various interrogations and replies.

This comparison of a stored time pattern with the received pulse patterns delivers the statement "agreement with the stored pattern" for a certain period of time which is related to the length of the individual pulses in the pattern.

An ideal, continuous correlation process would deliver a triangular signal as an indication of the degree of agreement. This signal would last for the length of two pulses if the received pattern precisely matches the stored pattern. In the case of digital correlators with a limited time resolution, the degree of agreement is indicated more by a rectangular wave pulse with a length equal to the length of one pulse if the received pulse pattern matches the stored pattern.
The pulse patterns of the modes, i.e. the intervals between the pulses, measured from one leading edge to the next, have tolerances, namely:

on the uplink:	P1 - P2	+/-	0.15 µs
	P1 - P3	+/-	0.1 µs and
on the downlink :	all pulses	+/-	0.1 µs

Luckily, the legal tolerances refer to the first pulse of each sequence, which means that the tolerances are not cumulative.

The various intervals between the pulses, namely 2 µs, 3 µs, 4 µs etc., is generally larger with respect to the legal tolerances, than is the case for the pulse lengths. The highest requirement for the time resolution exists for the detection of the data in Mode S interrogations, which are modulated with phase-shift keying. These occur at intervals of only 0.25 µs, which means that time increments of 0.25 µs or, even better of 0.125 µs, are needed for their resolution. This corresponds to a clock frequency of 4 or 8 MHz, respectively.

With a clock frequency of 4 MHz or 8 MHz, the pulse sequence times can be measured or compared with stored patterns with an accuracy of +/- 0.25 µs or +/- 0.125 µs, respectively, i.e. with a tolerance which is practically identical to the legal tolerances of the received pulses patterns (modes). This thus seems to be an acceptable value.

Two methods seem possible for the implementation of the correlation process:

1.) the use of shift registers with fixed pointers,

2.) the use of write-read memories with several ports.

The first method was used in the measuring equipment of the first generation. It is easy to handle but requires, due to the design of shift register modules, a large number of such modules and a lot of wiring for programming of the pointers.

The shift register shown in Fig. 4.4-1 is basically a digital delay line. The digitally measured amplitudes of the sampler (A/D) and various other characteristics of the scanning are shifted into its inputs E, shown on the right, and are then shifted one place to the left with each clock pulse (e.g. every 0.125 µs at a clock frequency of 8 MHz).

For detection of Modes 3/A and C (8 and 21 µs) at a time resolution of 0.125 µs, this would need 168 shift register elements with a depth of, for example, 8 bits each.
If commercially available 8-bit shift register modules are used, this version would need 168 modules just for the shift register.

In the simplified circuit shown in Fig. 4.4-1, the outputs of shift register elements 0, 16 and 168 are tapped and wired to AND gates. The taps on element "0" are called the reference point or the reference pointer.

When the first amplitude values of pulse P1 appear at this reference point "0", i.e. 21 µs after the arrival of this pulse in the receiver, then

- if a P2 pulse exists, the first amplitude values of P2, which arrived in the receiver 2 µs after P1, should appear at the outputs 16.
- if a P3 pulse exists, the first amplitude values of P3, which arrived in the receiver 8 µs after P1, should appear at the outputs 64.
- In the case of a P3 pulse of a Mode C interrogation, the first amplitude values of P3, which arrived in the receiver 21 µs after P1, should appear at the output 168.

At the points A, B and C, which are at the moment shown as AND gates for the purposes of simplification, the simultaneous presence and any identity or differences in the amplitude values can be checked. Since these pulses are 0.8 µs long, these amplitude values are present for 6 to 7 clock cycles, corresponding approximately to the length of a pulse.

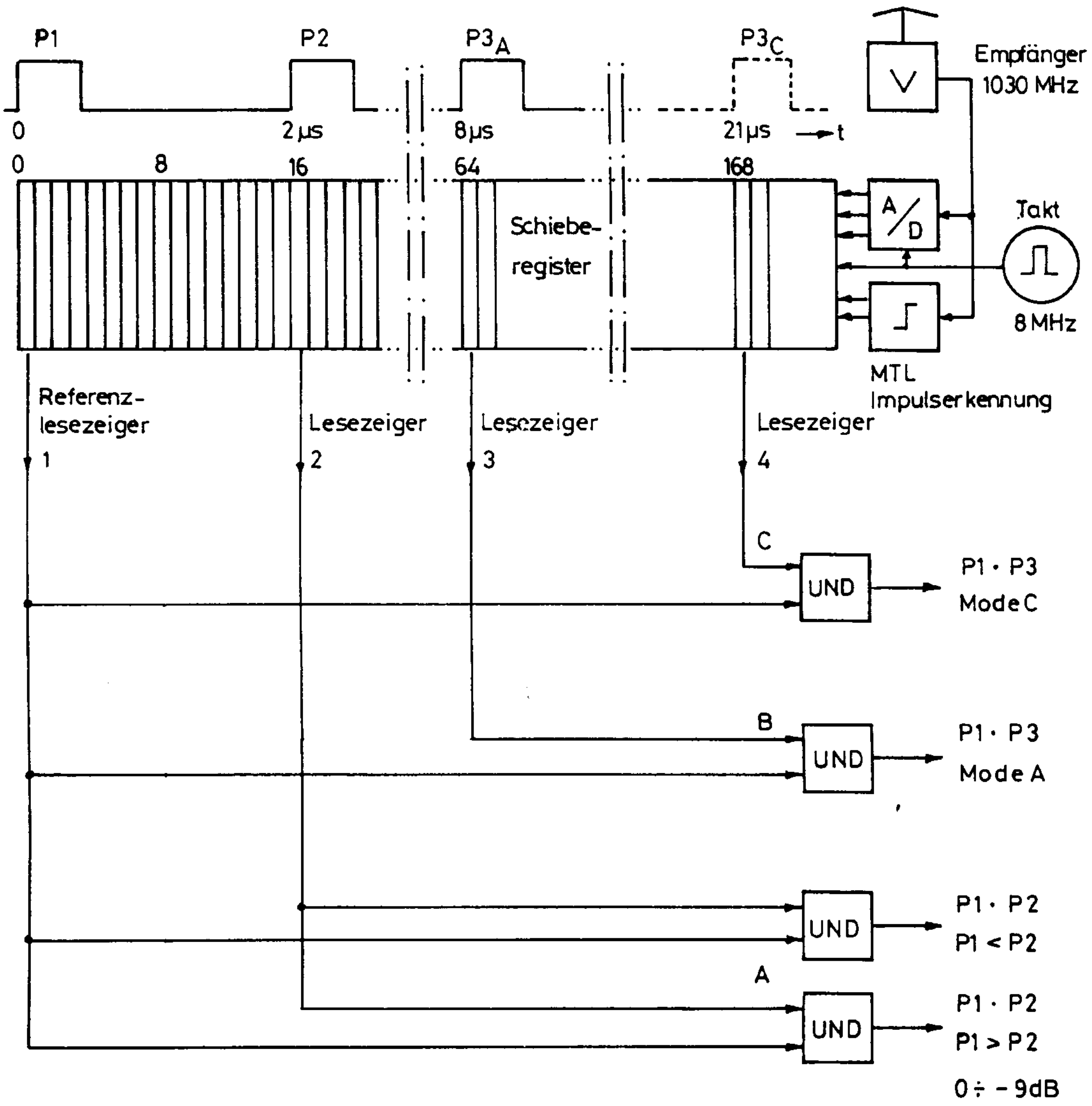

Fig. 4.4-1: Pulse pattern correlator with shift register

This fact provides an approach to the integration as part of the correlation, i.e. of the pulse pattern detection process.
If, as in a transient recorder, a very high clock frequency such as 32 or 64 MHz were used with a correspondingly large number of shift registers, there would be no loss of resolution. It would then also be possible, at the points shown in the diagram as AND gates, to check such things as

- whether the received pulses are usable, i.e. whether they reach a certain minimum amplitude with a sufficient signal-to-noise ratio,

- whether the pulses have a sufficiently significant pulse edge and, if applicable, a sufficiently long pulse top.

If, for cost reasons, a considerably lower clock frequency is used, i.e. 8 MHz as mentioned above, it is advisable to carry out such checks of the pulse detection with analogue methods directly after the receiver, i.e. in parallel to the A/D converter, where there are no sampling losses (see Fig. 4.4-1).

These functions "pulse detected" and "minimum level (MTL) exceeded" each move a bit into the shift register. These bits can then be read out at the pointer outputs of the shift register and processed further.
This design with shift registers requires an enormous number of integrated circuit modules at high clock frequencies. If, due to the very large number of different modes to be detected, a large number of shift register outputs have to be tapped and wired for programming, this method is extremely costly to implement.
If it is used, then only with a lower clock frequency and a preceding analogue circuit for checking the pulse detection. This shift register method will offer completely different technological possibilities only when programmable modules with thousands of gates (cellular arrays) can be programmed with special high-level languages (VHDL). However, this method demands enormous investments which only a few manufacturers and institutes can afford.

The development of the second generation of correlators was based on RAM modules with multi-port access. Such a module (e.g. 2K x 8 Four Port RAM) possesses, for example, 2000 8-bit cells, each of which can be accessed, read or written independently from each of the four ports. An internal circuit prevents two or more ports from accessing the same address simultaneously.

In contrast to the register technology, the data are not shifted with each clock cycle. Instead, the addresses are incremented in order to write the data arriving via the write port from the A/D converter into sequential cells of the memory. The other ports are used for reading the data with an address offset. Fig. 4.4-2 shows the same operation for detecting the time pattern of Modes 3/A, C and P1 - P2 as in the previous example, but using a RAM module with five such ports.

The address counter increments its 11-bit address by 1 in each clock cycle. This address is connected to read port 1, which acts as the reference pointer. The adders add certain fixed numbers to these addresses in order to form the addresses for read ports 2, 3 and 4 and for the write port 5.

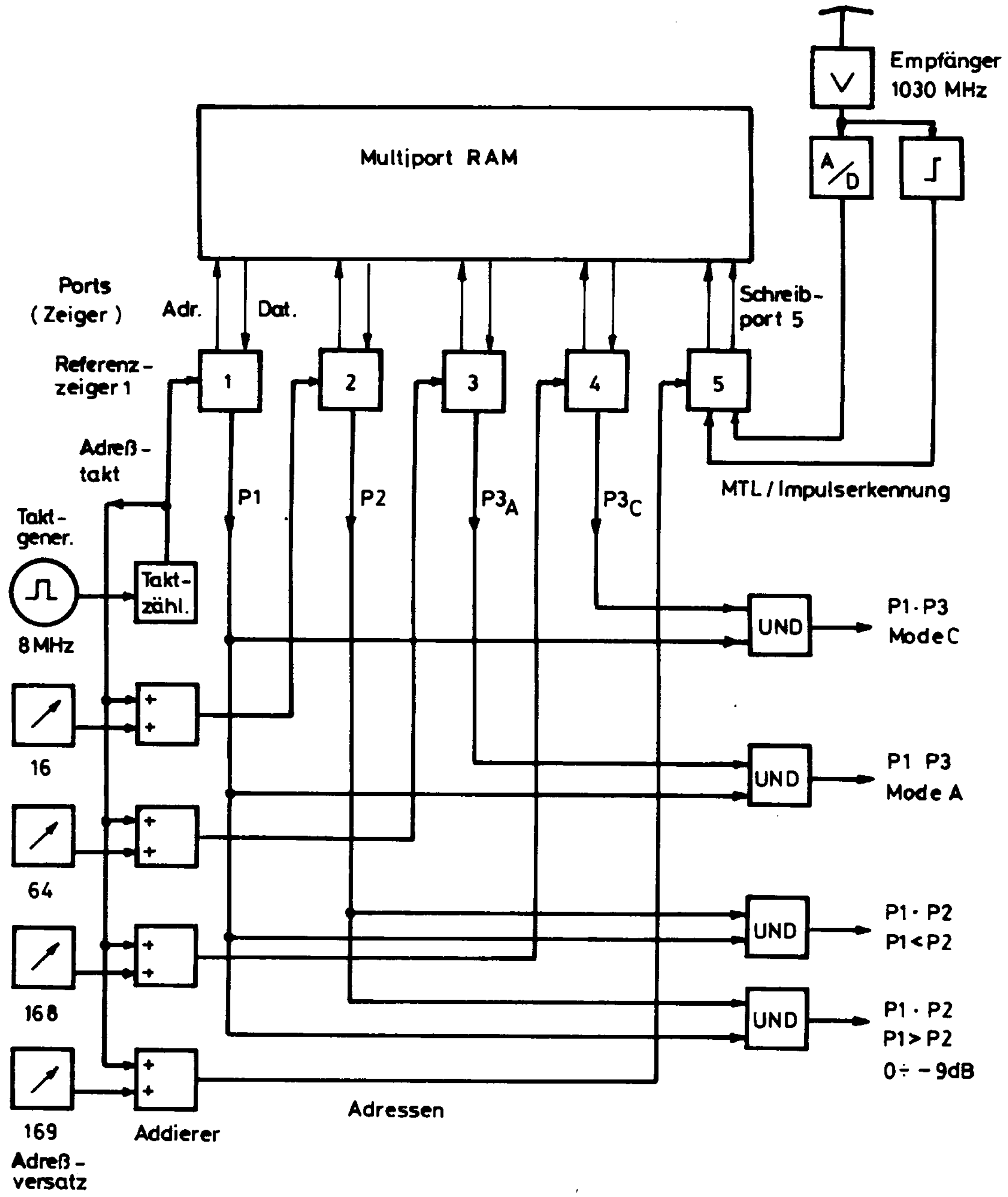

Fig. 4.4-2: Pulse pattern correlator with multi-port RAM

For detection of the patterns of pulses P1, P2 and P3 in Modes 3/A and C with a clock frequency of 8 MHz, the address of port 2 must be offset by 16, that of port 3 by 64 and that of port 4 by 168 with respect to the reference read port.
For this, it would be sufficient to shift the address of write port 5 by 169 with respect to the reference port. With a 1000-byte RAM, it would also be possible to correlate considerably longer pulse intervals.
The data outputs at ports 1 to 4 again supply the data which must be ANDed together, such as the pulse amplitude (e.g. 6 bits), "leading edge of pulse detected" and "minimum level exceeded". As far as I know, such RAM modules are commercially available with up to four ports. Since one port is needed for writing and one port acts as the reference port, only two ports are available for use as pointers for the detection of two pulse intervals. Adding a further 4-port RAM permits the detection of a further two pulse intervals, and so on, unless the selected multi-port RAMs are so fast, compared with the selected sampling rate (clock), that the shifted pointers (e.g. 2 and 3) can be set to two different addresses during a single clock cycle and the data from these addresses can be processed equally quickly in the logic gates. This consideration speaks for an economical design of the clock frequency.
It was possible to operate the multi-port RAMs in the last generation of measuring equipment at a clock frequency of 16 MHz, which means that the planned clock frequency of 8 MHz does not preclude this possibility of the multiple use of ports as read pointers. The use of so-called "cellular arrays" offers far more possibilities in this respect.

4.5 Distinguishing between many similar modes

4.5.1 In the interrogation channel

The objectives of this study differ from previous problems in the large number of different modes which are to be detected (Fig. 4.5-1). As can be seen from Fig. 4.5-2, this detection alone requires 17 read pointers for the interrogation channel, and it is by no means certain that this number is sufficient for reliable distinction of the modes.

With respect to the possibility of distinguishing between the various modes, a major problem is that the modes are very similar, particularly in that they often contain pulses at intervals of 2 µs. In the case of P1 - P2 or S-P1, these also require an amplitude comparison in order to detect whether they are suppression or non-suppression pulses. The same applies to the sequence P4 - P5 in Mode 4.

Another problem is that the detection of two pulses at an interval of 2 µs, or at intervals of 3, 5, 8 or 21 µs may not, for example in Mode 1, 2, 3/A or C, result in mode detection. Instead, the monitor must wait and see whether a P4 (short or long) follows, as this would indicate an intermode rather than Mode 3/A or C. It is also not clear, at present, whether military aviation is planning the introduction of a P4 (short or long) for Mode 1 or 2.

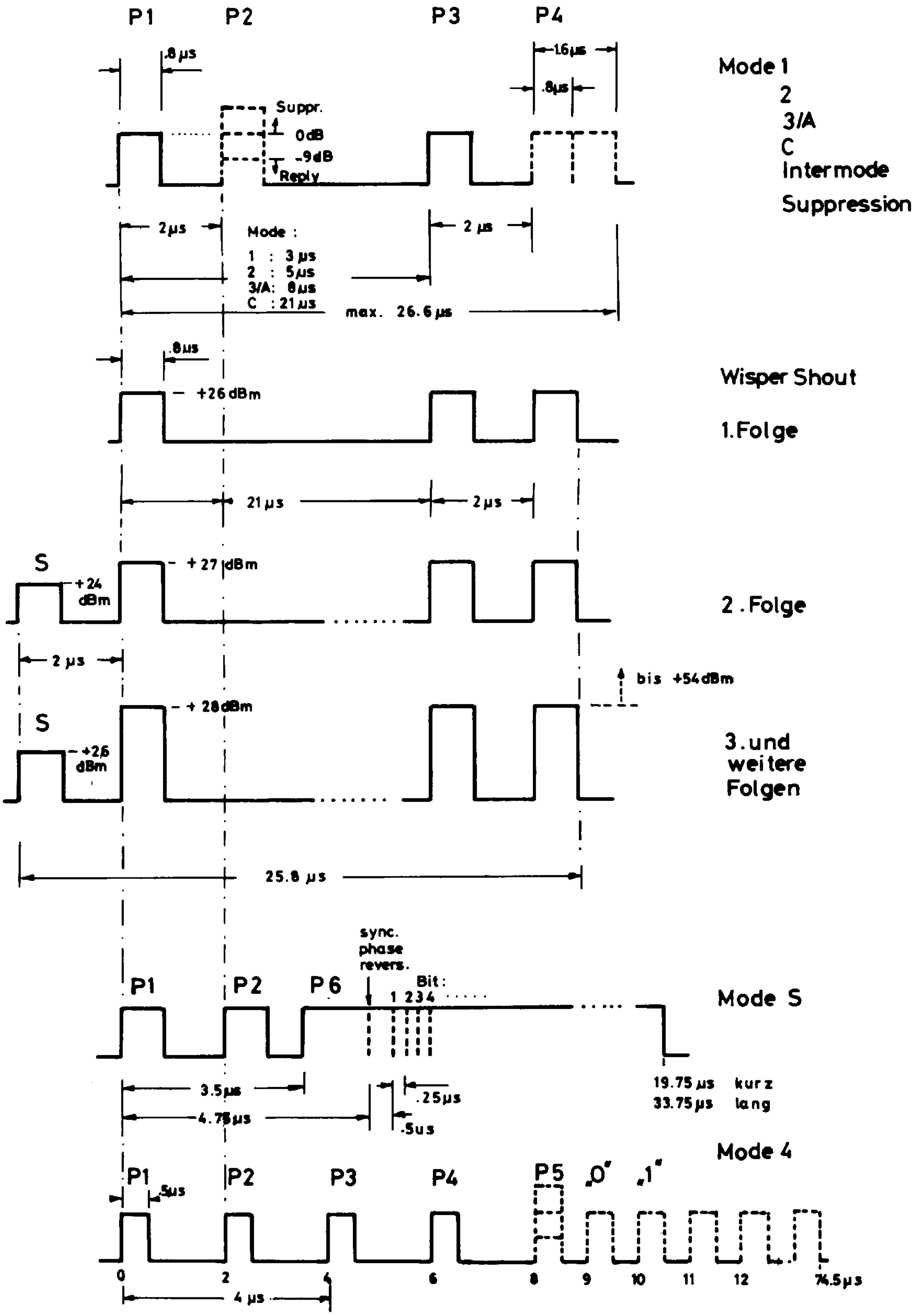

Fig. 4.5-1: Time patterns of interrogations

Initially, the detection of whisper shout sequences seems unnecessary, since the number of aircraft equipped with ACAS, and thus the frequency of the transmitted whisper shouts, can be estimated from the ACAS broadcasts. Quite apart from this, it would never be possible to receive the first sequence of a whisper shout in an SSR monitor station and only part sof the subsequent sequences could be received. The reason for this is described in Section 2.5.
Without detection of the S pulse, however, such sequences could be confused with Mode 3/A and C interrogations and counted wrongly, which could falsify the statistics.

This consideration shows that it is necessary to be able to detect whisper shout sequences, if only to exclude them from further processing.

As already discussed in Section 4.3, a Mode 4 interrogation will not necessarily be recognised on the basis of its shorter pulse lengths (0.5 µs instead of 0.8 µs), which means that the time pattern of the leading edges of the pulses must supply the main criterion for recognition. Under these circumstances, it seems that the preamble of the pulses P1 – P4, which appear at intervals of 2 µs, could easily be simulated by the random reception of a further pulse pair P1 - P2 at intervals of 2 µs. This random reception is also probable, since these pulse pairs occur extremely often as suppression.

For additional recognition of a Mode 4 interrogation and distinction from other simulated patterns, it is thus urgently recommended that further pulses of a Mode 4 interrogation be included in the recognition process. The use of P5 for this seems rather useless for this, since this pulse is often not receivable, i.e. it cannot be distinguished from the noise.

However, the following pulses of a Mode 4 interrogation are positioned according to the data, as shown in Fig. 4.5-3. In other words, in the next 32 pulse positions, which follow every 2 µs, a pulse is transmitted for "1" and no pulse is transmitted for "0". If there are two sequential zeros, a filler pulse (ALL) is transmitted between the two missing pulses (i.e. at an "odd" microsecond). A leading zero initiates such a filler pulse only 9 µs after the beginning of the preamble (see also Fig. 4.5-1).
As a minimum solution, one could, for example, at least check the existence of the first three data pulses of a Mode 4 interrogation. Depending on the actual data, these pulses could assume the eight signal shapes shown in Fig. 4.5-4 where, after the start of the preamble,

- there is always a pulse at position 9 or 10 µs and

- there is always at least one pulse in position 11 or 12 or 13 µs.

The detection of these positions 9,10,11,12 and 14 requires the five additional read pointers with the numbers 10 to 14 already shown in Fig. 4.5-2.

The many OR gates used in this complex recognition of a Mode 4 interrogation do not provide a high degree of safety against simulated signals, particularly since an Intermode interrogation (A/C only or A/C/S) could occur in the period 10 to 11.8 µs after the start of the preamble of P4.

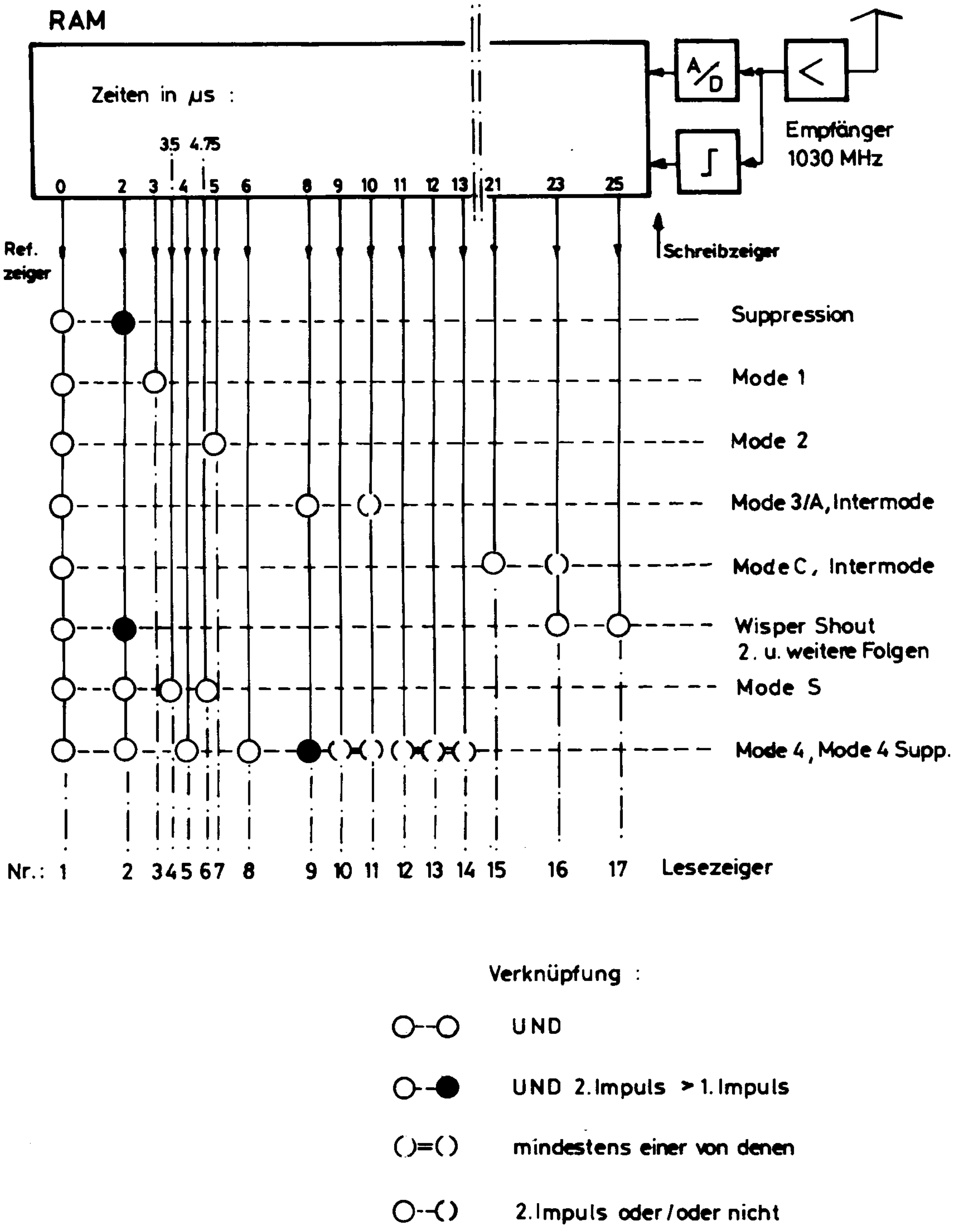

Fig. 4.5-2: Pointers for the recognition of interrogations

Mode 4 - Abfragen :

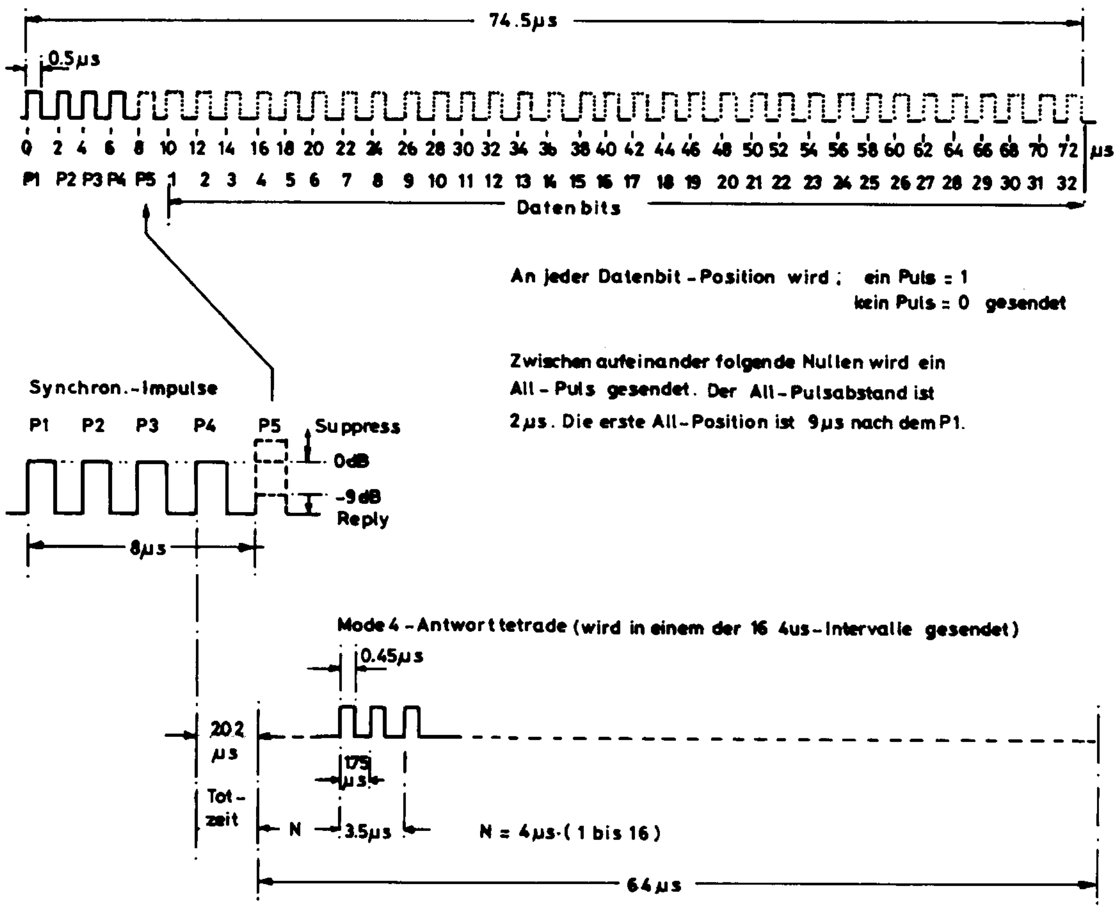

Fig. 4.5-3: Overview of interrogations and replies in Mode 4

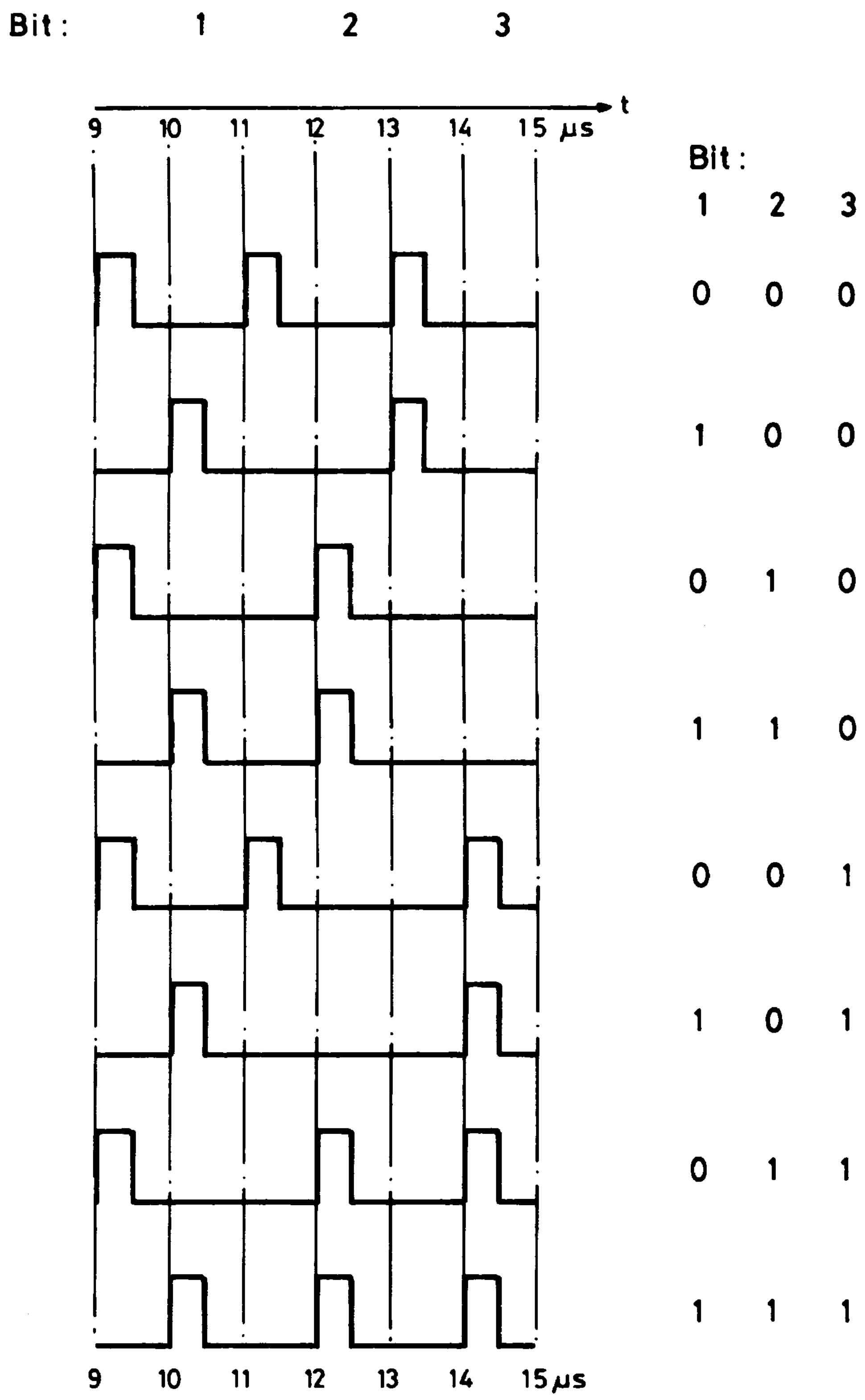

Fig. 4.5-4: Mode 4 data bit patterns in the first three bits

In addition to the reference pointer at position 0 (P1), Fig. 4.5-2 already shows, for the recognition of Mode S interrogations, three further read pointers at the positions 2 µs for P2, 3.5 µs for P6 and 4.75 µs for checking the phase shift (sync reversal) which occurs there.

If all four conditions are fulfilled, bit synchronisation and bit detection for demodulation of the data contained in the Mode S interrogation can be started. All bits except those in the address/parity field can be interpreted if their significance resulting from their distribution in the individual formats is known (see Section 4.7.1). The address in the interrogation can be recognised only after application of the decoding process (see Section 4.7-3). The decisive advantage of mode recognition as shown in Fig. 4.5-2 is that checking of a pulse is started only when it reaches the reference pointer at position 0. In the example in Fig. 4.5-2, this occurs 25 µs after it is received, i.e. at a time where it is already clear whether it is followed by, for example, a P2 or by other pulses of a legal pulse pattern (mode).

A random pulse or pulse pair which happens to exist anywhere within the digital delay line will interfere with this recognition process only if it is currently at one of the read pointer positions, thus simulating an incorrect pulse pattern.

The circuit shown in Fig. 4.5-2 thus possess all characteristics of a real-time pulse pattern detector which is also capable of detecting superimposed pulse patterns (garbling) separately. The protection against simulated pattern has limits which result from the many legal pulse patterns, which do not differ significantly from each other, and from the completeness and/or strictness of the checking.

The construction of the circuit shown in Fig. 4.5-2 with 4-port RAMs would require six modules for the 17 read pointers. The write pointers of all six modules receive their signals in parallel from the A/D converter, and their read pointers (three each) would have an address offset with respect to the reference read pointer (see Fig. 4.4-2).

At a clock frequency of 8 MHz (resolution 0.125 µs), it would even be possible to set each read pointer to two different addresses during each clock cycle, which means that only three 4-port RAMs could be sufficient for the recognition of all desired modes.
Each of these pointers would then need to have two buffers assigned to it to hold the data from the RAM and to pass these on to the following processors.

4.5.2 In the reply channel

According to the problem description, it is only necessary to recognise, in the replies in the reply channel (1090MHz):

frames F1/F2 in Modes 1, 2, 3/A and C,

the reply tetrad in Mode 4 and

all Mode S replies (short/long).

Fig. 4.5-5 shows the replies – wherever necessary – next to each other and to scale. Once again, it appears almost impossible to distinguish the pulse length of 0.45 µs of Modes 1 to 4 und C from that of Mode S (0.5 µs). (See also Section 4.4.)

Even if aircraft without the altitude-reporting facility reply to Mode C interrogations only with "empty" frames, most of the Mode 1,2,3/A and C replies should still contain data bits at the positions shown with dashes in Fig. 4.5-5. The positions of these data bits C1, A1, C2, A2, etc., namely 1.45 µs and 2.9 µs apart, are not significantly different from the positions of pulses P1, P2 and P3 of Mode 4, which are 1.75 µs apart. Furthermore, the P3 pulse of Mode 4 appears at the same time as pulse P3 of the Mode S reply. This fact is practical with respect to the number of read pointers in a detector, but useless for distinguishing between Mode 4 and Mode S.

In view of the pulse interval tolerances of +/- 0.1 µs (see Section 4.4) and the pulse intervals of 1 µs (Mode S), 1.45 µs (data in Modes 1,2,3/A and C) and 1.75 µs in Mode 4 which have to be distinguished from each other, a time resolution of 0.125 µs corresponding to a clock frequency of 8 MHz, again seems acceptable. The resulting error of +/- 0.125 µs in the measurement of the pulse intervals will not hide the slight difference in the intervals which exists, for example, between 1.75 µs in Mode 4 and any data pulses in Modes 2, 3/A and C.

On the basis of these considerations, it can be assumed that a correlator for recognition of the replies in Modes 1, 2, 3/A, C and 4 can be implemented with the aid of five read pointers, i.e. with two 4-port RAMs, for example. If the read pointers are used twice per clock cycle (see Section 4.5.1), it could even be done with a single 4-port RAM.

The first two generations of measuring receivers with correlators for recognition of Mode S replies used a separate pulse detector (leading edge, top), and checked the pulse pattern of the detected pulses for the time pattern of the preamble, consisting of pulses P1 - P4. When this was detected, decoding of the received Mode S reply was started at pulse P5.

The third generation uses a method without separate pulse detection but with improved time pattern detection for the selection of Mode S replies in the reply channel which normally carries a heavy load.
For this, the correlator not only checks the preamble pulses P1 to P4, but also the first two bits in the reply telegram P5.

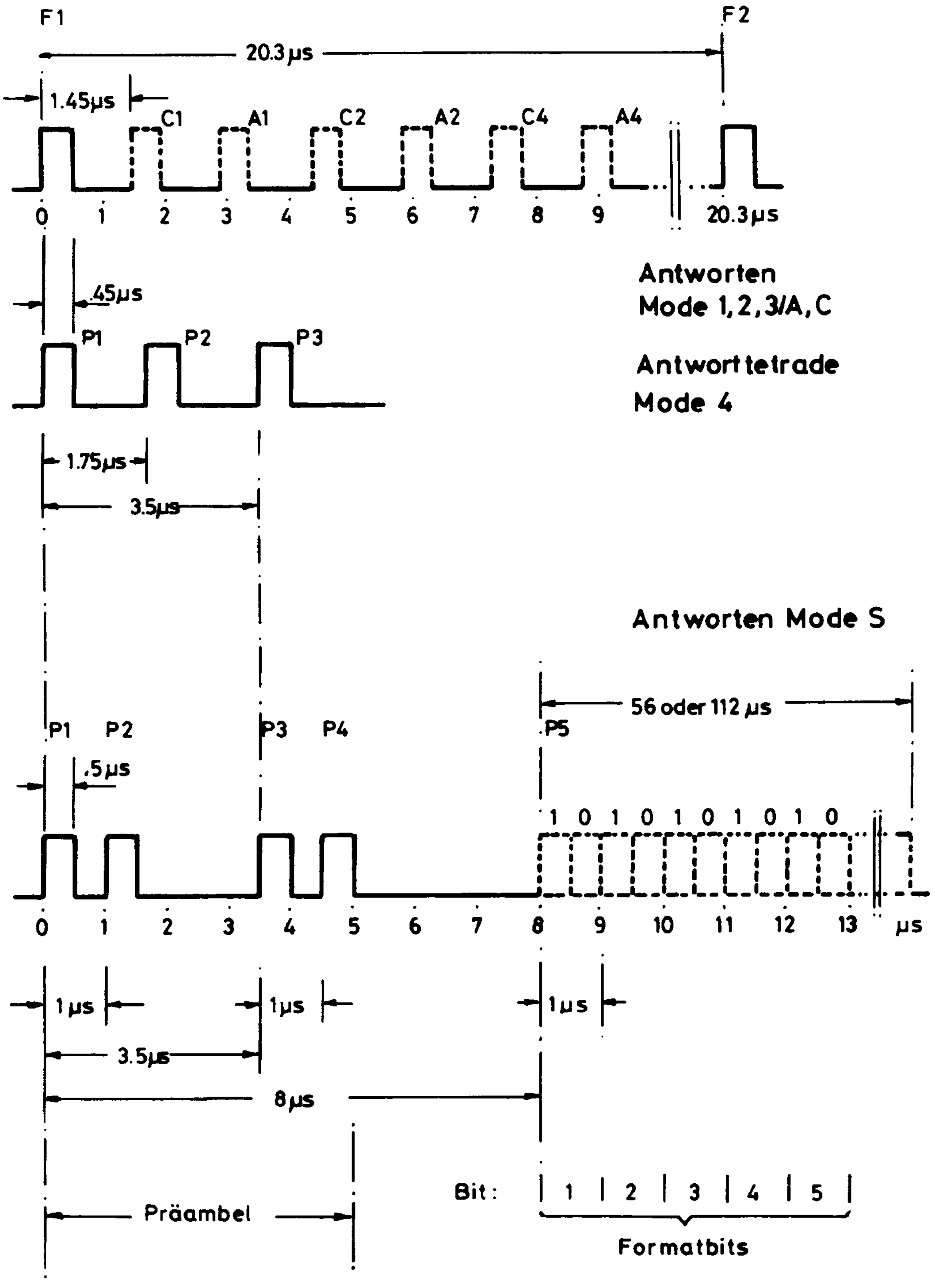

Fig. 4.5-5: Reply formats

These data bits can, of course, have either of two states, and these are indicated by the positional encoding of a pulse with a length of 0.5 µs. Within a time slot with a duration of 1 µs,

- a 0.5 µs pulse in the first half signifies "1"

- a pulse in the second half signifies "0".

For each data bit to be checked, the Mode S pulse pattern detector needs an OR function of two read pointers to determine whether a pulse appears in the first ("1") or second position ("0") of a data-bit time slot. A pulse must appear in one or the other position, since the reply is otherwise not a Mode S reply.
The newer measuring receivers therefore use, in addition to the write pointer, four read pointers for pulses P1 to P4 and four read pointers for the two data bits. In other words, they have three 4-port RAMs whose write pointers receive the information from the A/D converter in parallel.

This type of receiver has proved its value very well on airport properties (Cologne/Bonn). The idea of extending the check to cover the next three bits as well appears useful, since this would permit the format to be read immediately when a Mode S reply is recognised. In this manner, the formats listed in Section 1.2 of the problem description could be passed on for further processing (parity and telegram decoding) and all others could be discarded immediately.

With the six additional read pointers needed for this, a total of 14 read pointers would be needed, and this could be achieved either with five 4-port RAMs without double use of the read pointers or three 4-port RAMs with double use.
Another possibility would be the double use of the write pointers for reading data in order to further reduce the necessary number of such RAMs.

4.6 Resolution of pulse amplitudes and pulse edges and amplitude comparison (results of field measurements)

Complete and stringent testing of received pulse patters also includes the measurement and comparison of their amplitudes, for two reasons:

- the amplitudes of the pulses of a legal pulse pattern should, since they are subject to the same transmission conditions, be equal (within 1 to 2dB),

- unless they were transmitted with different amplitudes in order to assign them a certain legal significance, namely the suppression function.

However, reflections and the superimposition of signals can cause, as described in Section 4.1, unequal amplitudes of the pulses in a pulse pattern, thus also falsifying the amplitude differences of pulses which were transmitted with unequal amplitudes.
In view of the additional difficulties, mentioned in Sections 4.2 and 4.3, related to the assignment of a single amplitude to the top of a pulse, only very tolerant conditions can be

specified for the equality of the pulse amplitudes and the precision of the differences between them.

For orientation with respect to practical measurements, the following four pages (Figs. 4.6-1 to 4.6-4) show diagrams recorded at the same scale at the video output of the logarithmic amplifier at Frankfurt airport (1995). The vertical scale has increments of 100 mV and 100 mV corresponds to a change of 7.5 dB. For interpretation, the diagrams are numbered from 1 to 40.
Three further pages (Figs. 4.6-5 to 4.6-7) show the voltages at the video output of the logarithmic receiver, at a different scale, for the reply channel. These diagrams are also numbered, in this case from 41 to 70.

The antenna (ELTA, SEL) on the meteorological hut of Frankfurt airport was installed so that it was ideal for receiving signals in the interrogation and reply channels from the air. Examples 5, 9, 31, 39 and 40 show that signals from ground stations were also recorded, although such recordings with a transient recorder should actually be initiated by the reception of recognised Mode S signals.

One can see, for example, in diagrams 1, 2, 3, 4, 6 and 8, very clean Mode S interrogations whose P6 phase modulation can be seen only partially at the short glitches caused by the filters being used. Examples 7, 10, 11, 12, 16, 18 and 20 were subject to greater variations in the amplitude, apparently as the result of reflections which, particularly in diagrams 15 and 20, fill the pulse gaps P1 - P2 -P6 and decay only after the end of the signal. The amplitude variations are, for example in diagrams 7, 10 and 16, about +/- 7.5 dB and the leading edge of pulse P6 is reduced to steps of around 15 dB, and in some cases only about 10 dB.
An interesting feature of examples 22 and 39 is that they each contain a whisper shout interrogation from an ACAS device where the S pulse is, however, hardly 2 or 3 dB lower than the following P1 pulse.
In order to ensure good detection of at least the Mode S interrogations, amplitude variations of the pulses P1, P2 and P6 in the order of +/- 7.5 dB should be permitted.

Such wide variations are not visible in the reply channel, at least not for the Mode S replies. This is particularly easy to see in diagrams 55 and 57 where continuous "ones" were transmitted by mistake.
If relatively bad signals subject to reflections, such as those in diagrams 68 and 69, are to be taken into account, a window of, for example, +/-4 dB could be sufficient.
Accordingly, a resolution of the dynamic range from about -80 to –20 dBm into 16 steps (4 bits) of 3.75 dB each should be sufficient. Until now, however, far finer resolutions of 128 steps (7 bits) of 0.47 dB each have been used in order to permit precise definition of the amplitude window to be applied. Finally, amplitude windows of +/-13.5 dB were used.

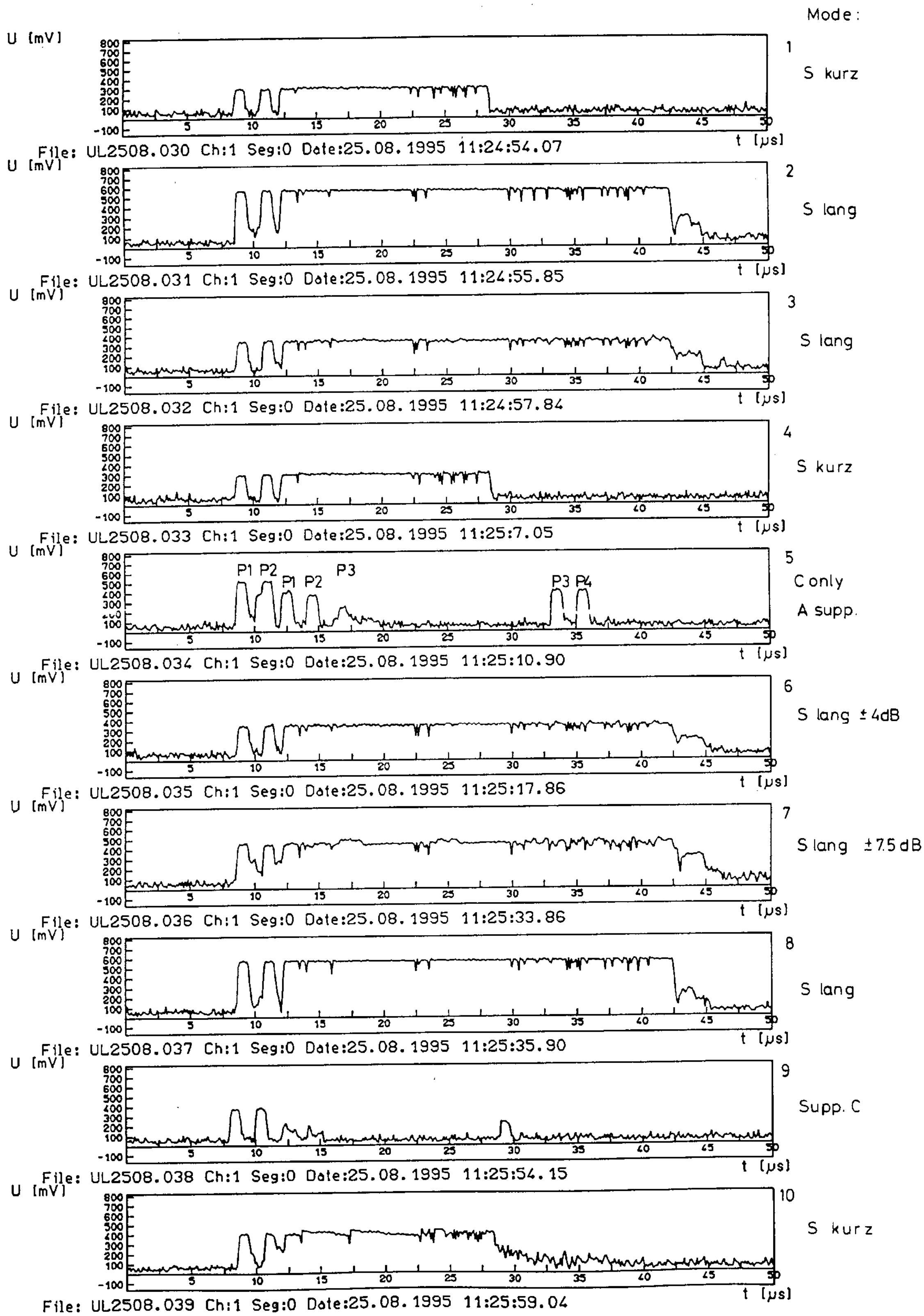

Fig. 4.6-1: Measured interrogations

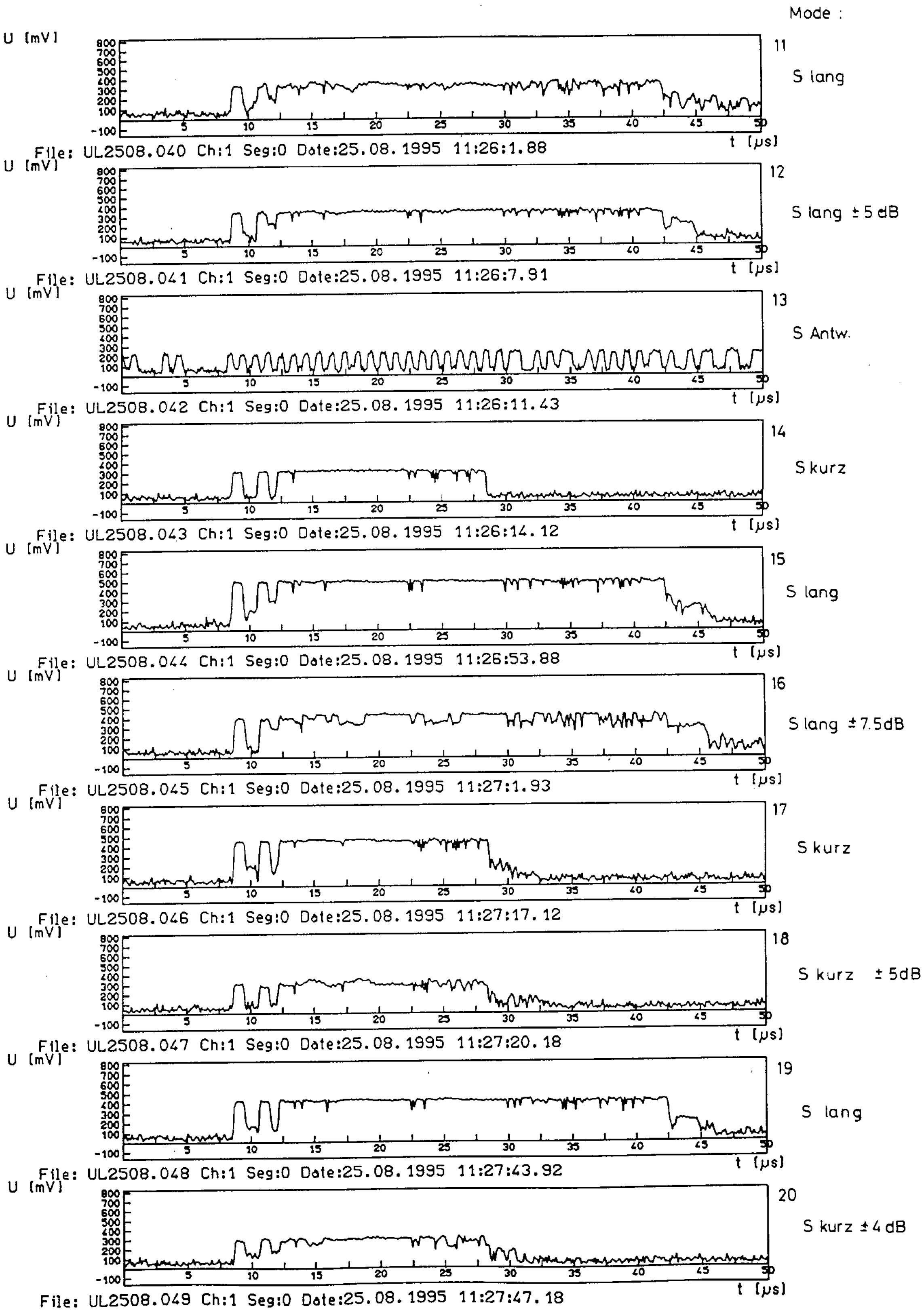

Fig. 4.6-2: Measured interrogations

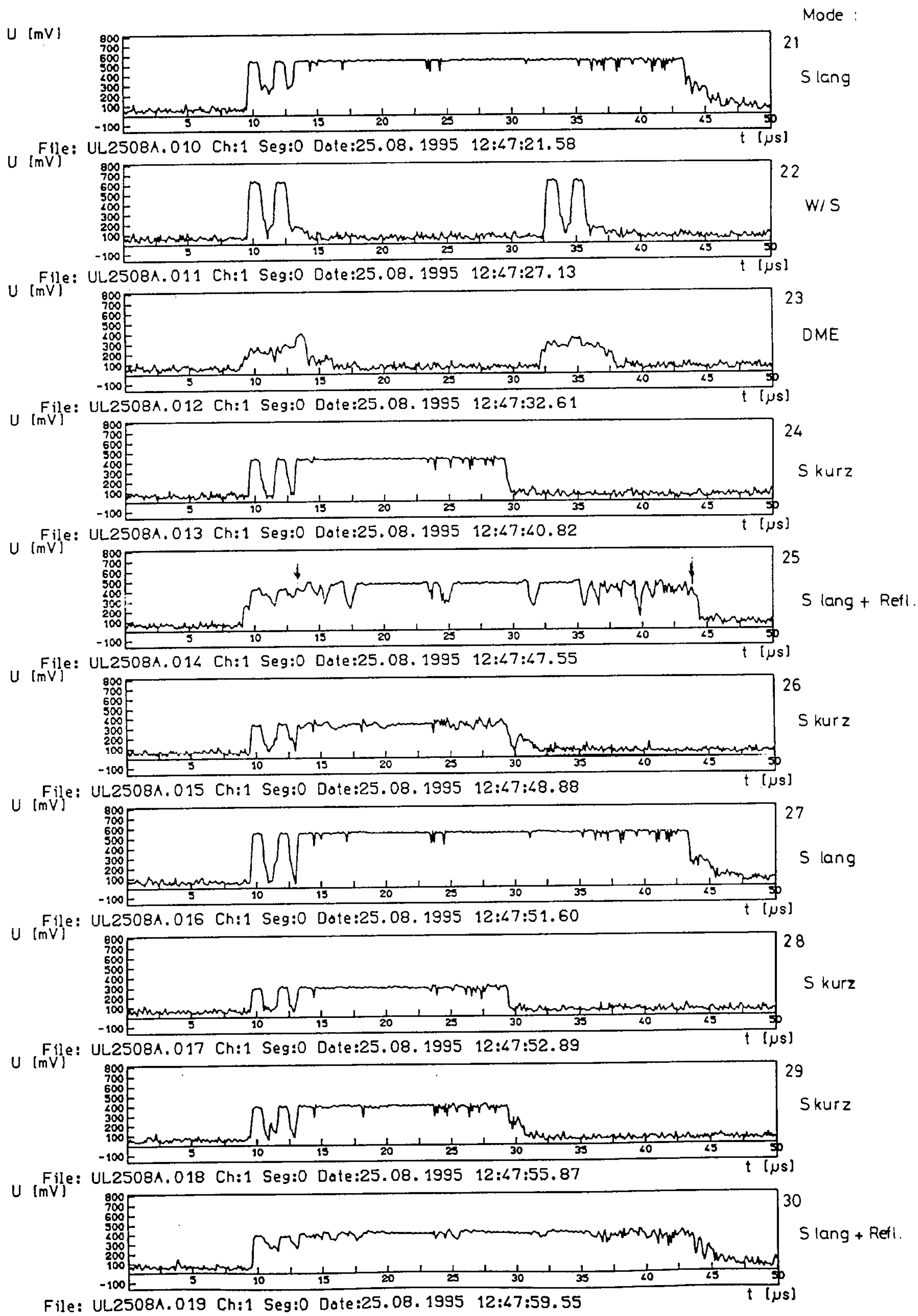

Fig. 4.6-3: Measured interrogations

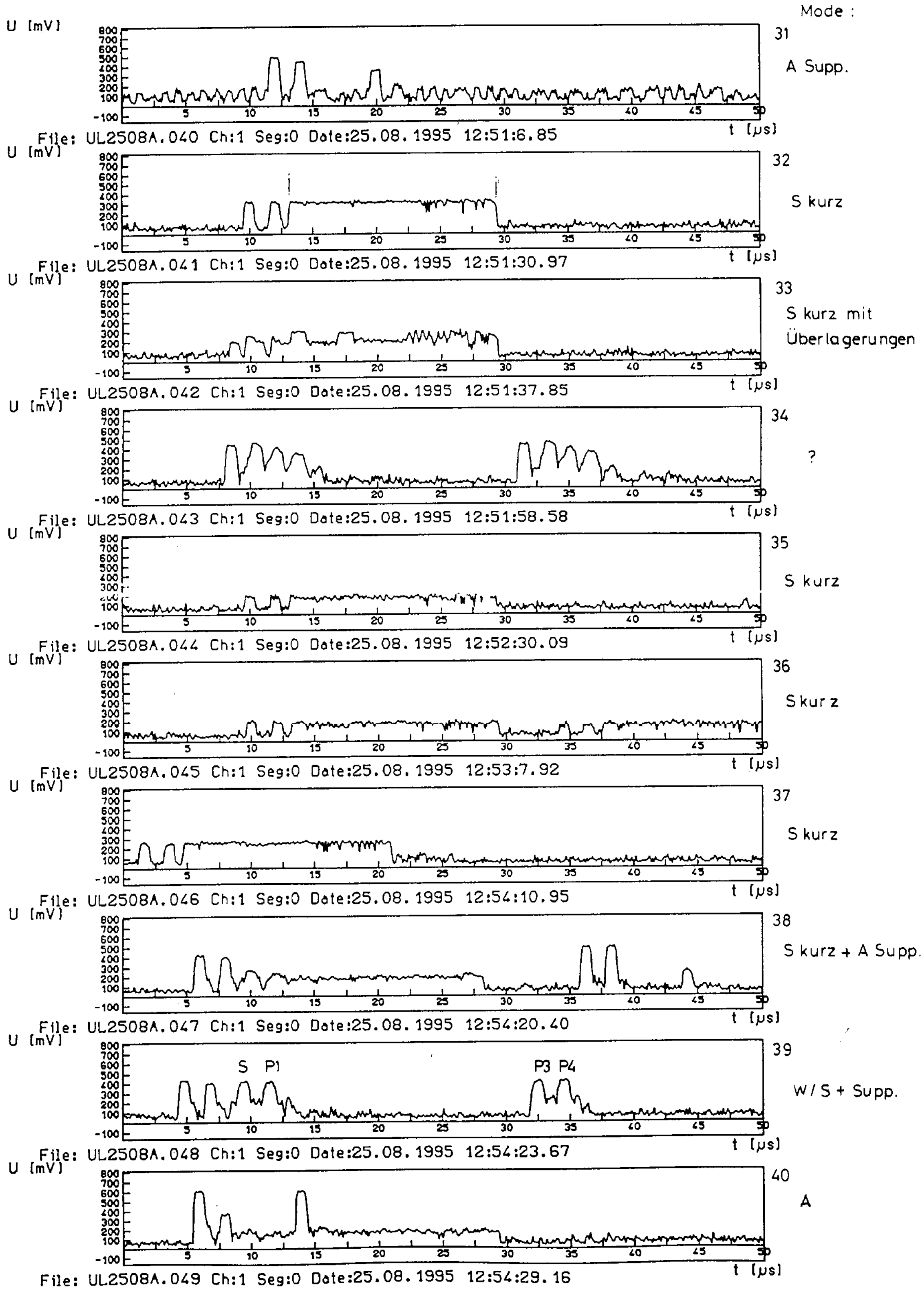

Fig. 4.6-4: Measured interrogations

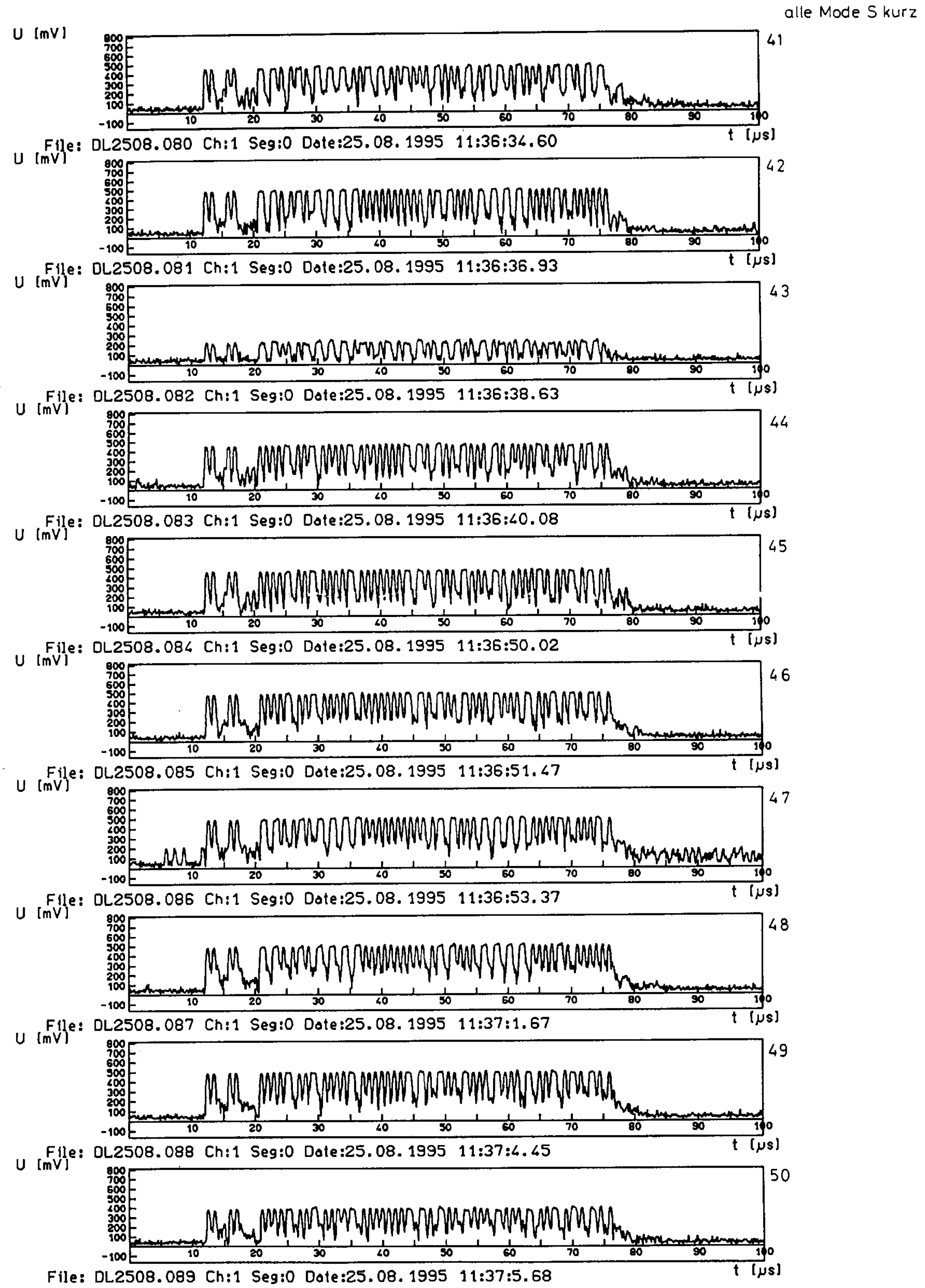

Fig. 4.6-5: Measured replies

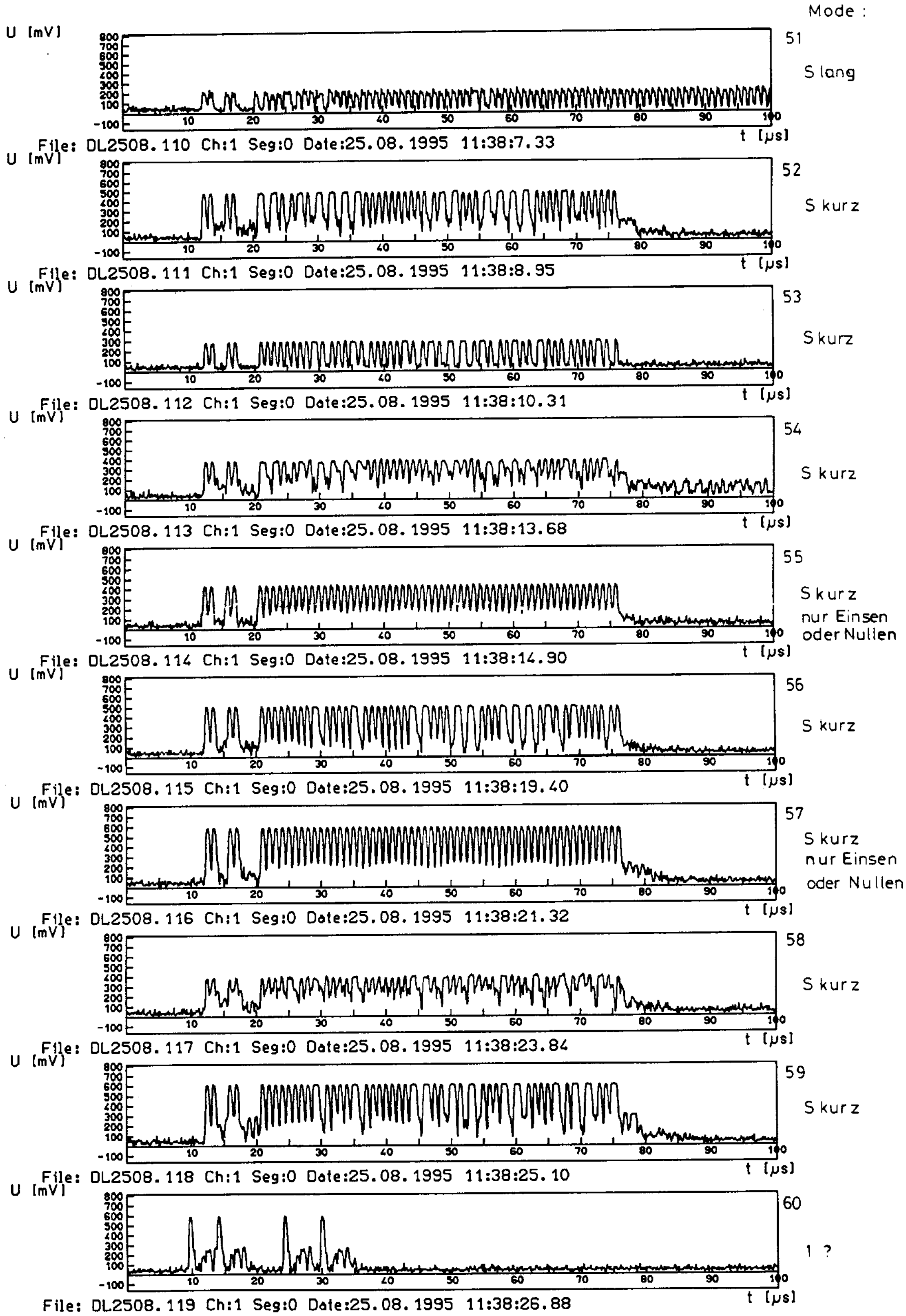

Fig. 4.6-6: Measured replies

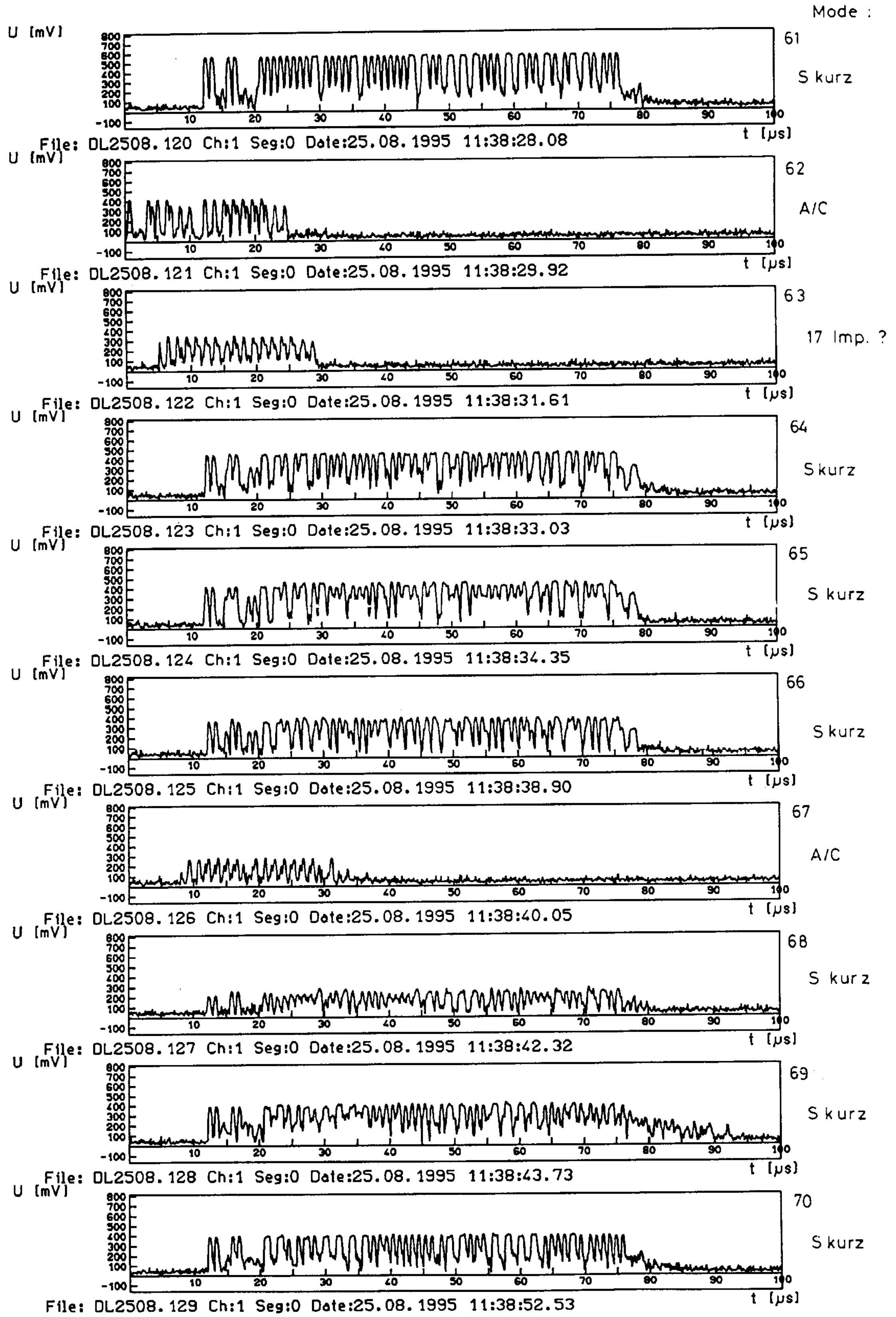

Fig. 4.6-7: Measured replies

As already indicated, the diagrams provide various hints for the detection of the leading edges of pulses. A step of at least 6 dB can apparently be expected, even if reflections have filled the pulse gaps. If a step is to be detected from the sampled (8 MHz) amplitudes, it must occur within three clock cycles. The detection of the leading edges of pulses before the signals are sampled with an A/D converter is subject to other rules.
The diagrams for the reply channel also show that the detection of data in pulse P5 of a Mode S reply should be executed by comparing the amplitudes in the first and second halves of the pulse, rather than by detecting the pulse edges. For this, a finer amplitude resolution than 3.75 dB seems very advisable.

For the detection of side-lobe suppressions, the amplitudes of two pulses, namely P1 and P2 in Modes 1, 2, 3/A and C or P4 and P5 in Mode 4, must be compared. Particularly for precise determination of whether the second pulse (P2 or P5) is larger than the preceding pulse again makes a finer amplitude resolution advisable unless an analogue circuit is inserted before the signal is sampled in the A/D converter and the (binary) output from this circuit is inserted as a bit into the digital delay line with the aid of the write pointer.
An amplitude comparison with a delay of 2 µs seems feasible with the aid of commercially available analogue delay lines, but this has not yet been tested.

4.7 Decoding the A/P and P/I fields of Mode S

4.7.1 The Mode S interrogation and reply format

In accordance with ICAO Annex 10, Section 3.1.2.3.2, Figures 4.7-1 and 4.7-2 show the interrogation and reply formats which have already been standardised and Figures 4.7-3 and 4.7-4 show the definitions of the fields and subfields.

The standard specifies that all bits are written and transmitted from the left, starting with the most significant bits (MSB). In other words, the format bits are transmitted first and the A/P and P/I fields are transmitted last. The actual message, consisting of 33 bits for short formats or 88 bits for long formats (including the format bits), is not encrypted before transmission. However, the meanings of the bits following the format bits change, depending on the format.
24 so-called control bits are appended to the 33-bit or 88-bit message. These 24 control bits are used on the one hand to detect transmission errors. On the other hand, they can contain the address of the interrogated or replying aircraft (A/P field), or the so-called identifier of a ground station (reply format 11) or the value "zero" if Squitters or Extended Squitters are transmitted in reply format 11 or 17.
It is therefore important, for example, that no aircraft uses the technical Mode S address zero. In such cases, ACAS would also be unable to coordinate an evasion manoeuvre.

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Format No.	UF								
0	00000	3	RL:1	4	AQ:1	18		AP:24	.... Short air-air surveillance (ACAS)
1	00001	27 or 83						AP:24	
2	00010	27 or 83						AP:24	
3	00011	27 or 83						AP:24	
4	00100	PC:3	RR:5	DI:3	SD:16			AP:24	.... Surveillance, altitude request
5	00101	PC:3	RR:5	DI:3	SD:16			AP:24	.... Surveillance, identity request
6	00110	27 or 83						AP:24	
7	00111	27 or 83						AP:24	
8	01000	27 or 83						AP:24	
9	01001	27 or 83						AP:24	
10	01010	27 or 83						AP:24	
11	01011	PR:4	IC:4	CL:3	16			AP:24	.... Mode S only all-call
12	01100	27 or 83						AP:24	
13	01101	27 or 83						AP:24	
14	01110	27 or 83						AP:24	
15	01111	27 or 83						AP:24	
16	10000	3	RL:1	4	AQ:1	18	MU:56	AP:24	.... Long air-air surveillance (ACAS)
17	10001	27 or 83						AP:24	
18	10010	27 or 83						AP:24	
19	10011	27 or 83						AP:24	
20	10100	PC:3	RR:5	DI:3	SD:16	MA:56		AP:24	.... Comm-A, altitude request
21	10101	PC:3	RR:5	DI:3	SD:16	MA:56		AP:24	.... Comm-A, identity request
22	10110	27 or 83						AP:24	
23	10111	27 or 83						AP:24	
24	11	RC:2	NC:4	MC:80				AP:24	.... Comm-C (ELM)

NOTES:

1. [XX:M] denotes a field designated "XX" which is assigned M bits.
2. [N] (dashed box) denotes unassigned coding space with N available bits. These shall be coded as ZEROs for transmission.
3. For uplink formats (UF) 0 to 23 the format number corresponds to the binary code in the first five bits of the interrogation. Format number 24 is defined as the format beginning with "11" in the first two bit positions while the following three bits vary with the interrogation content.
4. All formats are shown for completeness, although a number of them are unused. Those formats for which no application is presently defined remain undefined in length. Depending on future assignment they may be short (56 bits) or long (112 bits) formats. Specific formats associated with Mode S capability levels are described in later paragraphs.
5. The PC, RR, DI and SD fields do not apply to a Comm-A broadcast interrogation.

Fig. 4.7-1: Summary of Mode S interrogation or uplink formats

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Format No.	DF	Fields	Parity	
0	00000	VS:1, 7, RI:4, 2, AC:13	AP:24	.... Short-air-air surveillance (ACAS)
1	00001	27 or 83	P:24	
2	00010	27 or 83	P:24	
3	00011	27 or 83	P:24	
4	00100	FS:3, DR:5, UM:6, AC:13	AP:24	.... Surveillance, altitude reply
5	00101	FS:3, DR:5, UM:6, ID:13	AP:24	.... Surveillance, identity reply
6	00110	27 or 83	P:24	
7	00111	27 or 83	P:24	
8	01000	27 or 83	P:24	
9	01001	27 or 83	P:24	
10	01010	27 or 83	P:24	
11	01011	CA:3, AA:24	PI:24	.... All-call reply
12	01100	27 or 83	P:24	
13	01101	27 or 83	P:24	
14	01110	27 or 83	P:24	
15	01111	27 or 83	P:24	
16	10000	VS:1, 7, RI:4, 2, AC:13, MV:56	AP:24	.... Long air-air surveillance (ACAS)
17	10001	CA:3, AA:24, ME:56	PI:24	.... Extended squitter
18	10010	27 or 83	P:24	
19	10011	27 or 83	P:24	
20	10100	FS:3, DR:5, UM:6, AC:13, MB:56	AP:24	.... Comm-B, altitude reply
21	10101	FS:3, DR:5, UM:6, ID:13, MB:56	AP:24	.... Comm-B identity reply
22	10110	27 or 83	P:24	
23	10111	27 or 83	P:24	
24	11	1, KE:1, ND:4, MD:80	AP:24	.... Comm-D (ELM)

NOTES:

1. XX:M denotes a field designated "XX" which is assigned M bits.

   P:24 denotes a 24-bit field reserved for parity information.

2. N (dashed box) denotes unassigned coding space with N available bits. These shall be coded as ZEROs for transmission.

3. For downlink formats (DF) 0 to 23 the format number corresponds to the binary code in the first five bits of the reply. Format number 24 is defined as the format beginning with "11" in the first two bit positions while the following three bits may vary with the reply content.

4. All formats are shown for completeness, although a number of them are unused. Those formats for which no application is presently defined remain undefined in length. Depending on future assignment they may be short (56 bits) or long (112 bits) formats. Specific formats associated with Mode S capability levels are described in later paragraphs.

Fig. 4.7-2: Summary of Mode S reply or downlink formats

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Table 3-3. Field definitions

Field		*Format*		
Designator	*Function*	*UF*	*DF*	*Reference*
AA	Address announced		11	3.1.2.5.2.2.2
AC	Altitude code		4, 20	3.1.2.6.5.4
AP	Address/parity	All	0, 4, 5, 16, 20, 21, 24	3.1.2.3.2.1.3
AQ	Acquisition	0		3.1.2.8.1.1
CA	Capability		11	3.1.2.5.2.2.1
CC	Cross-link capability		0	3.1.2.8.2.3
CL	Code label	11		3.1.2.5.2.1.3
DF	Downlink format		All	3.1.2.3.2.1.2
DI	Designator identification	4, 5, 20, 21		3.1.2.6.1.3
DR	Downlink request		4, 5, 20, 21	3.1.2.6.5.2
DS	Data selector	0		3.1.2.8.1.3
FS	Flight status		4, 5, 20, 21	3.1.2.6.5.1
IC	Interrogator code	11		3.1.2.5.2.1.2
ID	Identity		5, 21	3.1.2.6.7.1
KE	Control, ELM		24	3.1.2.7.3.1
MA	Message, Comm-A	20, 21		3.1.2.6.2.1
MB	Message, Comm-B		20, 21	3.1.2.6.6.1
MC	Message, Comm-C	24		3.1.2.7.1.3
MD	Message, Comm-D		24	3.1.2.7.3.3
ME	Message, extended squitter		17	3.1.2.8.6.2
MU	Message, ACAS	16		4.3.8.4
MV	Message, ACAS		16	3.1.2.8.3.1, 4.3.8.4
NC	Number of C-segment	24		3.1.2.7.1.2
ND	Number of D-segment		24	3.1.2.7.3.2
PC	Protocol	4, 5, 20, 21		3.1.2.6.1.1
PI	Parity/interrogator identifier		11, 17	3.1.2.3.2.1.4
PR	Probability of reply	11		3.1.2.5.2.1.1
RC	Reply control	24		3.1.2.7.1.1
RI	Reply information		0	3.1.2.8.2.2
RL	Reply length	0		3.1.2.8.1.2
RR	Reply request	4, 5, 20, 21		3.1.2.6.1.2
SD	Special designator	4, 5, 20, 21		3.1.2.6.1.4
UF	Uplink format	All		3.1.2.3.2.1.1
UM	Utility message		4, 5, 20, 21	3.1.2.6.5.3
VS	Vertical status		0	3.1.2.8.2.1

Fig. 4.7-3: Definitions of the fields in Mode S

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Table 3-4. Subfield definitions

Subfield			
Designator	*Function*	*Field*	*Reference*
ACS	Altitude code subfield	ME	3.1.2.8.6.3.1.2
AIS	Aircraft identification subfield	MB	3.1.2.9.1.1
ATS	Altitude type subfield	MB	3.1.2.8.6.8.2
BDS 1	Comm-B data selector subfield 1	MB	3.1.2.6.11.2.1
BDS 2	Comm-B data selector subfield 2	MB	3.1.2.6.11.2.1
IDS	Identifier designator subfield	UM	3.1.2.6.5.3.1
IIS	Interrogator identifier subfield	SD	3.1.2.6.1.4.1 a)
		UM	3.1.2.6.5.3.1
LOS	Lockout subfield	SD	3.1.2.6.1.4.1 d)
LSS	Lockout surveillance subfield	SD	3.1.2.6.1.4.1 g)
MBS	Multisite Comm-B subfield	SD	3.1.2.6.1.4.1 c)
MES	Multisite ELM subfield	SD	3.1.2.6.1.4.1 c)
RCS	Rate control subfield	SD	3.1.2.6.1.4.1 f)
RRS	Reply request subfield	SD	3.1.2.6.1.4.1 e) and g)
RSS	Reservation status subfield	SD	3.1.2.6.1.4.1 c)
SAS	Surface antenna subfield	SD	3.1.2.6.1.4.1 f)
SCS	Squitter capability subfield	MB	3.1.2.6.10.2.2.1
SIC	Surveillance identifier capability	MB	3.1.2.6.10.2.2.1
SIS	Surveillance identifier subfield	SD	3.1.2.6.1.4.1 g)
SRS	Segment request subfield	MC	3.1.2.7.7.2.1
SSS	Surveillance status subfield	ME	3.1.2.8.6.3.1.1
TAS	Transmission acknowledgement subfield	MD	3.1.2.7.4.2.6
TCS	Type control subfield	SD	3.1.2.6.1.4.1 f)
TMS	Tactical message subfield	SD	3.1.2.6.1.4.1 d)
TRS	Transmission rate subfield	MB	3.1.2.8.6.8.1

Fig. 4.7-4: Definitions of the Mode S subfields

4.7.2 Encoding in interrogations and replies

In accordance with ICAO Annex 10, Section 3.1.2.3.3 and the Mode S Guidance Material, Section 9, the 24 bits of a control word are formed with the aid of the following process:

- The message to be transmitted M(x), namely the 32 or 88 bits including the format bits, are multiplied by x^{24}. This shifts the entire sequence of message bits M(X) to the left by 24 binary positions. The last (least significant) bits of the newly created word are at this point all zero.

- This newly created word, with a length of 56 or 112 bits, is then divided by a polynomial G(x), where

$$G(x) = x^{24} + x^{23} + x^{22} + x^{21} + x^{20} + x^{19} + x^{18}$$

$$+ x^{18} + x^{17} + x^{16} + x^{15} + x^{14} + x^{13} + x^{12}$$

$$+ x^{10} + x^{3} + 1$$

  i.e. by a polynomial in which positions

$$x, x^2 \text{ to } x^9 \text{ and } x^{11} = 0$$

  This division of the message M(x), shifted 24 positions to the left, and of the 24 least significant bits (which are zero) results, due to the use of the modulo-2 operation, in a remainder R(x) which cannot be divided further by G(x).

- If this remainder R(x) were inserted by a modulo-2 operation into the 24 least significant bits of the newly created 56-bit or 112-bit word, the resulting word would again be divisible by the polynomial G(x) without a remainder. Dividing the new word by G(x) again would therefore result in a word in which the least significant bits were again all zero, providing none of the bits has been changed by a transmission error.

- In Mode S, however, the remainder R(x) is not simply inserted into the 24 least significant bits of the newly created 56-bit or 112-bit word, but is first combined in a modulo-2 operation with the address of the aircraft to be interrogated and then inserted in these 24 bits.

- The address and the remainder R(x) are combined as shown in Fig. 4.7-5 in the transponder to form the reply to be transmitted, as described above. In the case of interrogation by a ground station or an ACAS, however, the address A(x) and the polynomial G(x) are first multiplied together as shown in Fig. 4.7-6 to form a product A(x) x G(x). The 24 most significant bits of this product are then combined by a modulo-2 operation with the remainder R(x) and inserted in the 24 control bits.

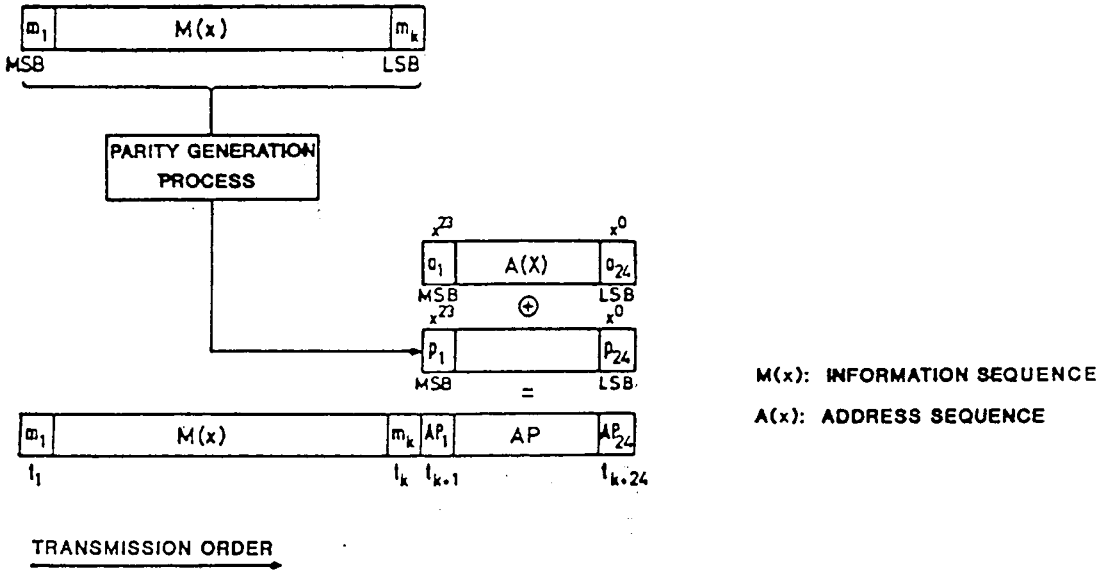


Fig. 4.7-5: Encoding of the reply in a Mode S transponder

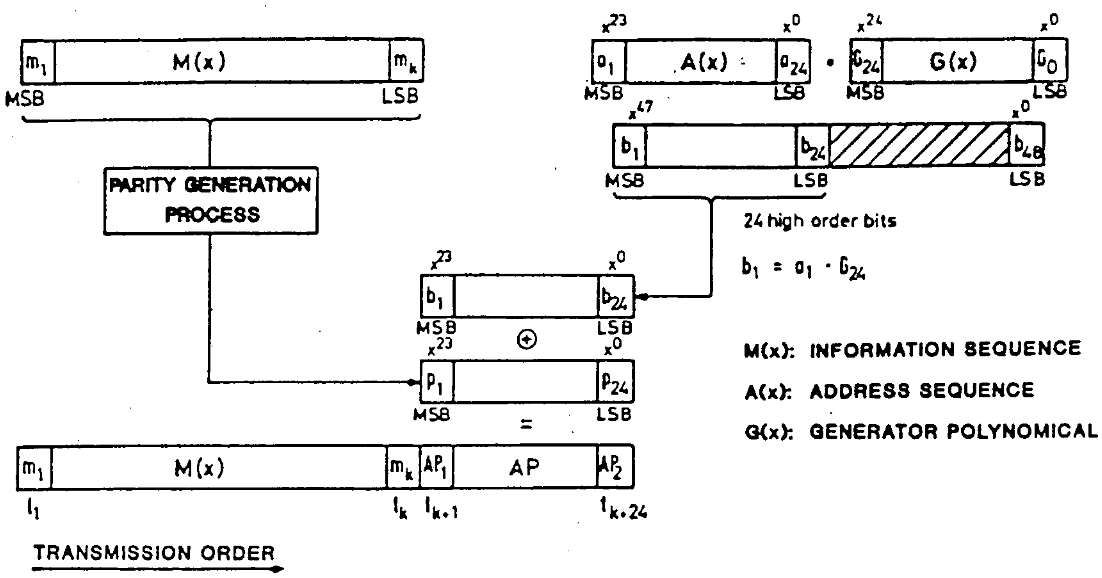


Fig. 4.7-6: Encoding of a Mode S interrogation

4.7.3 Decoding of the interrogations received in the transponder or in the SSR monitor

All bits of an interrogation received and DPSK-demodulated by a transponder are again divided by the polynomial G(x). The indivisible remainder resulting from this would be zero if the address to be interrogated had not been included during encoding of the interrogation. After division by G(x), the remainder would thus be the address, except for the fact that each transponder automatically exclusive-ORs the resulting remainder R(x) with its own address A(x) and would normally receive a remainder of zero if there have been no transmission errors. In addition, an interrogation with the address of another transponder would also result in a non-zero remainder. In both cases, the transponder cannot reply to the interrogation.

An SSR monitor with uplink receiver does not have an address. After division of the received interrogation by the polynomial G(x), the resulting remainder can thus be regarded only as an address. The correctness of this address cannot be checked spontaneously unless the aircraft remains within the reception range of the SSR monitors for some time and the replies are collected and compared with each other so that addresses falsified by occasional transmission errors can be corrected.

Division of the received message with modulo-2 operations is carried out, for cyclic codes, with the aid of shift registers with EXOR gates in the feedback paths or with the aid of so-called modulo-2 networks which also contain EXOR gates at the positions whose coefficients in the polynomial are not zero. Both of these circuit types are mentioned in the Mode S Guidance Material, Section 9 (see Figs. 4.7-7 and 4.7–8). The shift-register circuits are difficult to implement with commercially available shift-register modules, but have the advantage that they can be read out in parallel. The circuit proposed in the Section 9 of the Mode S Guidance Material (Fig. 4.7-9) is based on the modulo-2 network. All data, including the format, information block and A/P field (56 or 112 bits), which arrive serially, are fed into the input of the network for division. After the 56 or 122 clock cycles necessary for this, the address contained in the interrogation can be read out serially in a decoded form with a further 24 clock cycles.

4.7.4 Decoding of the downlink replies received in the SSR monitor

The necessary division by the polynomial G(x) is done here in the same manner as that described in Section 4.7.3 and Fig. 4.7-9, the only difference being that the address of the interrogated transponder appears. This also applies to the all-call replies (format 11), except that the result is the interrogation identifier of the station interrogating in format 11, rather than the address of the interrogated transponder. Furthermore, it applies to Squitters and Extended Squitters, where the result is 24 zeros (as a parity check) instead of the address.
Replies and Squitters on the Mode S downlink are pulse-position modulated, which means that they are more sensitive to falsification by superimposed replies in the modes 1, 4 and C than transmissions on the uplink.

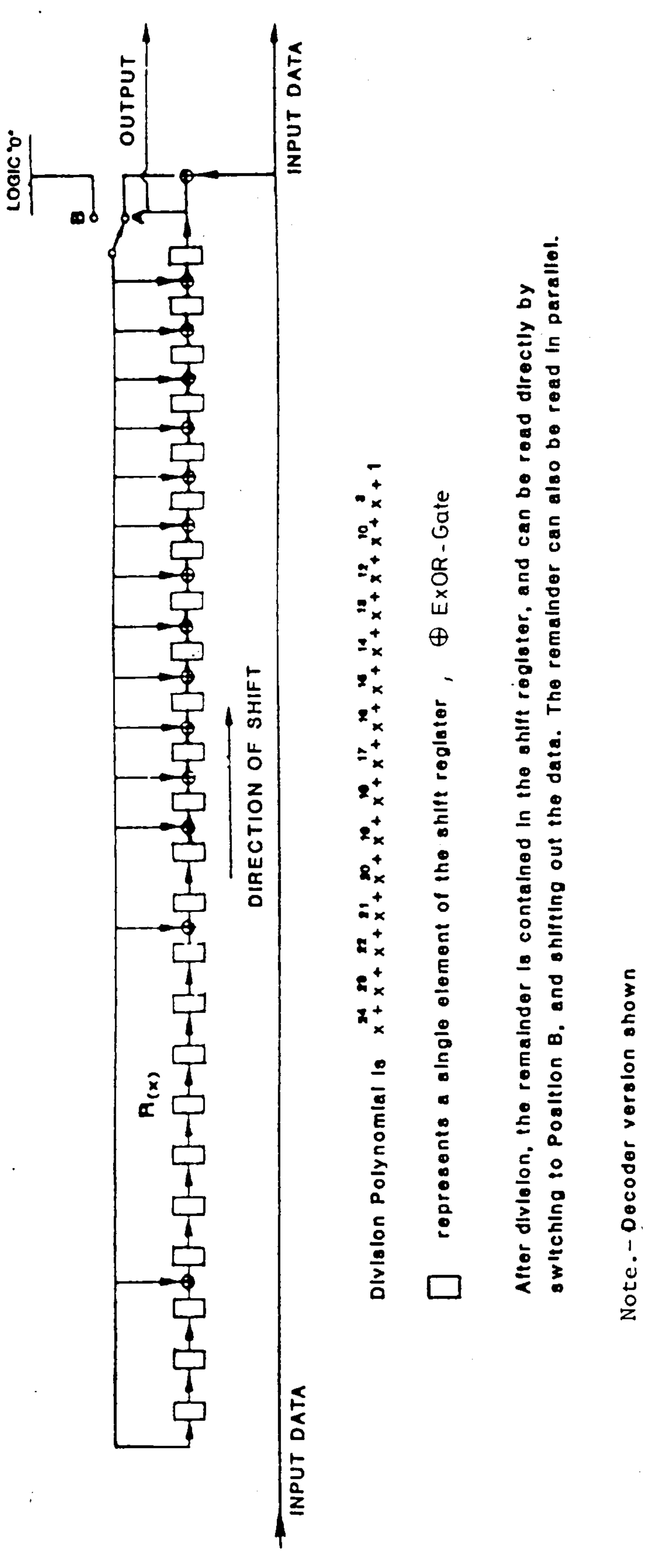


Fig. 4.7-7: Mode S decoder with shift register and EXOR gates in series

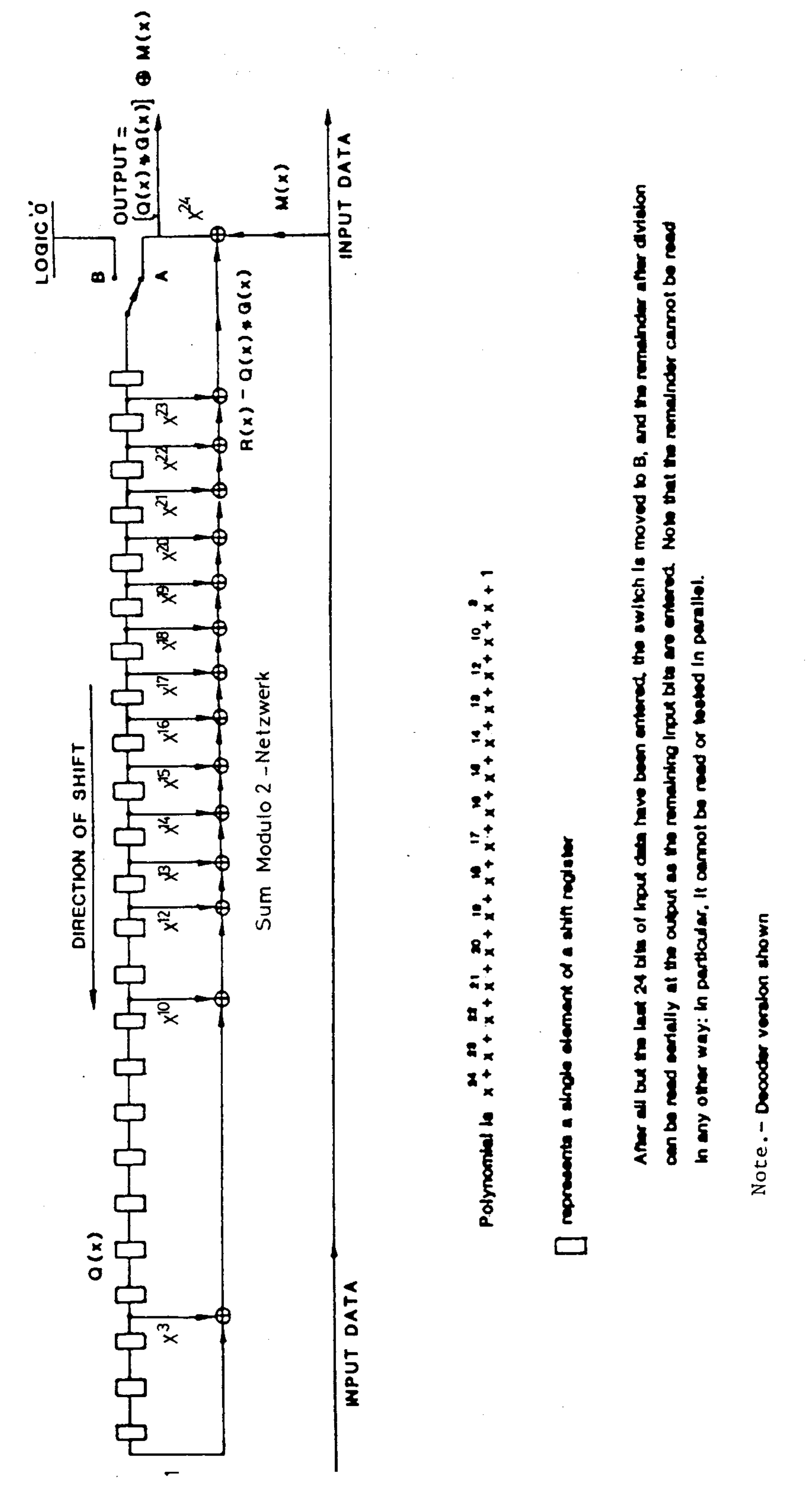


Fig. 4.7-8: Mode S decoder with shift register and parallel modulo-2 network constructed with EXOR gates

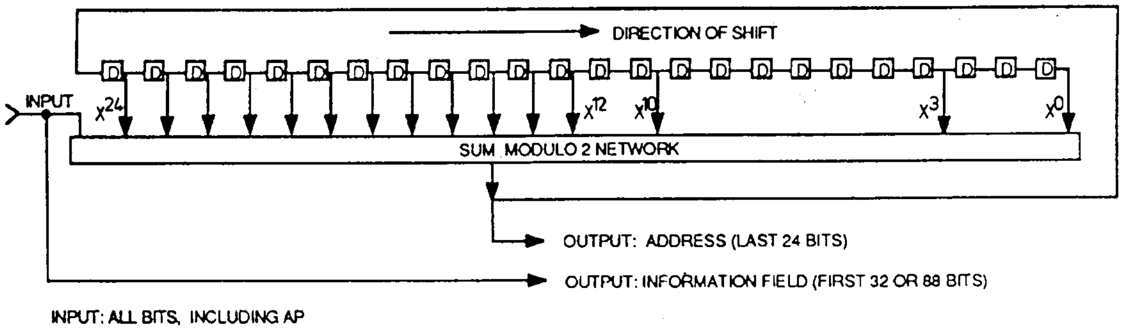


Fig. 4.7-9: Mode S decoder with modulo-2 network as shown in Fig. 4.7-8 for decoding Mode S replies and interrogations

An interrogating station, such as a ground radar or an ACAS aircraft, can compare the received addresses with those it has just interrogated, and can thus determine whether the interrogations have been answered. In the case of minor differences detected between the received and expected address, the interrogating station can also initiate a checking process which permits the variation of bits which were not received unambiguously in order to detect transmission errors.

An SSR monitor is not able to compare the expected addresses with the received addresses in order to start a correction process in the case of slight differences.
For this reason, this study does not present the various possible checking and correction processes. Instead, great importance is attached to a careful and thus complex detection of the received signals, i.e. detection of pulses and pulse patterns, which form the prerequisite for the bit synchronisation needed for demodulation of the data.
This is also the reason why the subject of bit synchronisation in Mode S is dealt with only after the subject of data decoding.

4.8 Demodulation and bit synchronisation in Mode S

4.8.1 In the interrogation channel

The individual bits (each one or zero) of a telegram encoded in accordance with Section 4.7 and transmitted in an interrogation are used to PSK-modulate the keyed carrier signal during pulse P6. A time interval of 0.25 µs is assigned as the chip width to each bit, and there is either a phase shift or no phase shift at the beginning of this period. A phase shift indicated a bit with the value "one", while the absence of a phase shift is interpreted as a bit with the value "zero".

Such a telegram may have a total length of 56 or 112 bits. Long telegrams announce themselves with the first format bit at the beginning of the telegram, which is "one" for such telegrams. Short telegrams begin with a "zero“.

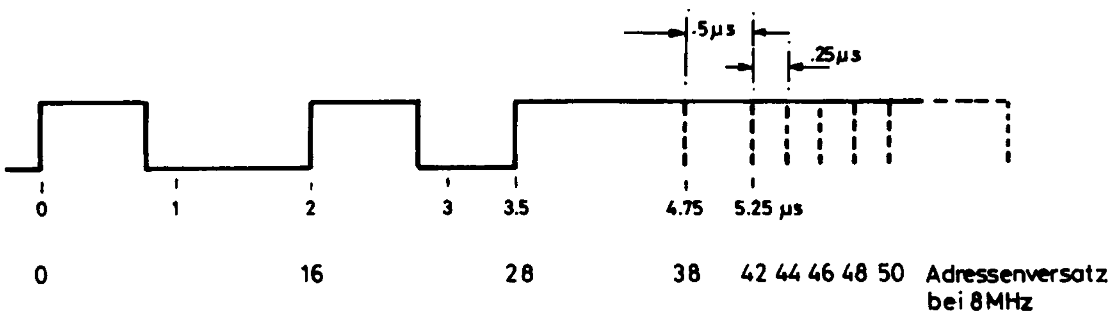


Fig. 4.8-1: Address offset in the Mode S interrogation correlator

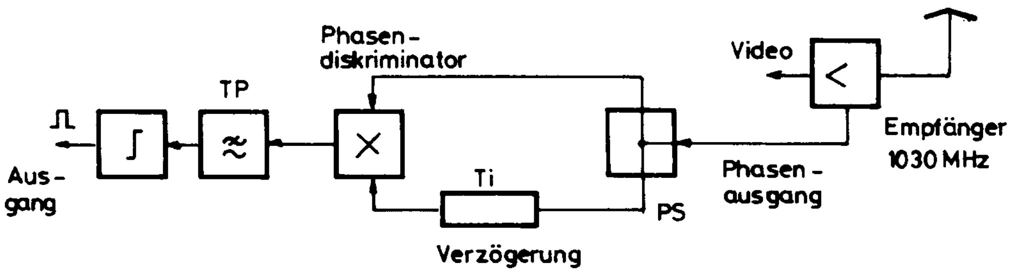


Fig. 4.8-2: Phase demodulator

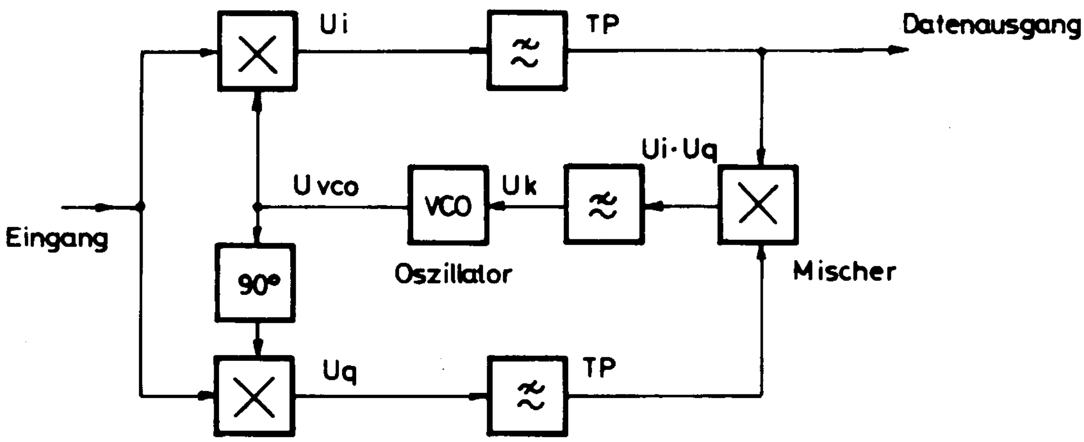


Fig. 4.8-3: Costas phase demodulator

As shown in Fig. 4.8-1, there is always a 180° phase shift during P6, 4.75   s after the start of the Mode S uplink preamble, which consists of the pulses P1 and P2 with equal magnitudes. This phase shift is not a bit; it is the start signal for bit synchronisation. This is necessary because, after a (settling) delay of 0.5   s, the phase shifts or the absence of phase shifts must be sampled at intervals of precisely 0.25   s (at a bit rate of 4 MHz) and allocated to the 56 or 112 bits of the incoming telegram.

In order to detect the phase shifts, the uplink receiver must have a phase demodulator which converts the 180° phase shifts into logically readable pulses so that they can be read out at intervals of 0.25   s. It should also be remembered that the Mode S transmission frequency of 1030 MHz has a tolerance of +/- 200KHz (Annex 10). If heterodyne receivers are used, a further frequency uncertainty may exist in addition to this frequency tolerance of +/- 200KHz.

The first devices used simple phase discriminators like that shown in Fig. 4.8-2. In such a circuit, the signal from the phase output (limited IF) of the logarithmic receiver feeds the IF signal resulting from conversion of the received signal into a power splitter (PS). From there, the signal passes via two paths, one direct and one with a delay of Ti, to a phase detector. The output of the phase detector passes through a low-pass filter (TP) to a voltage threshold detector which should deliver a pulse whenever a phase shift of 180° occurs. The chip width of 0.25   s dictates a delay of about half the chip width (Ti=0.125   s) so that a phase shift of 180° reaches input 2 0.124 µs after it reaches input 1. During this period, therefore, two signals with a phase difference of 180° are present at the inputs to the phase discriminator and the output voltage of the discriminator changes. In order to ensure that the output voltage has a defined (DC) value for a phase shift of 180° and is zero when there is no phase shift, the delay time Ti must also be an integral multiple of half of a cycle of the intermediate frequency. At an intermediate frequency of 30 MHz, this is 16.66 ns. The delay time must therefore be set precisely to, for example, 8 x 16.66 ns or 133.3 ns and kept stable at this value.
A variation of the 30 MHz intermediate frequency by the permitted tolerance of +/- 200 KHz changes the cycle length by 0.7% or by slightly less than 1 nanosecond. This corresponds to a phase difference of about 10°.
It would have been just as easy to set the delay to an integral multiple of one quarter of the IF cycle length (8.3 ns) so that the phase discriminator would react to +/-90° phase shifts and generate an AC voltage which could be digitalised with a comparator.

Instead of the phase discriminator described above, later devices were equipped with a Costas phase-locked loop (Fig. 4.8-3) which sets it frequency very precisely to the received or intermediate frequency during reception and thus tolerates frequency variations within its capture range. The use of this circuit as a phase demodulator proved its value very well in field tests, although the previously selected intermediate frequency of 30 MHz was not favourable for such a design, due to the high bit rate frequency of 4 MHz. With this circuit, an intermediate frequency of, for example, 60 MHz, would be far easier to handle.

A clock or a counter must thus be started with the first phase shift after detection of the Mode S preamble. This clock then shifts the output signals "0" and "1" from the phase demodulator into a shift register or a memory in the order of the telegram bits. At the same time, these data can be loaded as described in Section 4.7 into the register which decodes the telegram data in order to provide the contained address in clear text.
Until now, the first cycle of the 4 MHz clock, which starts as soon as possible after the first phase shift, was derived from a clock frequency of 16 MHz by dividing this by 4. This divider started to supply the time steps of 0.25 µs needed for saving the telegram data as

soon as the first phase shift was detected, i.e. not later than 62.5 s after this shift. Once again, other possible solutions exist.

4.8.2 In the reply channel

Telegrams in the reply channel are pulse-position modulated (See Fig. 4.8-4) and there is a period (chip) of 1 µs available to each bit, corresponding to a bit repetition rate of 1 MHz. A pulse of 0.5 µs in the first half of the time chip represents a "1", a pulse of 0.5 s in the second half represents a "0".
Reflections often fill in the gaps between the pulses in the preamble and the telegram, which are only 0.5 s or 1 s long (see also Section 4.6, Figs. 4.6-5 to 4.6-7). In order to detect the only slight amplitude differences which result from this, an analogue or digital comparator should be used to compare the amplitude in the first half of each time chip with that in the second half. It should also be remembered that an SSR monitor cannot carry out any correction of the demodulated data on the downlink, just as on the uplink (see Section 4.7.7), which means that the best possible demodulation method must be used.

The same applies to the detection of the preamble, since the pulses of the pulse pairs are also separated by gaps of only 0.5 s and since the telegrams cannot be read if the preceding preambles are not detected.

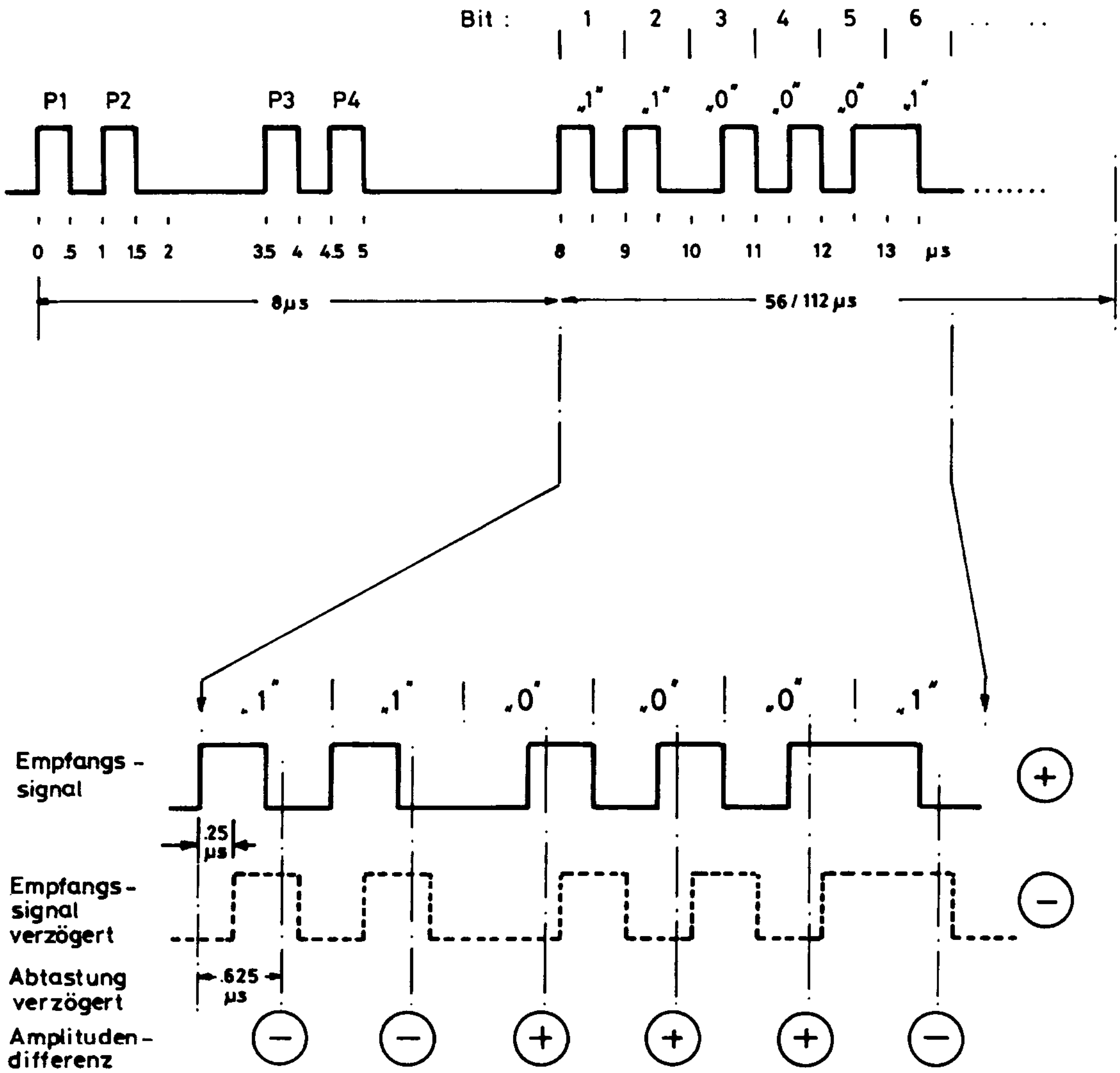


Fig. 4.8-4: Demodulation of Mode S replies

Fig. 4.8-4 shows the possible combinations of "1" and "0" bits, i.e. the sequences 1-1, 1-0, 0-0 and 0-1 and, in an expanded representation below these, the procedure recommended for demodulation. In this, the received signal and the signal delayed by 0.25 µs are connected to a comparator 3   s after detection of the preamble (P1, P2, P3, P4) and the output of this comparator is read 0.625 µs after the beginning of each time chip. This can be done with an analogue or digital circuit. The sequence of clock pulses for sampling the time chips is started 3 µs or 3.625   s after detection of the four preamble pulses and lasts for 56   s if the first bit is "0" or for 112   s if the first bit is "1".

4.9 Mutual interlocking of Mode recognition circuits

A look, for example, at the pulse sequences of a Mode S response telegram (Fig. 4.8-4) shows that the frame pulse detector F1-F2 will often signal the presence of such a frame during reception of the telegram. The same applies, in particular, to detection of Modes 1, 2, 3/A and C during reception of a Mode 4 interrogation.

It is thus advisable to suppress the other modes during detection of certain modes. The times during which the detection of other modes is suppressed (if these are significant) will have to be recorded so that they can be taken into account in the statistics.

5 Proposals for a solution of the problem

Sections 2 to 4 dealt with the detailed background of the problem description for the study and showed methodical solutions for the recognition of the various modes in the interrogation and reply channels and for the demodulation and decoding of Mode S interrogations and replies.

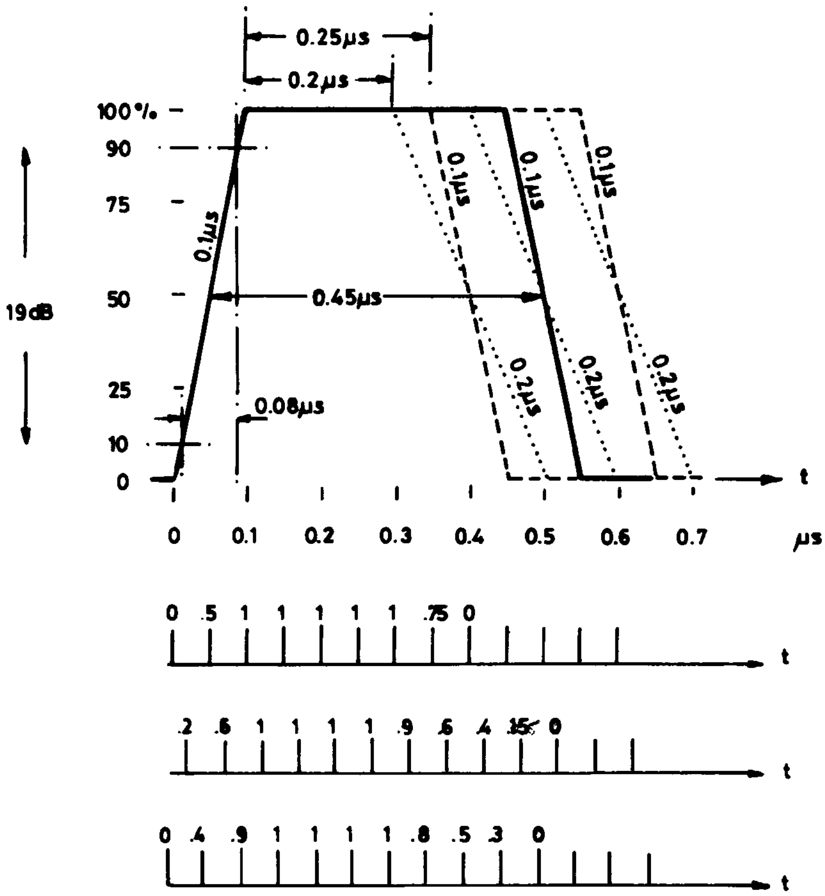
As far as possible, this was based on experience gained in previous studies on the recognition of Mode S signals and measurements with equipment of this type, and this experience was applied to the existing problem.

In view of the mixture of signals which arrive at the receiver antenna, particularly in areas with high traffic densities which are covered by several radars, it seemed important, above all, to concentrate on detecting and recognising the pulse patterns of the messages, rather than the individual pulses from which they are formed.
This method has the advantage of a process gain, because even pulses which would be difficult to detect individually can contribute to a pulse pattern. This basically improves the probability of detecting modes, but only to the degree with which the modes can be distinguished from each other.

Due to the presence of reflections around the trailing edges of the pulses, the detection of the pulses is restricted to the detection of their leading edges and a minimum length of the top of the pulse. This method is apparently suitable if the tolerance of the pulse interval in a pattern is relatively small, e.g. +/- 0.1 s, compared with the duration of each pulse (e.g. 0.8 s). This is certainly true for the interrogation channel for Modes 1, 2, 3/A, C, Intermode and Mode S, but not for the replies (F1-F2).
The following section therefore contain proposals for further improvement of the process gain. However, these have not yet been tested.

5.1 The problems of recognising the frame pulses of conventional transponder replies

Fig. 5.1-2 shows the ICAO tolerances (Annex 10, Section 3.1.1.6) for replies in the conventional Modes A and C, which are thus probably also valid for Modes 1 and 2. The diagram shows their effects on the individual pulses.



Abtastwerte des kürzesten Impulses mit 20MHz in verschiedenen Phasen

ICAO-Toleranzen für Antworten im Mode A und C :

Impulsanstiegszeiten	:	0.05 bis 0.1 µs
Impulsabfallzeiten	:	0.05 bis 0.2 µs
Impulslängen (50%)		0.45 ± 0.1 µs
Impulsposition		± 0.1 µs

eines jeden Impulses bezogen auf den Impuls F1.

Impulspausen	1 ± 0.15 µs

Fig. 5.1-1: Tolerances for reply pulses in Modes A and C

Whereas the nominal pulse has a duration of 0.45 +/- 0.1   s, measured between the 50% points, the top of the pulse is only 0.35 +/- 0.1   s long if the trailing edge is steep, i.e. 0.1   s long.
However, if the drop time is long (0.2   s), the length of the pulse top is reduced to 0.30   s +/- 0.1 s. In other words, the pulse top may theoretically be as short as 0.2 µs in the worst case.
Even at a sampling rate of 20 MHz, i.e. every 50 ns, and with the sampling phases shown in Fig. 5.1-1, the leading edge of the pulse will be detected only after the top of the pulse has already started, restricting the sampling of the pulse amplitude to four cycles in the worst case. The high costs for this and the results which can be achieved make it advisable to search for more powerful methods for the detection of pulses.

5.2 The problems of recognising Mode S reply pulses in the presence of reflections

It can be seen from the diagrams 41, 50, 51, 58 and 65 in Figs. 4.6-5 to 4.6-7 that the pulse gaps of 0.5 µs between the pulse pair P1-P2 and the pulse pair P3-P4 are filled with reflections. In other words, the reflections of the preceding pulse have not yet decayed sufficiently.
The same effect naturally occurs between the data pulses of Mode S replies, since the gaps between "ones" and between "zeros" are also only 0.5   s wide (e.g., diagram 65 in Fig. 4.6-7).
As a result of this, the leading edges of the following pulses (P2, P4) are only weak, since they do not start from zero but from some higher voltage values. These weak voltage steps, which are important for the recognition of the preamble and data pulses, represent a voltage change of not quite 80 mV or approximately 6 dB.

The previously developed circuits, particularly the last types used, detected the pulses in the correlator, which ran with a 16 MHz clock, 7-bit amplitude resolution and fast processors at each reference and read pointer for pulse detection and checking of the pulse amplitude tolerance. These were just able to detect such small voltage steps, but were evidently working at the limits of their abilities.

It will be even more difficult, using the existing methods in the correlator, to detect the pulses of conventional SSR replies with very short pulse lengths, as described in Section 5.1.

5.3 Proposed circuits for detection, demodulation and decoding in an SSR monitor

The basic idea of the method described here, which has not yet been tested, is to use an unclocked analogue circuit for detection of the pulses. This circuit generates output signals without the time delay which results from sampling. These output signals are then sampled and passed on to the correlator for comparison with legal pulse patterns.

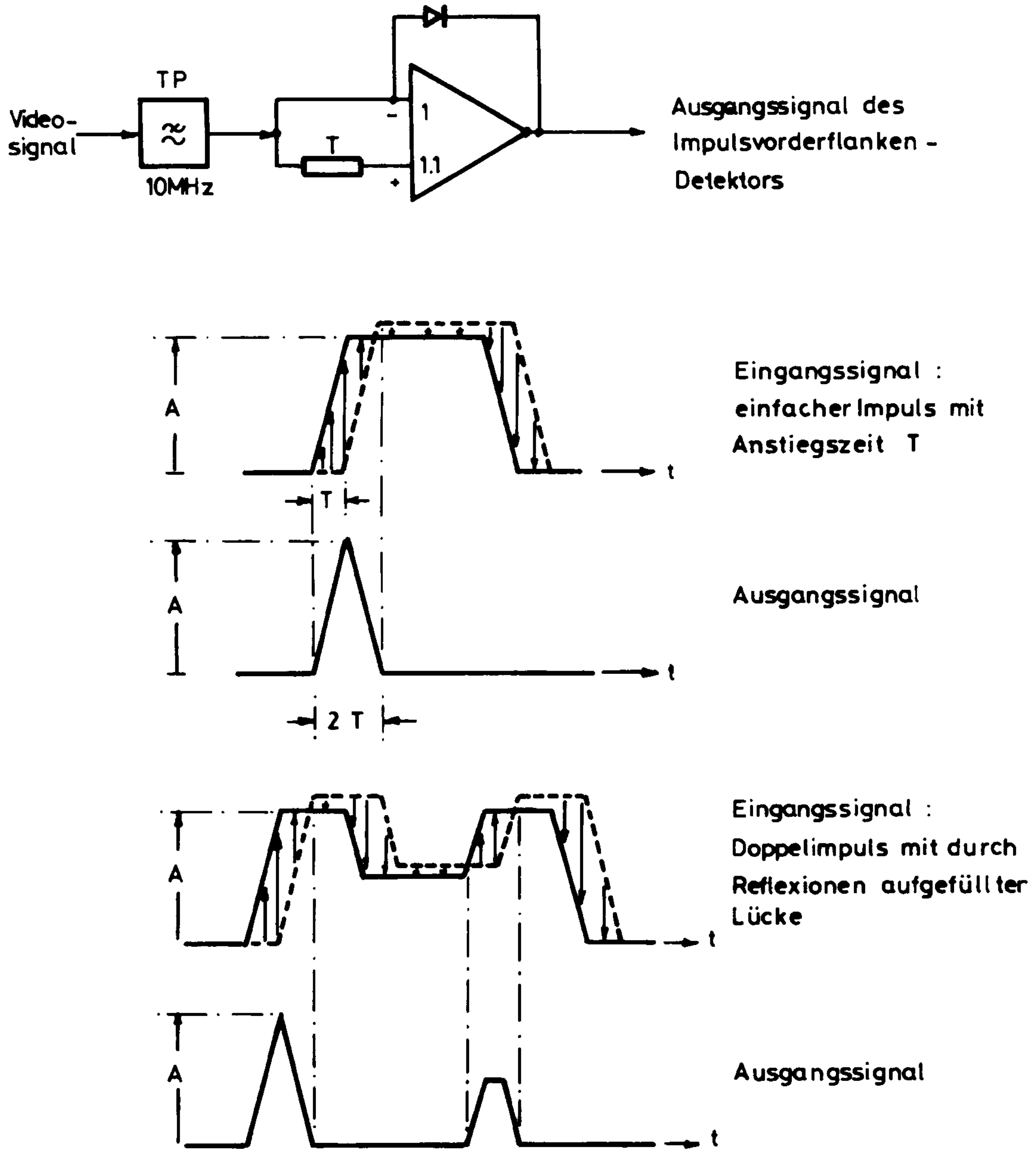


Fig. 5.3-1: Leading-edge detector

Differentiators for the detection of pulse edges increase the highly spectral components of the noise and are therefore not used here. Instead, as shown in Fig. 5.3-1, the rectified video signal of the 1090 MHz receiver is connected via a low-pass filter (10 MHz) to a linear operational amplifier, both to input 1 (-) and, delayed by about 100 ns and with a gain slightly greater than 1, to input 2 (+). Such a circuit with a diode in the negative feedback line delivers output signals without having a differentiating effect. These signals are shown below the circuit diagram for a simple pulse. An important feature of this circuit is that it also indicates the leading edge of the second pulse in the case of a double pulse with the gap filled with reflections, as is shown in the diagrams below the circuit diagram. This circuit thus differs from the commonly used, so-called "delay and compare triggers", which would return to the off state only when the voltage drops below a certain minimum level and would therefore never detect the leading edge of a second pulse under these circumstances.

If the delay time T in the leading-edge detector shown in Fig. 5.3-1 is set equal to the rise time of the SSR pulses (100 ns), then the output signal has a length of 2T or less, depending on the effective height of the detected edge. This already precise signal can be used as is or differentiated from the next sampling clock pulse (e.g. 8 MHz) to indicate that the video signal sampled with the A/D converter can be fed into the correlator two clock cycles (0.25   s) later.

In order to achieve a process gain, the video signal is not fed directly to the A/D converter, but via a low-pass filter with a cut-off frequency of, for example, 4 MHz, as shown in Fig. 5.3-2. This low-pass filter has an integrating effect, thus improving the signal-to-noise ratio, but also generates a rise time of about 0.25   s.

Such a low-pass filter with a cut-off frequency of 4 MHz would thus be suitable for the sampling of the frame pulses of conventional replies, even very short ones, as shown in Fig. 5.1-1.
For the sampling of the 0.5 µs long pulses of the Mode S replies, it would even be advantageous to use a low-pass filter with a lower cut-off frequency, such as 2.5 MHz, for this purpose. However, this would require a second A/D converter.

Fig. 5.3-3 shows the principle of the further circuit intended for Mode S replies with a quad-port RAM as the correlator. The incremental address generator for control of the write pointer, the reference pointer and the other read pointers can be implemented as shown in Fig. 4.4-2 and is therefore not shown in Fig. 5.3-3.

In Fig. 5.3-3, the quad-port RAM is shown at the top. The write pointer writes the digitalised video signal with, for example, a resolution of 6 bits into this RAM, together with the F bit set by the leading-edge detector. A clock rate of 8 MHz is assumed here, permitting the double use of the other three pointers, i.e. finding and reading two addresses per clock cycle (0.125 µs) and placing the contents of these addresses in buffers. With the aid of the F bit, which is also read out, coincidence of the pulses P1, P2, P3, P4 and a fifth pulse in the first data bit, i.e. a pulse occurring in the in the first or second half of the first data bit in the pulse pattern of a Mode S reply, could be detected.

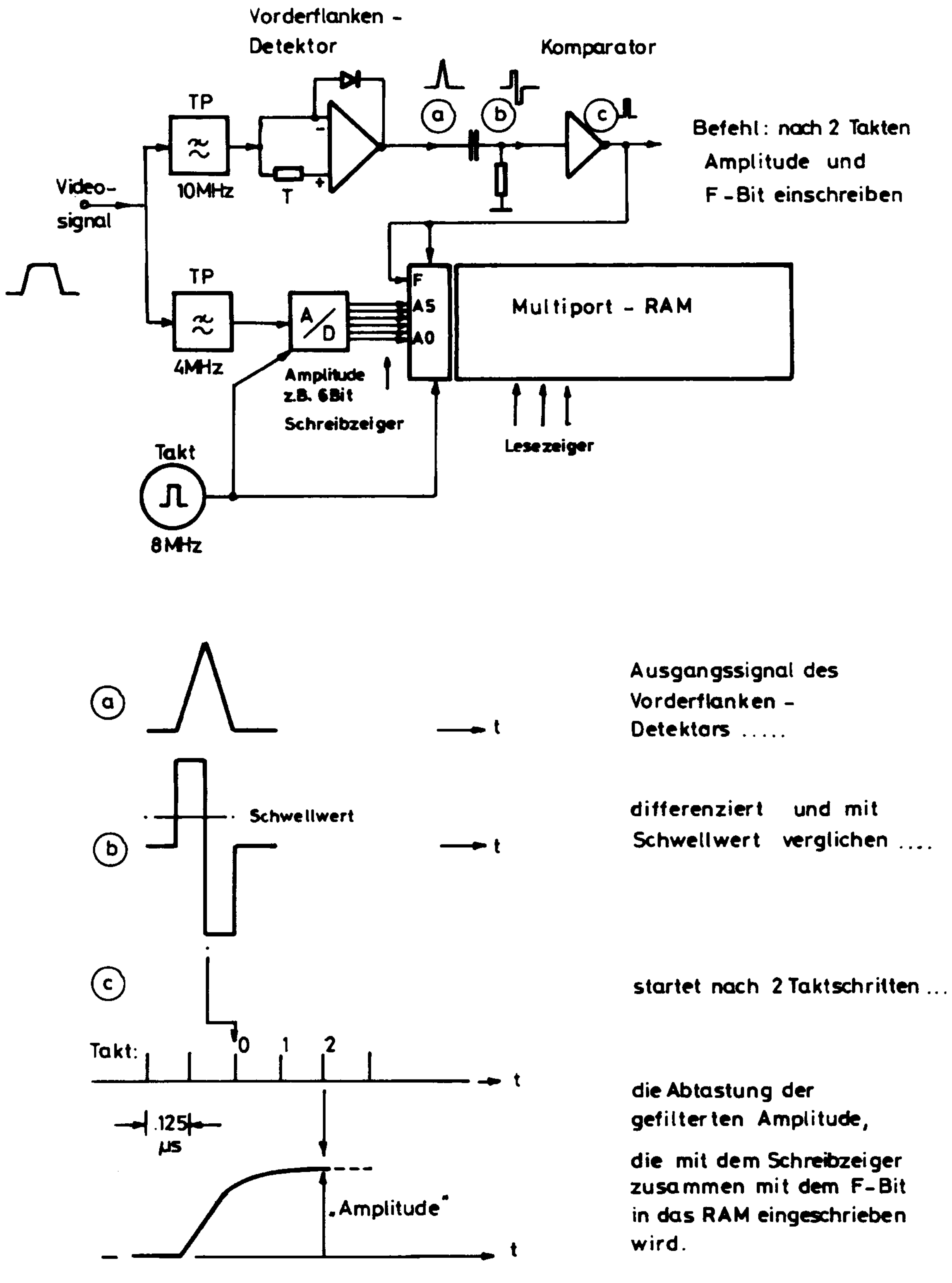


Fig. 5.3-2: Leading-edge detection and integration of the amplitude for the correlation

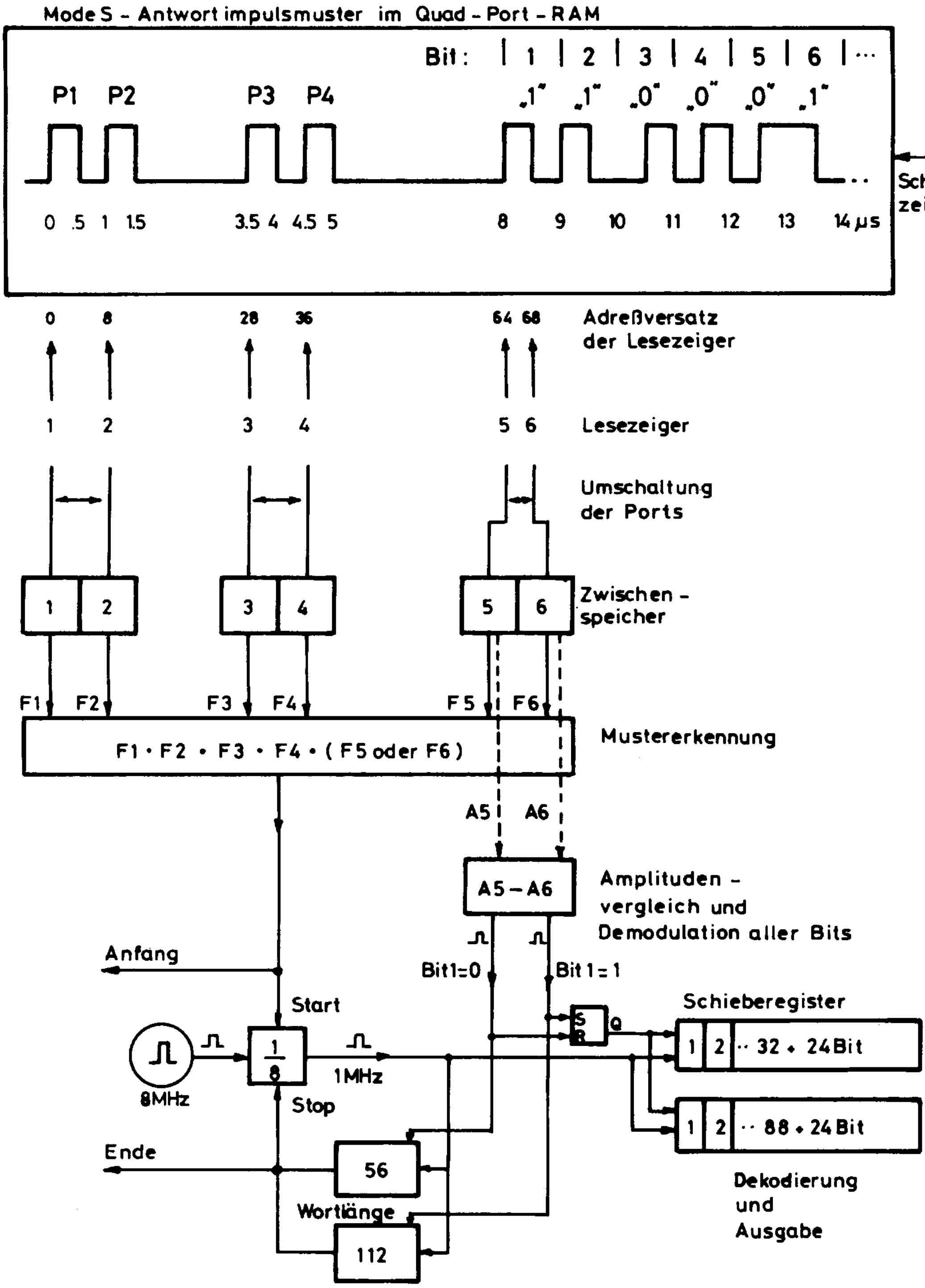


Fig. 5.3-3: Detection and demodulation of Mode S replies

Read pointers 4 and 5 not only send the F bits to the pattern detector, but also send the 6 bits which represent the "amplitude" to an "amplitude comparison" processor which forms the difference between the amplitudes in the first and second halves of the data bit in the Mode S reply. If this difference is positive, the first data bit in the Mode S reply is "1" and a long Mode S reply with 112 bits must be expected. If the difference is negative, the first bit of the Mode S reply is "0" and a short reply must be expected.
These read pointers 4 and 5 thus form, together with the processor, the demodulator for Mode S reply data as soon as the first data bit of the Mode S reply arrives. In the subsequent clock cycles, they act as the demodulator for all other bits in the Mode S reply without the need for further read pointers.

When the pattern detector detects coincidence, the clock divider is activated to divide the 8 MHz clock down to 1 MHz and this is used to shift the data stored in the SR flip-flop into one of the shift registers shown at the bottom right. The first data bit determines which of these shift registers is used and also whether the "56" counter or the "112" counter, each of which counts the cycles of the 1 MHz clock, will terminate this operation.

The shift registers for 32 + 24 = 56 bits and for 88 + 24 = 112 bits can also be used, as described in Section 4.7.4 for decoding the address contained in the Mode S reply. As a result of this, all data from the format to the address contained in the Mode S reply can be read out at the end of the reply and it can be decided, in accordance with the problem description, whether this Mode S reply is to be processed further or deleted.

The two signals "Start" and "Stop" shown at the bottom left of Fig. 5.3-3, which indicate the beginning and end of the Mode S reply, can be used for both time-stamping and for recording the period during which the recognition of other reply formats was suppressed. This even provides the prerequisites for starting time correlation between the interrogations and replies.

A similar circuit is also required for the recognition of the frame pulses F1 and F2 and of Mode 4 reply tetrads, but this does not need any amplitude comparisons.

This circuit needs a total of one write pointer, one reference pointer and three further read pointers for the frame pulse and the Mode 4 pulses P2 and P3 of the tetrads. These pointers could also be implemented by the double use of pointer shown in Fig. 5.3-3.

The technique of the leading-edge detector and the integrating effect of the low-pass filters with cut-off frequencies matched to the pulse duration could also be used to advantage for the interrogations in order to achieve process gains and cost reductions. Due to the suppression function, amplitude comparisons will be needed here for the pulses P2 of Modes 1, 2, 3/A and C, the S or P1 pulse of the whisper shout and pulse P5 of Mode 4 (see also Fig. 4.5-1).

A modular design thus also seems advisable for the interrogations. This could, for example, be divided into the following modules:

One correlator for Mode S, including PSK demodulation and decoding in a manner very similar to that shown in Figs. 5.3-1 to 5.3-3.

Two correlators for patter recognition, including suppression, of the interrogations in Modes 1, 2, 3/A, C, intermode and whisper shout.

One correlator for Mode 4 similar to that for Mode S replies (Figs. 5.3-2 and 5.3–3), combined if necessary with complete bit detection of the entire Mode 4 interrogation. This would have the advantage of recognising the entire duration of 74.5   s as the longest SSR telegram in order to unambiguously suppress the (probably) false recognition of other patterns.

If – as shown later in Figs. 5.5-1 to 5.5-3 of Section 5.5 – all sampling operations and all addresses for the RAMs are derived from a single clock generator (8 MHz) and a single address counter (10 bits), absolute synchronism will result for the time-stamping of all detected events.
This also provides the prerequisites for measurement of the times between interrogations and replies, which could be passed on for time correlation.

For this, and for interlocking, it is advisable to give all reference pointers (read pointers 1) the address offset "zero" and to give all write pointers a uniform address offset which takes the length of the longest telegram, i.e. the 112-bit Mode S reply (120 µs), into account. This, in turn, results in a RAM size of 1 kbyte for all correlators, i.e. the smallest commercially available RAM size, if a clock rate of 8 MHz is used.

With respect to the lowest possible technical complexity of the monitor, the clock frequency of 8 MHz proposed for the sampling appears very suitable, since it limits the needed RAM capacity to 1 kbyte and permits double use of the ports. However, a prerequisite for this is the use of the analogue leading-edge detector and signal filtering before the sampling operation, as shown in Fig. 5.3-2, as the basis for pulse pattern recognition.

A higher sampling frequency of, for example, 16 MHz would require a RAM capacity of 2 kbytes and would, on the basis of current experience, prevent the double use of the ports. This means that increasing the technical complexity by a factor of four would only permit sampling of the pulse amplitudes at twice the speed and faster sorting of the detected leading edges. However, at the time of this study, these possible gains seem to be of such low practical use for the problem that the increased technical complexity cannot be justified. The final dimensioning must be left to the actual development of the monitor.

5.4 Problems in the localisation of sources of significant interfe[redacted]

Particularly at the second meeting on 23 April 1999, it became clear tha[redacted] interest in the localisation of the sources of interference which have n[redacted] some areas, on the functions of the secondary radar system but ca[redacted] identified by the radar of air navigation services. Such sources m[redacted] bile military interrogators or also aircraft which do not comply w[redacted] (see also Sections 3.6.3 and 3.6.4).

On the basis of the circuits proposed in Section 5.3, it c[redacted] tional measurements with monopulse antennas, nam[redacted] / and phase resulting from the so-called monop[redacted] A/D converters and written into the correlator (quad-port RAM) with a write pointer. This makes it possible to specify the direction of reception for each pulse and each detected pulse pattern, in both interrogations and replies.

As described in Section 4.1, however, an SSR monitor needs antennas with a large vertical aperture which receive few ground reflections (such as DME station antennas, ELTA antennas (SEL)). It is not known whether and to which degree monopulse antennas for ground stations capable of measuring in all directions can be implemented with such antennas. There is also no related experience available.

In previous projects, an all-round monopulse antenna consisting of four monopole antennas was created for the use of the monopulse direction measuring technique in a flight inspection aircraft. However, this antenna was never used, since the appropriate approval could not be obtained. This antenna group was designed as an analogy to the antennas used in the ACAS/TCAS collision avoidance system, but these are only installed on top of the aircraft’s fuselage. Apparently, the engine nacelles generated such large glitches in the antenna characteristics that direction measurements from the lower side of the fuselage were impossible.

For these reasons, this study cannot, at the moment, make an effective contribution to the localisation of interference sources by means of monopulse direction measurements.

Other possibilities for the localisation of interference sources would result from the installation of several SSR monitors at points which stand out from their surroundings, such as at VOR and NDB sites of air navigation services, which would also provide the necessary power supplies for the monitor.

A possibility for localising interference sources results from multilateration, i.e. measurement of the arrival times of interrogations or replies at each station. The difference between these times of arrival (TOA) at two monitor stations provides a hyperbolic line on which the source is located. The difference in the arrival times at a third station defines a second hyperbolic line and the source is then located at the intersection of the two lines.

This type of localisation provides usable results only for sources located within a triangle with the three stations at its apexes. These stations should also form an equilateral triangle so that the hyperbolic lines intersect as closely as possible at right angles, resulting in an acceptable geometrical error (HDOP). Far better and more reliable results with fewer errors can be achieved by using four SSR monitors.

The only problem with this method, in addition to the necessary but possible time resolution, is that the participating SSR monitors must be time-synchronised with each other, since the measurement of the times of arrival will provide usable differences if the clocks used for this all sow the same time, i.e. are not too fast or too slow. GPS clocks seem suitable for this

Outside the triangle or rectangle formed by three or four monitor stations, the hyperbolic lines form something like angle baselines which radiate from the centre of each station, but with differing angular increments.

A second possibility of localising the sources thus exists in the use of groups of three or four stations. Here, the difference between the time of arrival and thus the "angular baselines" are determined within each group. The intersection of the lines of two groups, which are not necessarily synchronised with each other, is then the desired location.
These theoretical considerations and examples have been included in the study for the sake of completeness. Due to the lack of experience, no further approaches to the problem of localising interference sources have been included in the study or in the estimation of the effort.

5.5 Estimation of the effort

The methods and circuits for pulse detection, pattern recognition, demodulation and decoding shown here in principle already indicate some possibilities for solving the basic problems (Fig. 5.5-1).

The decisive factor for these proposals was a solution which matches the problem description and at the same time provides the prerequisites for further activities.

It was assumed that the subsequent processing of the received signals described here would be carried out in a specially designed real-time signal processor, rather than in a computer. The reason for this is that there will probably be very large numbers of signals to process.

It is therefore necessary to find suitable fast interfaces for connection of the signal processor to a computer and to develop both the hardware structures and the interface software.

This is necessary to create the basis on which the evaluation software can be developed for graphical display of the number of interrogations and replies counted in each specified time interval and for presentation of the decoded Mode S interrogations and replies in the form of lists in order to meet the basic requirements of the problem description.

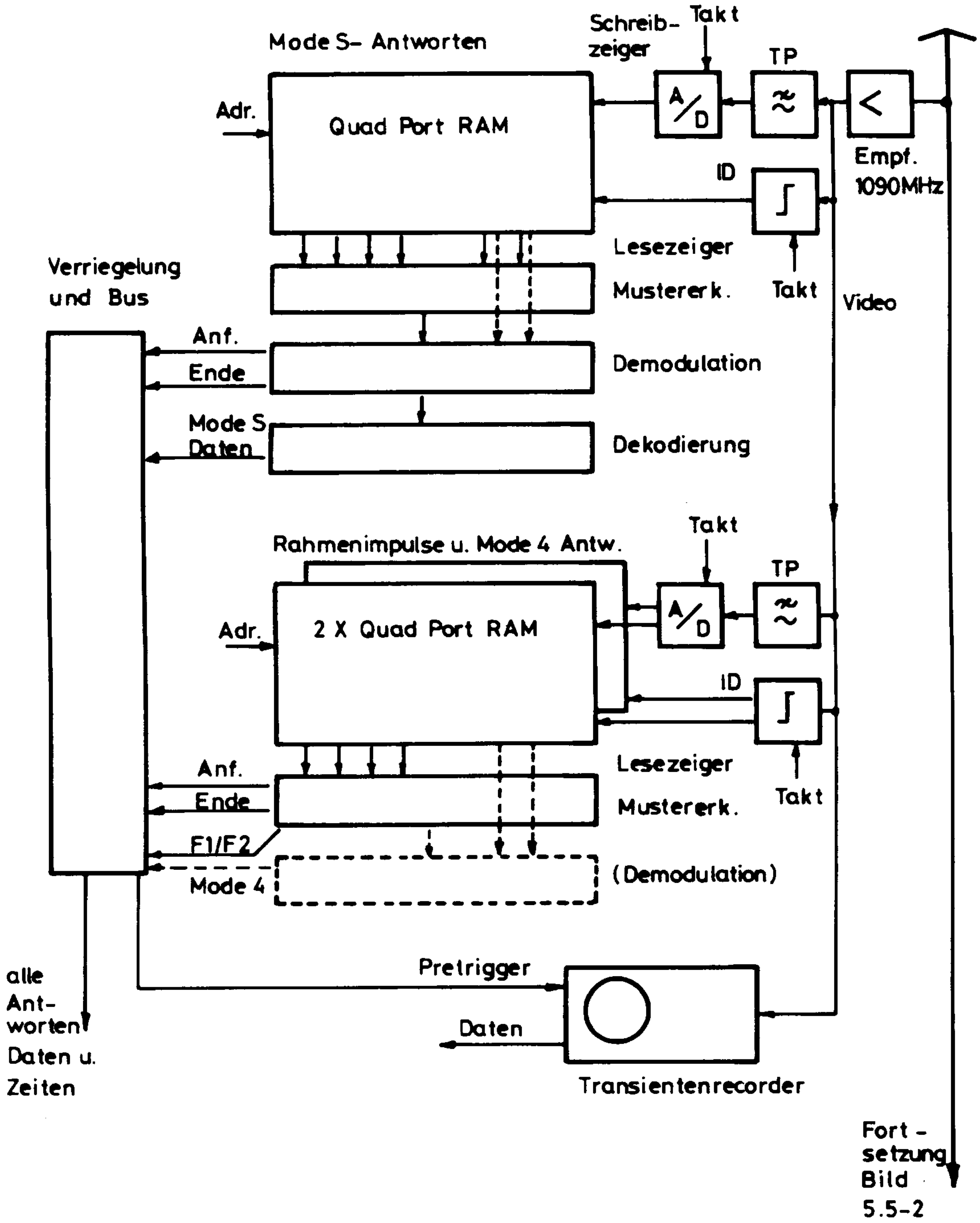


Fig. 5.5-1: Correlation, demodulation and decoding of all replies

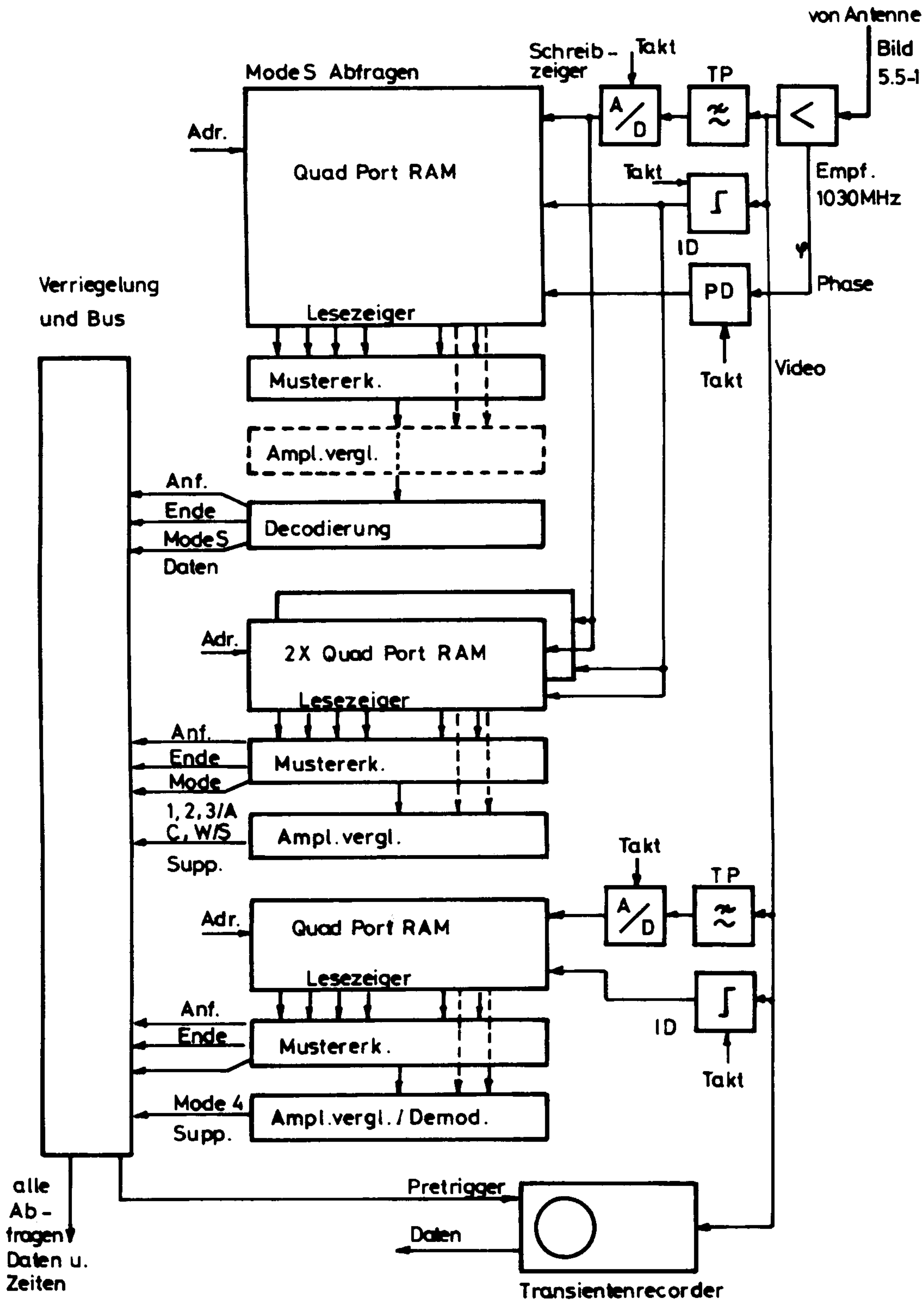
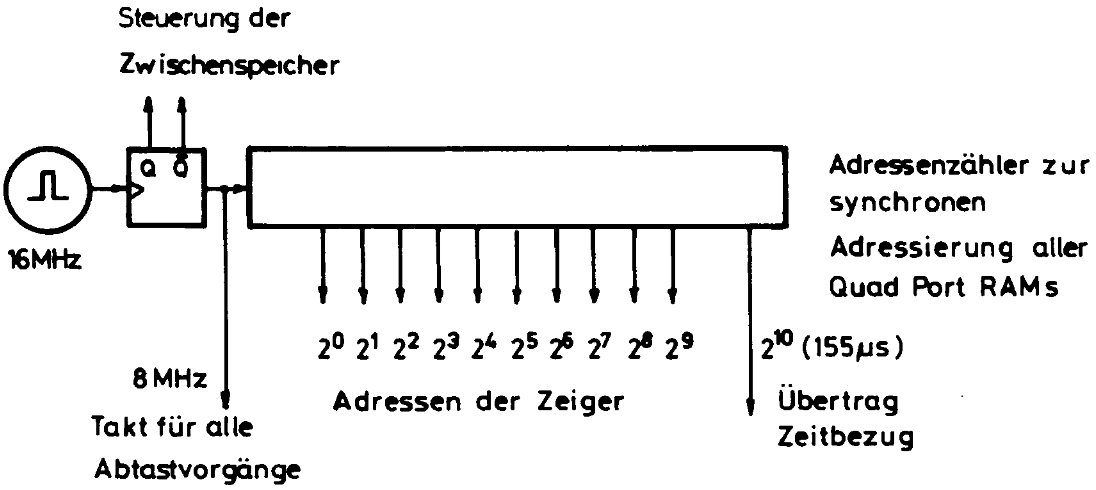


Fig. 5.5-2: Correlation, demodulation and decoding of all interrogations



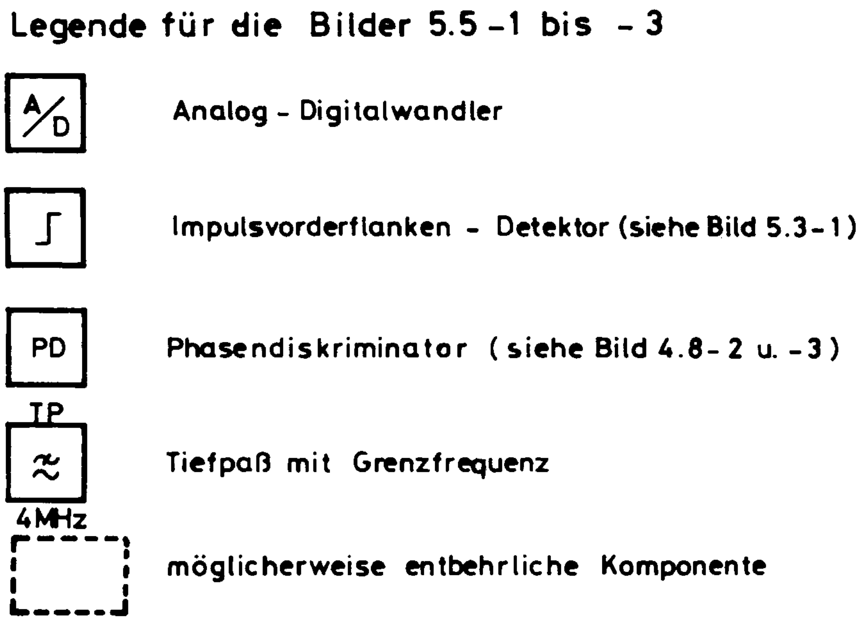


Fig. 5.5-3: Central clock generator for all sampling operations and synchronous addressing of all quad-port RAMs as a prerequisite for time correlation of interrogations and replies

Note: - All reference pointers have the address offset zero.
- All write pointers have the same address offset.

In further steps, based on the received interrogations, calculations of the transponder accessibility and time correlations, at least for each beam passage, would have to be developed at least for interrogations which are sent frequently (Modes1, 2, 3/A and C), and the value of these data obtained on the ground or in the air would have to be estimated.

This would incur the development of comprehensive software capable of handling these processes and also providing details of the radar quality, the number of participating stations and aircraft and the functions of the airborne equipment. It is difficult to estimate the effort for software development of this type, particularly if it is necessary to search for connections to radar data.

In contrast to the viewpoints described in Section 3, Section 5.3 proposes an arrangement which requires amplitude measurements only for the purpose of comparing the filtered amplitudes of two sequential pulses or for a demodulation operation. However, this type of amplitude is basically not suitable for the determination of the field strength, radiation density and received power at the antenna.

Nevertheless, the arrangement described in principle provides signals such as the mode type, the reception time and the data content, which permits transient recorders or digital oscilloscopes with pre-triggering to be started in almost any desired manner. With suitable resolution of the time (e.g. a time base of 100 MHz) and amplitude (10 bits), these could display and record the actual amplitude curves of a selected mode and even the contents of the telegram. It seemed best not to include this function in the proposed monitor, but to simply provide the prerequisites for the control of such a commercially available device.

If such measurements of the actual signal shape are required, then the transient recorder or storage oscilloscope and the related data storage in a suitable computer would be part of this SSR monitor.

6 The realisation of an SSR monitor

Sections 2 and 3 of this study provide the developer of such an SSR monitor with the necessary overview of the basic and extended problem description of the device to be designed.
Section 4 shows, in individual steps, the technical background of reception, pulse detection, pulse pattern detection, data demodulation and decoding together with procedures resulting from field tests of experimental devices wherever these seem interesting. This section thus sketches the elements of the proposed concept.

Section 5 is directed towards the solution, at an acceptable effort, of all points mentioned directly and indirectly in the problem description. This solution permits the implementation of all processes with very similar resources and with modern but non-specific modules and without the need for special and repeated calibration. Furthermore, this concept offers various approaches to the adaptation of the monitor to the local reception conditions on the ground or in a flight inspection aircraft.

The Mode S correlators developed for previous applications required 6 height units and a depth of 30 cm in a half-width 19" chassis and also require a PC for the decoding (and other tasks). This should give an idea of the degree to which the proposed concept reduces the scope and volume although it recognises all specified interrogation and reply modes and also carries out the complete demodulation and decoding of the date (Mode S) on both the uplink and the downlink.

Only this reduction in efforts and volume creates the prerequisites for installation in an aircraft. It also considerably reduces the costs for the development of real-time processing hardware.

The framework of this study, which was limited from the very start, permitted the implementation of an SSR monitor to be handled in detail only with respect to certain points, since the main emphasis was on the processing of an extremely large number of modes and of areas covered by many radars, with the resulting high interrogation and reply rates.

The development of a prototype with antennas, receivers, real-time signal processing, decoding, interlocking and computer interfaces will therefore require a considerable effort in the order of two man-years for the hardware, providing the appropriate laboratory infrastructure, particularly with respect to test generators for interrogations and replies for, above all, Mode S, already exists and does not have to be acquired before the work can be started.

It would also be advantageous for the maturity of such a prototype system if field tests could also be carried out during the development. These, once again, will also need a suitable infrastructure and appropriate competence in field-testing work.

The most important visible work in the area of computer connection, interfaces and software will certainly require at least one man-year before the function of the equipment can be demonstrated. This includes development of the first statistics, lists and correlation processes, together with suitable graphic representations. A prerequisite for this is, amongst other things, familiarity with the handling of graphical class libraries. In a previous project, the measurement results for a taxiing safety system were presented with the aid of the class library "Ilog Views" from Messrs. OOTEC. This provided valuable experience in problem-related visualisation.

A comparison of various operating systems based on Intel PCs shoed, with respect to the connection of external hardware to the computer and the real-time capability of the overall system, that the free Unix version "Linux" with its real-time add-on "RT-Linux" is predestined for such a system. Particular advantages are the fact that the operating system kernel of Linux can be adapted to meet special requirements and the high runtime stability of Linux, compared with other operating systems (such as MS Windows).

Since the main emphasis of software development is shifting increasingly towards object-oriented programming, the programming language "C++" has already been used successfully in previous projects and is a prerequisite for the use of modern class libraries.

The content of this study was discussed with several potential European manufacturers. In addition, an American research institute with long experience in the SSR environment research was consulted. It turned out that the most efficient approach would be a phased development:

1. develop a first prototyp including all r.f. and i.f. and digital hardware with limited decoding functionality
2. prepare initial equipment documentation
3. perform test measurements
4. optimise the hardware, tune the decoding software and develop initial presentation software
5. update equipment documentation
6. perform test measurements
7. optimise the decoding functionalities and develop presentation software
8. update equipment documentation
9. perform test measurements
10. optimise the complete system incl. presentation software
11. update equipment documentation
12. call for tender for additional units

This phased approach ensures modular equipment development in hard- and software. The process has to be performed in close co-ordination with both manufacturer and customer. It is recommended to work on two units. While one unit is under test, equipment documentation and further development is performed on the other. Taking this into account, the complete prototyp development schedule is estimated for 18 to 24 month depending on the knowledge and skills of the manufacturers personal.
Main costs are related to the development and to the r.f. hardware. An initial rough cost estimate for the completion of these two units sums up for about 1 MECU. Additional units should be much cheaper.

With respect to ACAS equipment monitoring and transponder behaviour major airports may wish to monitor their SSR environment. with stationary units. This might result in an installation of about 15 monitors in Europe. Since ICAO is recommending to states to monitor global ACAS implementation about the same number of units might be installed world wide (excluding Northern America). In parallel ATS providers may wish to monitor their own and other equipment operating on the SSR channels, perhaps with equipment installed on aircraft. All together the total amount of such units within the next 5 years may be in the order of 50 world wide.

A Appendix

A.1 List of abbreviations

Units of measurement:

m, km	Metre, kilometre
NM	Nautical mile (1.853 km)
s, ms, s, ns	Second, millisecond, microsecond, nanosecond
dB	Decibel: (1/10 of the logarithmic ratio of two power values or 1/20 of the logarithmic ratio of two voltage values)
DBm	Decibel, referred to 1mW
DBW	Decibel, referred to 1W
Hz, MHz	Hertz, Megahertz

Designations and terms:

A/D conversion	The conversion of analogue values into digital values
ACAS/TCAS	Collision avoidance system in accordance with ICAO
ASR	Airport Surveillance Radar
BMV	Bundesministerium für Verkehr (German Federal Ministry of Transport)
CW	Continuous Wave, unmodulated signal
FAA	US Federal Aviation Administration
FII	Flight Inspection International
ICAO	International Civil Aviation Organisation
IEV	Institut für Eisenbahnwesen und Verkehrssicherung der TU Braunschweig (German Institute of Railways and Traffic Protection at the Technical University of Braunschweig)
IFF	Identification Friend Foe
Mode 1, 2, 3 u. 4	Military signal formats of SSR
Mode A, C und S	Civil signal formats of SSR
PSK	Phase Shift Keying
RAM	Random Access Memory
SEL	Standard Electric Lorenz Stuttgart, today ALCATEL
SSR	Secondary Surveillance Radar
TU	Technical University of Braunschweig, Germany

A.2 List of figures

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ACAS PROGRAMME

ACASA PROJECT

Annex D to

Work Package 7

Final Report on

Automatic Safety Monitoring Tool
WP7 ASMT ModeS Monitoring

Edition 1.0
March 2002

Annex D to
Work Package 7

Final Report on
Mode S Monitoring of ACAS

Version 1.1, March 2002

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ACASA REF: 174D

EUROCONTROL EXPERIMENTAL CENTRE
Brétigny-sur-Orge, FRANCE

SAFI
SAFety monitoring for Indicators

Automatic Safety Monitoring Tool
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Final Report Mode-S RA ACAS Monitoring

1. Introduction

1.1 Purpose of this document

This report describes the work carried out to develop an ASMT (Automatic Safety Monitoring Tool) to provide ACAS Monitoring, using Mode-S, as part of the ACASA work packages.

It indicates the context and objectives of this work and outlines the capabilities of the resulting tool. Each functional capability is briefly described.

A requirements specification document (ref: ASMT/SSS/2.2) is available to provide technical details of the functionality of this tool.

1.2 ACASA Context

Eurocontrol formed the ACASA (ACAS Analysis) project in the framework of TENS 98 to assist in the study of on-board collision avoidance systems and to compliment the work of the EATMP ACAS programme. ACASA was formed of ACAS operational experts from a variety of national ATM providers and research organisations.

The ACASA project consisted of several work packages of which the following one is relevant to the work carried out described in this report.

Work Package 7: Mode-S monitoring of ACAS implementation.

This package has five tasks, tasks 7.1 & 7.2 are to define an automated ACAS-RA monitoring tool based upon the detection of Mode-S RA messages from both experimental and eventually POEMS Mode-S stations. The intention was to capture and record coverage data (surveillance and flight plans) during a period before and after each ACAS RA. The requirements for such a tool were described in a document created by the STNA (Service Technique de la Navigation Aeriene) for the ACASA group (ACASA/WP7/049)

The objective of this work was to facilitate the provision of independent monitoring of the ACAS system. Existing monitoring activities are based upon manual pilot and ATC reporting and are known to provide only a subset of the ACAS occurrences. Also the surveillance data needed to analyse a case in detail is rarely available. With this automatic monitoring all the ACAS events in the monitored airspace would be recorded with their relevant surveillance data.

Various existing tools were examined by the ACASA experts for their suitability for adaptation for this work. The ASMT was chosen since it was an existing operational safety monitoring tool which already provided much of the desired functionality and which although was only at this time being used for separation monitoring was developed with extension in mind for other types of safety occurrence.

1.3 ASMT Context

Eurocontrol had developed a Safety Monitoring Tool as part of a co-operative effort with the Maastricht Upper Airspace Centre. The general purpose of this ATM Safety Monitoring Tool (ASMT) was to perform independent monitoring of safety infringement occurrences corresponding to significant losses of separation.

The ASMT provides capabilities to:

- Carry out automatic recording (radar tracking) of proximity occurrences.
- Operate on-line on a 24-hr basis.
- Generate alerts to supervisors and occurrence investigators.
- Perform local occurrence storage to allow further Safety analysis.

This ASMT supports the activity of:

- operational supervisors monitoring ATC operations
- occurrence investigators analysing safety occurrences
- safety experts performing modelling studies on the safety of the airspace.

The ASMT has been developed to the stringent requirements of operational ATC staff. It has a user-friendly interface that allows rapid assessment of safety occurrences, provides both automatic and manual capabilities to classify occurrences and supports the investigation process.

The ASMT is currently being adapted for other operational centres that need other safety occurrences (such as altitude bust, missed approach, STCA [Short Term Conflict Alert], route divergence and runway incursions) as well as separation to be monitored.

It is also used to support simulations of new ATM environments or the introduction of new procedures and is being proposed as a training tool to demonstrate real recorded situations to trainee controllers.

It was decided to enhance the ASMT to provide monitoring capabilities for ACAS-RA alerts via Mode-S replies from ACAS equipped aircraft.

2. ASMT Description

2.1 ASMT basic functionality

The ASMT system detects safety occurrences in real time using radar, track and flight plan data and stores them in a secure database. It makes an automatic classification of each occurrence based upon the separations, geographical locations, aircraft involved and the conflict geometry.

These occurrences can be alerted to the ASMT users who can then see the details, replay the event and add information. Users are alerted only to those types of occurrences to which they have right of access and have subscribed. They can observe details, replay and add comments and classifications to the occurrences.

The ASMT provides storage of track and flight plan data for aircraft involved in each occurrence, for a volume around the occurrence and for a period of time before the start and end of the situation. It also stores the surveillance data for all neighbouring aircraft in this volume so that an accurate replay of an occurrence can be provided to operational staff.

The ASMT also provides the capability to select occurrences and export them for statistical analysis. The results of such analysis or documents that support the investigation of occurrences can be stored in the database with the corresponding occurrence data.

The ASMT system organises its users via user communities that correspond to different organisations or departments sharing the same equipment. Each user community has its own dedicated detection processes that may run on one or more detection servers. The occurrences generated belong to this community and are stored in separate databases. Only an authorised member of a community can extract these occurrences from the database e.g. ACAS events are only visible to ACAS analysts.

Each user of a community can observe neither an occurrence from another community nor an occurrence that their user profile has not been set to allow observation. An authorised user can also send an occurrence to another user community. Each user community has several predefined roles such as Supervisor, Investigator and Administrator.

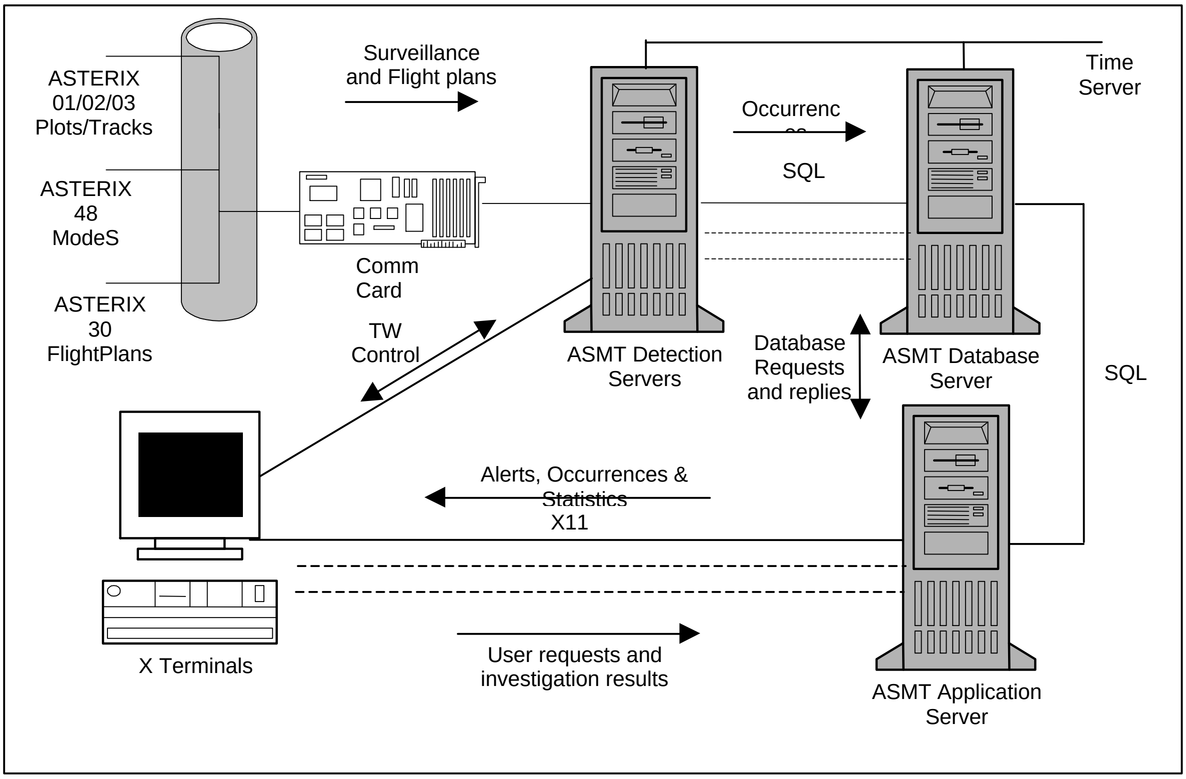
The supervisor role is specific to online operational safety monitoring of occurrences. This user makes an initial examination of occurrences immediately after they have occurred. This user does not make investigations but has the initial input with the assistance of ATC staff to give an appreciation of an occurrence and to recommend or not further action.

The investigator role is one where detailed analysis of an occurrence can be made with an assessment of the causes and risk. The investigator can also observe an occurrence in "real-time" like the supervisor or can use a terminal off-line. The investigator can add documents and can export data for statistical analysis. The investigator also has a technical display where he can examine the details of the surveillance data collected for an occurrence.

The administrator is a mandatory role for the ASMT. An administrator has control of the database and all the user accounts of a community. Only the administrator is able to delete occurrences and to observe the security logs.

2.2 Standard ASMT architecture

The diagram below shows the basic architecture of the hardware used for an ASMT system.



The radar, track and flightplan data is taken off the operational LAN via ethernet link. An X25 card can also be used to connect data sources. The data is translated into native ASMT format data, a large set of radar, tracker and flight plan protocols and formats can be captured and translated.

One or more Detection Servers analyse the data and generate the safety events. These servers are monitored for correct operation by a Technical Watch Supervisor who can start up and stop all critical ASMT subsystems and can observe any warnings or errors which occur either in the ASMT components themselves or in the data that is being provided.

The Detection Servers generate occurrences that are sent to a centralised safety database. This database also stores the surveillance and flight plan data associated with each occurrence. The detection is a "occurrence provider" for the database whereas operational users of the ASMT are "occurrence users" via the Application Server. The distribution of servers for the system assures security by providing a central storage of safety data that is not directly connected to either the operational or the user networks.

The users have X-terminals on the user LAN and can use their ordinary PC's to connect to the ASMT via the application server.

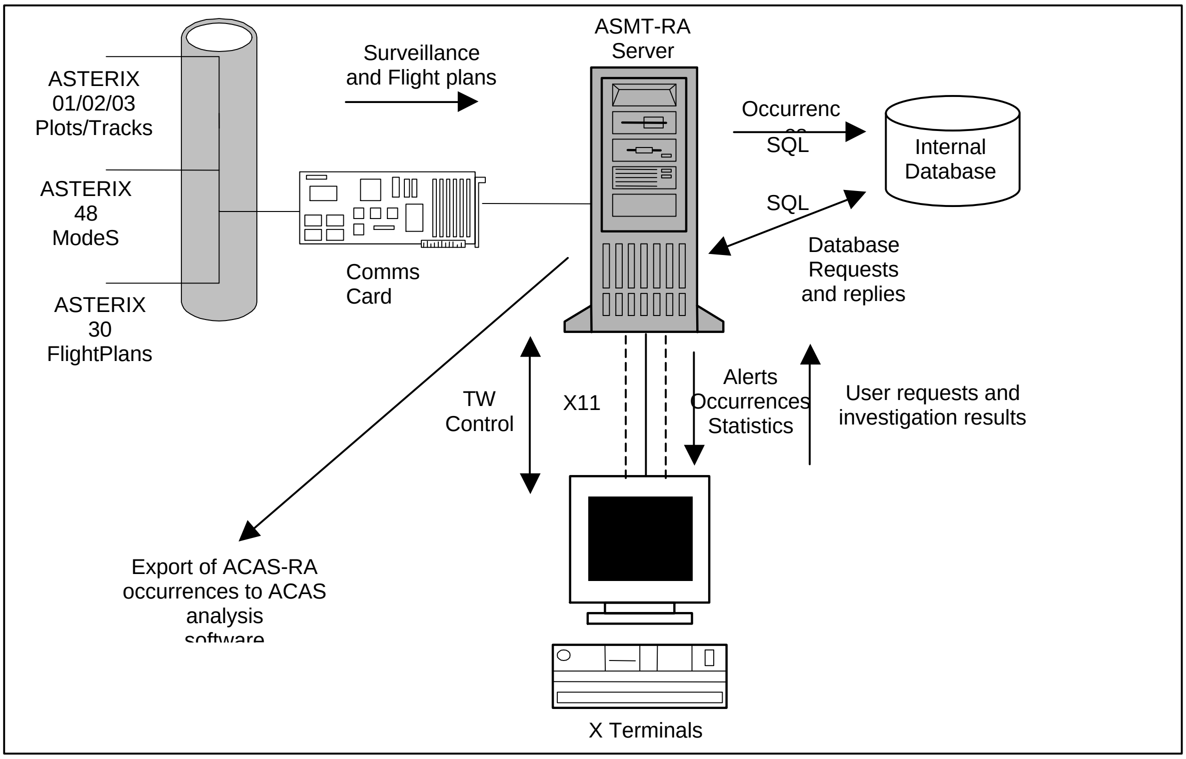
The three machine architecture assures both performance and security of the ASMT system when it is used in an operational ATC centre.

The performance is needed to assure that the system can treat up to 2500 simultaneous aircraft trajectories based upon incoming radar, tracker and flight plan data. It also needs to be able to treat a set of simultaneous operational users.

The security in this architecture is provided by isolation of the users from the sensitive data stored on the database. The database is connected on one side to the detection processing and on the other to the application server that provides the user interface. Two dedicated connections link the database server to these machines and so the database is unavailable to users except via the controlled interface of the application server.

2.3 Minimum architecture for ACAS Monitoring

The architecture for the ACAS monitoring can be either identical to that of the current ASMT system or can be a much simpler one shown below that uses a single server attached to the operational LAN. All depends on the security requirements and on the need for either an integrated or an independent ACAS monitoring system. It is possible at any time to upgrade to the full architecture.



The ASMT-RA detection can be provided alone or loss of separation can also be detected.

2.4 ASMT Development Methodology

The ASMT was developed using the UML methodology and the ROSE development tool. It is developed in C++ with the ORACLE 8 database and the RogueWave libraries. The design method chosen was that of Design Pattern which has been successfully used in other ATM tools.

2.5 ASMT Quality and Standards

The ASMT has been developed with the full co-operation of the software engineering unit of the experimental centre. IEEE standards have been applied throughout the development and analysis, design and coding reviews have been carried out for each release.

2.6 ASMT Testing and Acceptance

The ASMT was tested at unit level for each subsystem and then after integration was tested using a series of integration tests to assure the expected behaviour of the software.

For factory acceptance a Software Test Document was created that tested each of the ASMT functionalities and each user procedure with relation to the ASMT specification documents. The tests used both artificially generated scenarios and live data samples. A test report recorded the success or failure of each of these tests.

For site acceptance a second test plan was used which covers all the operational aspects of the continuous operation of the tool. This was carried out on the client site.

For the ASMT-RA testing National Air Traffic Services of the UK provided Mode-S RA test data and Gatwick has been selected as the first test site.

During the test process a testfile of 24hrs of data was provided by NATS. In this data several RA’s were detected and also several other anomalies were found. These anomalies were the several 25ft reporting problems (where the aircraft claimed 25ft capability but only reported 100ft data), a case where the Guillham coding of the ModeC showed “stuck-bits” and several cases of unexpected changes in ModeA address during flight.

A follow up of the 25ft reporting cases and the Guillham code problem were made with the relevant authorities.

3. Overview of ASMT ACAS-RA Functionalities

3.1 The capture of Mode-S and Flight Plan Data

The ASMT can be attached to a LAN or X25 source of ASTERIX Mode-S track data and captures this track data, reconstructing flights and associating them to flight plan data when this is available. The ASMT examines the Mode-S data and also extracts ACAS-RA messages from the ASTERIX 48 data format.

3.2 The detection of ACAS-RA occurrences

The ASMT extracts any RA information present in the ASTERIX 48 data. It creates new RA occurrences based upon the Mode-S addresses of the aircraft involved. It uses the mode-S address or the range and azimuth if provided to identify the threat aircraft. (see Appendix for details).

3.3 Collection of surveillance and flight plan data

The ASMT collects all flight plan and surveillance data for the aircraft involved in a RA it also collects the surveillance data for all aircraft observed in a user-defined volume of airspace around the RA and for a user-defined period before and after the event.

3.4 Classification of RA's

The ASMT classifies each detected RA according to the aircraft involved, the geometry of the occurrence, the severity and the airspace involved. The ASMT has an aeronautical database of the sectors, routes, beacons and TMA in an airspace and relates all trajectories to these areas. The operational type of aircraft is determined by either the correlated flight plan data or via area dependent mode A allocation code tables. These classifications are automatic.

3.5 Filtering of RA's

The ASMT examines each new RA with a set of criteria called "quality filters" which determines if it represents a real case. Examples of false cases are those due to failures of transponders, the surveillance system or due to the tracking used. Different quality filters are used for different types of occurrence. All occurrences which are "real" i.e. they pass the quality filter conditions will be stored on the database. This is independent of if they are to be alerted to none, one or more users.

The ASMT has also a second type of filter, which determines if a particular ASMT user has an interest in a particular occurrence and so therefore must be alerted about it. Many different filters are provided which can be combined in logical expressions to determine those occurrences of significance to the user.

The following filters are provided for all occurrences, several instances of the same filter with different parameters can be used.

- Area(s) of interest (Sectors, TMA….)
- Mode A code based
- Traffic type based (operational air traffic, general air traffic, VFR…)
- Areas to not monitor (Restricted airspace, areas of other ATC responsibility)
- Altitude bands
- Flight Plan availability
- Controller positions
- Severity

The ASMT provides user interfaces to control the parameterisation of detection, the quality and user filters. An examples of a user filter is shown below:

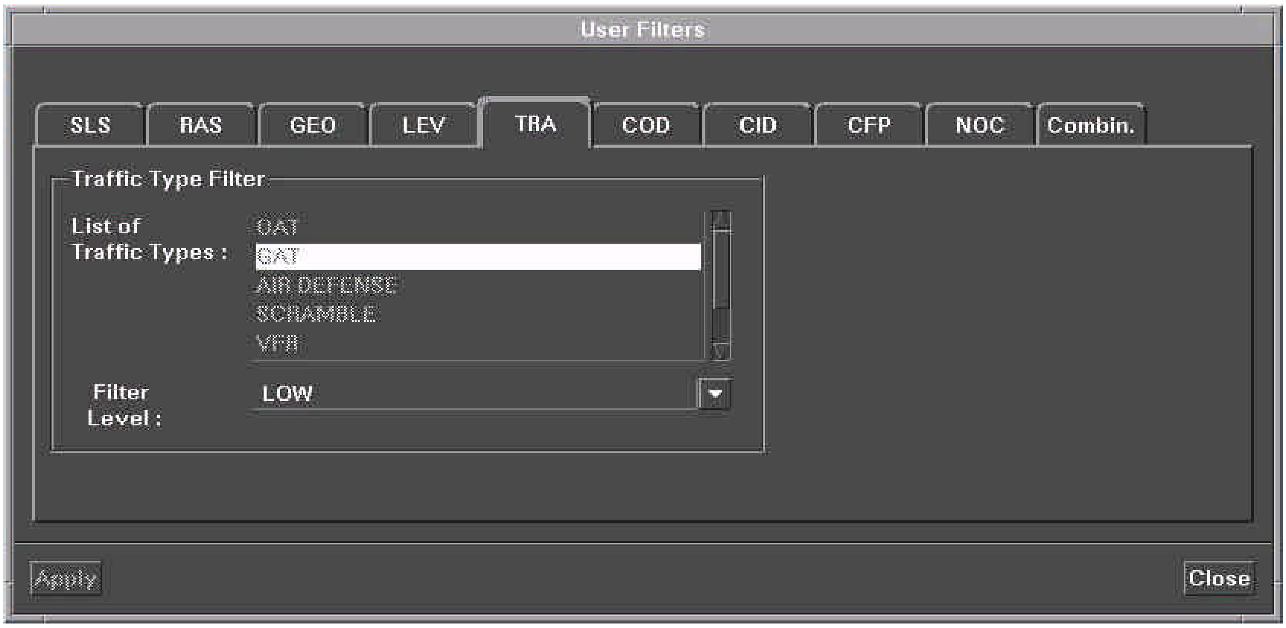


Figure A 'User Filters – TRA Tab'

3.6 Data Integrity

The ASMT examines the data integrity of all data used for detection. If problems are detected in the quality of surveillance or ambiguity is detected in flight plan correlation then this information will be noted with any occurrence.

3.7 Alerting of users

The ASMT provides an alerting interface which shows those occurrences currently under examination by a particular user (see figure below).

Occurrence Inventory Window - ASMT Supervision

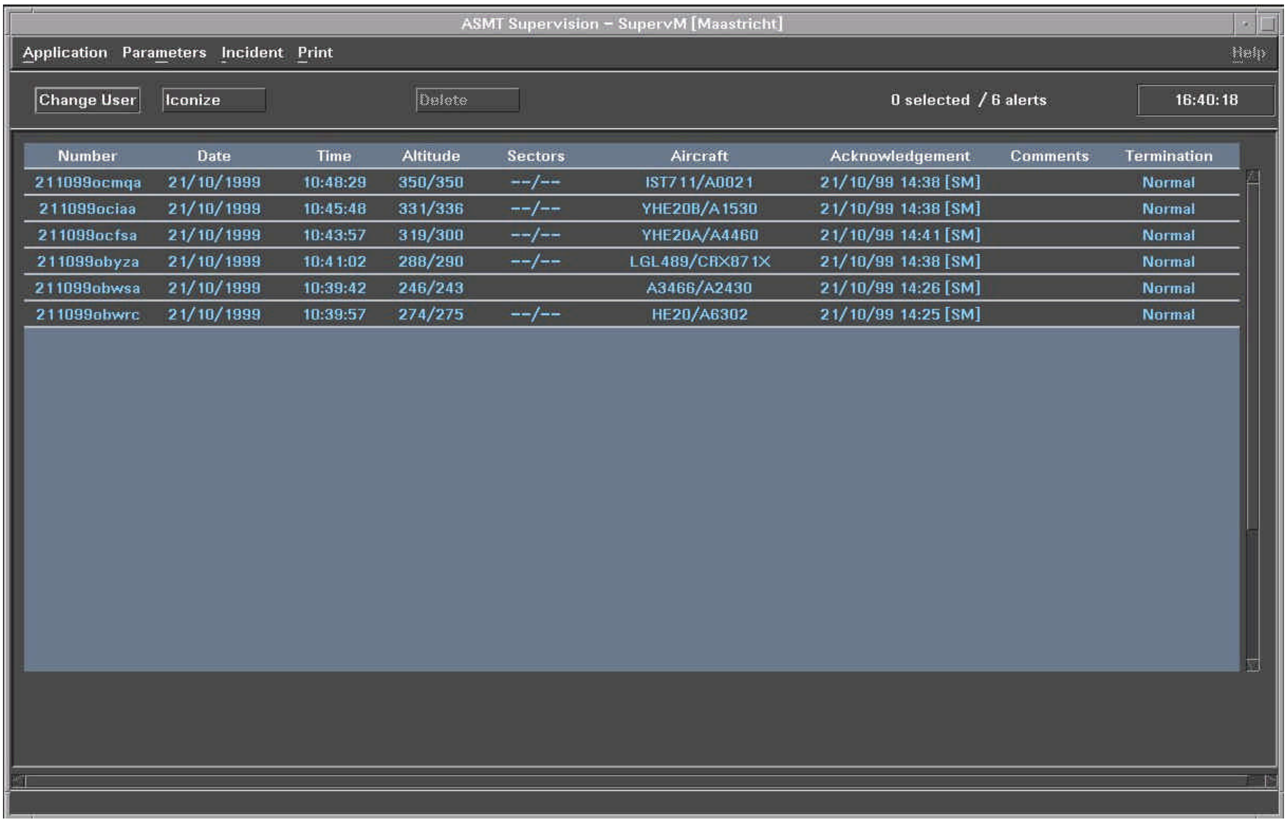


Figure B Inventory Window'

The Occurrence Inventory Window is displayed after successful login. It is composed of five major items, as described below. From this window, all other sub-windows and menus are generated.

3.7.1 Title Bar

The title bar displays information on the current environment:
type of the interface depending on the current user role:

- ASMT Supervision,
- ASMT Occurrence Investigation,
- ASMT Administration;

username of the user currently logged in;
community of the user currently logged in.

3.7.2 WorkArea

The Work Area is composed of:

- three or four function buttons (change user, iconize, delete buttons, and recall button for occurrence investigator user only) as explained below;
- two labels displaying the number of alerts currently listed in the inventory and the number of alerts currently selected
- a clock, displayed at the right of the Work Area, refreshed every second except during time consuming operations.

Work Area Function Buttons

Change User Button
The function button labelled "Change User" may be used to change the HMI current user. This menu is used to change the HMI user, i.e. to terminate the current user session and start a new user session. The selection of this menu opens the login window for authentication of the new user. After successful login, the current HMI is terminated and a new HMI is started for the new user.

Iconise Button
The function button labelled "Iconise" may be used to manually iconise the display. This action closes any open secondary window and only the inventory window will be reopened at de-iconization. The ASMT icon is displayed with the number of non-acknowledged alerts in the inventory specified as icon name.

Two ASMT icons are used by the application depending on the number of non-acknowledged alerts in the inventory. One, with red background colour, is used when some non-acknowledged alert remains in the inventory or whenever a new alert is generated. The other one, with grey background colour, is used when all alerts have been acknowledged.

The Occurrence Inventory Window is automatically iconified after a time period defined by the administrator (cf. User Preferences window). At de-iconifying, the login window is again displayed to perform a user authentication before re-display of the Occurrence Inventory Window. At that stage a change-of-user may be performed by overriding the username of the current user and entering username and password of the new user to login.

Figure C 'ASMT Icon'

Note that the ASMT Icon as depicted above indicates that no alerts are pending acknowledgement.

Delete Button

The function button labelled “Delete” may be used to remove occurrences from the list. Deletion is achieved by highlighting a record via the mouse (click in the number field of the record) or keyboard and selecting 'Delete'.

Recall Button

The function button labelled “Recall” may be used by any occurrence investigator (not available to supervisor users) to reload into the inventory a previously purged alert. When pressing the recall button, the user is prompted for the alert to recall as displayed in the conflict number column. The alert is retrieved from the database and reloaded at the top of the inventory in its acknowledge state.

3.7.3 Occurrence List

The set of detected occurrences is displayed by the aircraft involved appearing in a scrollable list, with the most recently detected occurrence presented at the top[ZEK1]. Each occurrence is presented as a summary record. This record is presented as one line consisting of tabular data arranged in the following fields (from left to right):

<u>case number</u>, which corresponds to a unique identifier made of ASCII characters and digits and computed using the storage time into the database of the associated occurrence;
<u>start date and time</u> (of alert generation), which corresponds to the alert generation time that is to the end time of the associated occurrence;
<u>altitudes of aircraft involved</u>;
<u>sectors or other areas associated</u>,
<u>callsigns of aircraft involved</u>; the callsign is extracted from the first update of the flightplan. Otherwise, the letter A followed by the mode A
<u>acknowledgement</u>, which consists of three fields if the occurrence has been acknowledged, i.e. date and time and user ID
<u>indication of the presence of comments for the occurrence</u>;

The alerts are displayed in the background colour corresponding to their current state, i.e. non-acknowledged or acknowledged alert.

Related occurrences involving multiple aircraft are presented as separate records; i.e. one record per occurrence is kept in the inventory. Those separate records are grouped in the inventory by borderlines.

The Occurrence Details Window, are generated only provided that one record is selected (highlighted) prior to selection of the corresponding menu item or function. Selection is achieved by clicking, i.e. highlighting, any field of the corresponding record displayed, or via the keyboard.

Double-clicking on an inventory entry will result in the simultaneous display of the

- Details Window ,
- User Assessment Window
- Replay Window
- Flight Plan Window

This is explained in more detail in section 3.8

The inventory also allows the deletion of an occurrence (only from the view of the user – the occurrence is not deleted in the database) once a user has finished treating the case.

One or more occurrences can be retrieved from the database via its identity or by a date/time range or via chosen callsigns or mode A codes.

A set of occurrences can be selected manually or automatically using selection criteria to send data for external statistical analysis. The data is sent in a token format which can be read into excel or statistical tools.

Surveillance data for a case can also be exported for use in an external tool for ACAS data analysis such as InCAS or OSCAR.

3.8 Analysis of Occurrence.

Each occurrence can be examined via selection from the inventory.

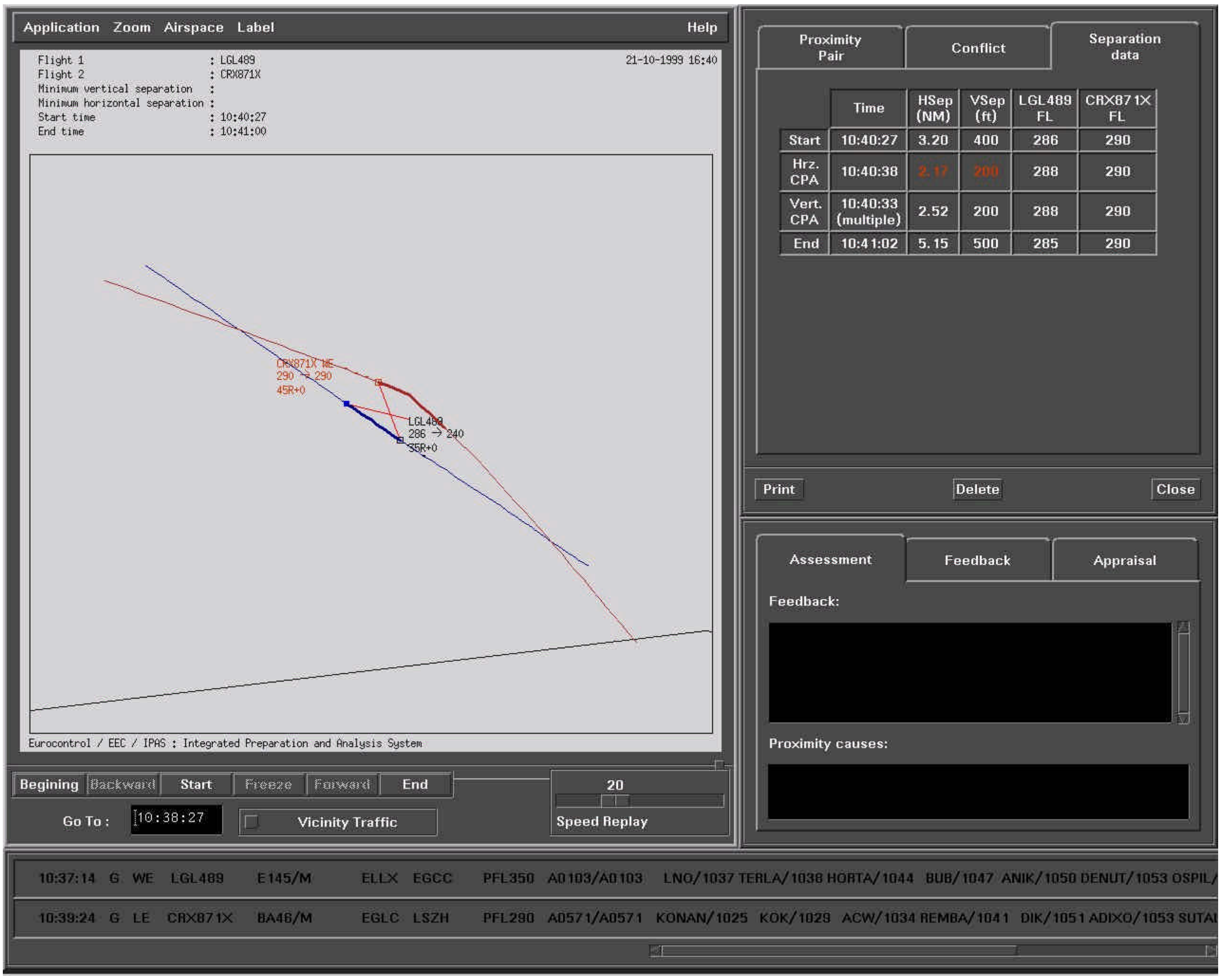


Figure D 'Occurrence Details'

The interface provides several distinct areas:

3.8.1. Replay Area (Graphical area)

This allows the replay in real or fast time of each occurrence. A particular time can be selected or the user can step forwards or back in updates through an occurrence.

The vertical profiles can also be simultaneously shown.

Any neighbouring traffic can be visualised.

The replay has a background aeronautical map for which the different elements can be made visible or hidden.

The replay shows the labelling for each aircraft that can be tailored to those seen on the operational display of the user.

The replay has zoom and centring capability.

The current view can be printed at any point in time.

3.8.2. Details window (top right)

This provides details of each occurrence.

Three tabbed windows are provided, one provides details of the classification another of the aircraft involved and finally the last gives the separations involved.

For the RA cases the separations are those calculated between the aircraft that generated an RA and the closest aircraft during the RA event.

The duration of the occurrence and the flight levels involved are also shown.

3.8.3 User assessment area (bottom right)

In this area the ASMT user is able to:

- Add comments concerning an occurrence
- Select from predefined trees of contributing factors (these are user-defined and are easily updated).
- Make a risk assessment
- Add or extract files for investigation

3.8.4 FlightPlan Display (bottom)

This shows the flight plan information for the aircraft involved in an occurrence.

It is scrollable to allow the route to be shown.

If dynamic flightplans are available then any changes to a plan will be shown as buttons to the left of these plans that allow the user to visualise each flight plan change. The times shown for validity of a flight plan are also shown so that the user can relate them to the replay.

3.9 Mode S data integrity

The ASMT also analyses the Mode-S information processed during the detection process and provides the user with a report of the following anomalies:

ModeS address is not unique (simultaneously used by more than one aircraft).

ModeS address is inconsistent (same trajectory different addresses observed).

ModeS Format Error (Data in ASTERIX48 was not within the format specification)

3.10 Detection of 100ft reporting from 25ft "capable" aircraft.

The ASMT reports cases where an aircraft which claims 25ft altitude reporting is in fact providing only 100ft quantised data (see Appendix for method used).

This transponder fault can lead to false RA's.

This detection can only be done with confidence when an aircraft has observed periods of regular ascent and descent.

3.11 Detection of Gillum code errors

The ASMT analyses the received ModeC data from the aircraft monitored and checks if certain bits in the grey code appear to remain set at 0 or 1. This is a known problem which leads to inconsistent altitude reporting and hence can create problems for ACAS.

This detection can only be done with confidence when an aircraft has observed periods of regular ascent and descent.

4 Contact Details

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APPENDIX. Technical description of methods used

ACAS-RA detection

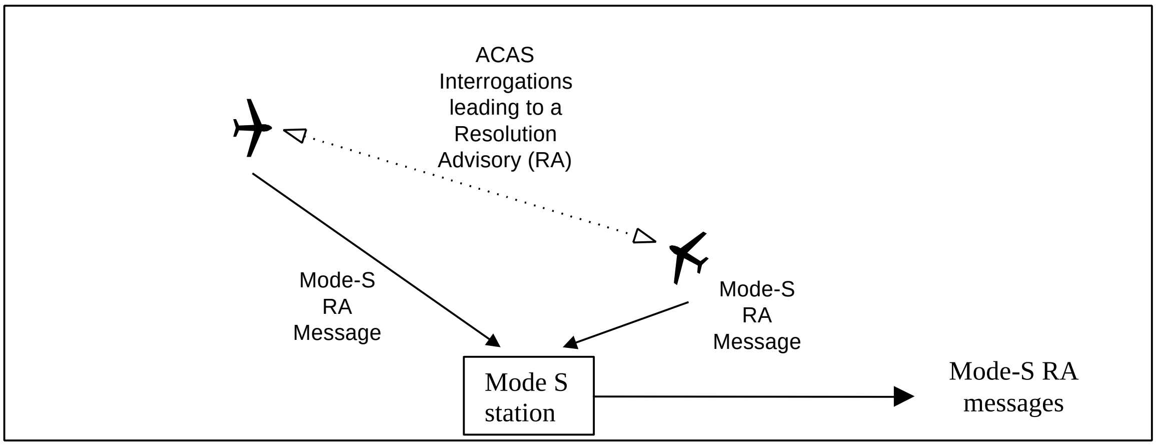

Figure 1: ModeS ACAS-RA occurrence

The detection is triggered by the presence of a ACAS-RA data element in an incoming ASTERIX 48 message.

Rules used :

- An occurrence can contain one or more triggering aircraft (sources of ModeS RA messages)
- If the ModeS RA message contains the ModeS address of the threat aircraft then this will be automatically associated as the intruder aircraft. If it only contains the range and approximate azimuth of the threat only if this can be used to determine a unique intruder is this taken as the intruder aircraft.
- When two modeS RA replies occur within the association distance and within 1 minute of each other in time they shall be taken as coordinated ACAS replies and the aircraft will be assumed to be in the same occurrence.
- In cases where only one aircraft of a pair is equipped and no threat data is provided the corresponding "intruder" aircraft will be collected passively with the other neighbouring aircraft. Although the aircraft with the highest closing rate can be determined it will not be automatically identified as the threat aircraft. It is up to the user to identify this aircraft.
- Further RA's from the same or proximate aircraft during a "RA active" time defined by the user (default 18 seconds) will result in the occurrence time being further extended by this period.
- CPA information for such an occurrence will be calculated with the nearest aircraft to any aircraft which issues an RA alert during the time period specified in the parameters after the first RA message received. This is not calculated with the “threat” but with the nearest aircraft.
- Geometrical classification shall also be made at the initial detection of an occurrence. The RA classification is made with the initial RA response received from each involved aircraft. All subsequent responses will however be recorded and available.

25ft Data Monitoring

The ASMT shall verify the data integrity of altitude (transponder mode C) information used for monitoring. It shall detect cases where an aircraft indicates that it has 25ft altitude reporting capability (via a ASTERIX48 data element) but which sends 100ft quantised data instead.

The altitude of each aircraft is monitored and if 25ft data (reported altitude is on a 25ft,50ft or 75ft boundary) is ever received an aircraft is noted as providing 25ft data. The number of samples where an aircraft is not in level flight and where an intermediate altitude (not at a 100ft boundary) would be predicted from the calculated vertical rate is noted.

At the end of observation of each aircraft when an aircraft has claimed 25ft capability is examined to see if 25ft data was received. If it was not received then a check is made to determine if sufficient samples have been observed where the 25ft quantisation should have been seen. If sufficient samples were processed but the 25ft data has not been observed then a high probability exists that the aircraft is not sending 25ft data as claimed.

A report is generated for each such anomaly with the callsign (or ModeA if no callsign was available), Mode-s address of the aircraft, date, time and duration of observation.

Gillium Code verification

For each observed aircraft the ASMT takes the mode C replies and converts them into grey code. Each bit in the grey code is examined to see if it ever changes during the observation of the aircraft. At the same time a predicted mode C based upon the calculated vertical rates is also converted into grey code to create a mask of the bits which would be expected to change. The number of times a change would be expected is also kept as a quality check.

Only radar validated mode C replies are used for this calculation. Garbled or invalid data is not used.

At the end of the observation of an aircraft the bits that have changed are compared with those that would be expected to change. If a bit is seen to be constantly 0 or 1 when several changes would have been expected then the aircraft displays a potential fixed bit problem.

Checks are also made for certain radar processing problems which can lead to large jumps in validated mode C and could otherwise lead to false reports.

If an aircraft is observed for sufficient periods of descent or ascent the algorithm is very effective at detection of such anomalies.

Reports are generated each time this is detected.