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TCAS II: REPORT ON UK OPERATIONAL TRIAL

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FOREWORD

The development of Airborne Collision Avoidance Systems (ACAS), which seek to provide a 'Safety Net' system independent of the ATC control process for civil aircraft operations, has been underway for some time. Most attempts have foundered on the need to fit all aircraft with special equipment, the costs of which were considered to be prohibitive for many types of aircraft operation. Latterly, a system based on the active use of SSR transponders has been developed into an operational system known as the Traffic Alert and Collision Avoidance System (TCAS). The development, by MITRE and MIT Lincoln Laboratory for the FAA, has been undertaken solely in the USA to achieve implementation timescales set by Congress.

The UK Civil Aviation Authority recognised that, as international airlines rarely operate fleets dedicated to a single region, most large companies are likely to equip all aircraft with TCAS equipment and thus will carry it in the UK FIR. It also recognised that, should TCAS be shown to provide a net safety benefit in the USA, aircrew or airlines may wish to operate the system in the UK. The airspace structure, operating procedures and constraints in the UK are different from those in the USA; therefore the Authority, in conjunction with Royal Signals and Radar Establishment (RSRE Malvern) (now Defence Research Agency Malvern), has undertaken a programme of work designed to evaluate the operation of TCAS in the UK FIR.

The work programme includes the use of simulations to evaluate TCAS logic, the overlaying of TCAS logic on UK traffic patterns derived from radar recordings to determine alert rates, and a series of flight trials. The programme is reviewed by a Working Group comprising staff from the National Air Traffic Services, Safety Regulation Group and Chief Scientist Division, CAA, and from RSRE. In addition, the Group has been supported by staff and aircraft made available by British Airways.

This report has been prepared to provide as full a record as possible of the flight trials. The report presents that data which has been or will be used by the Authority to help to assess the performance of TCAS in the UK FIR. In addition, other data which may be of value to TCAS designers or analysts has also been included.

This report has been drafted on behalf of the Working Group; the content has been approved by Group members at various meetings during 1991.

Finally, we would like to express our appreciation to David Howson for all his efforts in drafting the document, to British Airways for their co-operation by the loan of aircraft for the flight trials and, to Bendix/King Air Transport Avionics Division, Allied Signal Aerospace Company for the loan of the TCAS equipment.

A G Thorning

Chairman CAA/RSRE ACAS
Working Group 1986 to 91.

P H Thomas

Chairman CAA/RSRE ACAS
Working Group 1991 onwards.

SUMMARY

The Operational Trial of TCAS II organised by the UK CAA was carried out using airborne equipment supplied by Bendix/King Air Transport Avionics Division (ATAD), Allied Signal Aerospace Company, configured to a version of the MOPS Change 6, and installed on a B737 aircraft operated by British Airways. The trial commenced on 24th January 1989 and was concluded on 25th November in the same year, during which time the aircraft flew a total of just over 600 hours of revenue service in the UK and mainland European airspace.

Regrettably, with the exception of the certification flight trials performed at Aberporth, it was not possible to use the equipment in a fully operational manner during the trial as had originally been intended. The trial was thus constrained to a data recording exercise and a two week period during which the equipment was used operationally in 'TA only' mode. Nevertheless, a considerable amount of useful data was recorded, comprising data generated by both airborne equipment and ground surveillance radar. Indeed, the unique achievement of this trial was the number of operational events that were captured by on-board recordings and ground radar observations simultaneously.

The data associated with the TCAS advisories generated by the TCAS II equipment installed on the trials aircraft was recorded on board on hard disc. After processing on the ground the airborne data produced a total of 4 Resolution Advisories (RAs) and 203 (129 Mode C, 74 Mode A) Traffic Advisories (TAs). Allowing for estimated data loss due to disc overflow and equipment unserviceabilities, the RA and TA rates estimated were 1 in 108 and 1 in 2.1 hours respectively. The analysis of the airborne data concentrates on the TAs due, primarily, to the small RA sample size.

The ground surveillance radar data, collected mostly from the Debden station in Essex, was monitored and processed through a TCAS II software model supplied by the FAA Technical Centre. A total of 77 Mode C TAs were produced in this manner, of which 43 could be directly correlated with TAs generated by the airborne equipment. This represents an excellent degree of correlation in view of the factors discussed in the text.

In this study, the ground radar data obtained is used mainly in the comparison of airborne and ground observed TAs. This exercise was performed on the data from both the certification flight trials and the operational trials. Many aspects of TCAS behaviour, specifically the location, frequency and magnitude of deviations, cannot be satisfactorily assessed from an ATC point of view by flight trials. The analysis of ATC ground radar data offers an obvious alternative. The comparative results obtained during the trial provide encouraging evidence that this approach is sound.

The main points arising from the analysis of the airborne and ground data are that:–

- The TA rate observed (1 per 2.1 flight hours) was very high, and the majority of TAs (95% of all Mode C encounters) occurred in routine circumstances.

- A large proportion of TAs (69% of all TAs) were generated while the trials aircraft was at or below FL100.

- The average warning times for the TAs were frequently (77% of all TAs) and significantly shorter (average difference of –8.2 seconds) than the nominal warning times.

- The observed level of occurrence of track drop with Mode A intruders was very high.

- It is estimated that, even assuming CAVOK conditions, only about half of the intruder aircraft would have been visually detectable at the time of TA initiation.

- At the point of TA initiation, most intruders (73% of all intruders) were located ahead (within ± 45 deg relative bearing) of the trials aircraft.

- Good agreement between airborne and ground data in both qualitative and quantitative terms was observed.

On the basis of the analysis of the airborne and ground data, and the experience gained during the trials, the following recommendations are made:–

- The TA altitude threshold should be reduced from 1200 ft to a value below standard ATC separation for all sensitivity levels, subject to confirmation of freedom from adverse effects.

- Further testing and investigation should be carried out to determine the adequacy of the performance of TCAS in tracking Mode A equipped aircraft.

- The validity of modelling techniques employing ground radar data is considered satisfactory for the study of the general nature of TCAS behaviour (further developments of TCAS II, and assessment of the effects of TCAS III).

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GLOSSARY

ACAS	Airborne Collision Avoidance System
AEEC	Airlines Electronic Engineering Committee
AIDS	Airborne Integrated Data System
ARINC	Aeronautical Radio Inc.
ATC	Air Traffic Control
BA	British Airways
BAe	British Aerospace
BCAS	Beacon Collision Avoidance System
CAA	Civil Aviation Authority
CAAFU	CAA Flight Unit
CARDPB	Civil Aviation Research and Development Programme Board
CAVOK	Cloud and Visibility OK
CBT	Computer Based Training
CDU	Control Display Unit
CPA	Closest Point of Approach
DADC	Digital Air Data Computer
DRA M	Defense Research Agency Malvern (formerly RSRE)
FAA	Federal Aviation Administration
FAATC	FAA Technical Centre
FIR	Flight Information Region
FL	Flight Level
FMEA	Failure Modes and Effects Analysis
ft	Feet
GDSR	Group Director Safety Regulation
GPWS	Ground Proximity Warning System
IBM	International Business Machines
ICAO	International Civil Aviation Organisation
IFR	Instrument Flight Rules
IMC	Instrument Meteorological Conditions
IVSI	Instantaneous Vertical Speed Indicator
kt	Knot
LATCC	London Area Traffic Control Centre
LED	Light Emitting Diode
LIP	Limited Installation Programme
MOPS	Minimum Operational Performance Standards
NATS	National Air Traffic Services
NM	Nautical Mile
PC	Personal Computer

RA	Resolution Advisory
RAE	Royal Aircraft Establishment
RSRE	Royal Signals and Radar Establishment (now DRA Malvern)
RTCA	Radio Technical Commission for Aeronautics
SICASP	SSR Improvements and Collision Avoidance System Panel
SSR	Secondary Surveillance Radar
TA	Traffic Advisory
TAS	True Air Speed
TCAS	Traffic alert and Collision Avoidance System
TMA	Terminal Manoeuvering Area (now designated Terminal Control Area)
UAL	United Airlines
VFR	Visual Flight Rules
VMC	Visual Meteorological Conditions
VSI	Vertical Speed Indicator

1 INTRODUCTION

1.1 Background

1.1.1 *General*

The motivation for the development of an Airborne Collision Avoidance system has its roots in a series of mid-air collisions in the USA involving public transport aircraft. In particular, the accident at San Diego in 1978 and that at Cerritos near Los Angeles in 1986, resulted in considerable pressure within the USA for the implementation of a practical system. Earlier systems which had been developed suffered from the disadvantage that *all* aircraft would require special equipment in order for them to be effective. Later, however, both passive and active techniques utilising the standard SSR transponder were explored. The active mode was eventually developed into an operational system, initially known as BCAS (Beacon Collision Avoidance System), but subsequently renamed TCAS* (Traffic alert and Collision Avoidance System). TCAS functions independently of the ground-based equipment, and the version of the system studied in this trial (TCAS II) provides escape manoeuvre guidance in the vertical plane only. This report assumes that the reader is familiar with the general technical description and operating principles of TCAS.

1.1.2 *SICASP*

The development of an international standard for an airborne collision avoidance system has, over a number of years, been overseen by the ICAO SSR Improvements and Collision Avoidance System Panel (SICASP). The UK Civil Aviation Authority has been involved in the SICASP discussions from the outset, supported by staff at the Defence Research Agency Malvern (DRA M) – formerly Royal Signals and Radar Establishment (RSRE). As a result, considerable expertise and knowledge has been developed within the UK.

1.1.3 *CAA/RSRE ACAS Working Group*

The CAA/RSRE ACAS Working Group was formed to provide a focal point for input to the UK SICAS Panel Member. In 1985, from discussions within SICASP, the Group recognised that there was very strong political pressure in the USA to develop a practical system. Furthermore, there was a distinct possibility that its use in US airspace by airlines of all nationalities would be mandated. This had important implications in so far as the CAA was concerned. First, it would be necessary for UK operators to fit TCAS to all their aircraft operating to the USA. In practice this effectively meant that all UK registered long-haul aircraft would need to be TCAS equipped since it would be impractical for airlines to have dedicated fleets for destinations in the USA. Second, aircraft fitted with TCAS would expect to be able to use it on all routes, not solely those involving US airspace. It was thus apparent that aircraft of many nationalities with operating TCAS equipment would start to appear in UK airspace once production equipment installations got under way.

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* The generic term used for collision avoidance systems in international discussion is ACAS (Airborne Collision Avoidance System). The term TCAS (Traffic alert and Collision Avoidance System) is more specific and corresponds to the system developed in the USA. At present, TCAS is the only implementation of ACAS and hence the terms are effectively interchangeable. The difference between them should, however, be borne in mind.

The ACAS Working Group therefore decided that it was necessary to assess the operational impact of TCAS on both the ground and airborne elements of UK civil aviation operations. Furthermore, the Working Group felt that an operational trial was needed to provide hard evidence of the performance of TCAS in the UK environment. This view was endorsed by the Civil Aviation Research and Development Programme Board (CARDPB), and the Working Group drafted a proposal for discussion and approval by CAA Management.

1.2 The Trial

1.2.1 *Trials Aircraft Source Selection*

Three possible sources of an aircraft which could be used for the trial were considered:

- A dedicated test aircraft, e.g. the RAE (Bedford) BAC 1-11.
- A CAA Flight Unit* (CAAFU) aircraft.
- An airline aircraft operating on normal revenue services.

It was decided that an airline aircraft was the best option for the following reasons:

- The use of a dedicated aircraft would, to a great extent, have duplicated trials already carried out satisfactorily in the USA.
- Exposure of the system to normal line crews in a normal operational environment would be maximised.
- Use of such an aircraft would be the least expensive.
- The routes used by a dedicated aircraft and the manner in which it would be flown would not be representative of normal operations, which could prejudice the behaviour of TCAS observed, and would not provide sufficient exposure to the busy areas of UK airspace.

The CAA therefore approached British Airways who agreed, in principle, to participate in the trial.

1.2.2 *Airborne Equipment*

An informal offer of the loan of prototype TCAS II equipment had been made by the FAA in 1985. Following exchanges between CAA Senior Management and the FAA, and subsequent discussions at working level, it was agreed that the above equipment would be loaned to the CAA/British Airways. The equipment would be provided from the units manufactured by Bendix/King ATAD for the FAA as part of the US Limited Installation Programme (LIP). Bendix/King ATAD agreed to the loan on the understanding that any changes to the equipment would be minimal, and that they would be reimbursed for any costs incurred in support activities during installation.

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* Following internal reorganisation, the CAAFU no longer exists.

The equipment on offer had been programmed with the Minimum Operational Performance Standards (MOPS) Change 5 logic for the US LIP trials. Because simulation results indicated that the Change 5 RAs, if followed, would result in more rather than fewer close encounters, it was considered unlikely that the system could be certificated in the UK for Stage 4 of the proposed trials. The equipment was therefore upgraded, at the request of the CAA, to the then current draft MOPS Change 6 logic.

1.2.3 *Aircraft Type Selection*

In the very early stages of the planning of the trial the BA Boeing 757 aircraft, configured for the internal UK shuttle routes, was identified as being the ideal aircraft type. There were three reasons for this choice of type:

- The flight deck was large enough to accommodate an observer with a separate dedicated TCAS II display. There would, therefore, be a facility for observers from both the CAA and the airline industry to ensure the satisfactory operation of the equipment prior to its use by the operating crew.
- The aircraft would operate almost exclusively in UK airspace, giving advantages in terms of the availability of recorded ground radar data, and control of the trial in respect of implications to the UK ATC.
- British Airways Boeing 757 aircraft are equipped with a comprehensive data recording system. The Bendix/King ATAD TCAS II equipment had its own recording system but it was anticipated that extra flight data might be required for the trial.

Following discussion between CAA, British Airways and Bendix/King ATAD, however, it became obvious that it would not be possible to interface the LIP equipment (which was designed for analogue aircraft) with the all-digital B757 aircraft in a reasonable time period. The decision to look for another aircraft type was therefore taken. Technical considerations indicated that the B737-200 would be suitable, however the smaller flight deck would preclude the provision of a separate observer's position, and consequently Stage 3 of the trial had to be eliminated (see Section 1.2.5).

1.2.4 *Trials Management*

Following the agreement of British Airways to participate, and the approval of CAA Senior Management, a small Steering Group was formed to manage the trial. The Steering Group comprised staff from relevant departments of the CAA and RSRE, together with representatives from British Airways Flight Operations and Engineering Divisions. In addition, at the request of CAA GDSR, a member of the Operations Advisory Committee was nominated to represent the other UK airlines. The terms of reference and membership of the CAA Trials Steering Group are given in Appendix 1.

1.2.5 *Trials Programme*

The original proposal defined a trial divided into the following four stages :

Stage 1 Installation – airline engineering staff gain experience in fitting TCAS II equipment.

Stage 2 Initial Flight Evaluation – TCAS information not to be presented to the crew. Automatically recorded data to be analysed to ascertain alert rates for comparison with US experience, and with predictions based upon the analysis of recorded UK radar data.

Stage 3 Further Flight Evaluation – TCAS information not presented to crews but a separate observer's display to be provided. ATC to be made aware of the trials but not informed about specific flights. An observer to be present on the flight deck for as many flights as possible in order to supplement the recorded data.

NB: After Stage 3 a full review was to be held, following which the agreement of all parties would be required prior to proceeding to Stage 4. As a result of selecting the Boeing 737 for the trial, however, Stage 3 had to be omitted.

Stage 4 Final Flight Evaluation – equivalent to US LIP flight trials. TCAS flight deck displays to be activated and ATC to be briefed on detailed aspects of trial. Crew to record details of TAs and RAs and action taken. Observers to be present on as many flights as possible. TCAS II alerts to be responded to in VMC and IMC. ATC not to be informed of TCAS fit unless contacted by aircraft.

1.3 Objectives

1.3.1 *General*

The broad objectives of the trial were:

'To assess the operation of TCAS II in an airline environment, and to develop an understanding of the potential impact of alerts on UK airline operations, UK flight crews, and the UK ATC system.'

In addition, the trial would provide the CAA with experience of the operational and engineering aspects of the introduction of TCAS II, and help to identify the institutional questions which the CAA would need to address. It is unlikely that this exposure to TCAS would have taken place in as controlled an environment as can be provided by an operational trial, were the certification of installations and approval of procedures not to have been addressed until compelled by the introduction of TCAS, itself forced by US legislation.

The objectives can be sub-divided into three areas of interest; Institutional and Legal Aspects, Impact on Airline Operations, and Impact on ATC Operations.

1.3.2 *Institutional and Legal Aspects*

The objective of the trial in this area was to address, inter alia, the following topics :

- Operations in VMC; pilot responsibility in relation to the Rules of the Air.
- Operations in IMC.

- ATCO responsibility following TCAS II induced manoeuvres.

- Airworthiness aspects.

- Training requirements.

- Information to be given in airline Operations Manuals.

1.3.3 *Effect on Airline Operations*

Here it is appropriate to differentiate between the impact of Traffic Advisories (TAs), and Resolution Advisories (RAs).

In the case of TAs, one of the most important objectives was the estimation of the observed alert rate. Previous work in both the UK and the USA had suggested rates as high as one traffic advisory (TA) every 2 flight hours, which crews might find unacceptable. Other objectives were to establish whether :

- The TA is helpful.

- The observed rate of TAs increase pilot workload unacceptably.

- The TA display format is fit for the intended purpose.

- Circumstances exist under which crews contact ATC on receipt of a TA.

For RAs, the expected alert rate based on UK studies at the time was about one per 50 flight hours. Bearing in mind that this alert was to carry 'Master Warning' status (equivalent to, for example, GPWS), the attitude of crews would need to be assessed. Other topics to be addressed included :

- The effects of crew confidence in the system, and the nature and speed of pilot response.

- Pilot attitude to 'preventive' alerts, ie. those which tell the crew merely to monitor their vertical speed.

- The fitness of the IVSI display for the intended purpose.

- Acceptability and design of auditory warnings.

1.3.4 *Effect on ATC Operations*

The effect of TAs on ATC operations would depend very much on the extent to which crews contacted ATC on receipt of a TA. It had been suggested that, if ATC were aware that the aircraft was TCAS equipped, they might try to anticipate queries from the crew by providing more traffic information than would normally have been the case. ATCO workload constraints, however, were expected to constrain this practice once a large proportion of the traffic became TCAS equipped. Care would thus need to be taken in extrapolating trials experience into the future. The objective of the trial was therefore to estimate the general effects of TCAS on ATCO's duties.

In the case of responses to RAs there could be a significant increase in controller workload, especially if altitude deviations were to be such that traffic other than that generating the advisory would be affected.

2 PRE-TRIAL ACTIVITIES

2.1 TCAS II Equipment Installation

2.1.1 *Equipment Design Standards*

The trials equipment installation comprised a single Mode S transponder system and the TCAS II system. These systems conformed to ARINC/AEEC design characteristics ARINC 718 and ARINC 735 (draft) respectively. The overall system functioning was designed to be in accordance with the TCAS II implementation of the anticipated RTCA Minimum Operational Performance Standards (MOPS) DO-185, Change 6 (see 1.2.2).

2.1.2 *System Architecture*

The system architecture of the trials equipment installation is illustrated in Fig. 2-1. The aircraft system inputs comprised:

- TCAS Processor
  - Barometric altitude, ARINC 575 serial digital format.
  - Radio altitude, ARINC 552 analogue format (no.1 radio altimeter).
  - Radio altimeter valid discrete.
  - Pitch and roll attitude (no.1 vertical gyro).
  - Attitude valid discrete.
  - Magnetic heading (no.1 system).
  - Magnetic heading valid discrete.
  - L band suppression line.
  - Landing gear extended discrete (landing gear lever switch utilised).
  - Flaps extended discrete.
  - No climb altitude: 22,000 ft (program pins).
  - Maximum airspeed: 600 kt (program pins).
- Mode S Transponder
  - Barometric altitude (no.1 DADC).
  - Barometric altitude valid.
  - L band suppression line.
  - Air/ground discrete.
  - Mode S address (program pins).
- Symbol Generator
  - Magnetic heading (no.1 system).
  - Magnetic heading valid discrete.

2.1.3 *Controls and Displays*

The TCAS Display Unit, VSIs, TCAS/Mode S transponder Control Panel, Display Unit Control Panel, and the Recorder Control Panel controls and displays/indicators are described in Figs. 2-2 to 2-6 respectively.

2.1.4 *Aircraft Installation*

The general arrangement of the trials equipment installation is presented in Fig. 2-7. The aircraft installation was based, as far as was possible, on an FAA approved modification package purchased from United Airlines (UAL) who had installed similar equipment on one of their own B737 aircraft. This having been an earlier version of the B737, much of the installation data could not be directly applied to the later British Airways –200 variant used for the trials.

In order to limit the number of additional antenna installations required, the existing ATC transponders were deactivated, thereby releasing their associated L band antennas for use by the trials equipment. The transponder systems remained installed to permit reactivation in the event of failure of the trials Mode S transponder away from main base. No.1 ATC transponder antenna was used as the bottom Mode S transponder antenna, the No.2 antenna serving as the bottom (omni-directional) TCAS antenna. The top Mode S transponder antenna, and the top TCAS antenna (steerable), were provided by new installations on the top fuselage at stations 470 and 435 respectively. The Beam Steering Unit for the top TCAS antenna was mounted in the cabin ceiling space adjacent to the antenna.

The lack of space in the equipment bays and on the flight deck instrument panels dictated the removal of the existing Global area navigation system. The TCAS Display Unit was installed in lieu of the area navigation system CDU in the left hand side of the Pilot's Forward Radar Panel and the Mode S transponder, TCAS Processor, and TCAS Symbol Generator utilised the rack space in the electronics bay provided by the removal of the area navigation equipment. The TCAS Recorder was located in an existing spare rack slot on a different shelf to the remainder of the TCAS equipment.

The TCAS/Mode S transponder, TCAS Display, and TCAS Recorder control panels were installed on the centre pedestal. The former was located adjacent to the existing transponder control panel, and the latter two occupied spare positions at the rear of the pedestal. The dedicated TCAS speaker was positioned next to the GPWS speaker on the pilots' Overhead Panel.

One major problem with the installation involved the interfacing of the TCAS system with the VSIs. The VSIs available for loan were pneumatically driven, however the BA aircraft was equipped with electrical instruments, driven by the aircraft's Air Data Computer. The option to install pneumatic VSIs was rejected on the grounds that this would have entailed considerable engineering effort and, due to the different response characteristics of the pneumatic VSIs, would have invalidated the certification of the VSI installation on the aircraft. The existing VSIs were therefore modified to receive and display the TCAS data, adding the red and green LEDs ('eyebrow' lights) around the periphery of the instrument required for the display of the resolution advisory (RA) guidance data. This work was carried out by Harrow Instruments who also, in conjunction with Bendix/King ATAD, undertook the task of interfacing the instruments to the TCAS computer.

2.2 Aircrew Training

2.2.1 *Training Strategy*

The equipment used for the trial had been operated by UAL during the US LIP. UAL had compiled a training programme comprising printed material and an interactive Computer Based Training (CBT) aid. Whereas it would have been convenient to utilise the existing training package, this was not possible for a number of reasons.

First, the UAL CBT was configured to reflect the MOPS Change 5 standard of the LIP TCAS units which had been upgraded to MOPS Change 6 for the UK trial. Significant differences between the two standards existed, hence little of the original material was still valid. Similarly, much of the printed training material also required updating.

Second, with the practical difficulties associated with crew rostering, the inclusion of a CBT element in the training programme would have made it unlikely that sufficient trained crews could have been made available. Further, prior to the start of the trial, it was known that the production standard TCAS would differ from that to be used for the trial. Taking account of this fact, the resources that would have been required to update the CBT program could not have been made available.

The decision was therefore taken to limit the training material to printed matter only. A video of two scenarios, shot during the certification flight trials, was, however, compiled and shown to some crews.

Due to the planned limited extent of the trial (one aircraft for a period of several months), the aircraft Operations Manual amendments were presented in a single document with the training material. The start of Stage 4 of the trial could then have been authorised by the issue of a simple instruction. The training guide is reproduced in Appendix 2.

2.2.2 *Effectiveness of Training*

Firm conclusions as to the effectiveness of the training cannot be drawn since, in the event, Stage 4 of the trial was limited to a brief period of operation in TA only mode. Pilots were thus given little opportunity to operate the system and test their training in an operational environment. The majority of the available evidence was therefore limited to the replies to the quiz included in the training document. The distribution of incorrect answers for the 240 quiz replies received is given in Fig. 2-8.

For convenience, the following sub-paragraphs record the findings of the analysis of the quiz results, reported here rather than with the remainder of the data analysis and conclusions:

- Judged solely on quiz performance, pilots were apparently able to understand the basic outputs of TCAS and its principles of operation from the printed training material utilised. Operating rules, however, were either not so well understood, or the associated questions proved more difficult to phrase unambiguously.

- Of the 43 questions, 35 on general TCAS comprehension and 8 relating specifically to response to RA indications, only 6 gave any real problems. It was considered that 3 of the subject 6 questions (13, 31, and 34) could have been better phrased. The remaining 3 (26, 28, and 35), however, gave some cause for concern.

Question 26 asked if, having identified traffic which was not considered to be a threat, it is mandatory to follow the RA guidance, should an RA be received? The correct answer is *no*, but *29%* thought it *was* mandatory to follow the RA guidance regardless.

Question 28 covered the correct reaction to the typical softening of an RA changing from 'climb' to 'vertical speed restricted'. 21% failed to recognise that a reduction in rate of climb was usually intended. The absence of an accompanying diagram for this question may have been significant.

Question 35 asked whether it was advisable to pre-empt an RA by making an early, more gentle manoeuvre on the basis of the information on the traffic display, in order to avoid more abrupt action later. *Contrary* to the guidance material and ATC rules, *21%* thought it was.

Although limited in its scope, the above evidence of effectiveness of the training programme does indicate some areas where greater emphasis may be required in future. No conclusions as to the desirability of the use of CBT can be drawn, although its suitability for posing questions with a degree of realism may be of benefit.

The effectiveness of training was also evaluated using the observations made of crews operating TCAS in TA only mode. This study, given in Appendix 3, gave rise to the tentative conclusion that some scope for improvement exists.

2.3 Certification

2.3.1 *General*

The trials hardware and the aircraft installation were certificated independently by the CAA. The UK certification of the software, however, was to be based on an FAA certification, supported by the UK certification flight trials (described in Section 3.5).

The equipment supplied by Bendix/King ATAD was of a prototype nature and, furthermore, was designed to an interim specification. It was therefore necessary to apply special certification procedures for the avionic units and antennas.

2.3.2 *Hardware*

Although in prototype form, the trials hardware was, nevertheless, manufactured to normal air transport standards. The installation of the equipment on the trials aircraft was based on the FAA approved UAL modification package. In spite of the fact that much of the installation data was not directly applicable to the UK trials aircraft, the use of the UAL package did speed the certification process. This was particularly apparent with the antenna installation which required the approval of the aircraft manufacturer to cut into the fuselage skin.

A Failure Mode and Effects Analysis (FMEA) study was required for certification of the trials installation as a whole, and for recertification of the VSIs following the modification to permit the display of TCAS data. These studies entailed the identification of all possible fault conditions and prediction of their effects on the total aircraft system. Normally, this task would have been the responsibility of the equipment manufacturer but, due to the 'one-off' nature of the installation, it was agreed that the FMEAs could be performed by BA.

The installation of the trials equipment did necessitate the removal of the Global area navigation system which, although having operational implications, did not pose any certification problems.

2.3.3 *Software*

Unlike the hardware, the software for TCAS was not produced using normal air transport procedures, the major part of it being generated from the MOPS pseudo code.

The equipment was originally manufactured to MOPS Change 5 specification for the UAL trial. Bendix/King ATAD agreed, however, to upgrade the equipment to the proposed MOPS Change 6 (22 February 1989 vers.), for the BA installation (see Section 1.2.2). As this version had not, at that time, been certificated by the FAA, it was necessary to receive their assurances that they were satisfied that the software was of an acceptable standard for public transportation use in all conditions (VFR and IFR). This topic is addressed further in Section 3.6. For the 'record-only phase' (Stage 2), neither FAA certification nor any assurances were necessary since the TCAS data would not be presented to the crews.

The escape manoeuvre coordination logic of the software version used for the trial was known to be incompatible with earlier versions in existence at the time of the trial. Consequently, the experimental design ensured that the trials aircraft would not be operated in the vicinity of any other TCAS equipped aircraft. At that time the only other TCAS equipped aircraft likely to operate in UK airspace were those used by equipment manufacturers for demonstration purposes. The use of TCAS by these aircraft was limited by the CAA to the TA-only mode except when conducting demonstrations in pre-defined areas, away from controlled airspace where the trials aircraft could be operating.

3 DATA COLLECTION

3.1 General

In collaboration with the UK CAA, RSRE has over a number of years developed techniques for the analysis of ground radar data to assess the effects of TCAS in UK airspace. Suitably processed radar data is passed through a TCAS model to reproduce any advisories which would have been generated had one of the aircraft been TCAS equipped. In order to improve confidence in these techniques, and hence the results of any studies performed using them, it was considered desirable to compare actual TCAS generated data with ground radar derived data. One reason for conducting a comprehensive collection exercise of both air and ground data was therefore to be able to perform such a comparison. The ground radar data was also expected to provide the context within which any RA occurred, and would thus serve to assist analysis of any problems that the trial might reveal.

The means for collection of airborne data was provided by a recorder supplied with the TCAS equipment, which was capable of collecting relevant TCAS event information. In addition, during the final stage of the trial when the flight deck displays were to be activated, this information was to be supplemented with data hand-recorded by flight deck observers and/or aircrew.

While the trials aircraft was operating within airspace covered by a suitable UK ground surveillance radar, recordings from that radar station were made. In addition, when an RA was observed anywhere else within UK radar coverage, it was intended that the appropriate radar data would be extracted from the recordings made to meet statutory requirements.

It was also planned to collect information from Air Traffic Control Officers on TCAS-related events in the final stages of the trial.

3.2 Airborne Recording

The recording of airborne data was performed using the dedicated recorder supplied by Bendix/King ATAD with the TCAS equipment. TCAS information was monitored and buffered on a continuous basis. If either a TA or RA occurred, 15 seconds of buffered pre-event data was transferred to one of the associated 40 Mbyte hard discs, together with subsequent data. The recording of real time data continued until 10 seconds after the Collision Avoidance Logic no longer generated an advisory. When the first disc became full, data transfer was automatically redirected to the second disc. With a combined capacity of 80 Mbytes it was possible to collect data for a week before needing to change the discs. Disc changes could thus be scheduled by British Airways maintenance staff on a regular basis obviating the need to constantly monitor the 'disc full' warning lights located on the TCAS control panel in the flight deck. The discs removed from the aircraft were sent to RSRE for analysis and data validity checking, after which they were cleared and returned to British Airways for re-use. It should be stressed that only TCAS data could be recorded on these discs. Other relevant information, such as aircraft position, would have to have been obtained from other sources.

Additionally, in order to evaluate the response of the aircrew and aircraft in the event of an RA requiring pilot action, it was planned to obtain a readout of the aircraft's AIDS recorder. On the trials aircraft, the AIDS recorder was configured to record the same data as the flight recorder, which is used for accident investigation.

3.3 Ground Radar Recording

The ground radar data was transmitted to RSRE at Malvern from LATCC at West Drayton via a dedicated land line. As only one line was available for this purpose, data from only a single radar head could be recorded at any one time. The data source was the plot extractor output which comprised range, azimuth, Mode C altitude, and Mode A identity code. Time was obtained from the RSRE computer's internal clock. After analysis of the trials aircraft's planned routeings through UK airspace, it was decided that optimum cover would be provided by the Debden station in Essex. The Debden radar head was thus used throughout the trial except on some weekends when the Heathrow site was used in order to satisfy the requirements of others for radar data.

The relevant sections of radar data were isolated using the airborne recordings of advisory times together with the aircraft's block times supplied by British Airways, the latter being used to estimate when the aircraft was within cover of the radar head in use. The trials aircraft was identified on the radar recordings using the aircraft's transponder identification code, which was noted at the end of each sector and transmitted to RSRE on return to Heathrow. The sections of data so extracted were then run through the TCAS simulation model for comparison with the airborne data. Apart from supplying data for comparison with the airborne data, the ground radar data also provided geographical information associated with advisories.

3.4 Aircrew and Observer Questionnaires

The purpose of the aircrew questionnaire, reproduced in Fig. 3-1, was to gauge the reaction of the pilots to the system. The scope of the questionnaire was tailored to address both the human factors aspects of the TCAS/pilot interface, and some technical details to provide supporting data for the airborne and ground radar recordings. The questionnaire was associated with Stage 4 of the trials, during which period the flight deck TCAS displays were to be activated.

The observer questionnaire, reproduced in Fig. 3-2, was designed to provide technical data associated with the advisories that was not available from the airborne or ground radar recordings. It was originally intended to be introduced from the start of Stage 3 of the trials however, as this stage did not take place, it was first used during Stage 4.

3.5 Certification Flight Trials

3.5.1 *General*

A series of flight trials was performed at the Royal Aircraft Establishment's instrumented test range at Aberporth. The Aberporth range was selected for its accurate tracking facilities and large protected volume of airspace which would enable the flight test programme to be executed in safety. The objective of these trials was to support the certification of the TCAS II trials equipment for the purposes of Stage 4 of the operational flight trials programme. The flight trials entailed flying the TCAS II equipped British Airways aircraft against a CAA operated BAe 125 Mode C 'intruder' aircraft in a number of encounters designed to exercise some of the salient features of TCAS II.

The trials plan envisaged one day of activities with a reserve day in case of equipment failures or weather problems. In the event, the trials comprised three days of activities at Aberporth, known as Aberporth I, II, and III. This section gives a brief summary of these trials, highlighting the main points of interest. A full and detailed account of the trials is given in Reference 1.

3.5.2 *Aberporth I*

The first flight trials were conducted on 19 March 1989. The first fourteen encounters detailed in Table 3-1 were executed, successfully for the most part. The only really significant failure to produce the expected result was experienced with encounter 10 where, despite three attempts, the anticipated RA sense reversal was not generated. Although not considered important at the time, it was also noted that the 'clear of conflict' annunciation was rarely generated. It subsequently became apparent that this anomaly was symptomatic of the IVSI interface problem later confirmed after Aberporth II.

By far the major problem associated with these trials was the inability to extract any useful data from the TCAS recorder discs. The recorder and discs were returned to Bendix/King ATAD in a further attempt to recover the data, but to no avail. Although the equipment subsequently operated satisfactorily, no specific defect was found.

The ground radar data recording exercise was more successful, however. Data from the NATS Clee Hill radar station was transmitted to RSRE via a telephone line link where it was processed through the model of the Change 6 TCAS software standard. Although there was no airborne data with which to compare the processed ground radar data, correlation with flight deck observations was generally good.

Two interesting facets of the behaviour of the TCAS logic associated with encounter 7 (intended to illustrate the effect of delayed pilot response), and encounter 14 (concerned with the operation of the climb inhibit logic), were observed. These are described in some detail in Sections 5.2, and 5.3 respectively.

3.5.3 *Aberporth II*

Due to the failure to obtain airborne recordings of the TCAS parameters directly from the airborne equipment during Aberporth I, a repeat of the trial was conducted on 14 May 1989. The encounter scenarios flown were essentially as given in Table 3-1 but, as a result of the experience that had been gained, with the following modifications:

- Encounters 3 and 4 were eliminated.
- New encounters 8A and 9A were introduced which were identical to encounters 8 and 9 respectively, except that the intruder approached from below instead of above.
- The target level of separation for encounter 10 was reduced by 100 ft to 700 ft, in order to improve the chances of obtaining the desired crossing climb if the aircraft tended to level off too soon.
- Encounter 14 was split into 14A and 14B having initial vertical separations of 300 ft and 100 ft respectively, the objective being to invoke the two different responses described in Section 5.3.

Once again the ground radar data recordings were successfully obtained and, in this instance, so too were the airborne data recordings. Unfortunately, however, TCAS appeared to fail intermittently throughout the trial. The RA displays and auditory annunciations on the flight deck were reported to have been erratic, and the 'clear of conflict' message was frequently missing. Further, the strengths of the recorded RAs did not always agree with those observed on the flight deck. This behaviour proved to be symptomatic of the IVSI interface problem subsequently discovered.

An interesting effect of the Mode C altitude quantisation on the TCAS logic behaviour was noted with encounter 5, and this is described in Section 5.4.

3.5.4 *Aberporth III*

In order to confirm the resolution of the IVSI interface problem experienced during the Aberporth I and II trials, a third series of trials were conducted on 19 September 1989. Since the cause of the problem had been positively identified, and rectified, it was considered sufficient to repeat only a small subset of the original encounters. The subset selected comprised encounters 1, 2, 5, and 10. In addition, advantage was taken of the opportunity to try out a new encounter scenario (15), designed to illustrate the possible disruptive effects of TCAS. This head-on scenario required the intruder to fly level at FL 180, and the trials aircraft to descend from above at 3000 ft/min so as to pass 200ft below the intruder at the point of closest approach (CPA). Both aircraft were to maintain 400 kt TAS. The horizontal separation was set at 3.3 NM.

On this occasion the displays functioned correctly, although the IVSI fail flag was reported to have been observed in some instances. The new encounter scenario (15) was successfully executed and is described in Section 5.5.

3.5.5 *Summary*

In terms of the original objective of supporting the certification of the TCAS II equipment for the operational trials, the Aberporth trials were successful in demonstrating that the functioning of the equipment was, with the exception of the TA range test, in good accord with the requirements of the MOPS. The results indicated that a change to the logic for both the TA and the RA range tests required by Change 6 had been implemented only for the RA range test.

Of considerable additional benefit was the discovery and rectification of the display interface defect. Undetected, this defect could have seriously degraded the data obtained from the operational trial. An error in the FAATC Change 6 model used by RSRE was also discovered as a result of these trials, although this would not have had any effect on the operational trial.

In addition, from both qualitative and quantitative comparisons of the airborne and ground radar data, the validity of the use of ground radar data as a tool for investigating TCAS statistics was also confirmed.

3.6 **The Operational Flight Trials**

The operational flight trials commenced on 24 January 1989, and effectively ceased on 25 November in the same year. A summary of the significant events that occurred during the course of the trial is given in Table 3-2.

As is evident from the table, the trial was beset with airborne data collection problems. These comprised primarily recorder and/or disc hardware faults which, in many cases, led to the loss of data. It is estimated that these problems accounted for an overall data loss of about 30%. In other instances data was recovered but difficulties were experienced with its identification.

The definitive Change 6 software finally adopted for the FAA Ruling was a development of that installed in the trials equipment. It was eventually discovered that, as a consequence of this, the trials software had not been documented to the extent necessary for FAA, and hence CAA, certification for public transport operations. The FAA were therefore unable to give the required assurances, and Stage 4 of the trial had thus to be restricted to the TA only mode of operation.

In the event this restriction was somewhat academic since Stage 4 lasted for only two weeks. Although Bendix/King ATAD had already generously extended their support of the trials equipment well beyond the envisaged end of trial date, the FAA imposed TCAS retrofit timescales in the USA dictated the reconfiguration of their test facilities to accommodate production standard equipment. Bendix/King ATAD were thus no longer able to support the trials equipment which, in common with most prototype equipments, was somewhat unreliable in comparison with production standard equipments. The decision to terminate the trial was therefore taken.

4 DATA ANALYSIS

4.1 Data Processing

4.1.1 *Airborne Data*

The format and content of the data recorded on the TCAS recorder discs was that which had been specified by FAATC for the LIP trials. The data was extracted from the discs at RSRE using the TCAS manufacturer's program PCDRUT, running on an IBM compatible PC (Apricot Xen-xi), connected to the disc drive via a special interconnecting harness. In addition to stripping the data from the discs, this set-up provided information regarding the quantity of data, recording periods etc, and was used to clear the discs prior to re-use. The data was transferred from the PC to a VAX 11/780 computer for processing using proprietary software, the PC serving as a buffer during the transfer.

Once in the VAX, the raw data was archived onto magnetic tape. Using a program supplied by Bendix/King ATAD, the data was reformatted and transferred to magnetic tape. A further program provided by Bendix/King ATAD, XCRIBE, was then run to unpack, translate, and reorganise the data into character files. The character files comprised tables of groups of TCAS variables, listed second by second, with the MOPS identifier at the head of each column. In this form, the data could be more easily examined by eye, or processed further by computer. This analysis was performed at RSRE.

Due to an error in the implementation of the version of Change 6 software installed in the trials equipment, the modified tau criterion was still being used for the TA range test. The TA rate observed during the trial would thus not be representative of that which would have been experienced were production standard TCAS equipment to have been used. The surveillance data was therefore reprocessed through a Pascal model of the bona-fide Change 6 software, supplied by the FAATC, in order to examine the behaviour of the true Change 6 software and obtain an estimate of the true TA rate. Associated RSRE software was then employed to generate a summary of the cardinal features of the encounters e.g. miss distance, duration, etc. A further facility was provided for automatic processing of the summary data to generate histograms for the encounter parameters of interest.

4.1.2 *Ground Radar Data*

The data received from the plot extractor outputs comprised a series of samples taken at six second intervals, a function of the rotation of the radar head aerial (aerial rotation rate for Debden is 10 rpm). In order to obtain intermediate values at the one second intervals required for the FAATC model, a smooth line was established through the data points by use of a curve fitting technique employing a cubic spline. Using the one second interval data, the Cartesian coordinates of the trials and intruder aircraft were calculated, and then differenced to give the relative coordinates. The distance between the aircraft, the ground radar equivalent of the TCAS range measurement, was then calculated. The interpolated data was also used to derive the trials and intruder aircraft altitudes for input to the TCAS model. The trials aircraft smoothed altitude data was used directly, however the intruder aircraft altitude was first quantized to the nearest 100 ft.

4.1.3 *Aircrew/Observer Questionnaires*

As a result of the short duration of Stage 4 of the trials (effectively only two weeks), when the questionnaires were introduced, only a few were completed. The observations made were of interest nonetheless, since the sole function of TCAS is to furnish flight crew with appropriate information and guidance, and this was the only opportunity available to witness them actually using it.

An evaluation of the observations made has been the subject of a separate report which is reproduced in Appendix 3. Some defficiencies in the display functions and in the effectiveness of the training were highlighted.

4.2 **Results From Airborne Recording**

4.2.1 *General*

The results are divided into the two groups; Resolution Advisories (RAs), and Traffic Advisories (TAs).

TAs are themselves classified as either Mode A or Mode C according to the operating mode of the ATC transponder installed on the intruder aircraft. An aircraft may be equipped with a transponder capable of operating only in Mode A, or one which can support Mode C operation as well. TAs generated by Mode A intruders differ from those with Mode C or Mode S* transponders in that no altitude information is available from the intruder aircraft. For the purposes of establishing when to issue a TA in this case, TCAS II uses range data only. The TA, as defined by SARPs, is 'An indication given to the flight crew identifying the approximate positions of certain other aircraft'. In the case of a Mode A TA, however, the assistance to visual acquisition of the intruder is limited, since its vertical displacement from own aircraft is unknown.

4.2.2 *Hours Flown During the Trial*

The total number of flight hours associated with the trial was 605.3, with an average sector length of 1.1 hours. This figure, however, includes periods during which the

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* As the trials aircraft could not be operated in the vicinity of any other TCAS equipped aircraft (see Section 2.3.3), any Mode S equipped intruders would, in operational terms, respond in the same manner as if Mode C equipped. No distinction between the two is therefore made in this report.

TCAS equipment and/or the recorder were unserviceable, and also periods during which no data was recorded due to the recorder discs being full. The total duration of these periods, where no record of any TAs generated could have been obtained, has been estimated at 172.5 hours. This figure was arrived at by taking account of indicators such as; a number of consecutive TAs observed on ground radar with no corresponding flight data, pilot reports of 'discs full' annunciator on, and the TA rate observed when the equipment was thought to be functioning normally.

The 'corrected' total flight time for the trial is thus estimated to be 432.8 hours.

4.2.3 *Resolution Advisories*

Only three RAs were recorded throughout the trial, a further one being generated when the data was replayed through the FAATC model. The RA rate for the trial was thus 1 in 108 hours (432.8/4 = 108.2).

Of the three RAs recorded, one occurred on approach to Newcastle, one on approach to Heathrow, and the other in cruise in some unknown section of airspace (the time and date for this encounter was not known as the recorder clock was unserviceable). The latter was a disruptive RA (it required own aircraft to descend when the horizontal separation was adequate), whereas the former two were preventive (no action was required of own aircraft).

The additional RA generated by the FAATC model resulted from the range test being marginally passed, whereas in the output from the airborne TCAS software the range test was marginally not passed. The FAATC have independently performed the same experiment with the data and obtained the same result. Although no acceptable explanation for the difference has yet been forthcoming, the range tracker in the trials equipment is believed to have been different to that standardised by the MOPS pseudocode.

Although the RA rate observed is commensurate with that which has been obtained for UK airspace using ground radar data only (see Section 3.1), it is considered that, because of the low number of RAs observed, no reliable conclusions can be drawn from the data obtained. The plots associated with these encounters are, however, included for information (Figs 4-1 to 4-4).

4.2.4 *Traffic Advisory Rates*

The total number of TAs recorded by the airborne equipment during the period of the trial was 295, of which 173 were generated by Mode C intruders and 122 by Mode A. This total includes those TAs which subsequently developed into RAs.

Replaying the data through the FAATC model, for the reasons stated in Section 4.1.1, resulted in the elimination of 33 Mode C and 39 Mode A TAs, leaving a net total of 223 TAs composed of 140 Mode C and 83 Mode A encounters.

Study of the plots of the TAs, the times at which the TAs occurred and, where available, correlated ground radar data, suggests that in some instances two or more consecutive TAs had been generated by one intruder. It is considered that this phenomenon was caused by the airborne equipment losing track and then reacquiring the intruder, the reacquisition of the intruder being treated as a new encounter. A requirement to flight test the surveillance system has susequently been added by the TSO and will be added to the MOPS in due course. This action should ensure that this phenomenon will be less likely to occur with production standard equipments. It was therefore considered appropriate to merge the multiple TAs on the basis that the results would consequently be more representative. The process of merging the multiple TAs gives further reductions of 11 Mode C and 9 Mode A encounters. The net total number of TAs thus becomes 203, of which 129 (64%) were Mode C and the remaining 74 (36%) Mode A.

From the estimated total trial flight hours of 432.8, the TA rates are thus:

Overall	–	1 TA in 2.1 flight hours
Mode C	–	1 TA in 3.4 flight hours
Mode A	–	1 TA in 5.8 flight hours

NB: Due to the uncertainties inherent in the methods used to determine the total trial flight hours, the above rates should only be considered approximate.

4.2.5 *Aircraft Separation During Traffic Advisories*

Aircraft separation in the ATC environment is accomplished by the application of vertical and/or horizontal separation. For meaningful analysis, therefore, it is necessary to examine the individual components and their effect in combination for each encounter. The data required for this analysis, however, is only available for Mode C TAs where the relative altitude of the intruder aircraft is known. Assessment of the data in relation to an ATC separation standard reference frame can be readily accomplished by plotting vertical separation against horizontal separation on a scatter graph. Scatter graphs for separation at initiation of the TA and at CPA for the Mode C encounters are given in Figs 4-5, and 4-6 respectively.

Comparing the locations of the points plotted with the 1000 ft X 3 NM separation 'box' on Fig 4-6, it is interesting to note that in only 5 of the 108 (5%) encounters is the normal ATC separation standard violated to any significant extent. Of the five encounters, the two with vertical miss distances in excess of 500 ft are those associated with the preventive RAs recorded on approach to Newcastle and Heathrow. Casual inspection of the remaining three might suggest that they constitute category A airmisses, however, closer examination reveals that they rated TAs only because own aircraft altitude was below 500 ft in each case. All five encounters occurred with own aircraft on final approach to various airports in Europe, the intruders being the usual type of traffic that frequently appears close by in such situations.

A striking feature of the scatter graph in Fig 4-5 is the large number of points around the 1000 ft vertical separation/miss distance level. Examination of the TA data plots indicates that in 69 out of the 127 Mode C encounters (54%), both own aircraft and the intruder were in stable level flight prior to and after generation of the TA. In all but one of the 69 cases the vertical separation was between 900 and 1200 ft. Studies conducted on height keeping performance (see Reference 6) have indicated that, in European airspace, Mode C equipped aircraft remain within ± 100 ft of their cleared flight level for 98.7% of total flight time. A TA vertical separation threshold of 800 ft (1000 ft – 2 x 100 ft) would thus appear more appropriate than the current value of 1200 ft.

During processing a small section of the data base was corrupted, resulting in the loss of 2 Mode C TAs. The above analysis was therefore performed on the remaining data set of 127 Mode C TAs. It should also be noted that the 14 Mode C TAs for which CPA was not actually observed by TCAS, and the 5 Mode C TAs for which accurate horizontal miss distance data was not available, were excluded from Fig 4-6.

4.2.6 *Altitude at Initiation of Traffic Advisories*

The results of the operational trial for the altitude of the trials aircraft at the point of initiation of the advisory are given in Fig. 4-7.

Of particular note is the concentration of TAs at comparatively low altitudes. Of all TAs, 69% were initiated below 10,000 ft, of which 49% were Mode A and 51% Mode C. Inspection of Fig. 4-7 also indicates a general increase in proportion of Mode A to Mode C encounters with reducing altitude. Notably, of all TAs that occurred below 1,000 ft, 83% were Mode A and only 17% Mode C. This trend is to be expected as performance and regulations constrain the operation of the majority of Mode A equipped aircraft to the lower flight levels and altitudes. Indeed, 94% of all Mode A encounters occurred below 10,000 ft compared to only 54% of all Mode C events.

During processing a small section of the data base was corrupted, resulting in the loss of 6 TAs (4 Mode A, and 2 Mode C). The above analysis was therefore performed on the remaining data set of 197 TAs (70 Mode A, and 127 Mode C).

4.2.7 *Warning Times of Traffic Advisories*

The results of the operational trial for warning time, defined as the time from initiation of the TA to the time of CPA, are given in Fig. 4-8. A warning time of zero has been allocated to the 7 cases (1 Mode A and 6 Mode C) where the warning time was negative. A negative warning time is obtained when the TA is generated after CPA has occurred which can happen, for example, when the altitude test is not satisfied until late in the encounter.

Examination of the warning time histograms reveals a marked tendency for actual warning times to be shorter than the corresponding nominal value (τ) for the sensitivity level. Overall, the actual warning time was less than τ in 77% of encounters (70% of all Mode A events, 80% of all Mode C events). The differences between actual and nominal warning times are presented in Fig. 4-11. Overall the average difference was –8.2 seconds, the Mode A and Mode C warning times being an average of 6.5 and 9.1 seconds less than τ respectively.

It should be noted , however, that in 37 out of the 70 Mode A TAs (53%) and 14 out of the 127 Mode C events (11%), CPA was not observed by TCAS. In these instances the TA was foreshortened to some, unknown, extent due to track drop (cause unknown), artificially shortening the warning time. Eliminating these encounters affects only the proportion of Mode A encounters having warning times less than τ which reduces to 52%, lowering the overall proportion to 73%. The overall average difference between nominal and actual warning time also reduces from –8.2 to –6.4 seconds. For Mode C encounters, the average difference becomes –8.0 seconds but, more interestingly, the average difference for Mode A TAs reduces to only 1.2 seconds less than τ.

Further analysis of the data for the Mode C TAs gives an average difference between actual and nominal warning times of –3.1 seconds for the encounters where both aircraft were in level flight prior to and during the encounter (62 or 55%), and

−13.1 seconds for those where one or both aircraft were either climbing or descending (51 or 45%) – encounters for which CPA was not observed by TCAS were excluded from the analysis. The corresponding average values for horizontal separation at CPA were 1.85 NM and 2.19 NM respectively. Comparison of these figures illustrates the potential for the TA altitude test to reduce warning time.

The magnitude of the warning time deviations for the 62 Mode C encounters for which both the trials and intruder aircraft were in level flight, are plotted against the corresponding values of total separation at CPA on the scatter diagram in Fig. 4-9. Making due allowance for other variable factors, such as encounter geometry, the expected general increase in difference between the TCAS calculated and actual time to CPA with increasing separation at CPA is well illustrated in the results obtained. The four data points with disproportionately large time differences for the separations observed are due to reduction of relative velocity after TA initiation for the points labelled '1' and '2' (increased warning time), altitude test delay for point '3' (reduced warning time), and intruder manoeuvre (turning away) shortly after initiation of the TA for point '4' (reduced warning time). The corresponding scatter diagram for the remaining 51 Mode C encounters where one or both aircraft were either climbing or descending is given, for comparison, at Fig. 4-10.

During processing a small section of the data base was corrupted, resulting in the loss of 6 TAs (4 Mode A, and 2 Mode C). The above analyses were therefore performed on the remaining data set of 197 TAs (70 Mode A, and 127 Mode C).

4.2.8 *Duration of Traffic Advisories*

The results of the operational trial for TA duration are plotted by TCAS sensitivity level in Fig. 4-12.

The histograms indicate a predisposition for encounter durations as well as warning times to be shorter than the nominal warning time (τ). Overall, the duration of the TA was less than τ in 60% of encounters (60% of all Mode A encounters, 60% of all Mode C TAs). After elimination of the TAs for which CPA was not observed by TCAS (32 out of the 42 Mode A TAs (76%), 11 out of the 76 Mode C events (14%)) , this proportion drops to 52% (30% of all Mode A encounters, 58% of all Mode C TAs).

For 43 TAs (22%), the duration of the encounter was less than the warning time i.e. TCAS decided that the intruder no longer warranted a TA prior to CPA being reached. Of these events, 9 involved Mode A intruders (13% of all Mode A TAs) and 34 Mode C targets (27% of all Mode C TAs). For the Mode A events the TA duration was, on average, only 1.4 seconds less than the warning time. For the Mode C cases, however, the average difference was 8.4 seconds. In most Mode C cases (21 of the 34 TAs = 62%) own aircraft and/or the intruder were either climbing or descending. In the remaining 38%, both own aircraft and the intruder were in level flight prior to and following the TA.

During processing a small section of the data base was corrupted, resulting in the loss of 6 TAs (4 Mode A, and 2 Mode C). The above analyses were therefore performed on the remaining data set of 197 TAs (70 Mode A, and 127 Mode C).

4.2.9 *Slant Range of Intruder at Initiation of Traffic Advisories*

The results of the operational trial for the distribution of the slant range of the intruder at initiation of the TA are presented in Fig. 4-13.

The average slant range at TA initiation was 1.65 NM for Mode A intruders, and 5.49 NM for Mode C traffic. The slant range at TA initiation for Mode A intruders should be expected to be generally shorter due to the shorter warning times used (the RA τ value for the sensitivity level is used for Mode A threats) and also due to the typically lower airspeeds (and hence closing speeds) of Mode A equipped aircraft.

The slant range of the intruder can be used to provide some measure of its visual detectability. This aspect of the encounters is of interest as one of the first tasks the flight crew must perform on receipt of a TA is to attempt to visually locate the potential threat. The detectability of an aircraft is a complex function (see Reference 7) involving many variables for which no data is available from the trial. Assuming CAVOK conditions and daytime light level, and ignoring the effects of inherent contrast and target motion relative to the observer (ironically, a target on collision course remains in a fixed position on the windshield, reducing the probability of detection), detectability becomes primarily a function of apparent size and slant range. The apparent size of an aircraft is a function of actual size, shape, and orientation with respect to the observer. For the trial, all that is known in this respect is the type of intruder i.e. Mode A or Mode C equipped. Assuming a minimum detectable apparent target size of that subtending 5 minutes of arc at the observer, and effective visual areas of 13 m2 and 210 m2 for Mode A and Mode C intruders respectively, however, yields corresponding estimates of maximum slant range of 1.5 NM and 6.0 NM (discs of diameter 4 m and 16 m). The above areas are assumed to represent the average effective visual areas of typical Mode A (Cessna 172 fuselage length x depth at cockpit) and Mode C (average of B707, B727, B737, B747, and B757 fuselage length x diameter) intruders in broadside view.

Having assumed the above maximum slant ranges as the limit of reasonable probability of visually detecting typical Mode A and Mode C targets, an estimate of the proportion of intruders that would likely have been located at TA can be made. Inspection of the data reveals that, at TA, the slant range was 6.0 NM or less in 53% of Mode C encounters and 1.5 NM or less in 49% of Mode A events. Thus, it is estimated that there would have been a reasonable chance of the intruder being located in about half of all encounters. This aspect of the TA encounters is discussed further in relation to Mode C intruders in Section 4.2.10.

During processing a small section of the data base was corrupted, resulting in the loss of 6 TAs (4 Mode A, and 2 Mode C). The above analyses were therefore performed on the remaining data set of 197 TAs (70 Mode A, and 127 Mode C).

4.2.10 *Relative Bearing and Elevation of Intruder During Traffic Advisories*

The distribution of the relative bearing of intruders at TA and at CPA for both Mode A and Mode C encounters are given in Figs 4-14 and 4-15.

Although the majority of both Mode A and Mode C targets were located ahead of own aircraft at the time of initiation of the TA (77% Mode A and 71% Mode C within the relative bearing range ± 45°), the incidence of Mode C targets appears biassed to port (60% between zero and –90°, 31% between zero and +90°). Further analysis gives an average relative bearing at TA for Mode C encounters of –9.1°; an average value closer to zero was anticipated. The apparent shift in the data might indicate an installation error, an equipment design fault, or be symptomatic of the traffic patterns to which the trials aircraft was exposed. Assuming that the data follows a normal distribution, however, application of the two-tailed Z score test indicates that, given the standard deviation and size of the data sample, the apparent shift in the mean value is not statistically significant (Z score = 1.47).

At CPA, the distribution of Mode A and Mode C targets are quite dissimilar. Almost all (94%) of the Mode A targets are located between ± 135°, and are comparatively evenly distributed. The majority of Mode C targets appear between –45° and –135° (50%), and +45° and +135° (34%). As at TA, the distribution of the Mode C targets appears biassed to port. When reviewing the data for relative bearing at CPA it should be noted that the data given in Fig. 4-15 includes 28 of the 37 Mode A, and 8 of the 14 Mode C TAs for which CPA was not actually observed by TCAS.

The relative bearing of the intruder aircraft, derived from the directional antenna, is used by TCAS only in the construction of the traffic display picture. One of the functions of the traffic display is to assist and supplement the flight crew's visual look-out by locating proximate traffic and providing associated information. It is therefore of interest to examine the relative bearing and elevation of the target aircraft in the context of the cockpit reference vision polar diagram. The bearing and elevation of each Mode C event, at both initiation of the TA and at CPA, are plotted on the reference vision polar diagrams for the trials aircraft (B737-200) in Figs 4-16 to 4-19. The angle of elevation for each encounter (arcsine [vertical separation ÷ slant range]) has been modified to take account of own aircraft attitude (no bearing correction is required as the TCAS directional antenna is fixed to the aircraft axes).

Inspection of either Fig. 4-16 or 4-17 reveals a conspicuous lack of variability of intruder elevation at TA. Figs 4-18 and 4-19 illustrate the tendency for Mode C intruders to bunch around the relative bearings of +90 and –90 degrees at CPA. The two targets in the pilots' windshields are normal traffic, 978 ft and 1246 ft above own aircraft. It should be noted that the data plotted in Figs 4-18 and 4-19 includes 8 of the 14 Mode C TAs for which CPA was not actually observed by TCAS.

Table 4-1 has been compiled using Figs 4-16 and 4-17, together with the slant range data. From the Table it can be seen that on average, between the two pilots positions, the view of the intruder was impaired by cockpit visual cut-off and/or by a slant range in excess of 6.0 NM in 66% of encounters. It is interesting to note that cockpit visual cut-off alone would have impaired or prevented visual acquisition of the intruder in 32% of the sample of Mode C TAs (119), whereas range alone would have been a factor in 49% of them i.e in the sample obtained, the range of the target at TA appears to be a more significant factor affecting the ease with which a pilot might locate it visually.

During processing a small section of the data base was corrupted, resulting in the loss of 6 TAs (4 Mode A, and 2 Mode C). In addition, no bearing data was available for a further 8 Mode C encounters at TA, and 18 Mode A and 23 Mode C events at CPA. The above analyses were therefore performed on the remaining data set of 189 encounters (70 Mode A, and 119 Mode C) at TA, and 156 events (52 Mode A and 104 Mode C) at CPA.

4.3 Results From Ground Radar Recording

4.3.1 *General*

During the period of the operational trial, processing of ground radar surveillance data generated a total of 77 Mode C TAs. Of these, 43 could be correlated with TAs generated by the airborne trials equipment.

4.3.2 *Airborne TAs Not Recorded By Ground Radar*

One explanation for the absence of ground radar TAs for some of the airborne recorded TAs is that the trials aircraft was out of range of Debden radar. Using the criterion that a TA occurring more than 30 minutes from departure or arrival at Heathrow would be out of Debden radar coverage, it is estimated that the maximum number of correlated TAs that could possibly have been obtained was 64.

A second reason could have been that either the range test or the altitude test were only marginally passed on the aircraft, and not passed in the ground simulation. The possibility of this occurring is evident if the inevitable differences between the input data sets for the ground and airborne TCAS software versions are considered. Examination of the appropriate airborne records revealed this to be reasonable justification in 7 cases where ground radar TAs were not generated.

In the case of a further one airborne TA, both the trials aircraft and the intruder were at low altitude (around 300 ft) where there are a number of possible reasons for not obtaining a ground radar TA.

The remaining 13 events occurred during the period 27 January 1989 to 31 March. Due to ground equipment problems, no ground radar data was obtained on 19 February and incomplete data was obtained on 15 other days during this period. This may account for the absence of ground radar data in some or all of these instances. In addition, 9 TAs occurred during early March when the airborne recorder clock was not functioning correctly. Hence, for these events, the possibility also exists that the aircraft was out of ground radar range.

4.3.3 *Ground Radar TAs Not Recorded by Airborne Equipment*

Of the 77 ground radar TAs obtained, corresponding airborne TAs were not generated in 34 instances. In 14 cases, airborne TAs were not to be expected as they occurred when the airborne equipment (TCAS itself and/or the data recorder) was known to be unserviceable. Data recorder disc overflow and/or general disc problems accounted for the lack of a further 5 TAs. In 4 instances the aircraft was being used for crew training during which time the equipment would have been unlikely to have been switched on. It is also suspected that the equipment may have been switched off in an additional 10 cases during the period 15 May 1989 to 23 June 1989 – see Table 3-2. In the case of the remaining ground radar TA, the altitude test was only marginally passed (by less than 1 foot!) on the ground, and might reasonably be assumed to have only marginally failed in the air.

4.3.4 *Geographical Distribution of Advisories*

The availability of ground radar data for many of the encounters enabled them to be geographically located and might have contributed to identifying areas where TCAS could cause particular problems to ATC. In the event, the number of TAs observed during the trial was not adequate for this purpose. A study of the geographical distribution of TAs in the London TMA based on a considerably larger quantity ground radar data has, however, been conducted – see Appendix 4.

The locations of the ground radar TAs are, nevertheless, given in Fig. 4-20 for interest. The TAs which occurred within the boundaries of the London TMA area (73%) are also presented on an expanded scale in Fig. 4-21. It is interesting to note the concentrations of encounters in the Lamborne (LAM) and Ockham (OCK) holding areas; the predisposition for TCAS TAs to be generated in holding areas is also illustrated in the diagram given in Appendix 4.

Review of the trials aircraft's inbound routings during the trial (LAM 47%, OCK 28%, BNN 17%, and BIG 8%), suggests a tendency for the occurrence of TAs in any particular holding area to be more or less in proportion to the frequency of usage (ultimately time spent in the holding area). No particular significance is therefore attached to the greater incidence of TAs in the Lamborne and Ockham holding areas as opposed to Bovingdon and Biggin.

4.4 Comparison of Airborne and Ground Radar Data

4.4.1 *General*

Precise correlation between the airborne and ground radar derived results is not to be expected due to the differences in the characteristics of the input data sources. The intruder range data obtained from ground surveillance radar is derived from comparatively small differences between large quantities. It is therefore likely to be less accurate than that produced by the airborne system which measures intruder range directly. The ground radar data is also artificially smoothed by the process of interpolating between the data points, needed to compensate for its lower sampling rate (see Section 4.1.2). The airborne system, however, can suffer from degraded surveillance due to antenna shielding in certain encounter geometries. Ground radar does not suffer from this phenomenon. Imperfections such as these can have a significant effect on the behaviour of TCAS, and due account must be taken of this in assessing the results of any comparison performed.

The purpose of performing the comparisons is, however, to attempt to demonstrate that the techniques used for the modelling of TCAS behaviour using ground radar data are sufficiently sound as to produce valid results for studies employing large sample sizes. Accurate modelling of individual encounters cannot be performed reliably.

4.4.2 *Certification Flight Trials*

Two comparisons of the airborne and ground radar data (Clee Hill station) obtained from the flight trials conducted at Aberporth have already been performed, and are documented in References 1 and 5. Both papers report that the airborne and ground radar derived results were generally in broad agreement. The differences observed were, for the most part, considered to be attributable to the dissimilarities in the characteristics of the input data sources for the airborne and ground based TCAS implementations.

4.4.3 *Operational Flight Trials*

For the operational flight trials data, the exercise of comparing ground and airborne derived results is confined to the TAs, owing to the very small RA sample size available (only two RAs occurred within range of the ground radar stations used).

The ground and airborne generated encounters were subjected to a qualitative comparison during the process of pairing the TAs, and were generally found to be in good accord. In order to determine the degree of correlation in quantitative terms, however, the differences between the ground and airborne derived values for the relative positions of the trials and intruder aircraft at TA and at CPA, and the time interval between TA and CPA (warning time), were analysed. The results are presented in terms of average absolute differences, and as average percentages of the corresponding airborne values in Table 4-2. The relative positions of the aircraft at CPA and the warning times for the 8 correlated TA pairs, for which CPA was not observed by the airborne system, were excluded from the analysis. Ground radar data for horizontal separation at CPA was unavailable for a another two encounter pairs, and insufficient ground radar data was available to determine the warning time in a further 5 cases.

The distributions of the differences between the ground radar and airborne derived values are plotted as percentages of their corresponding airborne values in Fig. 4-22. Examining each of the 29 encounters for which all the compared parameters were available individually, all ground radar values were within 10% of the airborne data in 12 cases (41.4%), and only one parameter differed by more than 10% in a further 7 cases (24.1%). Two parameters varied by more than 10% in another 6 encounters (20.7%), three differed by more than 10% in another 2 and, for the remaining 2 encounters, four of the parameters were more than 10% adrift from the airborne values.

5 EVENTS OF INTEREST

5.1 General

Due to the paucity of RAs and the nature of the few that were recorded during the operational trials, events of any significant interest are confined essentially to the certification trials performed at Aberporth.

5.2 Increase Rate RA (Aberporth I & II)

In order to examine the effects of delayed pilot response to an RA, a head on (separated laterally by 3000 ft, and vertically by 100 ft) encounter was staged. The RA instructions were to be deliberately ignored until the 'increased rate' command was received (encounter no. 7 in Table 3-1). As anticipated, an 'increase rate' RA was generated but, in spite of a correct pilot response, it was too late to achieve a significant increase in vertical separation at closest approach.

Subsequent analysis revealed that the logic assumes that the standard 1500 ft/min escape rate has been achieved, and uses a set of somewhat arbitary conditions (see Reference 2, Section 7.4.4.4.1.1) to establish that this is proving inadequate. The basis upon which an increased rate is prescribed thus appears not to be adequate for all situations in which it might be expected to be invoked.

This encounter served to illustrate the consequences of the initial RA warning being missed where, were it not for the precautionary lateral separation introduced for the trial, it was judged that the aircraft would have come dangerously close to each other. It was considered that it was possible for the initial RA auditory warning to be 'blocked' by other flight deck audio.

5.3 Climb Inhibit RA (Aberporth I & II)

In order to illustrate the operation of the climb inhibit logic, a head on encounter (*intruder 300 ft below*) was flown. The equipped aircraft was at FL 220 with the climb inhibit threshold set to FL 220 (encounter no. 14 in Table 3-1). In spite of the fact that the actual vertical separation during the encounter was only 200 ft, *a descend RA was generated*. Examination of the TCAS logic for this situation establishes, however, that when climb is inhibited, a descend RA will be generated if it is estimated that at least 100 ft more vertical separation would be achieved than by issue of a don't descend command (the only alternative in this case). Repeating the experiment on the ground using an encounter generator to establish the desired geometry exactly, did result in a don't descend RA being produced. Reducing the horizontal miss distance from 0.33 NM to 0.3 NM, however, caused a descend RA to be generated.

This behaviour, which is counter-intuitive, is in accordance with TCAS's operating precepts. As the horizontal miss distance is reduced, estimates of apparent time to CPA and miss distance improve, which can result in changes to the way in which TCAS reacts to a given scenario. The point of interest here is that, although TCAS produces the correct result in each case according to its precepts, the outcome is not always what a flight crew might expect.

5.4 Effects of Altitude Quantisation (Aberporth II)

The possible effects of the quantisation of the intruder's altitude as reported in its Mode C replies, are well illustrated by the airborne data recorded for encounter no. 5, executed during the Aberporth II trials. The plots for this encounter are reproduced in Fig. 5-1. Here, the altitude level transition at TCUR = 23 seconds causes TCAS to adjust its estimate of the intruder's altitude rate, and declare a low confidence in this rate. This causes the RA to be delayed, in this case until the absence of any further transitions permits restoration of confidence in the intruder's altitude rate. (Unlike other situations in which an RA is delayed (see Reference 2), a low confidence delay is unbounded). The RA is finally issued at TCUR = 28 seconds, 3 seconds after both the range and altitude tests have been satisfied.

5.5 Disruptive RA (Aberporth III)

A possible disbenefit of the introduction of TCAS is the disruption to the flow of air traffic that could be caused by unwanted TCAS generated traffic deviations. An earlier study of the disruptive nature of TCAS II (see Reference 3), using ground radar data processed though the TCAS II Change 6 model, had illustrated the possibility of RAs being generated by aircraft crossing in altitude in spite of there being proper (3NM) horizontal separation. This scenario was investigated as part of the Aberporth III trial (encounter no. 15 – see Section 3.5.4). The encounter was performed successfully and a don't descend/climb/don't descend RA sequence was generated, demonstrating the potential for such events to occur and the severity of their effects (see Fig. 5-2).

The issue of an RA under such circumstances, where horizontal separation standards are maintained, is clearly superfluous and can only serve to increase the ATC workload. The rate at which this particular RA scenario might be expected to occur has not been estimated. The study described in Reference 3, however, indicates that, taking account of all types of disruptive RAs, over the three sectors studied (one terminal area, two en-route) a rate of one disruptive RA per day could be expected. The Reference also suggests that this particular type of disruptive RA would be expected to be more prevalent in certain sectors adjacent to terminal areas where a substantial portion of the traffic is climbing or descending.

It could be argued that the speeds involved (400 kt TAS for each aircraft) are more representative of the en-route environment where lateral radar separation standards are more likely to be 5 NM rather than the 3 NM used for the encounter. Current NATS plans, however, are to extend the areas of UK airspace where 3 NM separation can be used. The situation reproduced at Aberporth could therefore become more common.

6 CONCLUSIONS

6.1 General

In TCAS terms, the quantity of data collected during the trial is recognised to be comparatively small. Great care has therefore been taken in analysing the results to try to avoid reading too much into the data. Nonetheless, some significant and obvious trends have been identified.

Sub sections 6.2 and 6.3 describe the main features of the RA and TA data, respectively. The remaining sub sections discuss the implications of TCAS as they may affect aircraft operators, UK ATC providers, and the Safety Regulation Group of the UK CAA.

6.2 Resolution Advisories

As only a low number of RAs were observed during the operational trial, it is not considered prudent to attempt to draw any conclusions in respect of this aspect of TCAS operation.

The certification flight trials performed at Aberporth, however, did illustrate the potential complexity of the RA selection and generation process. While subsequent data analysis did confirm the proper functioning of TCAS within its precepts in all cases, the behaviour of TCAS in some situations did give rise to some puzzlement on the flight deck. It is quite possible that in some circumstances (e.g. where there is no obvious threat) an operating flight crew may well be tempted to ignore, or delay responding to, the RA.

6.3 Traffic Advisories

6.3.1 *Traffic Advisory Rate and Validity*

The TA rate observed of 1 in 2.1 flight hours was very high. Furthermore, at 95%, the proportion of TAs where the advisory was not considered to be helpful was excessive.

In 95% of all Mode C events, the normal ATC standard of 3 NM horizontal separation and 1000 ft vertical separation was not transgressed to any significant extent. Although this assertion can only be applied with any degree of confidence to the encounters with Mode C equipped traffic, the performance of TCAS in discriminating between real threats and normally separated traffic is not improved by the absence of altitude data in the case of Mode A intruders. Moreover, since the altitude test is by-passed, the incidence of unwanted TAs is expected to be higher with Mode A threats.

(Section 4.2.5).

6.3.2 *Vertical Distribution of Traffic Advisories*

The vertical distribution of TAs observed indicates a predisposition for TAs to be generated at lower altitudes, and for the proportion of TAs involving Mode A intruders to increase with reducing altitude. 94% of all Mode A TAs, and 54% of all Mode C TAs (69% of all TAs) occurred while the trials aircraft was below FL100.

The vertical distribution of Mode A encounters observed is considered commensurate with the vertical distribution of Mode A traffic. The potential for TAs to be generated in holding areas has been noted and this may, in part, also account for the distribution observed.

(Sections 4.2.6 and 4.3.4).

6.3.3 *Warning Time and Duration of Traffic Advisories*

Warning times were less than the nominal warning time threshold value (τ) in 77% of encounters and were, on average, 8.2 seconds shorter. TA durations, similarly, were frequently and significantly shorter than τ.

Variations about τ are to be expected due to the nature of the range and altitude data thresholds used to generate TAs, and manoeuvres after initiation of the TA. TA warning times and durations can be affected by either or both aircraft changing heading, altitude, vertical speed, or horizontal speed.

For Mode A TAs, CPA was not observed by TCAS in 65% of encounters to which a warning time less than τ was attributed. Elimination of those encounters from the data yields an average difference between nominal and actual warning time of only −1.2 seconds. Track drop is therefore considered to be the most likely cause of the bias in the Mode A results.

For the Mode C encounters, further analysis of the warning time data illustrated the effects of differences between the TCAS calculated and actual time to CPA, and/or the delay that can result when the timing is controlled by the TA altitude test. These effects appear to have been exacerbated by intruder manoeuvres and, possibly, by the truncation of recorded data.

(Sections 4.2.7 and 4.2.8).

6.3.4 *Surveillance of Mode A Intruders*

The frequency of occurrence of track drop with Mode A intruders observed in the trials data, at 53% (37), is considered to be unacceptably high.

For Mode C encounters, CPA was not observed by TCAS in only 11% (13) of events. The marked difference in the rate of incidence of track drop between Mode A and Mode C encounters suggests that the tracking performance of TCAS with Mode A targets may be deficient in some way.

6.3.5 *Visual Detectability of Intruders*

The estimations made of visual detectability demonstrate that, even assuming CAVOK conditions, in the majority of encounters (60%) it is unlikely that the intruder could have been visually detected by the flight crew.

One of the stated main functions of the TCAS traffic display is to aid visual acquisition of proximate traffic. It is estimated that visual acquisition of Mode A intruders at TA initiation would have been impaired due to excessive slant range alone in 51% of the 70 events. No account of cockpit visual cut off can be taken in the case of Mode A TAs, owing to the lack of relative altitude data and hence intruder elevation.

For the Mode C TA sample analysed (119 Mode C TAs) detection of the intruder would have been expected to have been impaired to some degree in 66% of encounters, due either to the magnitude of its slant range from the TCAS equipped aircraft, or by cockpit visual cut off.

It could be contended that TCAS would have improved the flight crew's surveillance in drawing their attention to traffic that they would not otherwise have been likely to notice. Alternatively, as the majority of TAs were considered to be unhelpful, it could be ventured that on a need to know basis the information provided by TCAS was mostly redundant.

(Sections 4.2.9 and 4.2.10).

6.3.6 *Relative Bearing of Intruders at Initiation of Traffic Advisories*

The relative bearing data obtained from the trial indicates that the majority of TAs (73%) were generated by intruders located ahead (within ± 45°) of the trials aircraft.

This characteristic of the encounters is in accord with expectations since relative velocity, and hence probablity of exceeding TA thresholds, is likely to be higher when the intruder is ahead of own aircraft. The apparent bias in the data for Mode C intruders of 9.1° to port was found to be statistically insignificant.

(Section 4.2.10).

6.3.7 *Modelling of TCAS Behaviour Using Ground Radar Data*

The comparisons made between the ground and airborne derived TCAS II data have confirmed the validity of the use of computer simulation techniques employing ground radar data.

The two existing studies of the certification trials data, documented in References 1 and 5, both report good agreement between the ground radar and airborne derived results. No further analysis of this data has been attempted.

Although the operational trial produced fewer than hoped for correlated ground radar and airborne generated TAs (about 33% of total), good reason for their absence was identified in all cases. Where correlated ground radar and airborne encounters were obtained, the overall degree of correlation observed was generally good. Although the average difference in horizontal separation at CPA of 19% may appear significant, it should be noted that it represents an average difference of only 150 metres! It is also worth noting that the accuracy of the correlation in individual events was generally much better than might have been expected, given the differences in the characteristics of the data sources.

(Section 4.4.3).

6.4 Implications for Airlines

6.4.1 *Nuisance Traffic Advisories*

The aspect of TCAS behaviour which is likely to have the most significant impact on airline use of the system is the high proportion of TAs that occur in unremarkable circumstances. The trials data indicates that the majority of TAs should be expected to occur at lower altitudes where crew workload is usually already high. The trials data also suggests that in most instances the task of intruder location and identification would not have been trivial. More than being a mere nuisance, therefore, the additional workload imposed by the occurrence of unwanted TAs is considered to represent a distraction to the flight crew which could be hazardous in some situations. In particular, the high incidence of nuisance TAs will detract from the flight crew confidence in the system necessary for it to be effective; a repeat of the experience of the introduction of GPWS is not wanted!

(Section 4.2.6)

6.4.2 *Mode A Traffic Advisories*

It is worth noting that the mid-air collisions that helped precipitate the legislation in the USA involved typical general aviation type aircraft in conflict with commercial jet transports, since this type of aircraft comprises the majority of Mode A traffic. Where Mode A intruders are concerned, TCAS is at its worst in discriminating between genuine threats and normal traffic and, apparently, in reliably tracking targets. Furthermore, in contrast to encounters with Mode C traffic, TCAS is unable to provide resolution advisories against Mode A threats. Visual acquisition or some other means of identification and monitoring of the intruder is therefore imperative. The foregoing implies that different flight deck procedures for dealing with Mode A threats may be appropriate.

6.4.3 *Training*

TCAS has demonstrated a potential for generating encounter resolutions that, although correct, may be at odds with that which a flight crew might intuitively expect. In the event of an encounter with a real threat, any delay in the response of the flight crew to an RA could seriously degrade the protection afforded by the system. For TCAS to be effective, therefore, it is imperative that flight crews have confidence in the system and fully understand its operating precepts and the full range of its behaviour. Consideration should therefore be given to ensuring that training programmes take due account of the human factors aspects of the introduction and operation of TCAS.

(Section 5.3).

6.5 Implications for ATC

The major impact of TCAS on ATC operations is likely to be the potential disruption to traffic patterns caused by RAs, which has already been addressed elsewhere. The trials data indicates, however, that the flight crew will experience some difficulty in visually acquiring the majority of TA generating threats. This may lead to an increase in RT activity as aircraft seek additional information from ATC on the relative position and intent of intruders. The increase in controller workload and in the use of RT channels might be considered a regrettable but worthwhile consequence of the introduction of TCAS; however the trials data also indicates that the majority of TAs are likely to occur in routine circumstances when controllers, themselves, may be busy.

(Section 6.3.1 and 6.3.5).

6.6 Implications for Safety Regulation Group (UK CAA)

6.6.1 *Carriage of TCAS*

From the limited exposure to TCAS II gained during the trials, it is clear that considerably more operational experience of the system would be required prior to contemplating the issue of a recommendation to require its carriage on UK registered aircraft. In addition, it is likely that further development of the system will be required to achieve a satisfactory standard of performance.

6.6.2 *Transponder Fit*

The results of the operational trial suggest that the adequacy of the performance and functioning of TCAS in relation to Mode A equipped aircraft is not commensurate with the risk of collision with such traffic. Should the installation and use of TCAS in UK airspace be mandated, serious consideration would need to be given to the continued acceptability of the use of Mode A transponders. A revision of the requirements for the carriage of Mode C transponders may be appropriate in certain circumstances.

7 RECOMMENDATIONS

7.1 General

On the basis of the analysis of the ground and airborne data from the trial, and the experience gained during the trials, the following recommendations are made.

7.2 Resolution Advisories

No recommendations are made in respect of this aspect of TCAS operation due to the low number of RAs observed during the operational trial.

7.3 Traffic Advisories

7.3.1 *Modification of the TA Altitude Test*

Subject to confirmation of freedom from undue adverse effects by testing with a data base of appropriate size, the TA altitude threshold be reduced from 1200 ft to a value less than the standard ATC vertical separation.

The TCAS TA vertical separation threshold is currently set at 1200 ft for all sensitivity levels. Consequently, normal Mode C traffic separated by a nominal 1000 ft has only to pass the range test in order to generate a TA. The results of the operational trial have confirmed the potential for traffic normally separated in altitude to generate TAs.

(Sections 4.2.5 and 6.3.1).

7.3.2 *Investigation of Surveillance of Mode A Intruders*

Further testing and investigation be carried out to determine the adequacy of the performance of TCAS in tracking Mode A equipped targets.

The data from the operational trial suggests that a significant proportion (37%) of TAs can be expected to be generated by Mode A intruders. The performance of TCAS exhibited during the trial is not considered to be of an appropriate standard for the anticipated level of exposure to Mode A traffic.

(Section 6.3.4).

7.3.3 *Computer Simulation of TCAS Behaviour Using Ground Radar Data*

It is recommended that computer simulation using ground radar data be performed to supplement any operational trials to benefit from the more meaningful sample size available. Furthermore, in the absence of the resources required for conducting an operational trial, it is recommended that computer simulation using ground radar data be considered as an alternative.

A need to analyse TCAS behaviour as it may affect the UK ATC system and UK flight crews is expected to remain for the foreseeable future. Development and refinement of the TCAS II logic continues, to be followed, eventually, by TCAS III. The practicalities involved with conducting operational trials necessarily constrain the size of data sample obtainable, and the number of times that such experiments can be repeated. The effort required to perform the same studies using modelling techniques and existing ground radar data bases is at least an order of magnitude lower, and the resulting sample size at least an order of magnitude higher.

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Table 3-1 Certification Flight Trials - List of Encounters Flown

Scenario	Type	Vertical Behaviour of Intruder (BAe 125)	Comments
1	Altimeter calibration	Intruder formates on B737 at same level with lateral separation of 300ft.	Calibration for Scenarios 2 to 12.
2	Tail chase	Intruder overtakes (IAS 270KT) 300ft below and with lateral separation of 300ft.	Illustrates surveillance performance under adverse conditions. RA not to be followed.
3	Tail chase	Intruder overtakes initially 600ft below and reduces vertical separation at under 1000ft / min to 300ft when B737 receives an RA.	Demonstrates slow development of TA and RA with possible surveillance problems. RAs to be followed.
4	Tail chase	Intruder overtakes initially 600ft above and reduces vertical separation at under 1000ft / min to 300ft when B737 receives an RA	Same as Scenario 3 except intruder above rather than below so there should be fewer surveillance problems. RAs to be followed.
5	Head on	Intruder level, 300ft below.	RA to be followed.
6	Head on	Intruder level, 300ft above.	RA to be followed.
7	Head on	Intruder level, 100ft above.	RA not to be followed until 'increase rate' command received. Illustrates the effect of delayed pilot response.
8	Head on	Intruder descending from above at 3000ft / min, projected to cross in altitude before closest approach to give a vertical miss distance of -300ft but levelling off 1000ft above.	Illustrates the beneficial effect of the 'altitude separation test' which delays RAs until an altitude crossing before closest approach geometry seems more certain. RA, if any, to be followed.
9	Head on, apparent altitude crossing	Intruder descending from above at 3000ft / min, projected to cross in altitude after closest approach to give a vertical miss distance of 300ft but levelling off 1000ft above.	Illustrates that the 'altitude separation test' does not delay the issue of an RA in these circumstances. RA to be followed.
10	Head on, apparent altitude crossing	Intruder descending from above at 3000ft / min, projected to cross in altitude before closest approach to give a vertical miss distance of -300ft but levelling off 800ft above.	Illustrates override of the altitude separation test by late level off followed by the requirement for a sense reversal. RAs to be followed.
11	Head on, altitude crossing	Intruder descending from above at 1000ft / min to cross in altitude before closest approach with an along-track separation of 0.1NM when at co-altitude.	Illustrates performance when an intruder does cross in altitude. RA to be followed.
12	Head on, altitude crossing	Intruder level. Equipped aircraft climbs from below at 1000ft / min to cross in altitude before closest approach with an along-track separation of 0.1NM when at co-altitude.	Illustrates performance when the equipped aircraft is crossing in altitude. RA to be followed.
13	Altimeter calibration	Intruder formates on B737 at same level (FL 220) with lateral separation of 300ft	Re-calibration for Scenario 14.
14 (a) & (b)	Head on	Intruder level at (a) 300ft, (b) 100ft below equipped aircraft at FL220 with the TCAS 'climb inhibit' threshold set to FL 220.	Illustrates the operation of the climb-inhibit logic.
15	Head on	Intruder level at FL180, 400kt TAS. Equipped aircraft descends from above at 3000ft/min, 400kt TAS, to pass 200ft below intruder at CPA.	Illustrates the possible disruptive effects of TCAS.

Table 3-2 Operational Flight Trials - Summary of Significant Events

Period	Event	Comments
24 Jan - 14 Mar	Scheduled operation with TCAS in record-only mode.	Some disc and/or recorder problems resulted in data gaps. First RA recorded on approach to Newcastle. Recorder clock began to show large error in early March so that date and position of second RA could not be determined. Third and last recorded RA obtained on approach to London (Heathrow).
15 Mar	TCAS processor removed for re-programming by the manufacturer.	This was done to bring the logic into line with recent changes - up to the draft MOPS of 22 February 1989, in fact.
19 Mar	Aberporth I.	Trial appeared to be fairly successful at the time although there were intermittent display failures and 'clear of conflict' was not always announced. No data was recorded on the aircraft although ground radar data was obtained (Clee Hill).
20 Mar - 08 May	Equipment returned to the manufacturer for testing and repair.	As far as is known, no specific fault was found.
09 May - 13 May	Scheduled operation with TCAS in record-only mode.	No problems apparent during this period.
14 May	Aberporth II.	Highly successful trial as far as invoking the desired type of RA was concerned, and obtaning airborne recordings. However, several display faults occurred leading to 'TCAS fail' annunciations.
15 May - 23 Jun	Scheduled operation with TCAS in record-only mode.	During this period the modified electronic IVSIs were removed for investigation of what was now seen to be an interface problem. TCAS could still function correctly in the record-only mode as long as the fully-operational mode was not selected. Thus the inadvertant selection of the latter mode would result in a 'TCAS fail' indication as a result of the absence of the IVSI. Several intervals where no data was obtained may have been as a result of this or, as is more likely, faulty discs or other hardware problems.
24 Jun - 09 Aug	TCAS out of action as result of Mode S transponder fault.	There was no spare Mode S transponder.
10 Aug - 13 Aug	Scheduled operation with TCAS in record-only mode.	It is thought that the IVSI interface problem had been resolved by this time and that the instruments had been replaced. The Mode S transponder problem had been fixed.
14 Aug - 11 Sep	Aircraft in the hangar for wing root modification.	This event was known about before the trial started. It was initially expected that the trial would have been finished by now.

Table 3-2 (Continued)

Period	Event	Comments
12 Sep - 18 Sep	Scheduled operation with TCAS in record-only mode.	Probably owing to a period of two days continous service in W Germany, the discs were not changed on schedule and some data was lost during this period.
19 Sep	Aberporth III.	A re-run of a subset of the encounters investigated on the two previous occasions in order to confirm that the IVSI problem was cured. The trial was successful and recorded data was obtained.
19 Sep - 18 Oct	Scheduled operation with TCAS in record-only mode.	After Aberporth III the final phase of the trial was not immediately embarked upon because of certification problems. Data recording was reasonably successful although there were still disc problems from time to time.
18 Oct - 12 Nov	TCAS out of action as result of Mode S transponder fault.	During this period it was decided that, when repaired, the equipment could not be certified for normal use by the flight crew but it could be certificated for use in the TA-only mode. This would enable some experience of the TA display to be obtained. Any RAs that might have occured would still be obtained from the recordings.
13 Nov - 25 Nov	Scheduled operation with TCAS in TA-only mode.	The first week was apparently quite successful but no recordings were obtained. The discs, if there were any on the aircraft at the time, could not be located. A pair of discs alleged to have been installed on 17 Nov and removed on 25 Nov yielded no useful data. During this latter period the equipment began to fail intermittently with increasing frequency.

Table 4-1 Breakdown Of TA Generating Targets With Respect To Cockpit Visual Cut-Off And Estimated Detectability

TA Generating Target Details		Number of Events		Average	
Location on Flight Deck Windows	Slant Range	Captain	First Officer	Number	% (Sample = 119)
Fully Visible	<= 6.0NM	44	37	40.5	34
	> 6.0NM	38	42	40	34
Partially Visible (Within Area of Monocular Obscuration)	<= 6.0NM	7	13	10	8
	> 6.0NM	20	15	17.5	15
Totally Obscured (Due to Cockpit Cut-Off)	<= 6.0NM	10	11	10.5	9
	> 6.0NM	0	1	0.5	0

Table 4-2 Operational Flight Trials - Average Differences Between Ground And Airborne Derived Separation At TA And CPA, And Warning Time

Parameter	Sample Size	Average Magnitude Of Difference Between Ground And Airborne Derived Values	
		% Of Airborne Value	Absolute Difference (NM/ft/sec)
Horizontal Separation at TA	43	12.64	0.41
Vertical Separation at TA	43	9.12	77.84
Horizontal Separation at CPA	33	18.69	0.079
Vertical Separation at CPA	35	3.98	41.71
Warning Time	30	13.62	2.83

Figure 2-1 TCAS Trials System Architecture

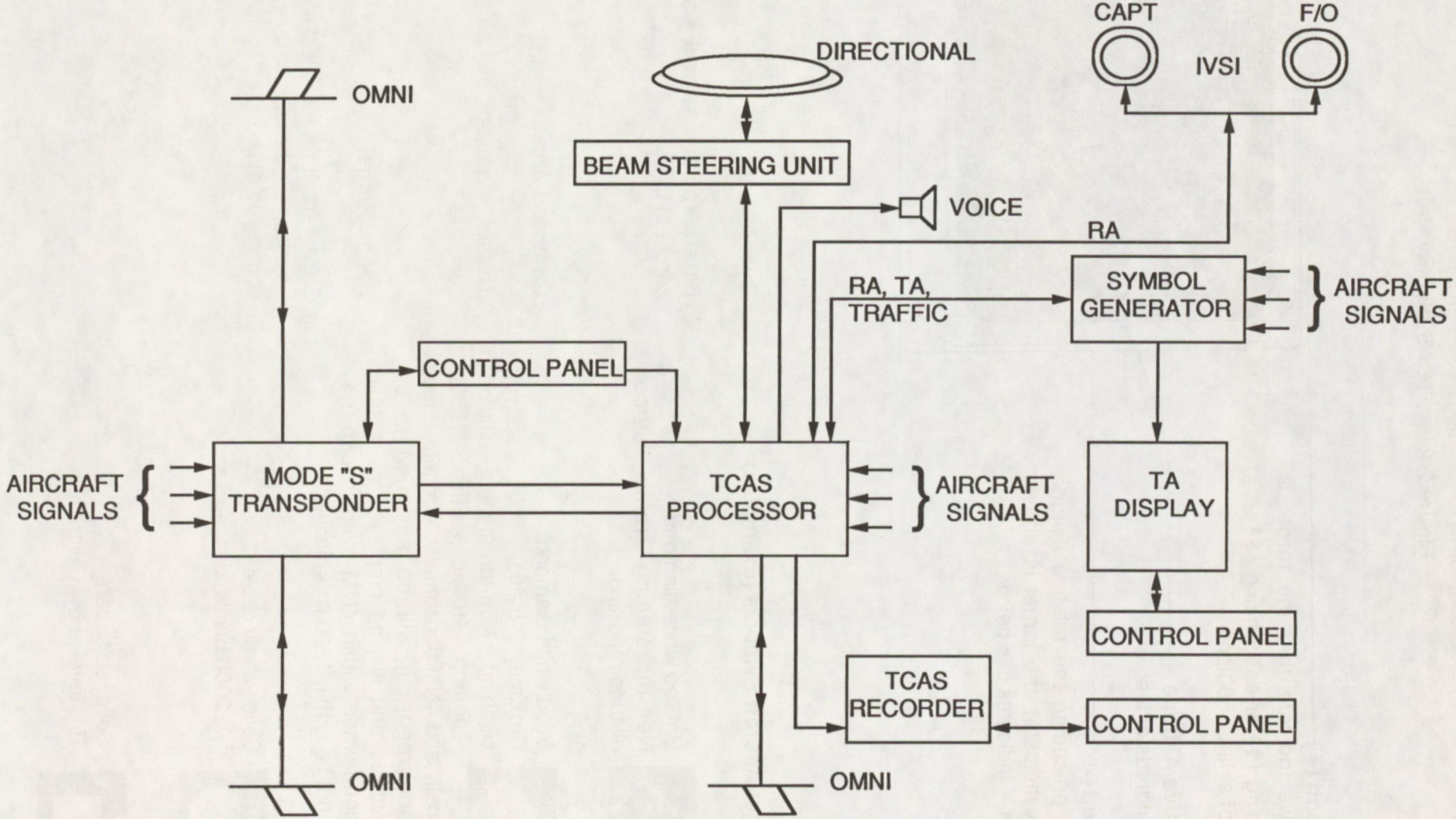
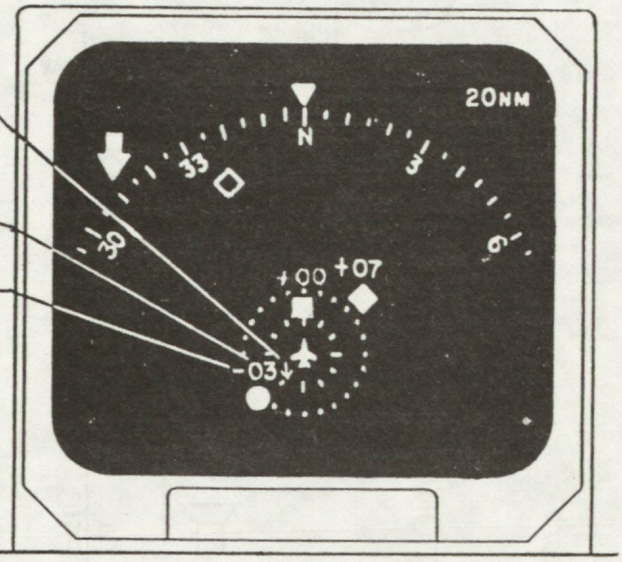


Figure 2-2 TCAS DIsplay Unit

(↑) and (↓)
Arrows indicate that the target is climbing (↑) or descending (↓) at a rate of at least 500fpm.

Relative Altitude
In hundreds of feet.

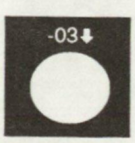
(+) and (-)
A '+' preceding the relative altitude block indicates the target is above, and a '-' indicates it is below.



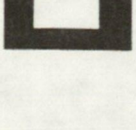
Target Aircraft Symbols (Examples)

Unfilled white diamond.
Non-threatening traffic without altitude reporting.

Solid white diamond.
Proximity traffic 700ft above, climbing. Non-threatening, altitude reporting traffic within 1200ft vertically and 4NM horizontally. Aircraft without altitude reporting will be assumed to be co-altitude and will be displayed as a solid diamond when within 4NM even though they may not be within 1200 ft vertically.



Solid yellow circle
TA, 300ft below, descending.



Solid red square
RA, level at own altitude.

Own Aircraft

Blue aeroplane symbol just below centre of CRT.

Compass Arc

This arc is a repeat of the Captain's compass.

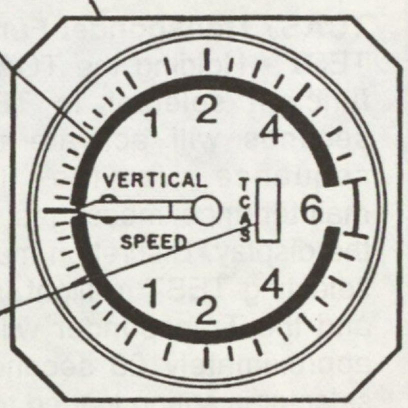
Range Rings

3NM - small ring with ticks at clock positions. 5NM - large ring composed of dots.

Figure 2-3 TCAS VSIs

Instantaneous Vertical Speed Indicator
Indicates vertical speed in feet per minute.

Eyebrow Lights
Eyebrow lights are not visible until illuminated for a TCAS resolution advisory or a system test. When illuminated, the green lights indicate the desired vertical speed range and the red lights the vertical speed range to be avoided to ensure safe traffic separation.



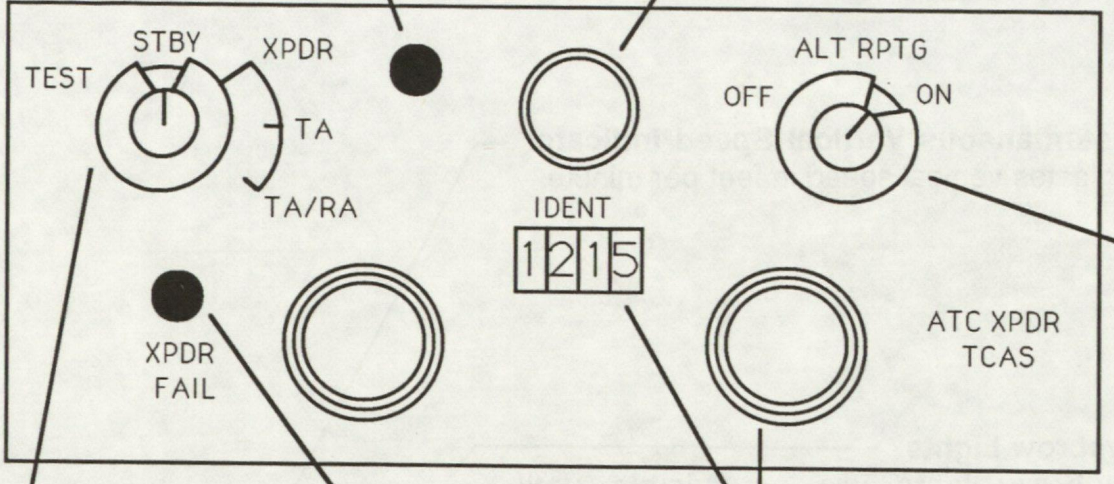
IVSI Status Window Flags
BLACK - Normal operation.

RED FLAG - Indicates TCAS information unusable.

YELLOW 'RA OFF' FLAG - Always displayed when TCAS/Transponder function selector is in STBY or TA. Will also be displayed with selector in TA/RA if RAs are inhibited and/or inoperative.

NOTE
The IVSI function of the instrument operates independently of the TCAS eyebrow lights and status window flags.

Figure 2-4 TCAS / Mode S Transponder Control Panel



TCAS / Transponder Function Selector
TEST - Holding the TCAS / Transponder function selector in TEST for 2 to 3 seconds will activate the system test sequence. In the TEST position, maintenance messages may be read on the display. Discretion must be used when selecting TEST in flight, since both TCAS and the Transponder will be inhibited for approximately 20 seconds. The function selector is spring loaded to STBY.

STBY - Activates TCAS and XPDR warm-up cycles.

XPDR - Transponder is on. TCAS is in warm-up cycle.

TA - Transponder is on. Only the traffic advisory, or TA, function of TCAS is on. No resolution advisories will be recieved in this position. The written warning 'TA ONLY' will appear on the display, and the yellow 'RA OFF' flag will be in view on both IVSIs.

TA / RA - Transponder is on. All TCAS functions are on. No TCAS flags should be present on either IVSI.

Warning Light (Amber)
Indicates both transponders are on.

ALT RPTG Selector
Provides automatic altitude reporting to ATC.

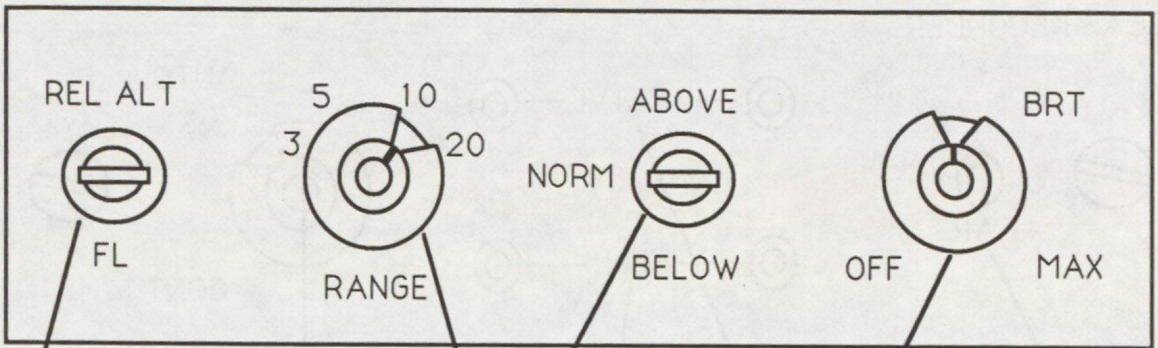
IDENT Button
Causes the word IDENT to flash in the aircraft data block on the ATC display.

Code Selectors
Select the transponder code. Left and right selectors consist of a large knob and a small knob. Each controls one digit of the code.

Code Indicator
Indicates code selected using the code selectors.

XPDR FAIL Light (Red)
Indicates a transponder system failure when the transponder is on. Illuminates during 'TEST' but goes off after approximately 3 seconds if the transponder is OK.

Figure 2-5 TCAS DIsplay Unit Control Panel



Paddle Switch REL ALT/FL Switch

REL ALT - Paddle Switch is spring loaded to the centre position. Display shows REL ALT in hundreds of feet above (+) or below (-) own aircraft.

FL - Momentary contact allows display of traffic flight levels, referenced to 29.92 in Hg (1013.25 mB), for 15 seconds. Own FL is displayed in lower left corner. Three digits are shown, except for negative flight levels which are shown as -XX (example -03 is negative 300ft).

TCAS Range

The compass arc is always set at range selected by the range knob. Ranges of 3, 5, 10 or 20NM are selectable.

BRT Knob

Controls brightness of the display.

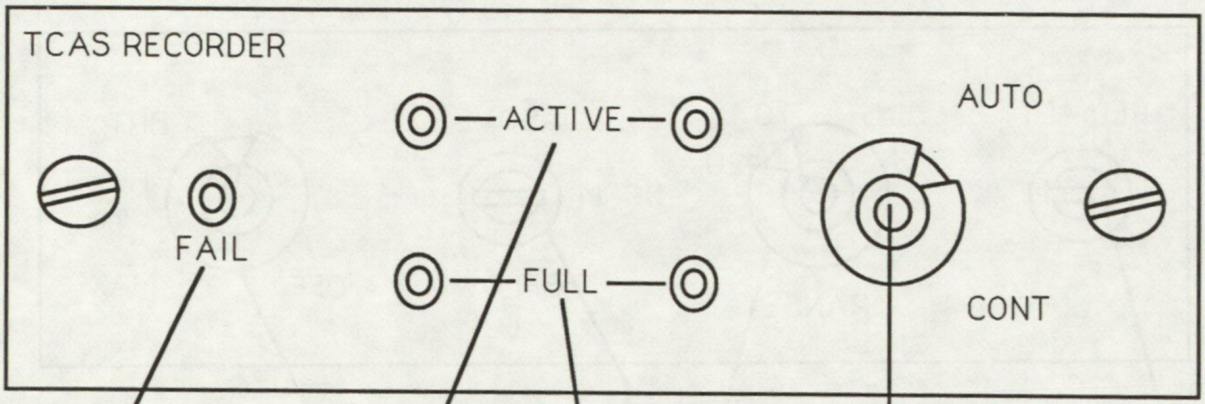
ABOVE NORM BELOW Switch

ABOVE - Displays altitude reporting traffic from 2700 feet below to 7000 feet above.

NORM - Displays all altitude reporting traffic from 2700 feet below to 2700 feet above.

BELOW - Displays all altitude reporting traffic from 2700 feet above to 7000 feet below.

Figure 2-6 TCAS Recorder Control Panel



FAIL Light (Red)
Indicates a TCAS Recorder failure condition.

ACTIVE Lights (Green)
Indicate associated disk drive is powered, selected, and ready to record when lighted steady green. Flashing green indicates that data is being recorded on the associated disk drive.

AUTO/CONT Switch

AUTO - selects automatic record mode. In this mode TCAS data is only recorded when an event trigger is received from the TCAS processor.

CONT - selects continuous record mode. In this mode TCAS data is recorded on a continuous basis.

FULL Lights (Amber)
Indicate all recording space on asociated disk has been filled.

Figure 2-7 Trials Equipment Installation - General Arrangement

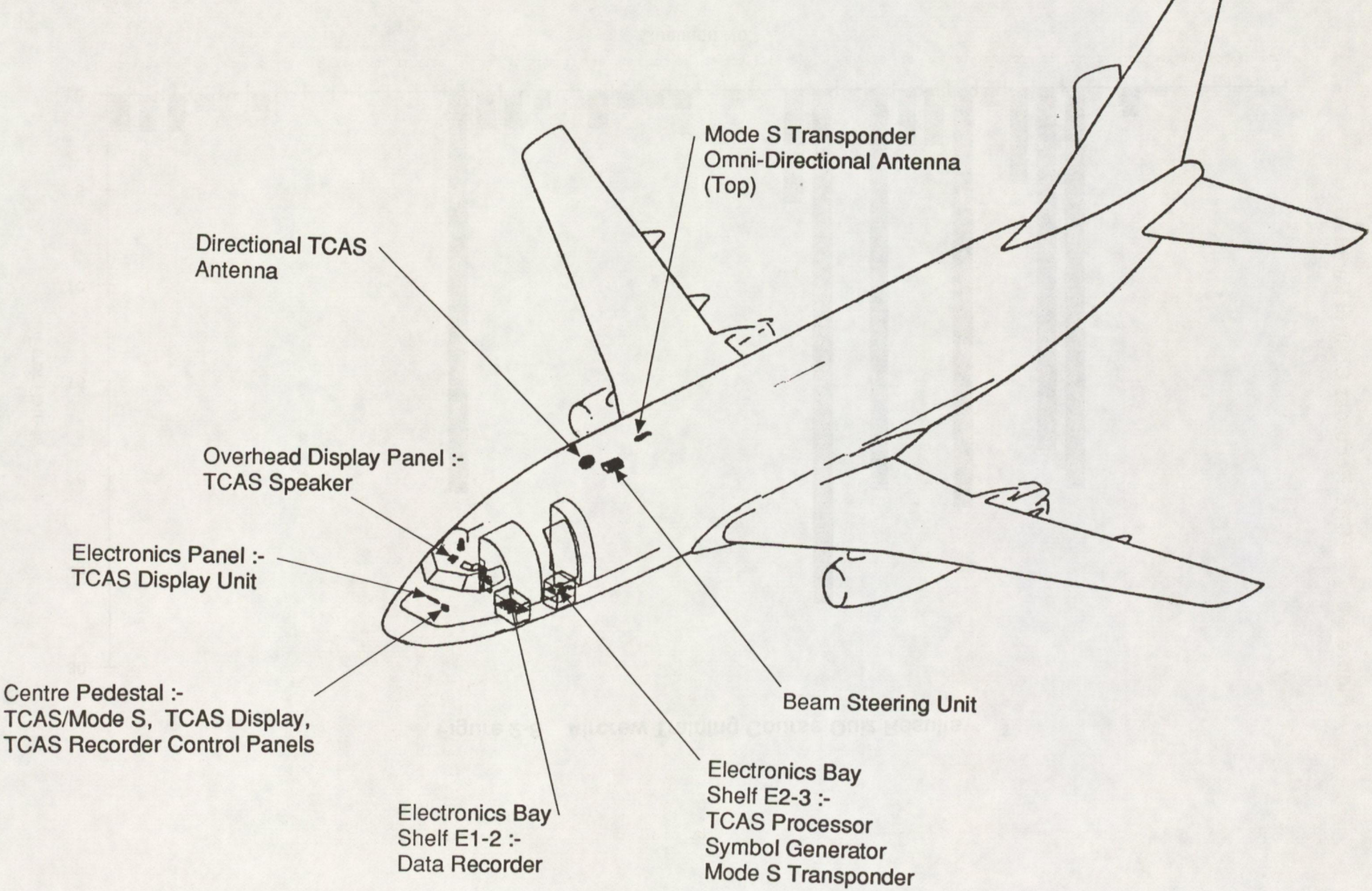


Figure 2-8 Aircrew Training Course Quiz Results

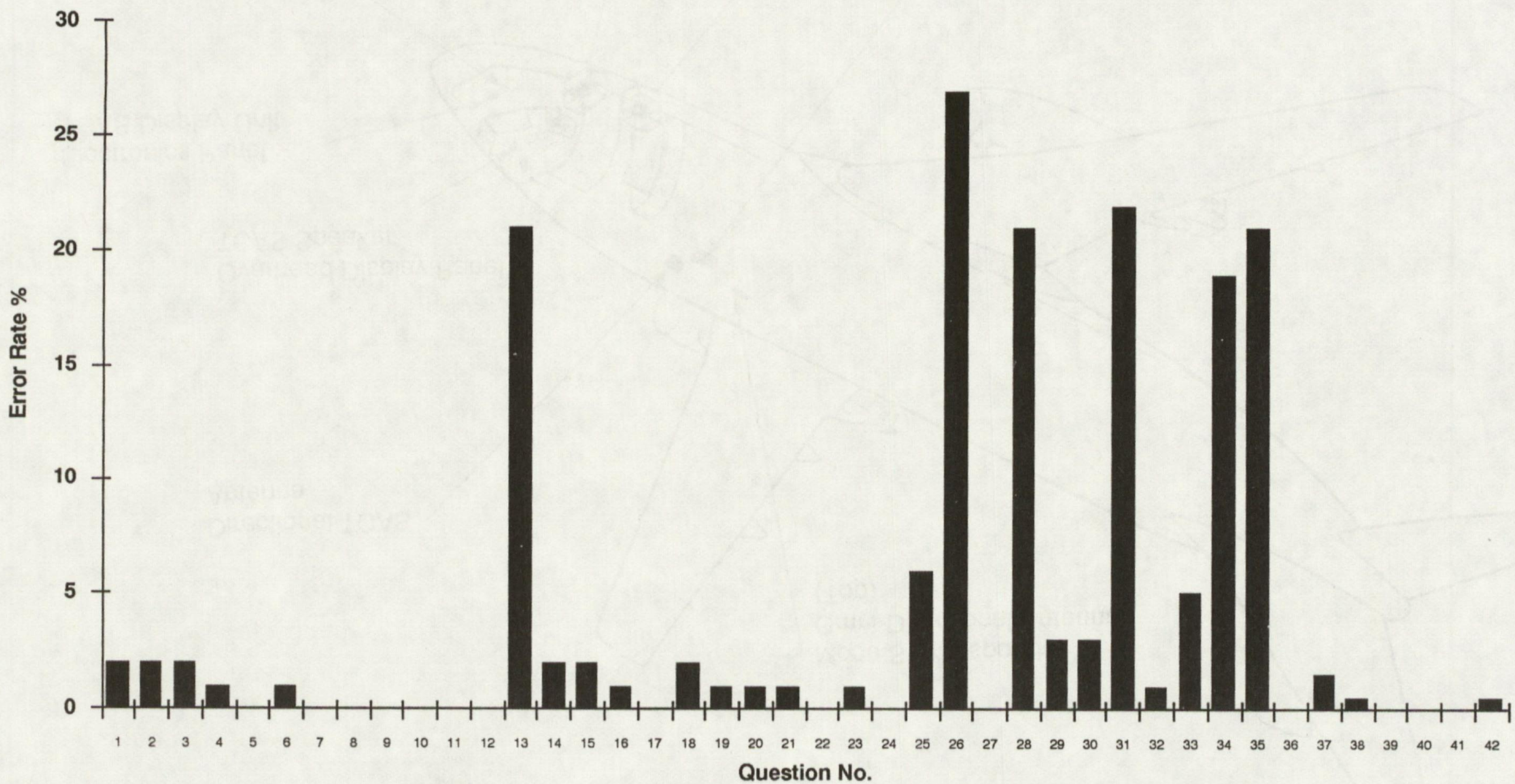


Figure 3-1 Aircrew Questionnaire

Please add any comments on TCAS generally

TCAS II OPERATIONAL TRIAL

LINE PILOT'S QUESTIONNAIRE

- - - - - - - -

Captain...

1st Officer...

Observer...

Airborne Time (UTC)...

Landing Time (UTC)...

SSR Code in UK Airspace...

Do you have any previous experience of TCAS?...

Please send this form to:

MR A FISHER
FLIGHT TECHNICAL OFFICER
S(326)
TECHNICAL BLOCK A
BRITISH AIRWAYS
HEATHROW

Comments on Traffic Display to be completed regardless of advisories

Circle Y or N

1. Was the symbology easy to read? Y/N
2. Were there occasions when the display became cluttered? Y/N
3. Did the relative bearing appear to be accurate? Y/N
4. Did the display become seductive to the extent of diverting your attention from other tasks? Y/N
5. Did you find the range selection useful? Y/N
6. Did you find the altitude band selection useful Y/N
7. Did you at any time change the display to show absolute rather than relative altitude? Y/N

Please amplify your comments if you wish:

Traffic Advisory Details

	1st TA	2nd TA
1. Did the intruder symbol include a relative altitude? enter Y or N	☐	☐
2. Time TA rec'd (if no observer)	....	....
3. Flight Conditions IMC or VMC	....	....
4. Was the TA: enter a,b or c — a) Useful b) Necessary c) Nuisance	☐	☐
5. Was the TA useful in visually acquiring the intruder? enter Y or N	☐	☐
6. Did you make visual contact with the intruder? enter Y or N	☐	☐
7. Did you talk to ATC as a result? Y or N	☐	☐
8. If so, to which Control Authority?	....	....
9. Had there been a TA in the previous enter a,b or c — a) 2 mins b) 5 mins c) > 5 mins	☐	☐
10. Was the aural warning enter a,b or c — a) too loud b) too soft c) about right	☐	☐

Please fill out an additional sheet if more than two TA's were received

Please amplify your comments if you wish:

Resolution Advisory Details — **Circle Y or N**

1. Was there a preceding TA? Y or N
2. Based on the TA, was the RA expected? Y or N
3. Was the RA a) preventive ? Enter a or b b) corrective ? ☐
4. If corrective, did you follow the RA? Y or N
5. If not, give reasons overleaf
6. If corrective, give any height gain/loss ....
7. Was the ISVI display suitable for guidance? Y or N
8. Was the RA timely? Y or N
9. Did you see the intruder: Enter a,b or c a) before, b) after the RA or c) not at all? ☐
10. Flight conditions IMC or VMC ....
11. Was the audio warning enter a,b or c — a) too loud b) too soft c) about right ☐
12. Was the audio warning intelligible? Y or N
13. Did the audio warning make it clear what manoeuvre was expected? Y or N
14. If you manoeuvred, do you think either passenger safety or comfort was affected? Y or N

Please amplify your comments if you wish:

PTO

Figure 3-2 Observer Questionnaire

TCAS OBSERVER REPORT FORM

DATE: / /

FLT No: BA

Sector

Captain

Observer

XPDR

Event: TA / RA

Time: Z

Own A/C prior event

Speed

Bank: ° L/R

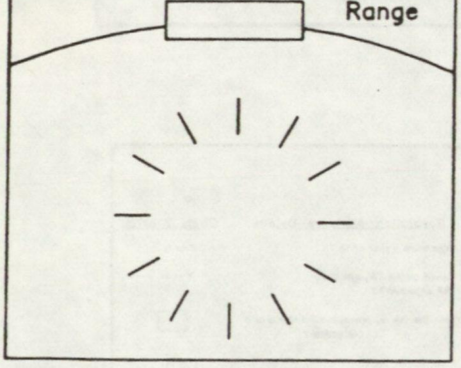
Flt Level/Alt

Vert Speed: ±

NO BRG

HEADING

Range



Intruder: Mode A / Mode C

Miss Distance

– at co.alt: nm

– at CPA: nm

ft

RA (indicate sequence)

CLB	CLB x CLB	CLB NOW	INC CLB
DES	DES x DES	DES NOW	INC DES
REDUCE V/S	MAINT V/S	V/S REST	

SEQUENCE OF EVENTS

ATC Advisory	1	2	3	4	None
TA	1	2	3	4	None
RA	1	2	3	4	None
Visual Contact	1	2	3	4	None

Response to RA

ft/m	CLB	DES	LEVEL

If originally level: max/min / Fl alt reached

FLIGHT PHASE

SID	CLB	CRZ
DES	HOLD	APP

FLIGHT CONDITIONS

VMC	IMC	DAY	NIGHT

AIRSPACE

TMR	TRANS	EN-ROUTE

LOCATION

VOR	Rad	DME nm

ATC Frequency in use: .

Was Intruder a threat to safe operation? Yes / No

Was there any conflict between TCAS and ATC? Yes / No

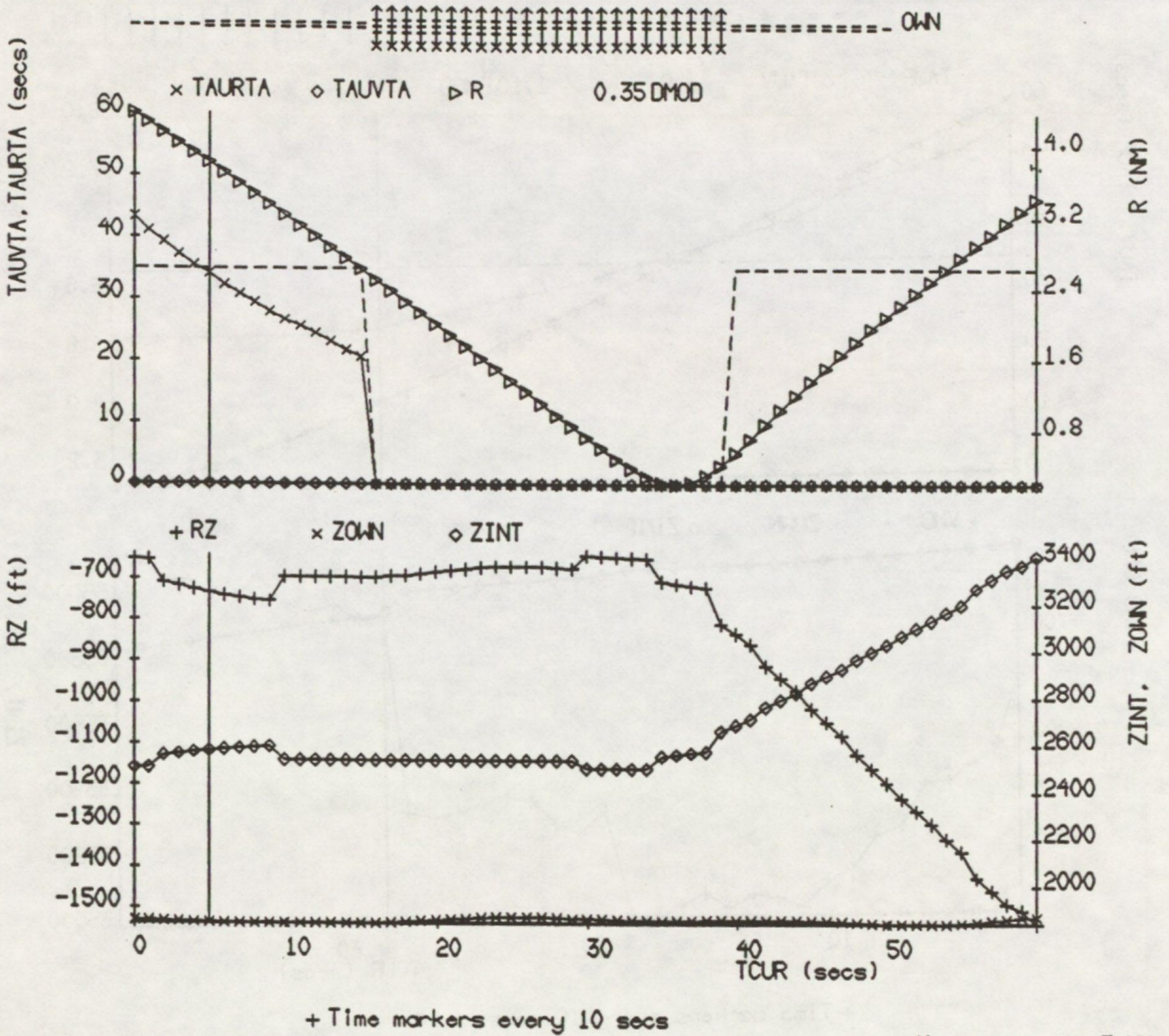
Was advisory :–

Genuinely needed	helpful/informative
nuisance	misleading

Did RA increase seperation? Yes / No

Comments

Figure 4-1 Reprocessed Airborne TCAS Data for Newcastle RA



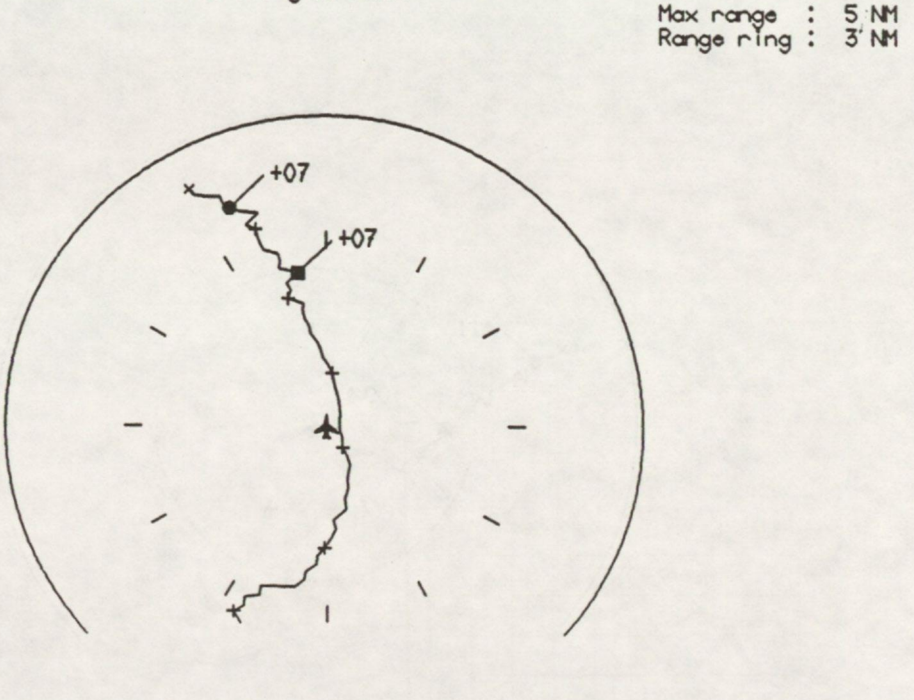


Figure 4-2 Reprocessed Airborne TCAS Data for RA In Cruise

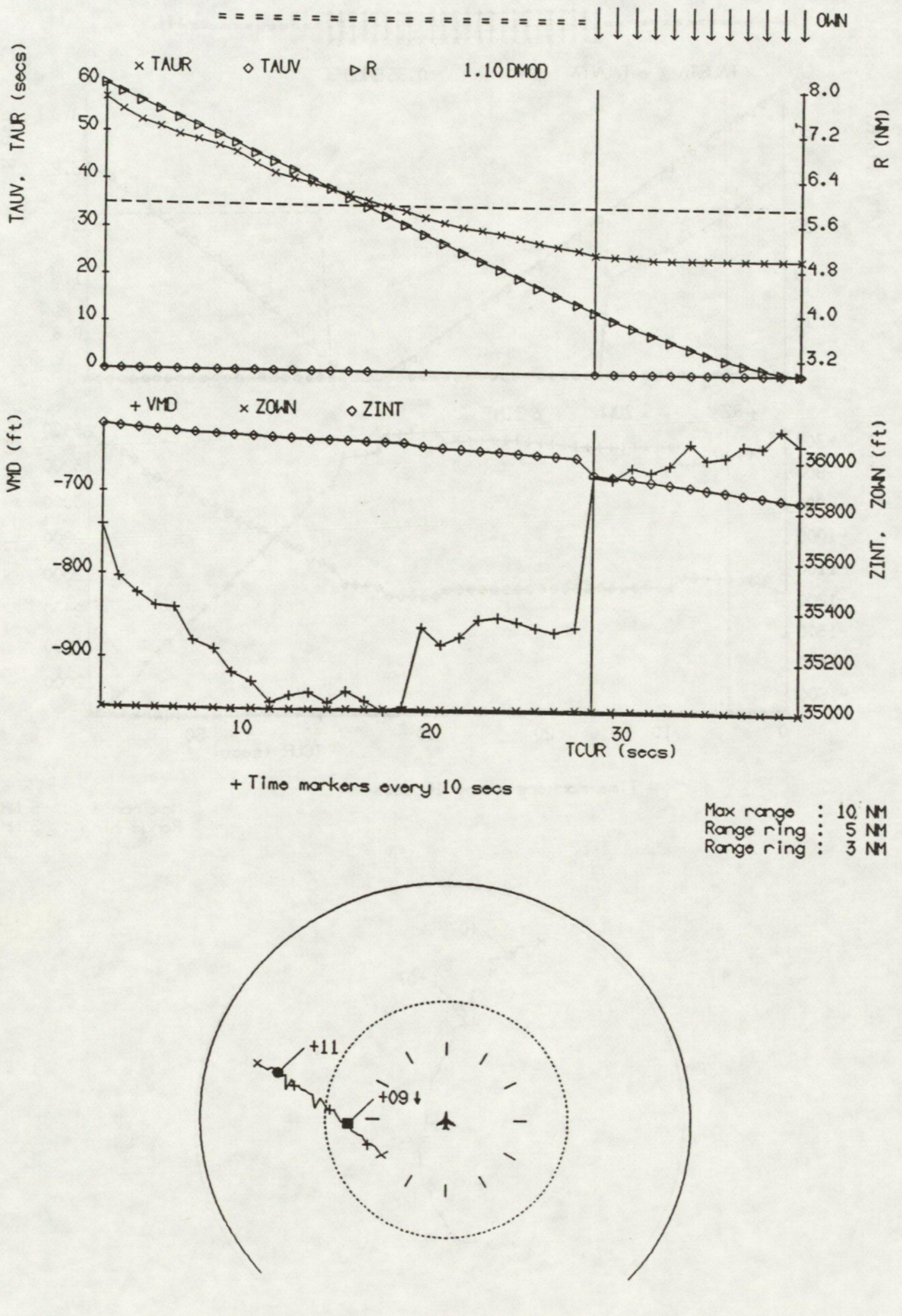


Figure 4-3 Reprocessed Airborne TCAS Data for Heathrow RA

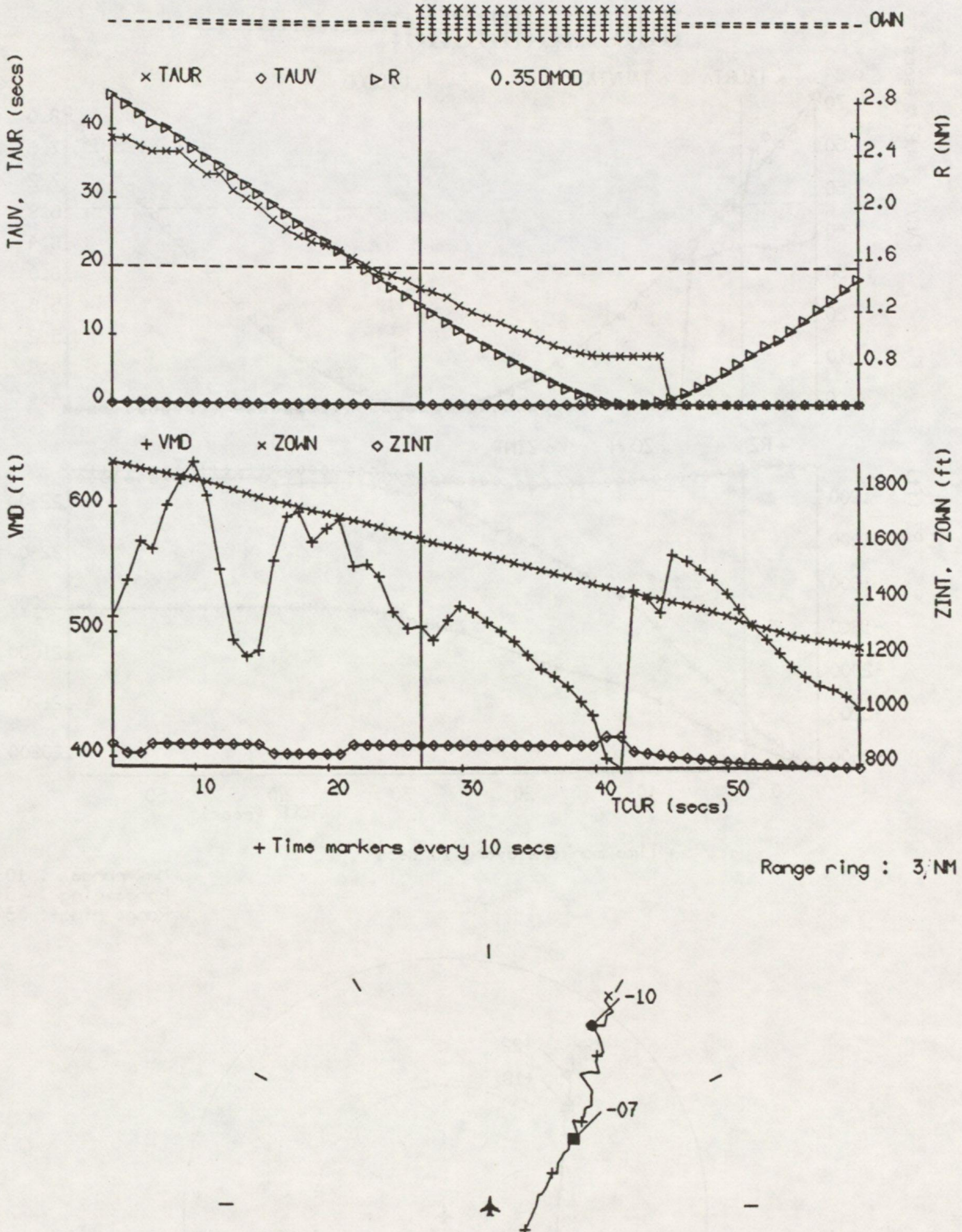
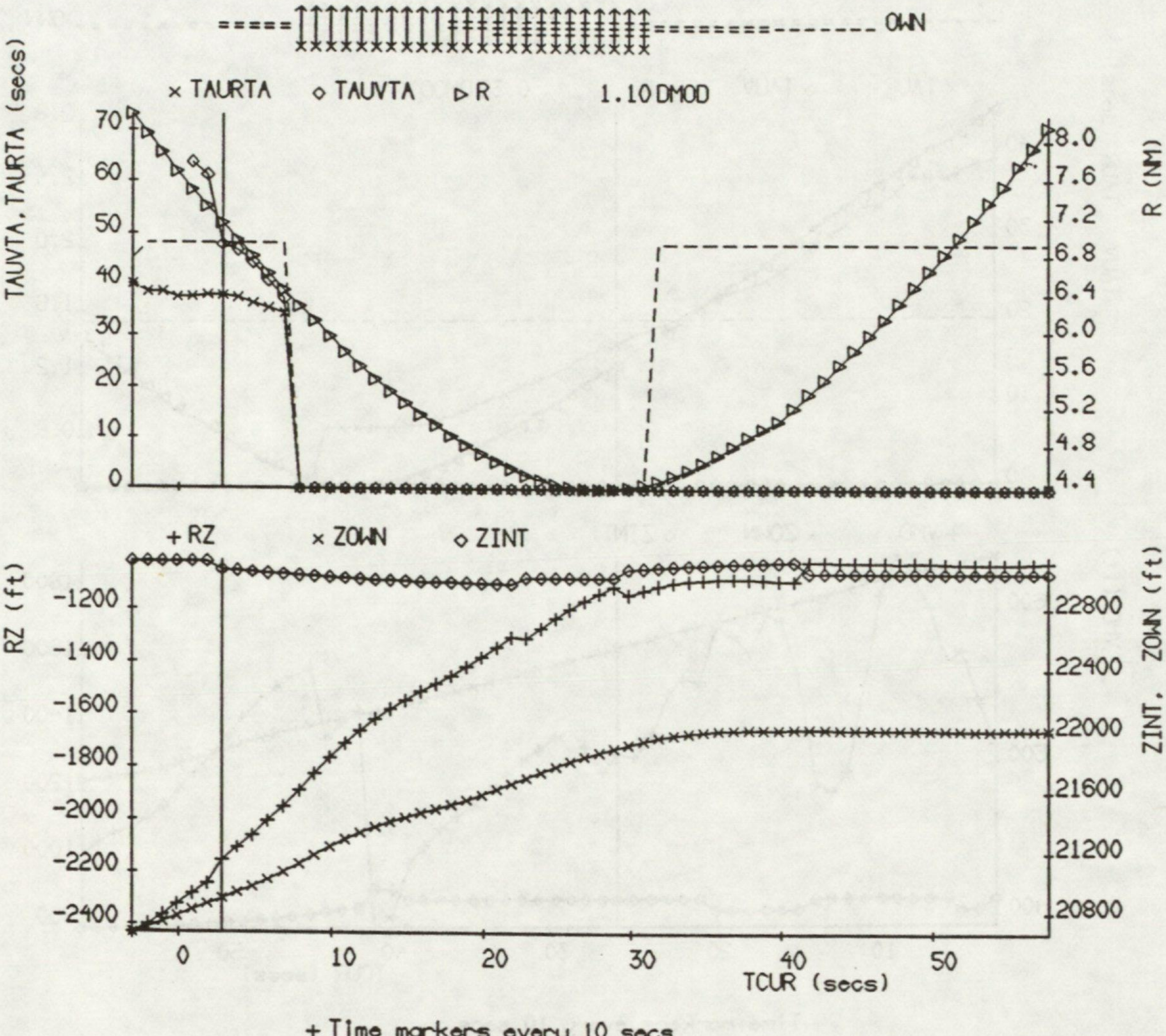


Figure 4-4 RA Obtained by Reprocessed Airborne TCAS Data Through the FAATC Model



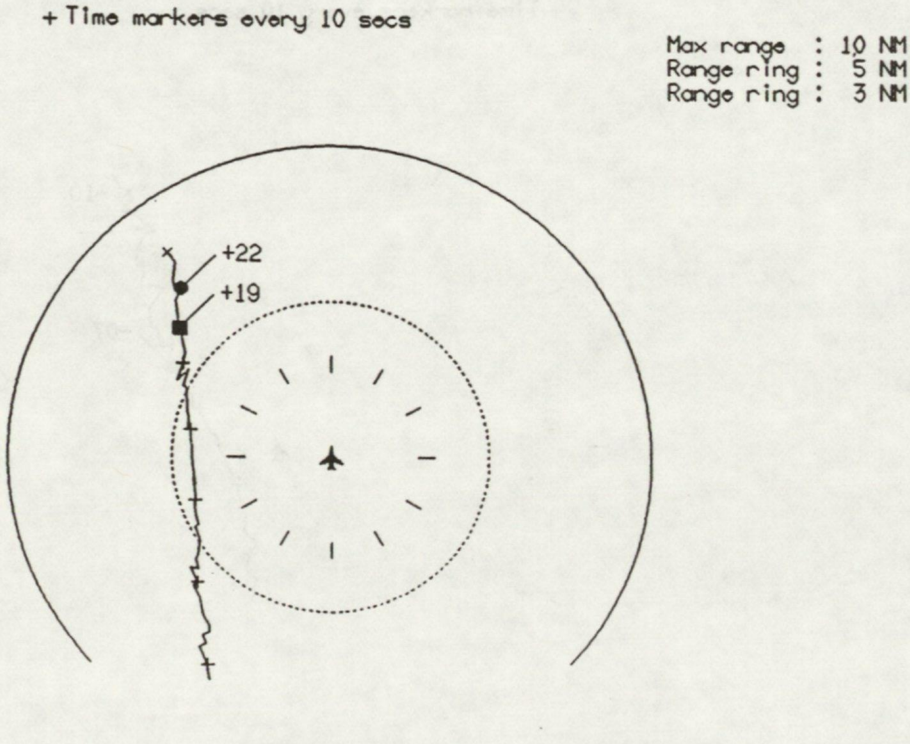


Figure 4-5 Scatter Diagram for Separation at Initiation of Advisory (All Mode C TAs)

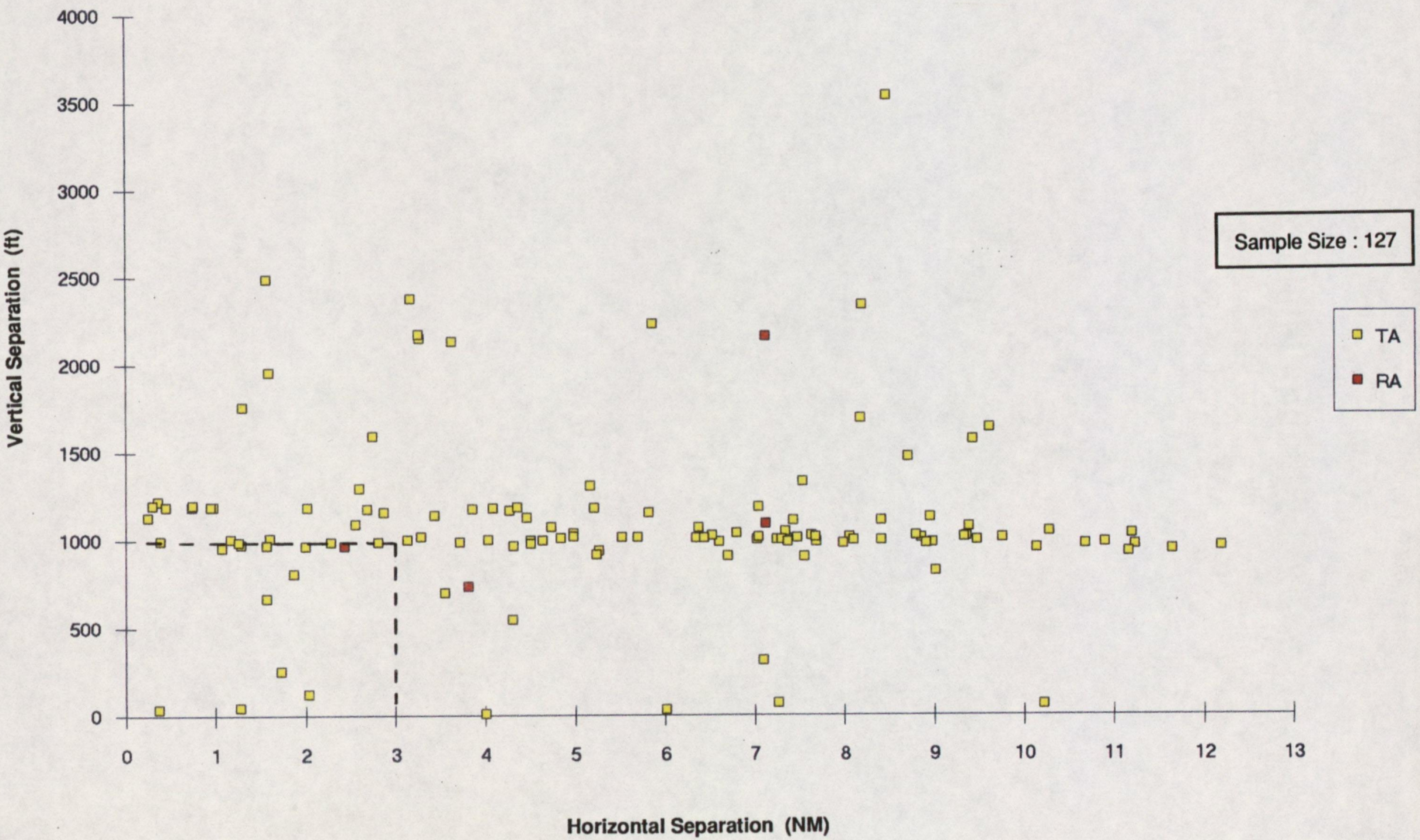


Figure 4-6 Scatter Diagram for Separation at CPA (all Mode C TAs for which CPA was observed)

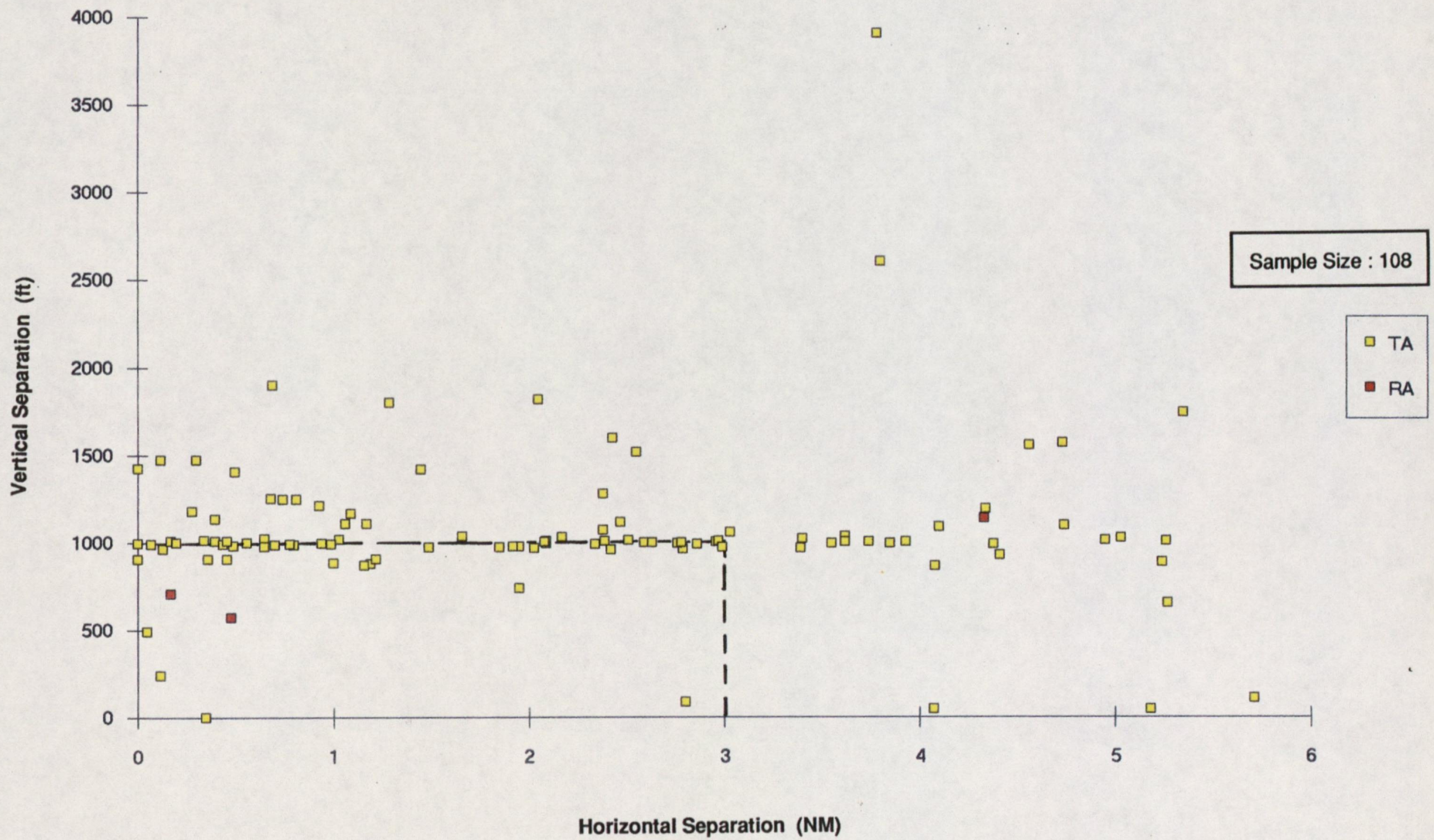


Figure 4-7 Distribution of Trials Aircraft Altitude at Initiation of TA

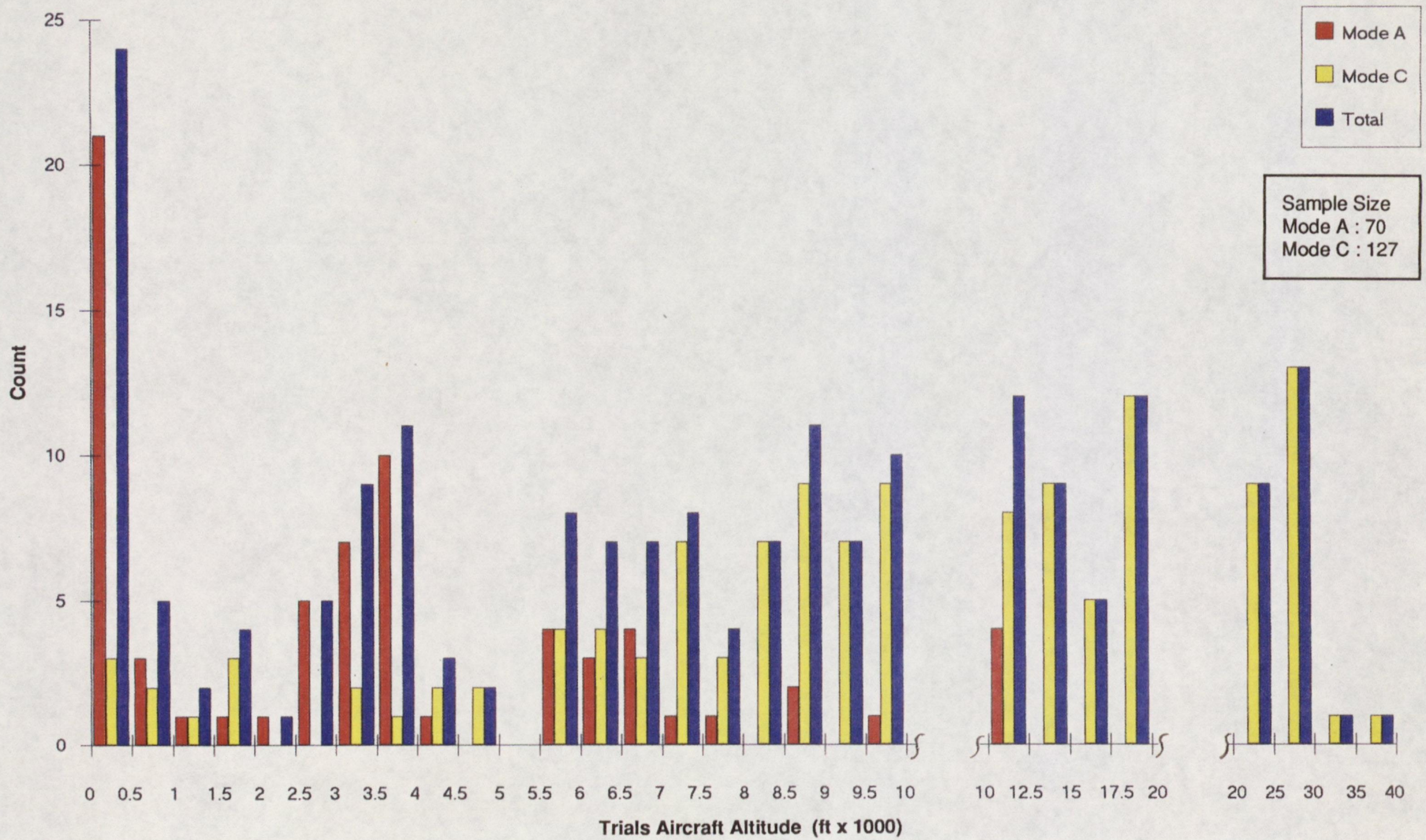


Figure 4-8(a) Distribution of Warning Time - Mode A TAs

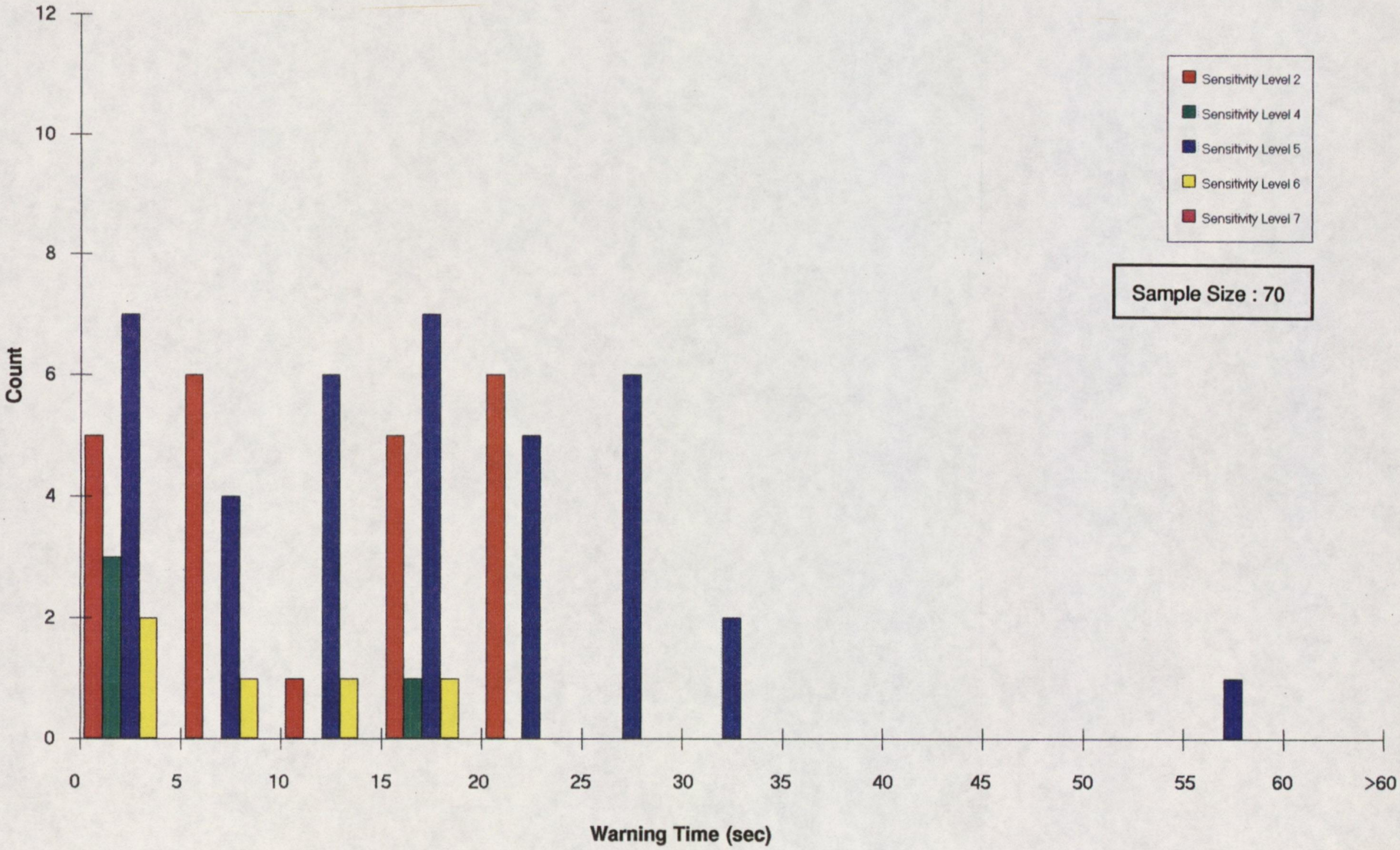


Figure 4-8(b) Distribution of Warning Time - Mode C TAs

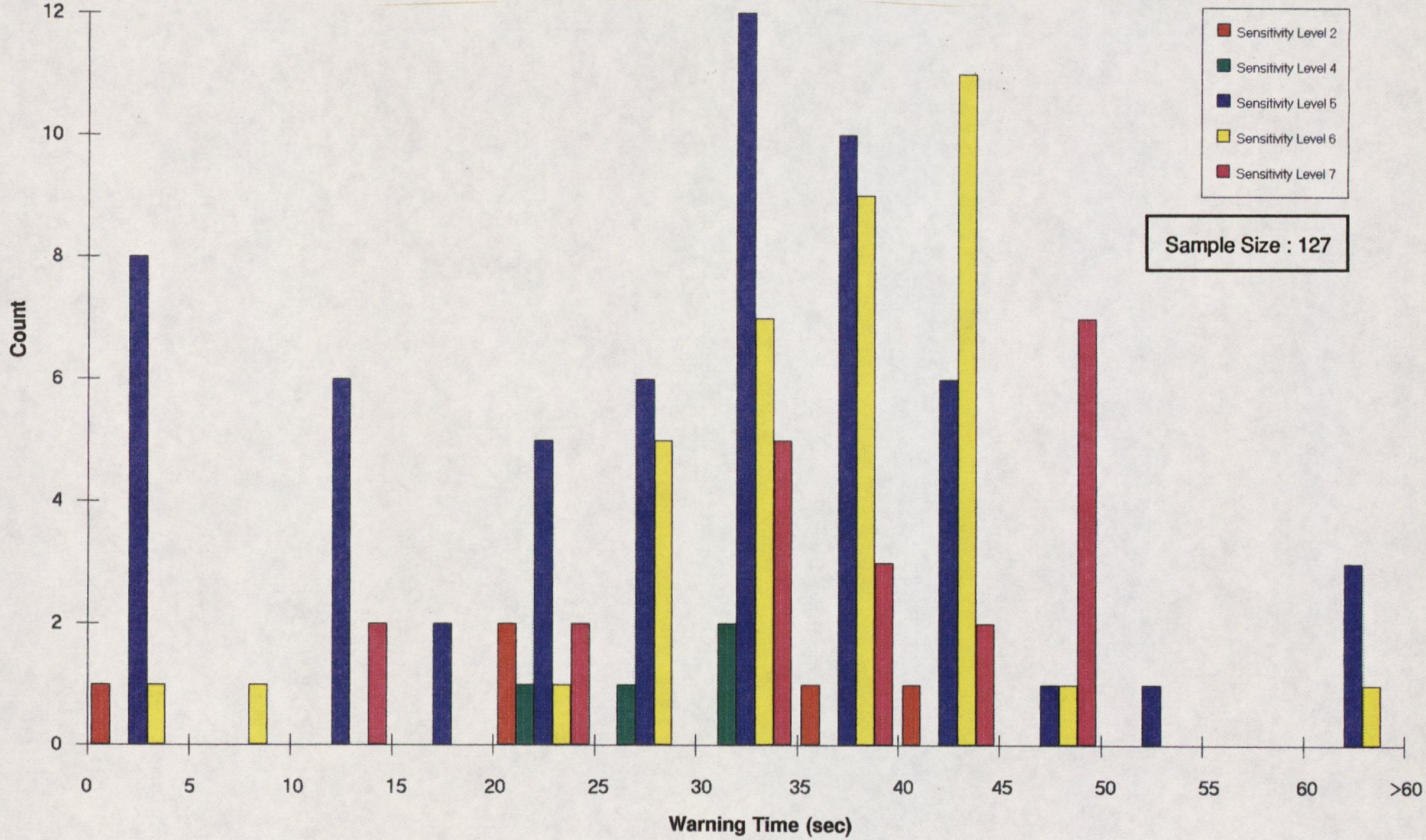


Figure 4-9 Scatter Diagram of Difference Between Actual and Nominal Warning Time as a Function of Total Separation at CPA (trials aircraft and intruder in level flight)

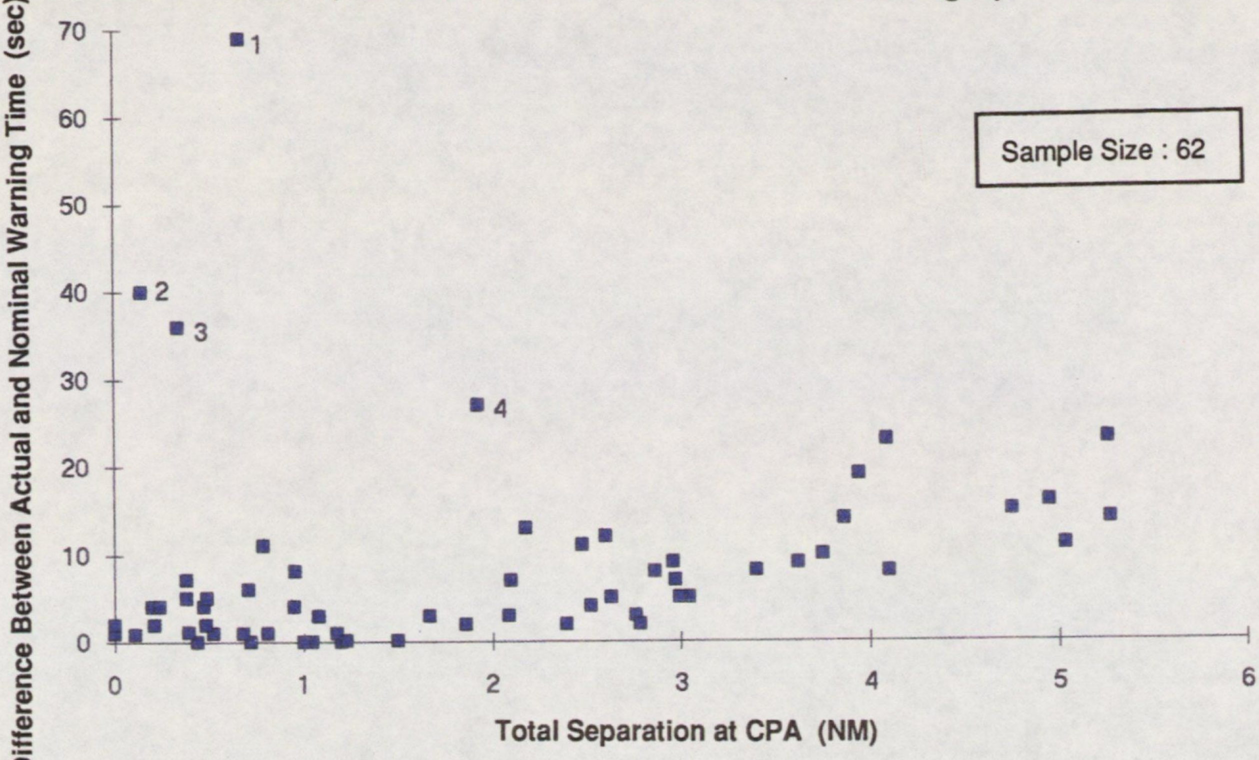


Figure 4-10 Scatter Diagram of Difference Between Actual and Nominal Warning Time as a Function of Total Separation at CPA (trials aircraft and/or intruder not in level flight)

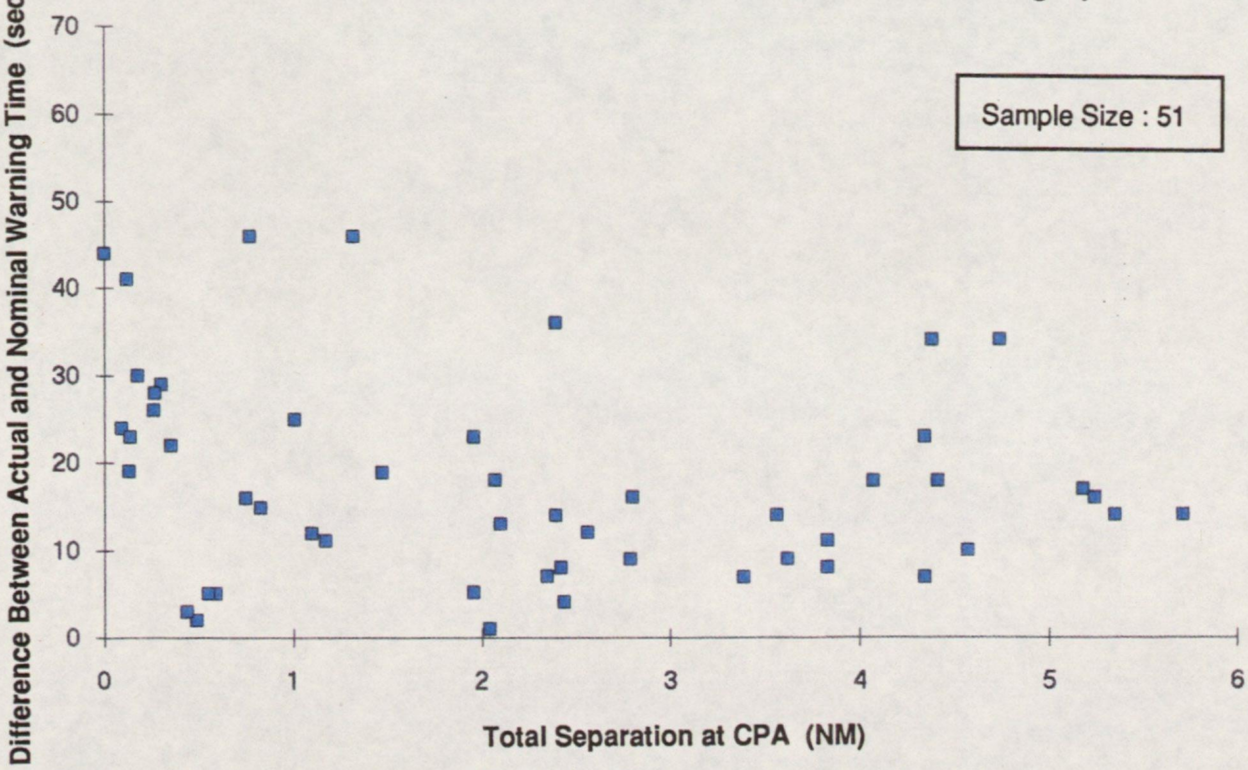


Figure 4-11 Distribution of Difference Between Nominal and Actual Warning Time

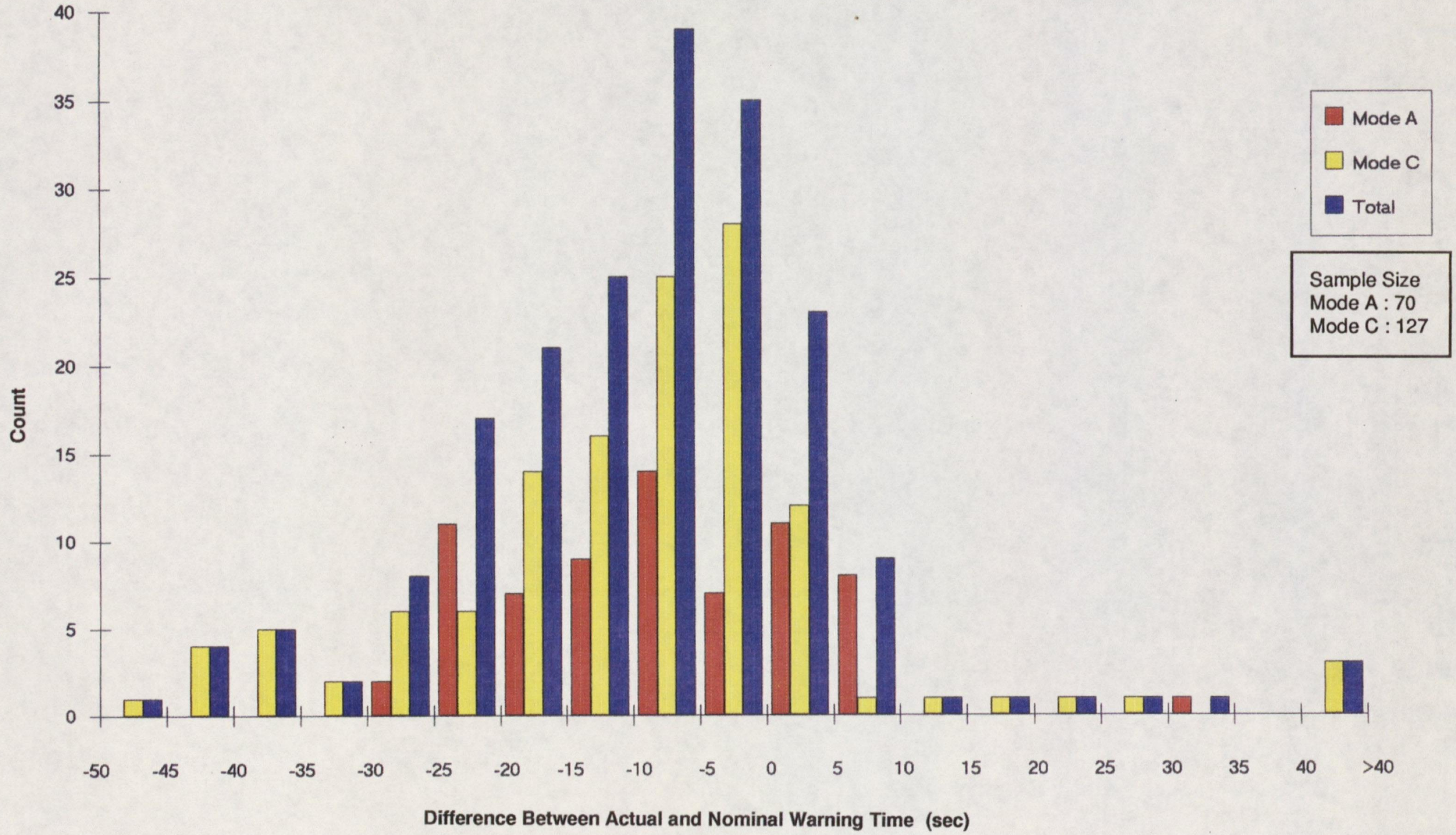


Figure 4-12(a) Distribution of TA Duration - Mode A TAs

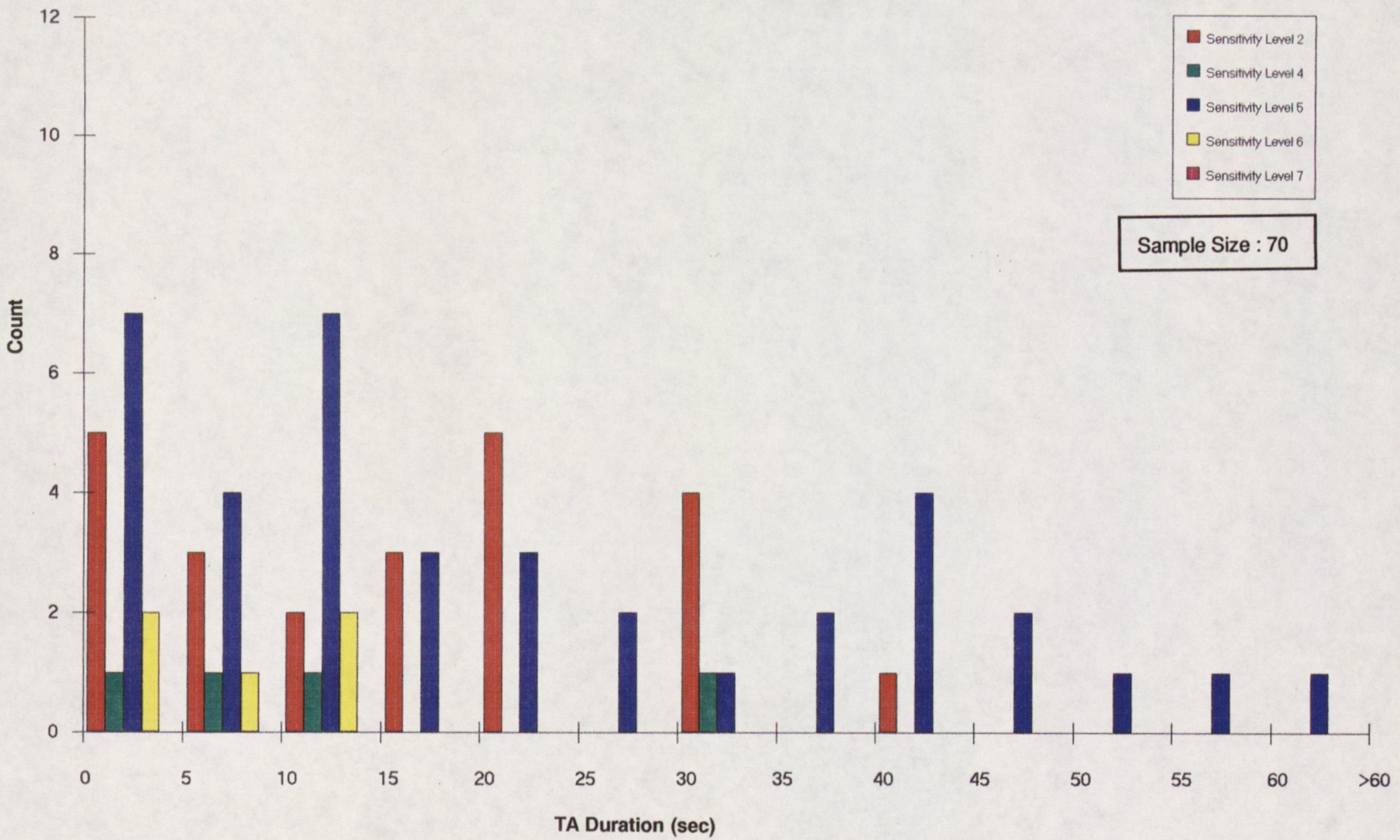


Figure 4-12(b) Distribution of TA Duration - Mode C TAs

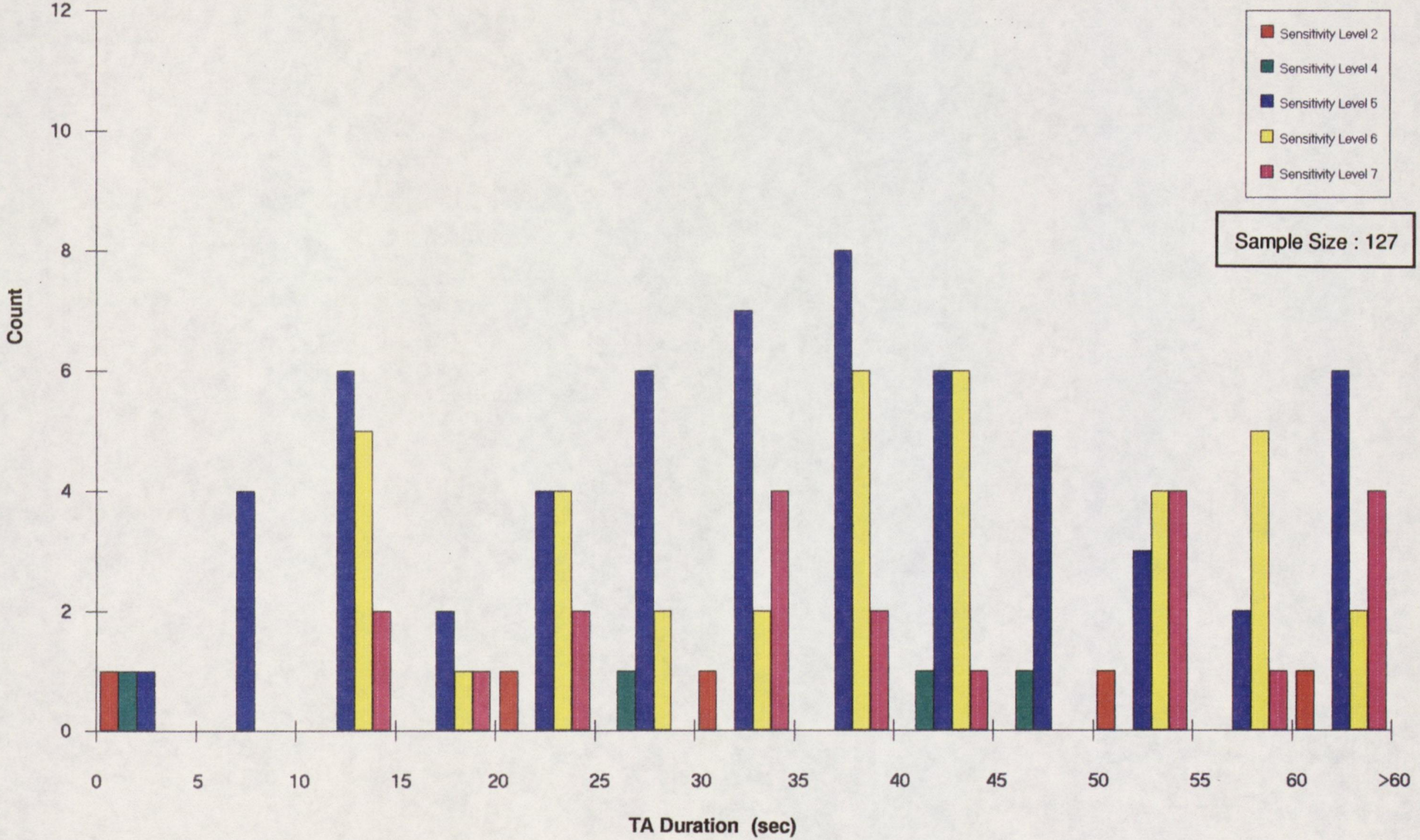


Figure 4-13 Distribution of Slant Range of Intruder at Initiation of Advisories

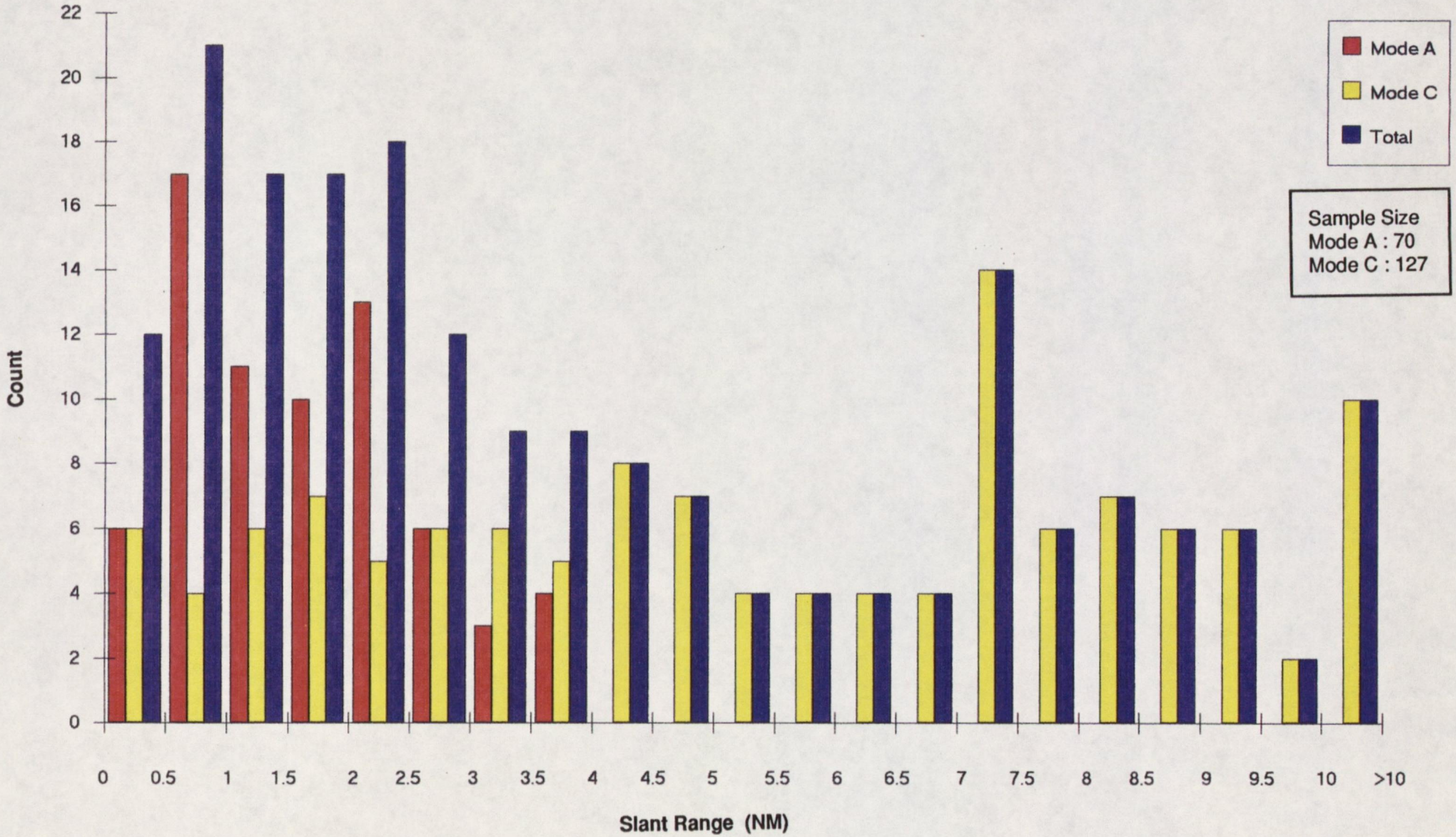
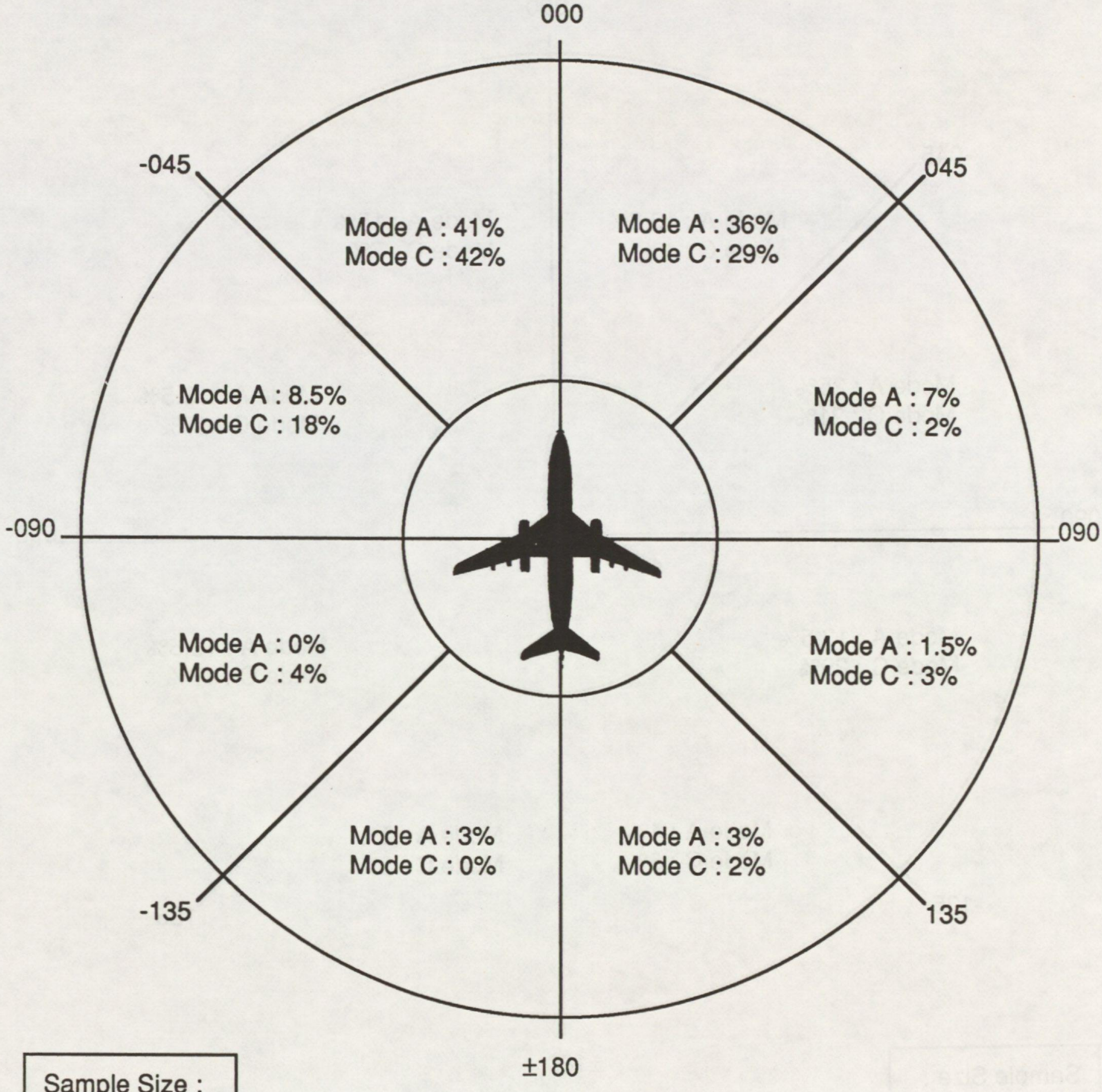


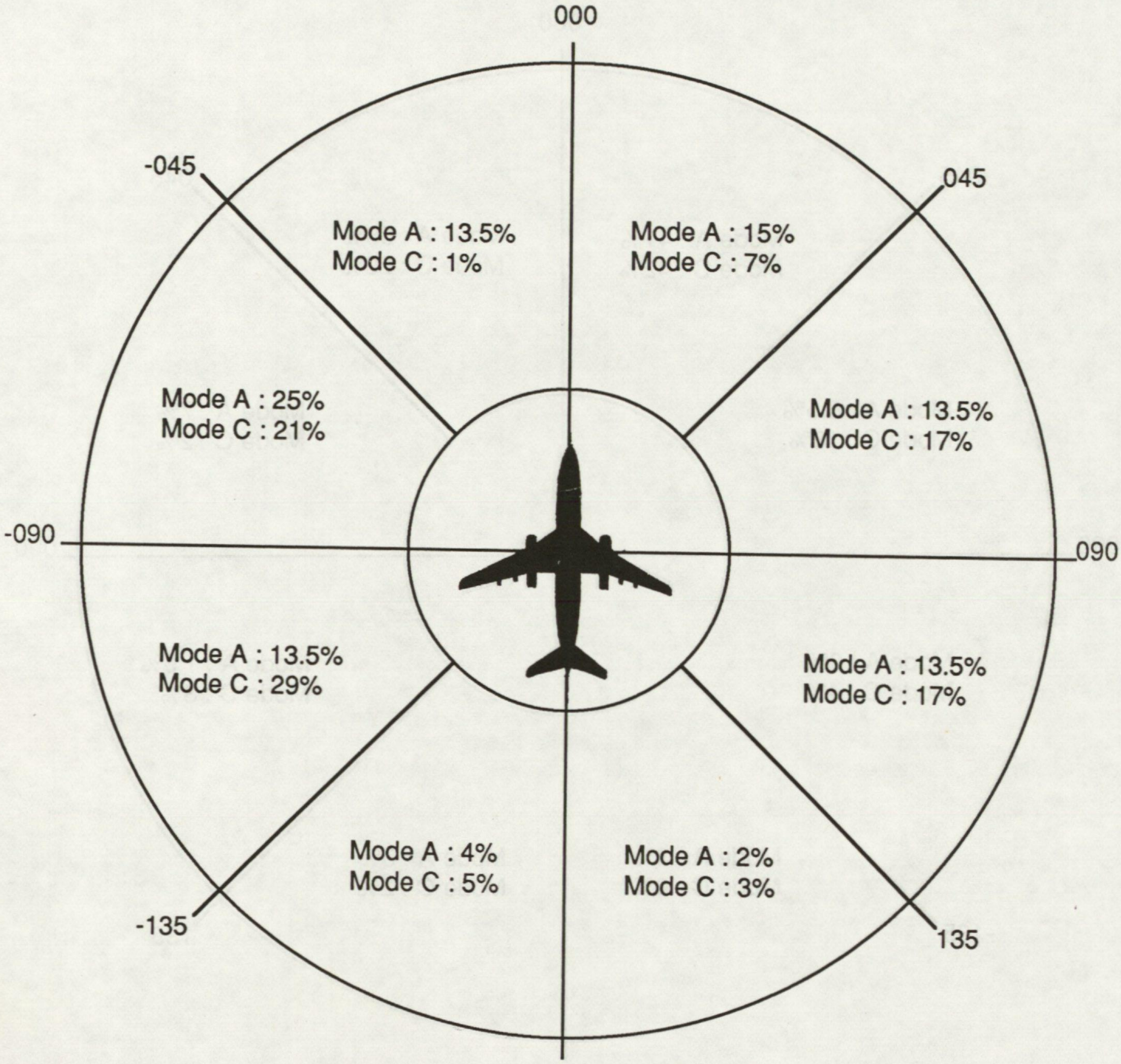
Figure 4-14 Distribution of Relative Bearing of Intruder at Initiation of TA



Sample Size :

Mode A = 70
Mode C = 119

Figure 4-15 Distribution of Relative Bearing of Intruder at CPA



Sample Size :

Mode A = 52
Mode C = 104

Figure 4-16 Relative Bearing and Elevation of Intruders at Initiation of TA - Captain's Position (Mode C TAs Only)

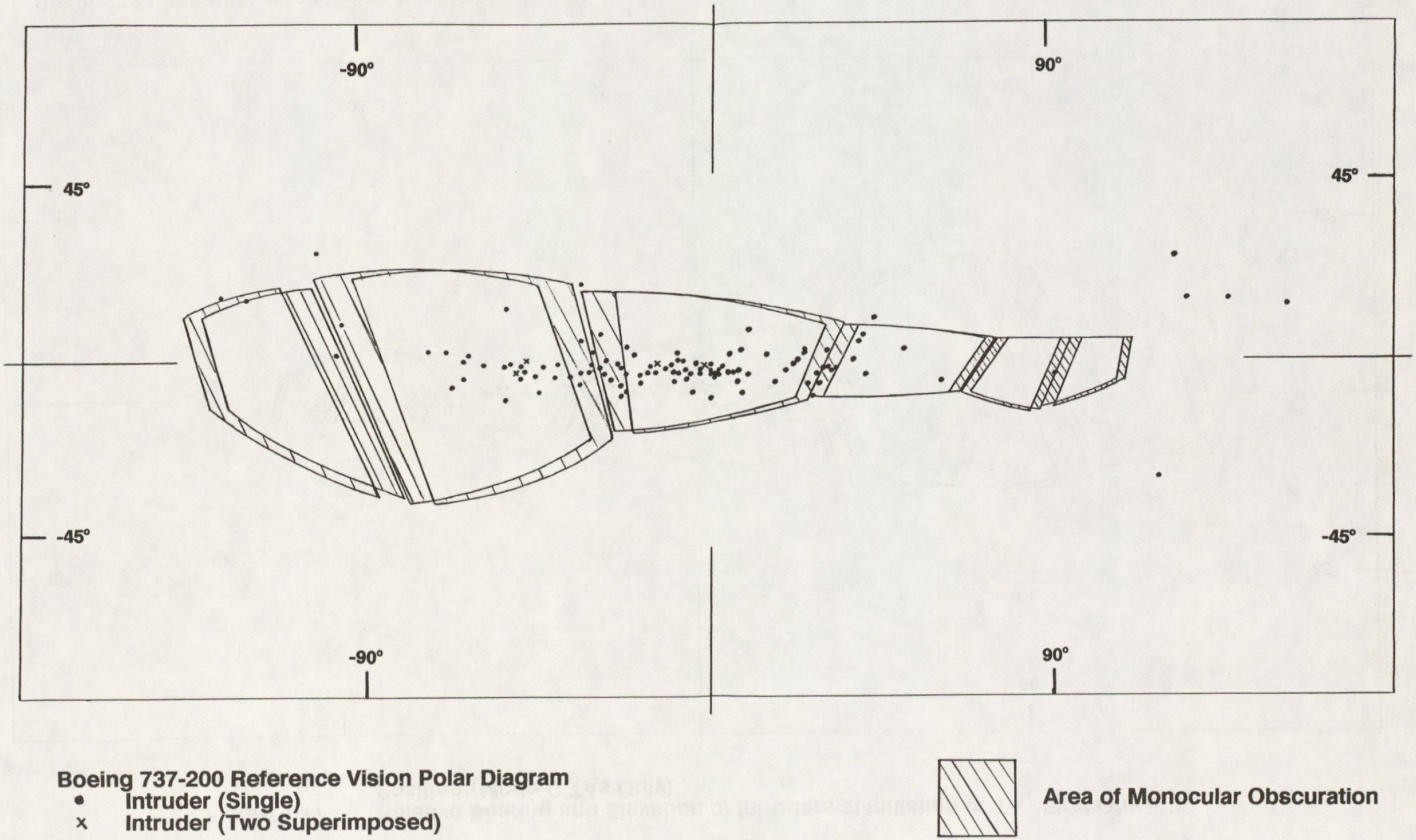


Figure 4-17 Relative Bearing and Elevation of Intruders at Initiation of TA - First Officer's Position (Mode C TAs Only)

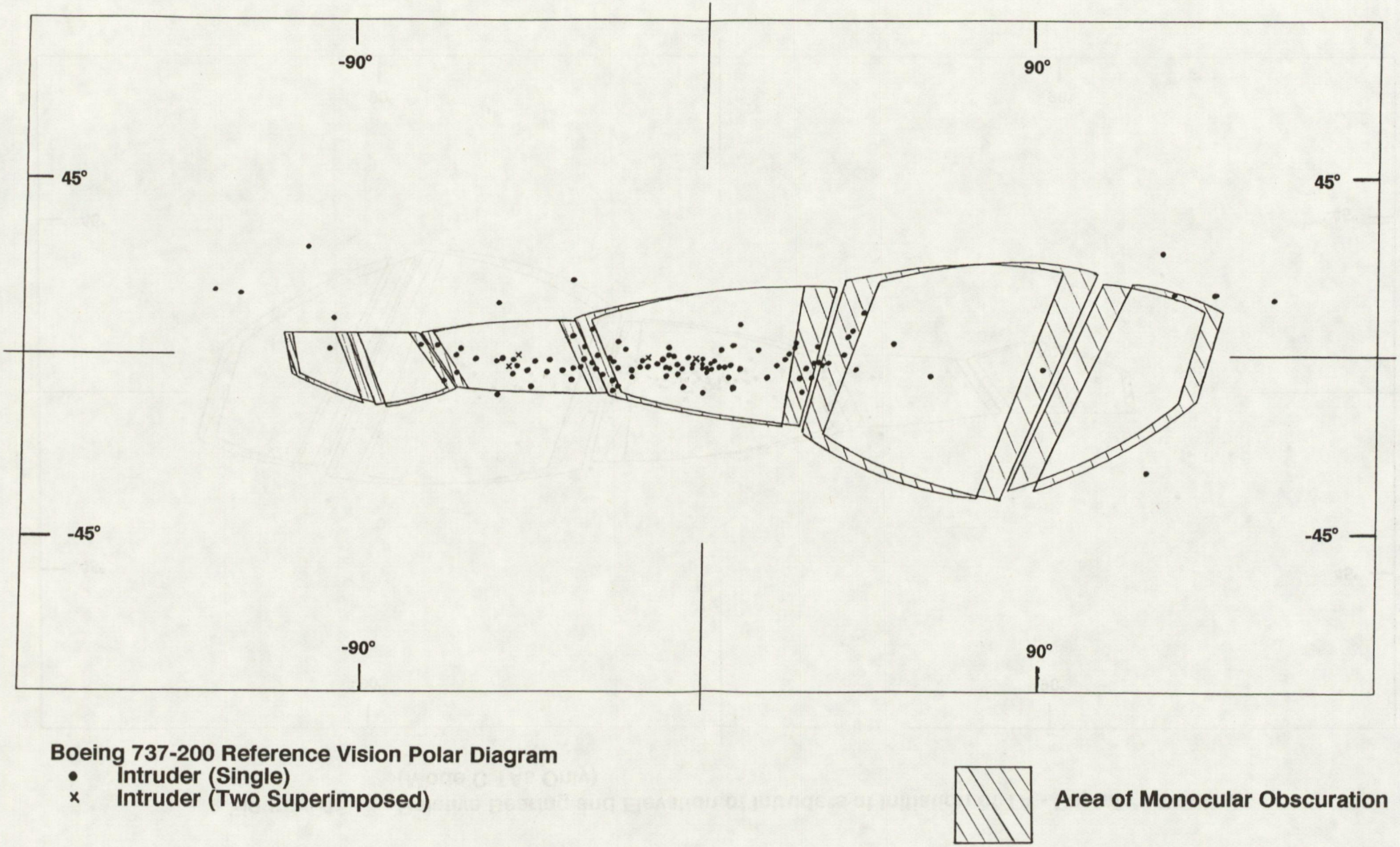
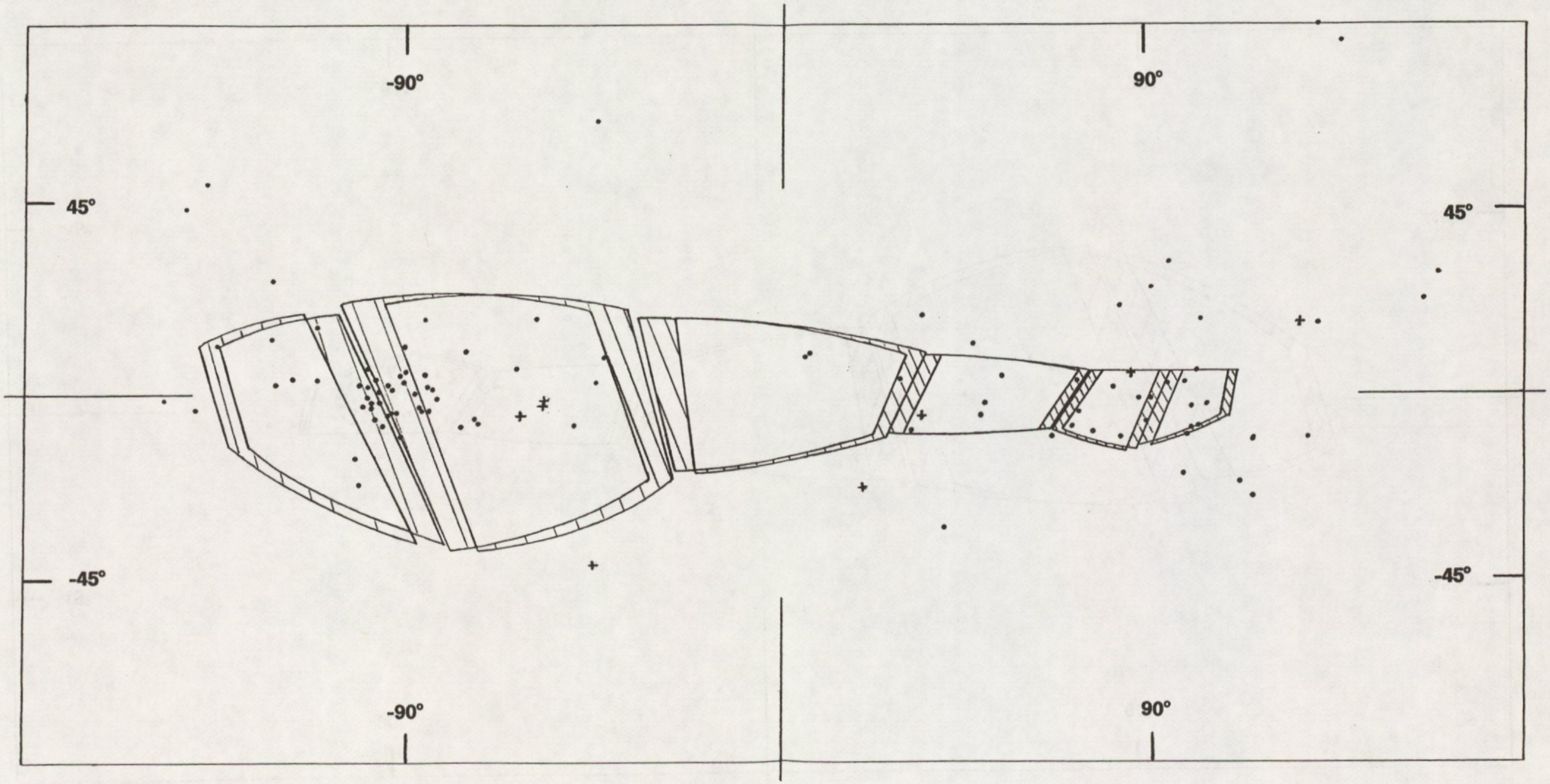


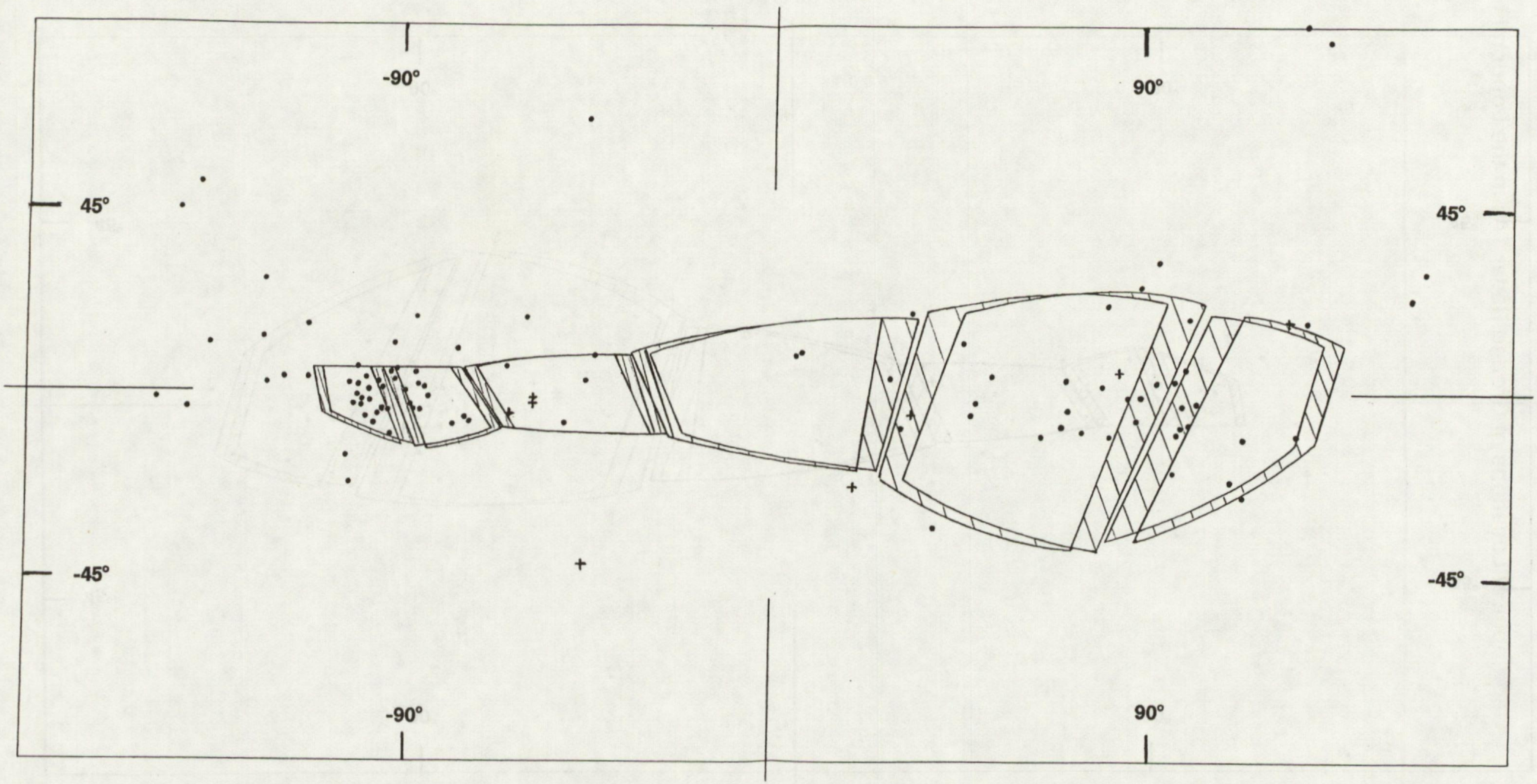
Figure 4-18 Relative Bearing and Elevation of Intruders at CPA - Captain's Position (Mode C TAs Only)



Boeing 737-200 Reference Vision Polar Diagram
- • Intruder (CPA Observed By TCAS)
- + Intruder (CPA Not Observed By TCAS)

Area of Monocular Obscuration

Figure 4-19 Relative Bearing and Elevation of Intruders at CPA - First Officer's Position (Mode C TAs Only)



Boeing 737-200 Reference Vision Polar Diagram
- • Intruder (CPA Observed By TCAS)
- + Intruder (CPA Not Observed By TCAS)

Area of Monocular Obscuration

Figure 4-20 Geographical Locations of Ground Radar TAs in the London FIR

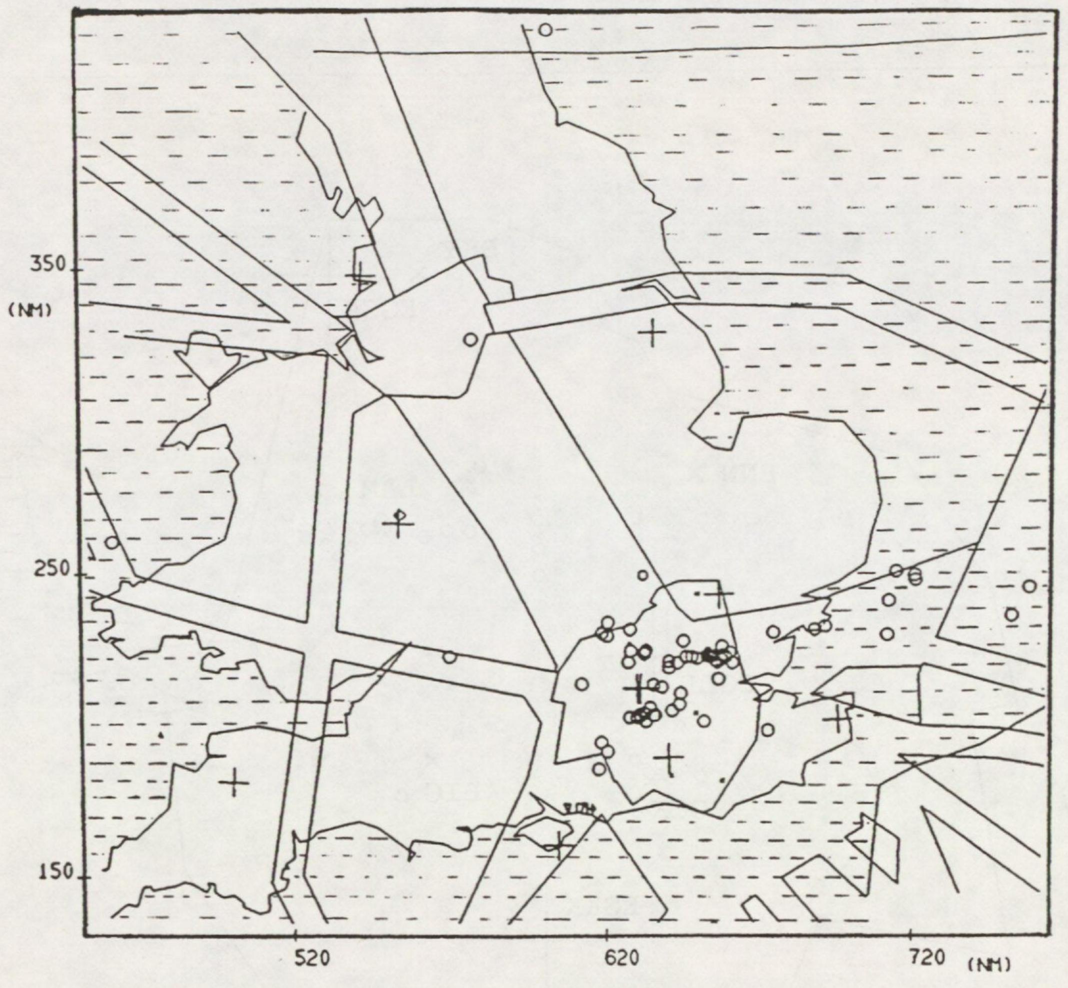


Figure 4-21 Geographical Locations of Ground Radar TAs in the London TMA

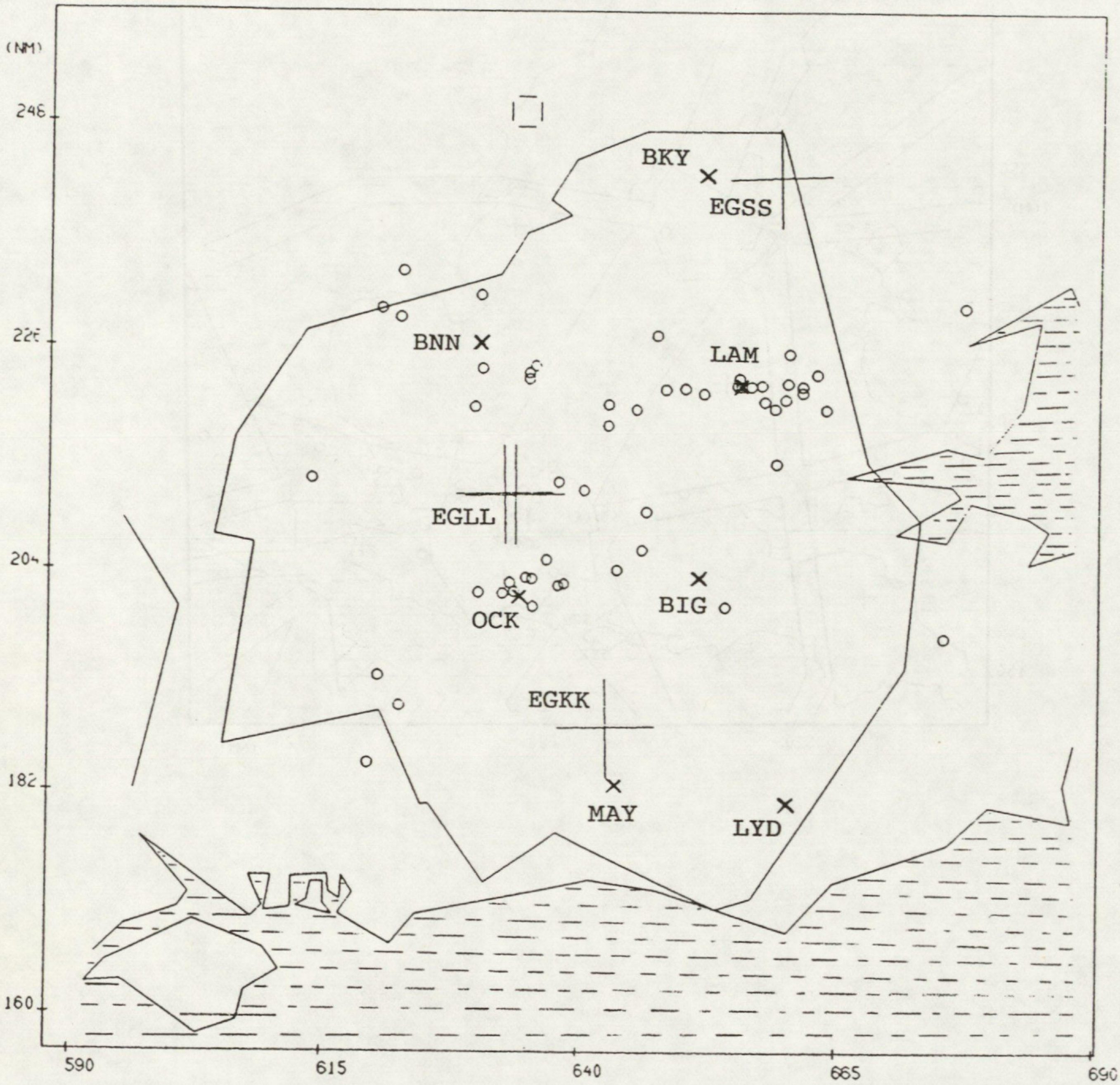


Figure 4-22(a) Distribution of Magnitude of Difference Between Ground and Airborne Derived Values for Horizontal Separation at TA

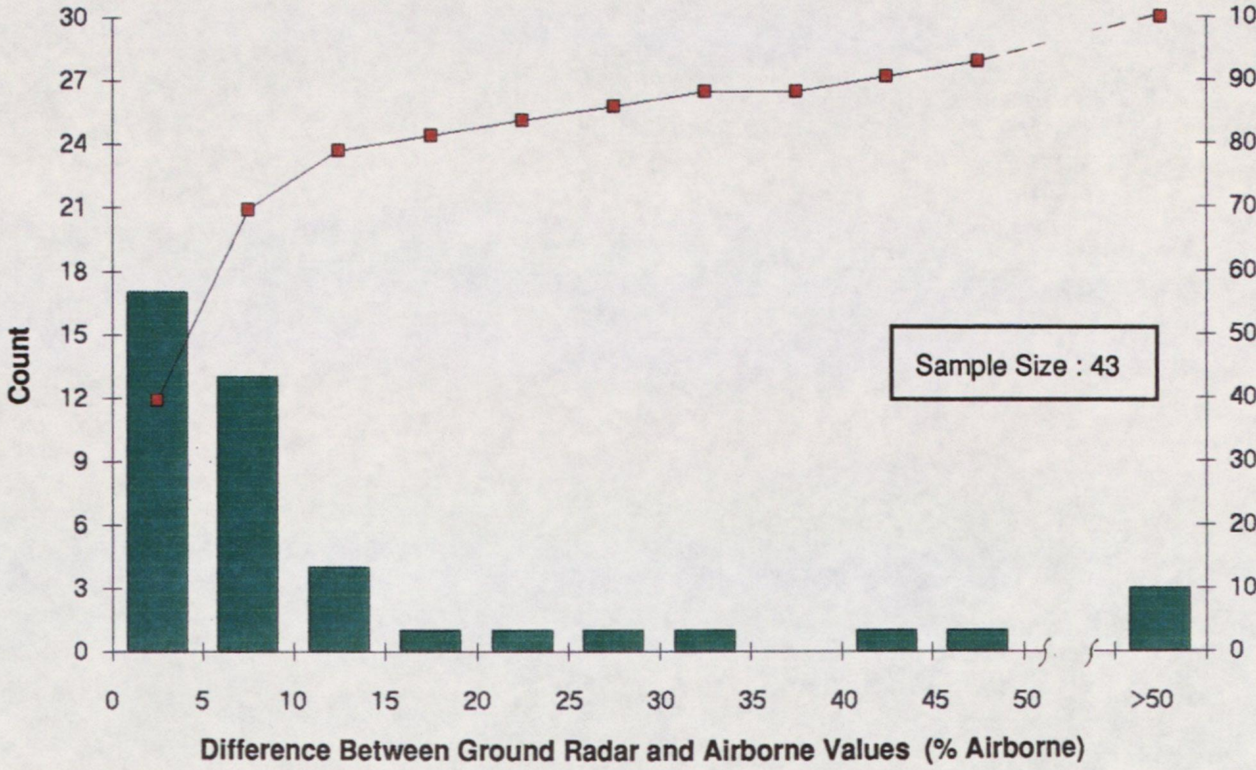


Figure 4-22(b) Distribution of Magnitude of Difference Between Ground and Airborne Derived Values for Vertical Separation at TA

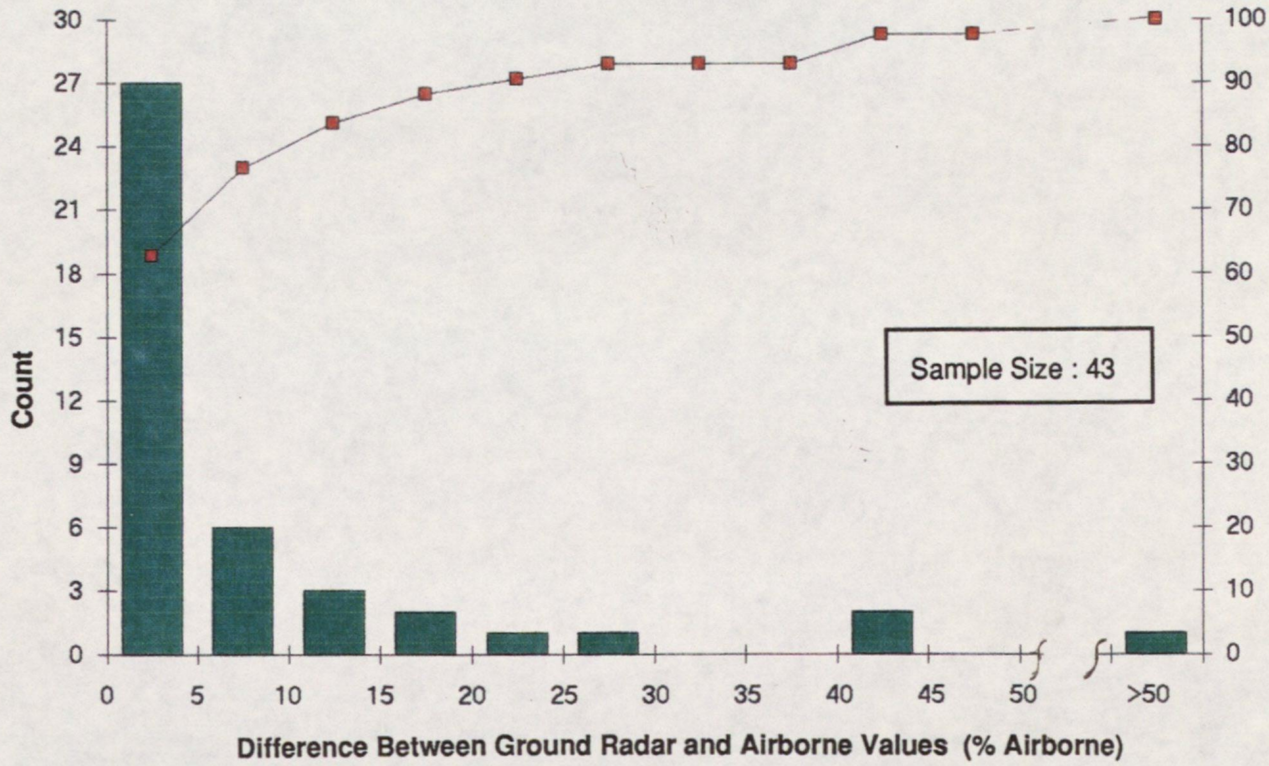


Figure 4-22(c) Distribution of Magnitude of Difference Between Ground and Airborne Derived Values for Horizontal Separation at CPA

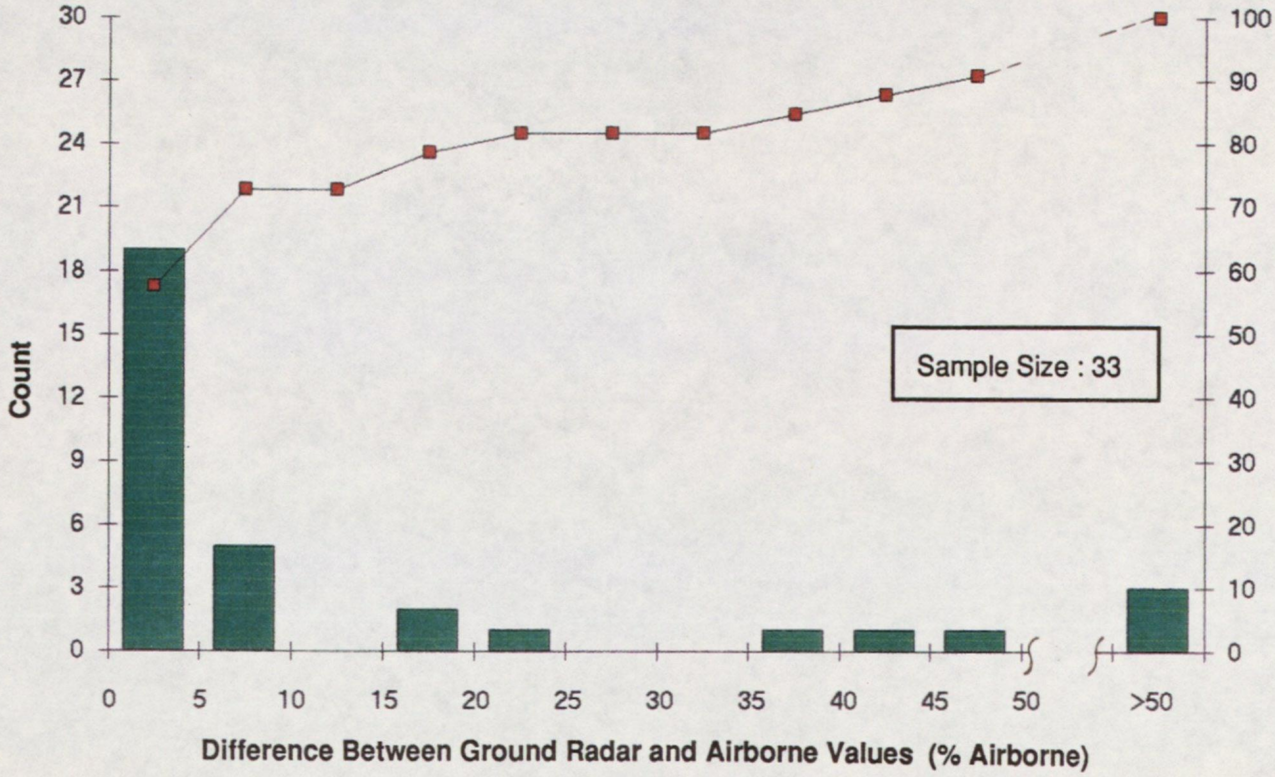


Figure 4-22(d) Distribution of Magnitude of Difference Between Ground and Airborne Derived Values for Vertical Separation at CPA

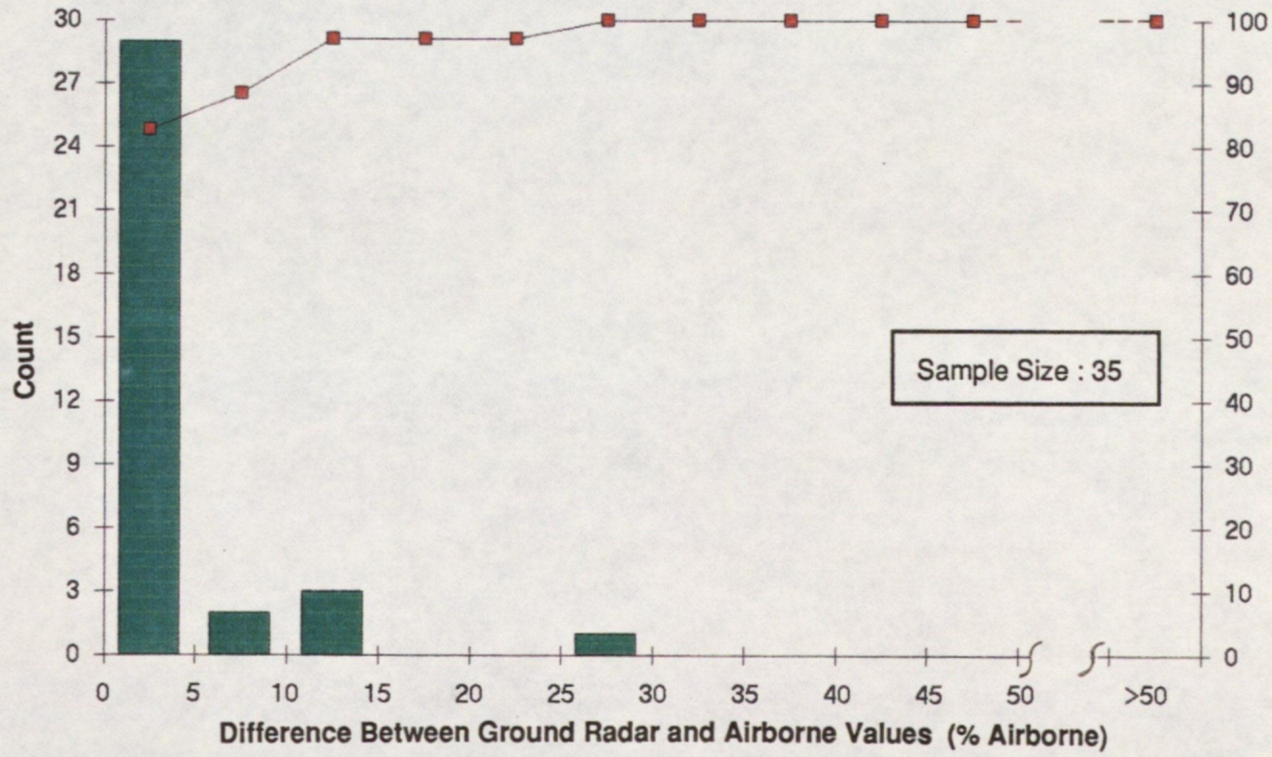


Figure 4-22(e) Distribution of Magnitude of Difference Between Ground and Airborne Derived Values for Warning Time

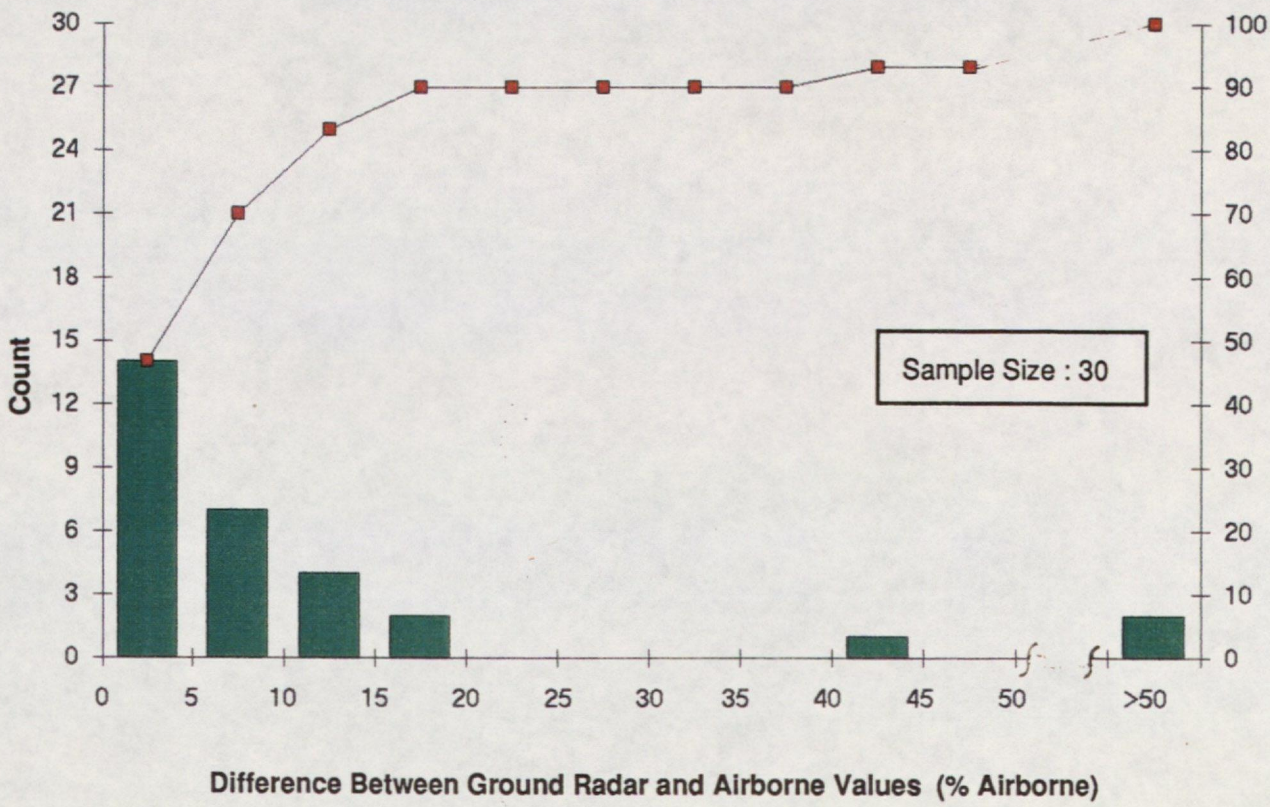


Figure 5-1 Airborne TCAS Data For RA Illustrating The Low Confidence Delay

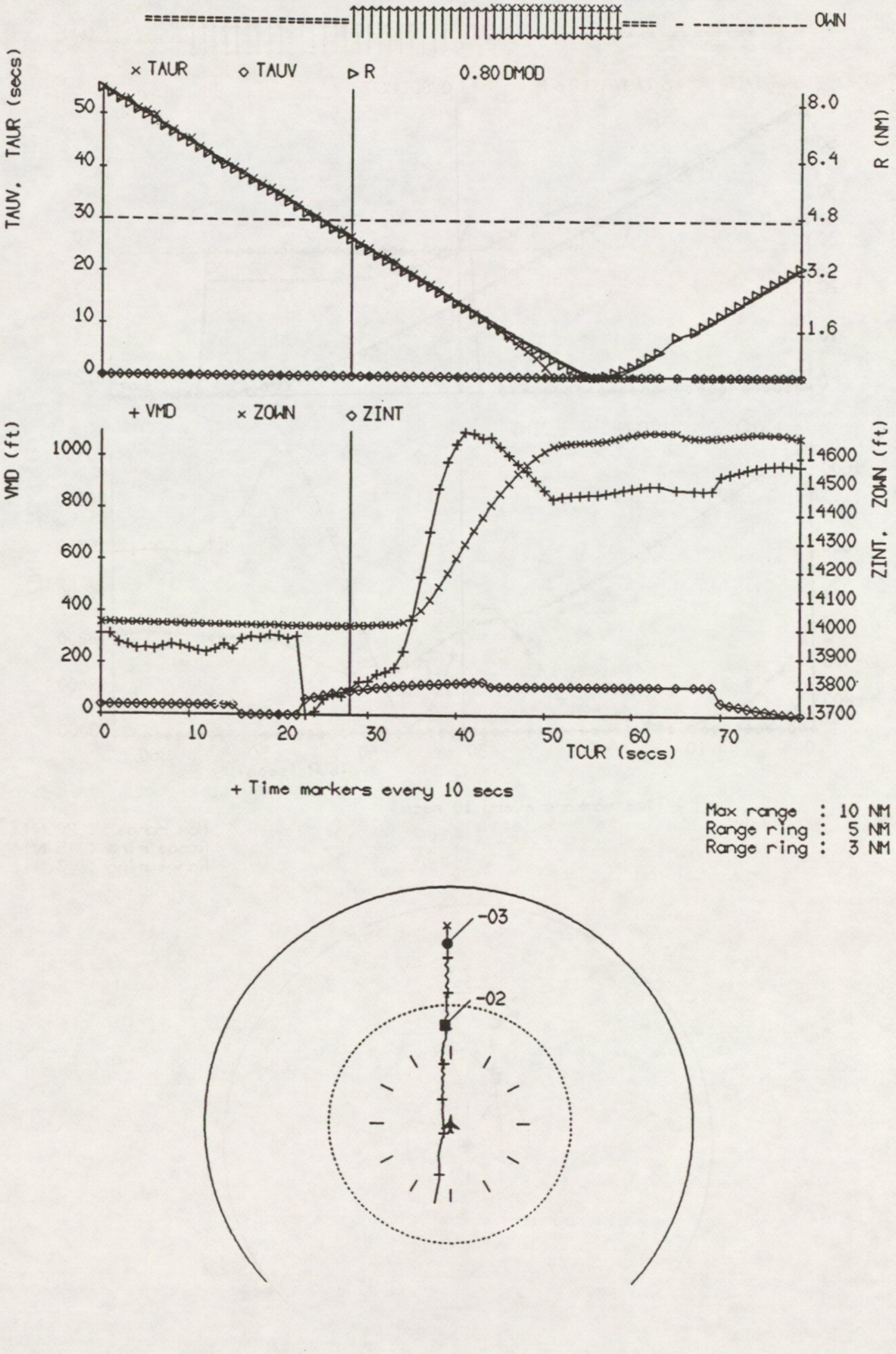
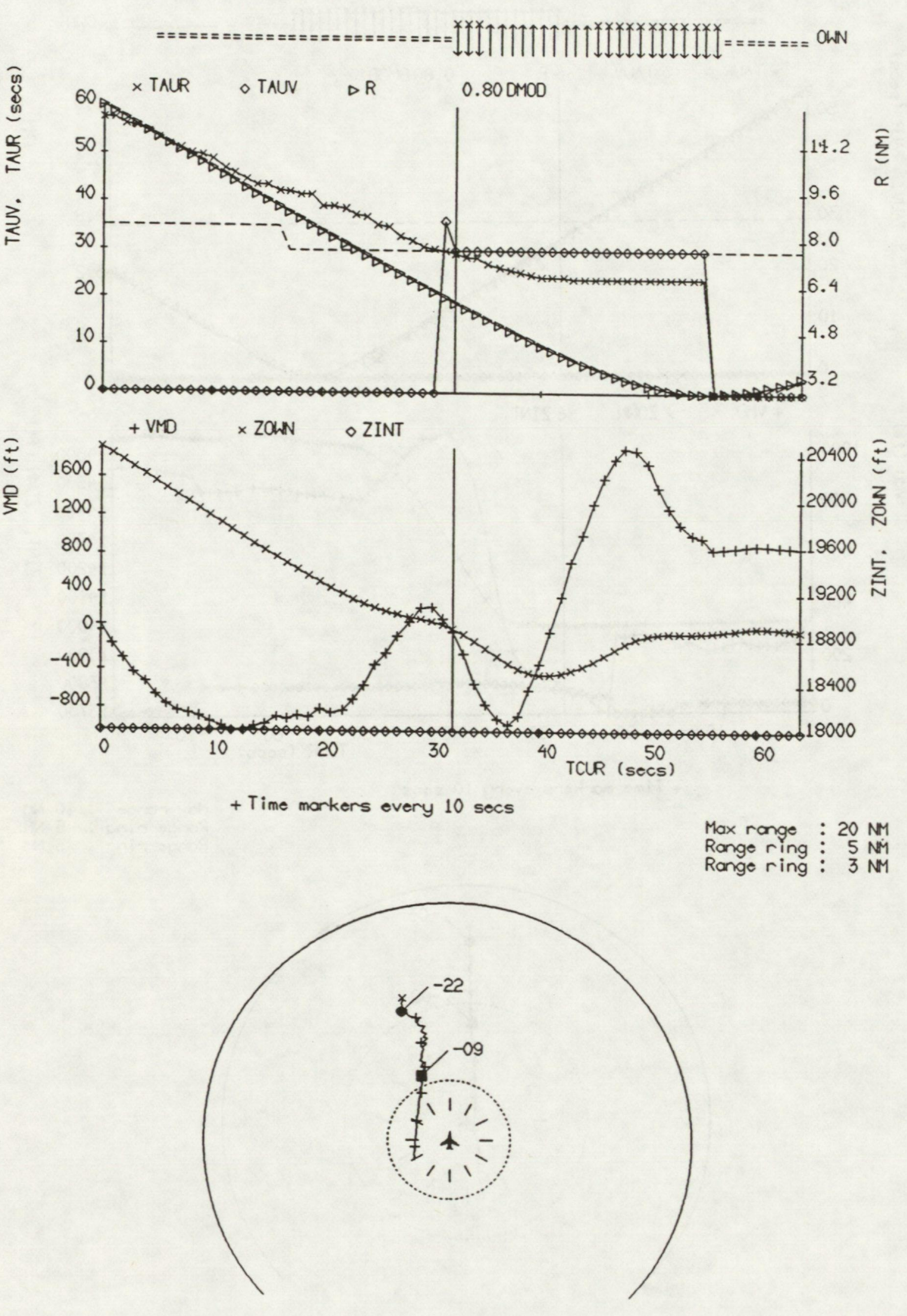


Figure 5-2 Airborne TCAS Data For Disruptive RA (Aberporth III)



APPENDIX 1

CAA TCAS TRIALS STEERING GROUP – MEMBERSHIP AND TERMS OF REFERENCE

CAA TCAS TRIALS STEERING GROUP – MEMBERSHIP AND TERMS OF REFERENCE

Membership

Deputy Director R&D, Chief Scientist's Div., CAA.	–	Chairman
RD2 Section, Chief Scientist's Div., CAA.	–	Trials Management
Control (Airspace Policy) Section 1, National Air Traffic Services, CAA.	–	ATC Operational Aspects
Airworthiness Division, Safety Regulation Group, CAA.	–	Airworthiness and Certification Aspects
Telecommunications R1d Section, National Air Traffic Services, CAA.	–	ICAO/SICASP Aspects
Operations Div. Safety Regulation Group, CAA.	–	Flight Deck Aspects
British Airways	–	Operations and Engineering Aspects

Terms of Reference

1 To oversee and direct the TCAS Operational Trial to ensure that the trial produces information based on which the CAA can formulate UK policy towards TCAS.

2 In conjunction with British Airways, to ensure that flight safety is not compromised during the conduct of the trial.

3 To consider, in the light of information gained, what changes in TCAS philosophy may be necessary in order to produce a system suitable for use both on UK aircraft and in UK airspace, and to recommend such changes for CAA consideration and possible submission to ICAO.

APPENDIX 2

AIRCREW TRAINING GUIDE

BRITISH AIRWAYS

TCAS

TRAFFIC ALERT & COLLISION AVOIDANCE SYSTEM

BRITISH
AIRWAYS

B 737

FLYING/TECHNICAL MANUAL
TEMPORARY SUPPLEMENT

ATP 1731A/1732A

This supplement describes the TRAFFIC ALERT and COLLISION AVOIDANCE SYSTEM - TCAS.

The procedures contained in this booklet are only to be followed when specifically authorised by FCN.

Applicable to Aircraft Reg. G-BGDK ONLY

This Manual complies with ANO (1985) Article 25, BCAR A6-7, CAP 360 and Technical Services Procedure T-DON-02-05. The inclusion of an uncertified revision will invalidate this certification.

Signed ....JAFaulmare........ Head of Technical & Training Flight Crew and where applicable, on behalf of Chief Engineer Technical & Quality Services.

Date ....29.4.89........ CAA Approval No. DAI/8566/78

This publication forms part of the British Airways approved Operations Manual

B737 Flying/Technical Manual

Temporary Supplement

TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM - TCAS

CONTENTS

B737 Flying/Technical Manual

Temporary Supplement

TRAFFIC ALERT AND COLLISION AVOIDANCE SYSTEM - TCAS (G-BGDK)

1. INTRODUCTION

1.1 The search for a practical and safe collision avoidance system dates back over 30 years. The FAA, in conjunction with Mitre Labs, has now developed a system which provides a measure of protection to all aircraft fitted with it, without the need for all aircraft to be so equipped. This is a significant advance on earlier proposals. In addition, recent advances in interference suppression techniques mean that equipment can now be designed to work in very high traffic density areas such as San Francisco and Los Angeles.

1.2 While the FAA is still conducting trials in US airspace, the CAA has obtained loan equipment from the manufacturer to allow a parallel study to be carried out in UK airspace. While in general there is not expected to be much diference from US results, there are nonetheless significant differences in the way controlled airspace is organised in the UK compared to the US which make an independent trial desirable.

1.3 Computer simulations of TCAS using recordings of live UK radar data have shown that the latest version, which is to be tested in the UK trial, appears to give a substantial net safety benefit. The purpose of the trial is to confirm these results using real equipment, and, no less importantly, to assess pilot and controller reaction to real time use of the system.

1.4 The trial is in phases:

1. Record only phase, no outputs to pilots. Pilot action required only to switch on the equipment and the recorder, and to record transponder code allocations (to permit tracking of the subject aircraft for later analysis). This phase is proceding currently.

2. CAA Test Flight. Deliberate close encounters have been flown against an intruder aircraft (the CAA's 125) over the Aberporth Range. Analysis of the results of this flight, together with the results of the first phase form the TCAS safety study which must be completed before:

3. Piloted phase (recording continues). Outputs routed to pilot displays, an observer will be carried on most flights to record system operation and pilot comments.

1.5 Once the review is complete, the go-ahead for the piloted trial will be given by an FCN. It is inevitable that at some time someone will receive a TCAS advisory which will require a departure from the current ATC clearance. The CAA has ruled that action following such an advisory, will be considered to be 'avoiding immediate danger', and as such permitted under Article 64(3)a of the ANO.

2. SYSTEM DESCRIPTION

2.1 TCAS is a Traffic Alert and Collision Avoidance System. It is designed to complement ATC, not replace it. It increases your ability to see and avoid, when appropriate, but it is not intended to allow you to carry out air traffic management functions.

2.2 The system hardware comprises:

Cockpit: Dedicated CRT display, forward electronics panel,left side; 2 modified VSIs with coloured 'eyebrow' lights; dedicated speaker (alongside existing GPWS speaker); TCAS/Mode-S Xpdr controller, alongside existing ATC controller (labelled INOP); display controller, recorder controller, both aft electronics panel.

E/E bay: Mode-S transponder (fitted in place of the No 1 ATC transponder); TCAS processor; voice message system; dedicated recorder.

External: Directional antenna, additional Mode S Xpdr antenna, upper fuselage; Omni directional antenna, lower fuselage.

2.3 Note: Though during the trial the aircraft will carry two transponders, 1 Mode-S, and the normal No 2 ATC Xpdr, the latter is not compatible with the trial set-up. Consequently if the Mode-S fails, the flight must continue without Xpdr to destination, where, if the failure persists, the No 2 Xpdr can be re-connected by ground maintenance action, and its controller reactivated. TCAS would then be inop.

3. SYSTEM OPERATION

3.1 TCAS interrogates other transponders out to approximately 14nm forward, 10nm to either side and 7·5nm aft. It displays the resulting targets on a CRT, colour and shape coded depending on their degree of threat, according to the range and altitude limits selected on the display controller. The display range can be selected between 3 and 20nm. If the intruder has a mode C (altitude reporting) or a mode S (selective address) transponder, a data block, alongside the target symbol and the same colour, shows traffic relative altitude and whether it is climbing or descending. If the intruder is mode A equipped (no altitude report), the data block blanks, and TCAS assumes it is at co-altitude. TCAS continues to track targets through its omni antenna when, due to blanking by aircraft structure, no bearing can be obtained through the upper, directional, antenna, though such targets cannot be displayed.

3.2 TCAS carries out Threat Detection and Conflict Resolution tests and processing on the data it receives through its two antennas. Both tasks use target range and relative altitude, and the rates of change of both. Relative bearing is not needed for either calculation; TCAS can declare a threat without knowing 'where the traffic is'. The purpose of the bearing measurement and display is to aid visual acquisition.

3.3 Although it is often said that TCAS establishes a protection volume around own aircraft, this is a little misleading. The volume changes for each intruder. The constant factor is the time until close approach; an intruder with low closing speed generates a warning closer than one with a high closing speed.

3.4 Threat detection results in three levels of threat. The first, is non-threatening, and such targets are displayed as white diamonds on the CRT, either open, or closed if they are within 4nm and 1200ft. Normally, non-threatening targets are shown within 2700ft of own altitude; the above/norm/below switch on the controller, sprung loaded to the central norm position, allows the upper or lower limit to be increased to 7000ft.

3.5 The next two threat levels give rise to two levels of 'Advisories', a Traffic Advisory, TA, and a Resolution Advisory, RA. Both cause existing target symbols to change shape and colour, or bring up a symbol if the traffic was originally outside the vertical display limits. If the target is beyond the current display range an appropriate 'Off Scale' advisory is given (see 3.18).

3.6 The TRAFFIC ADVISORY, TA, alerts you to a conflict that may later require avoiding action, and prompts you to seek traffic visually. TAs are announced by a voice message 'TRAFFIC TRAFFIC', and identified on the CRT by the traffic symbol changing to a yellow circle. Typically, targets giving rise to TAs are within 40 seconds of a 'close' approach (the actual times and distances vary according to own aircraft altitude).

3.7 The RESOLUTION ADVISORY, RA, starts the conflict resolution process, which is only in the vertical plane. If the intruder is also TCAS equipped, the two units coordinate their RAs via the Mode S data link. RA traffic is within about 25 seconds of a close approach, and appears as red squares on the CRT. RAs are accompanied by aural messages indicating the recommended avoidance manoeuvre eg CLIMB CLIMB CLIMB. A symbol also appears in the top left corner of the CRT to reinforce the message (in this case an upward pointing green arrow), but more precise conflict resolution advice is given on the modified VSIs. Arcs of 'eyebrow lights', show RED to indicate vertical rates to be avoided.

3.8 When the existing vertical rate lies within the 'avoid' band, a small GREEN sector shows a suitable vertical speed target. These are called CORRECTIVE RAs.

3.9 Where no change of vertical rate is called for, where TCAS is warning you not to do something, eg not to descend when there is traffic below, the RA is called PREVENTIVE. About half the RAs are likely to be this type; The usual aural is VERTICAL SPEED RESTRICTED, and there is no green band displayed on the VSI.

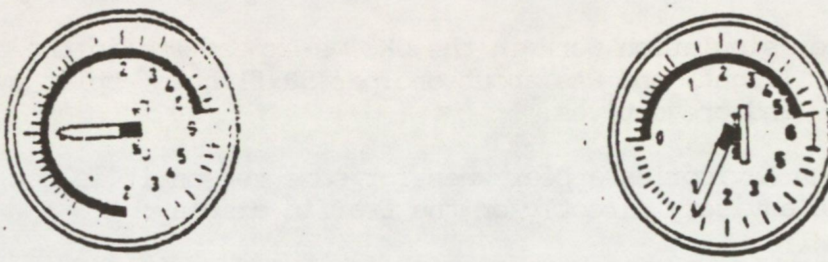
3.10 In determining the avoidance advice, TCAS assumes 5 seconds pilot reaction time followed, where necessary, by a 0·25g pull up/push over to 1500ft/min vertical rate. While 5 seconds is generous, 0·25 g is a lot by line standards. Adequate separation can be achieved by prompt application of an expeditious climb or descent manoeuvre.

3.11 The Autopilot applies too little 'g' application for a corrective advisory (it takes 13 sec from initial application to achieve 1500 fpm using the vertical speed control, a large proportion of the total warning time). Where a Climb or descent are required, they are best done manually. Aiming for 1500ft/min, apply stick force to achieve a 2^{o} to 5^{o} attitude change (cruise speed/terminal area speed) within 5 seconds, pause, and adjust accordingly. Try to avoid snatching; rate of rise of 'g' affects passenger comfort as much as, if not more than, actual 'g' achieved. Remember, though, that a preventive RA requires no immediate action; don't just disconnect the autopilot as soon as you hear the aural, think first.

3.12 The situation will probably be resolved quite quickly by the initial reaction, before half the standard vertical separation is eroded. For example, at FL100, a 'Descend' RA will probably resolve the situation, 'soften' to 'Limit Vertical Speed' before passing FL097, and then cancel, so you should be able to limit the excursion at FL096. From which it follows:

1. Try to avoid climbing or descending at more than the advisory vertical rate; more separation is not necesarily better separation.

2. Respect the original clearance as far as possible by trying to regain it within the limitations suggested by TCAS. In the example below, you could start to level off as soon as the RA softens.



A DESCEND RA softening to a LIMIT VERTICAL SPEED

3.13 In some encounters, manoeuvring by the intruder, or a delayed manoeuvre by own aircraft, may result in the original advisory being no longer adequate. TCAS can 'change its mind' and issue an 'enhanced' RA, either reversing the sense of the original, or demanding a greater vertical rate in the same direction. Appropriate VSI cues and aural messages, eg 'INCREASE CLIMB INCREASE CLIMB', accompany such RAs. In these cases only, vigorous action to comply with the RA is authorised and expected. Aim to achieve the same 2 to 5 degree attitude change in just 3 seconds, or a reversal in 5 seconds.

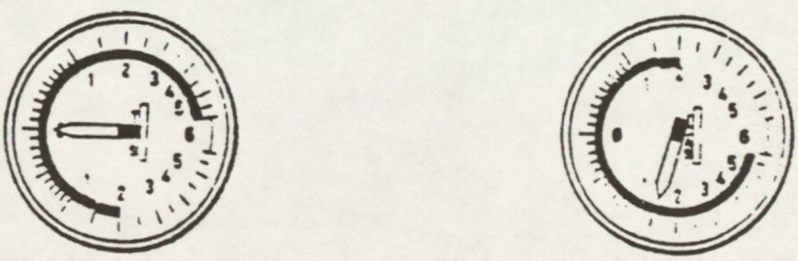


Illustration shows an initial DESCEND RA converting to a CLIMB.

3.14 When TCAS decides the threat has passed, a CLEAR OF CONFLICT message is issued, the VSI lights extinguish, and the CRT traffic display reverts to a white diamond. If not already doing so, you should return to your original clearance at about 500fpm, or resume previous vertical rate, unless specific instructions to the contrary are given by ATC.

3.15 Although the proper response to an RA is a vertical manoeuvre, and turning on the basis of the traffic display alone is not allowed (the bearing measurement accuracy is not sufficient), there is no reason why, if you are already in a turn when an RA is issued, you should not continue it while following the RA. You may of course turn if you sight traffic, and decide that it is appropriate to do so, but this does not come within the terms of use of TCAS; normal ATC incident reporting procedures would apply.

3.16 If a corrective RA has been received, and the aircraft has left its previous assigned clearance, ATC must be informed by the non-handling pilot as soon as practicable. This is the only time during the trial when you should reveal that the aircraft is TCAS equipped; the entire trial would be compromised if ATC gave the aircraft special treatment.

3.17 From earlier simulation work in the UK, we expect TAs in the order of 1 every other flight, and RAs about one per 50 flights, split evenly between correctives and preventives.

3.18 TCAS Written Advisories appear when for some reason it is not possible to display the advisory directly on the traffic display:

1. TA/RA OFFSCALE - yellow/red as appropriate in the top left part of the CRT indicates that the intruder giving rise to the TA or RA cannot be displayed with the display at its current selected range. An arrow of the appropriate colour indicates the intruder bearing. Selection of a greater range will bring the symbol onto the display.

2. TA/RA NO BRG - yellow/red in top left of the CRT indicates that the intruder return is being picked up by the lower omni antenna only and no bearing information is available. This does not reduce the significance of the RA in any way, though of course the TA is of limited use. In a typical dynamic situation, it is quite likely that in due course bearing information will be regained, or vice versa, once established can be lost. The NO BRG advisory gives some degree of continuity of warning.

4. TCAS LIMITATIONS

4.1 TCAS bearing mearsurement accuracy, though adequate for aiding visual traffic search, is not sufficient to allow horizontal manoeuvering away from indicated targets. Such manoeuvering solely on the basis of a TA or any displayed traffic information is not allowed.

4.2 The conflict avoidance rules in TCAS are complicated. Manoeuvering in advance of an RA on the assumption that a particular sense will be selected is unwise and not allowed.

4.3 TCAS is entirely unaware of non-transponder equipped aircraft. Normal vigilance is therefore required especially in area where such traffic is more likely.

4.4 TCAS cannot give any avoidance advice regarding aircraft equipped with only mode A, non-altitude reporting, transponders. For the purposes of threat detection, it assumes them to be at co-altitude, but for obvious reasons cannot give vertical clearance from a target whose altitude is unknown. TAs appearing without an altitude data block will therefore not turn into RAs. Conversely TAs without altitude readout can still be real threats; normal vigilance is still required.

4.5 TCAS will not give a climb RA above FL 220 (on the 737)

4.6 TCAS will not give a descend RA below 700ft Radio Height.

4.7 TCAS will not give an enhanced INCREASE DESCENT RA below 1800ft.

4.8 All aural messages are suppressed below 400ft RA.

5. ACTION TO BE TAKEN IN RESPONSE TO A TA

1. Never manoeuvre solely on the basis of a TA

2. Try to sight the traffic, using the traffic display as a guide. This is best done in co-operation; the pilot less well placed to see the traffic should divide his scan between the display and the outside to keep the other aware of changes of position and relative altitude of the intruder.

3. This effort should continue until the traffic is sighted or the TA symbol disappears.

4. If the traffic is sighted, and is perceived to be a threat, then you may manoeuvre as necessary. The non-handling pilot should inform ATC accordingly.

5. The handling pilot should prepare for a possible RA, whether or not the traffic is sighted.

6. In anticipation of a subsequent RA, clear the airspace around you visually if possible.

7. The non-handling pilot should check/select the Seat Belt signs ON in anticipation of a possible RA.

6 ACTION ON RECEIPT OF AN RA

1. If a manoeuvre is needed, the handling pilot should start it without delay, unless the intruder is positively identified, and is not a threat.

2. The following Corrective RAs require you to alter your vertical path. None require violent action.

   CLIMB/DESCEND - Disengage the Autopilot, establish a rate of 1500 fpm as indicated on the VSI; a 'firm but gentle' pitch attitude change of 2 to 5 degrees (according to speed) in about 5sec is needed.

   CROSSING CLIMB/DESCEND: Climb or descend as above. The manoeuvre may take you through the intruder's current altitude.

   REDUCE VERTICAL SPEED, adjust vertical speed to agree with lighted VSI arc (may need less change than the cases above). Disconnect the autopilot, and change pitch attitude accordingly.

   BE READY TO REDUCE VERTICAL SPEED IMMEDIATELY THE ADVISORY SOFTENS AND THE ARC OF RED VSI LIGHTS STARTS TO EXTINGUISH.

4. The following Enhanced RAs may follow one of the RAs listed above. They require a more positive response, either an additional 2 to 5 degrees in 3 seconds, or a reversal in about 5.:

   INCREASE CLIMB/DESCENT advisories follow an initial CLIMB/DESCEND. increase vertical rate to 2500fpm as indicated on the VSI.

   CLIMB/DESCEND NOW advisories indicate a change in direction of the avoiding manoeuvre is needed. Adjust vertical rate to 1500fpm in the opposite direction as indicated on the VSI.

5. The following Preventive RAs require no immediate changes in vertical rate when heard on their own. When issued following the RAs above, they allow return to the original clearance.:

   VERTICAL SPEED RESTRICTED, ensure vertical speed agrees with lighted VSI arc.

   MAINTAIN VERTICAL SPEED, self evident.

6. If the manoeuvre takes the aircraft away from a clearance, the non Handling pilot should inform ATC as soon as practicable.

7. When the CLEAR OF CONFLICT message is heard, return the aircraft to its last clearance at 500 fpm or less, or resume previous vertical rate, unless positive instructions from ATC to the contrary are received.

****
More separation is not necessarily better separation. Excessive vertical rates will only complicate the traffic situation.
****

****
Despite the apparent complexity of TCAS, it only tells you to go up, go down or stay where you are.
****

7. TCAS OPERATING PROCEDURES

NORMAL OPERATION

Due to the possibility of unusual vertical manoeuvres, keep seat belt signs ON below FL100.

Cockpit Preparation - Control Stand

TCAS Display Control..SET
Set BRT to suitable level, Range and Above/Below Switch as required.

TCAS XPDR Function switch..TEST
Hold to Test for 2 seconds; Xpdr fail- and TCAS recorder fail lights on for 2 seconds, then off; TCAS traffic display symbols appear and then disappear; VSI eyebrow lights cycle. Aural message 'Test Complete'. If any failure messages remain, or Xpdr or recorder fail lights remain on, contact ground engineer.

TCAS Recorder Function Switch..AUTO
If both disk full lights ON, contact ground engineer for disk change.

Before Takeoff

At 'Transponder.....SET AND ON':
TCAS XPDR Function Switch..TA/RA
Set Xpdr codes as required.

Taxy In

TCAS XPDR ....STBY

ABNORMAL PROCEDURES

TCAS FAIL (Fail flag in VSIs, TCAS Fail light ON)
TCAS XPDR Function switch..TEST
report failure messages in Tech Log. Testing system inhibits the transponder for some 20 seconds; overuse may cause ATC problems.
TCAS XPDR Function switch..TA/RA
If failure persists:
TCAS XPDR Function Switch.................................XPDR

TCAS XPDR Fail Lt ON

TCAS XPDR Function Switch..STBY
ATC 2 XPDR can be reinstated by ground engineering action at destination only. Flight must continue without transponder.

TCAS/GPWS Conflict. GPWS takes precedence

8. TCAS TRIAL PROCEDURES

1. OBSERVERS

There will be an observer on the jump seat for most flights with TCAS active. He/she will act as a back up to the recorder, whilst also being able to answer questions the recorder cannot, eg was the encounter IMC or VMC, was the traffic sighted, etc. The observers will be drawn equally from BA and the CAA/NATS; they will have been involved with the project for some time, and should be able to answer your queries. The second observer's seat on DK has been reactivated; we hope to include guest observers from industry throughout the trial on an opportunity basis.

2. TCAS AUTHORISATION

The TCAS equipment is only authorised for use in UK airspace, a restriction we hope to ease later. For practical purposes, UK airspace means being in contact with London or Scottish Control. Outside this area, the displays must be turned off using the brightness control; this leaves the computer and recorder active.

3. REPORTING PROCEDURE

Air Miss Reports must be filed as usual in the event of an actual air miss. An RA does not of itself constitute an air miss. Deviation from ATC clearance requires a written report under ANO 64(4), but an approved observer's report will suffice.

9. TCAS AURALS

TRAFFIC ADVISORY

TRAFFIC TRAFFIC

RESOLUTION ADVISORIES

Corrective

CLIMB CLIMB CLIMB

DESCEND DESCEND DESCEND

CLIMB CROSSING CLIMB, CLIMB CROSSING CLIMB

DESCEND CROSSING DESCEND, DESCEND CROSSING DESCEND

REDUCE VERTICAL SPEED, REDUCE VERTICAL SPEED

Enhanced

INCREASE CLIMB, INCREASE CLIMB

INCREASE DESCENT, INCREASE DESCENT

CLIMB CLIMB NOW, CLIMB CLIMB NOW

DESCEND DESCEND NOW, DESCEND DESCEND NOW

Preventive

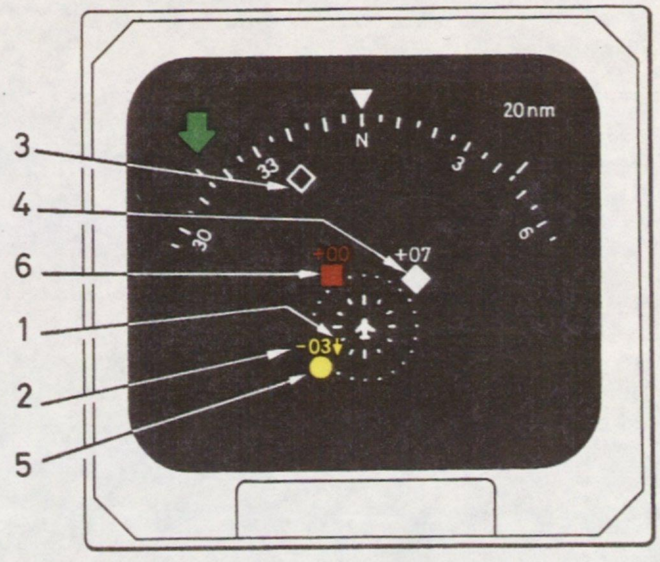
VERTICAL SPEED RESTRICTED, VERTICAL SPEED RESTRICTED

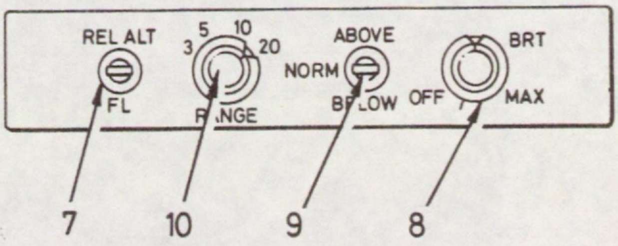
MAINTAIN VERTICAL SPEED, MAINTAIN VERTICAL SPEED

End of Encounter

CLEAR OF CONFLICT

TCAS TRAFFIC DISPLAY





1 Data Block (colour as target symbol)
- (↑) and (↓)
- Arrows indicate that the target is climbing or descending at not less than 500fpm.

2 - Relative Altitude in 100s of feet.

3 Target Symbols
- Open white diamond.
  - Non-threatening traffic

4 - Solid white diamond
- Non-threatening traffic within 1200ft and 4nm (traffic without mode C is assumed to be co-altitude, and will be displayed as solid symbol when within 4nm).

5 - Solid yellow circle.
  - Target subject of a Traffic Advisory (TA)

6 - Solid red square
  - Target subject of a Resolution Advisory (RA).

Range Rings
- Range rings are displayed depending on range selected.

- Range at Compass scale is range selected on range knob.

- 5nm ring (when appropriate) made of dots at 'hour' and 'half hour' positions

- 3nm ring (when appropriate) made of ticks at 'hour' positions.

7 REL ALT/FL switch
- Sprung loaded to REL ALT

- REL ALT displays rel alt of mode C targets

- FL (momentary contact) displays absolute FL of targets for 15 secs. Own FL is displayed in lower left corner. FL can appear as negative if traffic below 1013mb level, shown as eg -03.

8 BRT knob
- controls display brightness. OFF routes all TCAS outputs to recorder only.

9 ABOVE/NORM/BELOW Switch
- selects vertical range of non-threatening targets displayed.

- ABOVE, -2700ft to +7000ft rel alt.

- NORM, ±2700ft rel alt.

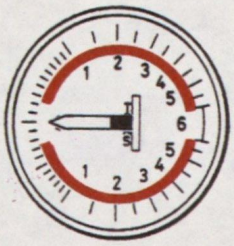
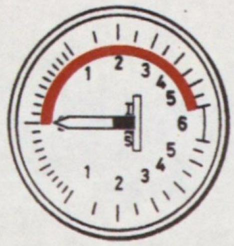
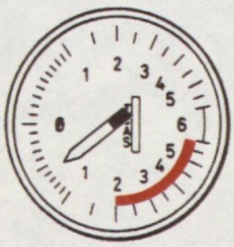
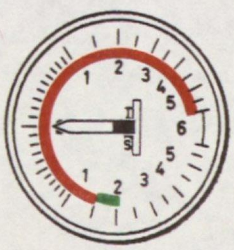
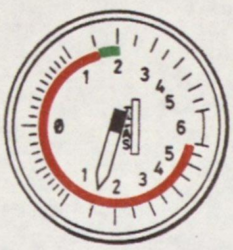
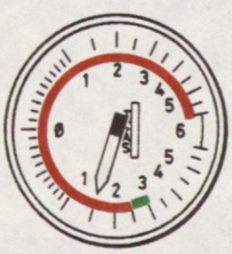
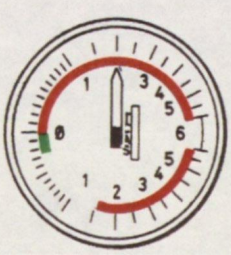
- BELOW, +2700ft to -7000ft rel alt

OWN AIRCRAFT just below centre

COMPASS ARC repeats Captains compass.

10 RANGE KNOB
- selects max horizontal display range. Selected range is repeated at top right.

EXAMPLES OF RESOLUTION ADVISORIES

AURAL WARNING	VSI INDICATION	TYPE	ACTION
MAINTAIN VERTICAL SPEED (TWICE)		PREVENTIVE	Do not reduce vertical speed below 3000 fpm
VERTICAL SPEED RESTRICTED (TWICE)		PREVENTIVE	Keep vertical speed within unlit area, there is traffic above and below.
VERTICAL SPEED RESTRICTED (TWICE)		PREVENTIVE	Do not climb, there is traffic above
VERTICAL SPEED RESTRICTED (TWICE)		PREVENTIVE	Do not increase descent beyond 2000 fpm
DESCEND (3 TIMES)		CORRECTIVE	Start descent at 1500 fpm now
CLIMB - CLIMB NOW (TWICE)		CORRECTIVE	Cancel descent promptly climb at 1500 fpm. Traffic has manovured invalidating original advisory.
INCREASE DESCENT (TWICE)		CORRECTIVE	Promptly increase descent at 2500 fpm
REDUCE VERTICAL SPEED (TWICE)		CORRECTIVE	Level off, but do not descend at more than 1500 fpm. There is traffic above and below.

Quiz

1. TCAS is designed to:

   a aid the controller,
   b allow pilot to perform air traffic control tasks,
   c serve as backup to the system.

2, TCAS:

   a interrogates other transponders,
   b listens to transponder replies to ATC,
   c interrogates mode S transponders only.

3. TCAS requires other aircraft to be:

   a Mode S equipped,
   b Mode C equipped,
   c Mode C, Mode A, or Mode S equipped

4. TCAS gives an advisory whenever

   a An intruder gets within a certain distance,
   b an intruder is within a certain time of close approach,
   c when traffic is detected.

5. Which of the following appear during Traffic advisories?

   a Aural message,
   b amber caution lights,
   c yellow squares.

6. TA is accompanied by VSI lights?

   a True
   b False

7. TA tells you to manoeuvre?

   a True
   b False

8 How would you be advised of 'altitude unknown traffic'?

   a blank alt block,
   b ?? in the alt block
   c XX in the alt block

9. TA No bearing

   a will not be a threat,
   b may turn into a threat.
   c Is too far away to be displayed.

10 TA offscale:

a is to far away to be seen,
b can be brought on scale by change of range,
c has no bearing information.

11 TA symbols are:

a yellow circles,
b yellow diamonds,
c yellow squares

12. A yellow arrow appears at 10 o'clock on the edge of the traffic display;

a there is a TA offscale,
b there is a RA offscale,
c the time is ten o'clock

13 How quickly does TCAS expect you to react to an RA?

a 3 seconds
b 5 seconds
c 5 seconds except for an enhanced RA, 3 seconds

14. An Upward arrow alongside a target means

a the target is above,
b the target is climbing,
c the target is increasing its vertical distance from you.

15. You should inform ATC of every TA.

a true
b false

16. You should inform ATC of:

a every RA,
b RAs that cause you to deviate from clearance,
c no RAs at all ,they must not know you are TCAS equipped

17. CLIMB CLIMB CLIMB means you should climb at

a 1500,
b 1000,
c 2500fpm

18. REDUCE VERTICAL SPEED will be accompanied by

a red arc,
b red arc + green sector,
c no lights on the VSI

19. CLIMB CROSSING CLIMB means that

a you may cross the intruder's current altitude in a manouevre,
b the intruder is projected to cross your altitude,
c you should change from descent to climb

20. MAINTAIN VERTICAL SPEED will be accompanied on the VSI by:

a no lights,
b red arc
c red and green arc

21. If there is an observer on board you need not fill in any air miss report in the event of an airmiss.

a true
b false

22. TCAS fail lt on means

a Mode S Xpdr has failed,
b you should select no2 Xpdr,
c you should test TCAS.

23. Xpdr fail lt on,

a reselect no 2 Xpdr,
b you will be AOG at next stop,
c the No 2 Xpdr can be reconnected at next stop.

24. First action on TA should be

a look out
b look at traffic display,
c avoid traffic.

25. You have identified traffic which is thought to be a threat and you receive a TA, you can manoeuvre.

a true
b false

26. You identify traffic which you determine not to be a threat. You then receive an RA. You must follow the RA

a true
b false

27. You receive an TA in IMC followed by an RA from traffic to the right of the aircraft. The Co-pilot is handling the aircraft.

a The Capt should take-over,
b The co-pilot should follow the RA,
c You should do nothing because you cannot identify the threat.

28. You receive a CLIMB RA, and start to climb. The red lights from +1500fpm through to zero extinguish, and you hear VERTICAL SPEED RESTRICTED. You should then:

a Maintain the current rate of climb
b Reduce the rate of climb
c Increase the rate of climb.

29. You are in a left turn when you receive a DESCEND RA. You should:

a. Maintain the turn and start to descend,
b Level the wings and descend
c Level the wings and level off.

30. There is no observer on board;

a You cannot operate TCAS
b You may operate TCAS as if the observer were present
c You may operate TCAS but must complete a written report if you deviate from an ATC clearance.

31. You are in cruise at FL330

a TCAS can only give DESCEND commands, and the above/below switch must be at BELOW
b TCAS can only give DESCEND commands, but you can operate the display as you wish
c TCAS can give any command other than CLIMB

32 After a RA, the Traffic symbol disappears, and RA NO BRG is shown.

a The threat is still present, but its bearing is unknown
b The threat has gone away.
c The threat is still present, and changing scale will bring it back on screen.

33. An Open diamond with no data block changes to a solid diamond.

a The traffic is now within 4nm
b The traffic is within 1200ft
c The traffic is the subject of a TA.

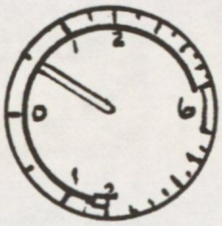
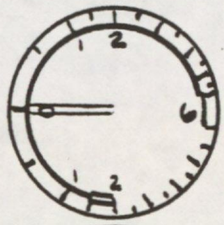
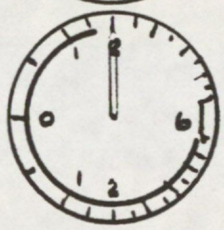
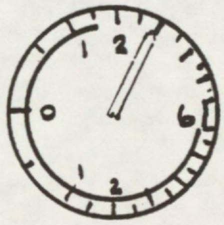
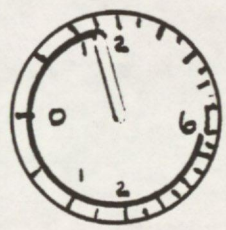
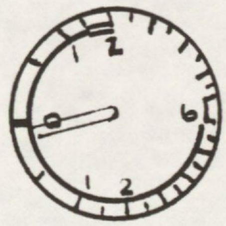
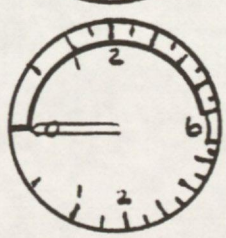
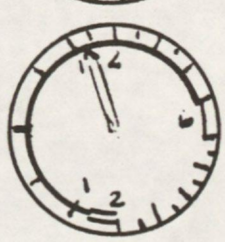
34. You see traffic that is not shown on the traffic display.

a It is not a threat.
b It has no transponder
c If it seems threatening, you should not wait for a TCAS warning before taking action.

35 You see traffic on the display at your level, converging. to avoid an abrupt manoeuvre later, it is best to start a gentle manoeuvre without waiting for an RA.

a True
b False

Select the correct vertical speed in each of the folowing situations:

AURAL	VSI
36. DESCEND DESCEND...	
37. DESCEND CROSSING DESCEND	
38. VERTICAL SPEED RESTRICTED	
39. VERTICAL SPEED RESTRICTED	
40. MAINTAIN VERTICAL SPEED	
41. CLIMB CLIMB CLIMB	
42. MAINTAIN VERTICAL SPEED	
43. DESCEND DESCEND NOW	

APPENDIX 3

'TCAS II FLIGHT TRIAL NOVEMBER/DECEMBER 1989 – EVALUATION OF OBSERVATIONS',

CAPT. T H SINDALL, 19 NOVEMBER 1990

TCAS II FLIGHT TRIAL NOVEMBER/DECEMBER 1989 – EVALUATION OF OBSERVATIONS

Introduction

TCAS has been designed to provide pilots with advice on manoeuvres they should initiate so as to achieve separation from conflicting traffic in the event that this need should arise. If the equipment fulfils this function reliably and efficiently it should reduce the possibility of mid-air collisions: an assessment now needs to be made as to the extent to which contemporary equipment satisfies the design objectives.

The BA B737 flight trial conducted in November/December 1989 provided an opportunity for representatives of several disciplines (airline, regulatory, air traffic services, scientific) to observe the displayed elements of TCAS II (MOPS 6 standard) working within the European air traffic environment. Results thus obtained supplemented those acquired earlier through on-board data records compared by RSRE Malvern with data provided by UK area radar.

The aim of this paper is to summarise observations made in the course of the BA flight trial concerning TCAS II performance, and to suggest the role that TCAS equipment might reasonably be expected to perform in future years.

Results

The equipment carried on board the BA B737 in November/December 1989 was not certificated to allow the production of resolution advisories (RAs): evaluation was therefore limited to observing symbols displayed full-time on the dedicated CRT, the production of traffic advisories (TAs), and functions achievable by operating switches on the control panel. Assessment was also made of the effectiveness of training provided to B737 fleet pilots. Results were as follows:

(a) *Information Displayed on a Dedicated CRT*: Symbols representing proximate traffic and associated data blocks were thought generally to be easy to assimilate, and effective in aiding visual acquisition of adjacent aircraft. However, unlike information displayed on weather radar CRTs (storm centres, coastal features), TCAS symbols suffered from a variety of disturbances that weakened their credibility. Symbols representing proximate traffic would frequently disappear, then reappear; sometimes they would 'jump' from one position on the screen to another; on occasion they would appear momentarily in 2 adjacent positions, or overlap; and sometimes single, some or all would 'swim' across the display. Altitude differences displayed in data blocks were relatively constant, and generally seemed believable.

Some pilots considered the constant display of symbols to be distracting. Certainly the disturbances described above detracted from the degree to which confidence might be held in the ability of TCAS to provide a true picture of aircraft in the adjacent airspace. On this basis it would seem likely that pilots might be disinclined to manoeuvre on the basis of displayed information alone (ie no visual sighting), but spend excessive time watching the display in order to appreciate the true nature of what was being shown.

(b) *Traffic Advisories:* A significant proportion of TAs were produced by non altitude-reporting transponder-equipped aircraft. These tended to occur mainly at times when flight deck workload was relatively high (initial departure, positioning for final approach to land) and were unquestionably a distraction to the pilots.

TCAS assumes non altitude-reporting transponder returns to be co-altitude. If pilots assume this too, and cannot sight the traffic (too busy, IMC) it follows that they must be concerned and thus suffer distraction. On the other hand, if they assume that TAs such as these are most likely to be generated by traffic well below them (as may often be the case with general aviation aircraft), they now show an element of complacency that might be interpreted as a lack of confidence in the overall capability of TCAS to provide alerts of 'real' conflicts. In either situation TAs such as these will be considered a nuisance.

(c) *Control Panel Functions:* The scope of options available to adjust the display of proximate traffic seemed reasonable, albeit not appreciated by many of the crews, some of whom were apparently unaware also of the test function intended to be used prior to departure.

(d) *Training:* A general lack of understanding as to what TCAS displays might be able to provide, the functions of the control panel, and a frequently-expressed opinion that everything associated with RAs seemed complex, suggested that the level of training and testing provided for pilots expected to be involved in the trial was somehow inadequate. Consideration will have to be given in future to including some form of enhanced instruction, possibly including formal lectures, inter-active training devices, and flight simulator exercises.

Most of the problems appeared to stem from the several different RAs that might be produced by TCAS, and the reactions these would require of crews: much of the training supplement content had been directed at this aspect of the equipment.

Discussion

A full-time display should assist pilots monitor the relative positions of proximate traffic and so become aware of possible conflicts before they turn into TAs and, occasionally, RAs. This benefit is eroded when the quality of the information is weakened through disturbances to displayed symbols.

Distractions caused by nuisance TAs should be reduced to a practical minimum. As TCAS can be used anywhere in the world it will not be sufficient to legislate only at national level to encourage or require carriage of altitude-reporting transponder equipment. Other solutions should be considered.

Conclusion

It is not apparent that TCAS II totally satisfies the design objective of operating reliably and efficiently to advise pilots of conflicting traffic. Disturbances to symbols displayed on CRTs have the potential to erode credibility in the equipment, nuisance TAs may cause distraction, and the current range of potential RAs has called into question the adequacy of the training provided.

If TCAS is to be effective as an aid to flight safety, pilots must have faith in its ability to alert and warn only when the need arises, and they must be able to respond correctly – in timely fashion and with certainty that the manoeuvre they have been advised to make does not erode other safety precautions.

TCAS II is handicapped in that it may only produce RAs that relate to manoeuvres made in the vertical plane. The Rules of the Air, and practice adopted by Air Traffic Controllers, commonly expect enhanced separation to be achieved by a change of heading, not by a short-term change of altitude. Is the philosophy behind TCAS II sound, or does the solution lie only in equipment capable of prompting manoeuvres also (or only) in the horizontal plane?

More research seems to be needed before any case for requiring carriage of TCAS II in its current state can be justified. The product is not yet fully developed.

Recommendations

It is recommended that:

(a) Improvements should be made to the quality, reliability and accuracy of displayed data.

(b) Solutions should be sought, and implemented, to reduce the incidence of nuisance TAs: global operation of TCAS equipment should be borne in mind.

(c) Pilot training programmes should take due account of the apparent complexity of responses required to be made to the range of RAs capable of being produced by current (MOPS 6) TCAS equipment.

(d) Consideration should be given to delaying the formulation of standards and recommended procedures until the concept of TCAS II, as it relies solely on RAs that require manoeuvres to be made only in the vertical plane, be proven beyond reasonable doubt.

(e) Until such time as reasonable confidence is gained in the ability of TCAS to operate reliably and efficiently, there should be no recommendation to require carriage of this equipment in UK-registered aircraft.

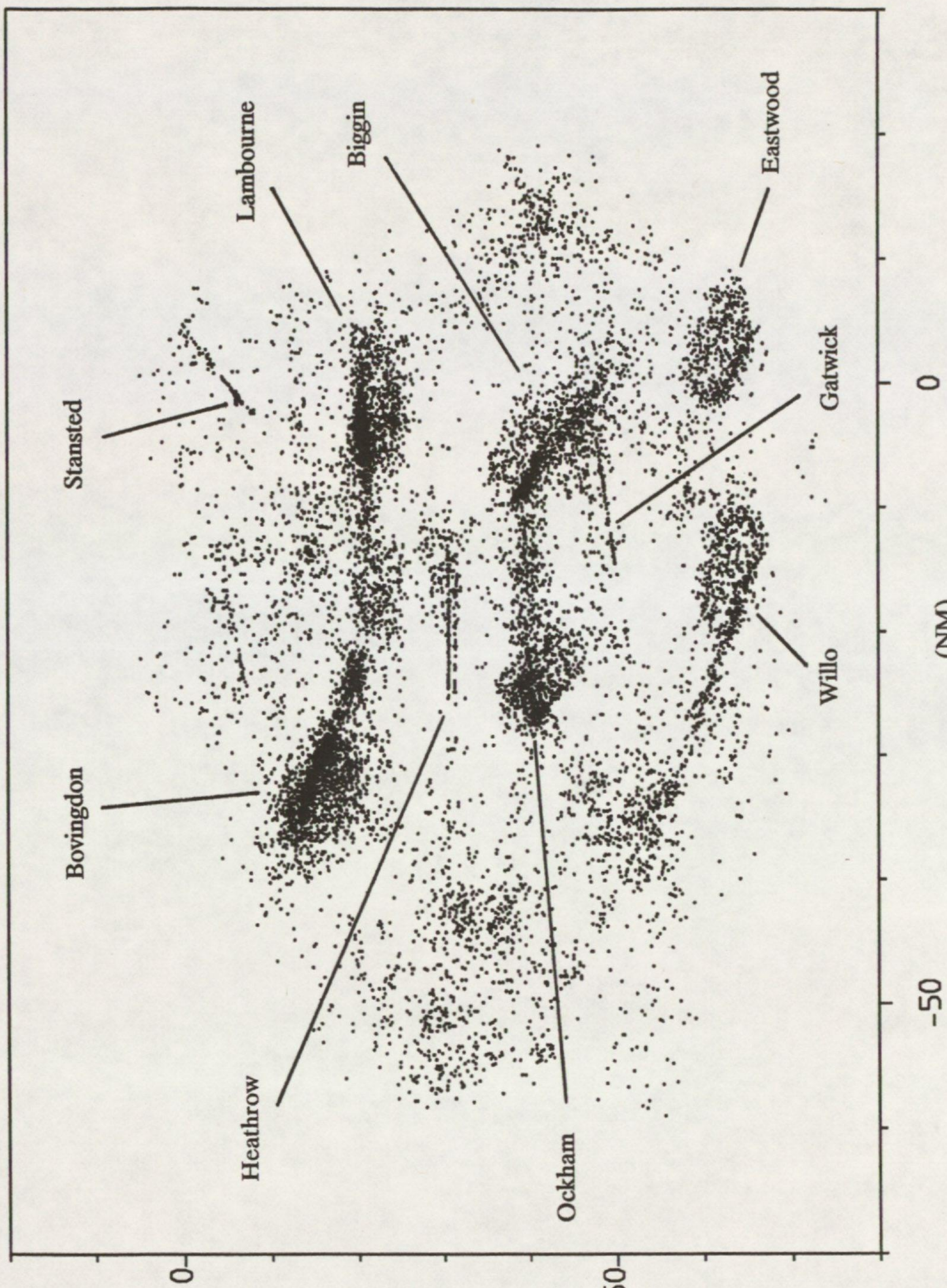
T H Sindall
Head of PT Standards

19 November 1990

APPENDIX 4

POTENTIAL DISTRIBUTION OF TCAS TAS IN THE LONDON TMA

1987 TAs (LTMA)



The potential distribution of TCAS TAs in the London TMA is illustrated in the figure above. It was generated by processing 3 months of ATC ground radar data collected during the summer of 1987 and identifies encounters that would have caused a TA had TCAS been fitted. For the purposes of the processing, it has been assumed that only aircraft with SSR codes corresponding to the conduct of IFR flight under civil ATC would be TCAS equipped. The diagram shows the position of each such aircraft at the point of closest approach in the TA encounter. The logic used for the TCAS simulations was Change 6, i.e. that currently installed in most equipped aircraft* and also used in the retrospective reprocessing of the data collected on the BA B737 during the UK Trial.

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* It is understood that one manufacturer has modified the TA logic in some of their equipments in order to reduce the frequency of TAs.