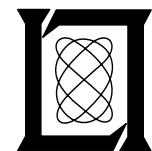


Mode S Beacon System: A Functional Overview

V.A. Orlando

29 August 1989

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18. Abstract This document provides a functional overview of the Mode S Beacon System, a combined secondary surveillance radar (beacon) and ground-air-ground data link system capable of providing the aircraft surveillance and communications necessary to support ATC automation in future traffic environments. Mode S is capable of common-channel interoperation with the current ATC beacon system, and may be implemented over an extended transition period. Mode S will provide the surveillance and communication performance required by ATC automation, the reliable communications needed to support data link services, and the capability of operating with a terminal or enroute, radar digitizer-equipped, ATC surveillance radar. The material contained in this document serves as an introduction to the more detailed information contained in "Mode S Beacon System: Functional Description," DOT/FAA/PM-86/19, 29 August 1986.					
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INTRODUCTION

Mode S is a combined secondary surveillance radar beacon system and ground-air-ground data link system capable of providing the aircraft surveillance and communications necessary to support air traffic control in the dense traffic environments expected in the future. It is capable of common-channel interoperation with the current Air Traffic Control Radar Beacon System (ATCRBS), and thus may be implemented at low user cost over an extended ATCRBS-to-Mode S transition period. In supporting ATC automation, Mode S will provide the accurate surveillance needed to support automated decision making, and the reliable communications needed to support data link services. In order to meet these requirements at en route facilities, Mode S sensors may operate with back-to-back beacon antennas to provide twice the beacon data rate available from a standard antenna. When operating in conjunction with a terminal or en route digitizer-equipped, ATC surveillance radar, a Mode S sensor will use the radar returns either to reinforce beacon tracks, or in cases of absence or failure of a transponder, to provide radar target reports.

A central Mode S design requirement was to assure that the system could be implemented in a evolutionary manner. By the time deployment of Mode S begins in 1991, there will be approximately 200,000 aircraft equipped with ATCRBS transponders and 500 ground-based interrogators. Mode S is designed to operate in this environment, in a way that would permit the gradual transition to all-Mode S operation.

The capability for such a transition has been achieved by providing a high degree of compatibility between Mode S and ATCRBS. Mode S uses the same interrogation and reply frequencies as ATCRBS, and the signal formats have been chosen to permit substantial commonalty in hardware. This degree of compatibility permits an economic and smooth transition, in which (a) Mode S interrogators will provide surveillance of ATCRBS-equipped aircraft, and (b) Mode S transponders will reply to ATCRBS interrogators.

Thus, Mode S equipment, both on the ground and in aircraft, can be introduced gradually and continue to interoperate with existing systems during an extended transition phase.

REPORT OVERVIEW

This report presents a functional overview of the Mode S system. It is intended to complement, and serve as an introduction to, the more detailed description of Mode S contained in the Mode S Beacon System Functional Description.*

The report begins with a definition of the current Air Traffic Control Radar Beacon System . This is followed by a description of the ATCRBS limitations that are observed in regions of high traffic and sensor density.

Next, details of Mode S are presented with emphasis on the improvements provided by the monopulse direction finding techniques and the specific features provided by Mode S surveillance and its integral data link.

This is followed by a description of the field measurements that were made to validate the Mode S design.

The report concludes with a summary of the key points.

* Project Report ATC-42D, Lincoln Laboratory, M.I.T. (29 August 1986), DOT/FAA/PM-86/19.

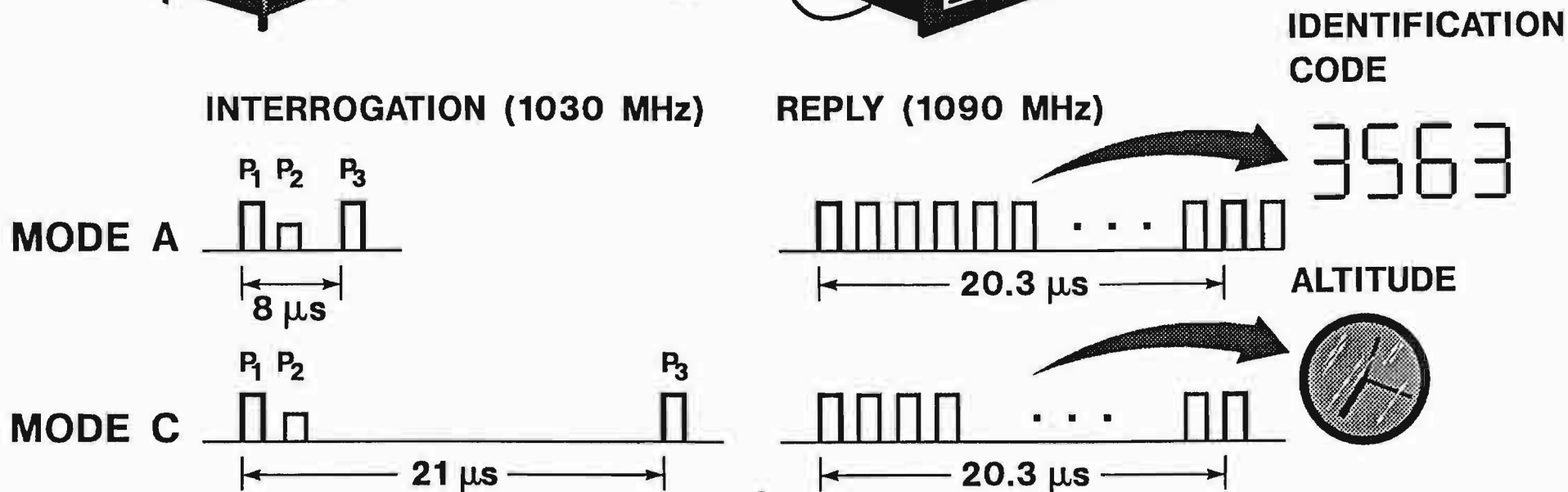
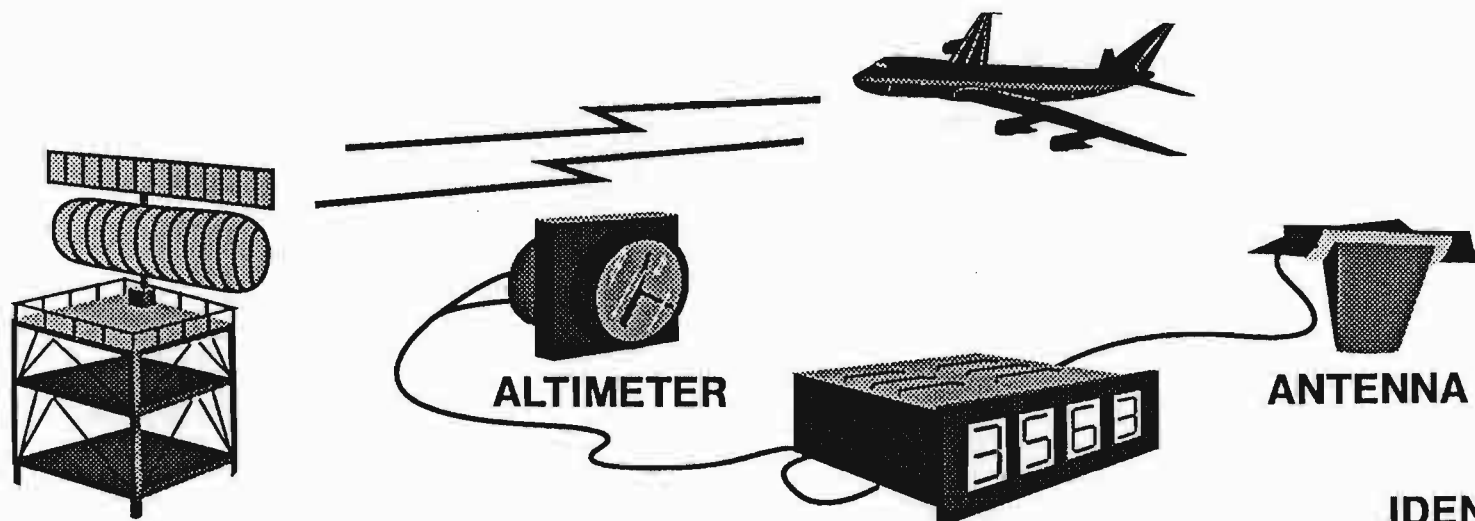
OUTLINE

- ➡ • **ATCRBS**
 - **DEFINITION**
 - **LIMITATIONS**
- **MODE S**
 - **MONOPULSE**
 - **SURVEILLANCE**
 - **DATA LINK**
- **DESIGN VALIDATION**
- **SUMMARY**

AIR TRAFFIC CONTROL RADAR BEACON SYSTEM

The operation of the current Air Traffic Control Radar Beacon System is illustrated schematically in the figure. The antenna used for ATCRBS is typically mounted above the antenna used for the primary radar. It has a fan beam pattern with a horizontal beam width of 2 to 3 degrees. The scan rate of the antenna is 4.8 seconds for a sensor used at a terminal and 10 to 12 seconds for an en route radar. Two types of interrogations are used for civil transponders. Mode A, which has an 8 microsecond P1-P3 spacing, elicits a 20.3 microsecond reply containing one of 4096 pilot-entered identity codes. Mode C, which has a 21 microsecond P1-P3 spacing, elicits a similar reply containing the aircraft's barometric altitude, referenced to standard atmospheric conditions. The purpose of the P2 pulse is described on the following figure.

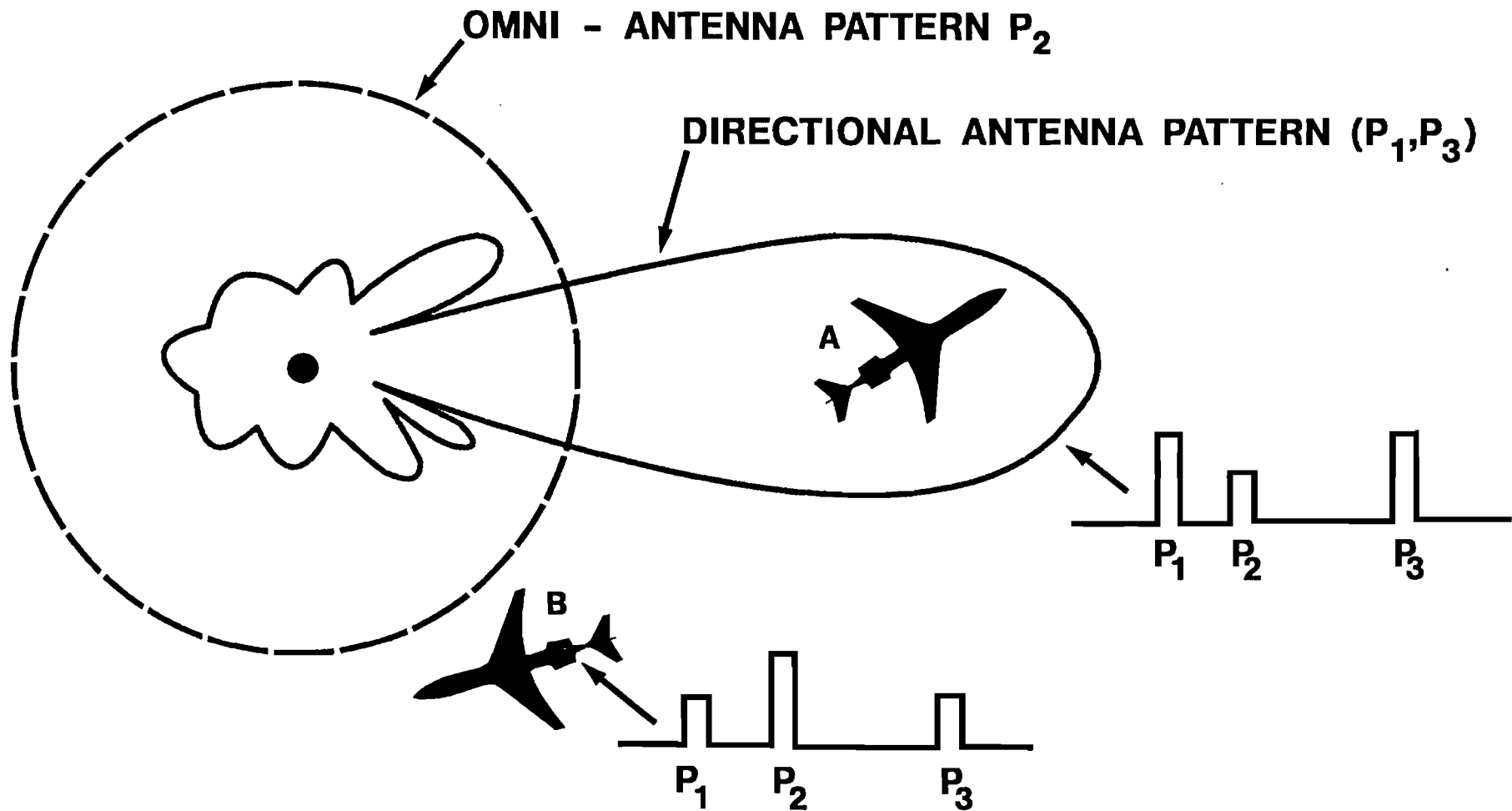
AIR TRAFFIC CONTROL RADAR BEACON SYSTEM (ATCRBS)



ATCRBS TRANSMIT SIDELOBE SUPPRESSION (SLS)

At short ranges, the signal strength may be sufficient to interrogate transponders via leakage through the antenna sidelobes. To control this phenomenon, aircraft in the antenna sidelobes are prevented from replying by a technique known as transmit sidelobe suppression. The P2 pulse of interrogation is transmitted on an omni-directional antenna at a slightly higher power level than the interrogatory power produced by the antenna sidelobes. Transponders are designed to reply only if the received P1 pulse is greater than the received P2 pulse. This condition is not satisfied in the sidelobes of the antenna.

SLS OPERATION



ATCRBS LIMITATIONS

While the current ATCRBS system satisfies operational requirements in most airspace, limitations to its performance can be observed in regions of high traffic density and high sensor density. The principal limitations are indicated on the figure.

Synchronous garbling and azimuth accuracy considerations are described in connection with the next two figures. A description of the remaining limitations is as follows:

- Fruit This is the name applied to replies received to interrogations from neighboring sensors. These unwanted replies are not synchronized with the local sensor's interrogations, and are thus received at random times. The presence of these replies can interfere with the reception of a wanted reply. High fruit rates can produce a detectable decrease in performance. The use of high pulse repetition frequencies (PRFs) for sliding window detection contributes to this problem.
- Over-interrogation In a region with many sensors, a transponder will receive a high rate of interrogations and suppressions. Thus, a transponder may be unable to reply when it receives an interrogation from the local sensor. This condition is made worse by the use of high PRF.
- Aircraft Identification In many regions of the world, the limit of 4096 different Mode A codes is insufficient to cover operational needs.

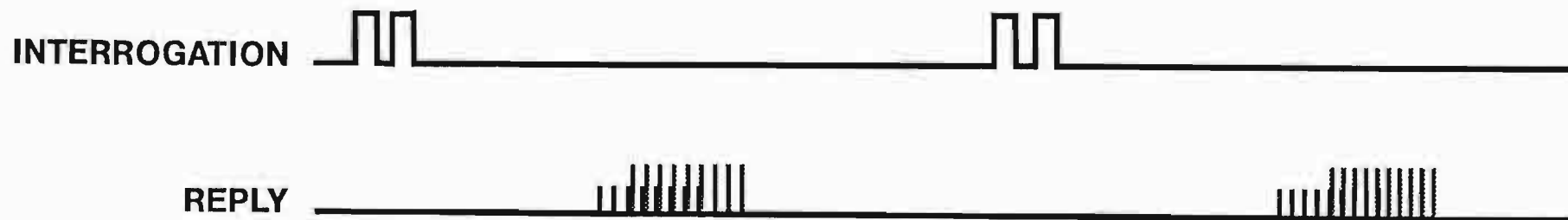
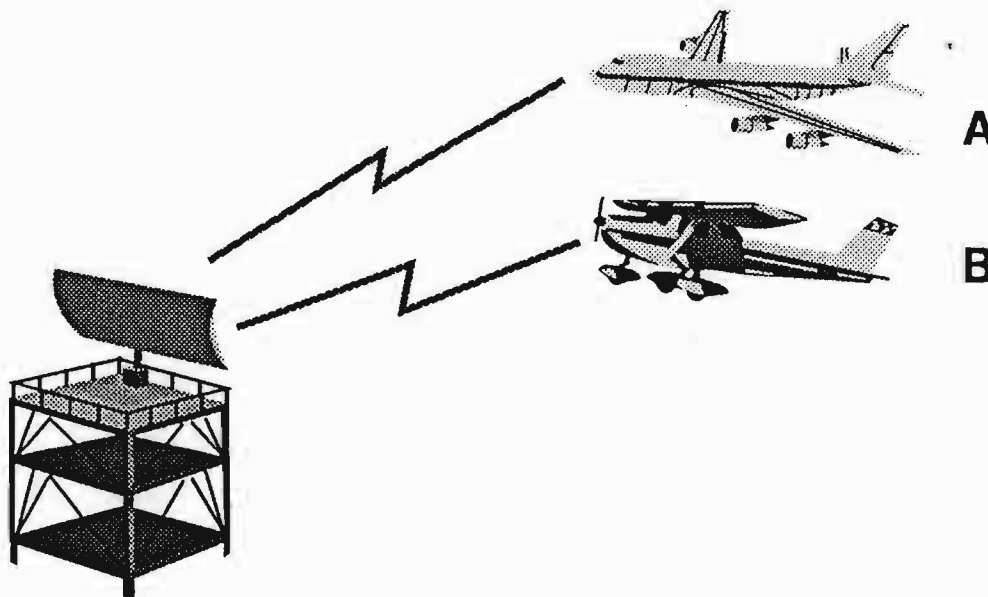
ATCRBS LIMITATIONS

- **SYNCHRONOUS GARBLING**
- **AZIMUTH ACCURACY**
- **FRUIT**
- **OVERINTERROGATION**
- **AIRCRAFT IDENTIFICATION**

SYNCHRONOUS GARBLING OF ATCRBS REPLIES

When two ATCRBS aircraft (shown as A and B on the figure) are near the same azimuth and slant range from the ATCRBS sensor, the transmitted interrogation elicits replies from both transponders at about the same time. The resulting overlap of reply pulses can lead to missing or incorrectly decoded replies, with a resulting loss of information on the controller's display. This condition persists until the aircraft change their relative positions. The reply overlap can therefore last for many scans, hence the name synchronous garble. Note that the aircraft do not have to be close to each other in altitude for garbling to occur.

SYNCHRONOUS GARBLING OF ATCRBS REPLIES



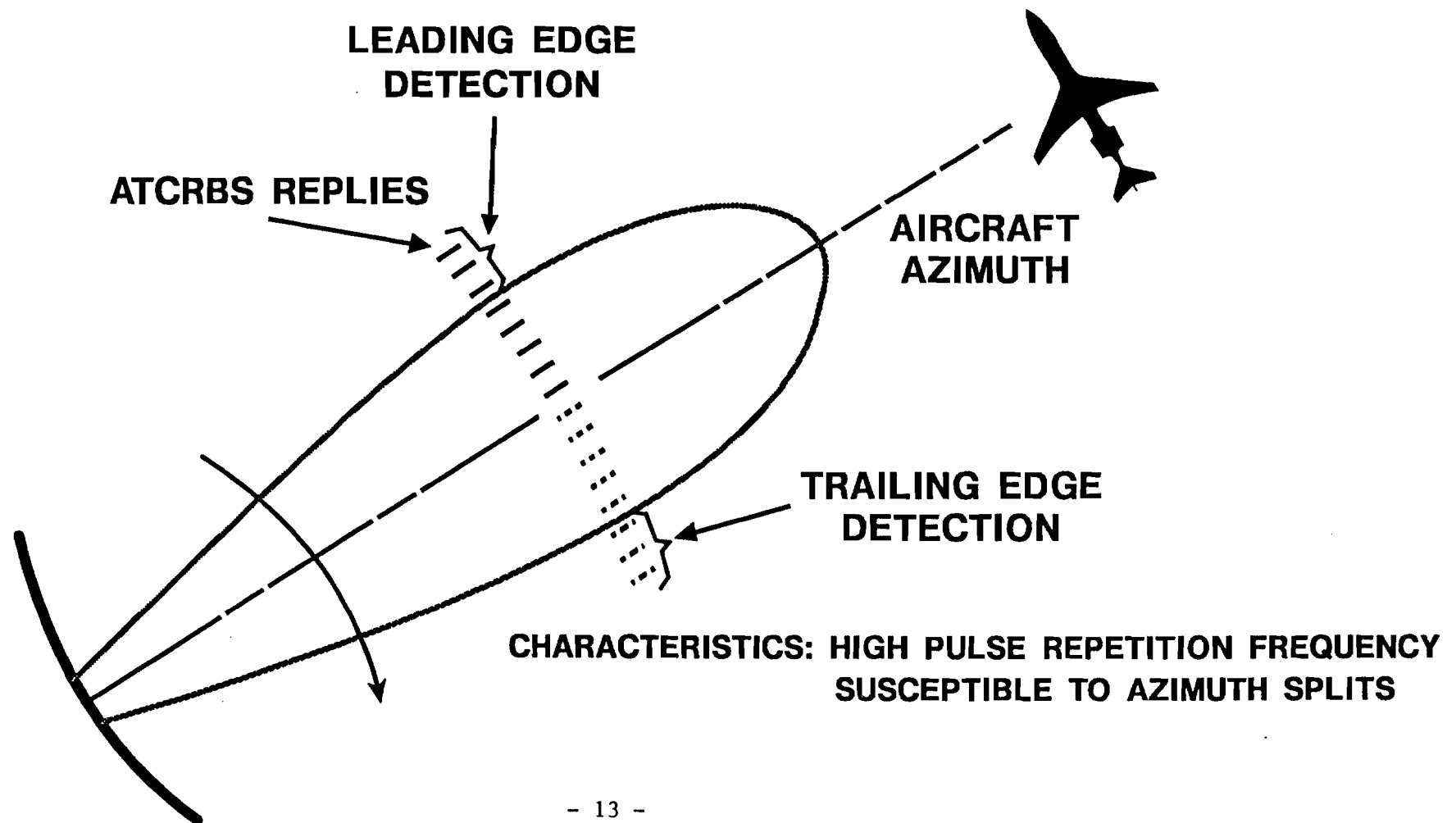
AZIMUTH ACCURACY

Current ATCRBS sensors in the United States determine an aircraft's azimuth by a technique called sliding-window detection. This technique determines azimuth by center marking the series of replies received as the sensor antenna beam scans past the aircraft. The beginning of the reply run length is determined by a leading edge detector. This is accomplished by detecting the presence of "m" replies out of the previous "n" reply opportunities (i.e., the listening interval following an interrogation). A similar technique is used for trailing edge detection. Once the leading and trailing edges have been determined, the aircraft azimuth is determined as the center of the run length, plus an offset to account for the bias introduced by the edge detectors.

An accurate determination of aircraft azimuth using a sliding-window detector requires that the interval between successive replies be relatively small. Typically, a PRF of approximately 400/second is used. This PRF produces the 15 or more replies required for sliding window beam splitting. This high PRF can interfere with the operation of neighboring sensors.

A second characteristic of a sliding-window beam splitter is its susceptibility to azimuth splits. This occurs when interference or blockage causes a loss of replies in the center of reply run length. This causes the false declaration of a trailing edge followed by a leading edge and results in the declaration of two target reports (from the one aircraft), neither of which contains the correct azimuth.

SLIDING WINDOW DETECTOR



OUTLINE

- **ATCRBS**

- **DEFINITION**
- **LIMITATIONS**

- ➡ • **MODE S**

- **MONOPULSE**
- **SURVEILLANCE**
- **DATA LINK**

- **DESIGN VALIDATION**

- **SUMMARY**

MONOPULSE TECHNIQUE

The Mode S sensor uses a technique known as monopulse for determining aircraft azimuth. Monopulse azimuth determination is based upon the use of an antenna that has multiple patterns.

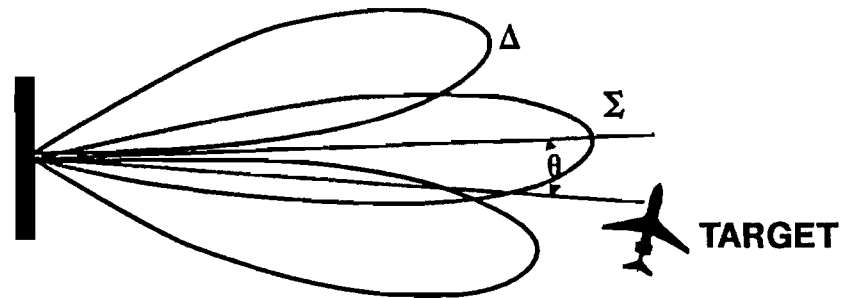
- Sum Beam. This is labelled Σ in the figure. It is equivalent to the single main beam in non-monopulse antennas.
- Difference Beam. This is labelled Δ in the figure. It is composed of two lobes with a null on antenna boresight.

When a reply is received from a target at angle Θ off boresight, it produces a different signal amplitude out of the receivers associated with the sum and difference beams. The monopulse processor produces a signal which is a function of Δ/Σ i.e., the ratio of the signal amplitudes in the difference and sum channels). This Δ/Σ value is used to obtain the off-boresight angle Θ by reference to a curve Δ/Σ versus Θ . This curve is determined by calibrating the sensor against a fixed transponder located near the sensor.

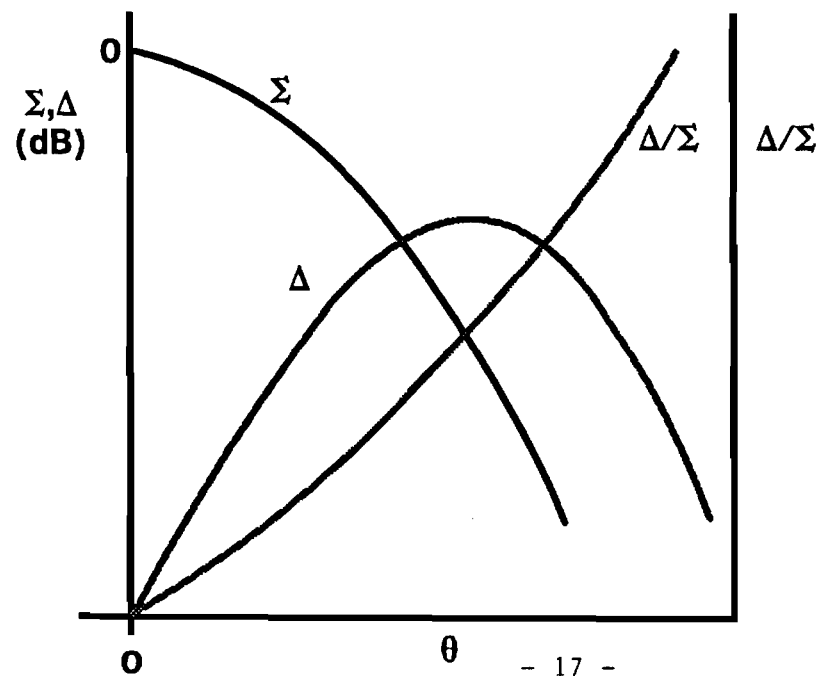
The use of monopulse makes it possible to estimate azimuth for each reply and therefore eliminates the principal mechanism that can cause an azimuth split.

MONOPULSE TECHNIQUE

- SUM & DIFFERENCE RECEIVE PATTERNS



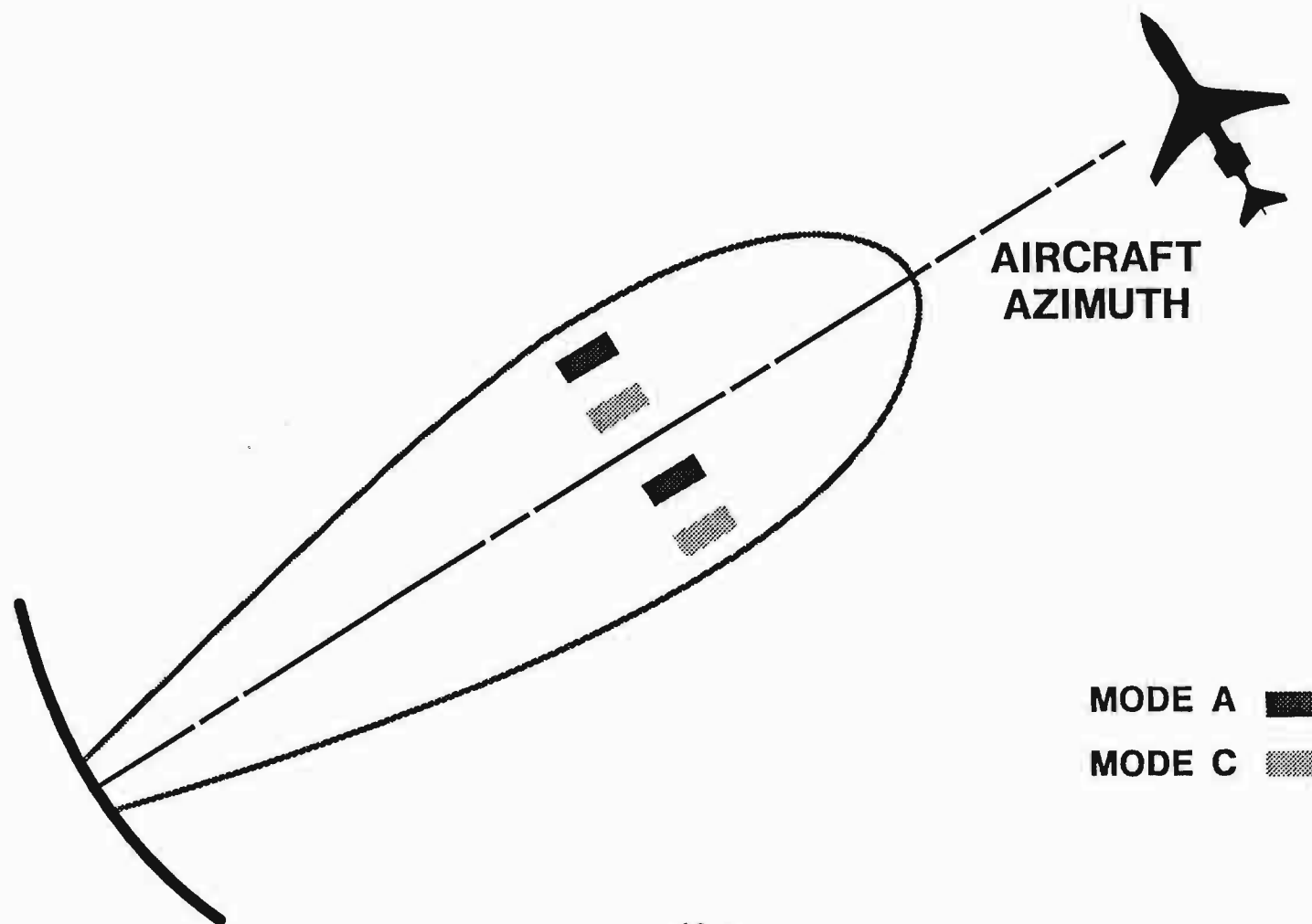
- MONOPULSE CHARACTERISTICS



ATCRBS MONOPULSE AZIMUTH DETERMINATION

The use of monopulse makes it possible to perform surveillance of ATCRBS at a very low interrogation rate. In principal, surveillance could be performed on as little as one Mode A and one Mode C reply opportunity per scan. In practice, additional replies are needed to ensure correct Mode A and C code reception and to suppress false alarms. The Mode S sensor interrogates at a rate sufficient to elicit two replies for each ATCRBS mode within the antenna 3 dB beamwidth (2.4°). This leads to a PRF of approximately 100/second.

ATCRBS MONOPULSE INTERROGATION RATE

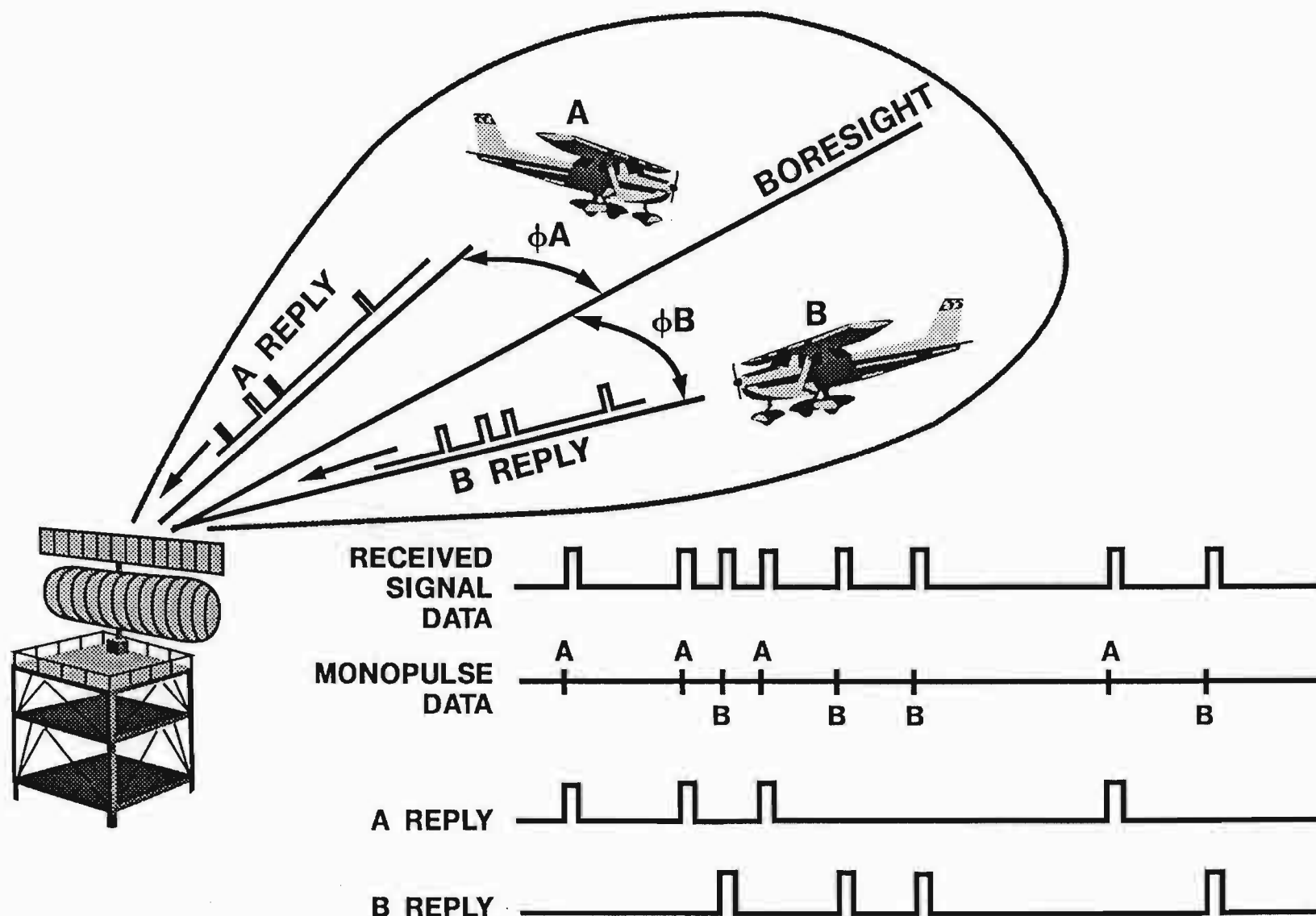


MONOPULSE DEGARBLING OF ATCRBS REPLIES

A second benefit of monopulse is in the degarbling of ATCRBS replies. The figure shows two aircraft (labelled A and B) simultaneously in the main beam and near the same slant range. The received signal data shows an interleaved mix of code pulses from the two aircraft. Reference to the monopulse data for each code pulse makes it easy to correctly sort the pulses into the appropriate reply.

In the example shown, the pulses are not overlapped, and hence could have been sorted into the correct replies based upon the use of pulse timing data. However, monopulse degarbling will continue to function in instances of pulse overlap that could not be resolved by timing alone.

MONOPULSE DEGARBLING OF ATCRBS REPLIES



MODE S SURVEILLANCE

The principal characteristics of Mode S surveillance are as follows:

- Selective addressing. Mode S signal formats provide for the selective interrogation of individual Mode S transponders. Over 16 million addresses are provided, enough for each aircraft in the world to have its own unique address.
- Monopulse Direction Finding. The development of monopulse was critical to Mode S, since selective addressing makes it impractical to use a sliding-window detector. That is, there is insufficient channel time to selectively interrogate each aircraft 15 or more times.
- Error Detection/Correction. The Mode S coding structure provides for a high degree of error detection (less than one undetected error in 10^8 messages). In addition, error correction is provided on the downlink.
- Single Surveillance Interrogation/Reply per Antenna Scan. The use of monopulse, together with a more capable message structure that provides altitude and the Mode S address in a single reply, makes it possible to perform routine surveillance with one transaction (i.e., interrogation/reply) per scan.
- Adaptive Reinterrogation. The use of selective addressing makes it possible to reinterrogate an aircraft when necessary, without receiving replies from all of the other aircraft in the beam. This makes it possible to schedule a second (and subsequent) interrogation to an aircraft when the expected reply was not received. Reinterrogation can significantly improve the probability of detecting an aircraft that is in a marginal signal condition due, for example, to aircraft banking.
- All-Call Acquisition. Provision is made for a Mode S sensor to obtain the address of an aircraft without any prior knowledge. This is done by periodically transmitting an "all-call" interrogation. This interrogation elicits replies from Mode S aircraft that are not currently being selectively interrogated.
- Lock Out. Once a Mode S aircraft is acquired via the all-call interrogation, it is instructed to not reply (i.e., to lock out) to future all call interrogations. This reduces the probability of synchronously garbling all-call replies.

MODE S SURVEILLANCE

- **SELECTIVE ADDRESSING**
- **MONOPULSE DIRECTION FINDING**
- **ERROR DETECTION/CORRECTION**
- **SINGLE SURVEILLANCE INTERROGATION/REPLY PER SCAN**
- **ADAPTIVE REINTERROGATION**
- **ALL-CALL ACQUISITION**
- **LOCKOUT**

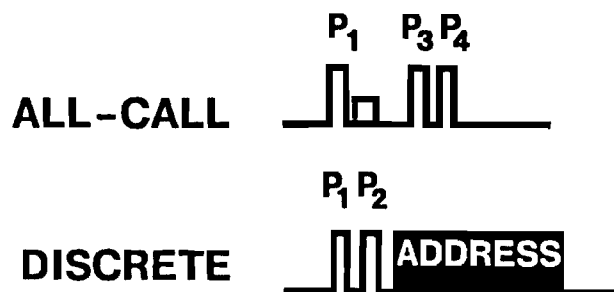
BASIC MODE S SURVEILLANCE INTERROGATION/REPLY FORMATS

The basic surveillance formats are as follows:

- All-Call Interrogation. This interrogation contains the same P1, P2, and P3 pulses used for ATCRBS interrogations. An additional pulse, P4, labels this interrogation as originating from a Mode S sensor. The P4 pulse is not detected by an ATCRBS transponder, so it replies with the appropriate Mode A or Mode C reply, depending on the spacing of the P1 and P3 pulses. A Mode S transponder detects the P4 pulse and replies with an all-call reply if it is not in a state of lockout. Thus one interrogation can satisfy both ATCRBS and Mode S All-Call requirements. Because of this it is also referred to as the Mode A/C/S All-Call. Note that a Mode S transponder never generates an ATCRBS reply to a Mode S sensor's Mode A/C/S All-Call interrogation. This is important since it means that there is no possibility that a Mode S aircraft will be reported as both a Mode S and an ATCRBS aircraft.
- All-Call Reply. The reply of a Mode S transponder to a Mode S All-Call interrogation is composed largely of the aircraft's Mode S address. This address is used in subsequent discrete interrogations to that aircraft.
- Discrete Interrogation. This interrogation contains the Mode S address of the aircraft that is to receive the interrogation. It also contains surveillance and communication control information.
- Discrete Reply. The basic surveillance reply to a discrete interrogation contains the aircraft pressure altitude code and its Mode S address.

BASIC MODE S SURVEILLANCE FORMATS

INTERROGATION



REPLY

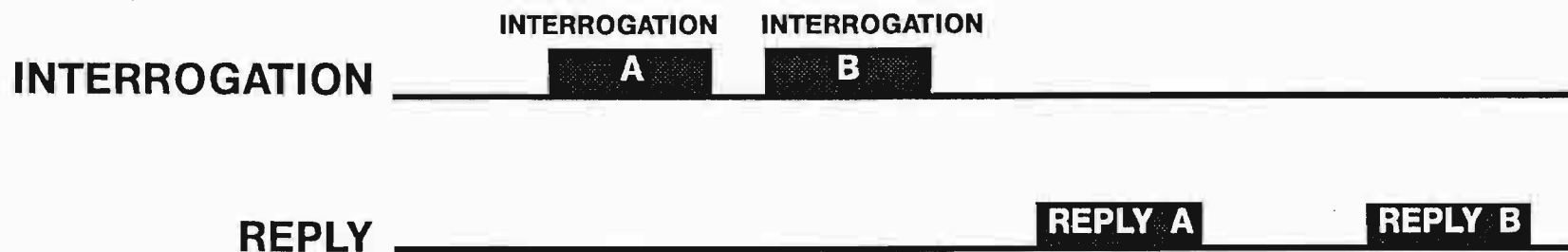
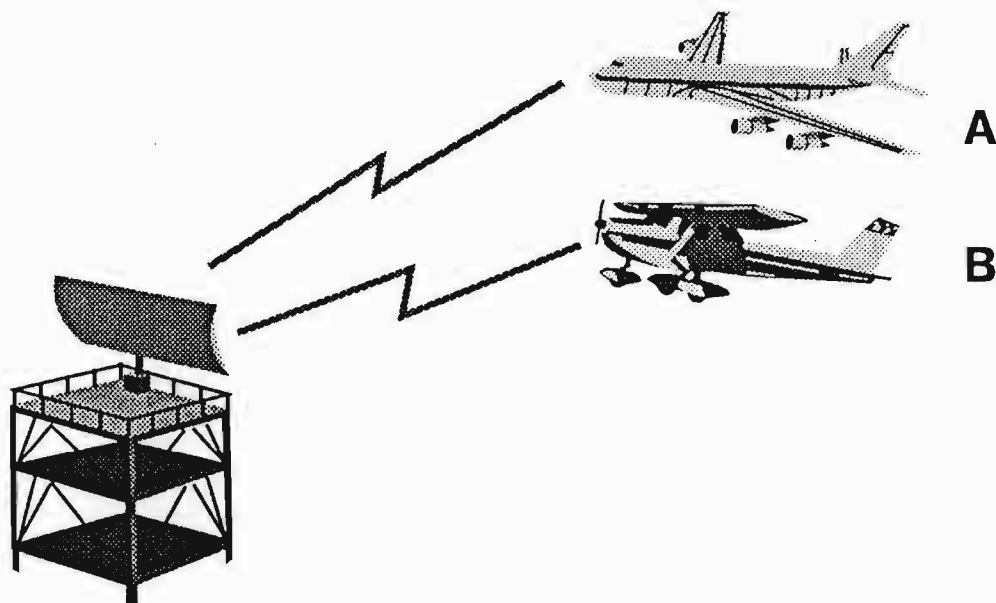


MODE S ELIMINATION OF SYNCHRONOUS GARBLE

The use of selective addressing completely overcomes the problem of synchronous garble. As before, the two aircraft in the figure are near the same azimuth and slant range. The sensor, having knowledge of the azimuth and range of each aircraft from the previous scan, schedules an interrogation to one of the aircraft. (A in the figure). It then schedules an interrogation to the second aircraft such that both the interrogation and reply for aircraft B occur at times that do not interfere with the reception of the reply from aircraft A. The scheduling technique can be extended to cover cases where three or more aircraft are near the same azimuth and slant range.

Provision is also made in the all-call acquisition process to handle the case of synchronous garble of All-Call replies. This technique is known as "Stochastic Acquisition." A special all-call interrogation is used that instructs the aircraft to reply to the all-call interrogation with a defined reduced probability. The resulting random loss of replies will ensure that a reply from exactly one of the garbling aircraft will be received after a few interrogations. Once acquired, that aircraft is locked out to further all-calls. The process is repeated until all aircraft in the garbling set are acquired.

MODE S ELIMINATION OF SYNCHRONOUS GARBLE

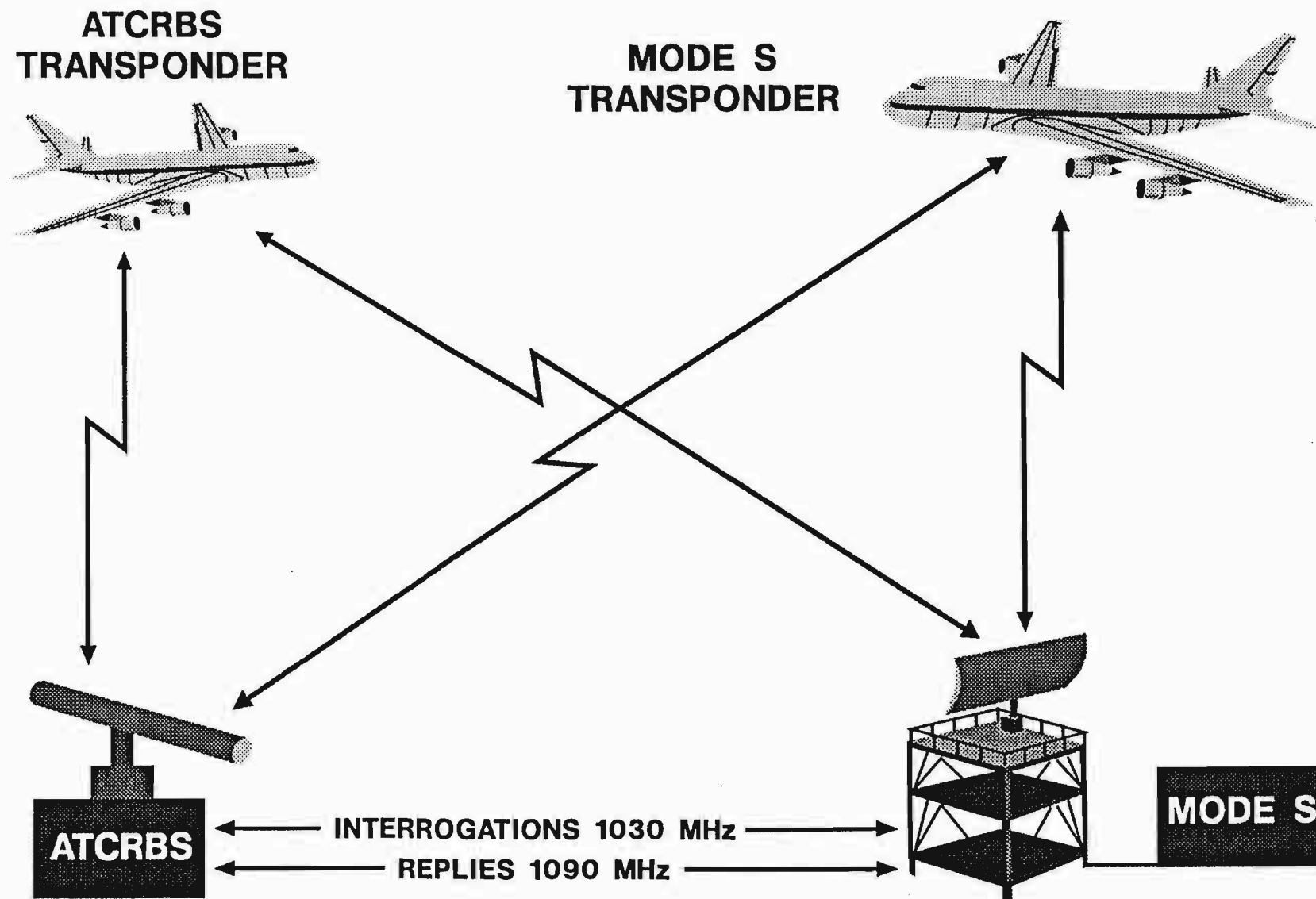


ATCRBS - MODE S COMPATIBILITY

Compatibility between ATCRBS and Mode S is achieved as follows:

- Mode S transponders respond to ATCRBS interrogations. A Mode S equipped aircraft will be detected as an ATCRBS aircraft by a conventional ATCRBS sensor.
- Mode S sensors interrogate ATCRBS transponders. An ATCRBS equipped aircraft will be detected and reported by the Mode S sensor.
- Mode S operates on the ATCRBS frequencies. Mode S operates on the same 1030 MHz uplink and 1090 MHz downlink used by ATCRBS. The use of the same frequencies greatly simplifies the construction of a Mode S sensor and transponder, since only one transmitter and receiver are required.
- Mode S waveforms were designed to prevent mutual interference with ATCRBS. Special care was required in the design of the Mode S waveforms to ensure that there would be no problems of mutual interference with ATCRBS signals. This will be described in connection with the discussion of the Mode S waveforms.

COMPATIBILITY BETWEEN ATCRBS AND MODE S

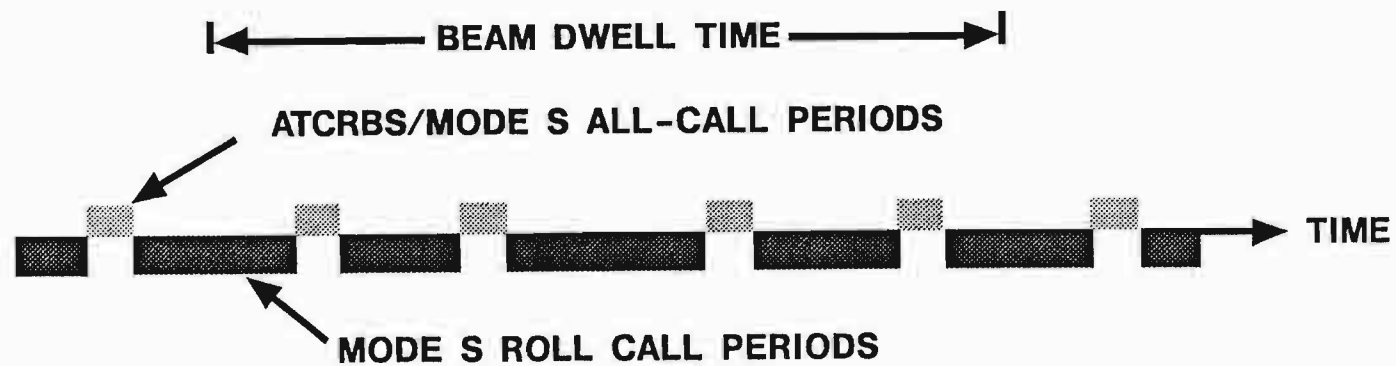


ATCRBS - MODE S TIME SHARING

A Mode S sensor provides surveillance on both ATCRBS and Mode S aircraft by time-sharing its activities. The figure shows a typical Mode S sensor time-line, drawn approximately to scale. During the time of one beam dwell (approximately 30 ms for a terminal sensor) the Mode S sensor provides four Mode A/C/S all-call periods. This provides the interrogation and listening intervals needed for the required two Mode A and two Mode C replies. All-Call acquisition of Mode S aircraft is also performed during this time.

Selective Mode S interrogations are scheduled during the Mode S roll call periods. Note that the use of monopulse for ATCRBS makes it possible to devote most of the time line to Mode S.

ATCRBS - MODE S TIME SHARING



MODE S ALL-CALL INTERROGATION

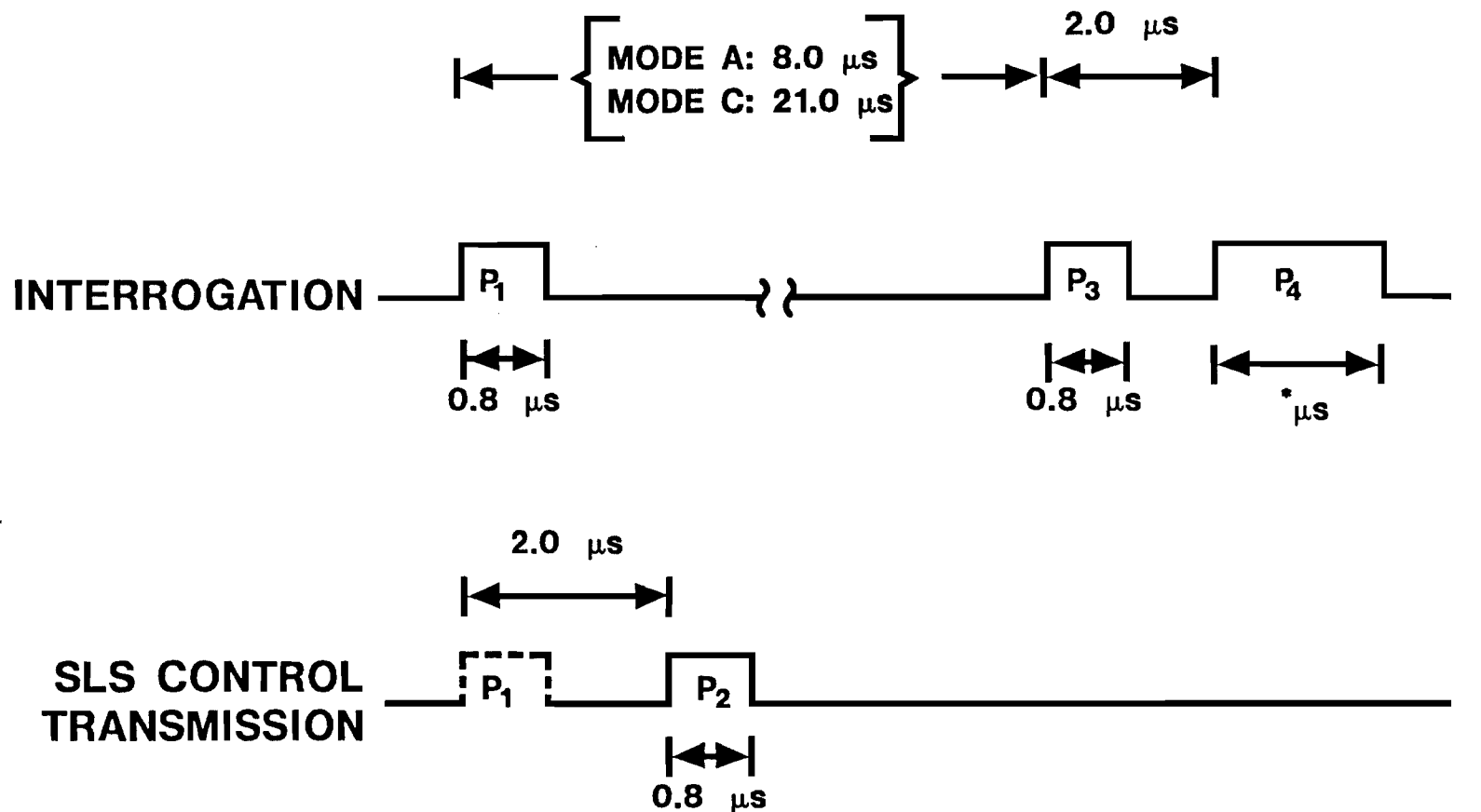
The all-call interrogation normally used by Mode S is shown on the figure. It is composed of the same P1 and P3 pulses used for ATCRBS interrogations. The P4 pulse identifies the interrogation as originating from a Mode S sensor.

If the P4 pulse is 1.6 μ sec long, the interrogation is a Mode A/C/S all-call. It elicits Mode A/C replies from ATCRBS transponders and Mode S all-call replies from unlocked Mode S transponders.

If the P4 pulse is 0.8 μ sec long, the interrogation is a Mode A/C only all-call. It elicits Mode A/C replies from ATCRBS transponders and no reply from Mode S transponders. It is used by the Mode S sensor in connection with a special Mode S-only all-call interrogation. It is also used by the Traffic Alert and Collision Avoidance System (TCAS) for surveillance of ATCRBS aircraft. TCAS acquires Mode S aircraft passively by listening for an all-call reply, known as a "squitter" which is generated spontaneously approximately once per second by all Mode S transponders.

The P2 pulse is used for sidelobe suppression of the Mode A/C and Mode A/C/S All-Call interrogations in the same manner as for the ATCRBS interrogation.

MODE S ALL-CALL INTERROGATION WAVEFORM



* MODE A/C/S ALL-CALL: $1.6 \mu s$
 MODE A/C ONLY ALL-CALL: $0.8 \mu s$

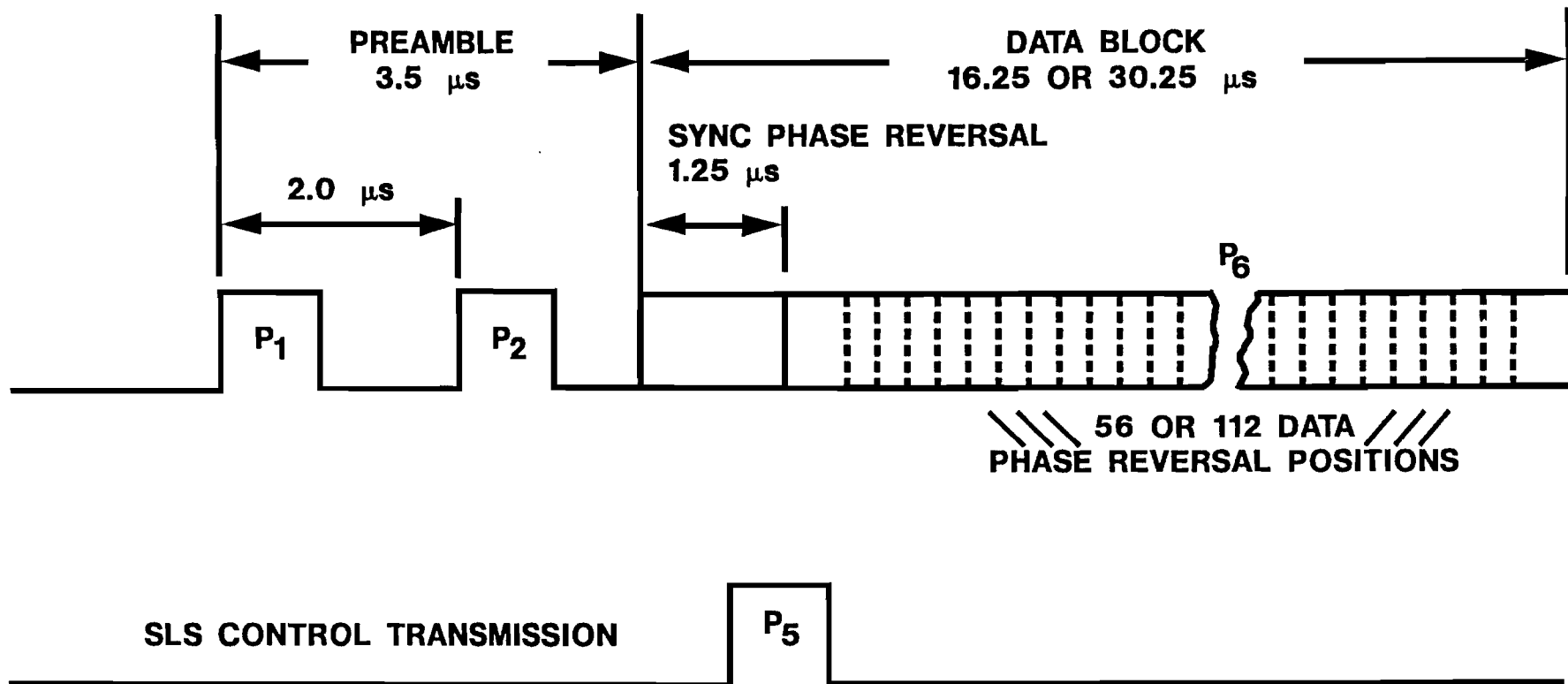
MODE S ADDRESSED INTERROGATION

A Mode S interrogation begins with a two-pulse preamble followed by a data block. The data block is encoded using differential phase shift keying (DPSK) at a 4 megabit/second rate. A logical "one" is encoded as 180° phase shift, a logical "zero" as the absence of a phase shift. DPSK was selected because of its resistance to interference. All data blocks begin with a sync phase reversal that establishes the timing for the remaining phase reversal positions. The data block is either 16.25 or 30.25 μ sec long, and provides for either 56 or 112 bits of data.

The two-pulse preamble is an important element in the reduction of mutual interference with ATCRBS. It is important that ATCRBS transponders not respond to Mode S interrogations. Such responses would produce ATCRBS replies that would interfere with the reception of Mode S replies. Moreover, they would be synchronized with the Mode S reply and would therefore lead directly to synchronous garble. Tests with many ATCRBS transponders indicated that there were no practical waveforms that were invisible to all ATCRBS transponders. The approach that was adopted was to precede the Mode S data block with a preamble consisting of a P1 and P2 pulse of equal amplitude. When received by an ATCRBS transponder, this will cause it to go into a period of suppression for 35 μ sec. The data block is sent during this interval, and is therefore not detected by the ATCRBS transponder. Note that it was the length of the suppression interval that dictated the maximum length of the Mode S data block.

Sidelobe suppression (SLS) is not required with a selective addressed Mode S interrogation, since the interrogation is transmitted while the addressed aircraft is in the antenna main beam. Other Mode S aircraft in the antenna sidelobes that receive the interrogation will not reply since the interrogation does not contain their Mode S address. However, the Mode S-only all-call uses the Mode S interrogation wave form. Thus, sidelobe suppression is required, as for any all-call type interrogation. The P2 pulse cannot be used for SLS since it is used in the Mode S preamble to prevent ATCRBS replies to Mode S interrogations. SLS for Mode S is provided by an additional pulse, shown as P5 in the figure. This pulse is transmitted on the omni pattern at the time of the sync phase reversal. The presence of the P5 obliterates the sync phase reversal for aircraft in the sidelobes. This makes it impossible to decode the interrogation. Note that there is no SLS circuitry in the Mode S transponder; suppression occurs through controlled interference to the sync phase reversal. Since the P5 pulse is transmitted at the same time as the data block, a second transmitter (of much lower duty cycle than the main transmitter) is provided in the Mode S sensor for this purpose.

MODE S INTERROGATION WAVEFORM



- DIFFERENTIAL PHASE SHIFT KEYING (DPSK) MODULATION
- DATA RATE 4 Mb/s

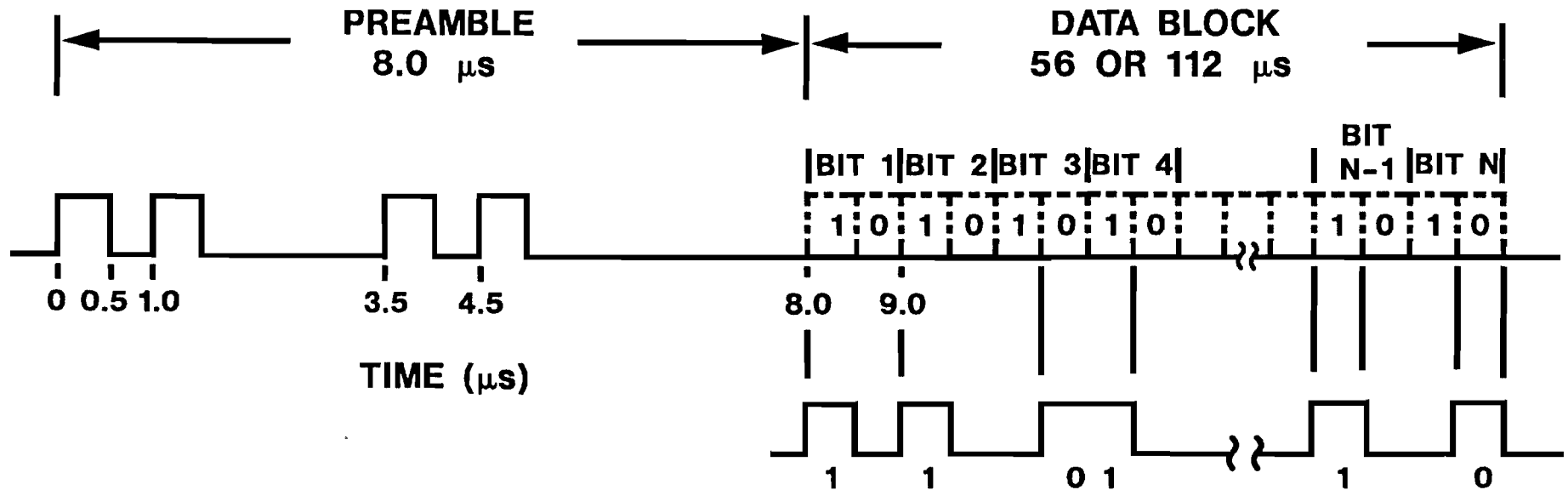
MODE S REPLY

A Mode S reply begins with a four pulse preamble followed by a data block. The data block is encoded using pulse position modulation (PPM) at a one megabit per second rate. A logical "one" is encoded as the presence of a 1/2 microsecond pulse in the first half of the one-microsecond data chip interval. A logical "zero" is encoded as the presence of a 1/2 microsecond pulse in the second half of the one-microsecond data chip interval. The data block is either 56 or 112 microseconds long, thus providing either 56 or 112 data bits.

A one megabit per second data rate was selected as the highest rate compatible with a low cost implementation for the Mode S transponder. PPM was selected to provide for bit interference detection and to enhance monopulse operation. Interference of a data bit position can be detected by comparing the received energy in both halves of the data chip interval. If there is no interference, there will be received energy in only one half of the interval. Energy in both halves indicates that an interfering pulse was received at the same time. PPM enhances monopulse performance since the data block contains 56 (or 112) bits, independent of the data content. This contrasts to the pulse amplitude modulation used in ATCRBS in which a message composed of all logical zeros does not contain any data pulses. The constant number of pulses in the reply makes it possible for a monopulse azimuth estimate for the reply to be based upon a large number (e.g., 16 or 32) of individual pulse azimuth measurements.

Mutual interference with ATCRBS is managed on the downlink through the use of a preamble whose spacing was selected such that it is unlikely to be synthesized by ATCRBS replies. This minimizes the possibility that the Mode S reply processor will be triggered by ATCRBS fruit, and hence be busy when the elicited Mode S reply is received. A second technique to manage mutual interference is the use of a burst error correcting technique that can error correct the effects of a single ATCRBS fruit reply that is received at the same time as the Mode S reply.

MODE S REPLY WAVEFORM



- PULSE POSITION MODULATION (Ppm)
- DATA RATE 1 Mb/s

MODE S DATA LINK

The selective addressing provided by Mode S provide a natural mechanism for a data link. The data link capability of Mode S provides the capacity and performance required to support air traffic services. The communications control features of this link have been designed to be compatible with the Open Systems Interconnection (OSI) Reference Model.

The link design provides for both ground-to-air and air-to-ground message transfers. Air-to-ground messages may be either pilot initiated or ground initiated. The latter type is provided to efficiently read technical information available on board the aircraft, e.g., roll angle in support of turn indication for ground trackers.

Messages sent over the Mode S link benefit from the high degree of error protection provided in the Mode S link design. Technical acknowledgement of the delivery of a message is provided. On the uplink, the receipt of a reply to an interrogation that delivered the message constitutes the technical acknowledgement. Finally, provision will be made in all critical applications for an overall acknowledgement to be provided by the aircraft crew, indicating receipt and acceptance of the message.

MODE S DATA LINK

- **AIR TRAFFIC SERVICES — COMPATIBLE WITH OSI* REFERENCE MODEL**
- **GROUND-TO-AIR**
- **AIR-TO-GROUND: PILOT INITIATED
GROUND INITIATED**
- **MESSAGE INTEGRITY: ERROR PROTECTION
TECHNICAL ACKNOWLEDGEMENT
PILOT ACKNOWLEDGEMENT**

*** OPEN SYSTEMS INTERCONNECTION**

MODE S DATA FORMATS

Mode S formats contain either 56 or 112 bits. All formats contain a 24 bit address/parity field. These two functions were combined into a single field to minimize channel overhead. For an interrogation, the Mode S sensor generates a 24-bit parity field from the entire message (either 56 or 112 bits) and overlays this on the address to form the address/parity field. When the interrogation is received by the transponder it performs a complementary decoding process. If the message was received error free, the intended Mode S address will be recovered from the address/parity field. The addressed transponder will thus accept and process the message. One or more errors anywhere in the message will cause a change in the decoded Mode S address. In this case, the addressed transponder will not accept the message since it appears to be addressed to another transponder.

Surveillance formats contain surveillance and communication control information, and on the downlink contain Mode C altitude or Mode A identity codes. Surveillance/communication formats contain all of the fields of a surveillance format, plus an additional 56-bit message field. This permits data link and surveillance activities to take place simultaneously. Provision is made in the Mode S data link design to link up to four of the 56 bit message fields into a single message entity.

Longer data link messages are handled by the communications formats. The use of these formats provides for greater link efficiency in two ways. First, the message field is longer, so fewer interrogations or replies are required for a given message. Second, the message transfers use the Extended Length Message (ELM) protocol. This protocol permits up to 16 communication interrogations to be acknowledged by a single reply, thus conserving channel time. A similar approach is used for downlink ELMs. The 16 eighty-bit message fields provide a message length of 1280 bits. Provision is made in the Mode S data link design for the linking of up to 32 of these messages.

MODE S DATA FORMATS

SURVEILLANCE INTERROGATION AND REPLY

FORMAT No. (5 Bits)	SURV. & COMM. CONTROL (27 Bits)	ADDRESS/PARITY (24 Bits)
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SURVEILLANCE/COMM. INTERROGATION AND REPLY

FORMAT NO. (5 Bits)	SURV. & COMM. CONTROL (27 Bits)	MESSAGE FIELD (56 Bits)	ADDRESS/PARITY (24 Bits)
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COMMUNICATION INTERROGATION AND REPLY

FORMAT No. (5 Bits)	COMM. CONTROL (6 Bits)	MESSAGE FIELD (80 Bits)	ADDRESS/PARITY (24 Bits)
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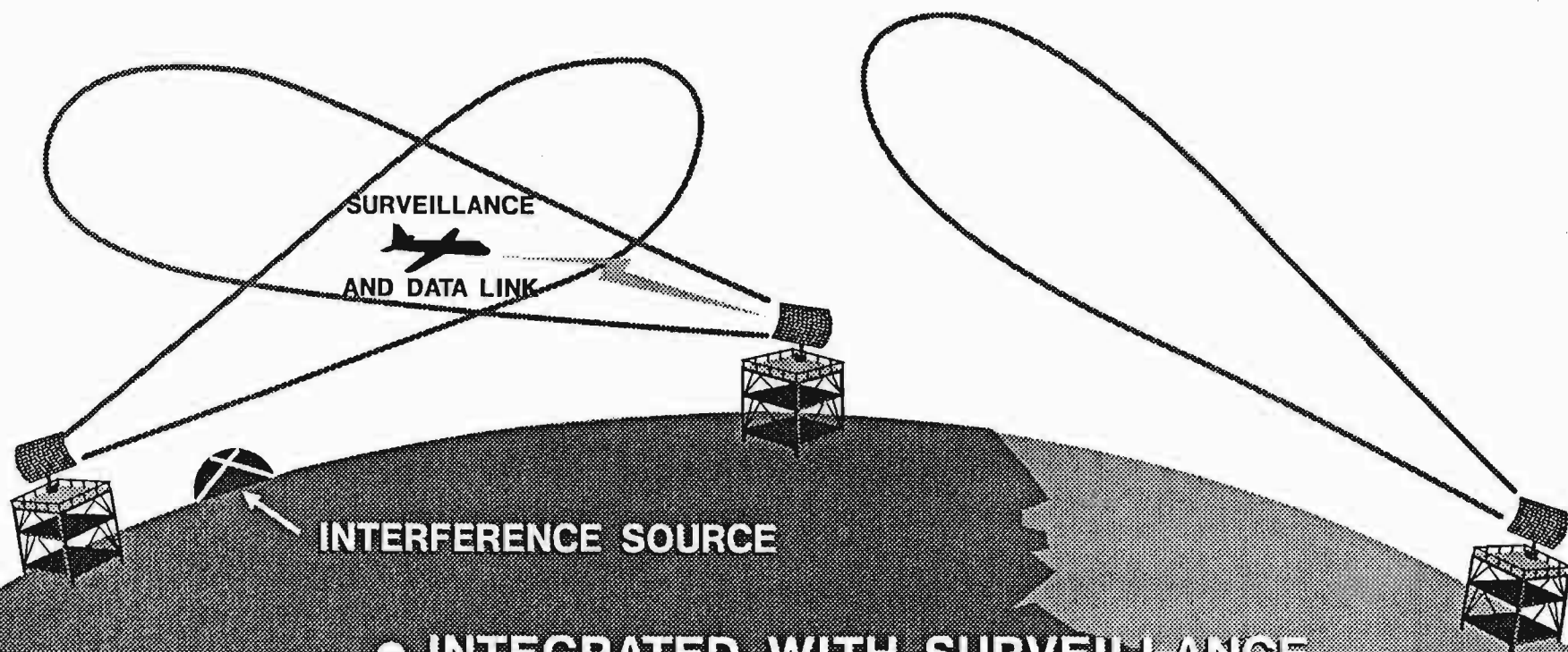
MODE S DATA LINK CHARACTERISTICS

The Mode S data link offers characteristics that are well suited to the needs of air traffic services.

The association of the Mode S data link with the surveillance function offers a number of operational benefits. Communication can be established with an aircraft based solely on surveillance detection. Thus, a message can be sent to an otherwise unidentified aircraft. This is important for safety services such as minimum safe altitude warning or notice of penetration into controlled airspace. Since the same address is used for both surveillance and communication, the possibility is eliminated of directing an intended message to the wrong aircraft due to an error in cross referencing the surveillance and communication identities. A third operational benefit is that communications coverage is assured whenever surveillance coverage exists.

The Mode S link provides a high level of integrity to accidental or intentional jamming due to the inherent characteristics of the Mode S ground station. Coverage is restricted to line of sight. This limits the airspace in which the sensor can cover traffic, but also limits the area in which an interfering source can affect the Mode S sensor. This area is further limited by the use of a narrow antenna beam. Thus a single interfering source would normally prevent operation in only a single antenna beamwidth. In the worst case, a single interfering source very close to a Mode S sensor could prevent operation of that sensor, but would have little effect on the operation of all of the other Mode S sensors. Thus, the distributed nature of Mode S makes it tolerant to interference. This natural tolerance to interference is important in a data link intended for civil use.

MODE S DATA LINK CHARACTERISTICS



- INTEGRATED WITH SURVEILLANCE
- HIGH LEVEL OF LINK INTEGRITY
- DISTRIBUTED ARCHITECTURE

OUTLINE

- **ATCRBS**
 - **DEFINITION**
 - **LIMITATIONS**
- **MODE S**
 - **MONOPULSE**
 - **SURVEILLANCE**
 - **DATA LINK**
- ➡ • **DESIGN VALIDATION**
- **SUMMARY**

MODE S EXPERIMENTAL FACILITY

The initial validation of the Mode S design was accomplished at the Mode S Experimental Facility (MODSEF) located at Lincoln Laboratory. Initially, MODSEF was used for link measurements and monopulse development. It was later upgraded to be a fully functional Mode S sensor.

While validation at MODSEF was a necessary first step, it was not sufficient proof of the Mode S surveillance design since the MODSEF site does not experience high traffic density, fruit, or the presence of ground reflections known as multipath.

MODE S EXPERIMENTAL FACILITY



TRANSPORTABLE MEASUREMENTS FACILITY (TMF)

The Transportable Measurements Facility (TMF) was constructed to observe Mode S sensor operation at FAA sites that were known to provide environmental difficulties.

The TMF includes its own antenna(s), tower and an equipment van that contains a transmitter, a receiver, and digitizing and recording equipment. The antennas shown in the figure are an ASR-7 antenna with a monopulse beacon feed and a monopulse-capable hog-trough antenna on loan from the United Kingdom. In operation, the TMF transmits, and then digitizes the received video pulses. This digitized information was recorded for later playback and analysis at Lincoln Laboratory.

At most sites, the TMF was operated as close as possible to the existing sensor in order to experience similar environmental conditions. In two cases, new off-airport sites were selected to determine the effect of improved siting on sensor performance. The figure shows the TMS at Washington's National Airport, with the operational ASR in the background.

TMF AT WASHINGTON NATIONAL



TRANSPORTABLE MEASUREMENTS FACILITY (TMF) SITES

The sites visited by the TMS are shown on the figure. Initial operation and shakedown took place at Lincoln Laboratory and Boston's Logan Airport. Measurements were then made at Philadelphia and Washington to experience the traffic and interference levels of the northeast corridor. The TMF was then taken to Las Vegas to operate in the significant ground-bounce multipath environment associated with that site. Final TMF measurements were made at Los Angeles to experience the highest traffic and interference levels in the United States.

TMF SITES



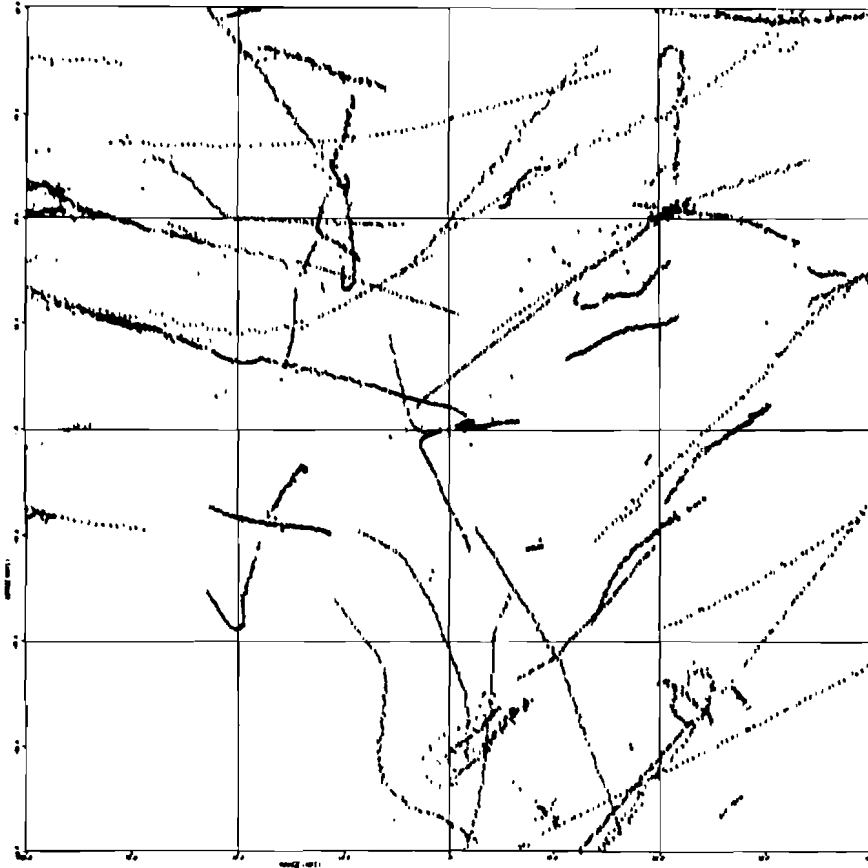
ARTS/TMF COMPARISON

At each of the TMF sites, provision was made to perform simultaneous data recording with the existing FAA sensor. This provided a direct comparison of the current Automated Radar Terminal System (ARTS) processing with the monopulse processing provided by the TMF.

An example of this comparison is shown in the figure for data collected in Philadelphia for an 80 by 80 nautical mile area. ARTS data is shown on the left, TMF data on the right. Each point represents an unsmoothed position report measured once each antenna scan. The reduced measurement errors of the TMF data are readily apparent.

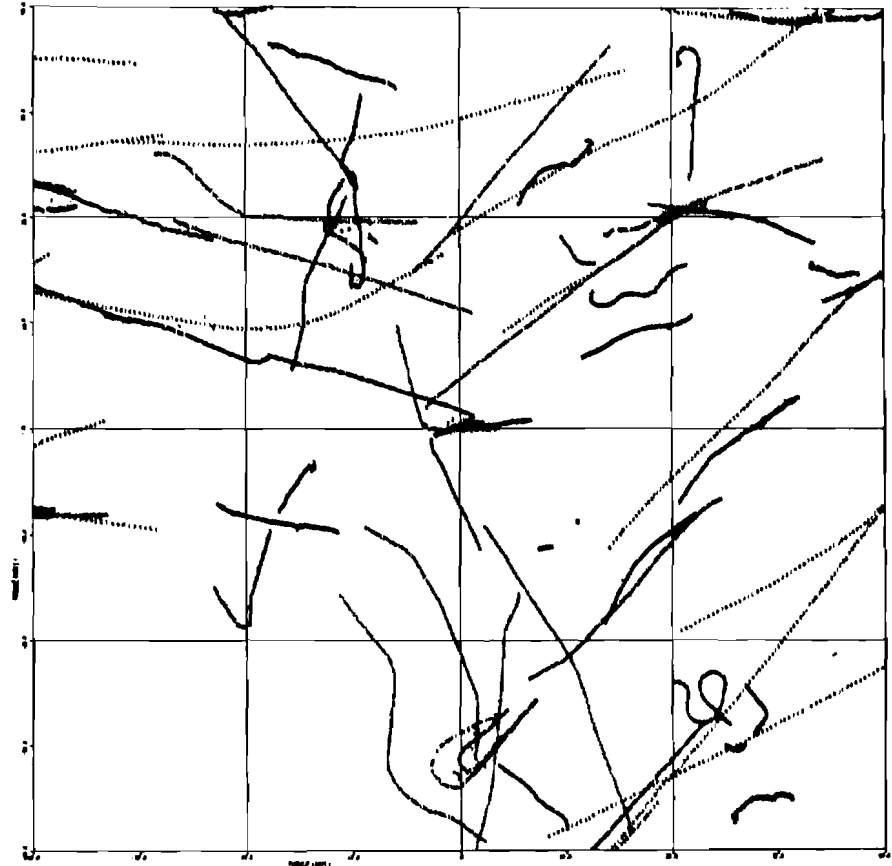
ARTS/TMF COMPARISON (80 X 80 nmi)

ARTS 5016 ALL TARGET REPORTS



ARTS

TMF 5016 CORRELATED TARGET REPORTS



MONOPULSE

SURVEILLANCE PERFORMANCE COMPARISON

A quantitative comparison of the average performance of the ARTS and TMF for all the TMF sites is shown on the figure and confirms the greatly improved qualitative performance seen in the previous figure.

The blip/scan ratio is the probability of generating a target report on an aircraft on a given scan. When all aircraft are considered, the blip/scan ratio is seen to be 94.6% for the ARTS and 98.% for the TMF. The most significant difference in blip/scan performance is revealed when only "crossing" tracks are considered. These are cases where aircraft were close enough together to present a possible synchronous garbling problem. For this subset of aircraft, the blip/scan ratio for the ARTS dropped to 86.9%, while the performance of the TMF remained at 96.6%. This result clearly indicated the benefit of monopulse processing in resolving garbled replies.

Monopulse processing was also responsible for the substantially smaller measured azimuth error of the TMF (0.05° , 1σ). The range error was also reduced to 24 ft from 124 ft by improved measurement of the reply time of arrival.

SURVEILLANCE PERFORMANCE COMPARISON

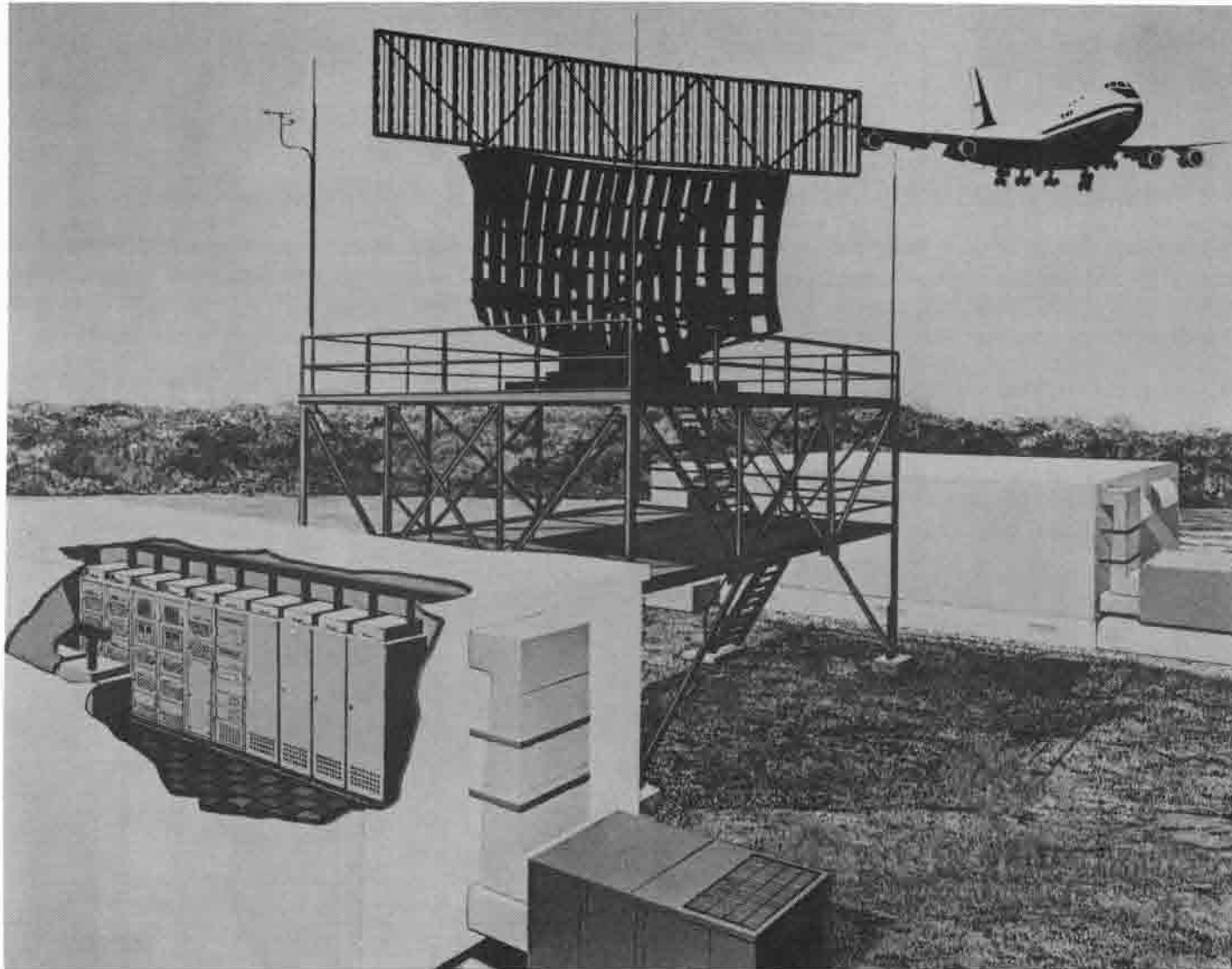
	ARTS		MONOPULSE	
	ALL	CROSSING	ALL	CROSSING
BLIP/SCAN	94.6%	86.9%	98.0%	96.6%
AZIMUTH ERROR (1 σ)	0.16°		0.04°	
RANGE ERROR (1 σ)	124 ft		24 ft	

ENGINEERING MODEL SENSORS

A major step in the validation of the Mode S design took place in 1975 when the FAA awarded a contract to Texas Instruments for the development of three engineering model sensors. These were delivered to the FAA Technical Center in 1977 for extensive field evaluation.

The figure shows a drawing of the engineering model sensor.

MODE S ENGINEERING MODEL SENSOR

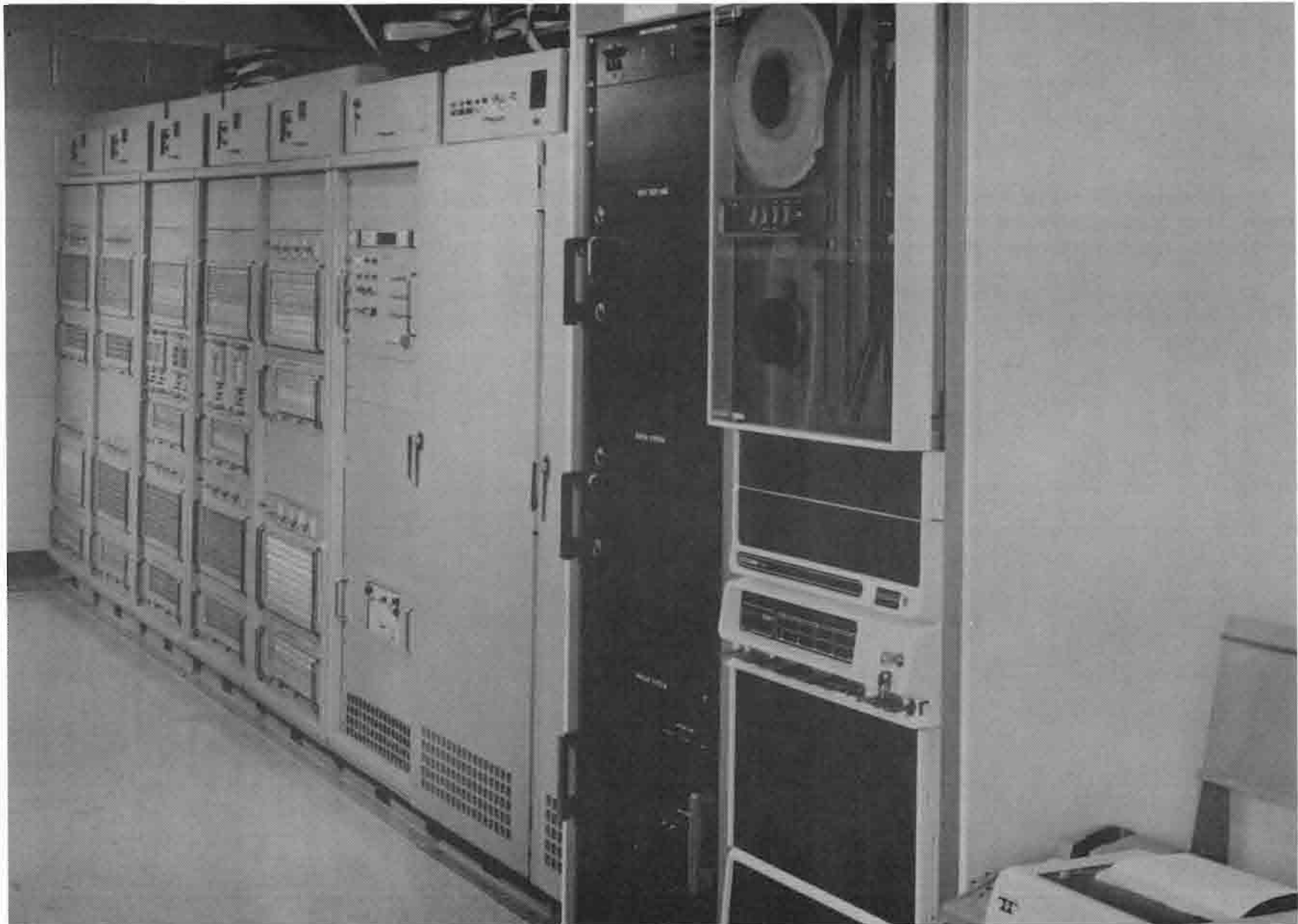


AIRCRAFT REPLY AND INTERFERENCE ENVIRONMENT SIMULATOR (ARIES)

The engineering model sensors were built to demonstrate a full-capacity sensor (400 aircraft total, a peak of 50 aircraft in a sector of 11 1/2°). Capacity tests of these sensors could not have been accomplished with real aircraft because an aircraft density of this magnitude did not exist for ATCRBS aircraft, even in the highest densities of Los Angeles. Further only a small number of Mode S transponders were available.

Capacity testing of the engineering model sensors were accomplished using a traffic simulator known as the Aircraft Reply and Interference Environment Simulator (ARIES). The ARIES interfaces with the sensor front end at analog levels and thus exercises the entire sensor, not just the computer subsystem. In operation, the ARIES listens to interrogations from the engineering model, and then inserts signals into the front end at the time that the transponder reply would have been received from the real aircraft. The ARIES also correctly simulates the monopulse signals according to the off-boresight angle of the simulated aircraft. This monopulse simulation is accurate enough to permit operation with a mix of simulated and real aircraft.

ARIES WITH MODE S ENGINEERING MODEL



ARIES CAPACITY TESTING

A principal objective of the Mode S engineering model development was to verify that Mode S sensor algorithms could achieve the required Mode S surveillance and communication capacity. Capacity testing was accomplished with the ARIES using a traffic model that represented a future worst-case scenario for the Los Angeles Basin.

The figure shows a display of traffic being processed by the Mode S engineering model sensor during a capacity test. A square indicated a Mode S aircraft, a circle an ATCRBS aircraft. The total traffic load is over 300 aircraft, most of which are contained in a 90 degree, 60 nautical mile sector.

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NO RED/YELLOW STATUS MESSAGES

SUMMARY

Mode S is an evolutionary improvement to the current Air Traffic Control Radar Beacon System. It provides enhanced surveillance performance through the use of monopulse, discrete addressing, and error protection. It includes an integral data link which provides unique benefits to air traffic control because of its association with the surveillance function and its resistance to interference.

Mode S techniques have been validated through extensive field measurements and through the development of an engineering model sensor.