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DABS Modulation and Coding Design – A Summary

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12 March 1976

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16. Abstract

The Discrete Address Beacon System (DABS) has been designed as an evolutionary replacement for the Air Traffic Control Radar Beacon System (ATCRBS). As with ATCRBS, DABS is a cooperative Air Traffic Surveillance System utilizing ground based sensors (interrogators) and airborne transponders. In addition to its surveillance function, DABS integrally accommodates ground-to-air and air-to-ground data link communication within the interrogations and replies. In DABS, each aircraft transponder may be individually interrogated, using its unique 24-bit address, giving the ground based interrogators freedom to schedule interrogations and replies to make efficient use of the channels essentially independent of the aircraft traffic distribution.

The evolutionary constraint on DABS, requiring the capability for one-for-one replacement of ATCRBS ground sensors and transponders, dictated the need to maximize commonality between the two systems. Thus, the ATCRBS interrogation and reply frequencies (1030 and 1090 MHz) were prime candidates for DABS operating frequencies.

This report presents the rationale for the selection of the DABS signalling waveforms and error control techniques. The main issues in arriving at the final link design were (1) affordable transponder cost, (2) electromagnetic compatibility with ATCRBS and TACAN, and (3) adequate performance in the channel environment, which includes interference from ATCRBS transmissions. The resulting DABS link design uses the ATCRBS frequencies, achieves surveillance reliability and accuracy superior to that of ATCRBS, and transmits ground-to-air data link messages with high reliability. This is accomplished without noticeably affecting ATCRBS performance, with less channel occupancy per target report than ATCRBS, and with transponders projected to cost approximately 160% of the cost of ATCRBS transponders.

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1.0 INTRODUCTION

1.1 General

The report of the Department of Transportation Air Traffic Control Advisory Committee (ATCAC) of 1969 [Ref. 1] recommended an upgrading of the Air Traffic Control Radar Beacon System (ATCRBS) to provide:

1. Increased traffic handling capacity for the dense regions of airspace by addition of a "discrete address" mode.
2. Use of the discrete address mode to provide two-way ATC data link capability to reduce the controller communication workload and provide for the efficient automation of control functions such as Intermittent Positive Control (IPC).

The ATCAC recommended a system design that allowed an evolutionary implementation in which transponders and ground sensors could be replaced on a one-for-one basis over an extended period of time, implying that the new transponders and sensors would have to be able to work with the old ATCRBS as well as new DABS sensors and transponders.

The DABS development program [Ref. 2] is the direct result of the ATCAC recommendations. One of the major influences in the design of DABS was the necessity for low-cost transponders, especially for the general aviation class aircraft, to assure an acceptable cost to the users. The requirement to allow one-for-one replacement of transponders, together with the transponder cost constraints, forced the combining of ATCRBS and DABS circuit functions to the maximum possible extent. Since the data processing of DABS associated with address checking and message handling has no counterpart in ATCRBS, the only possibility for combining ATCRBS and DABS functions in dual purpose circuits is in the RF and IF functions. Thus, from the outset of the DABS development program, the prime candidates for the DABS interrogation and reply links, from a cost viewpoint, were the frequency channels used by the ATCRBS. A major part of the DABS link design effort was therefore spent investigating electromagnetic compatibility (EMC) issues, i.e., the effect of DABS transmissions on the ATCRBS (and TACAN channels near these frequencies), and the DABS link performance in the presence of the radio frequency interference (RFI) generated by ATCRBS.

1.2 DABS Performance Goals

The specific DABS performance requirements, which were necessary to carry out the detailed system design, evolved over a period of time after the ATCAC report. They may be summarized as follows:

1.2.1 Surveillance

Much emphasis was placed on improved surveillance reliability (increased probability of target location per scan), although increased surveillance accuracy was also sought for automated conflict detection and resolution. The performance goals were:

- Data update interval ~4 seconds
- Probability of target location and identification on a single scan ~0.99
- Azimuth accuracy ~0.1° (rms)
- Range accuracy ~ 100 ft (rms)

1.2.2 Communication

The critical communication function identified was that of transmitting ATC command messages from the ground sensor to aircraft on collision or conflicting paths. All other messages considered for DABS were lower in priority and in performance requirements. IPC or ATC command message requirements were:

- IPC/ATC command message length ~ 50 bits
- Delivery requirement ~0.99 probability of delivery of the correct message within one scan (data update interval)
- Acceptance of erroneous messages with probability less than 10^{-7}

1.2.3 System Capacity

The ground surveillance system based on DABS was envisioned as incorporating a fail-soft capability by providing for multiple sensor coverage of aircraft whenever possible. Automatic system monitoring would be used, and network reconfiguration would automatically be done if elements of the system failed. These features, together with aircraft traffic projections into the 1990s, resulted in the requirement that an individual sensor must be capable of handling at least 2000 DABS aircraft.

1.3 Summary

This report presents the rationale for selecting the DABS signaling waveforms and error control techniques. Cost and equipment compatibility constraints placed a high premium on the use of ATCRBS frequencies of 1030 and 1090 MHz for the interrogation and reply channels, respectively.

The position taken during the link design effort was that DABS' use of these frequencies would be pursued until and unless they appeared infeasible from the viewpoint of DABS link performance or from EMC considerations.

The DABS link design philosophy was a conservative one that favored maximizing performance margins at a fixed level of transponder cost in order to allow a safety factor for such basic uncertainties as

1. Increase in the number of aircraft,
2. RFI environment projections (for ATCRBS and TACAN),
3. Increase in the variety of functions and applications that DABS may be required to support.

The remainder of this report covers the uplink and downlink designs and presents estimates of DABS link performance in projected channel environments. The detailed DABS signal formats, including waveforms and tolerances, are specified in Ref. 3, and an overall description of the DABS system is given in Ref. 4.

2.0 UPLINK DESIGN

2.1 Design Options

The two basic functions of the DABS uplink are

1. Interrogating individual DABS transponders to obtain surveillance data,
2. Delivering critical IPC and ATC commands (messages) to aircraft.

The most advantageous choice for the DABS uplink operating frequency is that of the ATCRBS (1030 MHz) from the viewpoint of transponder cost. Thus, the initial uplink design effort was directed toward the selection of signaling waveforms (including data modulation system and DABS interrogation modes), and a message/validation/error control system for 1030 MHz so that DABS link performance achievable on this channel could be assessed. The three major considerations in making design choices were:

1. Transponder cost impact, especially the general aviation class,
2. EMC with ATCRBS and TACAN,
3. Link performance.

The stringent transponder cost constraints reduced the data modulation options to the types consistent with very simple and inexpensive demodulator implementation. Thus, only binary modulation types using simple waveforms were studied, i.e., pulse amplitude modulation (PAM), on-off keying only, frequency shift keying (FSK), and phase shift keying (PSK).

The uplink data rate was loosely constrained by the window at 1030 MHz to less than 10 MHz. Very high data rates would be more costly to implement than low data rates, but the longer duration transmissions resulting from low rates would be more vulnerable to garbling and would affect the ATCRBS transponders more. In studying the response of a variety of ATCRBS transponders to the binary modulation formats listed above, it was deemed necessary to constrain the DABS uplink data block to lie within the ATCRBS suppression interval, which is specified as 35 ± 10 μsec [Ref. 5]. Thus, the transmission of approximately 100 bits in the DABS uplink message (24-bit address, 50-bit message, and 25-bit control), within a single ATCRBS suppression interval of 25 μsec, implied a one-shot data rate of approximately 4 MHz, which was not very different from the ATCRBS transponder bandwidth and would fit well within the channel window. Lower data rates, together with the constraint of having to transmit data only within ATCRBS suppression intervals, would necessitate two separate transmissions to deliver a 100-bit data block, each one constrained to 25 μsec and separated by enough time to allow all ATCRBS transponders to recover from suppression to enable them to be resuppressed by the second transmission. Thus, a 2-MHz data rate would deliver a 100-bit uplink data block in two segments, each 25 μsec long and separated by at least 45 μsec. Thus, approximately 100 μsec would be needed to deliver a 100-bit data block with a modulation rate constrained to 2 MHz. The slight relaxation in timing problems in going from a 4-MHz to a 2-MHz data rate was judged too small a gain to increase the channel occupancy by a factor of four and to complicate the logic of handling messages by requiring multiple segments. The single transmission of 100 bits in approximately 25 μsec was selected for the DABS uplink.

DABS surveillance required transmitting, at most, only 50 bits (24 address and approximately the same 25 bits for control), and could thus be accomplished with even lower channel occupancy than would be required by messages, but a very slight cost penalty would be incurred in requiring the DABS transponder to process two different DABS interrogation lengths. The difference in vulnerability to RFI of the two lengths is insignificant in a practical sense. However, two DABS interrogation lengths were adopted mainly to clearly distinguish interrogations from messages, thus lowering the probability of misinterpreting interrogations with errors as command messages.

The very stringent message validation performance goal left few realistic options other than parity check coding. Error correction was never seriously considered for the DABS uplink because of circuit complexity, although error detection schemes can generally be implemented at very low cost. The more serious cost of coding for message validation was considered to be the redundant bits, because of the tight time constraints on the uplink data block length.

In summary, the DABS uplink design options were constrained by cost, EMC, and performance consideration to the following scheme. DABS uplink messages (approximately 100 bits total transmission) would have to be transmitted in approximately 25 μsec, using a simple binary modulation scheme with a data rate of approximately 4 MHz. Parity check coding for simple error detection would be investigated to devise a plan that would allow simple decoder circuitry and require low message redundancy. DABS surveillance interrogations would be transmitted in shorter transmissions that would also use the parity check coding for error detection.

Including parity check coding for error detection on both surveillance and communication modes implies that DABS transponders will seldom respond to garbled interrogations or messages. The absence of a reply will therefore indicate to the ground sensor the need to retransmit. DABS uplink reliability in heavy RFI conditions will be entirely dependent on the immunity to the RFI provided by the data modulation. An efficient uplink design (one which maximizes reliability for a given cost) will result in minimum effect on the ATCRBS and TACAN operation and will also simplify the DABS sensor operation. Thus the key design choice in the DABS uplink is selection of a data modulation system that provides for the most efficient design in the RFI conditions.

2.1.1 Uplink Design Philosophy

It is impossible to precisely predict the RFI environment (on 1030 MHz) far into the future. Yet it would be highly undesirable to have DABS performance degrade seriously in heavy traffic environments, which are also likely to correspond with heavy RFI environments. The uncertainty in RFI environments, increase in aircraft traffic, and message traffic loads*, which DABS will experience over its operational lifetime, places a priority on achieving an efficient link design in realistic channel environments which include fading, RFI, and multipath. Furthermore, an efficient DABS link design (i.e., one that minimizes DABS channel utilization) is desirable to minimize or at least limit DABS interference to ATCRBS and TACAN. Thus the DABS link design was not accomplished simply to achieve some adequate level of performance in specifically stated RFI and traffic environments. A more conservative approach was taken in which the maximum DABS link performance during a variety of channel conditions was sought for a fixed transponder cost level.

There is another critical point that affects uplink design philosophy: once the DABS transponder specification is issued in the form of a National Standard, the uplink performance is essentially fixed for the life of the system while it will be possible to upgrade the performance of the downlink (at least up to certain fundamental limits) by replacement of the reply processors of the ground sensors. Therefore, it is highly desirable to incorporate the maximum uplink performance margin in the design consistent with a fixed transponder cost so as to assure as far as possible that such later system upgradings will not be seriously limited by the fixed uplink performance.

2.2 Electromagnetic Compatibility (EMC) Issues

The EMC issues of greatest concern to DABS are the effects of DABS transmissions on the operation of the ATCRBS and TACAN systems. The investigations into these issues were conducted at two levels: the first being concerned with the detailed responses of ATCRBS transponders and TACAN equipment to DABS transmissions, and the second being the characterization and assessment of the degradation of the overall (ATCRBS and TACAN) system performance resulting from DABS transmissions in terms of the DABS traffic load and link efficiency (i.e., DABS channel utilization).

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*Perhaps caused by as yet unforeseen applications of DABS.

2.2.1 ATCRBS EMC Considerations

The ATCRBS specification [Ref. 5] designates the required transponder responses to the standard interrogation modes of the system and to short pulses and CW inputs. It does not, however, specify transponder characteristics in sufficient detail to reliably predict the effect that DABS interrogations on 1030 MHz would have on ATCRBS transponders. Therefore, an experimental program, using a series of bench tests, [Ref. 6] was carried out to determine these effects on a variety of ATCRBS transponders, which included one military unit, two different air carrier designs, and nineteen different general aviation transponder designs. A later experimental series [Ref. 7] progressed to field tests on transponders installed in general aviation aircraft to verify the results of the bench test program. The important results of these investigations are briefly summarized here.

The single most important result of testing ATCRBS transponders is that virtually any form of data modulation, if sustained long enough, was found to trigger these transponders. Triggering of replies has the effect of inhibiting the transponder from replying to legitimate interrogations for the duration of its recovery or dead time (about 25 to 120 μsec), and also contributes fruit to the reply channel. The forms of binary modulation used in bench testing ATCRBS transponders included:

1. PAM-RZ (carrier returns to zero between pulse positions)
2. PAM-NRZ (nonreturn to zero between pulse positions)
3. PSK-CE (constant envelope)
4. Pulsed PSK (carrier returns to zero between phase coded pulses)
5. FSK.

ATCRBS reply triggering was observed even for specially constructed pulsed PSK formats with 1- and 2-μsec pulse spacing, which was intended to continuously suppress ATCRBS transponders before they would be triggered. (Upon recovery from an initial suppression by such a pulse train, it appears that the recovery of the transponder suppression circuitry is delayed relative to the triggering circuitry, and transponders thus tend to be triggered rather than suppressed a second time.)

This triggering phenomenon was exhibited consistently enough by a sufficient number of different transponder designs that the possibility of an "invisible" DABS interrogation waveform (one that neither triggered nor suppressed ATCRBS transponders) was firmly ruled out. The next most appealing approach was the adoption of a preamble for the DABS interrogations, which intentionally suppresses ATCRBS transponders, providing an interval of time (the transponder suppression interval) in which the DABS data could be transmitted without further effect on the ATCRBS transponders.

The ATCRBS suppression interval is specified as 35 ± 10 μsec. In order to avoid triggering a Mode-2 reply in any military transponder meeting this specification, the DABS data block following the preamble suppression pair would have to be no more than approximately 29 μsec (25 μsec for the minimum suppression interval plus 5 μsec could trigger Mode 2). Civil transponders, which respond to only Modes 3/A and C, would constrain the DABS data block to approximately 32 μsec. The limit for the duration of the DABS data block following a suppression pulse pair was measured for a variety of ATCRBS transponders; Fig. 2-1 illustrates some of these measurements. Although the data in Fig. 2-1 was acquired using a 4-MHz PAM-NRZ data modulation, the results are essentially the same for PSK or FSK. The measurements indicate that the DABS data block is constrained to a length of approximately 30 μsec, (or the overall interrogation is constrained to approximately 33 μsec).

If several successive DABS transmissions were to be used to deliver one uplink message, the interval between DABS transmissions must be long enough to assure resuppression of ATCRBS transponders, with the longest allowable suppression interval of 45 μsec. Thus, if more than one transmission of approximately 30 μsec is needed for uplink messages, then the channel occupancy of DABS increases sharply for each message.

A simpler message transmission plan (in a link protocol sense) would be to use a sufficiently high uplink data rate to include a complete message (including address and control bits) within a 30-μsec interval. The main effect that DABS uplink transmissions would have on ATCRBS would be to keep transponders suppressed a fraction of the time. The worst effect would be that those ATCRBS transponders at very close range to a DABS sensor (which could receive transmissions in the side and backlobes of the sensor antenna) may be suppressed by nearly all DABS transmissions. The fraction of time that an ATCRBS transponder would be suppressed by a single sensor in this worst case in indicated in Figs. 2-2a, and -2b as a function of the number of DABS transmissions per second and as a function of the total aircraft load handled by the sensor. For highly reliable DABS link operation, even a traffic load of 2000 aircraft for a single sensor does not keep an ATCRBS transponder suppressed more than a few percent of the time. Of course, the total effect of many DABS sensors must be considered by the system designer, but it is viewed as unlikely that DABS sensors would have to be deployed so closely spaced that an aircraft could be simultaneously within range of the side and backlobes of many sensors. It is clear that efficient DABS link operation requiring few repeated uplink transmissions and low sensor ERP tend to reduce the total ATCRBS transponder suppression effect by a network of DABS sensors.

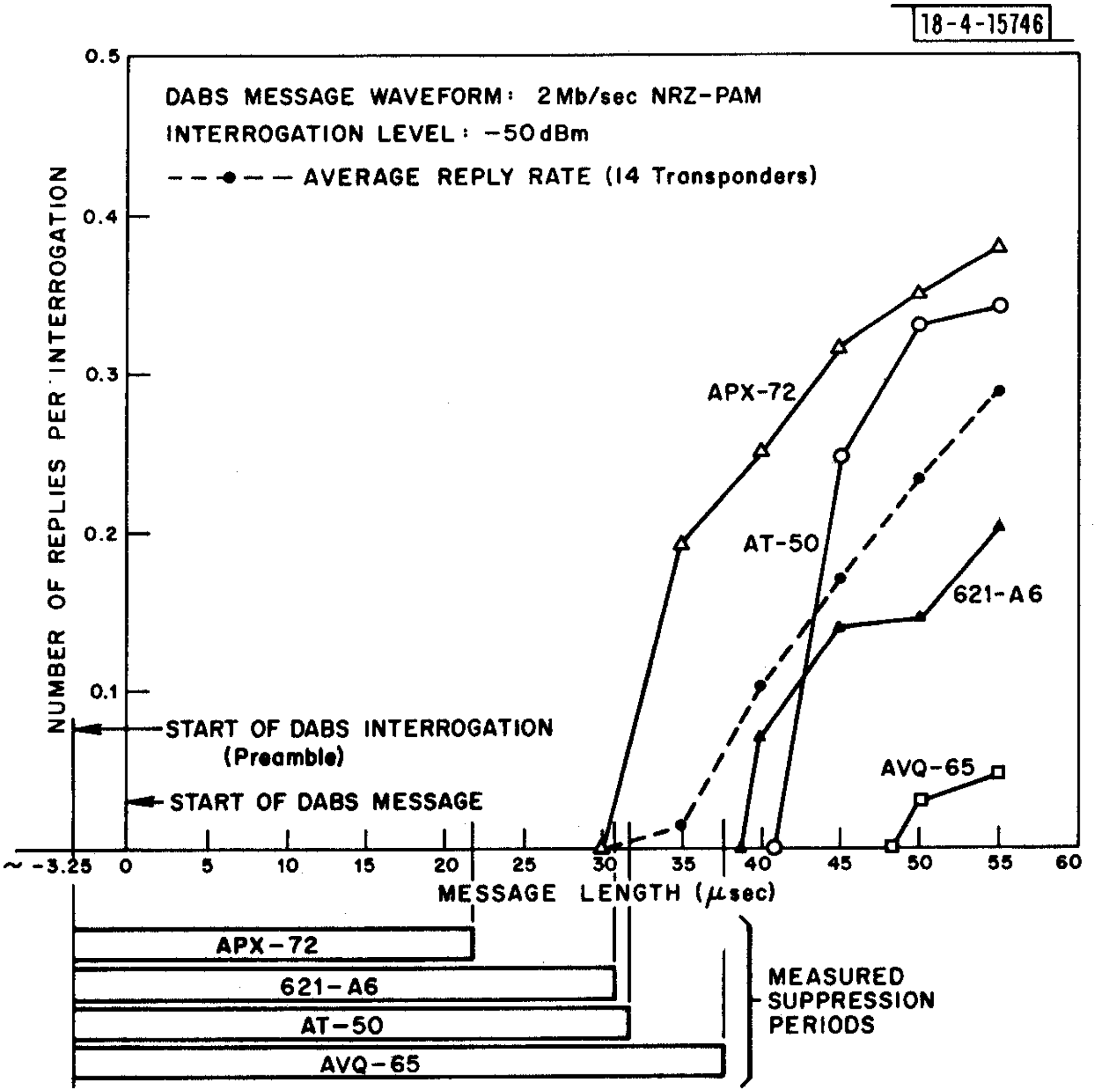

Fig. 2-1. Measured ATCRBS transponder triggering rates vs interrogation length (following a pulse-pair suppressing preamble).

ATC-52 (2a)

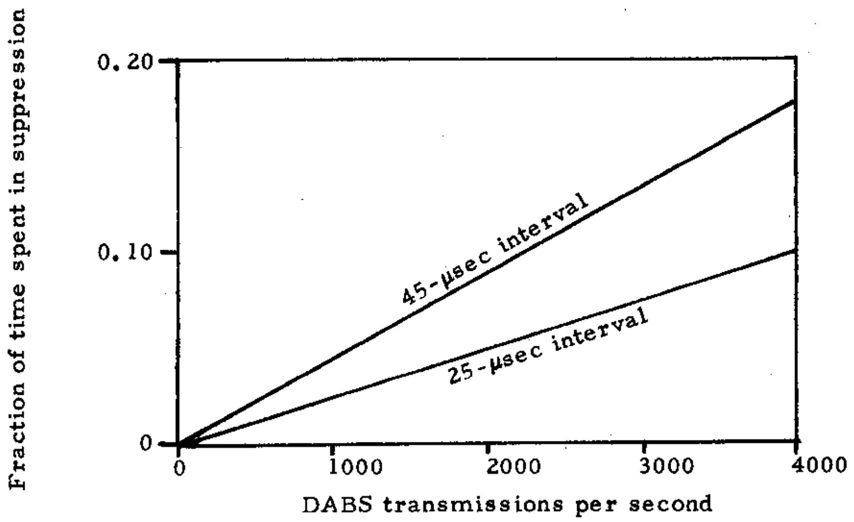

Fig. 2-2(a). ATCRBS transponder suppression in side and back lobes of DABS sensor.

ATC-52 (2b)

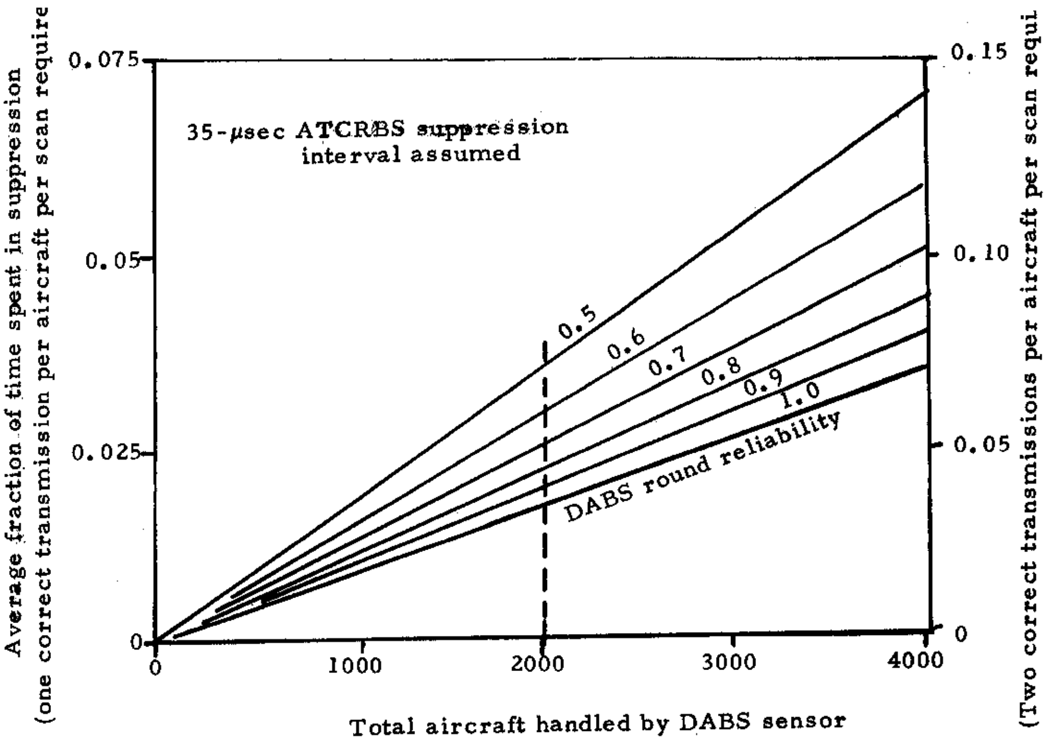

Fig. 2-2(b). ATCRBS transponder suppression as a function of DABS sensor traffic loading and reliability.

2.2.2 TACAN EMC Consideration

Acting in direct support of the DABS program, ECAC[*] has investigated the effects of DABS in TACAN/DME. The investigations have been primarily analytical in conjunction with laboratory measurements accomplished at NAFEC. The following material is based on an ECAC report [Ref. 8] giving interim results.

A. Major Effects of DABS Uplink Transmissions

The major effects of DABS uplink transmissions on TACAN/DME (ground based) beacons are:

- Loading (replies to decodes produced by DABS signals)
- Deadtime (both the deadtime associated with replies and deadtime caused by dynamic desensitization)

The major effect on TACAN/DME (airborne) interrogators is:

- AGC capture (according to an effective average interference power)

Because of the durations and signal structures of DABS uplink transmissions, it is possible that decodes and resulting replies will be produced in TACAN/DME beacons. Similar decodes may also be produced by DABS signals in TACAN/DME interrogators, although these are of little consequence relative to the AGC capture phenomenon. Beacon decodes are produced only when a DABS signal is received at sufficient power after the effects of path loss, antenna gains, and frequency filtering. Consequently, the resulting occurrence rates depend on location of the equipment and channel number as well as on transmitter power levels, antenna patterns, and DABS interrogation rates.

Laboratory measurements have demonstrated that the dominant interference effect of DABS uplink signals acting on TACAN/DME interrogators is AGC capture. The occurrence of this condition may be determined by calculating an "effective average interference power," (EAIP). The EAIP is calculated as the received average power level, adjusted for off-frequency rejection (OFR) and then adjusted for receiver saturation. If the EAIP exceeds an empirically determined maximum tolerable level, Max (EAIP), which depends on the power level of the TACAN/DME signal being interfered with, then a degradation condition exists. The manner of degradation that occurs just beyond Max (EAIP) is the inability to acquire azimuth lock. Other degradations such as azimuth breaklock, inability to acquire range lock, and range breaklock all occur at higher levels of interference.

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[*] Electromagnetic Compatibility Analysis Center, Annapolis, Md.

B. Degradation Criteria

For TACAN/DME interrogators, the degradation criterion used is simply that EAIP $\leq$ Max (EAIP). Lesser amounts of average interference power have no discernable effect on interrogator performance.

For TACAN/DME beacons, it has been difficult up to the present time to select a single specified level of loading and deadtime for use as a degradation criterion. Consequently, results generated by ECAC give loading and deadtime parametrically. ECAC is conducting a parallel effort to investigate the effects of deadtime and loading on the overall TACAN/DME functioning. The objective is to determine whether or not given levels of loading deadtime produce a noticeable effect on overall performance. Results available at this time suggest that if deadtime and loading are both approximately 5%, very little if any noticeable effect would result; by its nature, the TACAN/DME system is very tolerant to interference.

C. Estimated Levels of Interference

Based on reasonable assignments of transmitter powers, antenna patterns, DABS interrogation rates, etc., ECAC has calculated beacon loading and deadtime as functions of range and frequency offset. The calculations include power programming and include a mixture of long and short DABS interrogations. Typical results are shown in Fig. 2-3. Evidently the interference effects are quite small, such that in this case, in-band operations are also possible without exceeding the 5% loading-deadtime criterion mentioned above. Furthermore there is a large OFR improvement for out-of-band channels.

Similarly, ECAC has calculated interference conditions received at an airborne TACAN/DME interrogator. Typical results are given in Fig. 2-4. The data in the figure indicate interference conditions that are much less than the tolerable level, even for the smallest existing frequency offset (in this case 6 MHz). Whereas Fig. 2-4 pertains to an X-mode interrogator, ECAC has determined that the effects on a Y-mode interrogator are completely negligible.

2.3 Modulation Characteristics

Transponder cost constraints and EMC considerations lead one to use simple binary modulation schemes for transmitting DABS uplink messages at a data rate of approximately 4 MHz. Emphasis must be placed not only on simple demodulator circuitry to keep transponder cost down, but the selected system must also be sufficiently insensitive to synchronization errors to allow the use of simple synchronization circuitry as well. This section discusses the relevant performance measures of several binary modulation candidates for the DABS uplink.

ATC-52 (2-3)

- Worst case (min) TACAN/DME signal power
- Interrogation rate = 200/sec
- Range = 1 nmi

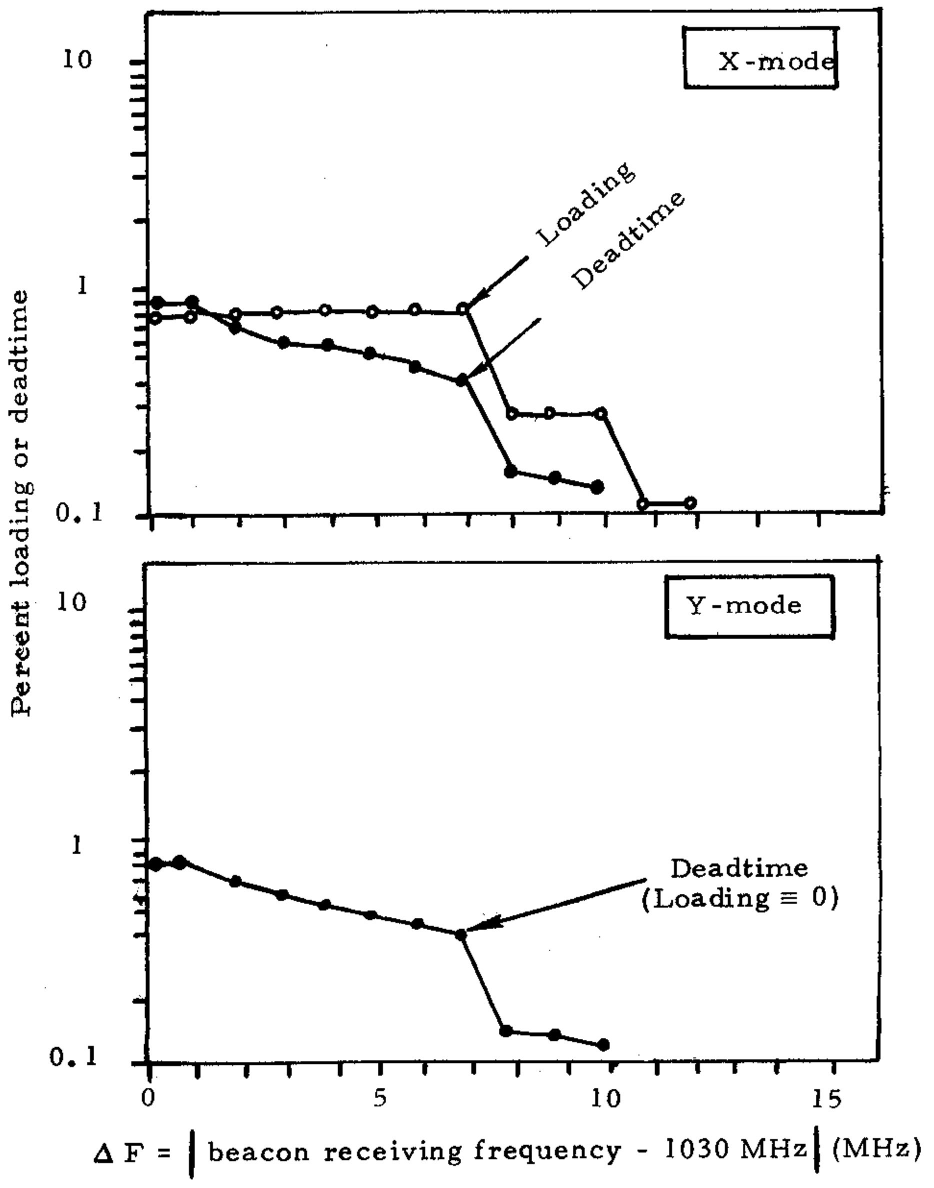
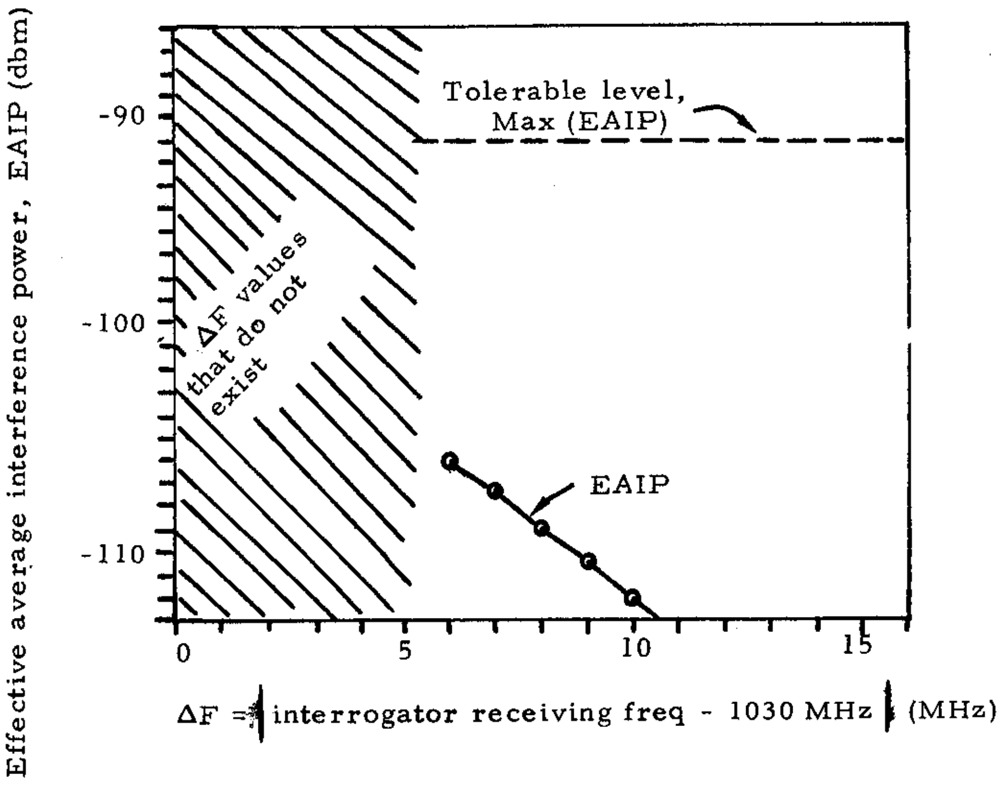


Fig. 2-3. Effects of DABS uplink on TACAN/DME beacons.

ATC-52 (2-4)



- Worst case (min) TACAN signal power
- Interrogation rate = 200/sec
- Range = 1 nmi
- X-mode interrogator

Fig. 2-4. DABS uplink effects on a TACAN interrogator.

The channel environment at 1030 MHz will include the following effects:

1. Fading caused by antenna shielding and lobing
2. Pulsed RFI from ATCRBS interrogations
3. Multipath garble, (the degree of severity of which is unknown and is determined by DABS sensor antenna design and siting).

Furthermore, EMC considerations dictate the use of minimum sensor effective radiated power (ERP) to minimize ATCRBS side- and backlobe suppression range. Thus, the relevant performance measures for a first comparison of modulation schemes are error rates (probability of bit decision errors = $P_{e/bit}$) as a function of signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR).

Since the ATCRBS interrogation mode decoding generally used a PAM-type demodulator, and the military Mode 4 interrogation is a discretely addressed interrogation using a PAM-RZ format, the initial bias for the DABS uplink modulation was in the direction of a PAM system. For DABS, PAM-NRZ was more advantageously suited to the 4-MHz data rate because it allowed smaller bandwidth occupancy than an RZ format would allow at the same data rate. Thus, the PAM system considered for the DABS uplink would transmit a particular information bit by the presence or absence of an RF pulse in a particular interval. In an NRZ format, successive bit intervals follow one another without spaces between them. The PAM demodulator would process the pulse incoherently (do envelope detection), sample the envelope video at a point within the bit interval, and compare the sample video amplitude with a threshold to decide whether or not a pulse was present (i.e., whether or not to decide the information bit was a one or a zero). Good performance in the presence of RFI requires that the decision threshold be a function of the received signal level. The PAM demodulator itself can be quite simply implemented, but both the bit synchronization (the sample times) and the decision threshold setting must be provided by other circuitry. Moreover, in a system such as DABS, in which the path loss varies over a wide range because of the target range from the sensor, the PAM processing circuitry must preserve the envelope fidelity over a wide dynamic range, or energy from adjacent pulses will make it difficult to recognize the absence of pulses (this effect is called intersymbol interference). Because of the 4-MHz data rate required by the DABS uplink, a simple modification to existing ATCRBS or Mode 4 decoders would not be possible. Therefore, PAM had to be considered on its own merits just as any other system that would require a new synch/demodulator system in the transponder.

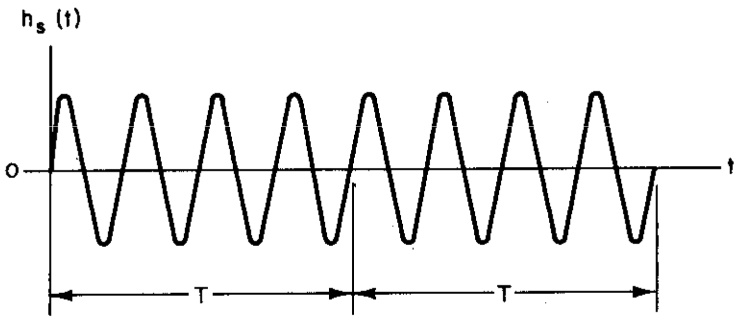
In FSK, one of two discrete RF pulse frequencies is used to transmit a particular information bit. A simple demodulator would compare the outputs of two filters tuned to the frequencies to make its bit decisions. Thus, there is no threshold setting in accordance with received signal level, which is a simplification. The use of simple filters in the demodulator is facilitated by increasing the frequency separation of the pulse, but this happens at a cost of increased bandwidth occupancy, which might affect EMC problems.

In PSK modulation, the RF phase of a pulse is controlled relative to a reference signal to transmit information. In a binary system, one of two RF carrier phase angles 180° apart is transmitted to signify the value of a particular information bit. In coherent PSK, a carrier phase reference must be established by the receiver. The time constraints of the DABS uplink and the complexity associated with this reference signal ruled out coherent PSK. However, the simpler differentially phase shift keyed variant, termed DPSK, uses the RF phase of the previous pulse as the reference in making bit decisions, thus simplifying the phase reference problem somewhat. A DPSK demodulator thus compares the carrier phase of a pulse with that of the previous pulse and decides whether or not the pulse phase is closer to being in phase or 180° out of phase with the reference pulse phase. Two common types of DPSK demodulators are shown in Fig. 2-5. Neither of these demodulator types requires the setting of a decision threshold dependent on received signal level. Moreover, a saturating limiter can generally be used to restrict the dynamic range of a DPSK demodulator while not seriously affecting performance in RFI.

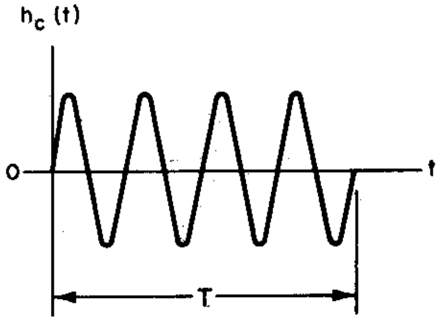
Figure 2-6 shows the probability of a bit decision error, P_e/bit, as a function of SNR (given by the energy per bit E over the noise power density N_o) for ideal processing of incoherent PAM and FSK, and DPSK [Ref. 9]. In this case ideal processing implies ideal matched filters in the demodulators, perfect bit synchronization, and perfect setting of the decision threshold in the PAM demodulator. Figure 2-6 also indicates sensitivity to interference of the various modulation types for an ISR (denoted by ρ in the figure) of 0.2. Figures 2-7a and 7b show P_e/bit as a function of ISR (interference-to-signal ratio (ISR) = SIR^{-1}) for SNR(s) of 16 dB and 24.8 dB. Again ideal demodulators were assumed. These calculations show that DPSK attains a given level of P_e/bit in the interesting range of 10^{-3} and 10^{-5} at significantly lower SNR(s) and SIR(s) than the other two schemes.

FSK displays no performance advantage over the other candidates, although it may aggravate some EMC problems. Since it also promises no significant cost advantage, if any at all, FSK was dropped from further consideration.

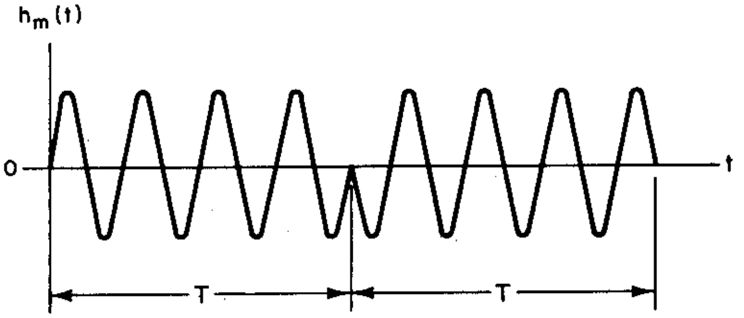
In order to assess the difference between ideal and real demodulator performance, PAM and DPSK demodulators were built and tested at Lincoln Laboratory. The ideal matched filters were replaced in the Laboratory demodulators by 5-section, 6-MHz bandwidth IF filters. Figures 2-8 and 2-9 show both calculated and measured values of P_e/bit as a function of SNR and SIR for demodulators with 6-MHz filters. These results are for perfect bit synchronization and PAM threshold setting. The sensitivity of the Laboratory demodulators (with 6-MHz filters) to bit synchronization errors is illustrated in Fig. 2-10, which plots P_e/bit vs demodulator sample time for a 4-MHz data rate. Figure 2-10 indicates that the performance of both PAM



(a)
IMPULSE RESPONSE OF A FILTER
MATCHED TO A SPACE



(c)
IMPULSE RESPONSE OF A FILTER
MATCHED TO A CHIP



(b)
IMPULSE RESPONSE OF A FILTER
MATCHED TO A MARK

Fig. 2-5. (a) DPSK demodulator, type 1. (b) DPSK demodulator, type 2 (delay and multiply receiver). (c) DPSK demodulator filter impulse responses.

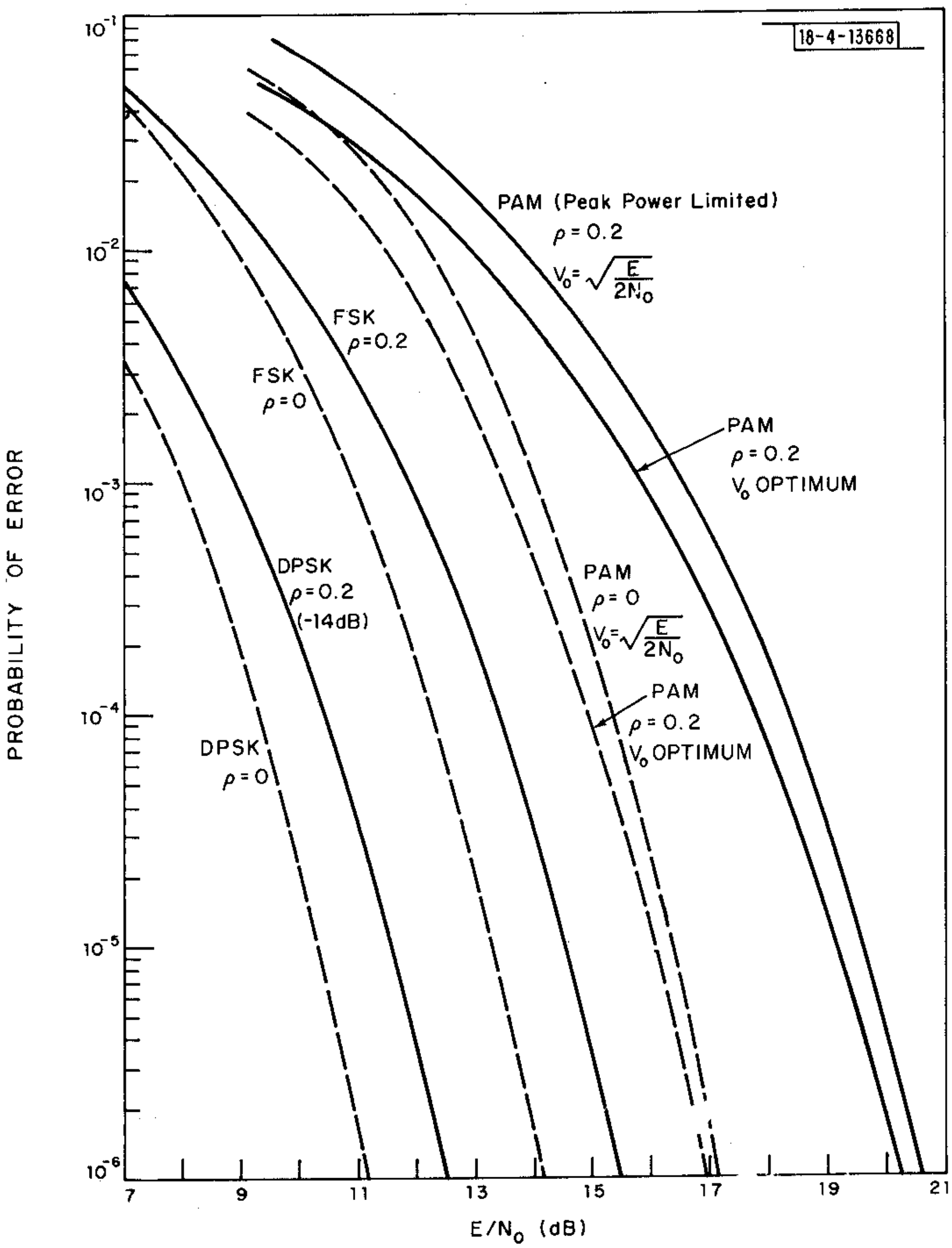


Fig. 2-6. Probability of bit errors for three binary modulations in noise only (ρ=0); in pulsed interference (ρ=0.2) or (SIR = -14 dB) vs SNR.

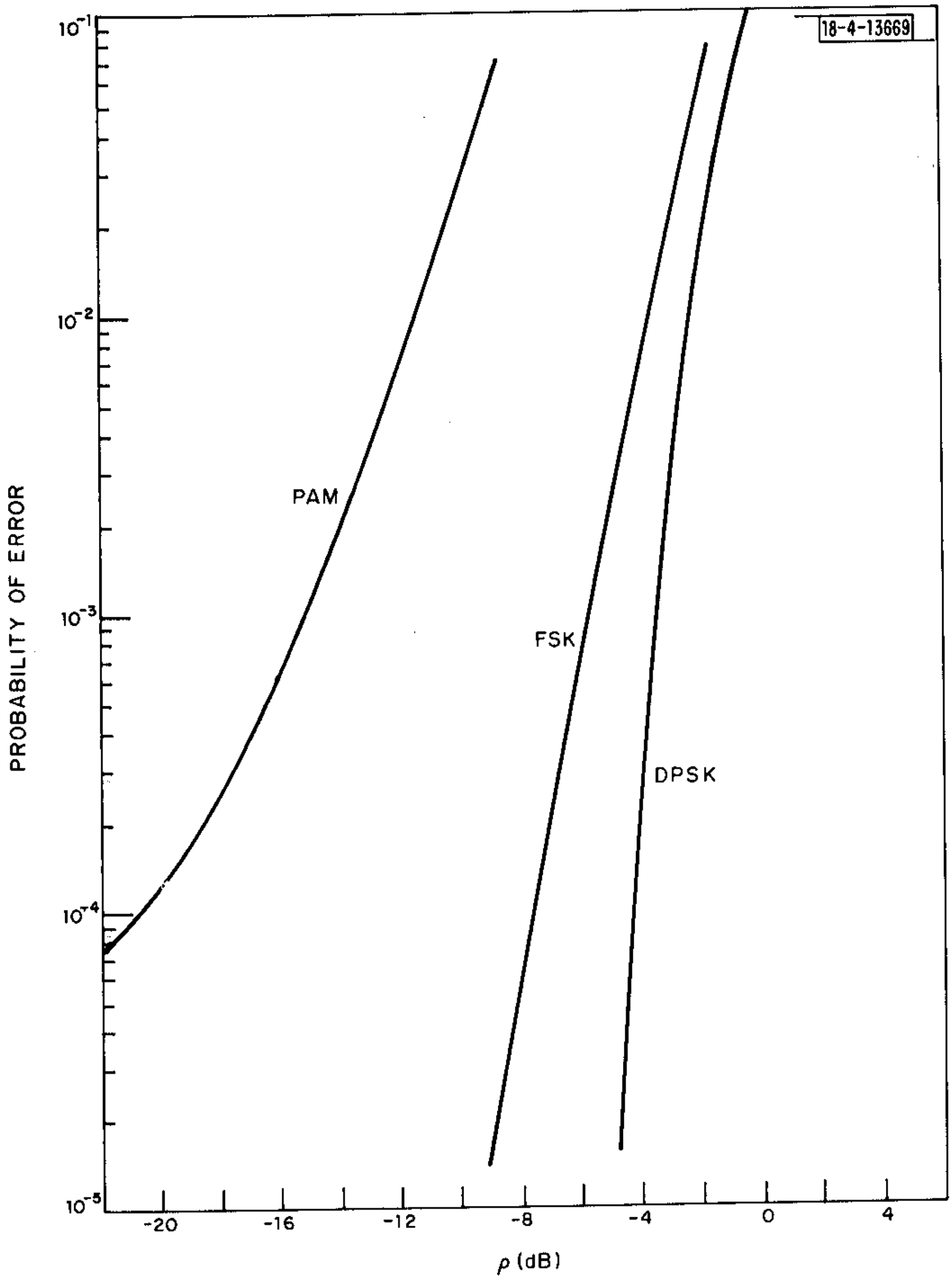


Fig. 2-7(a). Bit error probability vs interference-to-signal ratio (ρ); SNR = 16 dB.

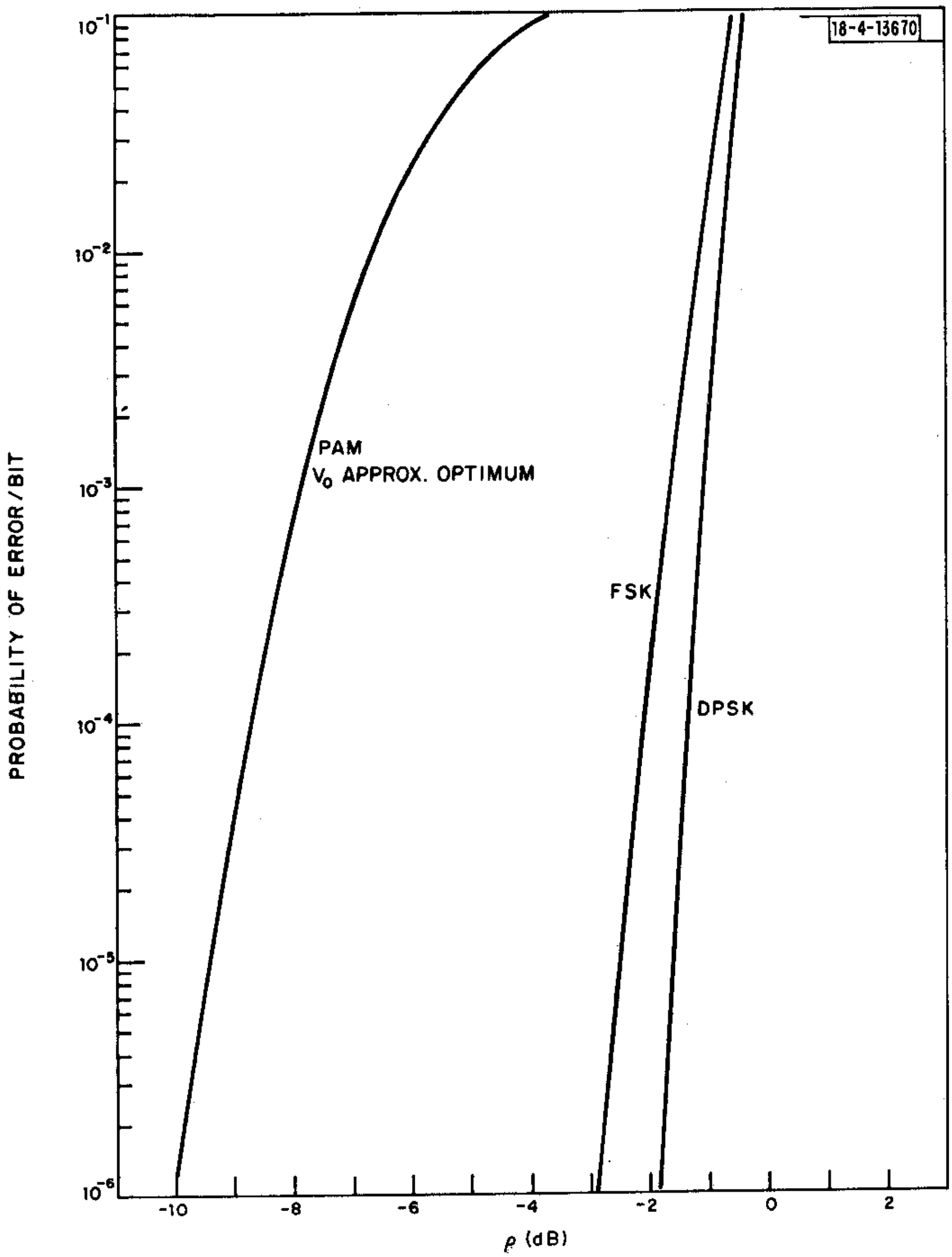


Fig. 2-7(b). Bit error probability vs interference-to-signal ratio (ρ); SNR = 24.8 dB.

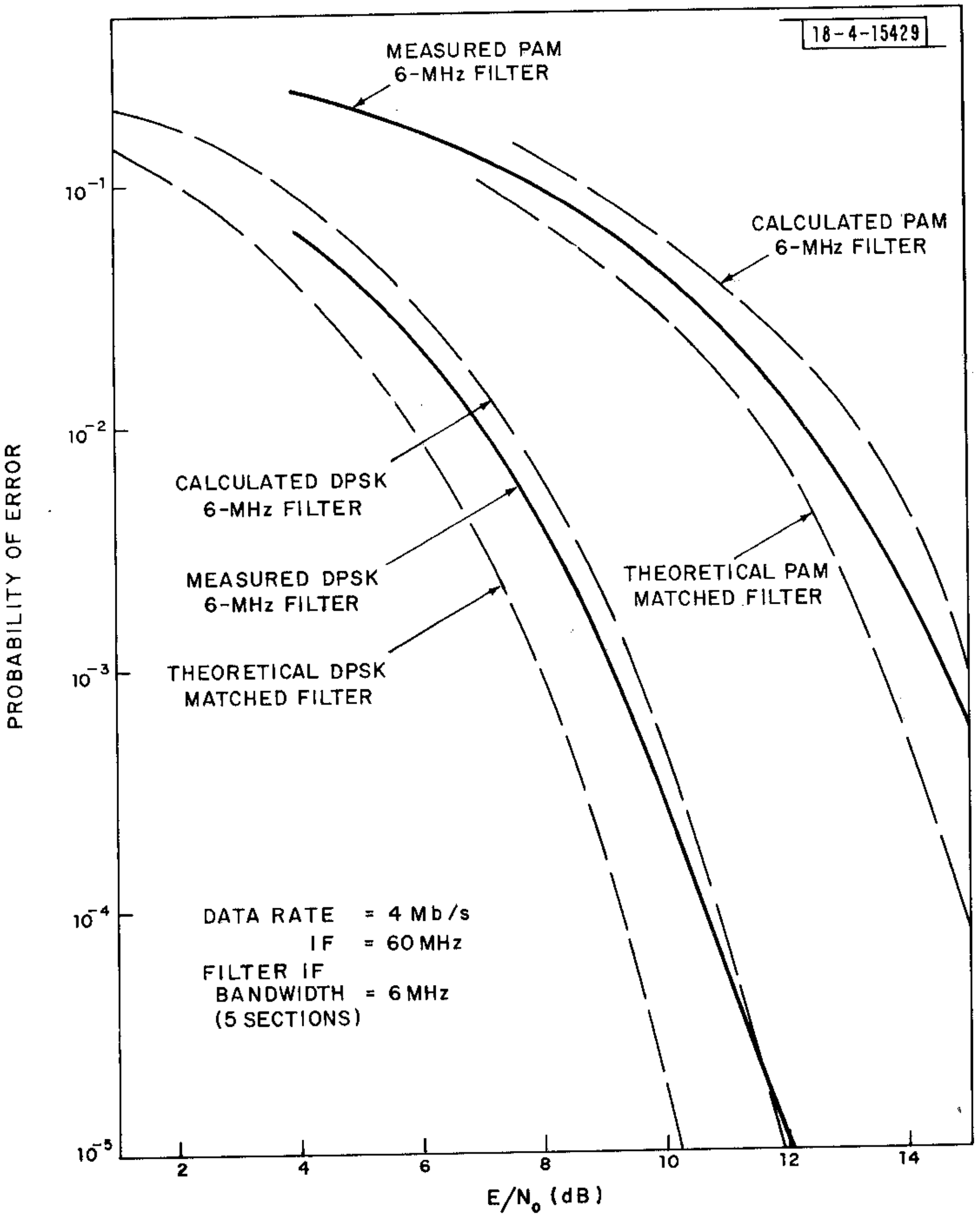


Fig. 2-8. Measured bit error probability vs SNR for PAM and DPSK.

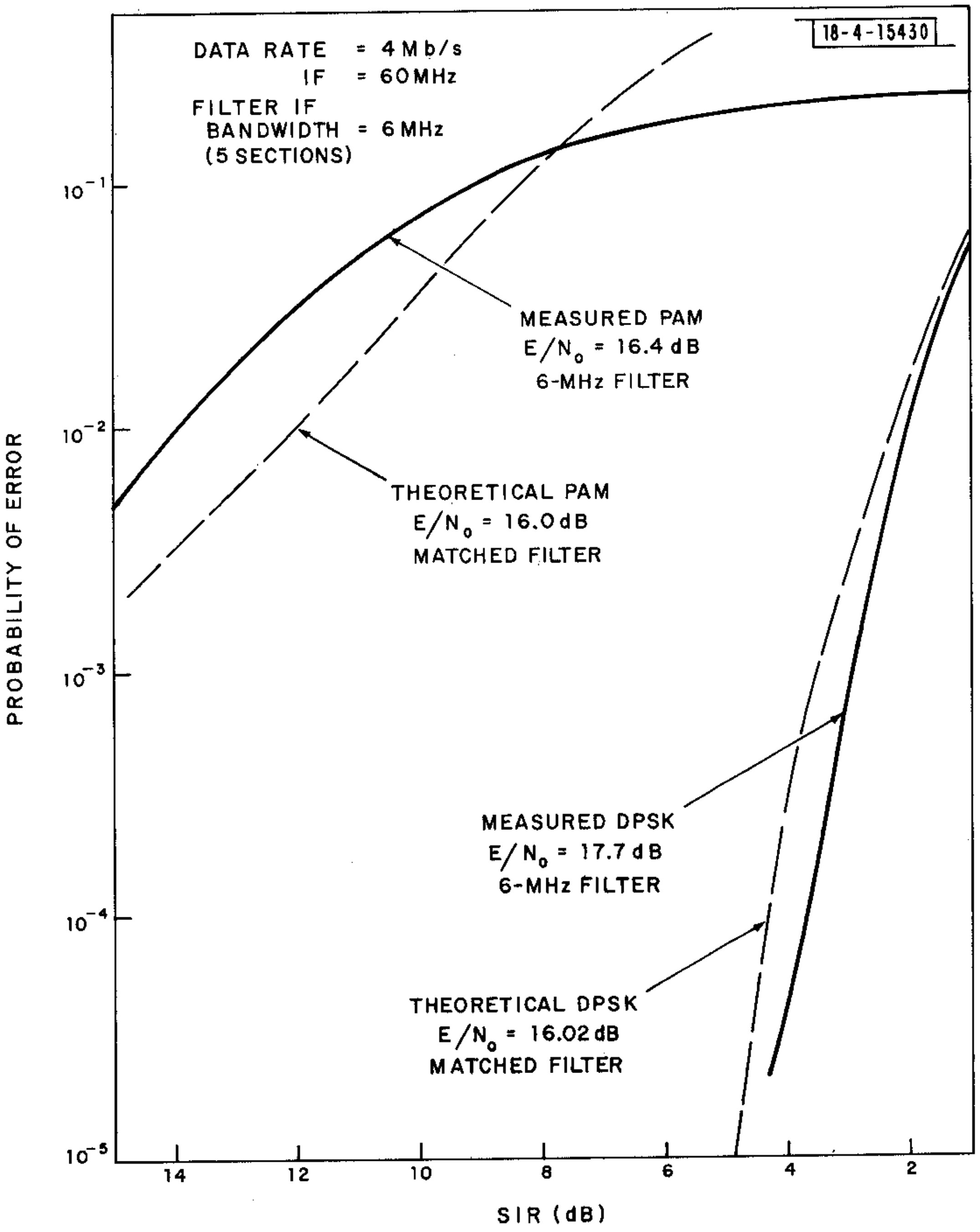


Fig. 2-9. Measured bit error probability vs SIR for PAM and DPSK.

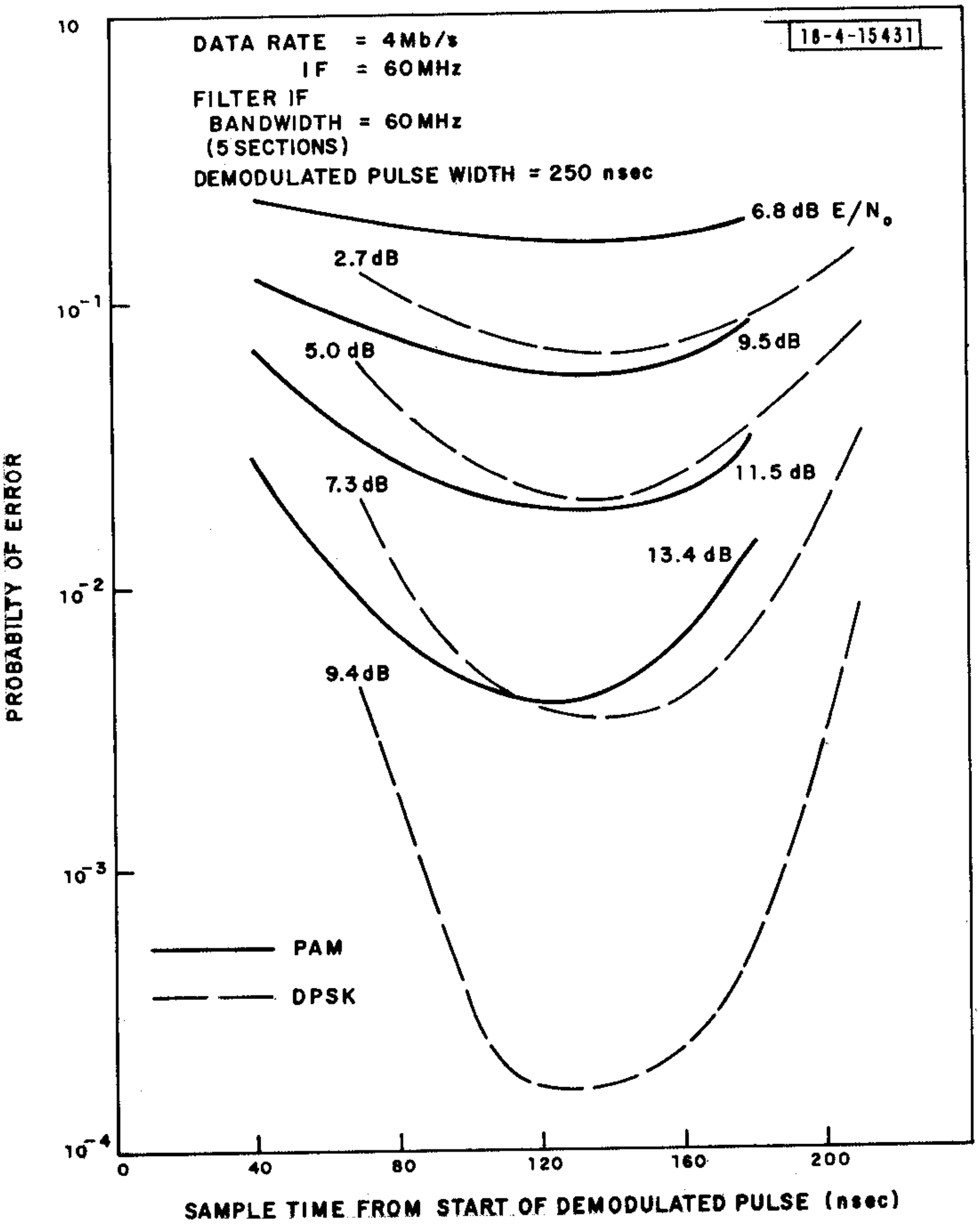


Fig. 2-10. Measured bit error probability vs bit sample time (synchronization offset) for PAM and DPSK laboratory demodulators.

and DPSK demodulators degrades the same amount with sample time offset at a given level of performance (i. e., the PAM and DPSK curves with minima in probability of error of approximately 0.3×10^{-2} track together fairly closely, although the signal-to-noise ratios required to achieve these curves reflect the 6-dB advantage of DPSK).

The critical component in the simple delay-and-multiply DPSK demodulator is the delay line. The stability of the delay line, with environmental conditions, is directly related to demodulator performance and cost.

Figure 2-11 illustrates the sensitivity of the delay-and-multiply DPSK demodulator to delay line variations, which result in phase reference errors [Ref. 10]. The table in the figure illustrates the delay line tolerance that is required to maintain satisfactory demodulator performance in the presence of RFI. At an ISR value of -6 dB, these data indicate that a delay error resulting in less than 60° (of carrier reference phase shift) would be needed to assure a $P_{e/bit}$ of 10^{-3} or less at an SNR ≈ 25 dB. For a 60-MHz IF frequency, this translates into a 1% tolerance on the delay line over all environmental conditions.

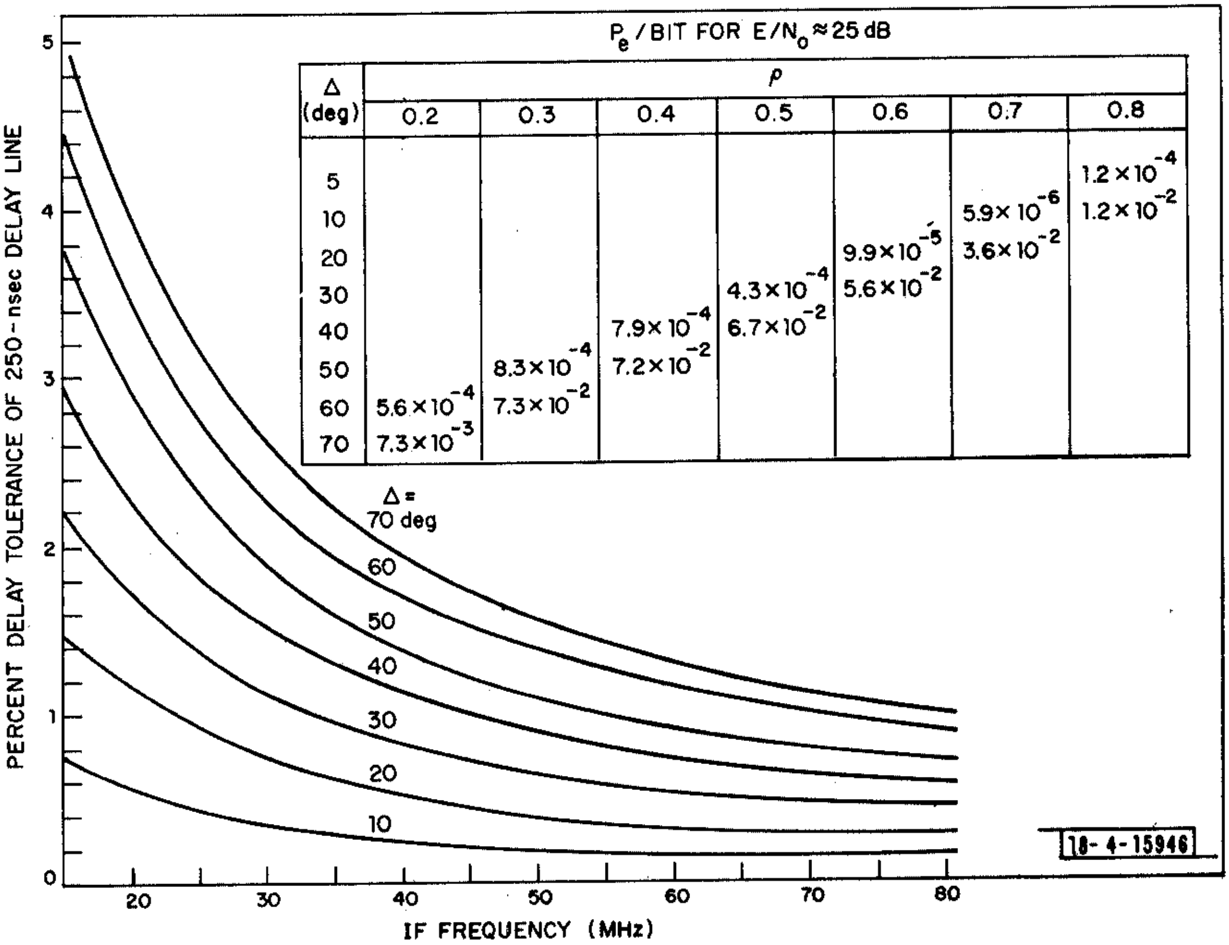
In summary, the study of simple modulation schemes for the DABS uplink RFI environment results in two candidates: PAM-NRZ and DPSK. DPSK indicates a clear performance advantage over PAM in both SNR and SIR required to achieve a particular error rate. Both schemes are basically equally insensitive to synchronization errors. The PAM system requires setting the decision threshold in accordance with the received signal level in order to achieve its calculated performance in RFI; DPSK does not require such threshold setting. DPSK is less sensitive than PAM to wide dynamic range effects of the system. The cost of the DPSK demodulator is greatly affected by the cost of a stable delay line. Cost comparisons will be treated in more detail in Section 2. 5. 1 of this report.

2. 4 Message Validation

The critical nature of IPC and ATC command messages for collision avoidance requires that messages containing errors be screened and rejected with great reliability. The performance goal of accepting no more than one in 10^7 messages containing errors under realistic channel conditions basically seeks to reduce such events to very unusual and rare occurrences. Message errors were anticipated from several different situations:

1. Low SNR (fading) conditions resulting in randomly distributed errors throughout the message block

2. ATCRBS interrogations and TACAN transmissions garbling, which would result in clusters or bursts of errors caused by the individual pulses of these signals



P_e/BIT FOR $E/N_0 \approx 25$ dB

Δ (deg)	ρ						
	0.2	0.3	0.4	0.5	0.6	0.7	0.8
5							1.2×10^{-4}
10						5.9×10^{-6}	1.2×10^{-2}
20					9.9×10^{-5}	3.6×10^{-2}	
30				4.3×10^{-4}	5.6×10^{-2}		
40			7.9×10^{-4}	6.7×10^{-2}			
50		8.3×10^{-4}	7.2×10^{-2}				
60	5.6×10^{-4}	7.3×10^{-2}					
70	7.3×10^{-3}						

Fig. 2-11. Delay line tolerance for DPSK demodulators as a function of bit error probability required.

3. Multipath transmission garbling, resulting in randomly distributed errors throughout the interval in which the direct path signal is garbled or overlapped by the reflected path signals.

Two approaches to message validation that received serious consideration were

1. Parity check coding to detect multiple error bursts as well as randomly distributed errors
2. Message parrotting (repeating the message to the ground where it is checked for errors, followed by transmission of an execution command when the correct message has been repeated to the ground).

Of the two approaches, the first offers the potential of acceptance, validation, and display of a message following a single error-free uplink transmission. The parity check coding approach thus results in message delivery times that are not dependent on the downlink reliability. This approach also requires fewer total transmissions to deliver a message, consequently reducing interference to other systems. The message parrotting approach suffers from having to establish a more complicated link protocol to enable the ground equipment to do the error checking while the aircraft withholds action on the received message. This approach also requires increased channel utilization and an unnecessary dependence on downlink reliability to deliver critical uplink messages.

A third approach to message validation was very briefly considered, namely, uniformly distributing the transponder address bits throughout the message block. This was intended as protection against bursts of errors, which would tend to garble at least one address bit, thus rendering the message unacceptable to its designated receiver. However, this approach offers no special protection against the random pattern of errors caused by low SNR conditions, therefore some form of parity checking would probably be included for this case. Thus, this approach was excluded in favor of the more systematic parity check coding approach to detect both error bursts caused by RFI and noise-like error patterns.

The selected approach to uplink message validation was parity check coding, which was capable of detecting multiple bursts of errors in a message block, as well as the randomly distributed errors caused by noise and multipath. The coding effort focused on simply implemented error detection circuitry consistent with transponder cost constraints.

2.4.1 Parity Check Coding

A parity check code, which is intended to protect a sequence of k message bits, "encodes" a message by producing a sequence of n bits, where $n > k$. The first k bits of the encoded sequence may be identical to the original message, in which case the code is called a "systematic" code. The remaining n-k bits, referred to as parity check bits, are redundant bits that are derived from the first k bits by a specified algorithm. After transmitting the encoded bits to a receiver, the received sequence of n bits is processed as follows. The first k received bits are used to generate n-k parity check bits, which are compared to the n-k parity check bits received over the channel. If these two parity check sequences agree bit by bit with each other, the received sequence is self-consistent and is assumed correct. If the two parity check sequences disagree, an error in transmission of at least one of the n bits has been detected.

Out of a total of 2^n distinct binary sequences of length n, there are only 2^k legitimate encoded sequences that are actually transmitted. Thus, it is possible for channel noise or RFI to change one encoded sequence into another sequence since there are $2^k - 1$ such remaining sequences that are legitimate. Such a transformation of one encoded sequence into another sequence would result in accepting the received sequence as a correct message, although it was not the message that was transmitted. Thus the accepted message would be erroneous, and the acceptance of such erroneous messages is precisely the type of situation the parity check code must be designed to control.

The parity check code design problem may thus be stated as follows. Study encoding algorithms that will reduce the probability that channel error sources will transform one encoded sequence into another to a suitably low value, and select the code (encoding algorithm) that accomplishes this objective with a minimum number of redundant bits (n-k).

2.4.2 Address-Parity Overlay

Since the DABS uplink transmissions were greatly time-constrained, the amount of redundance required was of primary concern. This motivated the acceptance of a technique proposed by British workers and used in the ADSEL system [Ref. 11], which is a British developed ATC discrete address beacon system. With parity check coding, a DABS transponder (or any discretely addressable receiver) must check the parity sequence as well as the address bits received before accepting any message. Since parity checking and address checking are very similar operations (determining if a sequence of bits agrees entirely with some prescribed reference sequence), the parity and address fields of an encoded message may be combined to save transmitting redundant bits. If the parity check sequence of an encoded message is combined with the transponder address by modulo two summation, the transponder can remove the parity check bits by modulo two summation of the parity check sequence derived from the received k message bits. If the parity check bits calculated in the transponder agree exactly with the parity check bits that have been combined with the address, the result of summing the two parity check sequences produces the transponder address unchanged. Thus, if the received message is entirely correct, the transponder can remove the parity check bits, and only the address bits need to be checked to accept the message.

If a received message contains errors, the parity check sequence derived in the transponder will disagree (with high probability) with that combined with the address, and the result will be that the address field checked by the transponder will contain the transponder address summed modulo two with the difference between the proper parity check sequence and that derived in the transponder from the incorrect message. Thus, the transponder will not find its address if the encoded message sequence has been received with errors. This scheme eliminates transmission of either the parity check sequence or the transponder address (whichever is smaller) as a separate bit field. This scheme was judged to be well suited to the time-constrained DABS uplink, and therefore it was adopted and is referred to as the "address-parity overlay" scheme to minimize the length of the encoded uplink message.

A penalty associated with the address-parity overlay scheme is misdirected messages caused by transmission error, i.e., an encoded message addressed to one aircraft may be received by another aircraft with errors in the received message, which result in changing the address of the first aircraft into that of the second aircraft. Thus, the address-parity overlay may result in acceptance of a message containing errors that was really intended for another aircraft. It is difficult to quantify this phenomenon, but it appears reasonable to consider an erroneous message decoded by a transponder as one in which the address bits have been completely randomized. Thus, if such a message is to be accepted by another transponder, the probability of that transponder's address agreeing with the scrambled address decoded from the erroneous message would be 2^{-A}, where A is the number of address bits used by the system (under the assumption of completely random scrambling by the disagreeing parity check sequences). Thus, if $A = 24$ bits, the probability of a misdirected message being accepted by a transponder is on the order of $2^{-24} \approx 0.6 \times 10^{-7}$. It is true that more than one transponder may receive a message intended for some specific aircraft, but this is offset somewhat by the fact that there is some probability less than unity that such messages are received erroneously. The conclusion is that a 24-bit address appears to lead to sufficient control of the probability that a transmitted message will be misdirected to some other aircraft by channel errors.

A further point to note concerning the address-parity overlay scheme is that the parity check sequence derived from the message is available only after processing the message bits. Thus, the logical location of the address-parity field is at the end of an encoded message. This implies that a transponder must store and process the entire received message before it can check the address to determine if it should accept the message. Even if the address were at the beginning of the message block, early rejection of a message addressed to another aircraft would not necessarily allow immediate processing of another aircraft message because the overlap of the two transmissions would likely result in errors. Thus there is no practical difference between having the address at the beginning or at the end of a message block, although there is a very significant saving in overall encoded message length that accrues from the address-parity overlay scheme.

2.4.3 The Selected DABS Code

Binary cyclic codes are a special class of parity check codes, which are generally well suited to burst error detection and also admit simple decoder circuit implementations. A further advantage of this class of codes is the flexibility of shortening the codes to suit established message length requirements while not compromising code performance. This property was beneficial in that it allowed coding studies to continue uninterrupted during the evolution of the uplink message length.

The code selected for the DABS uplink is a cyclic code generating 24 parity check bits, which makes maximum use of the address field to incorporate the redundant parity bits. The particular cyclic code selected is specified by its generator polynominal

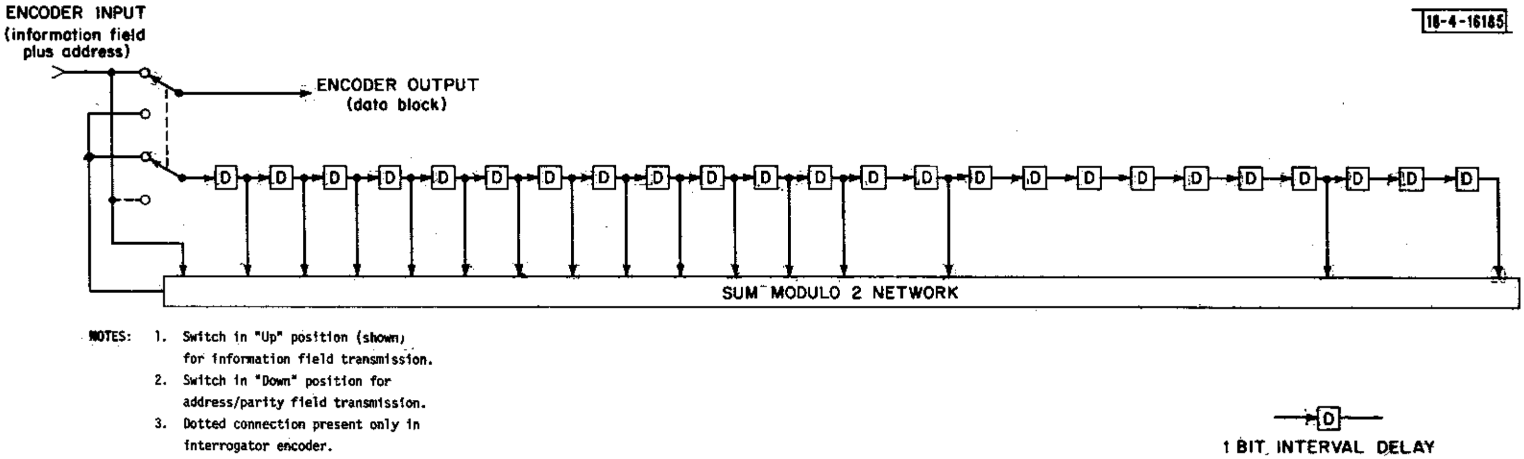
$$g(x) = 1 + x^3 + x^{10} + x^{12} + x^{13} + x^{14} + x^{15} + x^{16} + x^{17} + x^{18} + x^{19} + x^{20} + x^{21} + x^{22} + x^{23} + x^{24} \quad .$$

This code produces code words with a natural length of about 2.75 million bits, but it has been shortened for use with 88-bit messages (for a total encoded message length with address-parity overlay of 112 bits). This code is also used to encode the 32-bit DABS interrogations that do not contain command messages. The multiple burst error detection capabilities of this code, discovered by Kasami, have been extensively studied and are very well suited to the DABS uplink channel RFI environment [Ref. 12].

Figure 2-12 illustrates the encoding circuitry associated with the DABS uplink code. The basic circuit, which computes the parity check sequence from the message sequence, is a shift register with feedback connections back to its input. The details of the address-parity overlay logic for the uplink were chosen to facilitate the address checking in the transponder with feed-out shift register circuits.

2.4.4 Code Performance

The DABS uplink code performance was estimated when the DABS uplink transmissions were garbled by ATCRBS interrogations and TACAN pulse pairs. Performance evaluation consisted of calculating the probability of acceptance of a DABS message containing errors (undetected message errors) using known properties of the code. ATCRBS pulses were assumed to cause error bursts up to a length of 5 bits, and TACAN pulses were assumed



NOTES:
1. Switch in "Up" position (shown) for information field transmission.
2. Switch in "Down" position for address/parity field transmission.
3. Dotted connection present only in interrogator encoder.
4. Initial contents of 24-bit register all "0"'s.

Fig. 2-12. Functional diagram of DABS interrogator and transponder encoders.

to cause error bursts up to a length of 19 bits. The probability of a bit error within the burst, garbled by an interfering pulse, was assumed to be 0.5 for this calculation.

The calculated probability of undetected message errors is indicated in Table 2-1 for the most probable garbling signals, which are (for ATCRBS interrogations):

1. A single P_2 pulse
2. A P_1, P_2 pulse pair
3. A P_1, P_3 pair for modes 2, 3/A or C
4. A complete mode garble (P_1, P_2, and P_3) for modes 2, 3/A
5. Combinations of two of any of the above modes.

Table 2-1 indicates the calculated conditional probability of an undetected message error, assuming that a garble occurs, i.e., the probability that a garble will occur in a given environment is not included in these results. In addition, the conditional probability of undetected message error, given a garble by a TACAN mode*, is less than 2.14×10^{-8}. The calculation of these results is described in more detail in Ref. 13. (It should be noted also that the above calculations were done for a 96-bit encoded message block, which does not result in any practical difference in calculated performance for 112 bits for the coding scheme selected.)

The aforementioned results demonstrate that the selected DABS uplink code appears to be well-matched to the error detection function for the DABS uplink RFI environment. The performance goal of undetected message error probability of 10^{-7} in realistic channel environments appears to be attainable. Furthermore, the transponder cost associated with implementing the decoding (error detection) function is very small, since a storage register must be provided for received messages even without coding. The address-parity overlay scheme allows the attainability of the above advantages of parity check coding for DABS message validation without the penalty of having to transmit redundant bits.

2.5 Comparison of PAM and DPSK Uplink Designs

The foregoing discussion of uplink design issues and options may be summarized at this point as follows.

1. The DABS interrogation/message must begin with a two-pulse preamble to intentionally suppress ATCRBS transponders (to prevent them from being triggered).

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*Two 3.5-μsec pulses spaced 12 μsec apart and assumed to result in not more than 19-bit error bursts each.

TABLE 2-1

A POSTERIORI PROBABILITY OF UNDETECTED MESSAGE ERROR

	Mode Pairs M, M	Pr(UDME|M, M') 5-bit burst	Pr(UDME|M, M') 4-bit burst
P_2	P_2	0	0
	P_1P_2	1.17×10^{-6}	0
	P_1P_3 Mode 2	0	0
	P_1P_3 Mode 3/A	0	0
	P_1P_3 Mode C	0	0
	$P_1P_2P_3$ Mode 2	1.85×10^{-7}	0
	$P_1P_2P_3$ Mode 3/A	4.49×10^{-7}	0
	$P_1P_2P_3$ Mode C	6.78×10^{-7}	0
P_1P_2	P_1P_2	5.91×10^{-7}	0
	P_1P_3 Mode 2	5.48×10^{-7}	0
	P_1P_3 Mode 3/A	5.74×10^{-7}	0
	P_1P_3 Mode C	1.06×10^{-6}	0
	$P_1P_2P_3$ Mode 2	3.08×10^{-7}	3.65×10^{-9}
	$P_1P_2P_3$ Mode 3/A	6.49×10^{-7}	4.25×10^{-7}
	$P_1P_2P_3$ Mode C	8.11×10^{-7}	4.72×10^{-10}
P_1P_3 Mode 2	P_1P_3 Mode 2	5.34×10^{-8}	0
	P_1P_3 Mode 3/A	1.67×10^{-8}	0
	P_1P_3 Mode C	2.33×10^{-9}	0
	$P_1P_2P_3$ Mode 2	8.53×10^{-8}	1.59×10^{-8}
	$P_1P_2P_3$ Mode 3/A	1.82×10^{-7}	8.81×10^{-9}
	$P_1P_2P_3$ Mode C	3.27×10^{-7}	0
P_1P_3 Mode 3/A	P_1P_3 Mode 3/A	1.57×10^{-8}	0
	P_1P_3 Mode C	8.56×10^{-9}	1.4×10^{-8}
	$P_1P_2P_3$ Mode 2	1.19×10^{-7}	1.96×10^{-9}
	$P_1P_2P_3$ Mode 3/A	2.08×10^{-7}	2.32×10^{-9}
	$P_1P_2P_3$ Mode C	3.21×10^{-7}	1.06×10^{-8}
P_1P_3 Mode C	P_1P_3 Mode C	3.78×10^{-9}	0
	$P_1P_2P_3$ Mode 2	1.98×10^{-7}	7.89×10^{-10}
	$P_1P_2P_3$ Mode 3/A	4.36×10^{-7}	2.11×10^{-9}
	$P_1P_2P_3$ Mode C	6.51×10^{-7}	1.03×10^{-8}
$P_1P_2P_3$ Mode 2	$P_1P_2P_3$ Mode 2	6.08×10^{-8}	2.0×10^{-8}
	$P_1P_2P_3$ Mode 3/A	7.64×10^{-8}	5.79×10^{-8}
	$P_1P_2P_3$ Mode C	2.80×10^{-7}	6.06×10^{-9}
$P_1P_2P_3$ Mode 3/A	$P_1P_2P_3$ Mode 3/A	3.0×10^{-7}	1.20×10^{-7}
	$P_1P_2P_3$ Mode C	5.64×10^{-7}	2.34×10^{-7}
$P_1P_2P_3$ Mode C	$P_1P_2P_3$ Mode C	7.22×10^{-7}	3.87×10^{-9}

2. The data block of 112 bits, including an uplink message, is constrained to about 30 μsec to prevent triggering ATCRBS transponders recovering from the initial suppression.

3. The final 24 bits of an uplink transmission consisting of the combined address-parity bit field.

4. The DABS uplink data block should begin at a time following the preamble pulse pair which does not lead to confusion with an ATCRBS mode.

5. The data block should begin with a synchronization sequence (bit pattern) to allow the demodulator to achieve bit synchronization with sufficient accuracy.

6. The transmission of a synch sequence and 112 bits in approximately 30 μsec implies a data rate of approximately 4 MHz.

The key remaining item of significance in the uplink signal format is the selection of a form of data modulation. The preceding discussion of modulation systems indicates that the choice really narrows to PAM vs DPSK, since these two systems appear to span the practical range of performance that one can hope to achieve. The remainder of this section will compare PAM-NRZ and DPSK uplink designs from the viewpoints of transponder cost and uplink performance.

2.5.1 Transponder Design/Cost Studies

During the design phase of the DABS program the need for cost estimates for DABS transponders became apparent. Therefore, four design/cost studies were contracted to four different ATCRBS transponder manufacturers to examine the three different classes of transponders (air carrier, military, and general aviation). Each contractor studied only one class of transponder. Contractors were selected on the basis of their experience in specific classes of transponder design and manufacture. The contractors participating in the DABS transponder design/cost studies, and the class of of transponder each examined, are listed in Table 2-2.

The final phase of these design/cost studies consisted of the design of a number of complete DABS transponders for which transmitter power and receiver sensitivity were specified in addition to a complete description of the message processing capabilities. Although the message formats and link protocol specified for these studies differ in many details from that of the final DABS design, the resulting complexity of the transponder logic circuitry is quite comparable. For the purposes of comparing an NRZ-PAM link design to that of a DPSK design (with respect to transponder cost), the specifications used in these studies are quite adequate.

TABLE 2-2

DABS/TRANSPONDER DESIGN COST STUDY CONTRACTORS

Contractor	Transponder Type Studied	Abbrev.
Bendix Avionics Div., Ft. Lauderdale, Florida	General Aviation	GA 1
Hazeltine Corp., L. I., combined with General Aviation Electronics, Inc., Indianapolis, Indiana	General Aviation	GA 2
Collins Radio Co., Cedar Rapids, Iowa	Air Carrier	AC
Bendix Communications Div., Towson, Maryland	Military	MIL

The DABS transponder design/cost studies consisted of the detailed design (to the individual parts level) and cost of transponders for a 4-MHz NRZ-PAM uplink and a 4-MHz DPSK uplink, as well as other options. The results from these studies are given in Figs. 2-13, -14, and -15, which show the cost breakdown of each transponder into five categories (transmitter, receiver, video processing (which includes the DABS synch and demodulation circuitry), logic circuitry, and mechanical components). The cost of the contractor's most recent ATCRBS transponder design is also included for reference. Further details regarding these studies are given in Reference 14.

Several important conclusions may be drawn from the results of these studies.

1. Although the different classes of transponders differ widely in cost, the ratio of the estimated cost of the DABS transponders relative to the ATCRBS baseline transponders is in good agreement for general aviation and air carrier transponders.
2. The video portion of a DABS transponder is a small fraction of the total cost compared to the logic circuitry and mechanical portion.
3. The difference between PAM and DPSK costs (reflected only in the video portion costs) has a very small impact on the total transponder cost.

The preceding points imply that significant DABS transponder cost cutting is more likely to result from logic and mechanical cost reductions than from video processing. Thus the difference in overall transponder cost between NRZ-PAM and DPSK data modulation for a 4-MHz uplink is insignificant and probably not resolvable by the type of design studies carried out. The choice between NRZ-PAM and DPSK should thus be determined on the basis of achievable performance, since transponder cost differences (and EMC differences) are insignificant.

2. 5. 2 Uplink Performance Data

The 6- dB advantage that DPSK offers in comparison to PAM is presented in Section 2. 3 of this report. It remains to complete the comparison between these competing uplink designs by evaluating their uplink performance in the anticipated ATCRBS interrogation environments.

The first uplink performance evaluation concerns calculated miss rates along a Boston to Washington, D. C. route illustrated in Fig. 2-16, where the ATCRBS interrogation environment was estimated using the data provided by ECAC under subcontract to the FAA for this purpose. The PAM and DPSK miss rates, resulting from only ATCRBS P_2 pulses radiated on omni antennas, are presented in Fig. 2-17 for a nominal and an anticipated

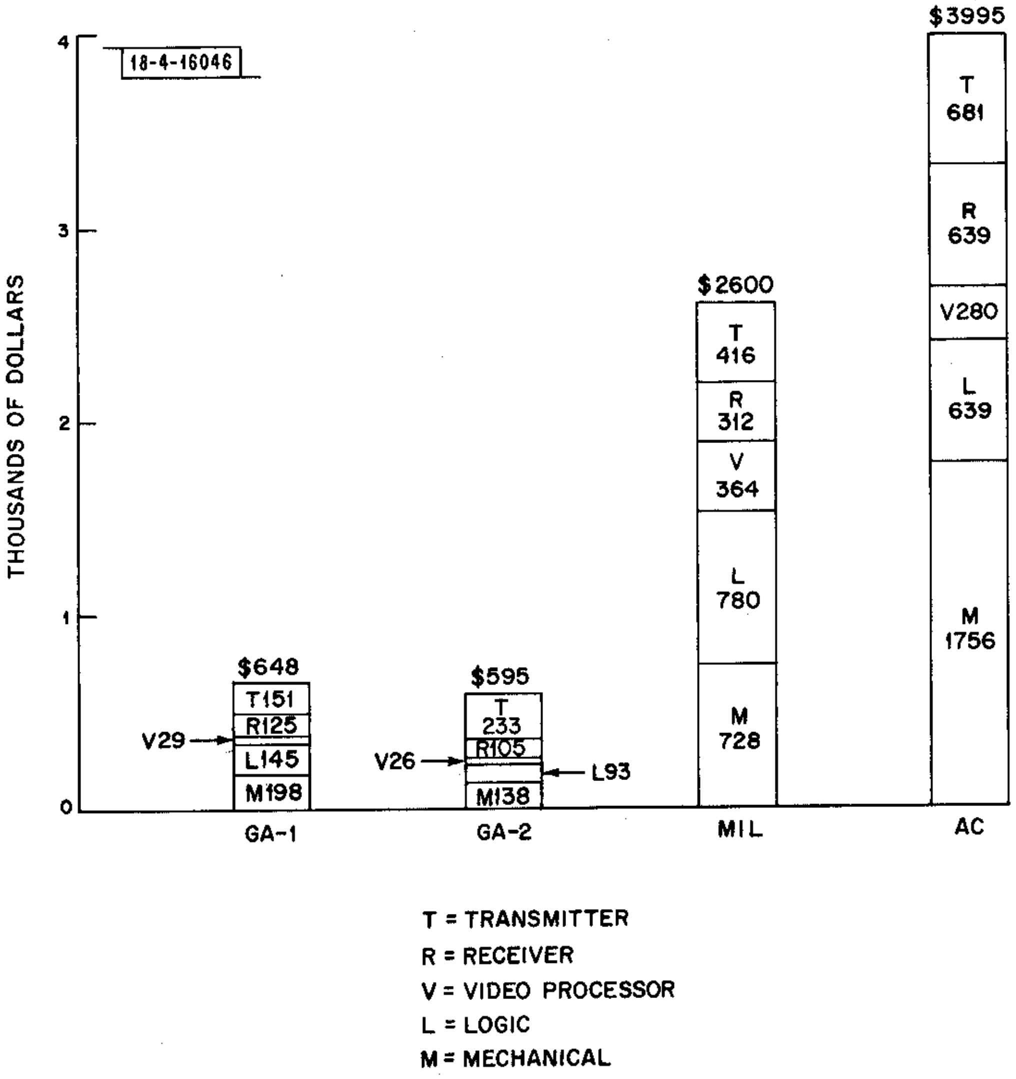

Fig. 2-13. Baseline ATCRBS transponder cost breakdown for the four design-cost studies.

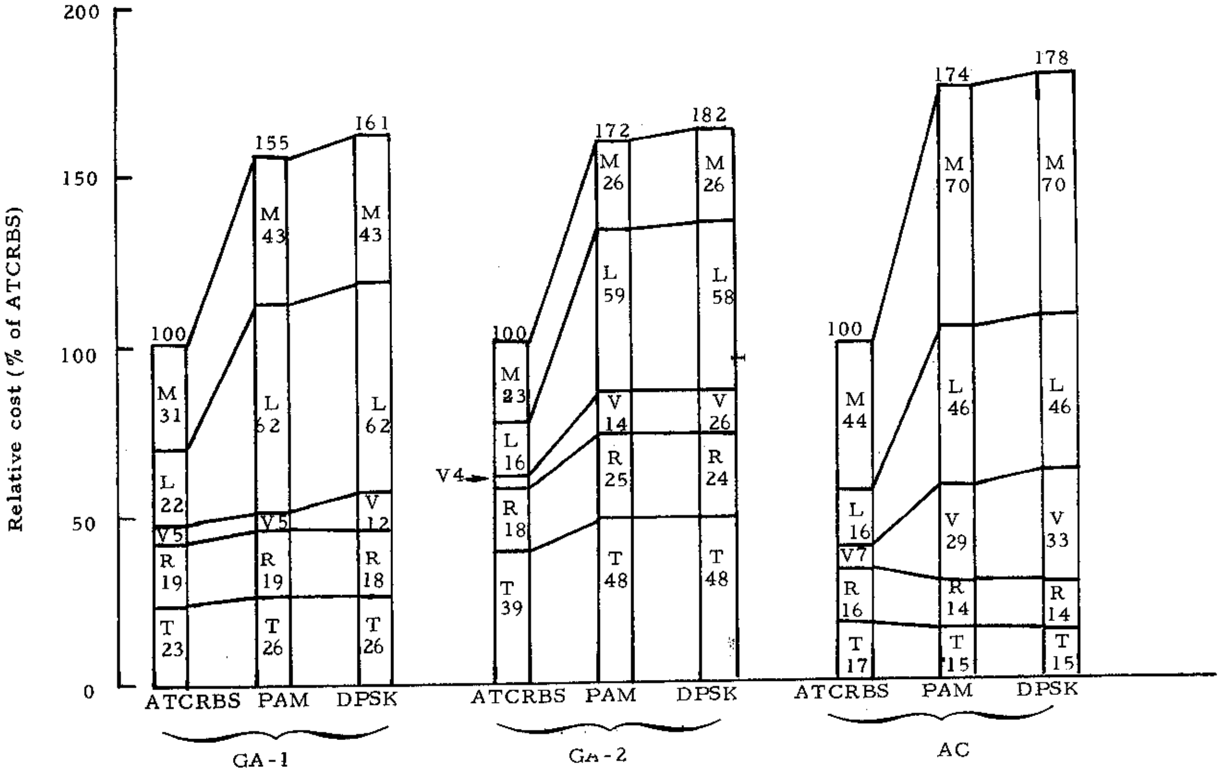

Fig. 2-14. Cost comparison of DABS transponder designs for both PAM DPSK uplink modulation with ATCRBS transponders for three studies.

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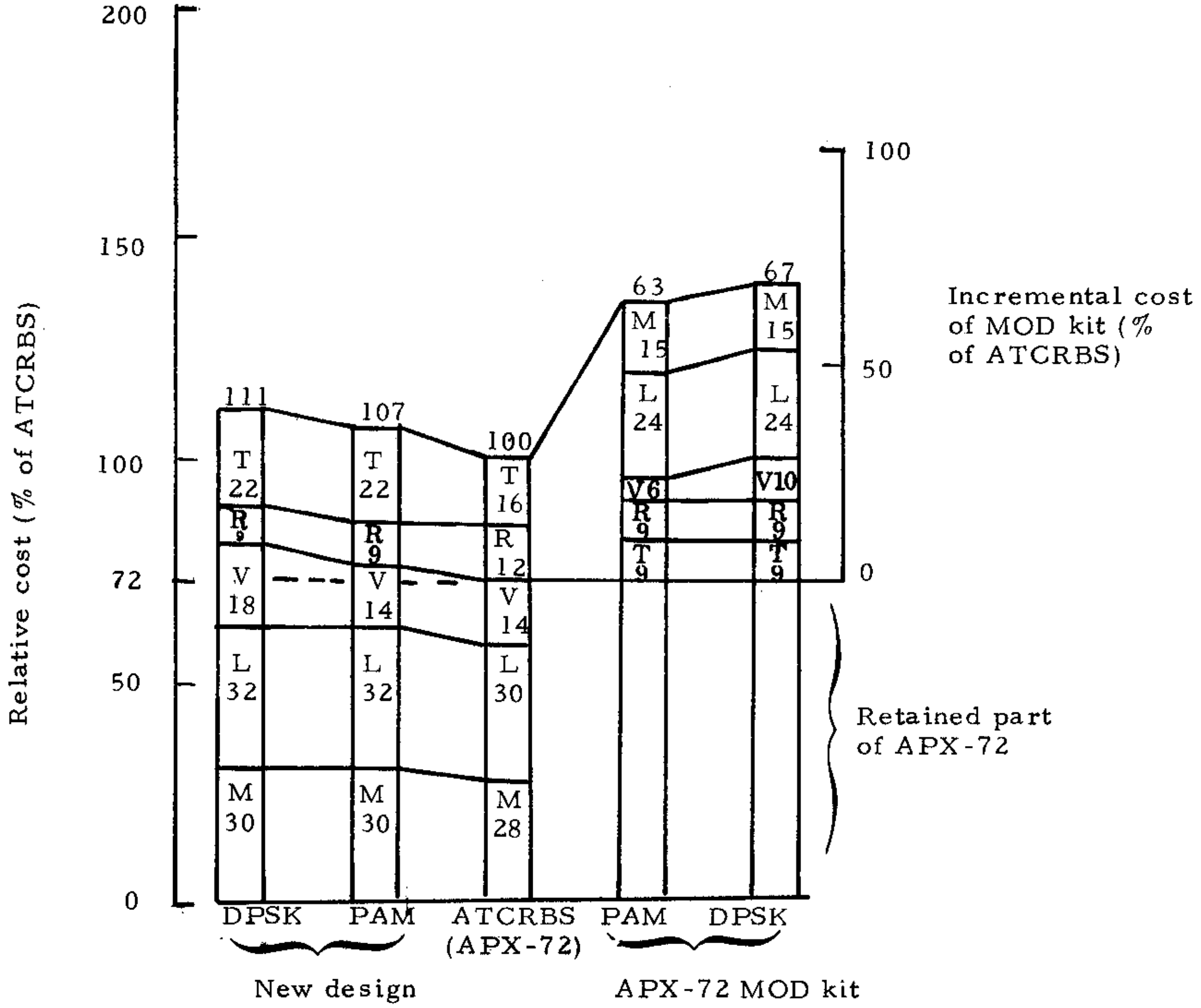


Fig. 2-15. Cost comparison of all-new DABS military transponder designs and APX-72 modification kits (for DABS) for both PAM and DPSK uplink modulation with ATCRBS APX-72 military transponder.

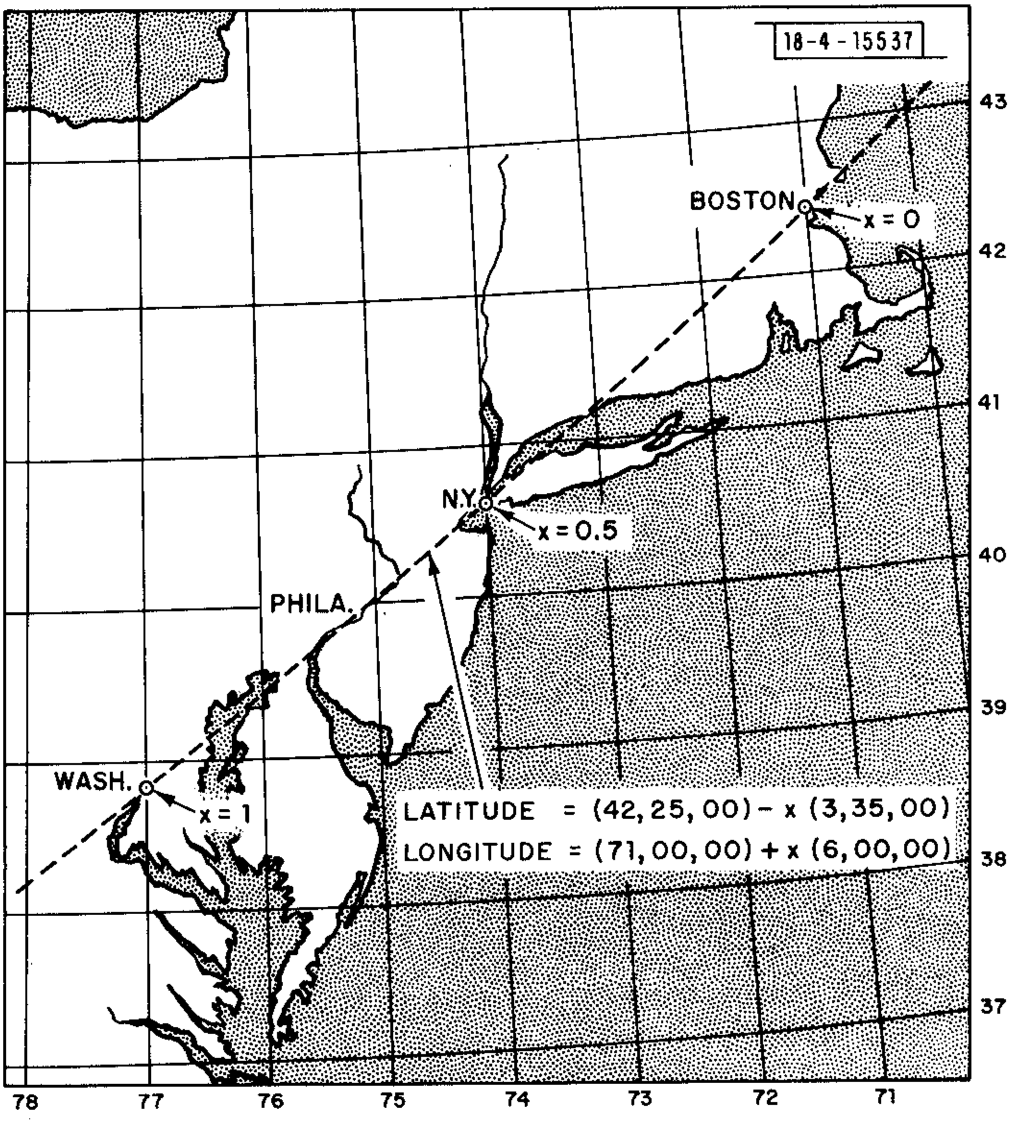
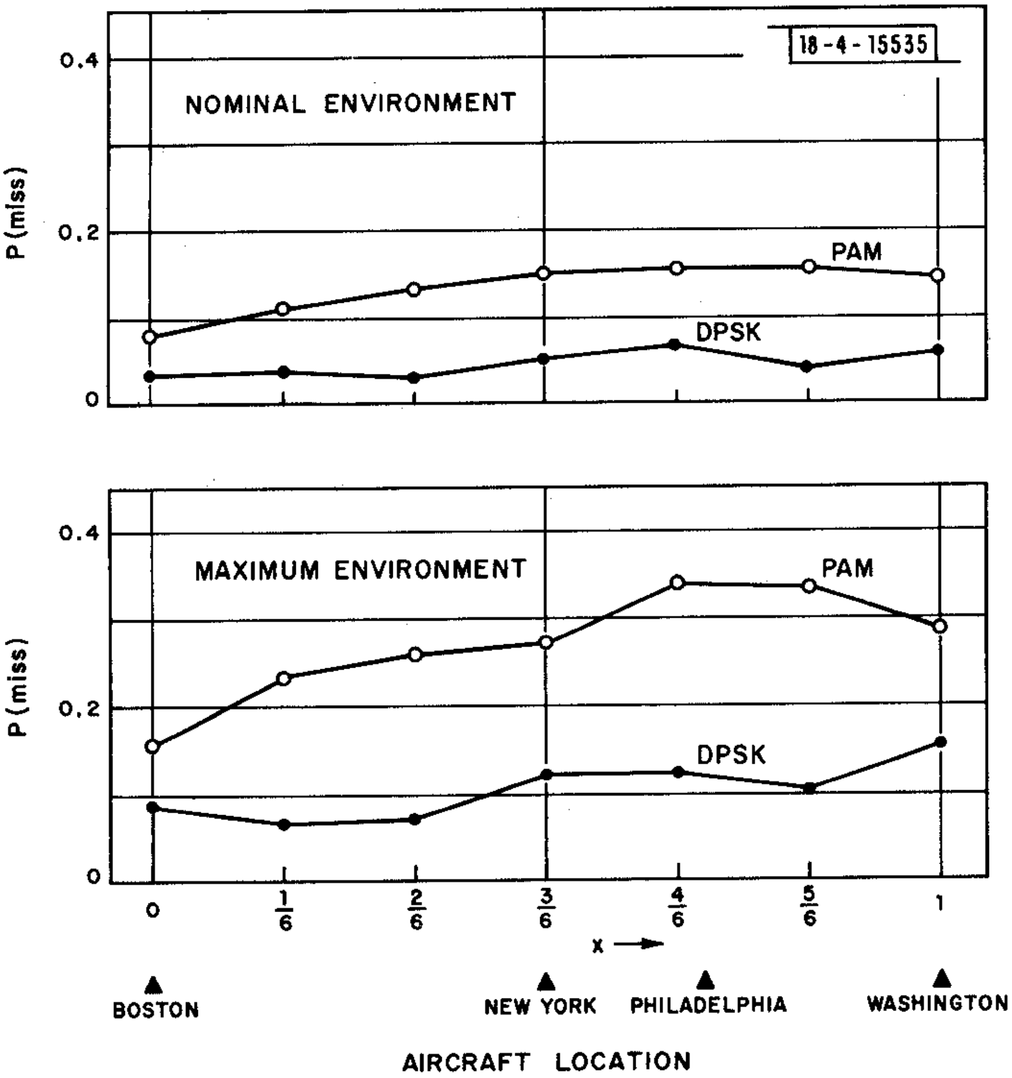


Fig. 2-16. Path along which DABS uplink miss rates were calculated for PAM and DPSK uplink modulation.



SIGNAL LEVEL = −70 dBm
SNR = 20 dB-DPSK, 26 dB-PAM
ALTITUDE = 10,000 ft

MATCHED FILTER DEMODULATORS
PAM THRESHOLD = −4 dB
τ = 0.8 μsec
CHIP DURATION = 0.25 μsec
n = 100 bits

Fig. 2-17. Calculated uplink miss rates for PAM and DPSK modulation in an ATCRBS P_2 pulse environment provided by ECAC.

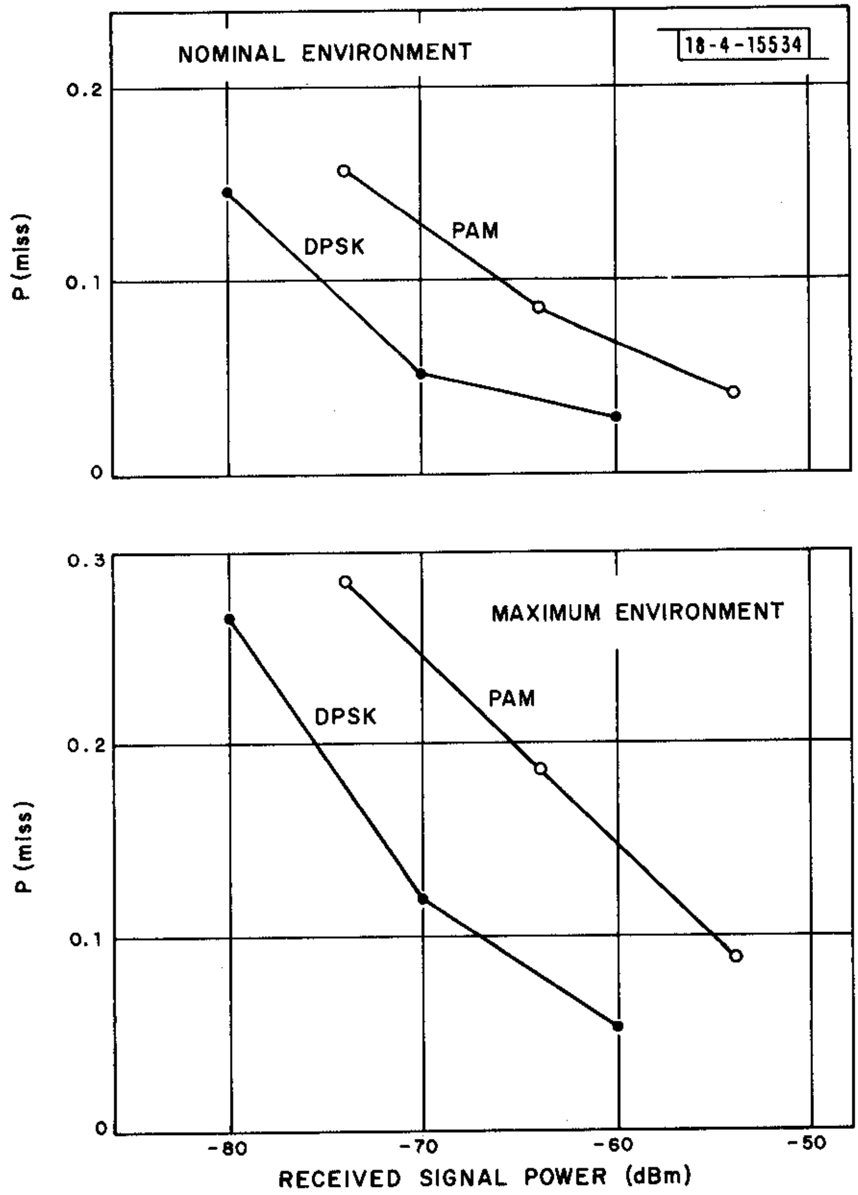
maximum ATCRBS interrogation environment. These calculations were done for received signal levels at the -70 dBm transponder i.e., very near threshold, where the difference between PAM and DPSK is very distinct. PAM and DPSK miss rates, as a function of received signal level at the transponder, are presented in Fig. 2-18 for a transponder located over New York City. The results indicate that the performance advantage of DPSK modulation translates effectively to a significantly lower miss rate at low signal levels or, viewed from another aspect, DPSK provides a larger fade margin down to a fixed uplink miss rate. Further details on the calculated uplink performance are in Ref. 15.

A further verification of uplink performance was provided by a series of flight tests in which DABS uplink miss rates were directly measured while flying along a Boston to Baltimore path [Ref. 16]. These measurements were made by interrogating a DABS test set capable of processing both NRZ-PAM and DPSK interrogations. The interrogator was on board the aircraft, and its signals were coupled into the cable connecting a standard beacon antenna to the test set so that the test set could be interrogated with a precisely controlled signal while also receiving the ATCRBS interrogations from the antenna.

The test set calibration curves are illustrated in Fig. 2-19 for both PAM and DPSK, verifying a clear 5-dB performance margin between the competing modulation systems realized by the demodulators of the test set. In order to rationalize the miss rate measurements, the ATCRBS interrogation environment was monitored simultaneously while interrogating the test set and measuring miss rates. A reference signal level was established corresponding to the signal level, resulting in a 50% miss rate of the DPSK demodulator. The interrogation counts and pulse counts for signals exceeding this reference level were also recorded in addition to miss rates. Thus it is possible to bound the expected miss rates in terms of the measured ATCRBS interrogation environment. A sample plot of measured miss rate vs time is presented in Fig. 2-20, which also includes measured Modes A and C interrogation rates, SLS rates, and total video pulse counts of signals exceeding the reference level.

Although the measured ATCRBS environment differs somewhat from the predictions provided by ECAC, the measured miss rates are quite close to those calculated for the ECAC environment. PAM miss rates were measured at an interrogation signal level 5 dB stronger than that of DPSK (bringing the reference signal level for interrogation counts to the 50% miss rate point on the PAM demodulation characteristic [Fig. 2-19]) and they were essentially the same as DPSK miss rates with this 5-dB power advantage.

The performance data support the conclusion that the theoretical advantage of DPSK over PAM is realizable in real channel operating conditions as a significantly larger fade margin or a significantly lower miss rate at low signal levels. Since there is an insignificant transponder cost increment associated with DPSK, its performance advantage should be utilized. For these reasons, DPSK was selected for the DABS uplink modulation.



LOCATION – NEW YORK
ALTITUDE = 10,000 ft
NOISE LEVEL = −90 dBm

MATCHED FILTER DEMODULATORS
PAM THRESHOLD = −4 dB
τ = 0.8 μsec
CHIP DURATION = 0.25 μsec
n = 100 bits

Fig. 2-18. Calculated uplink miss rates for PAM and DPSK for transponder located over New York City in an ATCRBS P_2 environment.

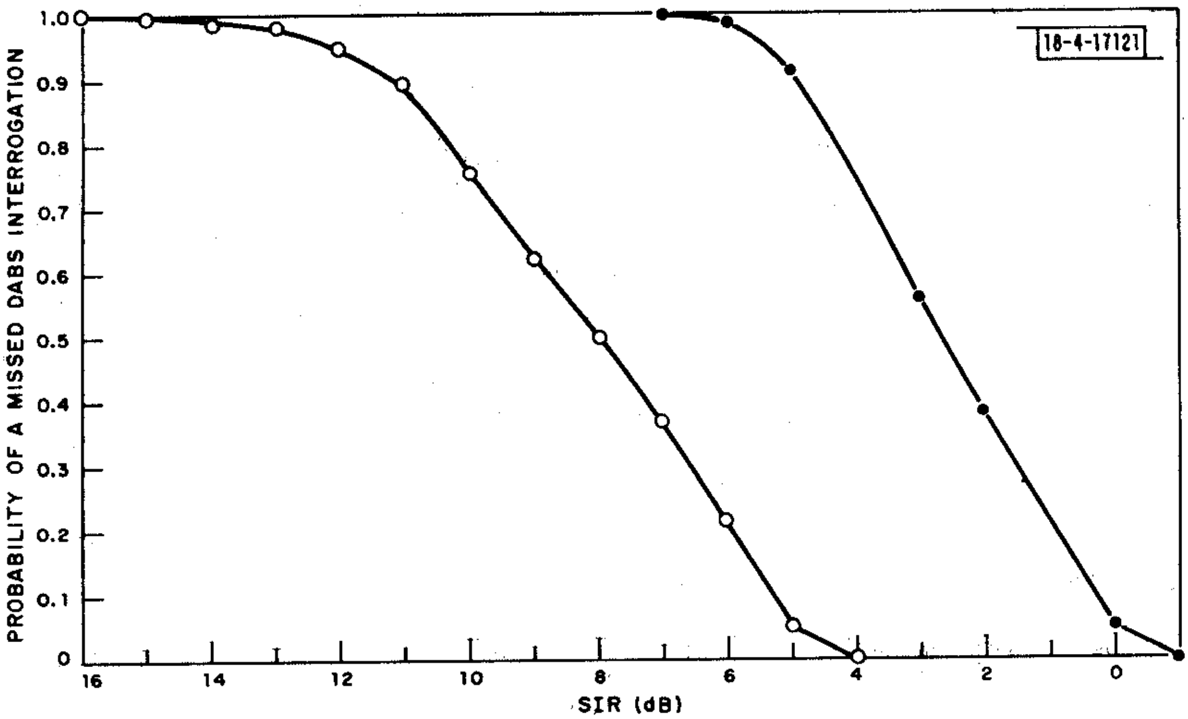


Fig. 2-19. Test demodulation calibration curves for PAM and DPSK miss rates vs SIR.

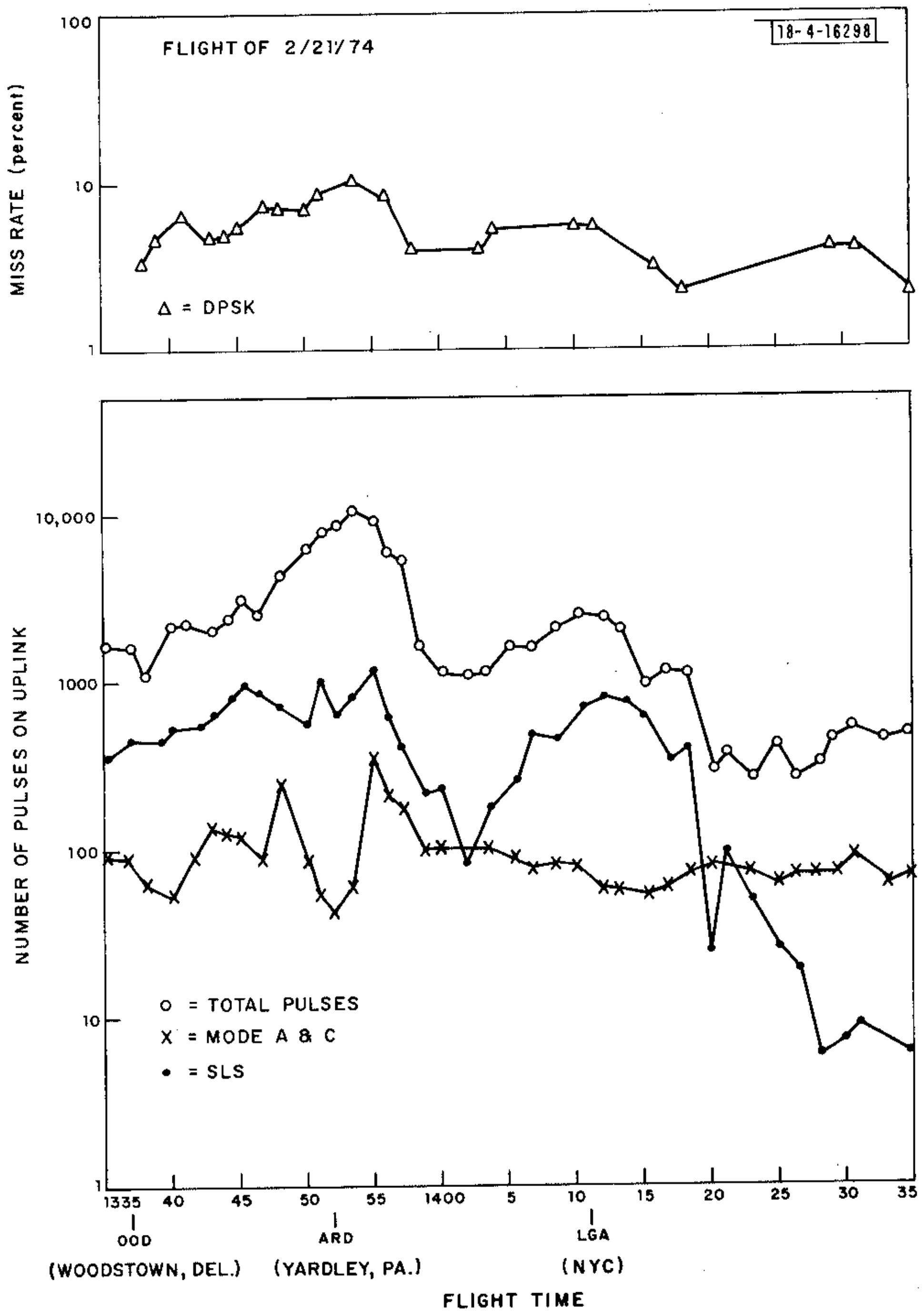


Fig. 2-20. Measured uplink miss rates vs time for DPSK (with measured ATCRBS mode and pulse counts).

2.5.3 Summary of DPSK Uplink Performance

Having reviewed the basic reasons for the selection of the DABS uplink signal format, this section provides extra data for reference concerning the DABS DPSK uplink performance. The performance of the parity check code was calculated based on models of error mechanisms caused by RFI. These calculations have been verified by laboratory measurements made on a DABS DPSK test transponder. Figure 2-21 indicates measured undetected message error rates for fixed DABS signal and interfering pulse levels [Ref. 17]. The measurements indicate that the burst error characterization used in the calculations was adequate. The measured undetected message error rate, conditional on an interfering signal being present, is of the order of 1 in 10^7, the initial DABS performance goal. The multipath sensitivity of the DABS uplink was also measured in the Laboratory using a DABS DPSK test transponder and a multipath simulator [Ref. 18]. The results are provided in Fig. 2-22 and illustrate satisfactory agreement with theoretical predictions.

A critical aspect of the uplink design is the reliability of the suppression preamble. The specification of the reliability of the suppression circuitry of ATCRBS transponders is looser near the minimum triggering level (MTL) of a transponder than the mode triggering circuitry. This effect is illustrated in Fig. 2-23 which shows measured ATCRBS transponder reply rates to DABS interrogations (indicating failure of intentional suppression preamble) [Ref. 7]. The DABS interrogation signal level was varied over the dynamic range of the ATCRBS transponders. Figure 2-23 indicates the maximum reply rates observed for two cases:

1. The suppression preamble ($P_1 P_2$) amplitude equal to the data block amplitude
2. The ($P_1 P_2$) amplitude 3 dB greater than the data block amplitude

The measured data indicate the maximum reply rates observed are quite high, but the figure does not indicate that the reply rates are limited to a very narrow range of signal levels. Thus, the total number of replies likely to be contributed by ATCRBS transponders, which fail to be suppressed by a DABS interrogation, is small (most interrogation levels received are outside the narrow triggering range). If observed ATCRBS transponder triggering rates are judged unacceptably high, the data indicate that increasing the amplitude of the suppression preamble by 3 dB relative to the data block would reduce quite significantly the peak triggering rates observed (and, hence, the total number of replies contributed to the channel). It should be pointed out that this approach complicates the sensor transmitter by requiring switching of power levels during an interrogation; consequently a clear justification of the necessity for this change in signal formats would be needed.

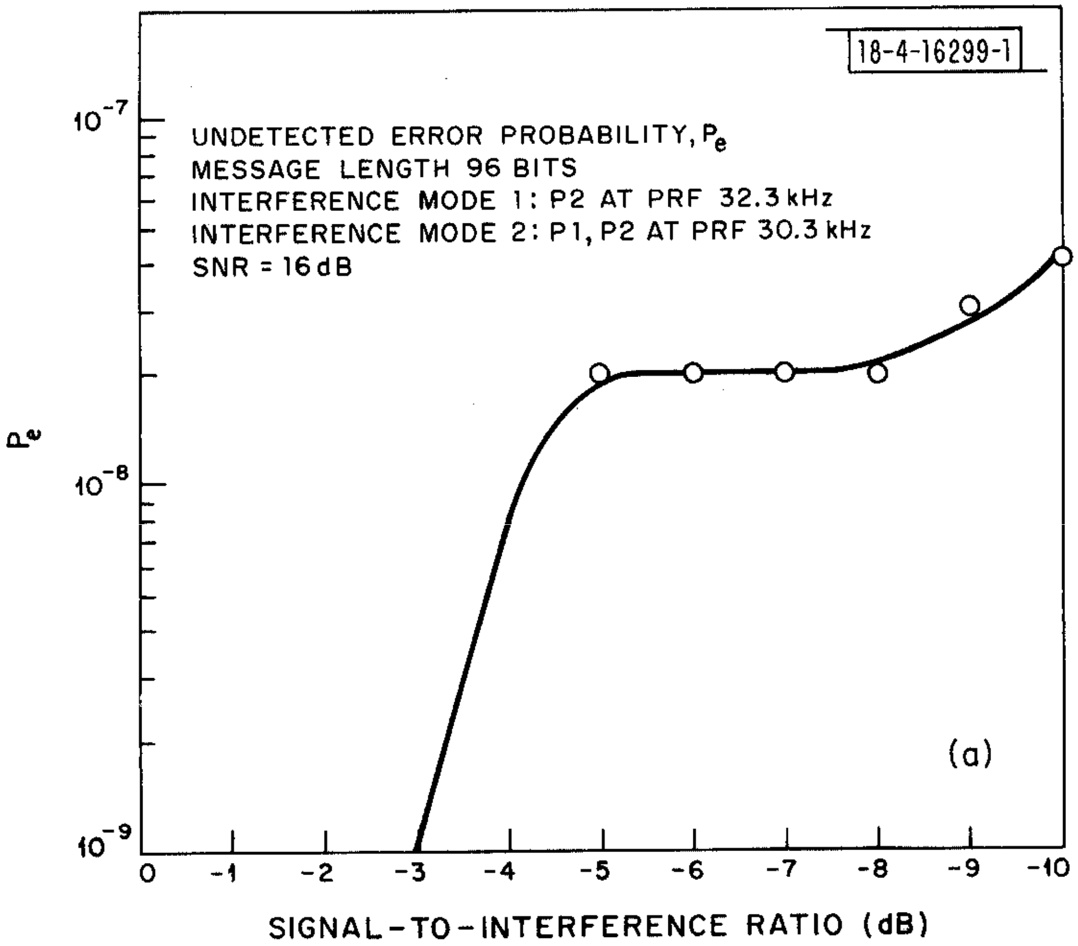


Fig. 2-21(a). Laboratory measurements of undetected message error probabilities (DPSK) for simulated garbling by an ATCRBS P_2 pulse and a P_1, P_2 mode.

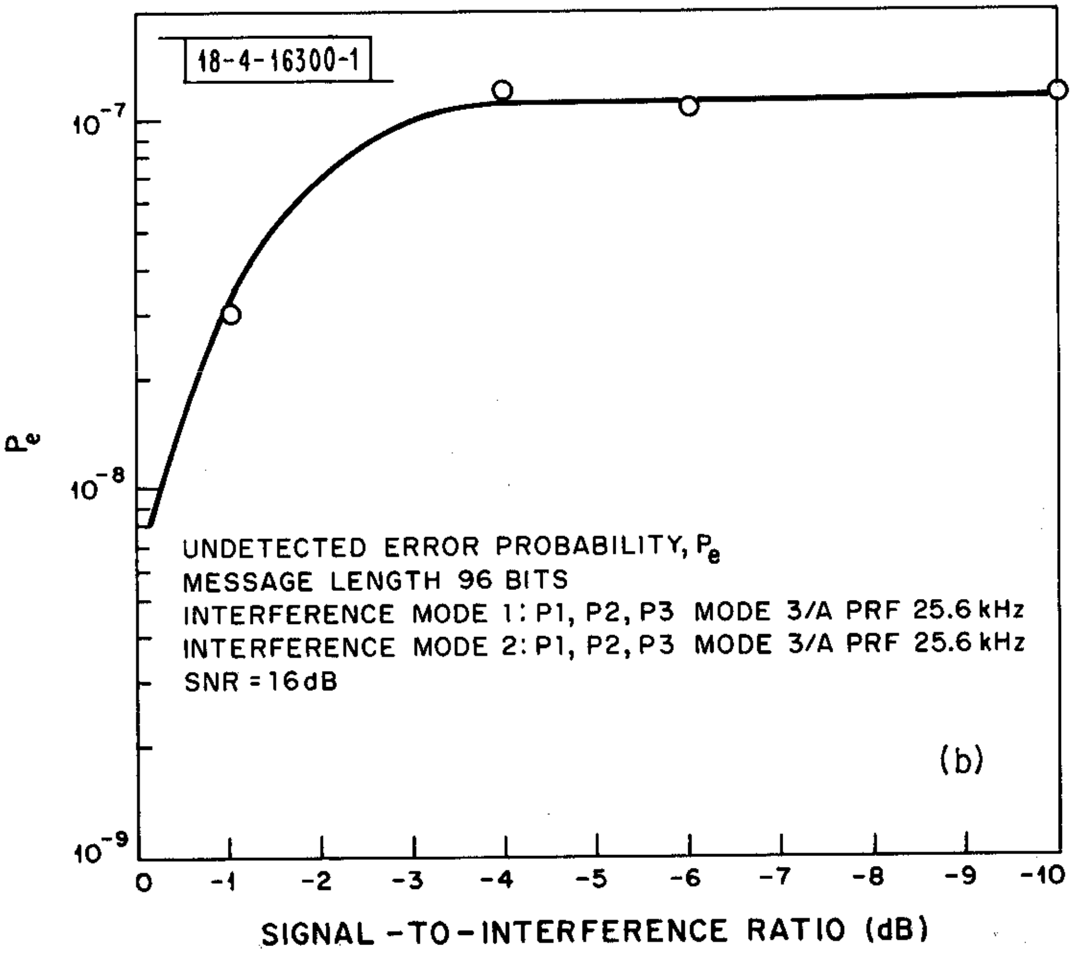


Fig. 2-21(b). Laboratory measurement of undetected message error probabilities (DPSK) for simulated garbling by two ATCRBS interrogations, each with P_1, P_2, P_3 present.

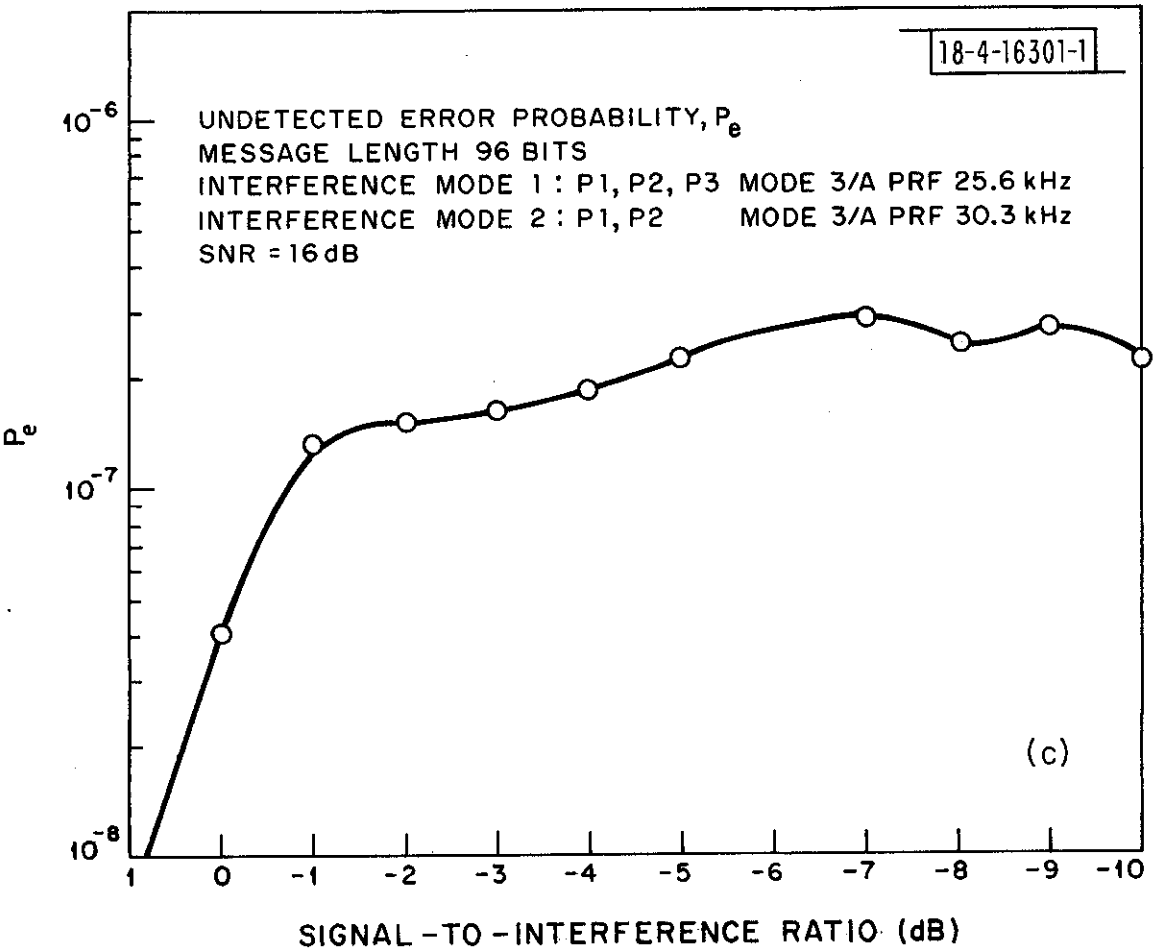


Fig. 2-21(c). Laboratory measurement of undetected message error probabilities (DPSK) for simulated garbling by two ATCRBS mode 3/A interrogations (one two-pulse and one with all three pulses present).

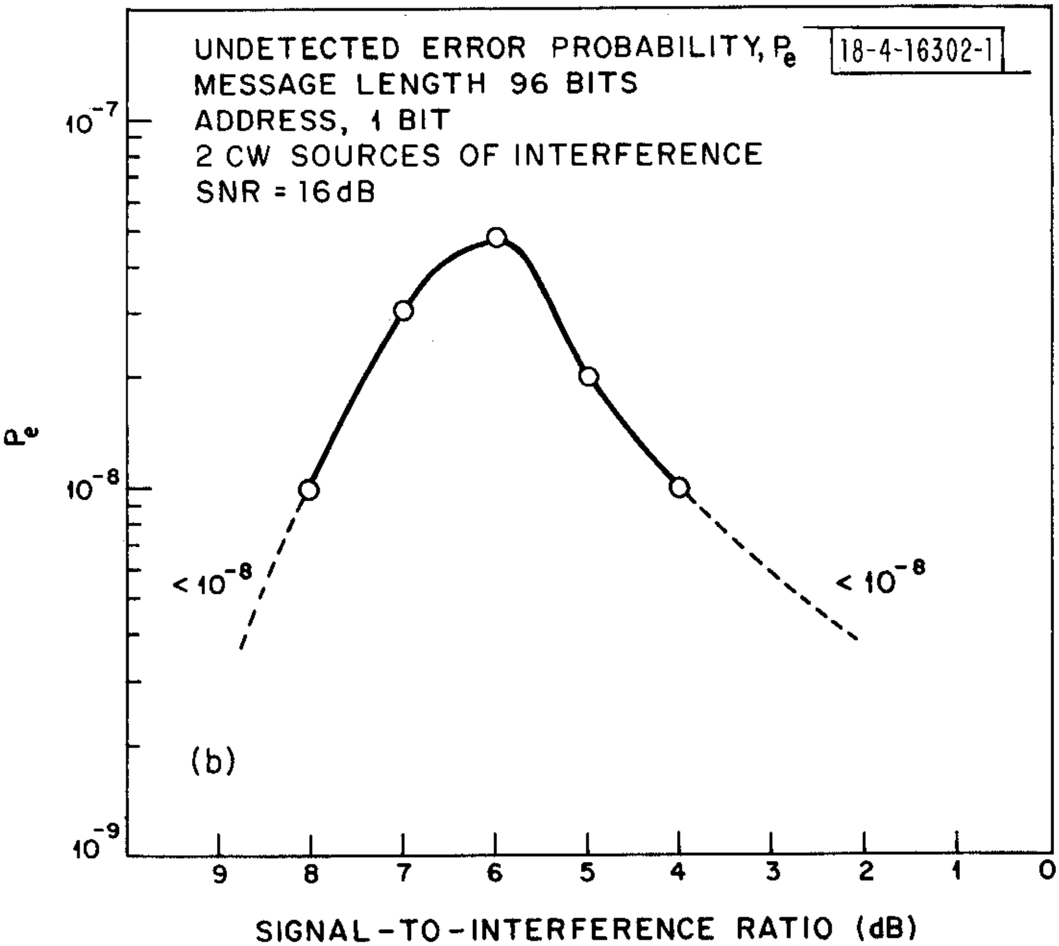


Fig. 2-21(d). Laboratory measurements of undetected message error probabilities (DPSK) with two CW interfering signals.

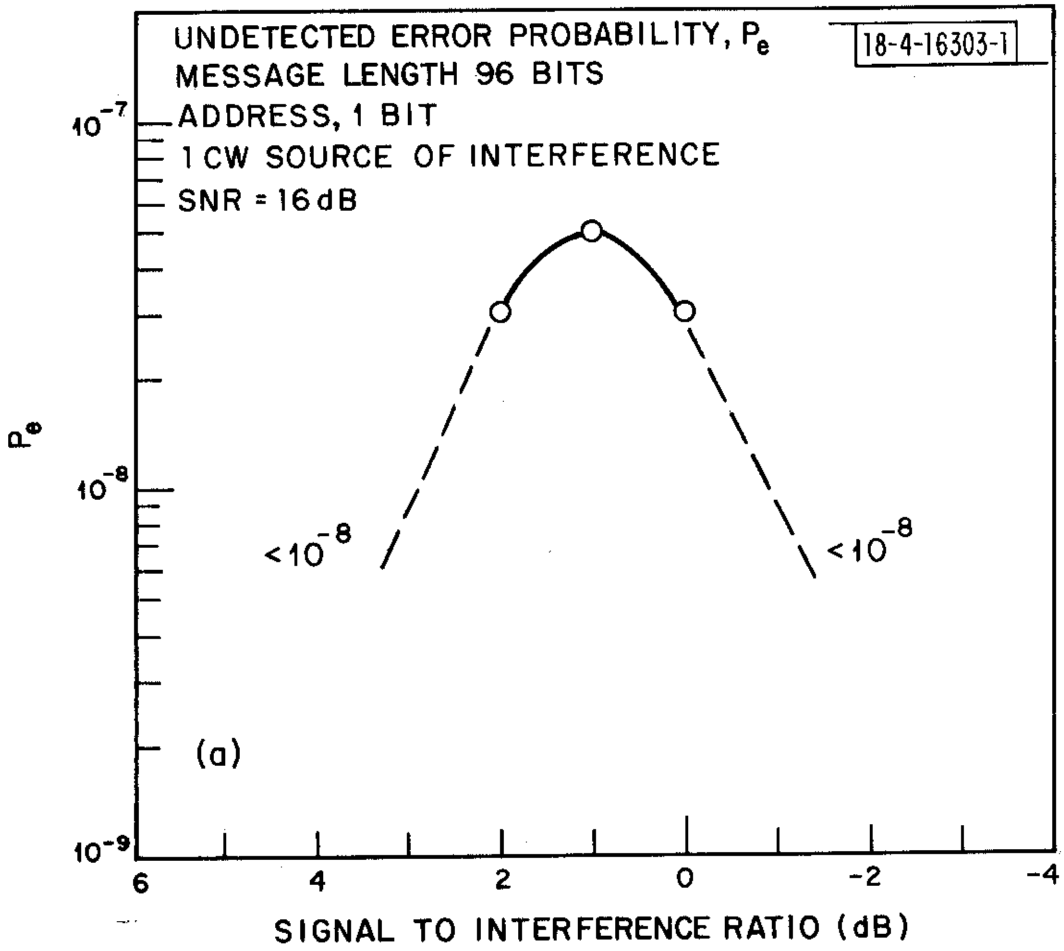


Fig. 2-21(e). Laboratory measurements of undetected message error probabilities (DPSK) with a single CW interfering signal.

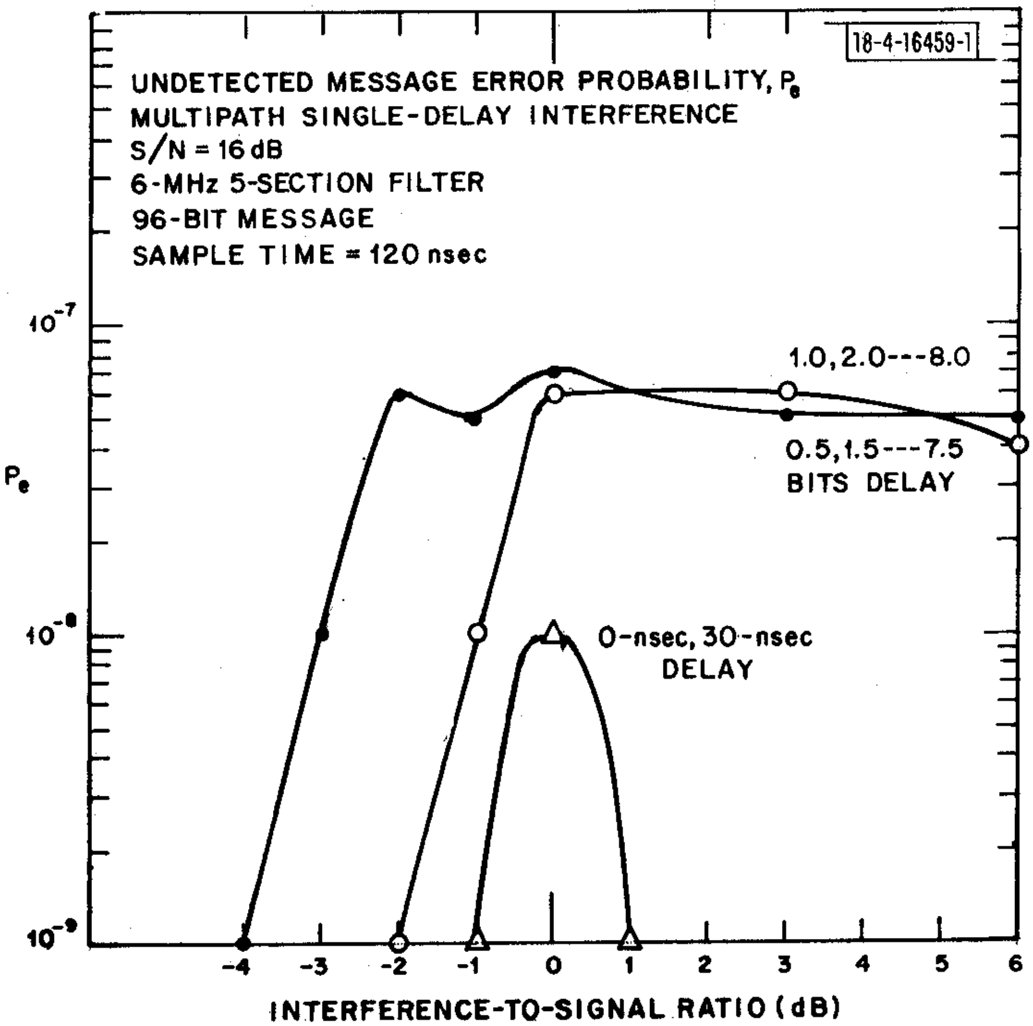


Fig. 2-22. Laboratory measurements of undetected message error probabilities in simulated multipath.

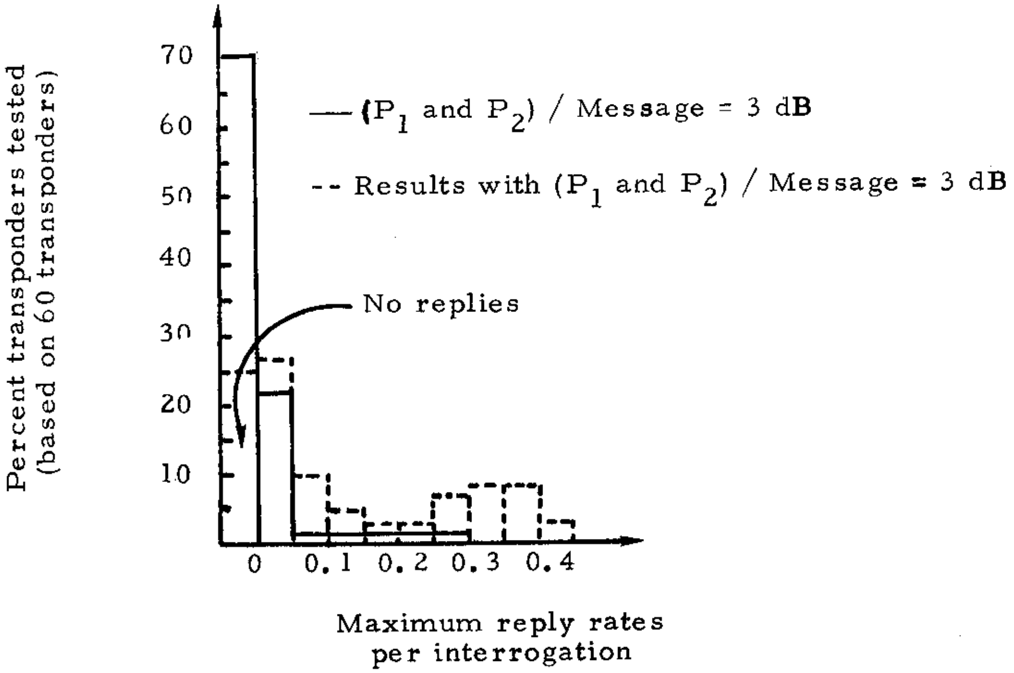


Fig. 2-23. Percentage of transponders reply vs maximum reply rate per interrogation for DABS preamble amplitude equal to message amplitude, and 3 dB greater than message amplitude.

2.6 DABS Interrogator Sidelobe Suppression System (ISLS)

Although DABS discrete interrogations will be scheduled on the basis of predicted target range and azimuth, uncertainties in these predictions as a result of measurement errors, tracking errors, and aircraft maneuvers will result in occasional discrete interrogation of aircraft that are on the edge of the antenna beam. This situation would result in calculating an azimuth estimate on the reply, with the monopulse processor operating beyond its design limits, which could lead to large errors in target azimuth estimates.

One method of reducing the incidence of such errors from targets off the beam edge is to limit the "interrogation beamwidth" by an Interrogator Sidelobe Suppression system (ISLS). Such a feature could be provided for DABS discrete interrogations in a manner exactly analogous to the method used in the ATCRBS, i.e., by transmitting a pulse on an omnidirectional antenna pattern for comparison in amplitude by a transponder with pulses radiated by the mainbeam pattern. This approach would not burden the transponder since pulse amplitude processing must be done for the ATCRBS modes in any case. However, a completely separate DABS ISLS scheme can be implemented with the DPSK modulation system without any transponder circuitry at all. Separation of the ATCRBS and DABS ISLS functions may be advantageous in the future if it should appear feasible to design a DABS-only transponder. For these reasons the DABS ISLS scheme is included in the link design.

The sensitivity of DPSK to interfering signals is illustrated in Fig. 2-7, indicating that the demodulator response to the combined signals is a very abrupt function of SIR. This characteristic can be used to provide an SLS type of function without any additional transponder circuitry. The DABS data block begins with a synch sequence consisting of a phase reversal to provide bit synchronization independent of signal envelope characteristics. If this phase reversal is not detected, accurate bit synchronization may not be assured and the message should not be processed. This synch phase reversal can be obliterated in the sidelobes of the antenna pattern by simultaneously transmitting a pulse on an omni antenna that completely overlaps this part of the data block. In the sidelobes, the omni-to-mainbeam signal ratio will be greater than unity, implying that the demodulator will not detect the phase reversal; conversely in the mainbeam, the mainbeam-to-omni ratio will be greater than unity, assuring reliable detection of the synch phase reversal.

The DABS ISLS system implies that there is an independent auxiliary transmitter at the sensor to generate the omni pulse. However, the system accomplishes its function with little or no transponder complexity, without requiring the use of the ATCRBS amplitude processing circuitry. A further advantage of a DABS ISLS system (of any kind) is that by clearly tagging mainbeam interrogations, misdirected messages can not occur with sidelobe aircraft, which will greatly reduce the misdirected message probability achieved by the system.

2.7 Target Acquisition

Efficient handling of targets by discrete address interrogations requires knowledge of the discrete address of the target and predictions of its range and azimuth. In an automated ATC system, pop-up targets and dropped targets should be handled automatically, i.e., a special acquisition mode should be provided to which a DABS transponder would reply with its discrete address and be located at the same time. To periodically search a sensor's coverage volume (for pop-up or dropped DABS targets) would require the use of such an acquisition or "all-call" mode. In this regard, the DABS all-call mode is analogous to the operation of the standard ATCRBS sensor in which periodic interrogations are transmitted and followed by a listening interval. Since a DABS sensor must provide position and identity information on ATCRBS transponders, more channel time would remain free if the DABS all-call listening period were shared with that of the ATCRBS modes. In order to share listening periods, the DABS all-call mode should be transmitted fairly close in time to an ATCRBS interrogation. Two alternatives are:

1. DABS all-call preceding the ATCRBS mode
2. ATCRBS mode preceding the DABS all-call.

Consider the second alternative first. The quandry in which this arrangement places a DABS transponder is whether or not to reply to the earlier ATCRBS interrogation. Two types of replies are clearly redundant. However, if the DABS transponder is to recognize that a DABS all-call follows the ATCRBS mode, it must do so quickly, i.e., in the 3 μsec between the pulse P_3 of the interrogation and the F_1 pulse of the reply. This observation implies that a combined ATCRBS/DABS all-call mode could be defined so that ATCRBS transponders process only the ATCRBS part of the mode, and DABS transponders do the same but also look for an indication pulse designating the mode as an all-call. Detecting such an indicator pulse would then result in the DABS transponder inhibiting its ATCRBS reply and transmitting a DABS all-call reply containing its 24-bit discrete address.

This combined ATCRBS/DABS all-call mode has been realized by appending a fourth pulse after the P_3 pulse to standard ATCRBS modes 3/A and C as illustrated in Fig. 2-24. Measurements were made during field tests on ATCRBS transponders to verify that the P_4 pulse had no significant effect on them [Ref. 7]. A very slight difference in the response thresholds for the standard ATCRBS mode A and the ATCRBS/DABS all-call (mode A with P_4 added) is indicated in Fig. 2-25. The data lead one to believe that ATCRBS transponders that are operating normally within specifications will not be significantly affected by the P_4 pulse.

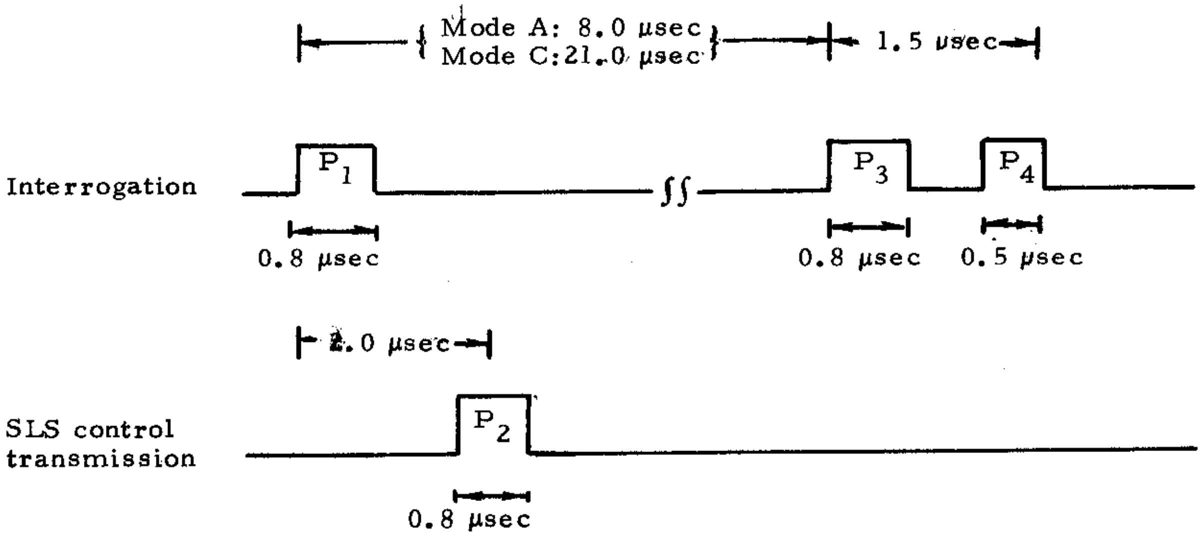


Fig. 2-24. ATCRBS/DABS all-call interrogation formats.

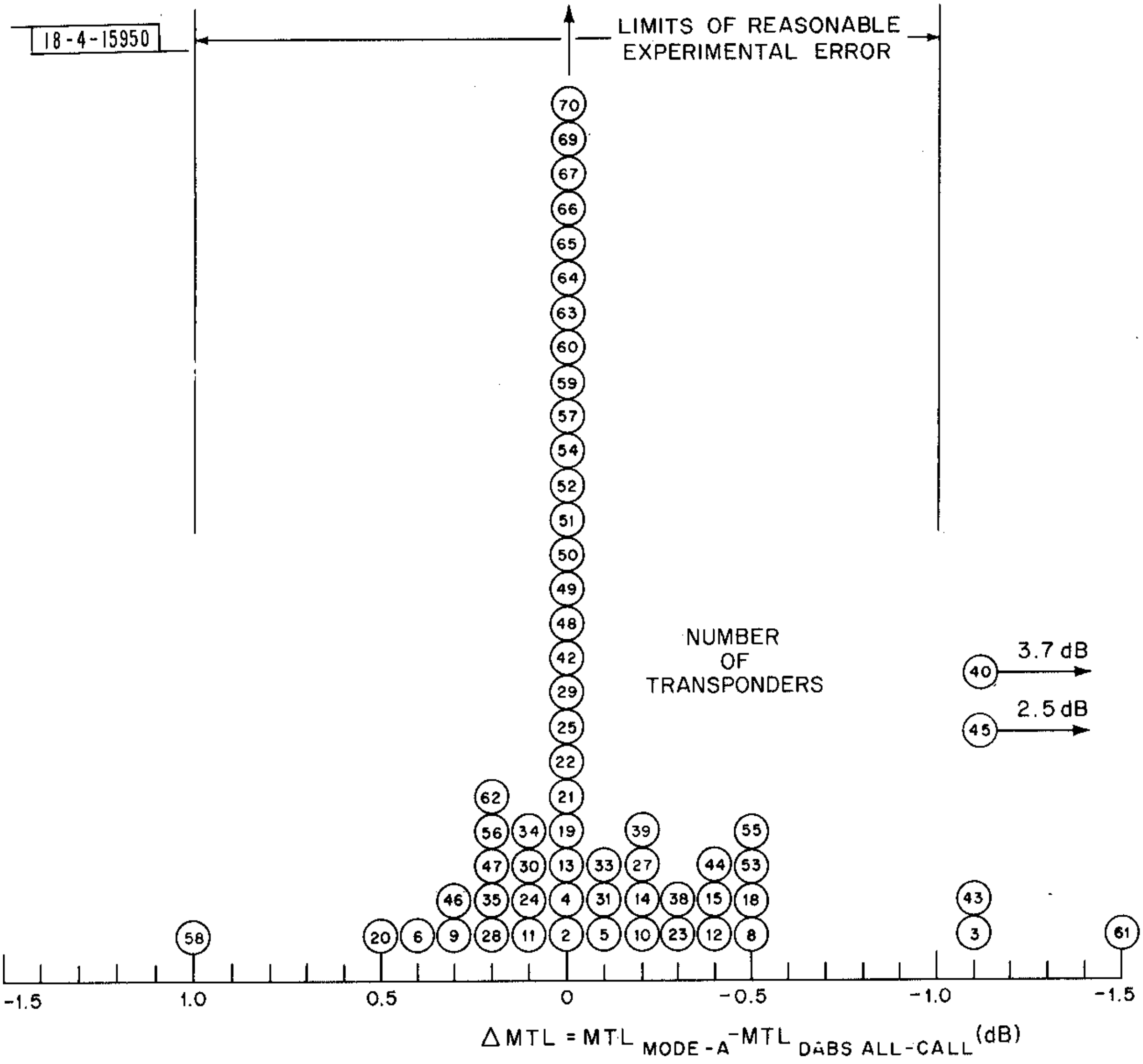


Fig. 2-25. Measured change in ATCRBS transponder threshold to DABS all-call mode.

Consider next the DABS all-call mode preceding the ATCRBS mode. The DABS transponder would respond to the all-call mode and probably would not see the following ATCRBS mode occurring during its reply or its dead time after replying. An ATCRBS transponder, conversely, must not reply to the DABS mode, and ideally, the DABS all-call mode should be "invisible" to ATCRBS transponders. However, as the bench testing program has indicated, such invisible formats are not feasible. The next best alternative is a DABS mode that intentionally suppresses ATCRBS transponders and elicits all-call replies from DABS transponders. Such a separate DABS-only all-call mode may be useful in that it would allow some flexibility in scheduling DABS all-call replies relative to ATCRBS replies, which could be used in mitigating synchronous garble between ATCRBS and DABS all-call targets. This flexibility, however, comes at a price of less overlap of the listening intervals as a result of the need to wait at least 45 μsec for the ATCRBS transponders to recover from the suppression caused by the DABS mode.

Both of the above approaches to the acquisition of DABS targets have been included in the DABS link design. The standard mode is the combined ATCRBS/DABS all-call mode, which appends a P_4 pulse after a standard ATCRBS mode 3/A or C interrogation and shares the full listening interval of both types of replies. The DABS-only all-call mode consists of a standard DABS DPSK interrogation (preceded by a suppression preamble) with an all-zero address that will elicit an all-call reply from DABS transponders*. The added complexity of checking for an all-zero address, in addition to the standard address checking, does not add significant cost to the transponder. The DABS-only all-call mode allows some scheduling flexibility between ATCRBS and DABS-all-call replies, if it ever appears to be of value, and it also provides a means of acquiring targets independent of ATCRBS mode processing circuitry, which may prove useful at some future data.

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*The data field of the DABS-only all-call interrogation consists of all-ones, to help distinguish this signal from CW or a long, unmodulated pulse.

3.0 DOWNLINK DESIGN

3.1 Design Constraints and Options

The basic functions of the DABS downlink are to:

1. Provide target range and azimuth estimates for DABS surveillance,
2. Extract downlink data from replies (target identity, altitude, pilot acknowledgments, etc,),
3. Support air-to-ground data link capability for noncritical messages.

The issues of transponder cost, EMC, and link performance are next discussed in this section with respect to the use of the ATCRBS reply frequency of 1090 MHz for the DABS downlink.

3.1.1 Transponder Cost

The transponder cost data of Section 2.5 indicate that the transmitter portion of an ATCRBS transponder is significantly more costly than the video processing circuitry*. This is especially apparent in the general aviation class of transponders. This is true in spite of the fact that transmitters for nonmilitary ATCRBS transponders are very simple pulsed oscillator circuits that generate incoherent, on-off keyed pulses suitable for PAM modulation formats. Although some military transponders have used solid state transmitters, the cost of such transmitters at the power levels required for the ATCRBS is not now cost competitive with the triode/cavity oscillators used in general aviation transponders. Cost projections of solid state transmitters are uncertain enough to avoid basing a DABS design on reasonable cost devices not available at this time.

Thus cost considerations constrained DABS reply format options (at least initially) to those that could avoid the necessity of a more sophisticated transmitter than that now employed by ATCRBS general aviation transponders. Even a second such simple transmitter required by DABS (at another frequency) would have a noticeable impact on transponder cost. For these

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*This is clearly true in all except the military transponder, wherein video processing circuitry is more complex as a result of Mode 4 processing functions. Civil transponders do not process this mode.

reasons, the DABS downlink signal design effort began by investigating modulation formats that could be generated by the low cost ATCRBS (general aviation) transponder transmitters. This implied that modulation formats based on on-off-keyed, incoherent PAM pulses were to be investigated until and unless it was discovered that they were clearly inadequate from a performance or EMC viewpoint.

3.1.2 EMC Issues (ATCRBS)

DABS replies can have two effects on the ATCRBS downlink operation that deserve investigation. They can result in (1) lost ATCRBS replies as a result of garble by a DABS reply, and (2) triggering ATCRBS reply detection circuits. The greater information content of a DABS reply implies a longer duration than that of an ATCRBS reply; therefore detection and correct decoding of an ATCRBS reply (by existing equipment), garbled by a DABS reply, is very unlikely unless the amplitude of the ATCRBS reply is much greater than that of the DABS reply. Mitigation of this effect will therefore depend upon reducing the frequency of occurrence of DABS fruit garbles.

A DABS reply input to an ATCRBS bracket detector is likely to result in repeated triggering of the circuit for the entire duration of the DABS reply data block. Such repeated and closely spaced bracket detections may confuse garble detection/phantom elimination logic in ATCRBS reply processors and may also cause undesirable artifacts on video displays. The main preventative measure against this effect is a defruiter, which would require near synchronous DABS replies on at least two successive scans to allow processing of a DABS reply data block by bracket detection circuits. Although most ATCRBS reply processors incorporate a defruiter, all equipment does not incorporate a defruiter (the Common Digitizer employed at some FAA en route radars being the most notable example). Consequently, this effect does deserve further consideration. The effects of DABS replies to discrete address interrogations and all-calls will be discussed separately with respect to the ATCRBS downlink operation.

Discrete Address (Scheduled) Replies

DABS discrete reply fruit reply rates will be much lower than that of current ATCRBS fruit rates because (1) only a small number (typically two or three) sensors will discretely interrogate each DABS aircraft, and (2) the average number of discrete interrogations per scan will be much less than that of the ATCRBS (an average of less than two per target per scan, compared to an average of 18 for an ARTS sensor). An additonal factor that will mitigate the effects of DABS discrete replies is the asynchronous nature of the DABS scheduling of discrete interrogations, which will tend to garble an insufficient number of ATCRBS replies per scan (for a given target) to affect target recognition (by human operator) or declaration (by automatic detection circuits). ATCRBS reply processors incorporating a defruiter will not be affected by DABS discrete replies. Moreover, as a result of this aspect, the very low DABS discrete reply rate, together with its highly asynchronous nature, will render the effects of lost ATCRBS replies insignificant even in processors without defruiters. However, the effects of occasional DABS replies that do get processed by conventional circuitry should be investigated further to determine if special measures must be implemented to prevent possible confusion of operators or automatic processors.

All-Call Replies

A DABS sensor acquiring new DABS targets by transmitting the combined ATCRBS/DABS all-call mode will be faced with occasional synchronous garble between an ATCRBS target and a nearby DABS target responding to the all-calls, and will also generate DABS fruit, which could affect nearby DABS and ATCRBS sensors. In the case of synchronous garble of an ATCRBS target and a DABS all-call target, if both replies are likely to be lost most of the time in such synchronous garble situations, the longer channel occupancy of the DABS reply will result in a larger garble cell*, and both targets may be lost for an extended period of time. The consequences of such synchronous garbles would be greatly mitigated by a very reliable DABS downlink that would allow rapid acquisition of the DABS target even in the presence of such garble. The DABS target could then be quickly switched to a discrete address mode and locked out to the all-call interrogations (inhibiting all-call replies by setting a control bit in the discrete interrogations to that aircraft). It would therefore be useful to design into the DABS reply signal format a degree of immunity to garble from ATCRBS replies, which would serve to aid rapid DABS target acquisition and minimize the loss of ATCRBS targets to synchronous garble (with DABS all-calls).

Surveillance of ATCRBS targets by a DABS sensor, compared to conventional ATCRBS sensors, will be accomplished using a low PRF. Thus, the low PRF of the combined ATCRBS/DABS all-call mode of a DABS sensor implies that less fruit will be generated by this mode than by a conventional ATCRBS sensor. Moreover, the all-call mode is transitory, in that aircraft would normally respond to all-calls for a short time until they could be handled using a discrete address mode and locked out to all-call interrogations. For these reasons, DABS all-call fruit is expected to have a very minor effect on ATCRBS operation. However, the low PRF and the longer DABS reply duration may occasionally result in synchronous garble with a nearby ATCRBS sensor operating at, or approximately at, a multiple of the DABS all-call PRF. Also, since all DABS sensors will operate at approximately the same low PRF, DABS all-call fruit from one sensor may garble all-call replies of another DABS sensor. Although these effects do not appear to be serious, it is difficult (without a fairly detailed system simulation of a mixed

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*Synchronous garble occurring for larger separations between the DABS and ATCRBS target than for two ATCRBS target.

DABS and ATCRBS sensor environment and a combination of DABS- and ATCRBS-equipped aircraft) to make a quantitative assessment of the operation of the combined ATCRBS/DABS all-call mode operation.

Summary of the ATCRBS EMC Issues

The very low DABS fruit rates (from both scheduled and all-call replies) will not deprive the ATCRBS system of enough information to seriously degrade its performance. However, peculiar ATCRBS reply processing equipment responses to DABS replies may result in undesirable effects, which could necessitate some minor equipment modifications. Experiments should be conducted to determine if there is a need for such modifications. The DABS all-call replies at a low but regular PRF may result in near synchronous interference with both ATCRBS and DABS sensors nearby (all-call mode). Assessment of such effects should be done (probably by a detailed system simulation that incorporates a realistic characterization of the DABS channel management function, sensor PRF assignments, etc).

3.1.3 ECM Issues (TACAN)

Major Effects

Again the major effects on TACAN/DME beacons are loading and deadtime, and the major effect on TACAN/DME interrogations is AGC capture.

Degradation Criteria

For interference to TACAN/DME interrogators, the AGC capture effect may be assessed in terms of the effective average interference power (EAIP). Performance is not noticeably degraded, provided EAIP≤Max (EAIP), where Max (EAIP) is an empirically determined tolerance level.

For interference to TACAN/DME beacons, the degradation criterion is kept parametric at this time, with the expectation that loading = deadtime = 5% will be shown to be acceptable in the future.

Estimated Levels of Interference

ECAC has generated estimates of TACAN/DME loading and deadtime (taking into account contributions from an assumed environment of DABS-equipped aircraft) [Ref. 8]. Typical results are shown in Fig. 3-1. A worst case is represented with the TACAN/DME beacon located at JFK Airport and with a conservatively high estimate of DABS transponder density. The results indicate that a 5% loading-deadtime criterion would not be exceeded for any channel separated by at least ±3 MHz. Furthermore there is a large OFR improvement for greater frequency separations. For reference with

- Worst case (min) TACAN/DME signal level
- New York 1982 worst case traffic model
- Location: JFK Airport.

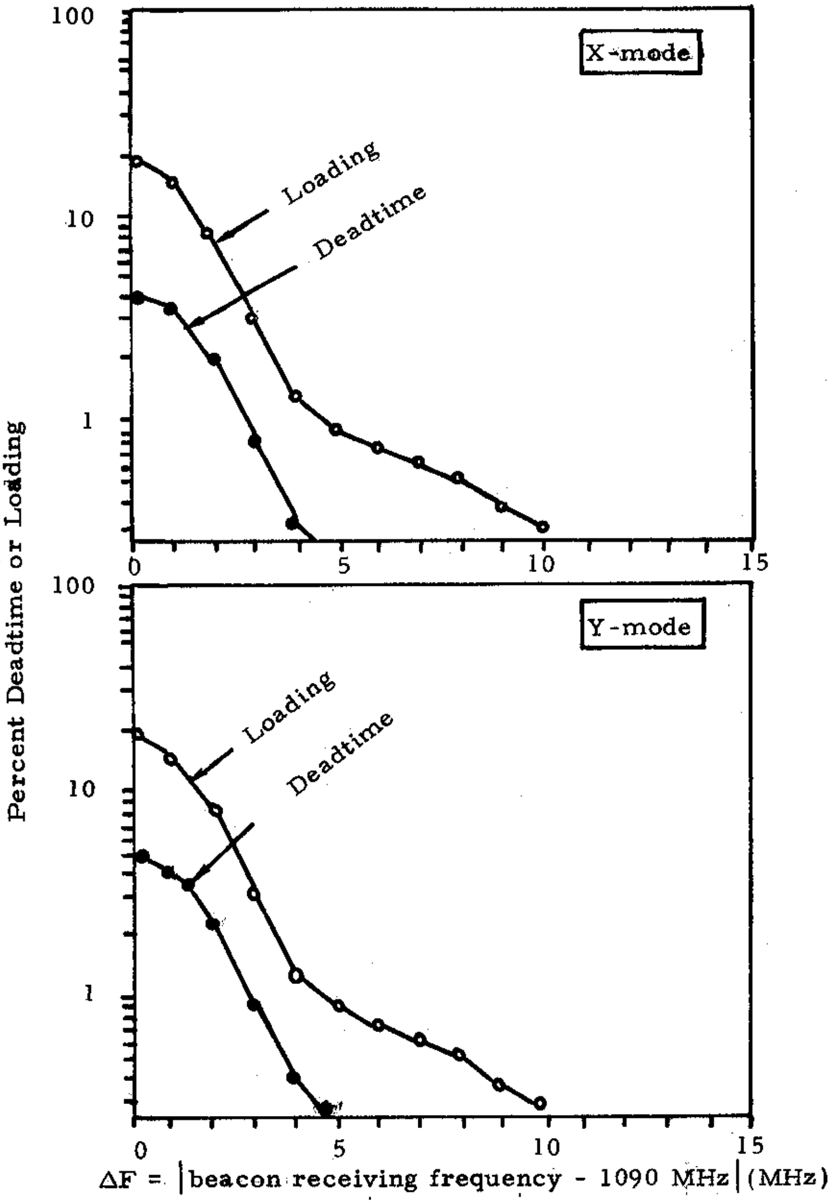

Fig. 3-1. Effects of DABS downlink on TACAN/DME beacons.

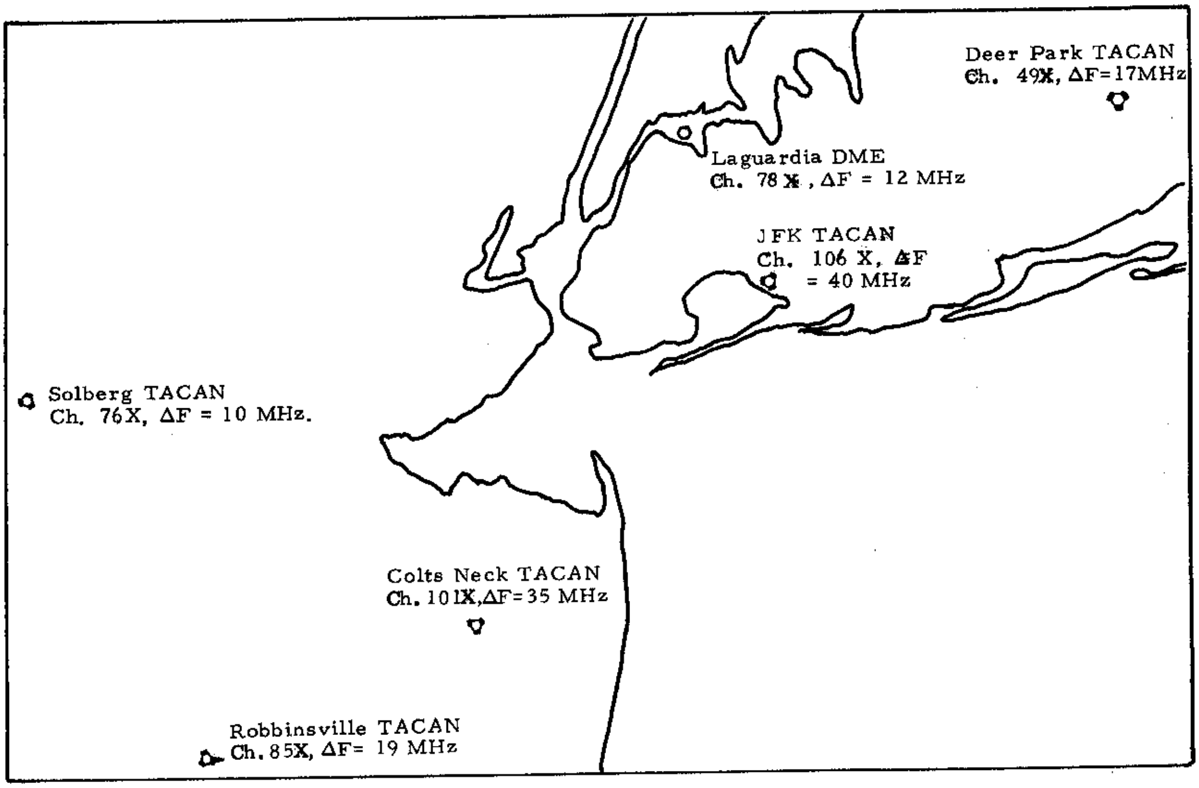

Fig. 3-2. Present TACAN/DME installations at various sections of New York.

the data in Fig. 3-1, it is worthwhile to note present-day deployments and channel assignments.

Figure 3-2 is a plot of the existing TACAN/DME equipment in various sections of New York. It is evident that all of these installations are out-of-band channels for which the impact of DABS would apparently be very small. Although a few in-band TACAN/DME beacons exist today (such as Westover TACAN, Mass., ch. 66, ΔF - 0), these beacons are not generally located near very high density airspace and are often non-FAA and/or part-time use installations. In a similar manner, ECAC has calculated the effects of DABS downlink transmissions on TACAN/DME interrogators. Only Y-Mode interrogators are of interest in this connection since, owing to the method by which channel frequencies are established, the minimum possible ΔF for an X-mode interrogator is 61 MHz. For a Y-mode interrogator, an example of the results calculated by ECAC is shown in Fig. 3-3. The results indicate that the interference conditions are much less than the tolerable level even for in-band channels, and out-of-band channels experience an additional significant reduction in interference.

3.1.4 Performance

The DABS downlink performance can be characterized by:

1. The probability of detecting, correctly decoding, and determining a target monopulse azimuth estimate for a reply (on a single attempt, on multiple attempts within a scan, and over multiple scans)

2. The accuracy of target range and monopulse azimuth estimates for replies that have been correctly decoded.

If reply detection and bit synchronization can be performed reliably, then the time of arrival will be known accurately enough to provide adequate range accuracy; therefore, range accuracy need not be treated as a separate issue. Critical parameters of the downlink are SNR and RFI conditions, which include the ATCRBS fruit environment and multipath garbling.

Consider first the magnitude of the ATCRBS fruit problem. At an ATCRBS fruit rate of 10,000 per second, approximately 20% of the total channel time is occupied by the fruit, and the probability of receiving an ungarbled DABS reply of 64-μsec duration (assuming Poisson arrival statistics) is only 0.427. (For an ATCRBS fruit rate of 20,000 per second, this probability becomes 0.182.) Although these calculations are not expected to be highly accurate, they do clearly indicate that ATCRBS fruit is likely to result in frequent processing of DABS replies that have been garbled.

- New York 1982 worst case traffic model
- Worst case TACAN signal power
- Location -- N.Y., 10,000 ft alt
- Y-mode interrogator

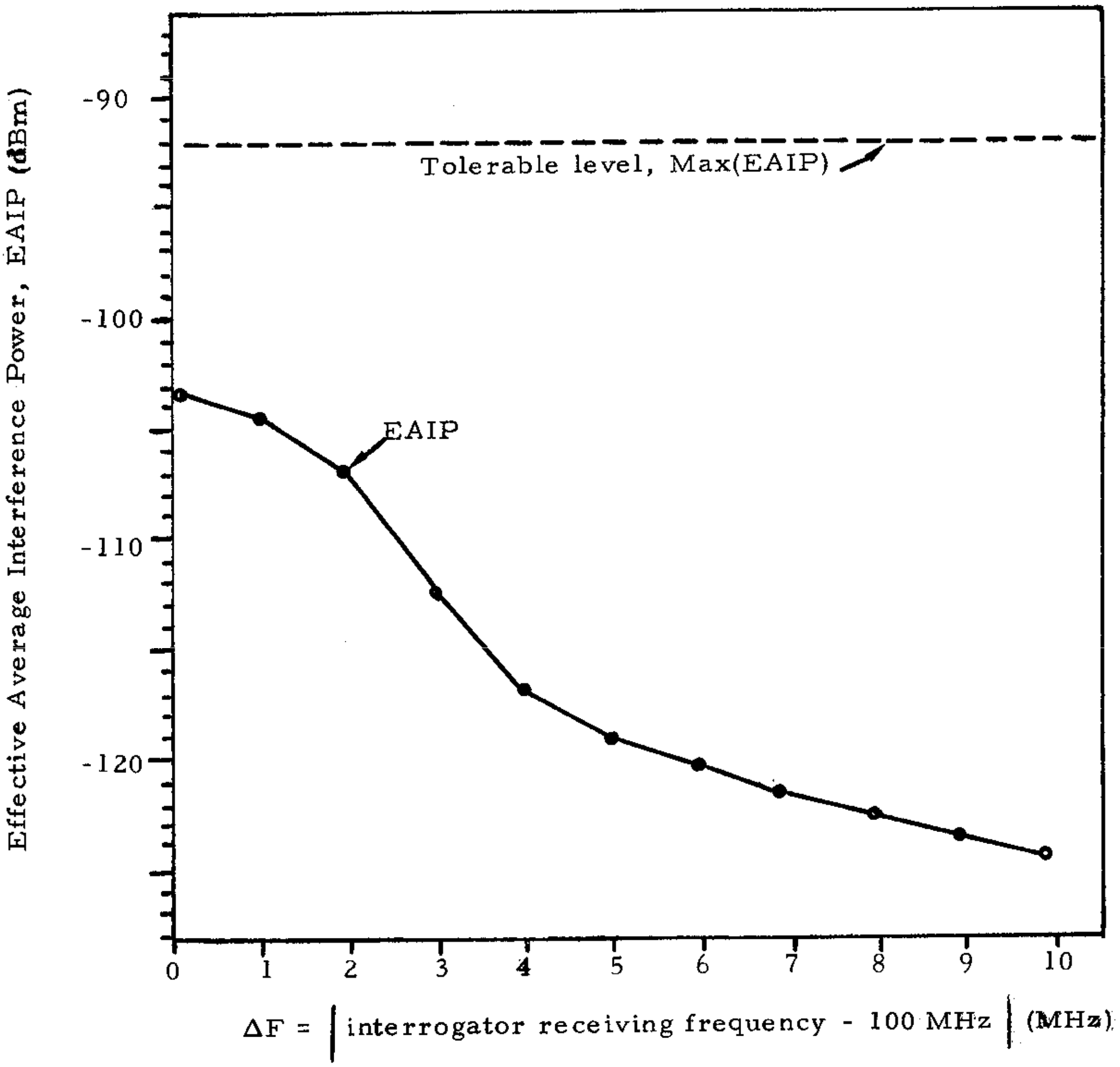

Fig. 3-3. DABS downlink effects on TACAN interrogator.

Two further points should be made in assessing the severity of the ATCRBS fruit problem. First, ATCRBS fruit is not as controllable a system parameter as the interrogation rate because, although ATCRBS sensor operation is government regulated, fruit depends on traffic density as well, which could peak up in localized areas. Second, heavy fruit rates are likely to correspond to heavy DABS traffic densities where the DABS sensor capacity is most likely to be stressed. Therefore, the DABS downlink design must seek an efficient link on 1090 MHz in the presence of heavy ATCRBS fruit levels, and a significant degree of immunity to ATCRBS fruit garbling will be a necessity.

Minimization of DABS channel occupancy implies the need for a link design and a processing system that can extract all necessary surveillance and communication information from the minimum number of replies. For this reason it was necessary to incorporate a monopulse processing system to provide azimuth estimation of targets on a single reply. Monopulse azimuth estimation involves the estimation of angle of arrival of an RF signal relative to the antenna boresight axis, which is then combined with the antenna pointing angle to determine target azimuth. Monopulse systems are known to be sensitive to interfering signals such as ATCRBS fruit garbles and multipath garbles [Ref. 19]. Monopulse processing of garbled DABS replies complicates the problem, especially since the monopulse accuracy goal requires averaging the monopulse samples taken on several individual pulses in order to reduce errors caused by noise. A garble sensing technique is necessary for editing the reply pulses to recognize garbled pulses so that they can be ignored by the monopulse system.

Multipath is another possible source of interfering signals which can lead to significant monopulse errors. The sensitivity of monopulse to interfering signals is such that it is expected that multipath garble will first result in erroneous monopulse estimates (or no monopulse estimate if a sensitive garble sensing technique is used) before data demodulation is limited by the interference. Thus multipath must be controlled for monopulse to work adequately, and if it is so controlled, it is likely that data demodulation will also work satisfactorily. This implies that multipath is a problem that must be controlled by sensor antenna design and siting rather than a modulation format that is immune to multipath garble.

3.1.5 Downlink Design Philosophy

Transponder transmitter cost will represent a significant portion of the overall cost of a transponder; consequently the transmitter cost constraints will be more conspicuous in the downlink design than in the uplink. DABS reply signal formats, which could be generated by present-day, low cost ATCRBS transponder transmitters (i.e., signal structure composed of phase incoherent, on-off keyed pulses), were thus the primary focus of initial design efforts. In addition to these waveform constraints, the performance considerations discussed in subsection 3.1.4 established the desirability of the following DABS reply features.

1. Reply Preamble: DABS reply detection should be based on a special preamble waveform at the start of each reply to avoid the inconvenience of the ATCRBS design in which a reply must be recognized only after the last (framing) pulse of the reply is received. The preamble should be designed for reliable detection and time-of-arrival (TOA) estimation in a heavy ATCRBS fruit environment. TOA accuracy should be dictated by bit synchronization accuracy that is required for reliable data block processing.

2. Modulation Immunity to RFI: Reliable message extraction in heavy fruit will require a data modulation format that has a significant degree of immunity to errors from garbling by ATCRBS reply pulse trains. Multipath sensitivity of monopulse processing is more severe than that of message extraction; therefore multipath considerations should not strongly drive modulation design.

3. Monopulse Constraints: Monopulse processing will require averaging monopulse samples of several pulses, and avoiding garbled pulses. Therefore, a minimum number of pulses per reply should be assured by the link design. Also a reliable means of sensing pulses that have been garbled should be provided for editing replies (avoiding the use of garbled monopulse samples).

4. Message Validation: Although the stringent message error detection capability of the uplink is not necessary on the downlink because of the less critical nature of aircraft originated messages, reasonable error detection capability is still desirable. The same parity check code used on the uplink, together with the address-parity overlay scheme, appears attractive from performance and cost viewpoints.

5. Error Correction: The uplink code, if used on the downlink, has a burst error correction capability that is worthy of investigation as a means of increasing immunity to ATCRBS fruit. The uplink code can correct a significant burst of erasures* with little decoder complexity. Erasure declaration is closely analogous to the garble sensing capability necessary for monopulse data editing. Thus a key feature to successful processing of garbled DABS replies is a means of reliably sensing garbled bits.

The DABS downlink design evolution will be discussed next with respect to the three different aspects of reply processing: (1) preamble detection/synch, (2) data modulation, and (3) message decoding.

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*Demodulated bits that are tagged as very uncertain decisions and are thus most likely to be in error.

3. 2 Modulation Design

The downlink modulation design must address the problem of reliably transmitting digital data included in DABS surveillance and communication replies in a severe RFI environment, contingent upon the constraints on transmitter cost and EMC considerations. A second function that the modulation must support is monopulse processing, i. e., averaging the monopulse samples of a number of ungarbled pulses in the reply.

The two critical aspects of the RFI environment are ATCRBS fruit and multipath garble. With respect to the fruit problem, the modulation design will have to provide a reasonable degree of immunity to errors from garbling (overlapping) ATCRBS fruit replies (and ATCRBS synchronous garble for the all-call mode). Multipath reflections of relatively short delay will result in extensive overlaps of the data block, and monopulse processing will degrade at a lower ISR than will message extraction. Thus, multipath considerations will be primarily dealt with by antenna design and siting constraints rather than data modulation. Garble sensing capability is required for monopulse data editing and for erasure declaration to aid on burst error correction and is therefore a function that must be provided by the modulation system selected.

3. 2. 1 Downlink Data Rate

The use of low cost ATCRBS transponder transmitters imposes some limitations on downlink data rates. The class of transmitters considered are pulsed triode/cavity oscillators that directly generate 200- to 300-watt RF pulses from dc excitation. The modulator excitation for these transmitters can be conveniently derived from a clocked digital signal to produce a pulse train of phase incoherent, variable width pulses at a constant power level.

More specifically, these transmitters are limited to pulse lengths of approximately 200 to 250 nsec. When operating these transmitters at high data rates, an important factor in receiver processing is the leading edge jitter of pulses, which consists of a random component (up to approximately 15 nsec peak-to-peak) and a component that depends on the state* of the circuit at the time the tube is pulsed. Frequency stability of the lowest cost cavity oscillators is well matched to the ATCRBS system tolerance of 1090 ± 3. 0 MHz. This class of transmitters appears to be able to support a variety of on-off keyed, phase incoherent pulse formats such as PAM (RZ and NRZ) and pulse position modulation (PPM) where minimum pulse widths of 250 nsec or greater are acceptable.

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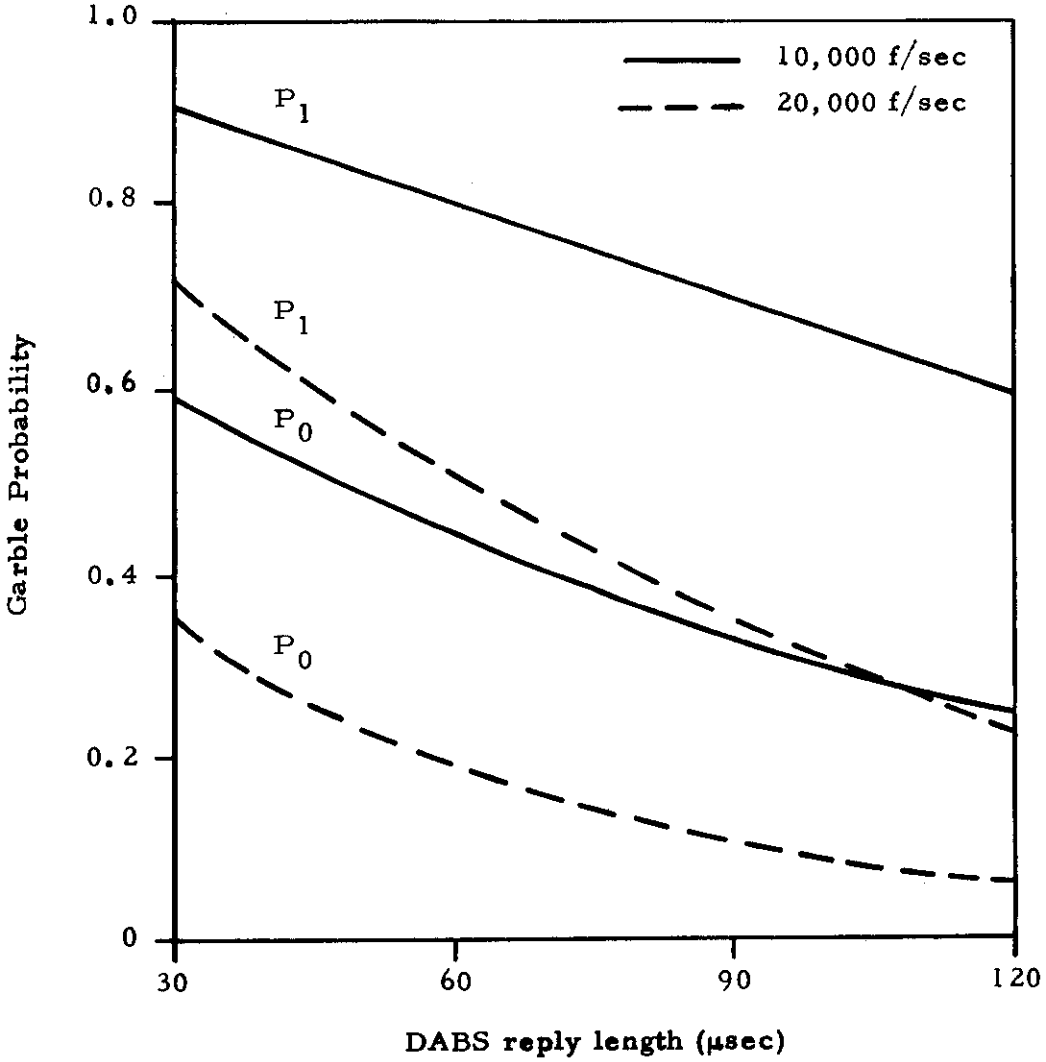
*The dominant parameter is the state of decay of the trailing edge of the previous pulse.

The ATCRBS reply channel window, at 1090 MHz, is narrow compared to the uplink window at 1030 MHz. The ATCRBS reply consists of 0. 45-μsec pulses with rise times specified from 50 to 100 nsec and with carrier frequency in the range of 1090 ± 3 MHz. Shorter pulse widths than the preceding, with the same frequency tolerance, would result in greater spillover of energy into adjacent TACAN channels. Even if DABS adopted the ATCRBS pulse characteristics exactly, the longer reply pulse train of DABS would cause increased interference to adjacent TACAN channels, but the lower DABS fruit rate must also be considered. The ATCRBS level of EMC was adopted as a nominal or baseline position for the DABS downlink, where shorter pulse widths would increase effects on TACAN, while longer pulse widths, compared to ATCRBS, would appear to ease these effects. There are two aspects of downlink data rate that affect performance: (1) Reply duration, which relates to the probability of fruit garble, and (2) pulse width, which determines the necessary IF filter bandwidth for processor settling time and TACAN rejection. Higher data rates will tend to decrease the probability of garble, but the attendant narrow pulse widths will require wider bandwidth IF filters, which will increase the receiver noise level and allow more TACAN RFI into the processor. Moreover, the shorter pulse widths will allow shorter sampling windows for the monopulse processor (even with a wider IF filter), and processor synchronization requirements will become more stringent; more careful consideration of processor sampling frequencies and transmitter jitter effects may be required. Figure 3-4 illustrates garble probabilities for DABS replies of various lengths in an ATCRBS fruit environment (Poisson statistics assumed). Both the probability of receiving an ungarbled DABS reply (P_0) and the probability of only a single ATCRBS garbling reply (P_1) are indicated. These calculations indicate that the garble probabilities are relatively insensitive to reply length and no dramatic change occurs between reply lengths of 30 to 60 μsec.

In summary, DABS reply pulse widths, which are equal to or longer than that of the ATCRBS, are clearly compatible with the class of low cost transmitters considered, and are comparable in out-of-band radiation levels to ATCRBS, but would result in very slightly increased garble probability. The shortest feasible pulse length for the transmitters considered appears to be approximately 250 nsec; this pulse length would push the transmitters beyond their present operating range, increase out-of-band radiation, and require more careful engineering of the sensor processing equipment. The interference immunity and garble sensing features will be discussed in the following subsections.

3. 2. 2 Modulation Candidates

ATCRBS replies consist of 0. 45-μsec pulses spaced 1. 45 μsec apart. In order to provide immunity to interference from such pulse trains, the DABS waveform used to represent a 'zero' ('one') information bit should not be easily convertible (by an ATCRBS pulse garble) into a waveform similar to that used to represent a 'one'('zero'). In an ordinary PAM-OOK (on-off



P_0 = probability of receiving an ungarbled DABS reply.

P_1 = probability of receiving a DABS reply garbled by no more than one fruit.

Fig. 3-4. Garble probabilities for DABS replies of various lengths for a Poisson ATCRBS fruit arrival model.

keyed) system, this implies a pulse length significantly longer or significantly shorter (in an RZ system) than 0.45 μsec. Garble sensing in a PAM system (based on received waveform shape*) would depend on pulse width checking (if an ATCRBS pulse were too long or too short to be accepted as a DABS pulse, then it could be recognized as interference). Simple PAM systems appear, then, to be limited to bit intervals of approximately 0.45 μsec or longer.

Another approach to interference resistance to ATCRBS replies is the use of two pulse positions separated in time to represent a single information bit, with the separation chosen in a manner that if one pulse position is garbled, the other position is likely to occur between pulse positions in an ATCRBS reply. Both pulse positions can be keyed on and off together (referred to as redundant PAM), or a single pulse can be sent in either the early or late position (referred to as binary pulse position modulation [PPM]). Garble sensing in the PPM system would be based on both pulse positions containing zeros or ones. Garble sensing, with redundant PAM, would have to be based on the ambiguous condition of a one and a zero. The PPM system, with sufficiently low data rate, would not require both pulse positions to be separated to avoid confusion by a single ATCRBS interfering pulse. The PPM system presents another format alternative.

A point in favor of PPM is that a fixed number of pulses is always present in each reply independent of the message content; this provides a clear design specification for the transponder transmitter. It also provides a guaranteed number of pulses for monopulse processing, which must average a number of pulses and avoid using pulses that appear to be garbled.

After a study of such PAM and PPM modulation formats based on an on-off keyed transmitter, the most promising formats that emerged for further study were:

(1) PAM-NRZ with pulse width (bit duration) longer than approximately 0.90 μsec

(2) PPM with bit duration longer than approximately 0.90 μsec and adjacent pulse positions

(3) PPM with separated pulse positions (bit duration less than 0.90 μsec possible).

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*Garble sensing, based on a monopulse quadrature channel, was thoroughly investigated and found to be inadequate from a reliability viewpoint [Ref. 20].

The performance of each of these formats is strongly dependent on the processor complexity considered. It is clear that in the absence of interference, all three formats perform equivalently as a function of SNR (peak received carrier power over noise power in the receiver bandwidth) because the receiver filter bandwidth (and, hence, the noise level) is essentially determined by the carrier frequency tolerance of ± 3 MHz. The performance in interference, however, is dependent on the receiver complexity one is willing to consider to reliably recognize signals distorted by interfering ATCRBS pulses. A reasonably simple demodulator scheme for PPM, which also admits a reliable garble sensing capability, can be based on the relative amplitude of the received signal level in each of the two pulse positions. The probability of error per bit for options 2 and 3 above were determined by computer simulation as a function of ISR, where the interference was taken as a single garbling ATCRBS reply (probability of an information pulse present taken as 0.5). The pulse widths for both of these formats were approximately 0.5 μsec for these simulations (data rate of approximately 1 MHz). The simulation results, indicated in Fig. 3-5, include IF filtering (which results in intersymbol interference effects), random bit synchronization errors, and receiver noise. A simple PAM system is included in the figure to illustrate the degree of immunity to ATCRBS pulse garbles provided by the PPM modulation format.

The NRZ-PAM format will behave asymmetrically in interference, i.e., interfering pulses are more likely to convert transmitted 'zeros' into 'ones' than 'ones' into 'zeros'. Under the demodulator constraint of two samples per information bit, it appears that less reliable garble sensing will be achieved with this format. With this format, the energy (number of pulses) contained in a reply will vary with the message contents, which entails some difficulties in transmitter design and monopulse processing. For these reasons, the NRZ-PAM format was considered the least desirable of the three formats listed above.

3.2.3 Modulation Selection

The choice between the two PPM formats is essentially a choice of data rate, with the alternatives being:

(1) ~ 1 MHz data rate, using two adjacent 0.5-μsec pulse positions

(2) ~ 2 MHz data rate, using two 0.25-μsec pulse positions (separated by approximately 1.5 x 1.45 μsec).

Assuming the performance of both of these formats is essentially equivalent from an SNR and an SIR point of view (for a single garbling ATCRBS reply as the interference), the factors favoring the choice of the low rate format are as follows.

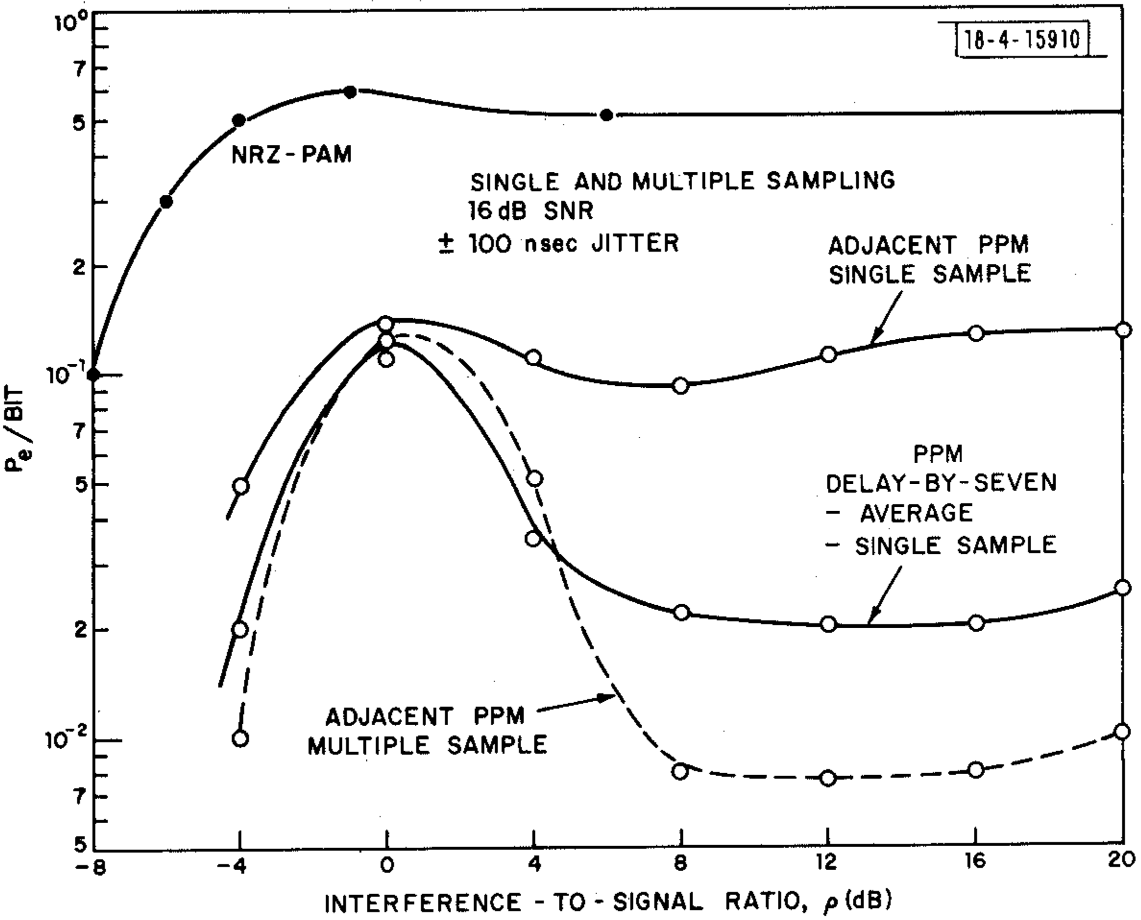

Fig. 3-5. Simulation results for bit error probabilities for downlink modulation options 2 and 3 with single ATCRBS reply interfering. (NRZ-PAM curve given for reference.)

(1) ATCRBS transponder-type transmitters would be operated well within their present pulse specifications on rise time, leading edge jitter and pulse width without effect on DABS processing.

(2) Regarding EMC with TACAN, out-of-band energy per pulse would be no greater than that of ATCRBS.

(3) The DABS receiver filter could afford a longer settling time for the monopulse processing and could provide greater TACAN signal rejection than the higher rate format.

(4) The pulse positions corresponding to a single information bit could be adjacent to one another, rather than separated and interleaved with other pulses as in the higher rate format.

(5) The burst length of erasures, caused by an ATCRBS garbling reply, would span no more than 24 bits, which the use of the uplink code could correct, thus providing an added degree of immunity to garbling by a single ATCRBS fruit reply.

The major disadvantage of the low rate PPM option is the longer duration of the DABS reply, which results in increased probability of garbling. When this is analyzed together with the burst erasure correction capability that the lower rate format admits, the overall downlink reliability in ATCRBS fruit is higher for the low rate format than the high rate format (without error correction). This can be seen in Fig. 3-4 where the ungarbled probability curve (P_0) for shorter reply lengths is higher than the single-garble curve (P_1) for longer reply lengths.

Thus, the only remaining consideration with regard to the duration of the DABS reply is channel occupancy or system capacity. Even with a full sensor load of 2000 aircraft, two replies of 64 μsec each, every 4 seconds from each aircraft, results in a downlink channel occupancy of 0.032 second per second*. The high rate format could reduce this by one-half, but it would be inconsequential at these low levels. For these reasons, the low rate PPM format was chosen for the DABS downlink, with the final data rate established at 1 MHz. Thus, an information bit is represented in this format by two adjacent pulse positions, each of which is 0.5 μsec in duration. A 21-μsec ATCRBS reply, consequently, cannot result in an error burst that spans more than 23 bits, and the use of the uplink code on the downlink can provide error detection capability as well as a useful burst error correction

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*This should be compared to the resulting ATCRBS channel occupancy for 18 interrogations per scan from a single sensor resulting in 0.189 sec/sec channel occupancy caused by a single sensor; many more than two or three sensors interrogate each aircraft.

capability when used in conjunction with a garble sensing indicator to flag doubtful bit decisions as erasures.

3.3 Message Decoding

Although downlink messages are not as critical as IPC commands, message validation and error detection are highly desirable in an automated sensor in order to recognize, reject, and minimize processing of corrupted reply data. The parity check code selected for the DABS uplink is quite well suited for this purpose. Other advantages of the parity check code are that it can be implemented for the downlink in the transponder by making use of most of the uplink parity checking circuitry, and it also has a 24-bit burst erasure correction capability that may be exploited on the downlink. Message decoding here refers to both functions of error detection and error correction.

3.3.1 Error Detection

The downlink message is encoded by the transponder in a manner that differs slightly from that used in the uplink. The message bits are transmitted unchanged, as in the uplink, while a parity check sequence is generated from these bits and combined with the address bits in a slightly different manner than in the uplink encoding process. (The change facilitates the removal of the address while leaving the parity check bits available for use in error correction.) The encoding circuit, with the indicated change in one switch connection for the downlink encoder, is the same as that illustrated in Fig. 2-12. The message decoder at the sensor then processes the demodulated data block to calculate the address-parity field from the message and compare it with the received address-parity field. If those two sequences are not identical, the demodulated data block contains at least one error. Thus, error detection on the downlink operates exactly as it does in the uplink with the same parity check code being used.

3.3.2 Burst Error Correction

The downlink message decoder first calculates the parity check sequence from the received (and demodulated) data block. The received address-parity field is first stripped of the expected address (by modulo two summing) and then combined with the calculated parity check sequence (also by modulo two summation) to produce a 24-bit sequence referred to as the error syndrome. A nonzero error syndrome indicates a disagreement between the calculated and received parity check sequences and thus implies that the received message is in error. The properties of the DABS code provide a simple relationship between a nonzero error syndrome and an error burst spanning a maximum of 24 bits within the message that would result in the observed syndrome. In fact, a simple sequential circuit can be designed to calculate a 24-bit error burst pattern corresponding to any particular location within the received data block that will result in the observed syndrome. An example of the circuit is illustrated in Fig. 3-6 in which the contents of a 24-bit shift register, when initially loaded with the error syndrome,

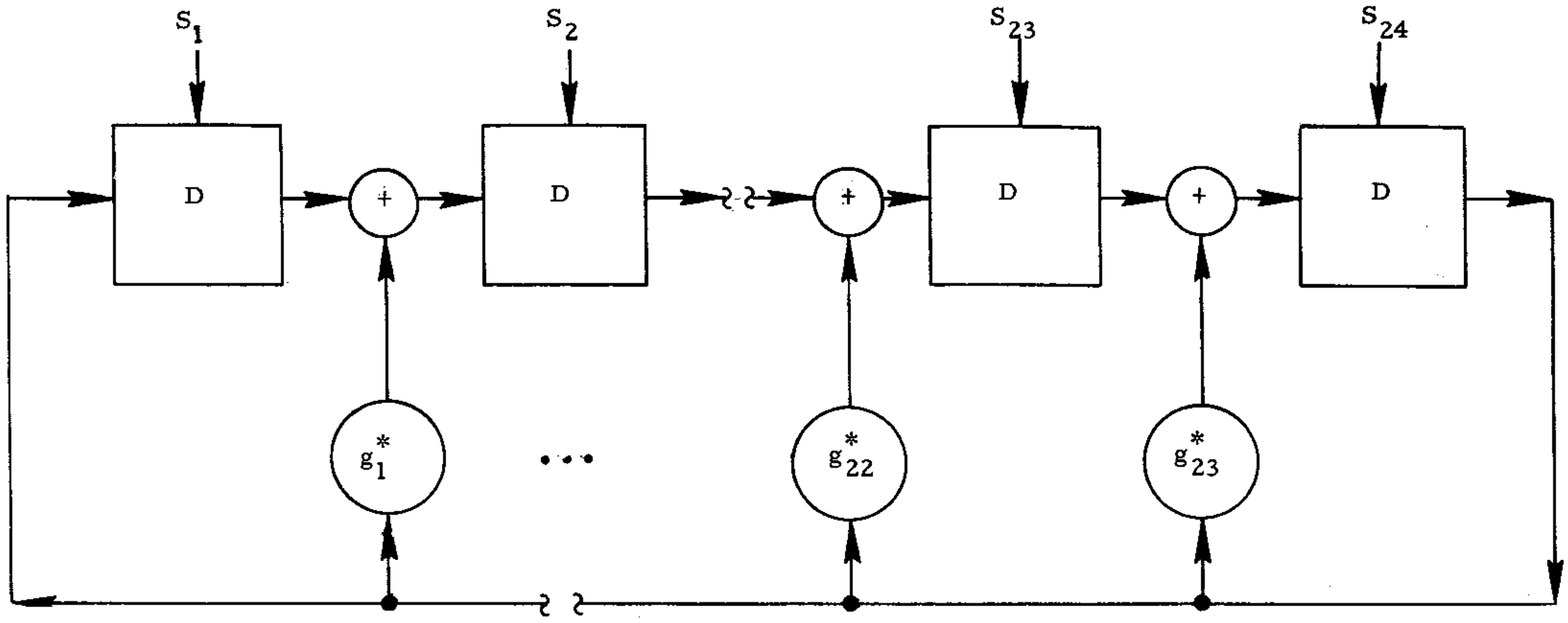

Fig. 3-6. Burst error pattern generator.

ATC-52 (3-6)

will indicate sequentially on successive shifts the error burst patterns corresponding to all possible 24-bit burst locations within the demodulated data block, beginning with the burst located in the last 24 bits of the data block (the address-parity field) and ending with the burst located in the first 24 bits of the data block. Any of the burst error patterns calculated by the circuit would give rise to the observed error syndrome. It thus remains to provide a means for selecting which of these burst patterns is most likely to have caused the observed nonzero error syndrome.

The demodulator produces a sequence of bit decisions from which the message decoder calculates the error syndrome to be used for error detection as well as generates candidate burst error patterns in the case of a nonzero error syndrome. The garble sensing capability of the DABS reply processor is intended to provide to the message decoder an indication of which demodulated bits are most likely to be in error as a result of garbling. This is accomplished by the demodulator outputting a binary sequence of confidence indications, one for each bit decision, to indicate 'high' or 'low' confidence in the bit decisions.

Burst error correction is then accomplished by comparing each calculated 24-bit error pattern with the confidence bits corresponding to the location of the error pattern. Whenever a burst error pattern, calculated for a particular burst location, indicates errors only in bits that have been flagged as 'low' confidence, then that error pattern in that location is assumed to be the one causing the nonzero syndrome. The 24-bit span of the bit decision sequence, corresponding to the error burst location, is then changed in accordance with this error pattern, the burst error location search is terminated, and the corrected sequence is output by the decoder as the decoded downlink message. The code properties assure that any single error burst pattern spanning a maximum of 24 bits in the bit decision sequence, in which all bits in error are flagged as 'low' confidence bit decisions, can be corrected by this technique. Many more bits than those in error can be flagged as 'low' confidence without disrupting the decoding scheme. Thus, the garble sensing capability must flag only actual bit errors as 'low' confidence bit decisions with high reliability, due to the fact that the decoder is quite insensitive to falsely flagging correct bit decision as 'low' confidence. *

In summary, since a 1-MHz downlink data rate implies that 24 bits span 24 μsec, the error pattern caused by a garbling ATCRBS reply of 20.75 μsec cannot span more than 24 bits, consequently the burst error correction capability of the DABS code can be used to provide immunity to garble by a single ATCRBS reply. The error correction capability is contingent on realizing very reliable flagging of bit decision errors as 'low' confidence bit decisions. If an error is unflagged or an error pattern that spans more than 24 bits is encountered, the decoder will attempt to correct a 24-bit burst, and this may result in (1) finding no error pattern that matches the confidence

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*A detailed description of the DABS downlink message decoding system is presented in Ref. 21.

bit sequence, and (2) finding a 24-bit error pattern that does match the confidence bit sequence, resulting in a burst correction and acceptance of an incorrect message. The probability of finding a correctable burst error pattern under the preceding conditions is related to the number of bits falsely flagged as 'low' confidence. The exact relationship between accepting incorrect downlink messages and the garble sensing circuit performance in real channel conditions is still under investigation. Simulation results for the error correction system will be presented in Section 3.5.2.

3.4 Preamble Design

DABS reply data block processing requires, at a minimum, early recognition of a reply and acquisition of bit timing. Thus, the functions to be realized by a preamble waveform at the start of each DABS reply are (1) reliable detection, and (2) reply parameter estimation in heavy ATCRBS fruit levels. The parameter estimates of interest are TOA for target range determination and bit synchronization, and reply amplitude and monopulse (off-boresight) angle estimates to be used as reference levels by the data block processor. Only the TOA estimation performance will be considered here, whereas the amplitude and monopulse reference extraction from the preamble are not used by the first generation DABS reply processor. However, more advanced DABS reply processing techniques, which use these parameter estimates, have been investigated in order to better understand the fundamental limits on DABS downlink performance. Such advanced processing techniques can achieve better performance in heavy RFI than the first generation reply processor; they may be of real interest at some time in the future.

The preamble waveform should, of course, be constrained to use the same basic pulse format employed in the reply data block, basically a 2-MHz PAM-RNZ format. A number of pulses should be provided to allow reliable detection. Pulse edge detection should be the basic method of TOA determination to be compatible with ATCRBS processing techniques. Determination of pulse TOA by the trailing edge detection in the ATCRBS reply processing has been determined to be much less accurate because of multipath, pulse stretching in the receiver, pulse width variations caused by the modulator/transmitter, etc. It was thus established as a ground rule in preamble processing that only pulse leading edges would be used to determine TOA. Thus, the preamble design problem can be stated briefly for the purposes of this report as the search for a 2-MHz PAM-NRZ waveforms with the number and spacings of the pulses chosen for reliable detection (recognition) and low false alarm probability, and accurate TOA determination* in heavy RFI environments composed of ATCRBS fruit and TACAN pulses. The preamble waveform should be kept as short as possible, consistent with these requirements, and should also provide a time interval after the last preamble pulse for processing time to initialize the data block processor.

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*To within approximately +200 nsec for adequate bit synchronization and monopulse sampling.

3.4.1 Preamble Candidates

The simplest and shortest preamble possible would be a two-pulse preamble that could be uniquely recognized on the basis of the leading edge spacing of the pulses. However, such a waveform is very vulnerable to garble by ATCRBS fruit since both pulse leading edges must be received in the clear to recognize this preamble and extract TOA.

A number of four-pulse preamble designs were considered in some detail, where the waveform structures were designed for processing as two pulse pairs. These preamble candidates are illustrated in Fig. 3-7. In order to compare performance achievable by each of these candidate preambles, the following ground rules for preamble processing must be defined.

1. Detection is based on sufficient energy detected within the four pulse intervals, the exact amount of energy required to declare individual pulses being set by an adjustable threshold.

2. Pulses with clear leading edges are recognized, and preamble declaration also requires at least two of the four pulses to have clear leading edges with proper spacing.

Digital implementation of this type of preamble detection circuit for preamble candidate 1 is presented in Fig. 3-8. The processing takes place in two stages. Pulse processing determines when sufficient energy is detected in 0.5-μsec intervals (compared to a threshold k) to announce a pulse present (output on lead P) and also simultaneously flags these detected pulses to denote whether or not a clear leading edge was detected for each (parallel output on lead L). A stage of video processing was assumed to produce the sampled (binary) video representation that was input to this preamble detector. The second stage of processing consists of two shift registers (for the P and L outputs), which are tapped to check pulse locations and leading edge spacing. The circuit details the six ways in which two clear leading edges out of four pulses can occur; any of these six combinations will be recognized by the circuit and result in the declaration of a preamble. This particular digital circuit was designed to operate at a 10-MHz clock rate, but the same principles of operation obviously apply to any other clock rate.

3.4.2 Preamble Performance

The basic detection/false performance for the preceding class of preamble detectors was investigated by digital computer simulation for all four preamble candidates. The simulated processor includes ATCRBS (interfering) and DABS waveforms, which have been filtered by a second-order IF bandpass filter, envelope detected to produce video waveforms,

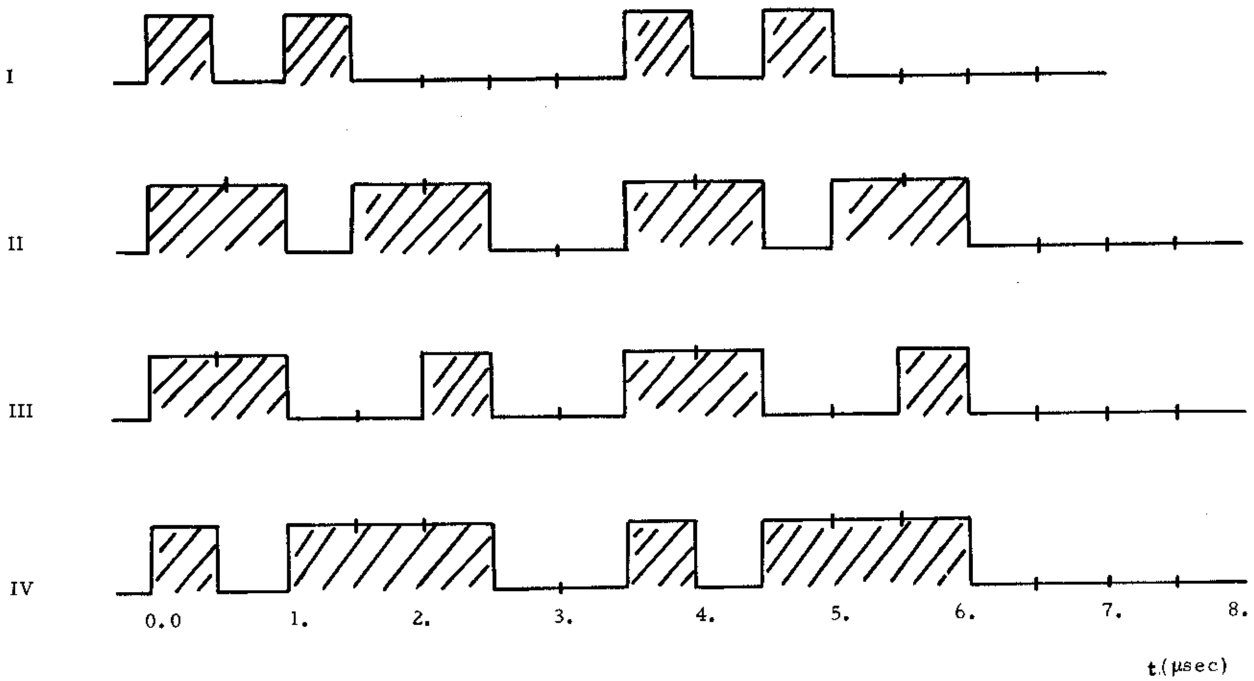


Fig. 3-7. Four candidate downlink preamble formats.

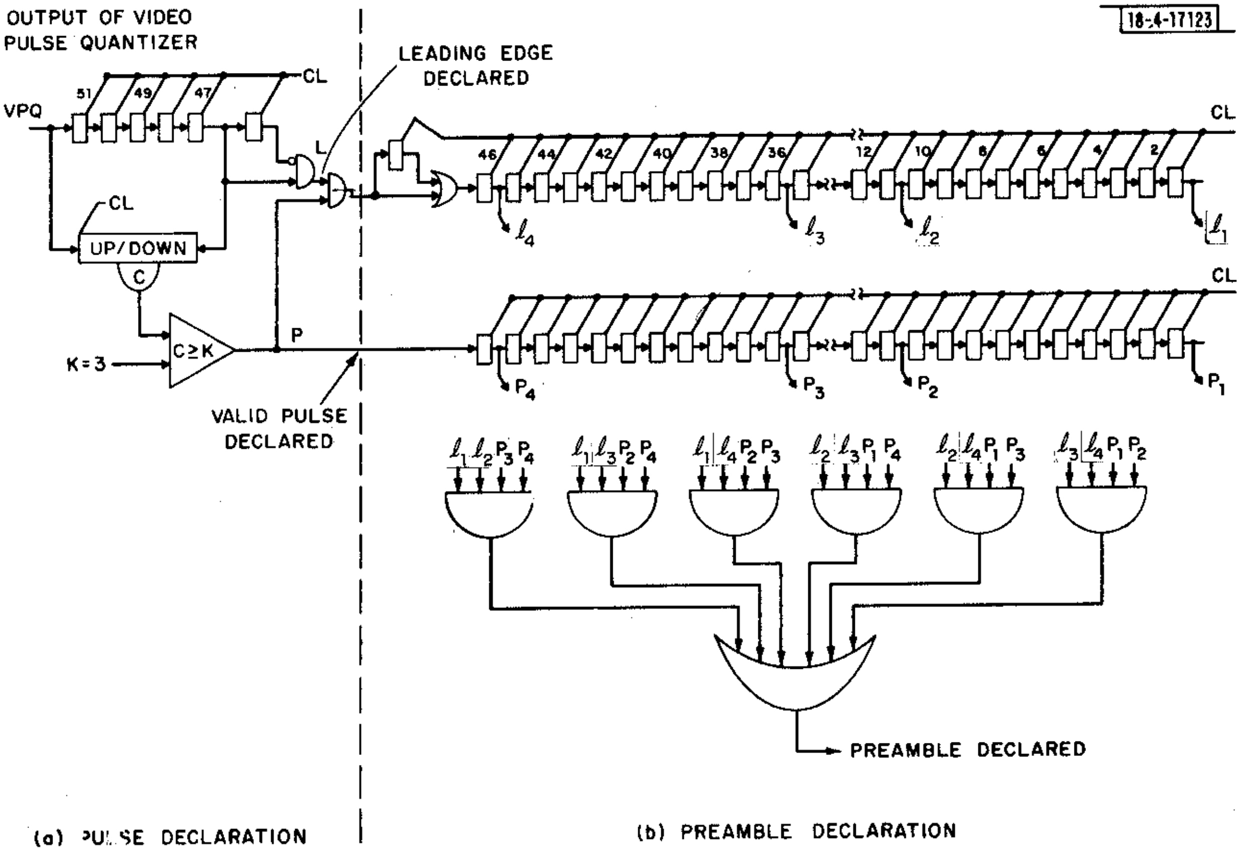


Fig. 3-8. Digital preamble detector circuit for a 10-MHz clock.

video processed to do pulse leading and trailing edge detection (based on slope changes of the video signal), and sampled to produce the binary data stream input to the preamble detector. The clock rate used in the digital processing was 20 MHz.

Detection/false alarm probabilities are indicated in Fig. 3-9 for all four candidate preambles. Detection probability (P_D) was evaluated with a single ATCRBS reply with all (14) pulses present garbling the preamble and with the same signal level as the preamble (SNR = 20 dB and SIR = 0 dB). False alarm probability (P_F) was evaluated with two ATCRBS replies overlapping and all 14 pulses present in each. The parameter γ denotes the fraction of a pulse that must be present to declare a pulse and is related to the pulse detection threshold parameter k in the circuit of Fig. 3-8. Of the four preamble candidates studied, preamble 1 displays significantly better performance than the others; consequently only this waveform was investigated in more detail to determine if other aspects of performance were adequate.

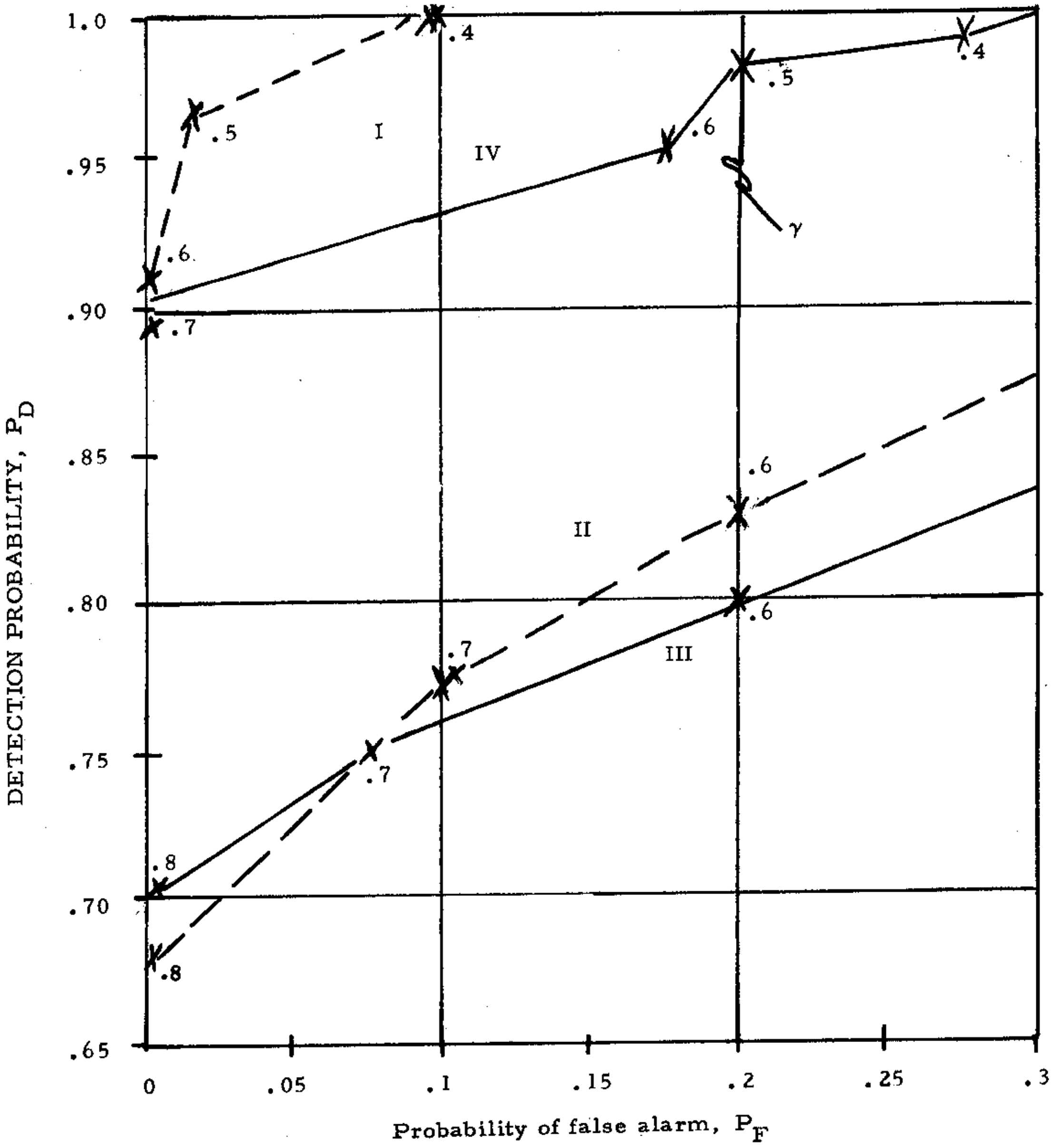
Both detection and TOA estimation accuracy are of interest in evaluating the DABS preamble performance. Figure 3-10 illustrates detection and TOA performance for situations when one and two ATCRBS replies are garbling the preamble. In Fig. 3-10, $P_T(\tau)$ denotes the probability of detecting the preamble and also obtaining a TOA estimate within $\pm\,\tau$ nsec of the true TOA. Curves of P_D, independent of TOA accuracy, are also presented in the plots for reference. The interference carrier frequency is assumed to be the same as that of the preamble. Detection and TOA performance, for the case when the ATCRBS interfering reply has a frequency that differs from that of the DABS preamble by 2 MHz, is illustrated in Fig. 3-11.

Preamble detection, and TOA and amplitude estimation performance are illustrated as a function of SNR for the selected DABS preamble in Fig. 3-12, where $P_A(\alpha)$ denotes the probability of the compound event of (1) preamble detection, (2) TOA estimate within ± 100 nsec of true TOA, and (3) an amplitude estimate within $\pm\,\alpha$ dB of true received amplitude.

In conclusion, it appears that preamble format 1 can provide adequate detection and TOA performance with rather straightforward processing circuitry. Thus, this preamble waveform was adopted for the DABS downlink design.

3.5 Downlink Performance Estimates

Tentative design choices for the DABS reply preamble, data modulation, and error correction coding were all made on the basis of providing good immunity to ATCRBS fruit garbles. In fact, the underlying ground rule in the downlink design was to provide complete immunity to a single ATCRBS fruit reply garbling a DABS reply; the performance estimates presented thus far have all represented specified garble conditions. It remains to provide



Note: γ is defined as the fraction of a pulse that must be present to detect a pulse. P_D is simulated for a DABS preamble in the presence of 1 ATCRBS reply with all code pulses on. P_F is simulated for 2 ATCRBS replies with all code pulses on (DABS preamble absent).

Fig. 3-9. P_D and P_F vs γ for each of the four candidate preambles of Fig. 3-7.

Upper plot: One ATCRBS reply present; each pulse randomly on/off.
Lower plot: Two ATCRBS replies present; each pulse randomly on/off.

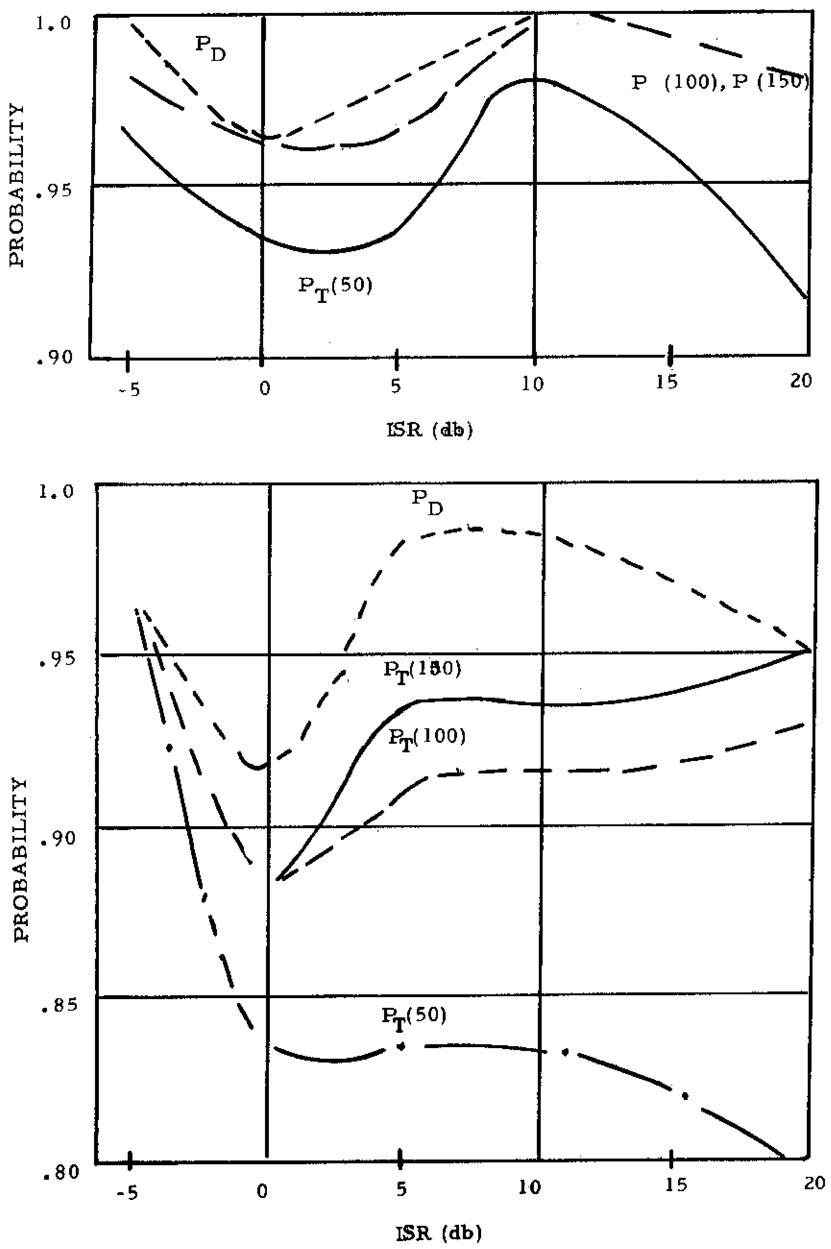
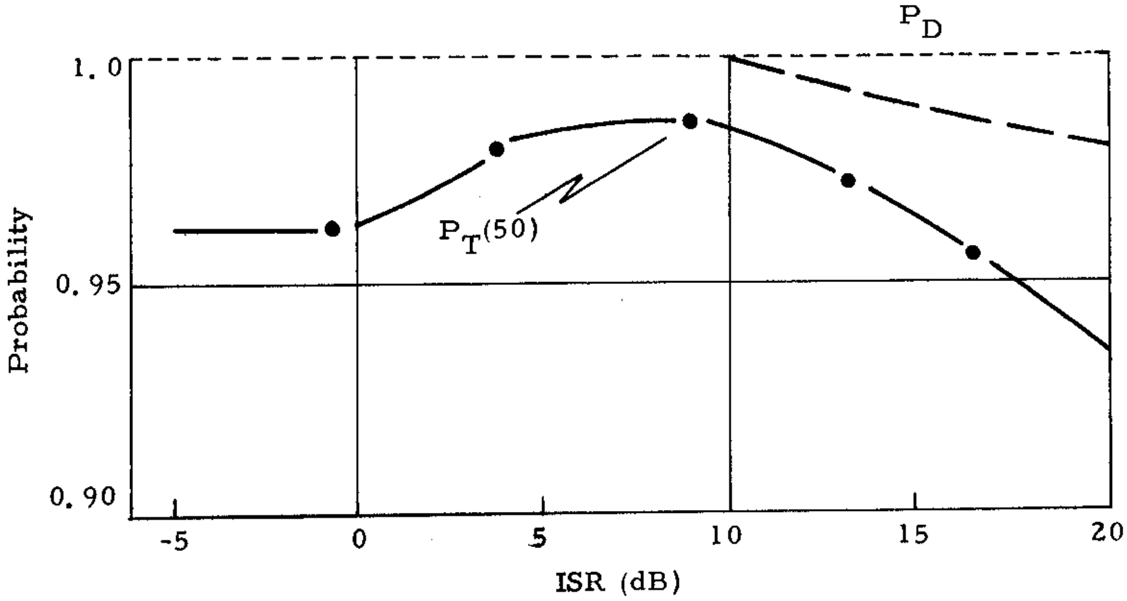


Fig. 3-10. Timing estimate performance for Format I preamble with 20-dB SNR, $\mathcal{Y}$ = 0.5, 20-MHz sampling, and no frequency offset.

ATC-52 (3-11a)



(a) 1 ATCRBS reply present; each pulse randomly on/off.

Fig. 3-11(a). Timing estimate performance of Format I preamble with 20-dB SNR, $\gamma = 0.5$, 20-MHz sampling, and 2-MHz frequency offset (1 ATCRBS reply present).

(b) 2 ATCRBS replies present; each pulse randomly on/off.

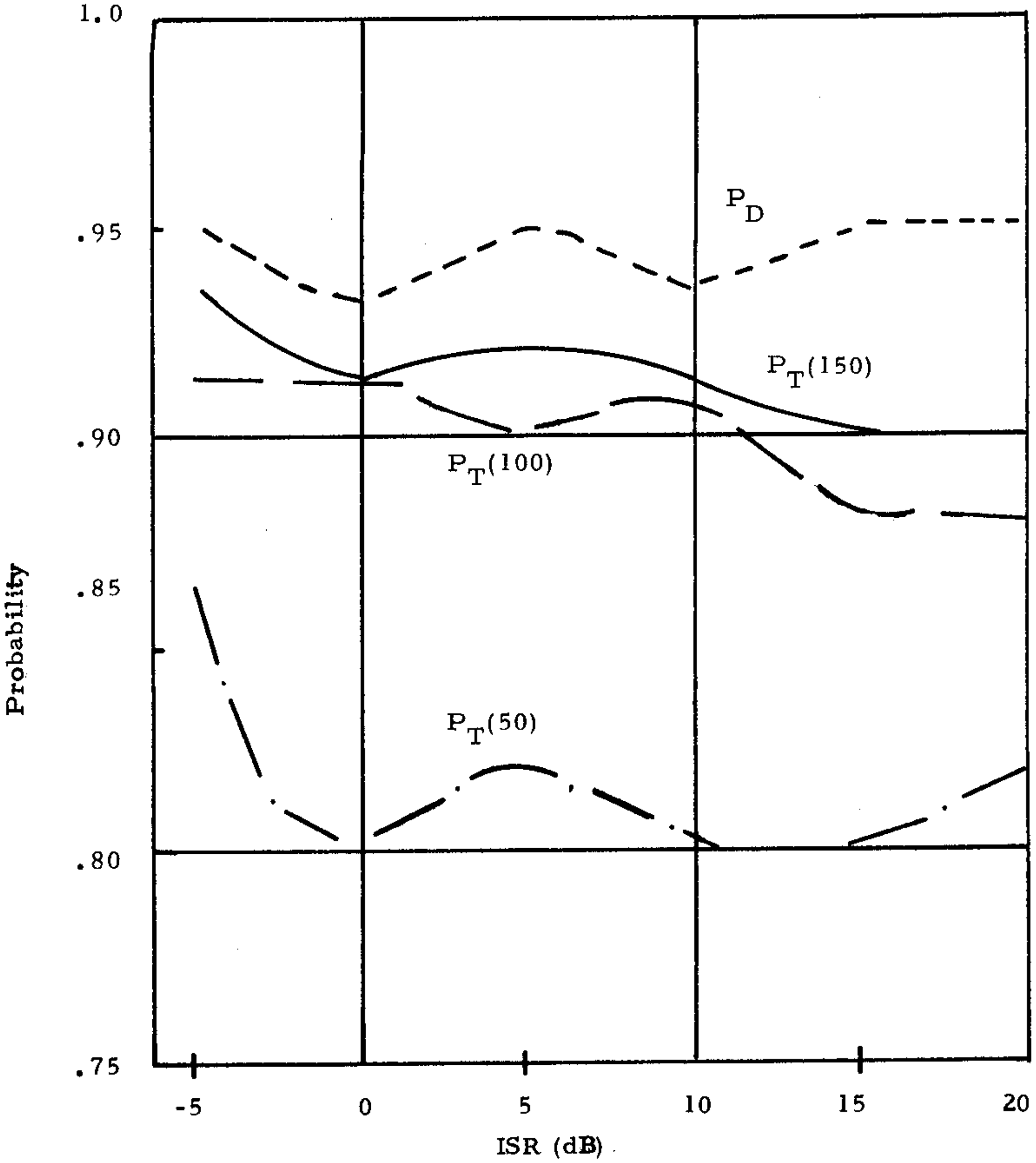


Fig. 3-11(b). Timing estimate performance of Format I preamble with 20-dB SNR, $\gamma = 0.5$, 20-MHz sampling, and 2-MHz frequency offset (2 ATCRBS replies present).

(1) MTL is held at 10 dB above noise level.
(2) Interference consisted of two ATCRBS replies (SIR = 0 dB), with each pulse randomly on-off. (P_D, $P_T(\tau)$ and $P_A(\ )$ are defined in the text.)

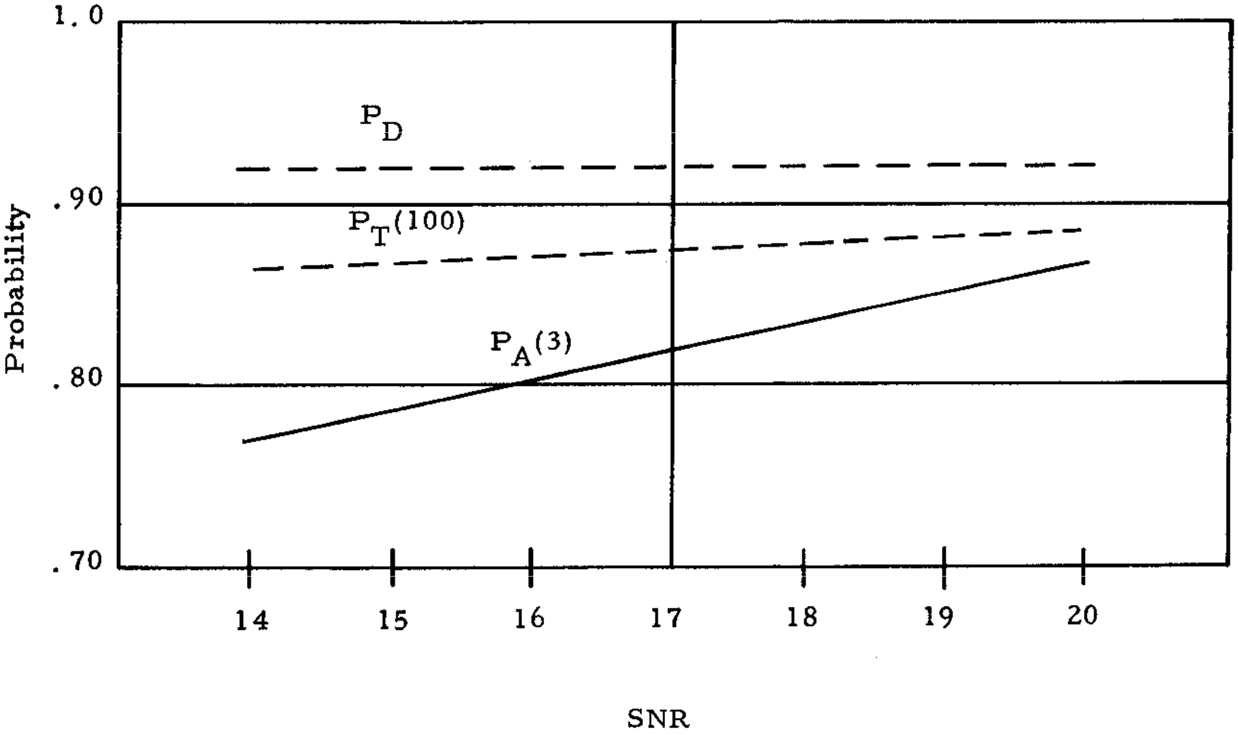


Fig. 3-12. Probability of successful decoding of Format I preamble vs SNR.

some estimate of how well each phase of DABS reply processing works in an ATCRBS fruit environment, which will determine the relative frequency of various garble conditions.

3.5.1 Performance Bounds

An analytical technique has been developed to calculate a lower bound on preamble performance in an ATCRBS fruit environment [Ref. 22]. The technique calculates the probability of successfully detecting and declaring a preamble (i.e., within ± 100 nsec of the actual TOA) for the worst case fruit arrival distribution under the constraint of a given average fruit rate. The performance bound is indicated in Fig. 3-13 for a 20-dB SNR, and an INR greater than 10 dB for all fruit replies. The preamble performance will be no worse than indicated in this figure for any fruit arrival statistics whatsoever (for a given average arrival rate).

The performance bounding technique has also been applied to data block processing. Message decoding performance under given garble conditions was first obtained by computer simulation. The probability of correctly decoding the entire downlink data block was determined in this simulation for as many as eight ATCRBS replies overlapping the data block; these data are presented in Table 3-1 for reply processing with and without error correction. The results were then used to determine a lower bound on correctly decoding the received data block when error correction is accomplished and when it is not accomplished (i.e., the demodulated data is simply checked for errors but no attempt is made to correct error bursts). The fruit was assumed to be 90% sidelobe and 10% main lobe fruit (which affects the distribution of SIR). Figure 3-14 is an example of the probability of correctly decoding a DABS reply with and without the burst error correction capability as a function of "effective fruit rate," which is the average arrival rate of fruit exceeding a signal level at which fruit garbles result in demodulation errors.

TABLE 3-1
SIMULATION RESULTS FOR THE PROBABILITY OF CORRECT DATA BLOCK DECODING*

No. of overlaps:	1	2	3	4	5	6	7	8
With error correction:	1.0	0.99	0.97	0.98	0.98	0.76	0.62	0.50
Without error correction:	0.91	0.74	0.62	0.29	0.22	——	——	——

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*For 90% sidelobe fruit, and 10% mainbeam fruit.

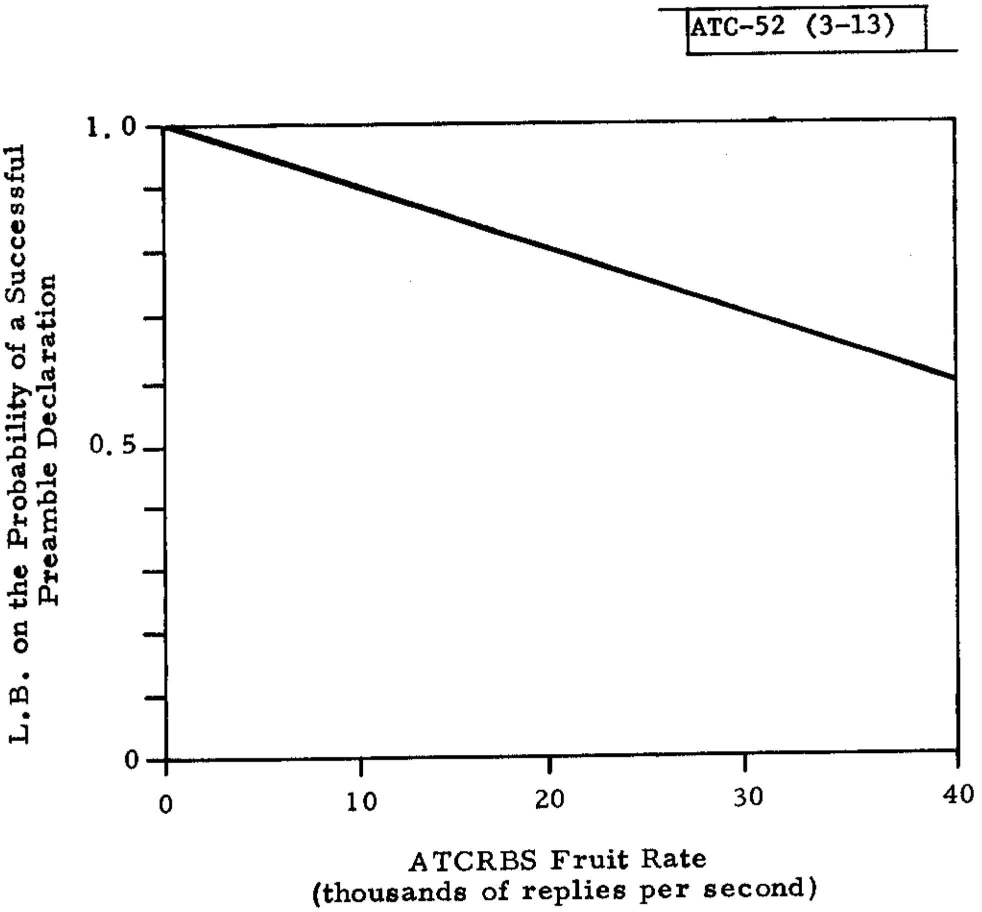

Fig. 3-13. Preamble performance bound in ATCRBS fruit.

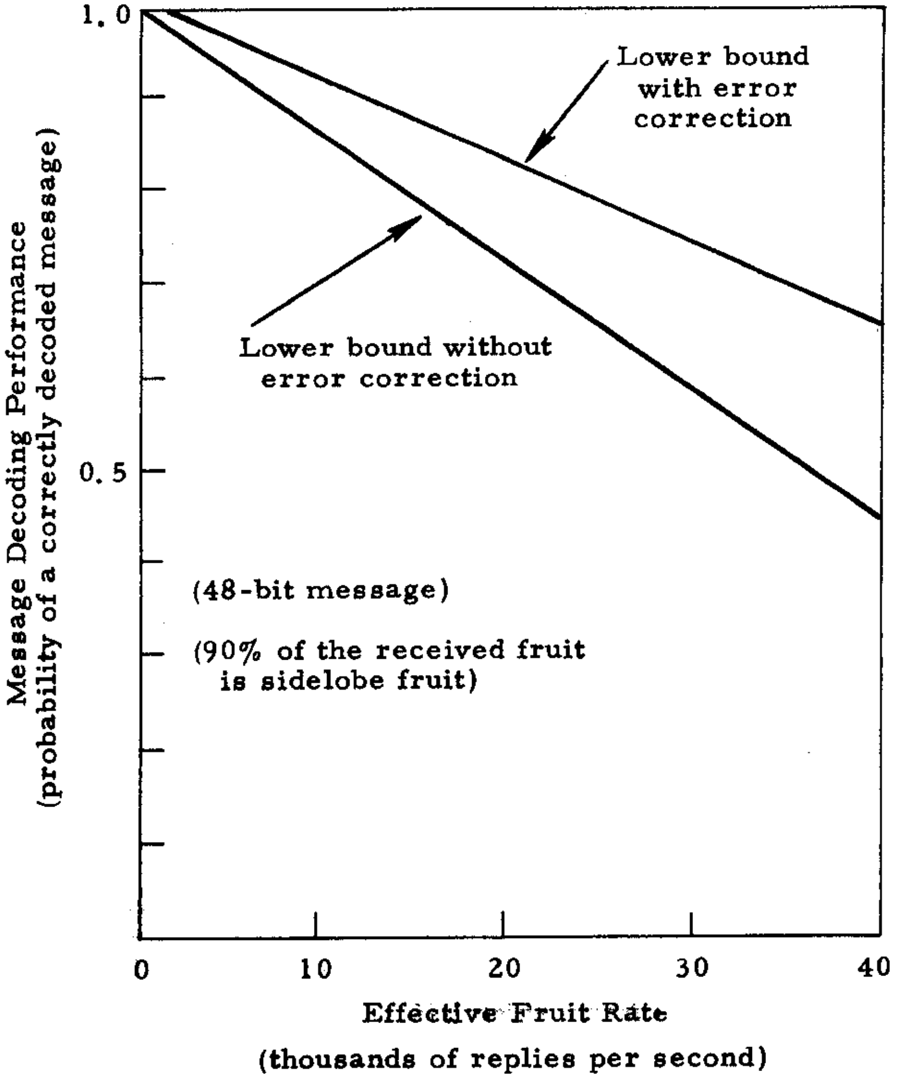

Fig. 3-14. Message decoding performance in ATCRBS fruit.

The performance bounds indicate that both the preamble detection probability and the correct data block decoding probability exceed 0.90 at 10,000 fruit per second and exceed 0.83 at 20,000 fruit per second. An upper bound on missed reply probability is just the sum of the missed preamble probability and the incorrect data block decoding probability. This results in a lower bound to the overall probability of successful reply processing of 0.08 in 10,000 fruit per second, and 0.66 in 20,000 fruit per second.

3.5.2 Reply Processor Simulation Studies

A general DABS reply processor simulation program has been written to provide more precise estimates of performance in controlled ATCRBS garble conditions. The simulation program includes:

- Generation of waveforms at IF to produce true envelope variations for garbling, phase incoherent pulses
- IF filtering
- Log detection to produce video waveforms
- A video pulse quantization circuit to detect leading edges and produce binary sampled data stream
- A preamble detection circuit providing bit synchronization
- A PPM demodulator circuit that compares relative amplitude of a single video signal sample for each PPM pulse position
- Generation of confidence bits based on the presence of energy above MTL in both PPM pulse positions, and also on a sidelobe pulse discrimination (by comparison of signal levels received on the mainbeam and omni antennas)
- ATCRBS fruit model for typical traffic distribution, transponder characteristics, and antenna patterns
- DABS reply SNR based on uniform range distribution for DABS targets from 0 to 170 nmi

Some results obtained from this simulation program are presented in Table 3-2 for three and six ATCRBS replies that overlap some part of the DABS preamble or data block (or both). The last four rows of entries in the table are for fixed DABS SNR of 15 dB and 30 dB. The results (especially the last four rows) clearly indicate that a significant degree of immunity to ATCRBS fruit has been achieved by the downlink signal format and reply processing.

The translation of these simulation results into overall downlink performance in a specified fruit environment is not straightforward. One method for translation is to assume that the probability of successfully processing a DABS reply, given n garbling ATCRBS fruit replies, is a monotone decreasing function of n. Then the probability of "success," given one, two or three garbling fruit, can be lower bounded by that determined from the simulation for three garbling fruit. Similarly, the probability of "success," given four, five or six garbling fruit, can be lower bounded by the simulation results for six garbling fruit. This type of bound has been evaluated for Poisson fruit arrival statistics, with some of the details of the calculations in Table 3-3. The results are considerably more optimistic than the multiplied lower bounds on calculated preamble and data block decoding success probabilities given above.

TABLE 3-2

DABS REPLY PROCESSOR SIMULATION RESULTS

Case No.	No. of Fruit Replies	Freq. Offset of Reply (MHz)	SNR of DABS Reply (dB)	Azimuth of DABS Reply (deg)	RMS Range Error (μsec)	RMS Azimuth Error (deg)	Probability of Preamble Detection	Preamble False Alarm Probability	Probability of Error Correction Failure for Detected Reply	Overall DABS Processor Failure Probability
1	3	0	Random (uniform 0-170 nmi)	Random (uniform ±4 deg)	0, 055	0, 003	0, 997	0, 003	0, 007	0, 010
2	6	0	Random	Random	0, 053	0, 005	1. 0	0, 0	0, 013	0, 013
3	3	±3	Random	Random	0, 052	0, 003	1, 0	0. 0	0, 003	0, 003
4	6	±3	Random	Random	0, 053	0, 003	0, 993	0, 007	0, 017	0, 023
5	3	0	30	+1, 0	0, 055	0, 006	0, 993	0, 007	0, 007	0, 014
6	6	0	30	+1, 0	0, 053	0, 011	0, 997	0, 003	0, 037	0, 040
7	3	0	15	+1, 0	0, 032	0, 045	0, 917	0, 003	0, 076	0, 153
8	6	0	15	+1, 0	0, 035	0, 094	0, 873	0, 023	0, 202	0, 303

TABLE 3-3

OVERALL DABS REPLY PROCESSOR SUCCESS PROBABILITY IN ATCRBS FRUIT BASED ON SIMULATION RESULTS

	Poisson Fruit Rate	
	10,000 per second	20,000 per second
Prob. of no fruit arrivals in T_G*	0.423	0.179
Prob. of 1, 2 or 3 fruit arrivals in T_G	0.565	0.725
Prob. of 4, 5 or 6 fruit arrivals in T_G	0.012	0.094
Prob. of "success," given no fruit garbles	1.0	1.0
Prob. of "success," given 3 fruit garbles†	0.847	0.847
Prob. of "success," given 6 fruit garbles†	0.697	0.697
Overall probability of reply processor success	0.910	0.859

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[*] T_G denotes the time window in which fruit arrivals would result in garbles, which, in this case is 64 μsec for the DABS reply, and 22 μsec for the ATCRBS fruit reply, or a total T_G = 86 μsec.

[†] The simulation results for 15 dB SNR are used here (cases 7 and 8 from Table 3-2).

4.0 SUMMARY AND CONCLUSIONS

DABS has been designed to operate on the ATCRBS frequencies of 1030 and 1090 MHz. The use of these frequencies demanded careful study of the effects of DABS on ATCRBS functioning, and tailoring the DABS design to operate satisfactorily in the RFI environment produced by ATCRBS and TACAN. The DABS link design will result in greater reliability and accuracy of surveillance than that achieved by the ATCRBS link; this will be accomplished with significantly less effect on the ATCRBS system than an ATCRBS sensor now produces, i. e., lower channel occupancy and lower suppression time for ATCRBS transponders. In addition to the surveillance function, DABS will deliver critical uplink messages with very high reliability and extremely low probability of displaying messages that contain errors. All these features have been engineered with avionics cost consideration foremost in mind, and it appears realistic to expect a DABS transponder to cost approximately 1.5 times the cost of an ATCRBS transponder.

The DABS uplink design was driven by the time constraint of transmitting uplink messages during the suppression interval of ATCRBS transponders. Although the effect of DABS sensor suppression of ATCRBS transponders is appreciable, it is predictable; the effect that DABS will have on the ATCRBS uplink can therefore be bounded. Among simple binary modulation schemes dictated by transponder cost constraints, there are no ultra-low cost solutions. The selection of DPSK modulation is decided on the basis of its significant performance advantages in noise and interference with an insignificant cost increment over other modulation candidates. The conservative view of maximizing the uplink reliability in an interference environment was taken in the case of the uplink because of the difficulty of changing transponder specifications to upgrade performance in the future. Thus, the ultimate uplink performance that one would ever expect to need must be specified in the initial system specification. Measurements of DABS uplink reliability in the heaviest ATCRBS interference eivironments of the east and west coasts of the United States verify that DABS will indeed operate efficiently, thus minimizing channel occupancy and reinterrogation.

The DABS downlink design was driven strongly by transponder transmitter cost considerations. Even in modest ATCRBS fruit environments, garbling of DABS replies by fruit will occur very frequently, dictating the need for a high degree of immunity to such interference for an efficient link design. Immunity has been attained by using the low-cost ATCRBS transponder transmitter to generate a binary PPM format, which is considerably more immune to ATCRBS reply pulse trains than an ordinary PAM format. In addition, use of the uplink parity check code on the downlink provides additional immunity to ATCRBS fruit by allowing correction of erasure bursts spanning up to 24 μsec. The DABS reply channel occupancy in time (per target) is less than that of ATCRBS, thus mitigating DABS effects on both ATCRBS and TACAN equipment.

The DABS link performance is currently being verified at the DABS Experimental Facility (DABSEF), MIT, Lincoln Laboratory, Lexington, Mass. Although the environment at DABSEF is rather benign, difficult interference conditions are being simulated while real transponders and hardware reply processor designs are being tested. The results are not complete, but available data, to date, indicate that the link performance estimates presented in the earlier chapters are realistic.

ACKNOWLEDGMENTS

This report presents the accumulative efforts and work of many people at Lincoln Laboratory who contributed to the design of DABS. References to their work are included in the text wherever documentation exists. The author has merely attempted to summarize in a single document the most important (in his mind) work supporting the selection of DABS modulation and coding designs. The author is particularly indebted to W. H. Harman for contributions to the text of this report, and to J. T. Barrows, J. R. Johnson, and J. D. Welch who proofread the draft of this report.

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