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MODULATION AND CODING FOR A COMPATIBLE DISCRETE ADDRESS BEACON SYSTEM

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16. Abstract

One of several possible candidate configurations for the Discrete Address Beacon System is described. The configuration presented is compatible with the Air Traffic Control Radar Beacon System, and it provides for gradual transition from one system to the other. A discussion of the effects of modulation and coding on the performance of the candidate DABS system is presented, and an experimental design is described. Some studies which will be required for detailed design are described.

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INTRODUCTION

This report provides an analysis and discussion of tradeoffs involving modulation and coding for an ATCRBS compatible discrete address beacon system. The report describes the effects of several modulation and coding options on system design and performance. A basis for evaluating different modulation and coding techniques, and a procedure for performing the tradeoff studies which will be required for a detailed system design, are presented.

The design of modulation and coding procedures for optimization of system performance interacts closely with the design of the interrogation repeat and scheduling strategies that the DABS system will use. This report is organized to provide a discussion of the system performance implications of the modulation and coding techniques presented, to provide a baseline for an experimental design, and to describe the analysis and experimentation that will be required for evaluation and optimization of the experimental design.

The second section, Compatibility Requirements and System Configuration, describes the DABS configuration which is used as the framework for discussion in this report. In addition to the ATCRBS/DABS compatibility requirements which led to the selection of that design are described.

In third section, Message Formats, Modulation and Coding, the modulation and coding options for the DABS system design are described. The most important point made in this section is that the conventional modulation performance measure, bit error probability, is strongly dependent on the noise model used for the performance evaluation, and that the DABS system to a large extent generates and controls its own noise environment. Therefore, even a gross estimate of the bit error performance will depend on the details of the system scheduling procedure, and the performance of the other users of the DABS/ATCRBS shared radio channel. The relationship between bit error probability and system performance is indirect, and however, wide ranges of bit error performance are expected to provide the required overall performance. The implications of modulation and coding with respect to system behavior and configuration, and the special provisions which must be made to guarantee the required performance are discussed in the third and fifth sections.

2. Accept target handoff and identification messages from an ATC center or other DABS ground stations.

3. Maintain a track on all known aircraft within the coverage area and provide track status reports to the ATC system.

4. Re-acquire tracks in the minimum possible time after recovery from a system failure.

5. Provide accuracy of position measurement, and traffic capacity, required in the upgraded third generation ATC system.

The accuracy requirement will not be discussed in detail in this report because antenna design is the principal accuracy limitation and antenna design is the subject of a separate report. The signalling waveforms do determine radial range resolution from the interrogator site, but the waveforms recommended here provide better resolution than the 500 ft recommended in the ATCAC report.

Evaluation of the traffic capacity of the system will require extensive study although present studies have indicated that during the early ATCRBS to DABS transition period the capacities of the minimal complexity DABS system will be in the area of hundreds of aircraft per interrogator and in an all DABS environment the capacity will be several thousand aircraft. This is described in additional detail in the fourth section.

SYSTEM DESCRIPTION

For the purpose of this discussion the DABS system can be divided into three major sub-systems with reasonably well defined interfaces. The interrogator sub-system consists of a transmitter, receiver, antenna, message formatting and detection hardware, and possibly hardware for garble detection. The computer sub-system performs the system search, detection, track, interrogator scheduling, message verification and repeat functions and ATC system communications. The transponder sub-system includes a transmitter, receiver, antenna, and timing circuitry, all of which are similar to, or identical to, equivalent parts of an ATCRBS transponder. In addition, the DABS transponder must contain a demodulator for the ground to air digital data, and hardware for message and address error checking, and response message generation. Block diagrams showing the functional elements of each of the three sub-systems are shown in Figures 2, 3 and 4.

The DABS system described here makes use of two one direction data links. The uplink (ground to air) messages can be discretely addressed DABS messages or non-addressed ATCRBS interrogations. The recommended message format uses conventional ATCRBS P_1 and P_2 pulses to generate synchronization information, and side-lobe suppress ATCRBS transponders. All messages are transmitted within 25us., while the ATCRBS transponders are still suppressed.

Message spacing, and target interrogation rate are determined by a relatively complex interrogator scheduling algorithm to maintain required track quality and search rates while transmitting data link messages as required by ATC system assigned message priorities. A priority scheduling algorithm, and target handoffs, will provide for gradual system performance degradation with partial hardware failure and unusual garble conditions or peak traffic loads. The recommended downlink (air to ground) is based on the ATCRBS down link. The only modification to this data link which has been considered is the addition of 8 additional data bits to allow the transmission of 20 bit identity codes. This modification does not appear necessary for an experimental design to be used only for evaluation of feasibility and performance.

The communication function requires that 50 bits of data be transmitted from the DABS interrogator to the aircraft, and that an appropriate acknowledgment be received on the ground to guarantee overall system performance. The 50 data bits include 20 bits to allow one million discrete aircraft addresses and 30 bits for the message. The message format is described in Reference 1.

The ATC system will generate all messages and assign priorities. The DABS system will provide service as required by message priority, and as the communication channel conditions allow.

The three sub-systems are described in greater detail later in this report. Several critical areas for design tradeoff studies have been identified and are described in the next section. In general, the function of the tradeoff studies is to determine the minimum cost system. This is because the ATCRBS compatibility requirements as interpreted here have forced an over designed system. The only risk of unacceptable performance occurs when DABS and ATCRBS interrogators are operating simultaneously in a high aircraft traffic density area. It is believed that a garbling analysis for this environment can only be performed by an extensive computer simulation.

MESSAGE FORMATS, MODULATION AND CODING

The ground to air data link services which the DABS system must provide can be handled with 50 data bits allocated as follows:

Unique aircraft ID	20 bits
Command type	6
Command extent 1	12
Command extent 2	12

These data fields are described in Reference 2. The modulation and coding techniques used in DABS will provide identical bit and word error performance for all command types. The DABS system control computer algorithms will maintain message error performance characteristics, which depend on the command type, by use of flexible message scheduling and repeat strategies.

The most critical message type for data link performance will be IPC commands. For this type of message the DABS system will be required to provide performance on the order of one incorrectly accepted message per aircraft, per 10^9 seconds of operation. This type of message is time critical and only a relatively small number of repeats can be tolerated in the worst case. If the scheduling algorithm described in Appendix B is used, there will be 10 to 20 possible time slots in which one aircraft can be interrogated, during one antenna rotation. If IPC messages are not accepted and confirmed by the aircraft during this time period there will be an additional delay of one antenna rotation period until the next attempt at transmission can be made. For efficient performance of the IPC function the probability of requiring more repeats than can be performed during one antenna rotation must be extremely small. When an IPC message has not been confirmed after one scan the priority of the IPC message will have to increase, and the DABS system, or the ATC system, should be able to take additional actions, such as attempting to use interrogators at other locations.

Message repeats have a low cost as long as only a small number are required. For example, if the probability of acceptance of a message on the first transmission attempt is .8, then the system will expend one fifth of its traffic capacity as the price for error free message transmission. In a DABS candidate system with excess capacity, the type of system described in this report, this is a negligible cost. Error correcting codes can not provide good performance in DABS type systems because the errors usually occur in clusters and will tend to destroy too much of any garbled codeword for reliable error correction. This is described in Appendix A.

In addition, error correcting hardware is much more expensive than decoders used only for error detection. For these reasons the baseline DABS system described in this report uses codes for error and garble detection, but does no error correcting. Whenever an error is detected the interrogator will repeat the message.

The downlink messages must allow the operational data required by the ATC system to be transmitted. This requires that aircraft ID and aircraft altitude messages be transmitted when requested. The DABS system will generate interrogations in these modes at the rates required to maintain track quality. The unique aircraft ID will require 20 bits, although the message size could be limited to a smaller number of bits by use of more complex communication control procedures. For example the least significant 12 bits of the ID could be transmitted as a response to one interrogation type, and the remaining bits as a response to a second interrogation type. In order to allow DABS to perform its data link function, the downlink must also be capable of carrying check information to indicate the acceptance of uplink messages. This information could be a yes/no acceptance message or check digits generated from the received uplink data. If the aircraft does not accept a message, it will not respond at all; the check digits allow the ground station to verify that the correct message has been accepted.

The modulation and coding baseline design and options are described in the following sections.

MODULATION ON UPLINK

All of the uplink modulation schemes proposed here rely on use of the ATCRBS SLS feature to control ATCRBS interaction. This leads to the message structure constraints shown in Figure 1. The two pulses preceeding the data burst are the conventional ATCRBS P_1 and P_2 interrogation pulses. In the fourth section several different levels of ATCRBS, DABS compatibility are described. In the lower traffic capacity systems it will be possible for ATCRBS transponders without the sidelobe suppression feature to operate without seriously degrading DABS performance.

The system performance criteria places several constraints on all modulation systems. They are:

1. At least 50 bits of data must be transmitted.

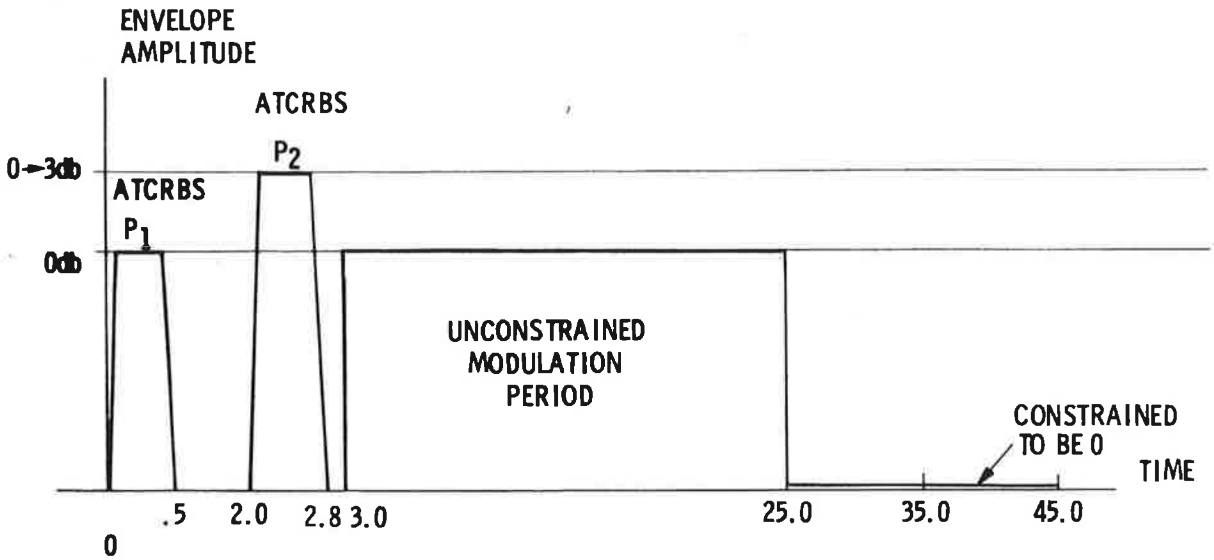


Figure 1. Modulation Envelope for ATCRBS Compatible Mode

2. 0 to 50 bits of parity data will be able to handle almost any forseeable error criterion and channel usage strategy (see Appendix A).

3. System traffic capacity will be significantly decreased, and transponder cost increased if more than one 25us. uplink data frame is required for a complete message.

The ATCRBS compatibility pulses, P_1 and P_2, can take several forms:

1. The P_1 and P_2 exactly as described in the National Standard.[3] Phase synchronization is possible in PSK or MSK systems.

2. Both pulses phase modulated in Barker or similar phase code. This will provide superior bit and word synchronization capability with no compatibility loss.

3. Pulses FSK modulated in Barker like sequence, this facilitates bit and word synchronization in FSK system but many compromise compatibility.

4. Pulses FSK or phase modulated with alternating 0,1,0,1, sequence. This allows good bit sync but does not optimize word sync.

5. In a PAM type DABS system P_1 and P_2 pulses may not be amplitude modulated since this would destroy compatibility.

One other option which exists is to gain compatibility by using codes which do not side-lobe suppress the ATCRBS transponders but are rejected because they always appear to request more than one ATCRBS mode. This type of system has not been considered because it appears to be sensitive to uncontrolled details of the ATCRBS transponder design and performance.

Some general implications of all of the DABS waveforms are:

1. DABS frequency tolerances require better oscillators than ATCRBS. This appears to be the only significant limitation that will be encountered if ATCRBS transponder transmitters and receivers are to be used in DABS transponders.

2. A binary signalling DABS system requires 4 Mhz bit rates and therefore requires approximately 6 dB more peak power than ATCRBS for equivalent signal to noise ratios. Some of this additional requirement can be made up using more efficient modulation than PAM (1.5 dB using FSK, 3 dB using PSK).

3. The DABS interrogator duty cycle is variable. Even in low density traffic the DABS interrogator may be called on to transmit as many as 30 interrogation frames in 2ms, although computer algorithms may limit this. Traffic capacity and duty cycle averaged over even 4 seconds will typically be much lower when rotating antennas are used instead of phases arrays.

Table 1 shows the relative performance that is provided by several of the most common modulation techniques in Gaussian noise. The noise on the DABS/ATCRBS frequency channels will be primarily fruit and garble which is not Gaussian, and clearly not spectrally flat. The data in Table 1, is meaningful only when fruit and garble cause negligibly few errors when compared with the desired bit error performance. This will be the case in all DABS environment.

TABLE 1. COMPARISON OF MODULATION SYSTEMS

MODULATION METHOD	SNR/CHIP FOR BPAM PERFORMANCE	SNR/BIT FOR BPAM PERFORMANCE	BANDWIDTH COMPARED WITH BPAM	RECEIVER COMPLEXITY
BPAM (Binary pulse amplitude)	0 db	0 db	1	Simple except if passband tightly controlled
B FSK (Binary Frequency Shift)	-1.0 db	-1.0 db	2	Simple
B PSK (Binary phase shift)	-3 db	-3 db	1	Simple frequency tolerance ≤ 1 mhz
4 PSK	-1.5 db	-4.5 db	½	frequency tolerance $\leq ½$ mhz
8 PSK	+1.2 db	-3.6 db	1/3	frequency tolerance $\leq ½$ mhz

Binary phase shift modulation appears to be the most promising candidate for the DABS system for several reasons. A hard limiting receiver eliminates the need for an AGC and provides for a simple constant false alarm rate system when combined with the recommended codes. The BPSK detector can be easily realized with currently available digital logic elements at low cost. The noise performance and bandwidth are superior to the other easily implemented systems (BPAM, BFSK). The need for word and bit sync, normally makes PSK systems somewhat more difficult to implement than PAM or FSK; however, in the DABS system the sync data is already available from the leading pulse time of arrival data used in the surveillance function.

UPLINK CODING

A description of possible coding techniques, and their performance, is presented in Appendix A; only the recommended baseline design is presented here.

The use of a truncated cyclic BCH code with 50 data digits and 49 parity check digits is assumed. Encoder and decoder realizations are shown in Figures A-1 and A-2. The connection polynominal for the shift registers is given in Figure A-1.

This code has been selected because it appears to provide adequate error performance at minimum cost. The apparently less complex alternative of repeating the message twice and requiring an exact match between the two copies will provide much higher probability of undetected error, and consequent erroneous acceptance of incorrect messages. There does not appear to be a significant cost difference between the two approaches.

MESSAGE ACCEPTANCE AND REPEAT STRATEGIES

At present it is envisioned that an aircraft will accept a message only if all bits have been correctly received. The aircraft will respond with an acknowledgment or data only if it accepts an interrogation.

The interrogator must repeat all messages until a positive acknowledgement is received. It does not appear feasible or useful for an aircraft to repeat messages back to the ground, but the limited data in IPC maneuver commands can be easily repeated.

Present ATC system loading is well within the traffic capacity of DABS and some excess uplink capacity can be utilized by repeating uplink messages. This type of strategy must be optional depending on the dynamic work load requirements of the interrogator, but it will rarely have to be disabled.

DOWNLINK MODULATION

The present data link requirements require no downlink data transfer other than the data contained in the mode 3/A and C ATCRBS beacon responses, with the exception that 3/A response may be 20 bits. The uplink data transfer requirements place an implicit requirement for data receipt acknowledgement. These requirements provide no impetus for major changes to the present downlink format. In particular the following recommendations are made:

1. Maintain pulse spacing, amplitude, and modulation as specified in the ATCRBS National Standard[3].

2. If additional bits must be added, the current pulse spacing should be maintained and the bits added after the second framing pulse in such a way that the SPI pulse appears in the third added bit position. For the DABS experimental design, which will be operating in an all ATCRBS environment, it will be sufficient to maintain a 12 bit, 4096 discrete codes, aircraft ID. This will allow use of the ATCRBS downlink with no modification at all.

3. Three message response formats are recommended.

   a. 3/A response: This mode can be made compatible with ATCRBS by assigning all DABS aircraft ID codes with at least one non zero bit in the last 8.

   b. C response: ATCRBS format is acceptable. The additional data bits may be used for parity in DABS.

   c. DABS data link command response: This mode is in response to accepted command messages. The 12 bit message size allows error checking by an echo of the 6 bit data link command identifier and any 4 bit maneuver commands. Additional bits could be check digits based on the aircraft ID.

DOWNLINK CODING

None of the downlink messages require unusually low error probabilities. The principal effect of a downlink error will be to force the repetition of the uplink message which caused the incorrect reply. In almost all cases an incorrect downlink message can be rejected on the basis of message content when a target track exists. Also a large majority of both noise and garble errors can be detected by analog pulse discrimination hardware in the receiver. The test facility can be used for experimental evaluation and design of hardware for garble discrimination. Its usefulness for this purpose will be somewhat limited because the high traffic density environment in which DABS will have to operate cannot be easily generated experimentally.

Since the track initiation process will account for a relatively small part of system traffic load, it appears reasonable to handle its relatively tight error performance requirements by use of repeated interrogations and repeated responses.

The addition of parity check digits to the downlink message would have two possible effects. With additional hardware, the check digits could be used to test for undetected garbling, or to correct digits known or suspected to be garbled. In terms of overall system performance both techniques for using the parity checks will decrease computer loading and interrogator repeat requirements. When the system is not overloaded, the check digits will have minimal effect on system error performance since excess capacity can be used for interrogation repeats. There is no basis for the evaluation of these effects without a computer simulation; the minimal design, without parity, has been assumed as a baseline. The effect of this decision is to decrease the test bed traffic capacity.

DABS TRAFFIC CAPACITY AND SYSTEM COMPATIBILITY

For a DABS system with the modulation format described in the third section the traffic capacity will be determined primarily by the scheduling algorithm. One of many possible scheduling algorithms is presented in Appendix B. This algorithm was recommended in Reference 4. By using this scheduling algorithm with different parameters and with slight modifications to the operational control procedures, there are several different levels of traffic capacity which can be achieved with the same DABS hardware. At each increasing traffic capacity level there will be a decreasing degree of compatibility between the DABS and ATCRBS systems. Since the different system traffic capacity levels differ only in software algorithms, it is reasonable to expect that all of them could be in use in an ATC system at the same time. The DABS interrogator in any area could preempt only that part of the channel capacity which it needs to perform its function. Only in the higher traffic density regions would the ATCRBS interrogator users need to have their equipment modified. The different system levels are described below.

If the DABS interrogator transmits only one interrogation per PRF period, the DABS interrogator will degrade ATCRBS performance no more than if it were an ATCRBS interrogator. This type of system has the two disadvantages that it does not improve the fruit environment seen by the ATCRBS interrogators, and its traffic capacity is even lower than ATCRBS. Nevertheless, in low traffic density environments this type of system provides the DABS data link services and can provide more complete automation of the tracking function than a conventional ATCRBS based system can, because of the unique identity data and the possibility of automated control functions through the data link function. When aircraft traffic is within the capacity of this type of system, there is no need to consider the more difficult to implement, higher capacity, systems.

The scheduling procedure described above can be considered to be a degenerate form of the ring scheduler in which one ring extends for the full range of the interrogator. The traffic capacity of the system described above can be increased by using smaller ring sizes so that larger numbers of interrogation time slots will be used. When this type of scheduler is used, the degradation to ATCRBS performance will be proportional to the number of time slots used by DABS. When the maximum number of time slots, described in the appendix, is reached, the DABS will essentially lock out the ATCRBS system in any region where DABS main-lobe or side-lobe transmitted energy is high. This will be done by suppressing the response of ATCRBS transponders to legal ATCRBS interrogations. It may be possible to control this type of interaction by having the DABS and ATCRBS antennas rotate at significantly different speeds, or by providing groups of unused PRF periods in the DABS schedule. In this type of system it is assumed that the DABS equipped aircraft will respond to all legal ATCRBS interrogations.

The highest traffic density can be achieved if DABS equipped aircraft do not respond to ATCRBS interrogations when they are being tracked by a DABS interrogator. This is described in the section on transponders. This will increase system capacity by eliminating garble transmission from DABS transponders. When most aircraft are DABS equipped, this will represent a major improvement in the garble environment. This type of system is ATCRBS compatible in only a limited sense. ATCRBS interrogators in the vicinity of a DABS interrogator will not be able to track any DABS aircraft. This will to some extent eliminate the benefits of using the ATCRBS interrogator unless it is being used to track aircraft which are known not to be DABS equipped, or it is being used to fill DABS blind spots. Control centers making use of data derived by ATCRBS interrogators will have to have a digital data link to any DABS interrogators in their control area to receive data on DABS targets.

TRAFFIC CAPACITY

Only rotating antenna interrogators are considered in this section. Traffic capacity is dependent on the spatial distribution of aircraft. If aircraft are uniformly spatially distributed, the rotating antenna interrogator has the same traffic capacity as a phased array interrogator, this capacity will upper bound the possible DABS capacity. Traffic capacity can be lower bounded by assuming that all aircraft are in the neighborhood of a single point. This appears to be an unreasonable spatial distribution for any medium or high traffic density area. A more reasonable low limit for traffic capacity might be generated by assuming that aircraft are uniformly distributed along a single line. In this case interrogator placement will strongly affect the capacity.

The required tracking accuracy, and aircraft maneuvers which can be expected, are the principal factors which impact antenna rotation speed. All other things being constant, track capacity will be linearly dependent on rotation speed. For the tight accuracy requirement of the DABS system, track drop will not be a problem as long as the system is operating correctly and the aircraft is responding to interrogations. The track

DABS SUB-SYSTEMS

TRANSPONDER

A block diagram of a transponder is shown in Figure 2. The primary difference between the DABS receiver and the ATCRBS receiver is that DABS will require somewhat tighter frequency tolerances for its binary phase modulated signalling. Frequency accuracy of ± .5 MHz will provide negligible degradation of performance in a DABS receiver with 250 µs signal bit duration. The receiver may not be hard limiting because the pulse amplitude data is used to detect signal arrival and generate the word sync for the decoder.

Altitude encoding is assumed to be identical to the present ATCRBS encoding. Identity is assumed to be hardwired. The nature of the data entry and display device will depend on the details of ATC procedures.

It is recommended that the transponder have two modes: a search mode and a track mode. In the track mode the transponder replies only to discretely addressed messages. In the

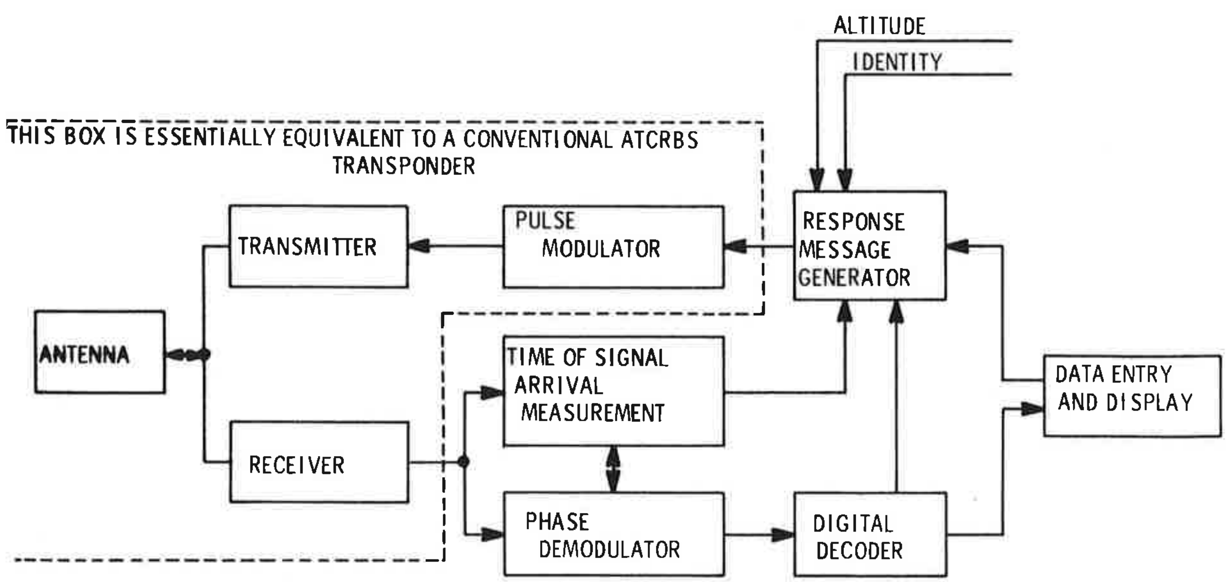


Figure 2. Transponder Block Diagram

search mode the transponder replies to a search message. The search message can be either a dummy address in the standard DABS format, or an ATCRBS mode 3/A interrogation. If a DABS transponder is in the track mode and it has not been interrogated for a preset time period, it must revert to the search mode.

If the DABS system must be compatible with the ATCRBS system in the sense that aircraft which are tracked by DABS must be simultaneously tracked by ATCRBS interrogators then the ATCRBS mode can not be disabled. During early stages of DABS implementation this will have little effect on DABS performance since the number of DABS users will be much smaller than the number of ATCRBS users. During the later stages of system evolution the aircraft traffic density will increase beyond ATCRBS capacity and this unnecessary use of the ATCRBS mode will be the principal limitation on system performance. Use of modes other than 3/A or C to which DABS aircraft respond will not have as serious an effect on the garble environment.

INTERROGATOR

A block diagram of the interrogator sub-system is shown in Figure 3. This block diagram assumes the use of a rotating reflector antenna.

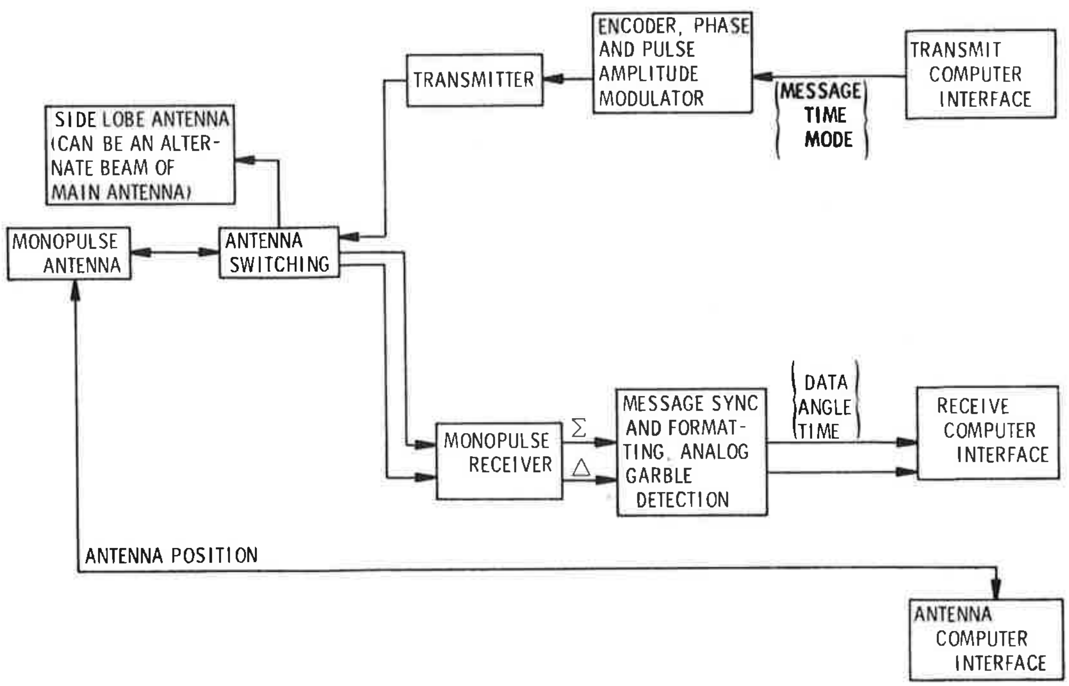


Figure 3. Interrogator Sub-System for Mechanically Rotating Antenna

The modulator must be capable of generation of both the on/off keyed ATCRBS and the combined on/off keyed and phase modulated DABS waveforms. For the present discussion it has been assumed that spurious signals generated by the transmitter in the receive band will prevent receiver operation. If spurious signal levels are low, the scheduling strategy may be designed so that the receiver operates simultaneously with the transmitter. This will increase system traffic capacity by approximately 50%.

In the DABS system approximate target range is usually known. It therefore becomes possible to set transmitter power as required for each target. The inclusion of this added complexity depends on a cost and reliability analysis for the resultant system. In any case power reduction for near targets will have a significant effect on uplink garble problems in multiple interrogator environments. The garble effects can only be adequately determined by a detailed computer simulation.

The side-lobe suppression antenna is used only in the ATCRBS mode. In the DABS mode the SLS pulse is transmitted on the main beam. Since monopulse is required, the most economical realization of an SLS antenna may be the use of the monopulse difference beam.

The receiver for the DABS and ATCRBS modes will be identical and discrimination between the two types of signals will be made by computer software. The receiver should provide for garble discrimination consistent with the performance of current ATCRBS receivers. The monopulse receiver must generate an independent arrival angle estimate for each detected bit (pulse) in the received data stream. In an operational DABS system a relatively complex digital signal processor would have to be considered for the detection of full transponder replies, and for garble detection. For an experimental system in an RFI environment which does not approach the density of the operational environment it appears that a simple shift register decoder with pulse shape discrimination will be adequate. Alternatively, a dedicated high speed minicomputer with a small amount of specialized signal processing hardware may be able to perform the full signal discrimination function without excessive hardware development costs.

INTERROGATOR TO COMPUTER INTERFACE

The computer generates interrogator schedules and messages and performs some of the detection signal processing function. The data items which must be transferred over this interface are listed below.

Interrogator Schedule

One data item is a message (50 data bits) and its transmission time. For the scheduling algorithm currently being proposed transmission time is specified in 25 μs increments but two messages must be at least 50 μs apart. Two additional bits to select ATCRBS 3/A or C or DABS mode are required. Transmission power may be optionally selected by additional interface bits.

Received Data

One data item is time of arrival, quantized in 100 μs increments, message contents (22 bits including SPI and X pulses), and monopulse offset angles.

Antenna Control Data

For a rotating antenna system this can be either the current NAS type azimuth change and mark pulses or a parallel transfer of measured data.

For a phased array antenna the beam switching characteristics determine the data transfer format. A fast switching array (<<50μs) can have beam position as an additional word in the interrogator schedule described above. For slower switching arrays, beam switching will preempt transmission and reception time slots and must be considered as a different type of scheduled event. Scheduling algorithms for phased array interrogators have not been considered in this report.

Interface Timing

Typically all of the data transfers described above will occur at rates bounded above by the interrogation rate of the DABS system, or approximately 50 μs per transfer. It is not expected that the interrogator will provide any data buffering other than the one message buffer required for precision timing. This will require interrupt service times in the 5 to 25 μs area.

COMPUTER SUB-SYSTEM

Figure 4 shows the basic computer algorithm and table

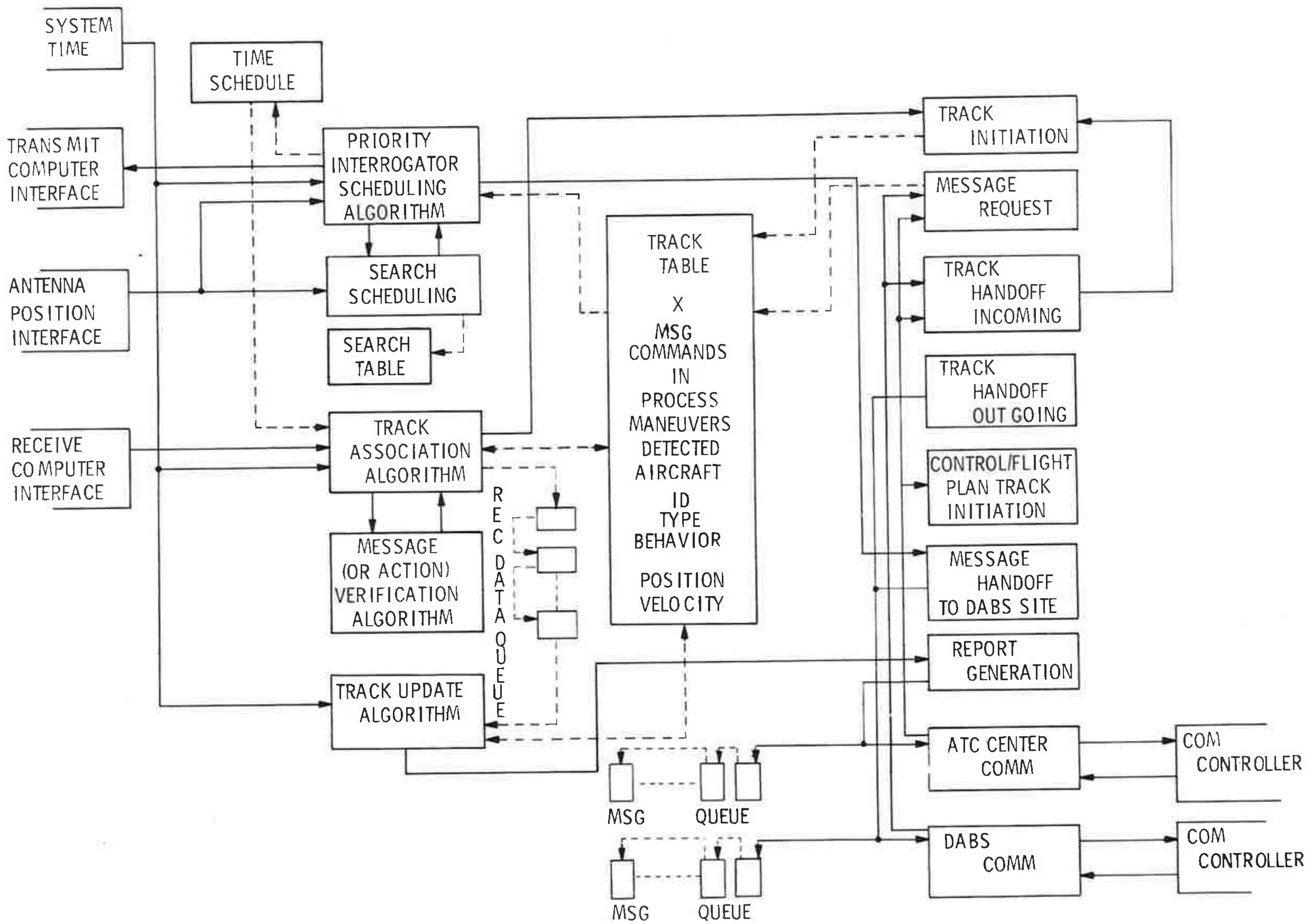


Figure 4. Computer Algorithm Interaction and Tables

interaction.

The computer system is subject to several important trade-off studies. The most critical of these studies will be involved with the scheduling, detection, tracking and track data association algorithms. Several of these problem areas are described below.

The interrogator scheduling algorithm is critical for determining system behavior; several alternative approaches exist and must be examined. It is expected that scheduling will be a major consumer of computer time and that careful study will be economically worthwhile. Signal detection and track association algorithms also may contribute significantly to system loading and clearly effect overall performance. Study to determine the correct hardware/software split and to select reasonable compromise algorithms is required.

The track table appears to be the most significant consumer of storage space. Several hundred bits per aircraft track will be required. With track loads which could reach several thousand this will be a significant problem.

Some approaches to a few of the basic software algorithms are presented in Appendix B.

FUTURE WORK

The design of the DABS system is closely interlocked with the design of the entire upgraded third generation ATC system. The function of this paper has been to describe a test design which can be used to verify the feasibility and performance of proposed hardware designs, and of different modulation and coding techniques. For this reason, only the basic system design features have been considered in detail.

The dense traffic environment in which the DABS system must operate does not at present exist. The ATCRBS environment in which the test facility will exist can not approximate the RFI environment that will exist during the introduction of the DABS system on a large scale. It therefore seems most practical to construct only the simplest type of system described in the fourth section. This type of system will provide experimental verification of the hardware performance. It will not provide a significant amount of information about the performance or feasibility of the high traffic capacity DABS systems.

The important technical questions about DABS to which answers are not yet available are involved with how to design, build, and optimize it for use in a very high traffic environment. The following technical studies are required in order to design a DABS system of the type discussed in this report, if it is expected to operate in a high traffic density area.

A computer simulation is required to verify the garble performance and traffic capacity of the system presented here. This simulation must include the details of the scheduling algorithm and of the interaction between several interrogators. Appendix C describes the simulation in greater detail.

Studies of alternative scheduling algorithms, and of combined scheduling of multiple geographically separated interrogators should be performed when the exact antenna parameters and switching performance are known.

For the construction of a minimum cost experimental design the present level of modulation and coding analysis appears to be adequate; for an operational system much more study would be required.

Testbed software will not require the extensive ground ATC communication facilities, self checking and monitoring, and gradual failure characteristics that the operational system must have. There will still be a significant effort required for selection and programming of the detection, search, tracking, and message repeat processes that are required to provide the skeleton of an operational system.

It is envisioned that the development of low cost hardware designs for the transponders will be one of the principal results of the test program. This will have to be the result of a continuing effort.

APPENDIX A

CODING FOR THE DABS DATA LINK

INTRODUCTION

In this appendix the coding requirements for the DABS data link will be discussed, and the rationale used to select the baseline coding scheme for the testbed will be presented. To place the role of coding in its proper perspective, the DABS radio environment will be discussed first. Next, the interaction of the recommended modulation waveforms and the interference environment will be discussed. Following this, strategies for providing the required level of reliable data communication will be outlined including their performance and their suitability for the DABS data link. Finally a baseline coding scheme will be described.

CHANNEL ENVIRONMENT

At the initial introduction of DABS into the ATC system the interference environment will be essentially that of the ATCRBS system. This is the worst environment in which DABS will operate. As DABS transponders and interrogators become more common and eventually supplant ATCRBS, the radio channel environment should improve, or at least not get worse, if the DABS system is well-designed and planes' interrogations and replies are properly scheduled. Therefore, as a worst case, the ATCRBS radio environment at the time of DABS introduction is assumed.

The characterization of the DABS radio channel environment will be divided into separate uplink and downlink analyses. The uplink channel is assumed to have an inherently high average signal-to-noise ratio, but it is subject to burst interference caused by ATCRBS interrogators. The statistics of these interference bursts depends on the number, placement, and relative PRF's of the ATCRBS interrogators as well as the mode of interrogation (e.g. I.D., Altitude). The downlink channel is also assumed to have a high average SNR with interference bursts caused by the ATCRBS transponder replies. The statistics of these bursts depend on both interrogator parameters and the number of transponders and their data format; in general the burst error statistics will be worse than for the uplink. How the characteristics of these radio channels affect data link performance depends of course on the form of modulation and receiver structures used.

CHANNEL MODEL

The channel model includes both the effects of modulation and the interference environment, and therefore characterizes the overall effect on transmitted data symbols. The data is assumed to be binary encoded and modulated. Three basic types of modulation were considered; PAM (on-off keying), PSK (bi-phase modulation), and FSK. It was recommended in the body of this report that PSK be used on the uplink and on-off keying on the downlink. We shall consider the implications of these two recommendations on the channel model. Since the ATCRBS interrogation waveform is on-off modulated, the effect on PSK modulated DABS uplink is to add bias to the detected output. For small interrogation pulse amplitudes the effect is to decrease the effective SNR at the detected output. However, as the interfering interrogator pulse amplitude increases, the background noise pulse interference causes the detection threshold to be consistently exceeded, generating bursts of errors. On the downlink since both the ATCRBS and DABS transponders use on-off keying, the problem is aggravated by the indistinguishibility of signal and interference and non-optimality of the waveform. Therefore, as with the uplink channel, the downlink channel will exhibit error bursts, but they will be considerably more frequent that on the uplink. Given these channel error models, possible methods for providing the required data link performance will be discussed next.

DABS ERROR CONTROL

In this section, the possible methods of error control for the DABS data link will be discussed. The trade-offs between the use of various receiver demodulator realizations and coding will be presented.

The DABS data link requirements are dictated both by ATCRBS compatibility and its proposed functional use. The constraints force the data uplink to operate in 25 μsec. transmission bursts during which time 50 bits of information must be conveyed with an extremely low probability of undetected error in certain modes. This severe error rate requirement demands the use of some form of coding. There are three general types of coding strategies possible: 1) error correction; 2) erasure correction (i.e. position of likely errors determined by detection hardware before correction by the decoder); 3) error detection with feedback (utilizing a feedback channel to initiate retransmission). In conjunction with these coding techniques, various demodulator options can be used. For example, interference and garble detection can be accomplished by pulse shape discrimination. Also various parameters can be measured from the received signal and used as a measure of interference level. The outputs of simple circuitry of this type can be used for erasure detection or burst error detection along with an appropriate decoding method to improve data link performance.

In choosing an appropriate form of error control for DABS, the following rationale was adapted:

1. Do not choose an error control technique which places the burden of cost and complexity on the airborne transponder. The techniques have been designed for an environment which will improve or at least change its character drastically as time goes on. The airborne transponder appears in by far the largest number of all the system elements.

2. Place the burden on the ground processing; namely the scheduling and interrogation control algorithms. These elements can be modified most easily.

3. Because the DABS system constrains us to transmit in bursts we can not efficiently utilize the long term statistical behavior indicated by our channel model. This means in effect that sophisticated techniques using complicated burst correcting codes and burst interleaving hardware will not allow us to reach capacity of this burst channel.

4. Incorporate as much flexibility as possible into the error control techniques chosen for the testbed configuration.

Applying this rationale, error detection, with feedback initiated message repeats (i.e. automatic repeat request) has been chosen as a baseline for the data uplink. On the downlink interference garble detection circuitry, with no coding, is the proposed baseline. This does not exclude the possibility of testing simple interference monitoring equipment on the uplink and possibly coding (e.g. erasure correction) on the downlink depending on the performance of the baseline configuration.

On the uplink, a rate 1/2 block code is proposed (50 information bits, 49 parity bits) with airborne error detection. As a rule of thumb, it takes about twice as many parity checks for error correction as error detection. Also it can be seen that the error patterns which will go undetected are those which transform the transmitted symbols into another legitimate codeword; this can be made an extremely unlikely event. In the case of error correction, however, the error performance depends much more strongly on the detailed nature of the code and decoding method. The proposed DABS concept has the required data link and processing capacity to support the chosen message repeat strategy.

The specific coding chosen is a rate 1/2 truncated BCH (127,78) cyclic code. The encoder and decoder for a cyclic code is easily constructed from a feedback shift register. The feedback shift register is shown in Figure A-1. The shift register tap connections are specified as the coefficients of the connection polynomial $g(x) = g_0+g_1x+g_2x^2+...+g_{49}x^{49}$ or as a vector $g = (g_0, g_1 ..., g_{49})$ and are either zero or one.

In this particular case 49 shift register stages are required and g(x) is specified in Figure A-1. The feedback shift register encoder realization is quite general and allows the specification of an arbitrary cyclic code with less than 50 parity bits. This suggests that for the testbed it may be reasonable to have the taps programmed or at least manually switchable.

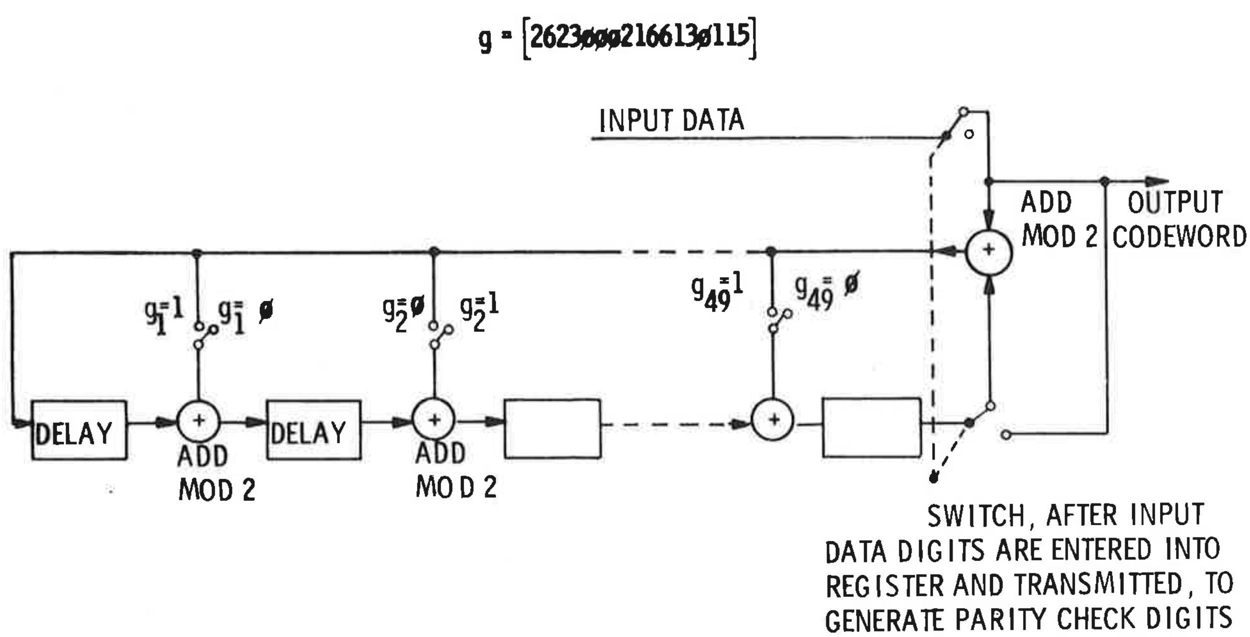


Figure A-1. Shift Register Encoder

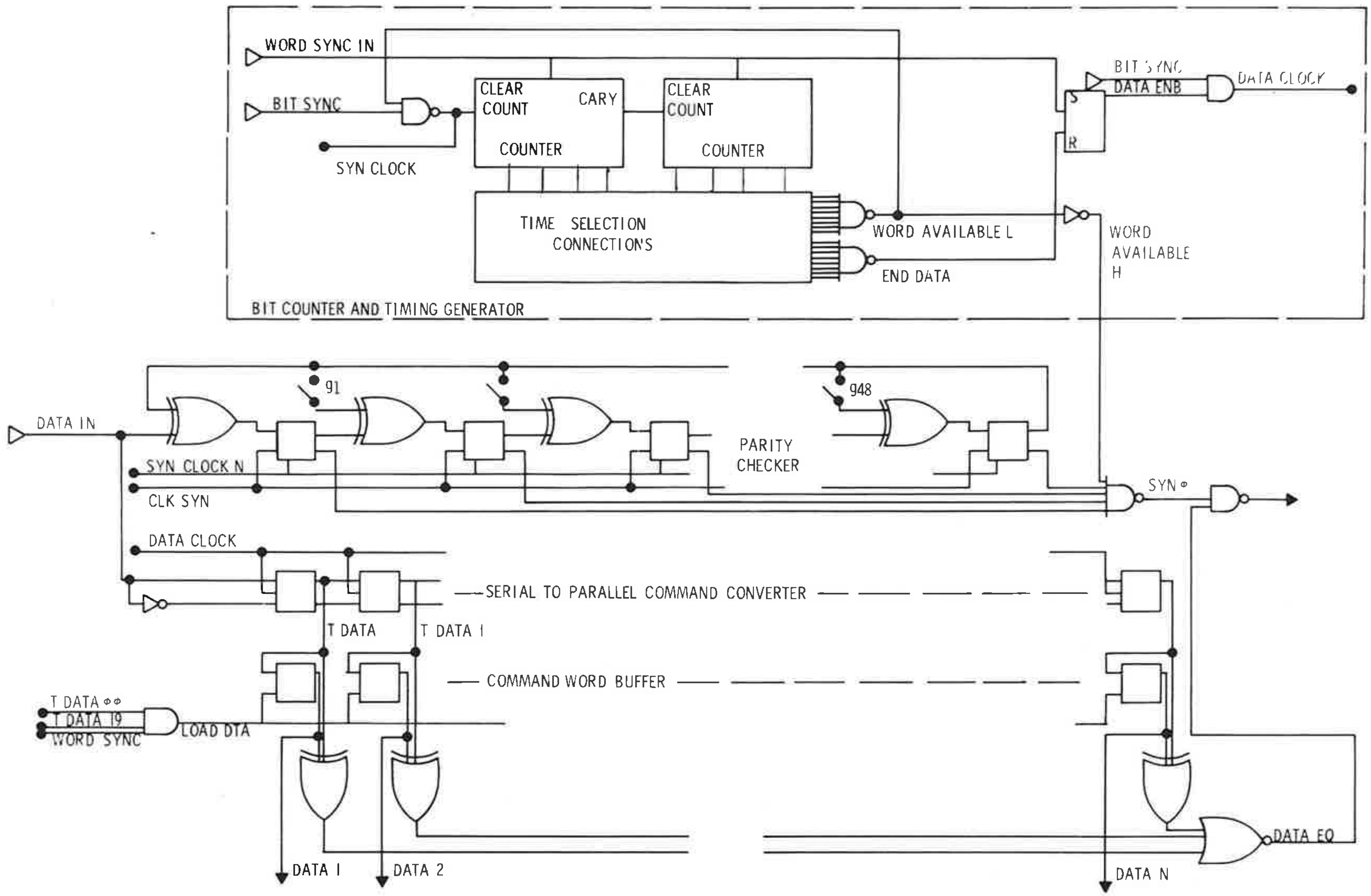


Figure A-2. Decoder, Parallel Data Output

APPENDIX B

COMPUTER ALGORITHMS

INTRODUCTION

The interrogation scheduling algorithm is the least well defined element of the DABS software. One of several possible candidate approaches is described in Interrogator Time Slot Scheduling. This technique described in the following paragraph was proposed in Reference 2. The algorithm is proposed for use in an experimental design because it is one of the simplest which can provide the full scheduling capabilities required by the DABS system. It is expected that with more complex scheduling procedures a more efficient schedule can be generated. No phased array scheduling procedures are presented here. There appear to be no general rules for design of phased array schedules which are independent of antenna properties.

A few flow charts are presented for some of the data processing algorithms in order to give some idea of the complexity of the data processing function.

INTERROGATOR TIME SLOT SCHEDULING

A relatively simple procedure for interrogator scheduling is presented in this section. This type of scheduler organization generates a burst of several interrogations during which no data is received, followed by a receive period in which no data is transmitted. The first interrogation is for the longest range target, the last interrogation is for the nearest target. The entire time frame for receive and transmit is approximately equal to a conventional beacon system PRF period. This procedure has several convenient properties. It can generate a constant PRF period interrogation system even though dynamic scheduling is used. This is convenient if it is desired to interlock the transmit times of ATCRBS and DABS interrogators in contiguous areas. If interrogator power is made proportional to aircraft range, this type of scheduler will guarantee a reasonable distribution of interrogation powers during each period, rather than allowing several to be at peak power.

The scheduler discussed here is a slightly modified form of the range ring scheduling algorithm. A range ring is an annulus of inner radius R and thickness d. The ring scheduler described here uses two PRF periods to cover the entire track volumes. During each period, it attempts to interrogate the highest priority target in either every odd or every even numbered range ring.

Selection of the DABS search mode, or discretely addressed mode, is on a priority basis. A search interrogation will preempt an entire PRF period of the interrogator whenever the search priority exceeds the sum of the priorities of the discretely addressed targets in the competing discretely addressed interrogator schedule.

Interrogation time slots are 35 to 40 μs. This allows 25 μs for transmission and 10 to 15 μs for ATCRBS transponder recovery so that replies from non-DABS aircraft can be suppressed. All interrogations to be made during one PRF period are transmitted in one burst, followed by a single receive period. A modified ring algorithm is proposed.

The receive time slot for ring scheduling must be:

$$\tau_s = \tau_m + \frac{2d}{c} + \frac{n\sigma_t}{c}$$

long where: τ_s is slot length
d is ring thickness
σ_t is track standard deviation
n is between 4 and 8
τ_m is aircraft response duration

Assuming response durations of 36 μs, and track standard deviation of 500 ft. this yields

$$\tau_s \simeq (12d + 40)\,\mu s$$

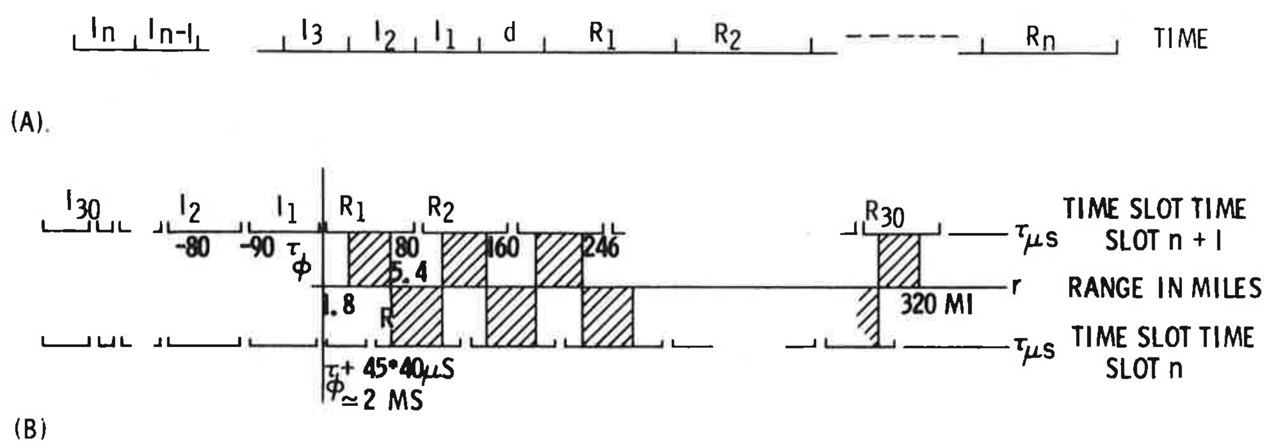
where d is in miles.

For an M time slot system, the time sequence at the antenna appears as shown in Figure B-1. In that figure, d refers to a dead time of duration τ_d. Then maximum range is

$$R \simeq (\tau_d + M\tau_s - 22\mu s)c$$

and for beacon system design, the optional value of d must be selected to maximize the average number of interrogations per second. When d is large, slots tend to be full but there are few slots; when d is small, slots are empty but there are many slots. There are, of course, an infinite variety of schemes for filling empty slots.

A simple baseline scheme is as follows: Select τ_s = 80 μs so that d is about 3 1/2 miles then two successive PRF periods with τ_d respectively. 0 and 40 μs will cover the entire volume once. Then, whenever two adjacent cells are empty, a target from the alternating range cell group can be interrogated. This



(A) SINGLE FRAME TIME SLOTS

I_n IS THE nTH TRANSMISSION

R_n IS THE CORRESPONDING REPLY PERIOD

(B) TWO SUCCESSIVE TIME FRAMES, SHOWING ALLOWABLE TARGET POSITIONS FOR EACH TIME SLOT BY SHADING

Figure B-1. Interrogator Time Frame Description

is shown in Figure B-1.

If only a small number of ATCRBS targets are present, then DABS and ATCRBS modes can be mixed on an interrogation. Use of the ATCRBS identity reporting mode for DABS search will facilitate mixing the two systems.

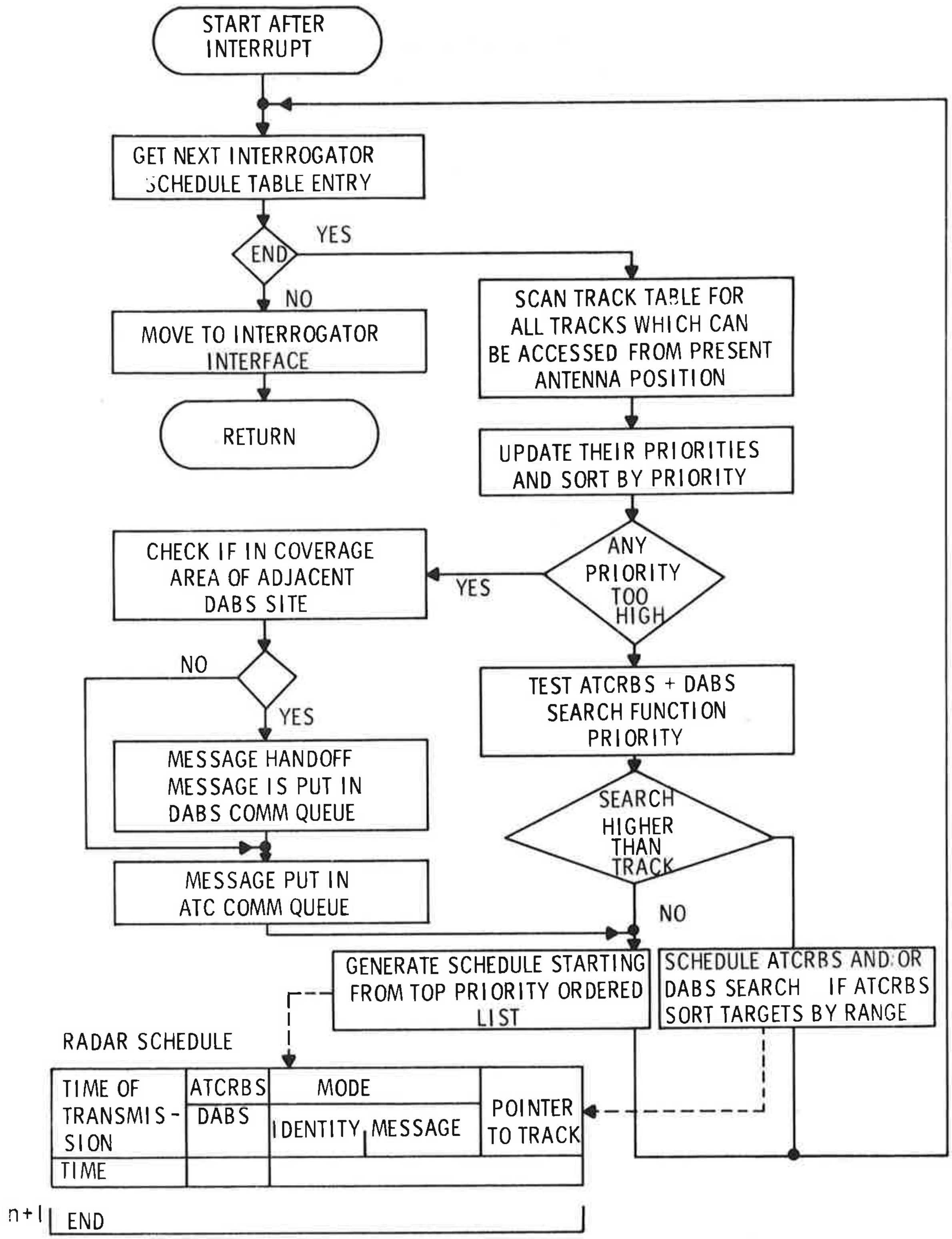


Figure B-2. Interrogator Scheduling Algorithm

APPENDIX C

COMPUTER SIMULATION

A computer simulation of the DABS system is a basic design tool. Simulation is required for the following purposes:

1. To allow the empirical design and optimization of scheduling algorithms.

2. To determine the number of garbled responses which can be expected by a DABS receiver and, consequently, to allow the evaluation of error correcting codes, and relatively complex garble resolution hardware.

3. To determine the number of fruit returns accepted by the primary track association algorithm. To allow the verification of estimated computer loading due to additional processing of fruit returns, and to evaluate the need for, and the performance of, more selective track association procedures.

4. To determine the number of re-interrogations which are caused by garbling on either the up or downlink. This analysis should also provide data for the evaluation of system response time under various load conditions in order to verify overall system performance.

5. To allow the evaluation of the interaction of a DABS site with neighboring ATCRBS interrogators. This should allow the selection of procedures such as synchronizing PRF rates, controlled offsets of PRF rates, randomized PRF rates, inhibiting PRF periods, and preprogrammed rather than priority scheduled search mode interrogations.

6. To evaluate the effect of antenna beamwidth on system traffic capacity.

7. To provide statistical data for the analytic evaluation of actual system error performance.

In order to perform these functions in a meaningful manner, the simulation must approximate conditions under which at least several hundred aircraft are in the DABS coverage area. There appears to be no need to simulate more than a few interrogator beam widths of angular coverage, or to simulate aircraft attitude. Aircraft position must be simulated if track association algorithm, and fruit performance are to be evaluated.

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4. Technical Development Plan For A Discrete Address Beacon System, FAA, October 1971.