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TIME/FREQUENCY SYSTEMS

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16. Abstract This report summarizes the work performed at DOT/TSC on the Time/Frequency ATC System study project. Principal emphasis in this report is given to the evaluation and analysis of the technological risk areas. A survey and description of proposed T/F system is included. The technical risk areas include the effects of multipath on signalling over radio links. Material is presented which bears on the comparative analysis of T/F with alternative technologies, including satellite and beacon-based system concepts. It is concluded that the most critical problem areas requiring further study are (a) multipath effects on T/F systems, and (b) systems operability under non-ideal conditions leading to graceful degradability.			
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1. INTRODUCTION

This interim report presents the results to date on the Time/Frequency Systems study defined by Project Plan Agreement FA10. Due to cancellation of funding near the end of FY71 it will not be possible to carry the investigation to the technical depth we would prefer, and *a fortiori* impossible to present conclusions and recommendations in as polished and well documented a form as would be desirable. Since this interim report is in a necessary sense also a final report, we have not hesitated to express our best current engineering judgment on some matters which would normally have been reserved for later reports.

We make no attempt to have this report be a comprehensive treatment of T/F. Rather, we build on previous work as much as possible, discussing it only to the extent necessary to make it relevant to the current project, and providing a bibliography for further information. As one of our tasks we conducted an investigation of significant past and current work in T/F; these results are discussed in the third section. As requested by the FAA, we have given special emphasis to the study carried out by Autonetics, "An Analysis of an Advanced Time-Frequency National Air Space System Concept" (Ref 1). In studying past work we have had a problem of where to draw the line, since there have been many T/F systems studied and proposed and many reports written (150 reports on PLRACTA alone, Ref 9). With the limited manpower and time available, we decided to concentrate on those systems that have actually been implemented, in addition to the Autonetics study. We were also concerned primarily with "control" systems, and considered time service systems as an overlapping but essentially separate activity, despite the importance of the interface between these two activities.

Multipath is a potential problem in all ATC communication systems. In the fourth section we discuss this problem along with the existing multipath data base. In section 5, data is given which bears on the comparison of the T/F with superbeacon and satellite system, as envisaged by the "white paper" task that was later added to the Program Plan Agreement. The final section contains conclusions and recommendations.

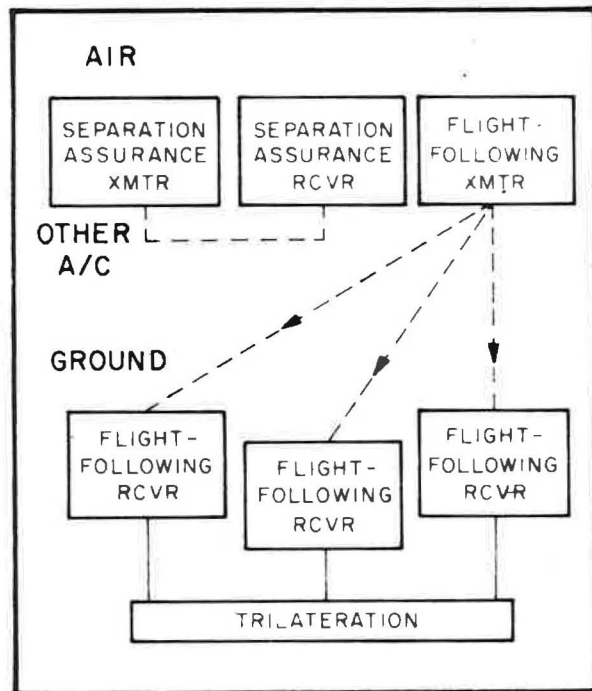
2. TIME/FREQUENCY AND AIR TRAFFIC CONTROL

DEFINITION OF T/F

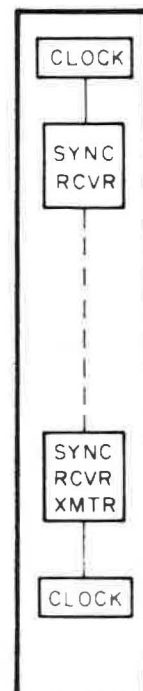
"Time/frequency" (T/F) has been commonly used to refer to a technology which uses precisely synchronized, physically separated clocks, controlled to a common frequency and phase. One-way ranging between stations can be performed by measuring the time lag between scheduled transmission time and time of arrival. One-way doppler frequency measurements can be made from a comparison between the received and reference frequencies, providing a method for determining closing speeds between stations. Data communication among stations can be provided by time-division and frequency-division multiplexing in a natural way by assigning users unique time/frequency slots. These techniques can be applied directly to ATC functions. The term "time-ordered" is often used interchangeably with T/F. Finally, "T/F system" will be taken to mean a system which utilizes T/F techniques.

Precise definitions of time/frequency are customarily not stated, or if stated, are not always followed. In this report we use the term rather broadly to refer to use of precise time or frequency either on the ground, in the aircraft, or both, to assist in any of the measurement or communication functions which must be performed by an Air Traffic Control (ATC) system. Examples of operational T/F systems are the McDonnell-Douglas EROS collision avoidance system (CAS) and the military station keeping systems which are used for precise control of aircraft spacing within groups. However, our meaning of T/F is not restricted to the conventional meaning of revolutionary complex, expensive systems. We wish to allow for the use of T/F in very modest ways, possibly employing "cheap" clocks and utilizing T/F in an evolutionary way in one or more of the ATC functions. An example of the use of T/F in an ATC system is shown in Figure 1, taken from an appendix to the ATCAC report (Ref 6). Here, four major functions are identified: separation assurance, consisting of airborne CAS and flight following; time synchronization of the clocks; communications; and navigation. In this report we have considered the use of T/F for a new ATC system (Fourth Generation) as well as for an evolutionary application to the Third Generation system.

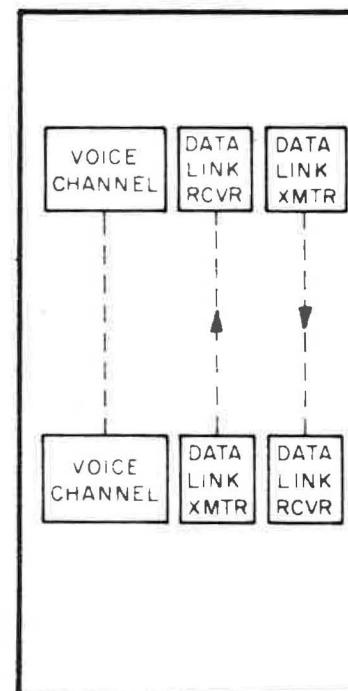
SEPARATION ASSURANCE



TIME SYNCHRONIZATION



COMMUNICATIONS



NAVIGATION

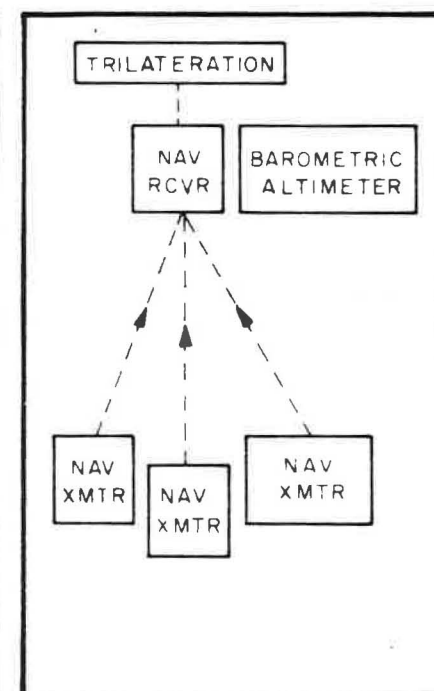


Figure 1. Block Diagram of ATC System Functions in T/F Environment

In the next sections, the relationship between T/F and ATC system functions is presented, and a hierarchy of T/F systems is defined.

ATC SYSTEM FUNCTIONAL DESCRIPTION

The following functional description of the ATC system is particularly well-suited to the study of T/F. The background data for this description has been assembled from the ATCAC report (Ref 6) and other relevant sources of information including FAA reports, contractor studies, private communication with individuals at FAA and TSC and individuals outside the civil government including the military and private industry.

In order for an ATC system to perform its basic functions a fundamental set of data is required both in the aircraft and on the ground. It is convenient to consider the data gathering and data using aspects of the ground traffic control center and airborne user as separate subsystems: the Data Acquisition Subsystem (DAS) and the Data Processing Subsystem (DPS), respectively. This view of the ATC system is shown in Figure 2. Note the duality between ground and airborne ATC elements. The view of ATC is not new since the present ARTS and NAS Enroute system descriptions essentially follow this format; moreover, their data processing subsystems may be adequate or expandable to act as the DPS for an entirely new DAS. Examples of typical airborne elements are shown in Figure 3 for third generation ATC.

T/F techniques apply primarily to DAS functions. We concentrate attention on the ground and airborne DAS and the role which T/F based subsystems can play in the DAS, as discussed further in the next section. In this spirit, we identify the functions which the DAS may be expected to perform in future ATC systems. This is not a list of hardware or software modules, only of functional requirements.

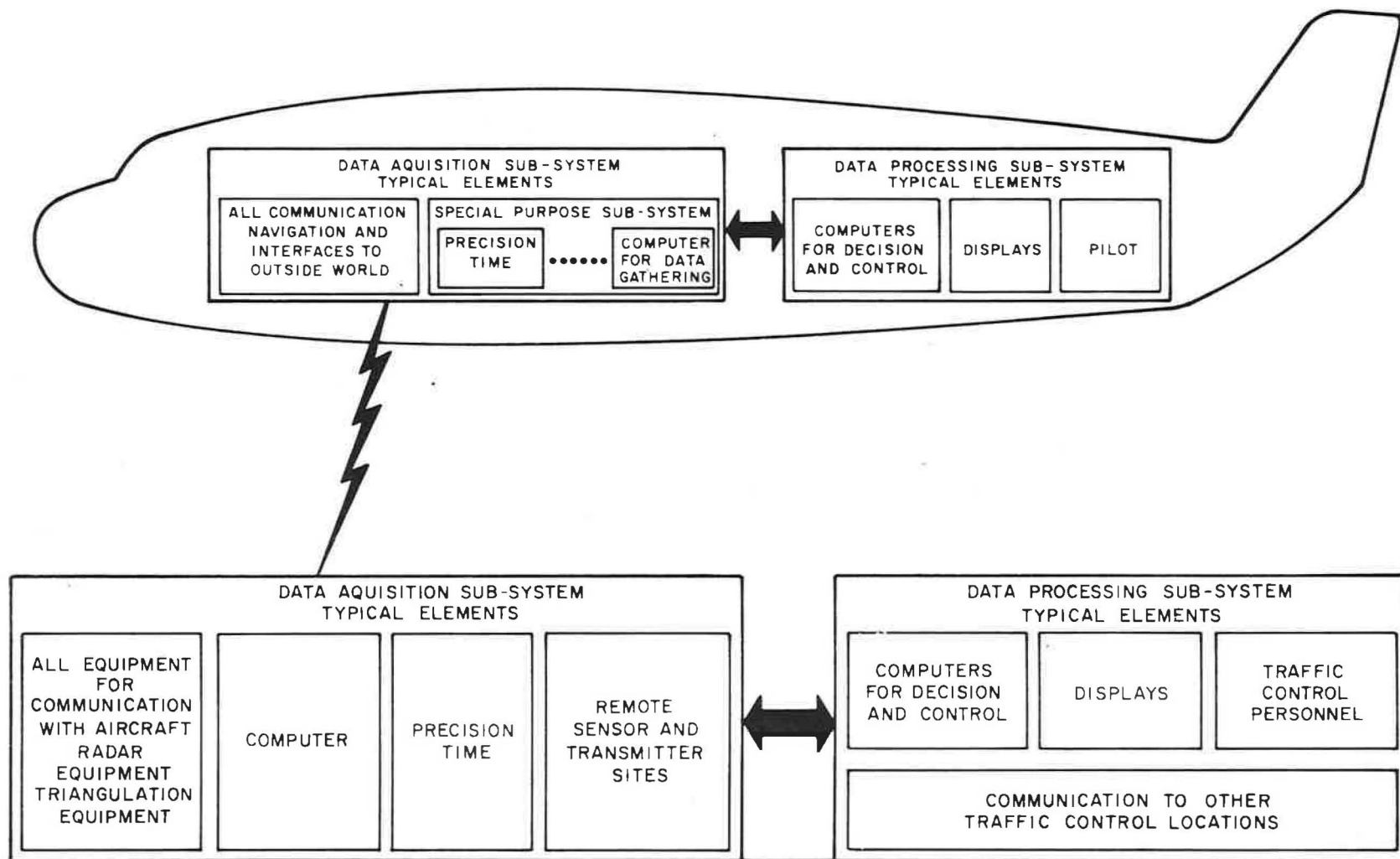


Figure 2. AIC Functional Description

AIR CARRIER		GENERAL AVIATION	
DAS	DPS	DAS	DPS
• VHF/FM VOICE LINK	• PILOT	• VHF/FM VOICE LINK	• PILOT
• ENCODING ALTIMETER	• DISPLAYS	• ALTIMETER	• INDICATORS
• TRANSPONDER	• COMPUTER FOR	• TRANSPONDER	
• VOR RECEIVERS	DECISION MAKING	(OPTIONAL)	
• DME RECEIVERS	AND AIRCRAFT	• VOR RECEIVER	
• COMPUTER FOR DATA	CONTROL FUNCTIONS	(OPTIONAL)	
GATHERING (OPTIONAL)	(OPTIONAL)	• DME RECEIVER	
		(OPTIONAL)	

Figure 3. Typical Air DAS/DPS Configurations (Third Generation)

GROUND DAS

1. Data for surveillance
 - a. aircraft identification
 - b. aircraft status reporting (e.g., altitude and velocity information, status of aircraft systems, emergency conditions)
 - c. detection of non-cooperative aircraft (e.g., primary radar skin return)
2. Data necessary to provide aircraft position and velocity with sufficient accuracy for airspace management including possible flow control and flight monitoring.
3. Measurement of additional data necessary for prediction of potential conflicts.
4. Capability for data exchange
 - a. control functions (e.g. IPC)
 - b. emergency messages
 - c. advisory reports

AIR DAS

1. Data for location determination
2. Data for flight path following
3. Data for collision avoidance
4. Data for landing aids
5. Voice communication
6. Capability for data exchange

- a. receipt of control commands
- b. emergencies
- c. status changes

Given the DAS requirements the criteria for evaluation of acceptability of candidate T/F based DAS subsystems are:

- 1. Performance
 - a. accuracy
 - b. capacity
 - c. signal integrity in RFI and multipath
- 2. Reliability
 - a. failure modes
 - b. modes of degraded operation
 - c. maintainability
- 3. Cost
- 4. Error control
- 5. Spectrum utilization
- 6. Adaptability to needs of each user
- 7. Ability to evolve
- 8. Ease of implementation
- 9. Ground vs. cockpit decision-making.

This evaluation will not in many cases require the selection of numerical requirements but only a statement of performance which can be provided by each candidate. We believe that T/F

technology can provide performance superior to that actually required and that any difficulties will arise primarily from the other evaluation criteria.

DATA ACQUISITION USING PRECISE TIME

In this section we will attempt to classify the bewildering variety of T/F systems which have been proposed as candidates for the DAS function in the ATC system. The only thing that all of these systems have in common is that a precise time standard is used somewhere in each of them. For the purposes of this study, we define T/F Systems to be those systems utilizing precise time to satisfy one or more of the DAS functions of the ATC system. We believe that this definition is consistent with common usage of the term.

ATTRIBUTES OF T/F SYSTEMS

Precise knowledge of time has been recommended as having the capability of improving the ability of a DAS to perform the following activities:

1. Ranging (e.g., one-way ranging)
2. High density multiplexing (time and frequency slotting for interference control and enhanced capacity)
3. Security (e.g., using coding and frequency hop)
4. Efficient spectrum utilization
5. Range rate measurements
6. Possibility of moving control functions from ground to air or air to ground for redundancy and configuration management.
7. Possibility of redundant information and cross-checking
 - a. DME and collision avoidance sharing and referencing
 - b. Time/position duality (i.e., ability to trade time and position data for each other.)

8. Operation outside ground coverage (e.g., airborne systems capable of operating independently of ground control)
9. Broad capability range (i.e., modular, adaptable to user needs)
10. Variable/controllable data rates.

For this list it is clear that T/F Systems are distinguished from other systems by their handling of DAS functions rather than DPS functions.

POSSIBLE T/F CONFIGURATIONS

This section lists the set of proposed T/F configurations by describing the variety of ways in which each of the system constraints (i.e., numbered items) can be satisfied in forming a specific system.

1. Time standard location
 - a. ground only
 - b. air only
 - c. both ground and air
 - d. ground and some aircraft or satellites
 - e. data transponded from satellites
2. Time slot management
 - a. all aircraft transmit simultaneously
 - b. orthogonal time slots assigned to aircraft
 - c. spare time/frequency slots are assigned to control probability of interference
 - d. transponder in aircraft triggered by time ordered interrogation

3. Frequency management
 - a. all users use single frequency
 - b. frequency hop system
 - c. multiple channels dynamically assigned to users
4. Aircraft identification
 - a. derived from transmitted data
 - b. derived from time slot or frequency
 - c. not necessary to system functioning
5. Ground station function
 - a. data gathering for ground ATC only
 - b. rebroadcast measured data to users
6. Position measurement
 - a. single range angle measurement
 - b. three range measurements (i.e., triangulation)
7. Waveform complexity
 - a. use of no coding or error detection
 - b. coding for error protection
 - c. coding to allow non-orthogonal time/frequency space occupancy to overcome multipath and mutual interference
8. Location of control functions -- systems differ widely in availability of sufficient data for making decisions in aircraft or on the ground.
 - a. collision avoidance function in air or on ground
 - b. navigation in air or on the ground

ROLE OF T/F IN SATISFYING ATC DAS FUNCTIONS

One of our principal objectives is to identify the role that using precision time can have in satisfying the requirements of each of the DAS functions described previously. Where possible, we shall give examples of presently operating T/F based systems and those proposed for the future. More specifically, Third Generation, Upgraded Third Generation including Super Beacon, and Fourth Generation ATC Systems will be discussed, and the possible role of precise time in each will be considered in detail. As an indication of the broad range of possible T/F application, we may mention that it includes such diverse uses of precise time as:

1. A proposed scheme for an upgraded non-saturable DME utilizing precise time for one-way ranging.
2. A proposed form of Super Beacon using time-ordered interrogations to:
 - a. range-order replies for prevention of mutual interference and suppression of channel propagation effects.
 - b. promulgate precise time to aircraft and remote sites for navigation and other ATC functions.
3. The proposed T/F System selected by Autonetics which is described in the following section.

3. OTHER WORK IN T/F SYSTEMS

Surveys and reviews have been made in the past of various T/F systems. We will not attempt to repeat the results of these studies here. We discuss instead only those systems, military and civil, that are among the more relevant for our current work, and we cover only the more important data acquisition details of each system. For the numerous other systems that have been investigated, we list the pertinent reports in the references. Of particular note is Volume II of the Autonetics report (Ref. 1) which contains summary descriptions of several important systems.

One should recognize that collision prevention (flight safety), the ATC performance measure that receives major emphasis in civil ATC systems, has a lower priority in military ATC systems. For this reason, and the fact that the whole civil environment is quite different than the military environment, we should not expect that the military T/F systems could be transferred intact to civil usage. We should be surprised if they did not require major modification for civil use. However, the T/F techniques and the performance of these techniques in operation are important items of information.

EROS

In 1960, two F-101B's under positive radar control collided in the St. Louis area. Two crew members were killed and both planes were lost. This incident led to the McDonnell Douglas investigation of collision avoidance, which gave birth to the T/F system called EROS. (EROS is an acronym for "Eliminate Range Zero System".)

The McDonnell Douglas investigation initially considered non-cooperative systems, such as IR devices, conspicuity enhancers, and active radars, and it was determined that none of these provided the protection deemed necessary for a system that had to handle aircraft over a wide velocity spectrum, in all weather, and during maneuvering flight. It was decided, after an intensive study, that T/F technology should be employed and this resulted in the EROS airborne CAS. During 1965 EROS became operational on every test aircraft operated by McDonnell Douglas. Approximately 14,000 EROS flights have been logged in F-4 aircraft. The EROS-CAS was used as a basis for the ATA-CAS discussed below.

A summary of the performance characteristics of EROS is given below:

SUMMARY OF EROS SYSTEM FOR ST. LOUIS INSTALLATIONS

Range	40 Miles Air/Air - 120 Air/Ground/Air
Number of User Slots	1000 Slots
Epoch (Cycle Time)	2 Seconds

Slot Duration	2000 Microseconds
Altitude Range	-1000 to +60,000 Feet
Doppler (Range Rate) Range	0-3000 Knots, ± 50 Knots
Transmitter Power	300 Watts Air - 1000 Watts Ground
Frequency	1545 MHz

The use of T/F technology upon which EROS-CAS is based has been expanded by McDonnell Douglas to other ATC functions as follows:

- a. FLIGHT FOLLOWING. The EROS ground station in St. Louis might be considered a typical ATC Center for a T/F system. The ground station console shows aircraft as discrete points instead of the wide beacon slash. It also shows aircraft altitude, range, identification and flight plan information. A minimum of voice communication is needed.
- b. STATION KEEPING. This refers to assigning an aircraft to follow and "station keep" on a so-called leader aircraft, and to displaying relative range, bearing, and altitude with respect to it. Thus traffic can be ordered by a controller by assigning separation ranges in a stream of aircraft at any point in his sector. Safe separation of one aircraft with respect to another can be assured, by both aircraft having readouts of range from the EROS-CAS. A continuous stream of positively controlled and spaced traffic, can be established for transoceanic flight.
- c. TRILATERATION(RHO/RHO) and AREA NAVIGATION. With three ground stations participating in the time-ordered system, three range measurements can be made from a participating aircraft using the EROS-CAS signal. Also, three range measurements can be made the reverse way, from the ground stations to the aircraft. A simple trigonometric solution, using the range of the aircraft

and the known location of the ground stations, will produce the position in space. In applying this scheme to area navigation, McDonnell Douglas estimates, as an example, that eight T/F ground stations would provide the position accuracy required to properly control traffic anywhere in the Northeast corridor, a swath 150 miles wide from Washington to Boston, above 10,000 feet.

ATA-CAS

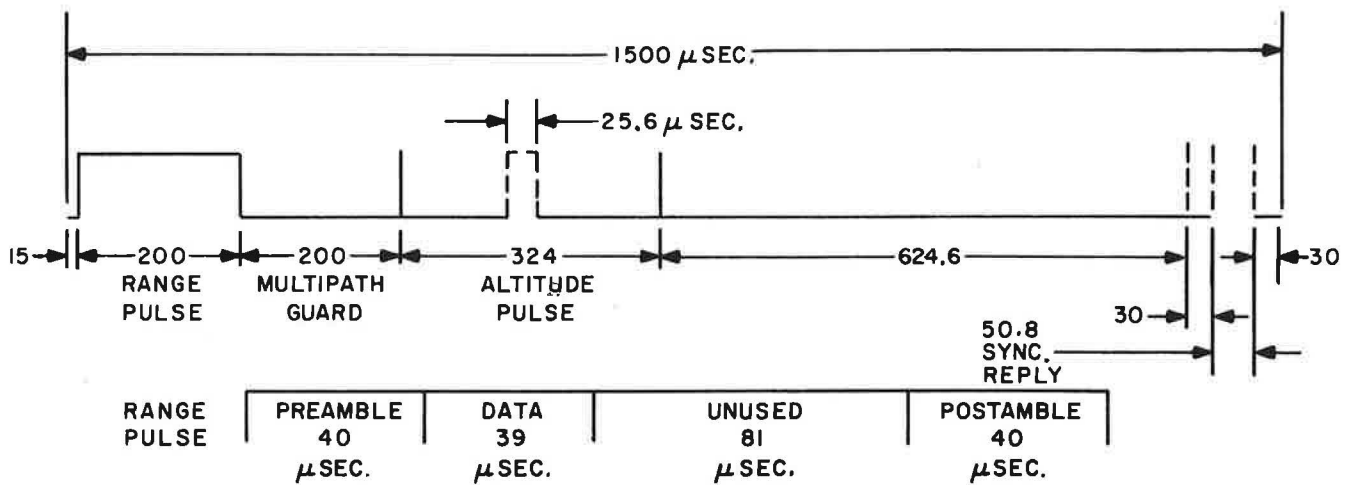
The Air Transport Association-Collision Avoidance System (ATA-CAS) is a cooperative airborne system designed to provide an equipped aircraft with sufficient data to determine the existence of a collision threat with any other similarly equipped aircraft and, in addition, to display the appropriate avoidance maneuver command in the cockpit. Each ATA-CAS contains a precise T/F device capable of maintaining time and frequency accurate to one part in 10^8 or better. The ATA-CAS evolved from the McDonnell Douglas EROS, discussed above.

Some of the performance characteristics of ATA-CAS are:

Range	40 N Miles
Number of User Slots	2000 Slots
Epoch (Cycle Time)	3 Seconds
Slot Time	1500 Microseconds
Altitude Range	-1,000 to +80,000 Feet
Frequencies	1600, 1605, 1610, 1615 MHz

The ATA-CAS is not intended to be a substitute for a ground-based ATC system, nor is it intended that the ATC system be designed to rely on the ATA-CAS for separation of aircraft. ATA believes that the best solution to the problem of potential mid-air collisions is a positive, fail-safe, ATC system under the jurisdiction of a central agency exercising control from ground facilities. The role of an airborne CAS is to provide safe separation of aircraft when, for any reason, the ATC system does not fulfill its intended role. The ATA-CAS is not dependent upon the ATC system.

Some of the details of the message format for each time slot are shown in the following diagram:



<u>Data Message</u>	<u>Number of Bits</u>
Marker	1
Time Hierarchy	6
Parity	1
Sync Request	11
Parity	1
Identification	18
Parity	<u>1</u>
Total	39

The altitude is transmitted by pulse-position modulation, where the leading edge of the pulse can be placed in 81 different positions, each 1 μ s apart and spanning the 324 μ s interval. The altitude is given in increments of 250 feet. The timing for the range and altitude pulses is obtained by leading-edge detection, i.e., the time of occurrences of 50 percent voltage of the respective pulses.

The structure of the range pulse has changed somewhat in recent years. The latest signal design is to transmit the preamble and postamble as cw at the same phase. The data bits are 1 μ s bursts transmitted by NRZ biphase modulation. The marker bit is a 1 μ s burst that differs by 180° from the preamble. For the other data bits, for logic level 1 the phase of the 1 μ s burst is identical to the phase of the previous 1 μ s burst. For logic level 0 the phase of the 1 μ s burst differs by 180° from the phase of the previous 1 μ s burst.

In looking at the full 1500 μ s message format, one is impressed by the low utilization of the channel (less than 25 percent). Some of the unused time is needed as a multipath guard but there appears to be a good deal of room left for future expansion, with proper signal design.

Normally aircraft time synchronization will be accomplished by listening to highly accurate ground stations. A network of ground stations is to be provided for this purpose by the FAA. A means has been provided to extend this ground station master time through aircraft-to-aircraft relay. This extension of ground station time establishes time of descending accuracy or time-hierarchy. Fully equipped aircraft will provide an estimate of the expected accuracy of their time by including their time-hierarchy number in their transmissions. Aircraft out of range of a ground station will request master time from other aircraft of better time-hierarchy status. This request will be accomplished by discrete address to the desired donor using the donor's message slot number in the address.

A flight test and evaluation program of the ATA-CAS was conducted by Martin-Marietta in 1969. This involved a total of approximately 200 hours of useful flight time. Although this

was a limited test, both in time and capacity (mostly two aircraft tests with some three aircraft tests), Martin-Marietta has concluded that "the tested collision avoidance concept works." It was demonstrated that ATA-CAS could detect and evaluate the collision hazard and select and command appropriate maneuvers to allow aircraft to achieve safe vertical separation before reaching the potential collision point.

Considerable data were obtained to determine the effect of multipath transmission signals. Although multipath was clearly present, enough multipath protection has been built into the CAS to allow it to operate properly. Further discussion of these multipath results is included in Appendix B.

AUTONETICS STUDY

GENERAL COMMENTS

The work done by Autonetics under Contract FA67WA-7172 is reported in four volumes (Ref. 1) dated August 1969. Volume I contains a summary description of the recommended system concept, selected configuration, summary of cost estimates, and a recommended research and development plan. Volume II is a compendium of time and frequency techniques, concepts, and systems including precise oscillators and synchronization techniques. A comprehensive bibliography on T/F is given. Volume III provides a detailed description of the system concept; the methodology used for synthesizing, analyzing, and selecting the recommended system; a description of the recommended system; cost estimates to develop and implement the system; description of a cost prediction model; and a recommended research and development implementation plan. We believe the recommended or "selected" system is the most amenable to our technological approach, and therefore we concentrate our efforts on this part of the report. Our analysis of this system is given in the next subsection. Volume IV is a SECRET document describing several T/F military systems. It is not necessary to include any of this classified material in the present report.

The following general comments are made only because we were specifically tasked with a review of the Autonetics study.

In general, we feel that the Autonetics study would have been more useful if it had been addressed more toward in-depth treatment of critical technical problems rather than high-level systems methodology. A case in point is the multipath problem. This is very likely a major hurdle for all future ATC systems (not just the T/F type) and until further technical work is done it is difficult to make meaningful system tradeoffs. (The multipath problem is discussed in the section Multipath Effects of the present report.) Although Volume II (subcontracted to Sierra Research) does have an impressive technical content in the area of synchronization and time promulgation techniques, this material could have been better integrated into the rest of the report. The methodology which is developed for rating "over 500,000" (sic) alternative system configurations appears unwieldy and totally unrelated to practicality; the reduction could have been handled more simply (and probably better) by straightforward engineering judgment.

DESCRIPTION OF THE AUTONETICS SELECTED SYSTEM

This section presents the operation of the ATC system selected by Autonetics. The functioning of the system is described herein relative to the list of DAS functions given previously.

The Autonetics selected system represents an attempt to generate an entirely new fourth generation ATC system, using T/F technology wherever it appears desirable. The proposed system is organized around a high data rate time-division-multiplexed air-to-ground digital data link using precise time, one or more relatively conventional ground-to-air digital data links, a channel for synchronization and navigation, and voice channels (Table 1). The system is described in Volume III of Reference 1.

Ground Based DAS Functions

1. Data Acquisition for Surveillance

a. Aircraft Identification

The system identifies received data on the air-to-ground digital data link by the time slot in which it is received.

TABLE 1. AUTONETICS-SELECTED ATC SYSTEM: DATA LINK DESCRIPTION

Data Link Name	Transmit Location	Function Performed	Modulation Method
Air to Ground Digital Data	Air	All Pre-planned Air to Ground Communications (Position and Status Reporting)	Time Division Multiplexed Phase Shift Modulated
	Air	Alternate Proposal for Air Based Collision Avoidance	Time Slots with Guard Band Phase Shift Modulated
Ground to Air Digital Data	Ground	All Pre-planned Ground to Air Communications (Time Slot Assignment, Positive Control)	Phase Shift Modulated
Synchronization	Ground	Precise Clock Synchronization	Phase Shift Modulated
	Air	Ground Based Navigation and Position Measurement	Time Slots with Guard Band Phase Shift Modulation
	Air	Identification of New Aircraft	Time Slots with Guard Band Phase Shift Modulation
Navigation	Ground	Air Based Navigation	Time Slots with Guard Band Phase Shift Modulated
Position Rebroadcast	Ground	Air Based Collision Avoidance	Phase Shift Modulated
Voice Ground to Air	Ground	All Emergency and Backup Communications	VHF FM
Voice Air to Ground	Air	All Emergency and Backup Communications	VHF FM

A new aircraft is identified to a ground site by either:

1. direct transfer with the new time slot assigned through the previous center's data link, or
2. aircraft identifies itself by an asynchronous transmission on the synchronization channel. A time slot is then assigned to the aircraft over the ground-to-air command data link.

b. Aircraft Status Reporting

A high data rate (78.6K bits/sec) time-division-multiplexed data link will provide the required data communication capability.

c. Detection of Non-cooperative Aircraft

Non-cooperative aircraft cannot be detected or identified by the proposed system.

2. Aircraft Position and Velocity Measurement

Aircraft position is measured by triangulation. The aircraft transmits a triangulation waveform on the air-to-ground synchronization data link. The waveform is transmitted in a preassigned time slot with sufficient buffer time to prevent interference between widely separated aircraft. It should be noted that approximate time knowledge is required for the aircraft to transmit in the designated time slot, but that small synchronization errors will not affect the accuracy of the position measurement since it is determined by time-difference methods. Exact signal arrival time within a time slot is used for a check on time synchronization quality if it is required.

3. Conflict Prediction Data

Measured position data and reported altitude and velocity data are used.

4. Additional Data Exchange

The digital data links should provide sufficient capacity for most foreseeable data exchanges; a voice data link is also provided.

Airborne DAS Functions

1. Navigation

a. Flight Path Following

The ground stations transmit identifiable messages at a known time over the navigation data link. The aircraft senses arrival times, and relative time delay is used to define a flight path. Precise knowledge of time is not required since only relative delay is used in this mode of operation.

b. Area Navigation

Aircraft coordinates are determined by either of the following:

1. Measurement of precise time of arrival of pulses transmitted by two ground stations. Position is at the intersection of two circles defined by oneway range measurements. Precise knowledge of time is required.
2. Relative time of arrival for signals from three ground stations provides position at intersection of two hyperbolas. Precise knowledge of time is not required. Triangulation and range measurement data will typically provide poor altitude data because of ground station geometry and therefore, altimeter data is utilized.

2. Air Collision Avoidance

Two alternate methods are proposed:

- a. All aircraft positions are broadcast by ground traffic control center on a separate data link. Each aircraft must monitor this

channel and examine each broadcast position message for possible conflict.

The implication is that this will be done by a piece of special purpose digital hardware in each aircraft.

- b. Aircraft broadcast their position and velocity data at assigned times on the air-to-ground digital data link. Guard bands will be required for other aircraft to receive ungarbled messages. This of course will have major implications on the data link traffic capacity.

3. Landing Aids

The relative time delay measuring system proposed for the navigation function will also be used for this purpose.

4. Additional Communications

The digital data links should handle all pre-planned messages. A voice communication channel is also available.

A block diagram showing the various data links and processing elements is shown in Figure 4. This figure was generated by us from the description in Ref 1 Vol. III but it may differ in some details due to ambiguities in Vol. III.

There are only two places in the Autonetics proposed DAS where precise time knowledge is a critical requirement. One-way range measurements used by some of the navigation options transform a 1 μ s time error into a position error of approximately 1000 ft. The air-to-ground digital data link requires errors of no more than a few microseconds for efficient multiplexed operation. Otherwise time errors of a few hundred microseconds can be tolerated by the other data links and functions.

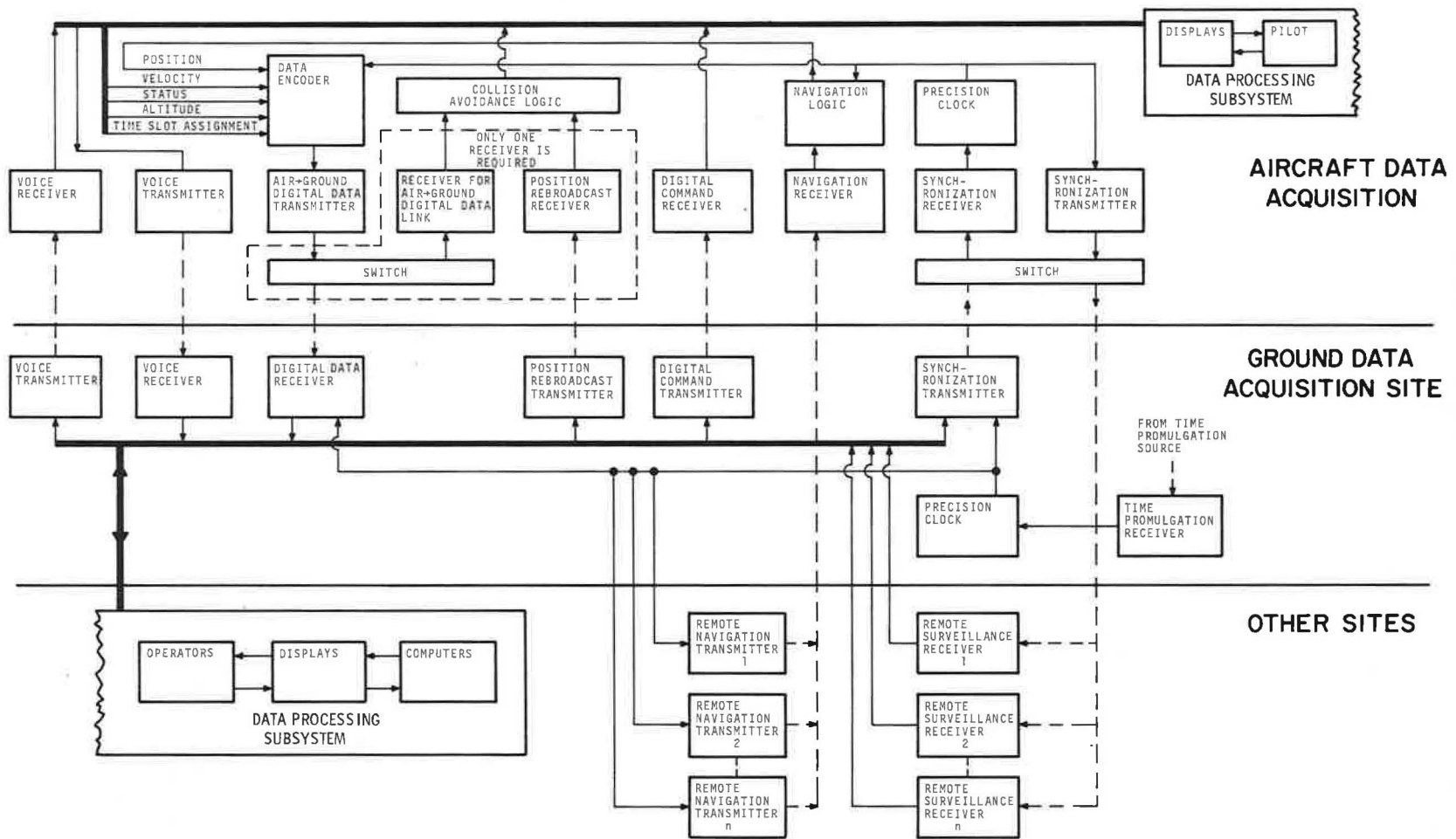


Figure 4. Autonetics Proposed T/F Data Acquisition System Datapaths.

STRENGTHS AND WEAKNESSES OF THE AUTONETICS SELECTED SYSTEM

In this section only the full configuration of the Autonetics selected system is considered, primarily because an adequate subset of reduced performance systems was not defined in the Autonetics Report. The organization of this section follows the list of DAS functions given previously.

Ground Based DAS Functions

1. Data Acquisition for Surveillance

The proposed system is very strong in that it provides adequate two-way data transfer for all control and reporting functions required. It has, however, no ability to handle non-cooperative aircraft. This will necessitate the maintenance of third generation primary links. The Autonetics system will not improve the ability of the ATC system to handle general aviation.

2. Aircraft Position and Velocity Measurement

More than adequate data is generated by the ground DAS; however, many isolated ground navigation receivers and associated ground communication facilities will be required (similar to the present third generation system), and extensive data processing will be used.

3. Conflict Prediction Data

Expected system performance would appear to be adequate.

4. Additional Data Exchange

Digital data links will handle almost all data exchange from cooperative aircraft in an extremely efficient manner, but non-cooperative aircraft will probably overload the voice data transfer facilities.

Airborne DAS Functions

1. Navigation

The system will provide all data necessary for area navigation. The simplified techniques proposed for flight path following will require ground-based navigation transmitters at fixed positions along preplanned flight corridors. The system will not provide as much flexibility as the present VOR-based system. The system may provide an improvement in accuracy over the VOR, but it is unlikely that aircraft users will derive any important benefit since the present system is regarded as adequate.

2. Air Collision Avoidance

Two options have been proposed for air collision avoidance. The first option uses aircraft position data rebroadcast by a ground station. This option is considered feasible. It does not, however, offer any performance improvement when compared to IPC. In view of the added cost due to an entire additional data link and possible need for special purpose hardware for the airborne processing of the received data, there seems to be little excuse for the consideration of such a technique to replace the IPC with ground based processing proposed for the third generation systems which will precede this system.

The second option is the use of the air-to-ground data link with time guard bands for the CAS function. Assuming a 2 ms. guard band this will require approximately 10 seconds of data link time for a single transmission by all aircraft in a peak traffic location in 1995; this will not permit operation of the data link in its normal mode at all. The entirely airborne CAS function can therefore only be used in lower traffic areas.

3. Landing Aids

We do not know whether the L-band navigation link in the Autonetics system can provide the same quality of performance provided by microwave ILS.

4. Additional Communications

The same comments as in the section on ground-based additional communications apply.

We do not believe that there are major technological risks in the Autonetics system. The system presently assumes data rates much lower than those which theoretically can be provided on the digital data links. This is wasteful of spectrum but it will reduce the effects of multipath. We consider multipath to be the main technological restriction on overall system performance because of its effects on precise time measurements and communication channel capacity. The proposed Autonetics system actually requires very little from its precision time subsystem. Its only function in most of the system configurations is time slot selection, and in this function several microseconds of error can be tolerated. Only one of the many navigation subsystem configurations will require truly precise time for one-way ranging.

It should be noted that a key design criterion for the equipment configuration selected in the Autonetics system is that all possible data processing functions be performed in the controlled aircraft. This system design decision is discussed only in an extremely cursory manner and is not technically supported in any part of their report.

Since the "Autonetics-selected system" is in fact a collection of system configurations based on a wide variety of subsystem alternatives (many of the configurations not utilizing T/F) no single specific system was identified to the level of detail needed for meaningful system tradeoff studies. Further progress could best be based upon specific design choices within this generalized collection of possible configurations.

PLRACTA

The Position Location, Reporting, and Control of Tactical Aircraft (PLRACTA) system is based on time-division multiple access. "Time-division" means "time ordering" and "multiple access" means that many participants are involved, the result being a T/F system in the terminology of this report. The development of PLRACTA is being handled through the Air Force Electronic Systems Division at Hanscom Field, with technical assistance from The Mitre Corporation. The purpose of this system is to provide a capability for more effective tactical resource management by improving the ability of forces to locate themselves relative to one another and to communicate their position and status.

The details of the final design of the PLRACTA system have not been specified yet. However, a prototype system has been devised and is currently undergoing tests in the Boston area. Six PLRACTA terminals have been constructed, three at fixed ground stations, one ground mobile station, and two aircraft. These terminals are being operated to verify in a line environment (a) the design of the time-division cyclic reporting system; (b) the system management rules of operation required by such a system; (c) the recursive position finding/clock synchronization algorithms as may be derived from the simulation development.

Each of these six PLRACTA terminals is composed of a digital data transceiver, a digital computer, and a control display unit. The receiver delivers to the computer a series of messages received from other members of the time-ordered reporting net. The computer generates replies, acknowledges commands, computes and generates position and status reports, generates special requests, etc., and delivers them to the data transmitter which then transmits them as a short burst at the assigned slot time. Off-the-shelf equipment is being used for these tests.

Some of the performance characteristics of the PLRACTA system as specified for the current tests are:

Number of User Slots	100
Epoch (Cycle Time)	1 Second
Slot Time	10 Milliseconds
Altitude Range	0 to 51,150 Feet
Frequency	1018 MHz

The message format for each 10 ms time slot consists of a 15 bit sync burst followed by a 160 bit total message. The 160 bits break down into 135 information bits and 25 parity check bits. The parity check bits are used for error detection only, not error correction, and messages with detectable errors will be discarded. The 135 information bits are comprised of nine 15-bit blocks. Forming a 9X15 bit matrix with these information bits, one parity check bit is added for each row and each column. The resulting ten 16-bit blocks are transmitted row by row. Note that the bottom row consists of all parity check bits.

There are ten different message types to make up the 135 information bits. Included in these messages are bit allocations for position (latitude and longitude), altitude, synchronization data, heading, speed, etc. The specific details of the message structure can be found in the literature (Refs 4, 5).

The data are transmitted by on/off keying. A bit is a pulse 0.5 μ s wide. Pulses are spaced approximately 1.6 μ s in the sync portion and 10 μ s in the data portion. This means that a very small percentage of the channel capacity is used. The large guard space (9.5 μ s) between the data bits is an attempt to avoid multipath degradation.

The airborne tests that are currently underway are designed to (a) determine the reliability of the air-ground and air-air data link; (b) determine the ability of the moving terminal to maintain time synchronism with the ground system; (c) determine the accuracy of positions derived from arrival timing of data link messages; (d) determine the interaction effects between multiple moving platforms. Of particular interest will be the nature and severity of the adverse effects of aircraft maneuvers and multipath propagation on the data link. From these effects requirements for error correction and detection can be determined.

It has been stated to us by the developers of the PLRACTA system that the concepts underlying this system are applicable to civilian Air Traffic Control (Ref 7). At present they believe the PLRACTA concepts have great potential for (1) improving aircraft-to-aircraft and aircraft-to-controller coordination, (2) providing control links for positive centralized control, and (3) a basis for a wide area surveillance, position location, and navigation capability.

SIERRA RESEARCH STATIONKEEPING SYSTEMS

A stationkeeping system is an electronic system installed in a group of aircraft that allows them to fly in formation regardless of the visibility conditions. Each aircraft can maintain its own position/station throughout a mission.

Sierra started developing a family of T/F Stationkeeping systems for the military in 1957. They claim to have produced the only operational stationkeeping system in existence. The latest version of these systems is designated AN/APN-169A and is used in the U.S. Adverse Weather Aerial Delivery System. This system provides up to 36 aircraft with stationkeeping capability to maintain formation flight during day or night operations, including adverse weather. Other specifications are:

Range(determined by one-way ranging)	200 feet to 10 nautical miles
Range accuracy	200 feet to 5% of full scale
Frequency range	S-band
Power output	100 watts (nominal)
Clock type	Precision crystal

The AN/APN-169 stationkeeping system has been carefully designed to suppress multipath reflections that are primarily due to vertical multipath forward scatter. The multipath reflections are suppressed through the use of pulse leading-edge detection, subsequent receiver muting, stored-slot AGC, and antenna directivity. Thus the system operates at any altitude including ground level.

Multipath reflections may also occur because of bounce-off from another aircraft in the formation, or near the ground from large metal building structures. In this case the direct signal and multipath echoes arrive from different bearings.

The use of stationkeeping and cluster control for future non-military ATC systems has been discussed in a report by Group III of the ATCAC (Ref 10). This report considers the problem of saturation or near-saturation of existing airports and the resulting air traffic delays. An obvious solution is to build more runways and airports. However, this is a costly solution and an alternative method should be considered for accommodating a larger flow of traffic with existing terminal location of nearby aircraft to increase traffic flow (station-keeping). The capability for flying through the more congested regions of airspace in a more orderly manner, and especially for flying in the immediate vicinity of the terminal approaches with the aid of a situation display, should speed the flow of traffic while maintaining flight safety in the most critical areas. The ATCAC report recommends that "the air traffic control system for 1980 be based on the assignment of airspace to clusters of aircraft which would maintain their own internal separation."

OTHER SYSTEMS

In surveying and reviewing past work in T/F, one has to draw the line somewhere and drawing the line is very closely related to the problem of defining T/F. By all the popular definitions of T/F, there has been a vast amount of work done and there are a large number of systems in various stages of development. For example, the Naval Electronics Laboratory in San Diego has been working on T/F applications since 1944! But, using a "reasonable" definition of T/F, and for the purpose of the present project, we have compiled a list of relevant T/F systems in Table 2.

Of particular note is the outstanding work done at the Naval Observatory in precise time and at the National Bureau of Standards Time and Frequency Service. We do not think of this work as being strictly T/F work, but do recognize its implications for T/F. Our interest in this work at the present time is focused mainly on the relationship of the work to control systems, especially ATC systems where one-way ranging is involved.

TABLE 2. TIME/FREQUENCY SYSTEMS

Name	Sponsor	Purpose	Reference
1. STARS-Synchronized Time Automated Reporting System	Army-Ft. Monmouth	ATC system	Autonetics, Vol II
2. TOTES-Time Ordered Techniques Experimental System	Army-Ft. Monmouth	ATC system	Vol II; TSC files
3. 621B, NAVSAT-Navigation Satellite	Air Force	Navigation	Vol IV; TSC files
4. *PLRACTA-Position, Location, Reporting and Control of Tactical Aircraft	Air Force - Hanscom Field and Mitre	ATC system	TSC files
5. TULACS-Tactical Unit Location and Command System	Navy/Marine Corps Pt. Mugu	Classified	Vol IV
6. EELS-Electronic Electro-magnetic Locating System	Navy/Marine Corps Pt Mugu	Classified	Vol IV
7. LISANS-Low Intercept Support Air Navigation System	Navy - San Diego	Navigation	Vol II
8. TIFCO-Time/Frequency Correlation	Navy - San Diego	IFF	
9. TIMATION-Time Navigation	Navy	Navigation	TSC files
10. LORAN C	Navy	Navigation	TSC files
11. OMEGA	Navy	Navigation	TSC files
12. TRANSIT	Navy	Navigation	TSC files
13. TACTAFS-Tactical Time and Frequency Service	Navy	Time Service	Vol II

* Discussed in this report.

TABLE 2. TIME/FREQUENCY SYSTEMS (Cont)

Name	Sponsor	Purpose	Reference
14. TACSATCOM-Tactical Satellite Communication	DOD, Tri-Service	Communication	Vol IV
15. *ATA-CAS-Airline Transport Association-Collision Avoidance System	ATA	CAS	Ref No. 3
16. *EROS-Eliminate Range Zero System	McDonnell Douglas	CAS	TSC files
17. *AN/APN-169 STATIONKEEPER	Sierra Research	Stationkeeping	TSC Files

*Discussed in this report.

4. MULTIPATH EFFECTS

INTRODUCTION

Every proposed ATC system includes some sort of broad-band waveform signaling system for precision position and/or time measurement. It is our conclusion that the design of these broad-band links is the only technological area in which many proposed ATC systems may not prove to be feasible. It is also a critical area because some proposals (e.g., Autonetics Proposed T/F System, Section 3) have radically sub-optimized their entire system configuration in an attempt to minimize the possible signaling risks. All of the proposed ATC-DAS systems pose relatively difficult questions with respect to command and control and data processing functions. It is, however, likely that none of these problems will be insoluble and that their principal effects will be on system cost. The data links and "RADAR-T/F-BEACON" parts of the DAS present the only technological limitations to overall system performance. This section is devoted to an analysis of the factors limiting the ultimate performance of the DAS. We describe the type of information and analysis which is required to lend credibility to a claim that a DAS will meet performance specifications, to optimize DAS performance and configuration, to select signaling waveforms, and to design DAS system hardware.

The DAS design is non-trivial because of the relatively complex radio environment from which its signals are propagated. This environment is characterized by two effects; noise is added to the received signal, and the signal is distorted because of multiple propagation paths by way of reflecting and scattering objects. The problems presented by additive noise are well understood and in the absence of severe multipath distortion can be easily handled with current technology. The simple but costly expedient of increasing transmitter power will often suppress the noise problem. When signal distortion and multipath propagation are problems, increasing power levels is not generally a solution and has different effects depending in detail on the exact situation.

For the broad-band signals used in proposed ATC systems, multipath propagation will have two effects. Received signals will always be somewhat distorted copies of the transmitted signal and more than one received signal may be detected if paths with widely different lengths are present.

The remainder of this section concerns itself with the following questions. How can multipath distortion be described, and what descriptive data is available? How can this data be used for system design and evaluation? And what additional data is required?

As a rule of thumb, multipath errors will become critical for system bandwidths on the order of a hundred kilohertz or time accuracies of a few microseconds. At this time, measurements required for wideband characterization of UHF and L-band radio channels proposed for ATC-DAS use have not been performed and are not planned.

CHARACTERIZATION OF THE MULTIPATH CHANNEL

The term multipath is used in this study to denote the generic class of signaling degradation caused by time and frequency dispersion of signals transmitted over the variety of signaling paths which comprise the ATC network. This general definition is widely used and includes the effects due to multiple reflection of the transmitted signal.

In general, when a signal is transmitted from one point to another, it is affected by the medium through which it is sent. These effects may be conveniently classified as time and frequency dispersion and the medium generally termed a multipath channel. For example, the transmission of a single frequency tone will, in general, be received attenuated with time delay and Doppler frequency shift, the former caused by spatial propagation delays through the transmission medium and the latter by relative motion among the transmitter, receiver, and the transmission medium. In many cases, including those of interest to us, the multipath channel can be considered linear and in general time-varying. This means that the effects of the channel on a transmitted signal at each instant of time can be determined as a linear combination of fundamental responses to the elemental signals which comprise the transmitted signal (e.g., impulses, frequency tones, etc.). This characterization of the multipath

channel implies that we can view the channel as composed of a continuum of point scatters, each of which introduces an attenuation, time delay, and Doppler shift which in general varies with time (e.g., due to changing geometry, physical conditions, etc.). The received signal is therefore a linear combination of the responses due to each of the scatters caused by the transmitted signal.

Because of the inherent variability and complexity of the transmission medium and transmitter/receiver geometry, it is necessary to introduce statistical variability into the channel characterization model. This is accomplished by defining a random linear time-varying channel by considering the time-varying frequency and impulse response system functions of the channel to be random processes. The introduction of this random element into the multipath channel model is necessary because at present the general problem of deterministic modeling is analytically intractable. In principle, the deterministic model can be solved using electromagnetic field theory, the detailed structure of the scatterers, and the associated geometry (Ref 30). In general, however, the time-varying scattering structure and geometry is not known in detail; even if these details were known the problem would still be very complex. However, deterministic methods have proven useful. They can be used, for example, to establish bounds on the maximum time and Doppler frequency spread that should be expected over the channel.

Statistical analyses have been made using randomized surfaces. These techniques give rise to random scattering models which have been useful in limited cases (such as rayleigh fading and rician fading (Refs. 27, 28, 29)). However, these models can also be obtained using the random linear time-varying channel model. The theory of the characterization of random linear time-varying channels is well-developed (Refs. 12, 13, 14) and is a direct extension of the classical theory of random linear time-invariant systems.

The familiar concepts of system functions such as frequency and impulse response can be extended to time-varying systems in a natural manner. For example, a time-varying system can be characterized by a frequency response $H(j\omega, t)$ which is a function of time; if we transmit a single frequency tone $\sin \omega t$ over our channel as in our previous example, we would receive $|H(j\omega, t)| \sin [\omega t + \theta(j\omega, t)]$ where $|H(j\omega, t)|$ and $\theta(j\omega, t)$ are the magnitude and phase of $H(j\omega, t)$. The form is the same as for the linear time invariant case except that both the amplitude and phase of

the received signal are functions of time, causing both time and frequency dispersion. Also, in practice, we do not have to physically model the channel as a continuum of scatterers. The finite bandwidth constraints in real systems impose limitations on our ability to resolve a continuum of scatterers. Therefore, for a given finite bandwidth, we can model the channel by a finite number of scatterers (the number being proportional to the bandwidth).

Based on the above considerations, we can model the multipath channel as a tapped delay line with tap spacings and tap gains which depend on the delay and attenuation introduced by these scatterers. If we now take into account the random nature of the channel, we observe that a complete characterization involves knowledge of the multi-dimensional statistics of the underlying random processes. In view of this, it is important that various levels of completeness in characterization of the multipath channel be considered, and the advantages to be gained, if any, by going to increasing levels of complexity (completeness) be established. This will be done in the following sections.

CHANNEL MEASURES OF PERFORMANCE

In the characterization of a random linear time-varying channel, three natural levels of completeness can be identified. Each should be carefully considered to determine which is most applicable to the problem at hand and what, if anything, is gained or sacrificed at each level of characterization.

These levels are:

- Level 1) Determination of parameters which characterize the gross behavior of the channel. They are parameters which depend simply on first- and second-order statistics of the frequency and impulse response system functions of the channel (e.g., "width" of their corresponding correlation functions and power spectra). Determination of these parameters should not require explicit determination of second-order statistics such as correlation functions and power spectra.

Level 2) Determination of the second-order statistics of the channel. For example, determination of the correlation functions and power spectra of the channel system functions; note that this is a complete representation if the underlying random processes are gaussian.

Level 3) Complete characterization by determination of the frequency and impulse response system functions of the channel as a function of time.

Note: Between Level 2 and Level 3, there exist increasingly higher order characterizations beyond second-order approaching complete characterization of the channel.

Having identified these levels, we shall give some examples of channel measures of performance at each level. In the following section we will discuss their impact on modulation and coding.

Level 1) Examples of channel measures include:

a) $T_{\max}$ = maximum delay spread

The maximum time delay experienced by the scattered transmitted signal resulting in any significant received energy. In terms of the theory, this can be related to the "width" in delay of the scattering delay power spectrum.

b) $D_{\max}$ = maximum Doppler frequency spread

The maximum Doppler frequency shift experienced by the scattered transmitted signal resulting in any significant received energy. In the theory, this can be related to "width" in frequency of the scattering delay power spectrum

c) T_c = coherence time

The time over which the received signal can be assumed to be coherent. In the theory, this quantity can be related to "width" in time of the time/frequency correlation function of the channel. Due to the relationship between the time/frequency correlation function and the scattering delay power spectrum (i.e.,

they are inverse double Fourier transforms of each other), $T_c \approx 1/D_{\max}$.

d) W_c = coherence bandwidth

The frequency band over which the signal frequency components are strongly correlated. In theory, this can be related to the "width" in frequency of the time/frequency correlation function and $W_c \approx 1/T_{\max}$.

e) S = received signal power matched to the transmitted signal.

This is the amount of received power at the output of a filter matched to the transmitted signal.

These quantities give a rather crude first order measure of channel performance and provide rough criteria for system design. They can be experimentally measured by relatively simple means directly off the channel (Ref. 15) and, in some cases, computed from the geometry and theory.

Level 2 examples include:

a) Delay Correlation Function

This is the correlation function of the impulse response of the channel as a function of scatterer delay.

b) Scattering Delay Power Spectrum

This function measures the received scattered signal power as a function of both time delay and Doppler frequency shift. In theory it is the Fourier transform of the Delay Correlation Function with respect to the correlation variable.

c) Time/Frequency Correlation Function

This function measures the cross-correlation between the different frequency components in the received scattered signal. It is the Fourier transform of the Delay Correlation

Function with respect to the delay variable or, equivalently, the double Fourier transform of the Scattering Delay Power Spectrum

At this level considerably more information is available about the channel. For example, the received scattered power can be resolved at each scatterer time delay and frequency shift. In the absence of a good tractable physical model, these functions must be measured from the channel. Practical techniques for measuring correlation functions and power spectra are well-known (Ref. 36). For techniques specifically tailored to the problem see Ref. 15.

Level 3 samples are, of course, the impulse and frequency response system functions of the channel. Techniques for their measurement include pulse-probing and cross-correlation for impulse response and multitone methods for the frequency system function (Refs. 15, 38).

IMPACT ON MODULATION AND CODING

In this section, we discuss how the various multipath channel measures can be utilized in the design of signaling waveforms and receiver structures for them. We will attempt to systematically point out how increasing levels of channel characterization can be utilized to yield enhanced performance.

At Level 1, the channel measures allow us to characterize the channel. Knowledge of the maximum delay spread $T_{\max}$ allows the choice of a transmitted signal duration and spacing (i.e., repetition rate) which avoid intersymbol interference; also the signal duration can be chosen to be less than $T_c \approx 1/D_{\max}$ to assure coherence at the receiver if $D_{\max}$, the maximum Doppler shift, is known. This allows a safe design which avoids multipath generally at the expense of operation at data rates well below channel capacity and with excessive signaling bandwidth. This is inexcusable in cases where high data rates are necessary and spectrum is at a premium. Such methods usually lead to simplistic receiver structures (e.g., leading edge detection) and intersignaling gaps. In fact, assumptions at this level (i.e., leading to underutilization of channel) have led some to underestimate the possible performance benefits which can accrue from detailed channel characterization and signal design (Ref. 43).

These channel measures allow a general classification of channels into two types: (1) underspread, $T_{\max} D_{\max} < 1$, and (2) overspread, $T_{\max} D_{\max} > 1$. The significance of this classification is best demonstrated with an example. If the transmitted signal duration T_s is chosen such that $T_s \gg T_{\max}$ to avoid intersymbol interference, in order for this signal to be received coherently $T_c > T_s \gg T_{\max}$ or $T_{\max} D_{\max} \ll 1$; i.e. the channel must be underspread for this technique to work.

The received signal power S at the output of a filter matched to the transmitted signal can also be measured and used to determine fade margin for a bounded risk design. In general, this throws away a good deal of the power in the received signal and can significantly degrade performance. However, a quantity like received signal power can be defined as the output of a mismatched filter, and in many cases (depending on more detailed knowledge of the channel) can be used as criteria in modem design (Refs. 35, 42). However this depends in general on making more detailed measurement on the channel approaching those of Level 2.

At Level 2, second-order statistics of the channel are available. These are necessary for any detailed analysis of signaling schemes including digital communication. In the case where the underlying random process of the channel is gaussian, second-order statistics yield a complete characterization. Even in the non-gaussian case where matched filter receivers are used, second order statistics are necessary for modem analysis and design, and under certain conditions yield near-optimum results (Ref. 35). The usefulness in signal design of a second-order characterization is readily apparent; for example, the Scattering Delay Power Spectrum measures the amount of scattered received power at each time delay and Doppler frequency shift introduced by the channel scatterers.

At Level 3, a complete characterization of the channel exists. This is clearly the most ambitious level and yields complete information for modem design. This data is utilized in practice to either develop an analytical model of the channel or to simulate the channel by literally recording its time-varying system function and playing it back. The advantages of this are obvious. The playback system can be utilized in the laboratory to design and evaluate candidate systems. The systems can be compared on an equal basis by playing the recorded channel over and over again. Worst case situations can be recorded or artificially created as test sequences.

This concept of complete characterization has in fact been used in the design of adaptive modems. Some early work of Price and Green (Ref. 31) in the area of digital communication at HF frequencies introduced the idea of a Rake receiver. This receiver structure continuously makes measurements of the multipath channel attempting to construct an inverse filter to the channel to eliminate its effects. This is the same basic technique used in adaptive equalizers on telephone lines and in some commercially available high speed modems. This is an extension of the fixed line equalizer where measurements of the channel are made periodically and used to vary tap gains in the equalizer to match the channel.

WAVEFORMS FOR SURVEILLANCE AND TIME SYNCHRONIZATION ON MULTIPATH CHANNELS

The design of waveforms for use in an ATC surveillance system of the T/F or beacon type with a multipath environment parallels the design of radar signals in clutter with one significant difference: multipath cannot be distinguished from the desired signal by differential Doppler shifts, whereas clutter can often be distinguished from a real target by taking advantage of differential Doppler shifts with an MTI (i.e., moving target indication by Doppler filtering). The two problems are similar in that the techniques for generating and analyzing waveforms with the required range (or equivalently time) and Doppler resolution are identical. Another distinction is that some of the proposed surveillance systems operate with higher signal to additive noise ratios than most current long-range search radars.

For range (or time synchronization) accuracies of the type required in the ATC system, it seems likely that the ultimate waveform selection will be similar to the results for present high resolution radar systems. These include chirp FM, some sort of coded chirp FM, broad bandwidth phase-coded sequences, or any of these combined with frequency hop as the likely contenders. From this set, when one adds the requirement for extremely large traffic capacity and data encoding for addressing or data transfer, the phase-coded sequences with possible additional frequency coding become the very likely candidates.

A waveform design study is required to evaluate the complete set of reasonably economical waveforms available for surveillance system use. The evaluation should be specifically

directed toward determining their multipath performance for the range of environmental and geographic conditions under which the system will have to operate.

In addition to this work, there are a variety of situations in which more sophisticated receiver structures than a simple time invariant filter may provide radical system performance improvements. We believe that there is a requirement for research in system design with waveforms and receiver structures which adapt to measured channel characteristics to improve performance.

PREVIOUS WAVEFORM DESIGN WORK

The principal theoretical work on waveform design for broad-band multipath channels in future ATC systems is presented in Appendix E1 of the ATCAC report. Since current planning for future ATC communications and data acquisition sub-systems appears to be based in part on the work presented in that Appendix, we will here undertake to point out some limitations of that analysis.

Conclusions presented in Appendix E1 are:

1. "Conventional IFF ranging and data transfer techniques...are non-optimum against multipath and garbling." (Introduction)
2. "Substantial improvements against multipath can be achieved only by using large time-bandwidth and high resolution coded waveforms with matched filter detection." (Introduction)
3. Performance is improved by spreading the system bandwidth. (Eq. E1-19 and discussion)
4. A signaling waveform with essentially a flat spectrum will provide optimal detector performance (Eq. E1-22 and discussion). Design of a set of "anti-multipath" signals then only requires that spectrally flat waveforms with good cross-correlation properties among themselves and their time translates be found.
5. Performance can only be improved when signal spectra are flat and an optimal receiver is used by spreading the system bandwidth.

Assertion 1 above is almost certainly correct. Assertions 2 through 5 are probably not correct as general propositions. Furthermore, the question of time (or range) resolution for the proposed waveforms was not directly addressed. The proposed modified Reed-Solomon codes are typical of the class of waveforms with coarse time resolution and sharp Doppler resolution for a given bandwidth, time duration, and signal set size. In general, Reed-Solomon type codes with narrow-band chips will be a poor selection for surveillance, and combined surveillance and communication systems. They show some promise for communication without combined surveillance systems if their cost can be justified and reasonable receiver structures are used.

Assertions 2-5 reflect several assumptions in the mathematical analysis presented in Appendix E-1. In particular we will comment on the assumptions which were made regarding the multipath model, the receiver structure, and the signal set selection.

The mathematical model of multipath used throughout the analysis is quite specialized; a single specular signal with noise-like multipath returns is assumed. The model assumed is not a worst case model and since it yields unreasonable results its selection seems unwarranted. Stationarity of the multipath process (Eq. E1-5) is only a reasonable approximation if the duration of the total waveform (whole codeword) is less than the channel delay spread and if a continuous stream of waveforms is transmitted. This approximation is weak for the proposed Reed-Solomon codes, because of their low subchannel occupancy. This approximation excludes a variety of promising waveforms and receiver structures from the mathematical analysis. In addition it restricts the usefulness of the model for evaluating receiver structures. Finally, in equation E1-7 and the following discussion it is assumed that the noise $n(t)$ (composed of the multipath signal components lumped with white gaussian noise) is independent of the signal $s(t)$. This is not justified and is in general an unreasonable approximation.

The receiver structure assumed is not optimal in general. It is stated in the introduction and implied in the analysis (Eq. E1-11 and discussion) that a matched filter receiver will be optimal. For the types of channel behavior expected in the ATC environment this will rarely be true (Ref 35). Under many

circumstances conventional receivers using diversity, non-coherent combining, and non-linear decision rules will provide superior performance to the matched filter receiver for the proposed waveforms.

The signal set selection is unnecessarily specialized. The codes presented in ATCAC Appendix E1 utilize an orthogonal alphabet of chips. This is an unnecessary severe restriction for a coherent or partially coherent communication channel of the type modeled there. Relaxation of this requirement, for example by allowing phase modulation of chips, may radically improve performance.

In conclusion, it is agreed that the assertions 2 through 5 may well be correct for some specialized conditions but should not be accepted as generally valid propositions in planning future ATC systems.

A relatively simple mathematical description of the anti-multipath Reed-Solomon waveform encoding proposed in the ATCAC appendix is presented in Appendix C. It includes an example of a specific set of code sequences in an attempt to provide some insight into the mathematical properties of these codes.

ADEQUACY OF EXISTING DATA BASE

In the previous sections, we have discussed the characterization and measurement of the multipath channel for different levels of completeness and the inherent benefits and shortcomings at each level. Much of the work performed to date has involved Level 1 type gross channel measures computed from geometry or measured from the channel. References to such work are too numerous to mention since measures of this type are necessary for any level of modem design and are easy to make assuming ready access to the signaling link (e.g., access difficulties exist in satellite links). Some workers have claimed complete channel characterization at Level 3 (Refs. 39, 20). Closer scrutiny of their experiments shows that a simple single-tap (i.e., single small scattering region) channel model was assumed implying that a single time function had to be measured to completely characterize the channel (i.e., the model assumes the channel amplitude modulates the transmitted signal).

With these underlying assumptions, experiments of this kind are of limited usefulness since they imply *a priori* assumptions about channel behavior. Further information is needed to determine the effects of the channel on wide-band transmissions proposed for a number of ATC links. For further details see Appendix A.

Extremely broad-band measurements of the multipath channel at L-Band have been made recently at M.I.T. Lincoln Lab (Ref 46). The channel was pulse-probed utilizing 30 ns pulses at 1280 MHz. The transmitter was in an aircraft at 3000 feet with the receiver on the ground. Reflections were measured from soil, water, and buildings at three different sites. The characteristics of the reflections were correlated with the conditions on the ground, such as soil type, roads, and building shape and location based on physical arguments and the geometry. These measurements confirm the wideband scattering mode. Because of the wide bandwidth used, individual scatterers were resolved. These measurements agree with our basic qualitative understanding of the multipath effect. However, even though sufficient resolution was available for wide-band channel characterization at Level 3, no attempt was made to record the received signals other than with photographs of an oscilloscope display, since the intent of the experiment was a qualitative understanding of multipath.

An adequate characterization of the multipath channel at Level 3 beyond a single tap model has not been performed for the VHF/UHF aeronautical bands. However, there has been work performed at HF in characterization and hardware simulation of the troposcatter channel including modem design (Ref. 16). In this case a theoretical physical model of the channel was derived and used to design a hardware simulator which could artificially generate the channel (i.e., a tapped delay line channel model whose taps are artificially generated gaussian random processes). A modem was built using the simulator which outperformed existing tropo modems on real links. Another experimental program currently underway for UMTA at TSC (PPA UM-03) includes the design and use of channel recorder/playback equipment for measurement of urban channels at VHF/UHF (Ref. 17).

The fact that such Level 3 characterizations in the VHF/UHF aeronautical bands have not been performed should not be construed to mean that they have not been proposed before this study. A proposal had been made to FAA/SRDS in 1967 (Ref. 45). Another has been made recently to the FAA for

stored-channel instrumentation for L-Band Communication and Navigation System Evaluation directed toward satellite links (Ref. 18) using Level 3 techniques. Also, in response to the malfunction of the ATS-5 satellite, a feasible method was proposed to use this spinning satellite to perform multipath channel measurements at L-Band (Ref. 19).

Additional multipath background data is available in a literature search on multipath effects prepared for the FAA Frequency Management Division (Ref. 26). Our examination of this material has disclosed no significantly detailed data at relevant frequencies. In some cases multipath effects are only implicitly measured in terms of gross system parameters.

We present in Appendix B the results of an experimental evaluation of the effects of multipath on the performance of ATA-CAS. This evaluation was based on system performance and only system parameters were measured. We understand that another evaluation of ATA-CAS as well as its competitor SECANT (Ref. 44), an asynchronous CAS, will be conducted this summer or fall at NAFEC in Atlantic City, and that it will be the same general type of measurement.

5. COMPARISON OF T/F WITH ALTERNATIVE TECHNOLOGIES

INTRODUCTION

A key goal of this project was to have been the preparation of a "white paper" comparing T/F techniques with other approaches for meeting the evolving requirements of the ATC system. Due to last minute cancellation of FY72 funding this goal could not be achieved. As preparation for this task, a number of preliminary analyses were undertaken, which are summarized here.

A comparative analysis and evaluation of alternative ATC system configurations at a detailed technical level has been an integral part of the DOT Fourth Generation ATC System Study (PPA OS-04). We have worked closely with this study group and some preliminary outputs from this interaction, having a direct bearing on T/F, are reported in this section.

A related issue is that of the evolutionary capabilities of T/F, mentioned earlier. We will also discuss some proposed evolutionary possibilities for T/F and indicate that these approaches are consistent with increased capacity and the other evolving requirements of the ATC system.

A third issue treated here is concerned with providing a basis for the comparative study. The motivation here is to avoid an "apples vs. oranges" comparison suggested by the phrase "comparison of T/F vs. satellites vs. beacon-based systems." It is emphasized that, for example, a satellite ATC system can contain T/F or beacon-based subsystems and vice-versa. In fact, one would expect in general that candidate ATC Systems will be composed of subsystems utilizing all three technologies. Earlier we listed the attributes of T/F and gave a synopsis of the variety of system configurations utilizing T/F techniques. We will list comparable attributes and possible system configurations for other candidate technologies, in an attempt to provide a basis for comparative analysis and meaningful system trades.

INTERACTION WITH FOURTH GENERATION ATC STUDY

As an integral part of our study we have maintained close liaison with the Fourth Generation ATC Study Group. In addition to the in-house efforts, this group is monitoring two DOT/OST sponsored contracts for Fourth Generation ATC System Study and Concept Formulation. The contractor proposals had emphasized T/F techniques, but the emphasis shifted as the study progressed. When the interim reports (January-March 1971) were received for each contractor (Refs. 22, 23), we reviewed them from the viewpoint of the work relevant to the T/F project involving ATC data acquisition subsystem configurations (as defined in the Time/Frequency and Air Traffic Control section). At this halfway point in the contract, the contractors had identified a few basic system alternatives based on what appear to be very general ATC functional requirements. Two points are to be noted for their impact on T/F:

1. The basic system alternatives identified by the study can be divided into two groups which appear to comprise the major system tradeoff areas: ground-based vs. satellite-based systems.
2. Emphasis has switched from T/F as the principal candidate technology to asynchronous systems for high capacity multiple-access satellite surveillance and data relay as well as interrogator-based systems. This is consistent with an approach which views T/F primarily as an available technology, leading to possible hybrid systems utilizing diverse technologies including T/F based subsystems.

A study of the evolutionary manner by which T/F technology could be used to progressively upgrade the present ATC system was not within the scope of their contracts.

EVOLUTIONARY T/F

A hierarchy of T/F systems listed previously ranged from a revolutionary system concept (e.g., the Autonetics Selected System) to progressively less revolutionary possibilities. It

is the purpose of this subsection to re-emphasize the possible evolutionary use of T/F in upgrading existing air traffic control. We do not attempt to give an exhaustive list of evolutionary possibilities but only to give credibility to the concept.

T/F systems have been traditionally stereotyped as requiring expensive and complicated equipment in the cockpit. The definition of T/F fundamentally implies the exploitation of the general principle of time/position duality. The key point in its utility is the availability of a common precise time reference available to each system user. There are a number of ways to obtain this. The most obvious, of course, is by each system user having a highly accurate expensive clock. At the other extreme, the user can be provided with an inexpensive unstable clock kept in synchronism with those of other users by frequent comparison with an external standard reference. A fundamental problem in this case is providing this synchronism universally to all users cheaply. In general, the set of users will maintain their common time reference in different ways by methods intermediate between these two extremes. If each user transmits in independent intervals and listens the remainder of the time, he is effectively transmitting his relative position to everyone and receiving theirs by computing time of arrival. The implications for air-to-air collision avoidance are obvious and have led naturally to the development of the EROS and ATA-CAS (section entitled Other Work in T/F Systems).

A simple extension of this concept allows the various nav aids (i.e. VOR; DME), when considered as stationary system users, to be used to determine position and bearing using one-way ranging. Sierra Research has proposed a T/F DME which performs distance measurements in this manner as an alternative to the conventional interrogated DME's which are currently becoming saturated (Ref. 24). Using two T/F DMEs, simple flight path following may be performed by nulling time differences; more detailed navigation data requires more complex airborne processing. A basic problem remaining is synchronization for the network of system users. A scheme to overcome this problem was also proposed to accomplish this by Sierra Research (Refs. 24, 25). Using the DME interrogator for an initial two-way range measurement to determine synchronization error, the airborne clock is corrected and subsequently one-way range measurements are performed using the T/F DME. Sierra Research is looking

more deeply into these schemes and their ability to provide low-cost synchronization for collision avoidance for general aviation aircraft.

Finally, we will provide an example of T/F used in beacon-based systems. The concept of interrogation is the key element here. A beacon-based system with the capability of discrete-addressed interrogation (e.g., Super Beacon) can be used as the basis for a time-ordered system. By utilizing appropriate interrogation strategies, the discrete-address interrogator can trigger transmissions by each system user at prescribed times under centralized control. Stationary beacons located at fixed geodetic points can also be triggered to act as navaids. The resulting time-ordered system behaves similarly to classical T/F (where each user is responsible for properly initiating his own transmission) and includes an airborne collision avoidance capability. The centralized control provided by beacon-based T/F has a great many desirable characteristics. Among these are the use of a wide variety of interrogation strategies including variable repetition rates for different users and implicit network synchronization. The beacon-based T/F concept includes a variety of possible configurations. For example, each individual user can retain a large portion of his autonomy in transmission with interrogation required much less often primarily to align user clocks in order to maintain network synchronization. Beacon-based T/F schemes of the general class mentioned here have been proposed as an extension of the Super Beacon concept (Ref. 21).

BASIS FOR COMPARISON OF PROPOSED SYSTEMS

There are two basic Data Acquisition System configuration decisions which must be made. These are whether to locate the ATC system sensors on the ground or in satellites, and what type of position measurement scheme to use. The three basic types of position measurement techniques are:

1. Range-angle measurements, such as those made by ATCRBS, radars, and proposed Super-Beacon systems.
2. Time synchronous measurements of the type proposed in some T/F systems. In this type of system range to three or more known stations is measured by one-way signal propagation time. A common precise time reference will be required in this type of system.

3. Time-difference range measurements. The difference between arrival times of signals from pairs of stations is used to define aircraft coordinates in a hyperbolic coordinate system. The classical example is Loran. A common precise time reference is not required by the user in this case.

There are a series of hybrid systems which mix the properties of some of the above systems.

In the remainder of this section we will describe the principal performance differences between the different system configurations, and give an example of the type of detailed technical analytic support we feel is a prerequisite for system evaluation and tradeoffs.

SATELLITES VS. GROUND-BASED SENSOR

Essentially the performance differences come in the following areas:

1. Altitude measurement: Satellite systems typically provide altitude measurements far superior to ground-based measurements.
2. Traffic handling capacity: Satellite systems will have much larger coverage areas than ground-based systems and consequently will require somewhat more sophisticated techniques for providing the required traffic capacity.
3. Costs: Satellites clearly require fewer but more expensive sensors than ground-based systems.
4. Jamming: Satellite-based systems will always be much easier to jam than ground-based systems because their large coverage area with a small number of sensors makes jamming from a protected location relatively easy. Phased array radars with sidelobe suppression appear to be the only possible technique for control of jamming. Complex anti-jam waveforms are probably too expensive for use in this type of system.

POSITION MEASUREMENT TECHNIQUES

The essential performance differences are:

1. **Traffic Capacity:** Time-ordered discrete-addressed beacon systems can provide traffic capacity in excess of any other type of system. This is because radio channel scheduling need be considered at only one spatial point and complex algorithms for optimal interrogation times can be used without excessive cost. Most of the proposed synchronous T/F type systems use time-slots with guard-bands to allow propagation of signals to multiple receivers. This provides much lower traffic capacity; however, the capacity still appears adequate for a ground-based Data Acquisition System. The asynchronous signaling systems (for example, SATANS, LIT) offer a traffic capacity higher than T/F with guard bands in exchange for more complex signal processing.
2. **Cost:** For the very high capacities possible in the future, beacon-based systems will require an expensive phased-array radar. Asynchronous time-difference ranging systems typically require expensive signal processing. Synchronous T/F systems generally require a clock and a synchronization subsystem. Cost comparisons without reference to specific systems are impossible. It is true in general that proposed synchronous T/F systems have been the most expensive alternatives due to the requirement for high-performance air-to-ground and ground-to-air data and time measurement radio channels, clocks, and relatively complex specialized digital hardware in every participating plane. This cost difference seems to be justified only if fully airborne collision avoidance data acquisition and data processing is a system requirement. It is not within the scope of this report to make recommendations on that requirement. In this regard, it makes little sense to consider the

relaxation of the requirement in the proposed T/F systems for a common precise time reference for all users in order to decrease overall system cost, since this would degrade air-based collision avoidance to a point where the synchronous T/F system would not out-perform less expensive systems.

3. Jamming and RFI: Beacon-based systems will be intrinsically less vulnerable to RFI or jamming because of their directional antennas. Synchronous and asynchronous transmission T/F type systems can only be protected by siting the antennas to minimize the coverage of regions where radiated signals can not be controlled.
4. Evolutionary systems: Beacon-based systems using IPC for collision avoidance seem to provide one of the easiest transitions from the present system. If airborne data acquisition and processing is required there is a proposed beacon system which provides some possibility of compatibility with present beacon transponders (Ref. 21). The proposed classical T/F systems provide no compatibility with the present ATC system other than the use of redundant subsystems and the sharing of digital data links.

6. CONCLUSIONS AND RECOMMENDATIONS

Specific conclusions with respect to prior work have been reported in earlier sections (particularly for the study carried out by Autonetics) and need not be repeated here. The present section is addressed to a broad summary of where we stand in assessing the application of T/F technology and an outline of the additional work which would be required to complete a valid assessment. Many of the conclusions stated in this section are necessarily of a preliminary nature (as noted in the Introduction) and might not have been presented at this time under normal circumstances. Since there will now be no opportunity to develop and refine the conclusions as we would prefer, they must be regarded as our current best engineering judgement on these important matters.

PRINCIPAL CHARACTERISTICS OF T/F TECHNOLOGY

The features of T/F based systems which may lead to benefits relative to systems based on alternative technologies are:

- a. One-way ranging. The positional data needed for flight plan following, collision avoidance, and/or navigation can be made available directly in the aircraft with minimum reliance upon data transmission and processing.
- b. Range-compensated precise time-division multiplexing. By initiating each air-to-ground transmission at a clock phase calculated solely from range to a ground station, the air-to-ground transmissions can be micro-scheduled to arrive at the ground station without overlapping (thus minimizing garbling) and with minimal time lost due to guard times (thus assuring capability for handling the maximum number of aircraft).
- c. Functional unification. It should be possible to accomplish ATC, CAS, and navigation functions with a single technology and with much commonality of equipment. (However there is no requirement for implementing these functions simultaneously.)

In addition to these potential benefits associated with T/F technology it should also be pointed out that equipment presently being considered, such as high speed digital data link and certain types of navigation, also involve requirements for precise time and could efficiently share timing sources and processing with a more comprehensive T/F system.

MAJOR QUESTIONS TO BE RESOLVED

We identify four major areas of concern in the application of T/F technology. These areas are:

- a. Feasibility of establishing common precise time
- b. Evolutionary implementation
- c. Multipath vulnerability
- d. Systems operational problems.

We see (c) as the only problem area which may present technological limitations. However, each of these areas requires further study.

- a. Feasibility of establishing common precise time

At this point there can be little doubt as to the technical feasibility of establishing common precise time in the aircraft and on the ground, and of promulgating precise time throughout a network of users. Economic feasibility has sometimes been questioned, particularly for smaller aircraft, and references (particularly Vol. 2 of Ref. 1) discuss the probable costs for installation and maintenance of precise time equipment. The cost figures presented in the literature probably cannot be regarded as definitive, although we present no figures of our own. We believe that the cost of alternative methods of establishing common precise time for a network of users is a major issue, but we find no reason to doubt either technical or economic feasibility within the current state-of-the-art and within quantity production economics. We have not, however, done the detailed cost analysis which is required to fully answer this question.

b. Evolutionary Implementation

A frequently heard criticism of T/F technology is the implication of great revolution in the design of the ATC system. According to this view most of the major electronic equipment in the aircraft and on the ground would have to be replaced more or less abruptly, matching the radical change in ATC system philosophy as compared with the present system.

We do not dispute the sweeping nature of the ultimate changes required to implement an ATC system based entirely on T/F technology. (A similar comment can be made about satellite systems or other fourth generation candidate systems.) However, we do believe that there exist rational evolutionary pathways permitting an orderly, time-phased transition which should be considered in ATC system design. This belief is based upon the very broad set of functional allocation options listed earlier as well as the discussion in the previous chapter; these suggest several possibilities for progressively improving ATC functions by T/F techniques. Unfortunately, it has not been shown that this will lead to the best ATC system. Several steps now being seriously considered could become the first steps along such evolutionary pathways:

- i. If ATC-CAS is adopted, both the ground and the equipped aircraft would have the essential elements of a system which could later be incorporated into the ATC system.
- ii. One of the high speed digital data link proposals now being considered as an important supplement to ATCRBS involves precise time division multiplexing on a common channel with range delay compensation for time ordering of received replies. The degree of clock precision involved on the ground and in the air will depend on further design considerations, but in any event the rudiments of a T/F ATC system will be present.

c. Multipath Vulnerability

The multipath problem is of course universal and is not peculiar to time/frequency systems. It is sometimes argued that leading-edge range determination proceeds independently of multipath because of the time separation of the direct signal and the fastest echo. Although this may be partially true in special cases (such as ATA-CAS) the argument obviously cannot extend to other parts of the signal (carrying information as to aircraft identification, synchronization quality, etc.) which will be corrupted by multipath. Furthermore, in the presence of noise and interfering signals, leading-edge determination can be a severely non-optimum detection technique for time of arrival measurement. A study of multipath signaling techniques is required to answer the following questions:

1. What are the maximum economically feasible data rates?
2. What are the effects of multipath on precision range (time of arrival) measurements?
3. What are appropriate signaling waveforms and decision structures?
4. What is system error performance?

The problems have much in common with other signaling problems such as those which will be encountered in the DABS.

Considerable interest has been expressed in the adequacy of the existing multipath data base to establish T/F system operating performance. This has been discussed in detail in a previous section. For all practical purposes no data which is usable for the required analyses, system design, or system optimization has been gathered.

Flight operational testing may appear at first sight to be a direct, practical route to assessing vulnerability of T/F systems to multipath. This type of

measurement is suitable for the engineering development phase of system design; however it does not provide the type of information required for evaluation of the large variety of modulation and coding systems which are available. In addition, without a detailed understanding of multipath properties, reasonable specifications for data link rates and error performance, or surveillance system capacity and accuracy cannot be set. Generalized multipath measurements are required in order to allow systematic concept formulation and development.

d. Systems Operational Problems

It is important to understand how specific T/F systems can operate under various non-ideal conditions, such as individual clock malfunction. (How is this condition sensed and diagnosed? How corrected? Must other aircraft be notified? How can clock discipline be controlled in the face of two simultaneous mavericks?) Specific system operational problems include strategies for general airspace management as well as algorithms for communication and surveillance such as those required for demand and polling systems. For example, the decision to use T/F or an alternative technology affects the overall ATC system configuration (e.g., allocation of functions between the cockpit and ground). This significant problem area should receive careful study before any specific proposed T/F system can be regarded as completely designed even at the functional level.

RECOMMENDATIONS

We recommend that a multipath measurement and analysis program be undertaken. The analysis should include simulation of the effect of multipath upon specific T/F systems. The immediate goal of this program is to determine the limits of performance which can be guaranteed for proposed system configurations in order to allow specifications and cost tradeoffs in future analysis. Data gathered by such a program can later be used for detailed system design and optimization.

Caution is urged in accepting the conclusions of Appendix E1 of the ATCAC report in planning future ATC systems. This recommendation is based upon limitations of the analysis which we have discussed in the chapter Multipath Effects.

It is recommended that, for one or a few selected or postulated T/F systems, a systems feasibility study be conducted which examines systems operation in the face of partial systems failures including malfunctions of individual clocks. Particular attention should be given to the feasibility of suitable policing and alerting procedures, and to graceful-fallback system operating modes. This study should be conducted in combination with studies for other fourth generation ATC system concepts.

7. APPENDIX A

NARROW-BANDWIDTH MULTIPATH MEASUREMENTS

INTRODUCTION

In this Appendix we show the relationship between the multipath channel characterization, described in the chapter Multipath Effects, and measurement data from some previous and proposed experimental programs.

This Appendix addresses the class of multipath measurement experiments in which received signal envelope amplitude is the principal measured statistic and multipath characteristics are determined from analysis of the envelope amplitude data.

MULTIPATH MEASUREMENTS FOR NARROW-BAND CHANNELS

Present and proposed radio channels for ATC system use are time spread, but only slightly Doppler spread, which in this case means that, although the received signals may be shifted in frequency, their spectra will be essentially unaltered in shape. This typically results in multiple tap delay line propagation models being required, but the tap gains will vary at rates much slower than the expected modulation rates.

If for this type of channel the bandwidth is much less than the reciprocal of the time spread for fixed position multipath scatterers, there will be little time or frequency distortion in the received waveforms. This is because the impulse response of the channel is wideband with respect to the signals on the channel. A more detailed discussion of this subject can be found in Ref. 37. The effect of such a channel on a time-ordered sequence of time-limited waveforms is to multiply each waveform by a constant and shift it through a random phase angle. If the signal set $[S_i(t - k_\tau) e^{j\omega_c t}]$ is used to transmit the symbol i during period k then the received signal set can be modeled as:

$$r_{i,k}(t) = A(k_\tau) S_i(t - k_\tau) e^{j\omega_c t} \quad A.1$$

where $A(k_\tau)$ is a complex random process. A description of the random process $A(t)$ is a complete description of the effects of multipath on the communication channel. It should be clear from the discussion of multipath Effects that this is identical to the degenerate case of the tapped delay line channel model with a single tap.

When narrow-band phase shift-keyed modulation signals are used A.1 is often a good model for evaluation of communication system multipath performance.

The model in A.1 can be generalized to apply to FSK and frequency hop type signals. In this case:

$$r_{i,k}(t) = A_i(k_\tau) S_i(t-k_\tau) E^{j\omega_{c,i}t} \quad A.2$$

and now a complete description of the communication channel requires that the complex vector random process $\underline{A}(t) = [A_1(t), A_2(t) \dots]^T$ be fully described. If the channel bandwidth is narrow enough the $A_k(t)$ will be essentially identical and model A.1 may be used. It should be noted that for any FSK or frequency hop system if model A.1 describes channel behavior then there can be no improvement in performance for the broader band systems when compared to the narrow-band (e.g., PSK, DPSK, MSK) systems.

Communication channels for which the single-tap-delay-line model is valid will exhibit gaussian behavior for the random process $A(t)$ unless there are highly structured scatterers and consequently the measured envelope amplitude for $r(t)$ will be rician. In normal measurement situations the parameters of this gaussian distribution (covariance matrix and mean) will be time-varying and consequently the rician envelope amplitude distribution can only be measured with appropriately short, sample intervals. It may not always be possible to get a sufficient number of independent samples from the envelope random process $A(t)$ to demonstrate the short term rician behavior of the channel. When the channel is single-tap rician, performance and its effects on any modulation scheme can be determined solely from knowledge of the covariance function. The single-tap model applies only when narrow-band signals are used on the channel, and when the scatterers are not highly structured. Being not highly structured means that the scattering can not be dominated by a single

scatterer or by a small set of scatterers. This unfortunately is not the case in most ATC applications and a more complex analysis must be conducted as described later. Measurement of the maximum signaling bandwidth for which this model is useful must be made. This bandwidth is commonly referred to as the coherence bandwidth. Coherence bandwidth is an upper bound on the usefulness of the model. For reasonable accuracy, signaling bandwidth must be less than half of the coherence bandwidth. The coherence bandwidth is in no way a limit on the bandwidth of modulating signals which can or should be economically used on a communication channel; it is only a description of the range of validity of the simplified mathematical model of channel behavior given by A.1. When signaling waveforms are sufficiently narrow-band to permit use of A.1, receiver structures will be less complex (logically) than structures for broader-band waveforms. The cost tradeoffs in communication system design are relatively complex and the added complexity required for broader bandwidths can sometimes be justified in terms of lower overall system cost.

The remainder of this Appendix is concerned with the measurement of the properties of the random process $A(t)$ and the coherence bandwidth.

MATHEMATICAL BASIS FOR MEASUREMENT

The channel gain $A(t)$ can be measured relatively easily. Coherence bandwidth is a time-varying second-order statistic and is therefore much more difficult to measure.

Since $A(t)$ is a property of the channel and not of any one modulation technique a single measurement may be used for comparison of any narrow-bandwidth modulation technique, if the appropriate conditions are met. The conventional measurement technique is to transmit an unmodulated or narrow-band modulated constant envelope signal over the radio channel and measure the received signal amplitude using a receiver AGC circuit with the AGC feedback loop broken. If the measurement signal is narrow-band with respect to the receiver this may be modeled as:

$$r(t) = A(t) e^{j\omega_c t} \quad \text{A.3}$$

An equivalent block diagram of a receiver is shown in Figure 5.

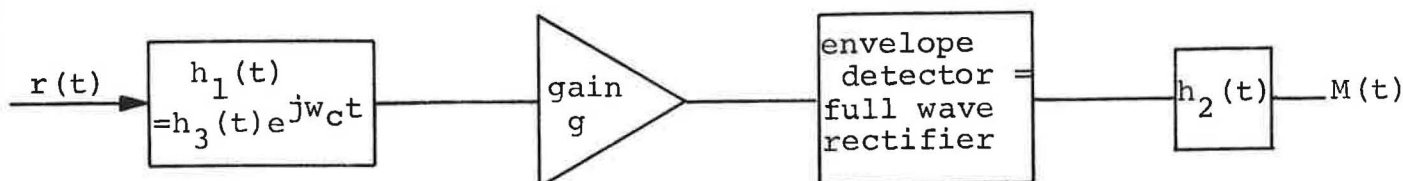


Figure 5.

Where $h_1(t)$ represents the combined impulse response of the linear portion of the system (RF and IF) and $h_2(t)$ is the AGC filter impulse response. The measured envelope amplitude is $M(t)$. The response of this system is:

$$M(t) = g/A(t) * h_3(t) / * h_2(t). \quad A.4$$

When the receiver IF bandwidth is broad with respect to the bandwidth of $A(t)$ this can be approximated as:

$$m(t) = g/A(t)/* h_2(t). \quad A.5$$

The significance of $m(t)$ is strongly dependent on the AGC integration time. If AGC integration time is much less than the reciprocal of the coherence bandwidth (or equivalently, $h_2(t)$ has bandwidth much greater than $A(t)$) then $m(t)$ may be sampled to provide direct information about $A(t)$. If $h_2(t)$ is not broad-band with respect to $A(t)$ then the envelope amplitude of $A(t)$ can not be determined. Nevertheless some usable information about the performance of particular communication systems can be obtained if $h_2(t)$ is broad-band with respect to a proposed modulation waveform. This is, however, inconsistent with the conditions for validity of the single-tap multipath channel model.

Coherence bandwidth can be measured several ways. The minimum frequency spacing to a second carrier frequency $W_{c,2}$ which provides an independent process $A_2(t)$ can be measured, or the time duration of the channel impulse response can be measured with a broad-band proving signal and the reciprocal of this time duration used for the coherence bandwidth estimate.

If it is desired to measure the full random variable $A(t)$ rather than just its magnitude two approaches may be taken. A coherent receiver with identical in-phase and quadrature channels may be used as shown in Figure 6.

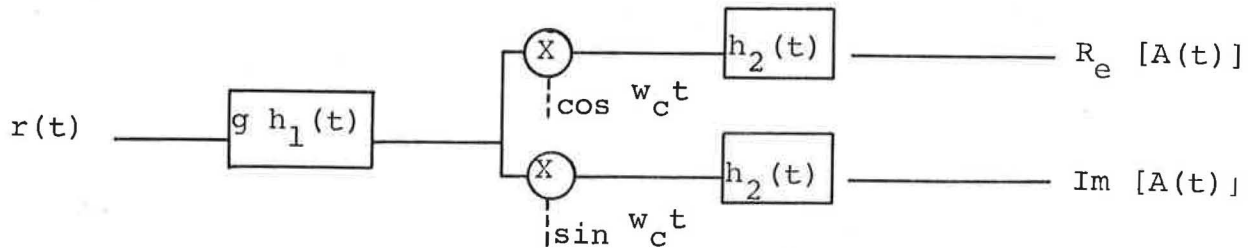


Figure 6.

With appropriate filters $h_1(t)$ and $h_2(t)$ this type of receiver can generate sufficient data to completely record $A(t)$. Alternatively, the envelope detector shown above, and a phase detector, may be used to generate magnitude/angle representation of $A(t)$.

The discussion to this point has assumed an essentially noiseless channel and is useful only in the high signal-to-noise ratio region. When this is not the case a more detailed analysis is required (Ref. 38).

CHANNELS WITH STRUCTURED SCATTERERS

Previously, a channel model which is applicable for totally diffuse scattering channels was described. This model can only simulate channels whose transfer function has a flat spectrum. When specular scatterers are present the spectrum is not flat and this type of model will have limited usefulness since it suppresses important effects.

As an example of a simple channel which illustrates the problems, assume two propagation paths with unknown but fixed gains. Then the spectrum will be a sinusoid with period equal to the reciprocal of the time delay between the two propagation paths, or equivalently, the coherence bandwidth. Then if the bandwidth of a radio channel is much less than half of the coherence bandwidth, the channel will have a more or less flat spectrum as long as no zero of the spectrum is near the region of interest for signaling. It should be clear that no narrow-bandwidth measurement can characterize such a channel.

If the previous model is altered by assuming that the properties of the channel are changing in a deterministic manner with time, then the variation of the channel transfer function with time may be sufficient to fully characterize the channel. An example where such a model might be applicable is an aircraft flying through an environment known to contain one fixed scatterer with known cross-section, and a direct path to the other end of the radio link.

When the narrow-band channel gain ($a(t)$) is measured, the data-reduction process in effect amounts to parameter estimation for assumed models. This will often provide sufficient information for an exact characterization of the measurement data. However, when the effects of the channel on other waveforms must be determined, the validity of the model must be examined. When measurement signal-to-noise ratio is high and the data fits a deterministic model closely the model may be considered to be verified. If the model is probabilistic, as most real channels are, then the model verification process is relatively difficult and typically will require additional measurements.

A separate technical note (Ref. 47) describes an example of a fairly general procedure for estimating parameters of assumed models.

L-BAND/VHF SATELLITE MULTIPATH MEASUREMENTS

An L-Band/VHF Satellite Multipath Measurement Program has been designed by the Telecommunication Division of the Systems Development Directorate at TSC (Ref. 20). In this program the quantity $A(t)$ defined in equation A.1 is measured in a direct manner. Correlation bandwidth is estimated by use of a geometric model which is described in Figure 7. In the multipath model shown in Figure 7 it is assumed that only two propagation paths exist; a direct path between the source (satellite or balloon) and the receiver, and a scattering via the earth's surface. From this geometric picture the delay spread (difference between signal propagation time from shortest and longest paths) can be calculated. This yields a delay spread of less than 10 μ s and results in correlation bandwidth on the order of 100 kHz. The geometric model is not clearly justified and the experiment has not been conservatively designed in that it does not examine the validity of its underlying assumption.

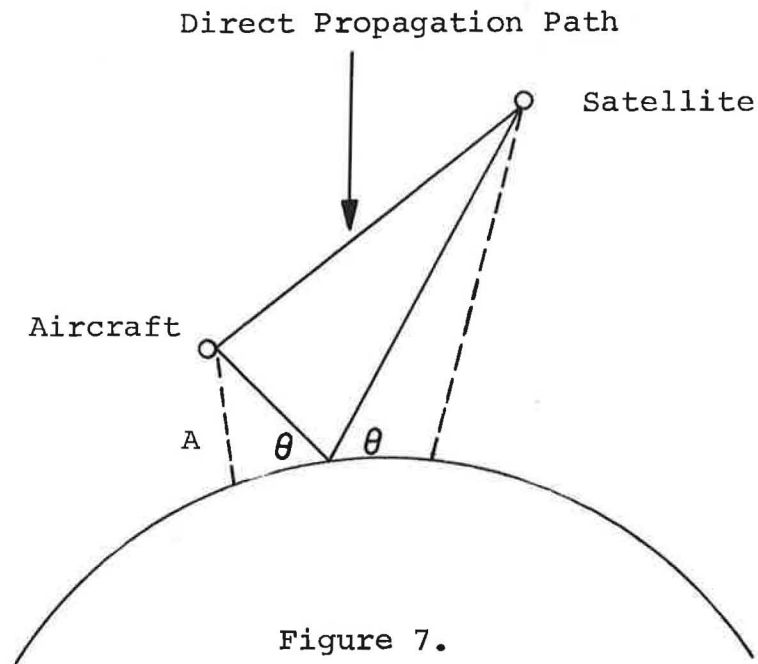


Figure 7.

As has been described above, this type of test yields data which can provide a characterization of the radio propagation channel only if additional data about the channel is assumed. In this particular case it is reasonable to assume that when channel bandwidth is small the model in Figure 7 might be a good channel characterization, and evaluation of parameters of the model would provide a complete characterization. There is no data gathered in this experiment which can be used to examine the bandwidth over which the model is valid. It should be noted that coherence bandwidth is not related to the bandwidth of the characterization with this model.

There is no way to tell if the parameters of a particular channel model can be measured from the experimental data without performing the type of analysis described in Reference 47.

The experiment is high risk in that the data is usable only if subsequent analysis shows that it closely fits a guessed channel model. If a model which provides a close fit is found it may be possible to perform analyses for that model which estimate the bandwidth over which the model is valid.

In any case it seems extremely unlikely that 10 MHz bandwidth systems of the type proposed for satellite-based (e.g., SATANS, LIT) or beacon-type surveillance systems can be evaluated using the data gathered in this manner.

APPENDIX B

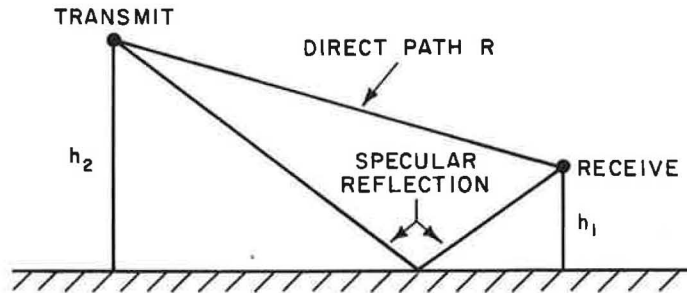
ATA-CAS TEST DATA

Considerable multipath data were taken in the ATA-CAS Flight Test and Evaluation Program, conducted by Martin Marietta (Ref. 34). Most of the data were for the air-air link between two aircraft at the same altitude. Emphasis was on pulsewidth tests and antenna switching tests.

Pulsewidth tests were made on altitude and range pulses. The altitude pulse was a burst of RF energy 4 μ s wide whose leading edge is positioned so as to indicate the altitude. Two tests were made: "min" and "min/max". The "min" test checks for the presence of signal prior to the end of the pulse. The "min/max" test checks for signal presence prior to, and signal absence after the end of the pulse. Naturally the min/max test is more stringent than the min test and the data verified this by showing more rejections due to failure to pass the min/max test. The max portion of the min/max test would detect the presence of multipath reflections. The min test would allow more erroneous altitude readings but this was not found to be significantly higher. The conclusion was to use a min altitude pulsewidth test and increase the pulsewidth to 25.5 μ s. Similar results were observed on the range pulse.

In its normal operation, this system uses omnidirectional antennas on top and bottom of the aircraft for transmission and reception. The antennas are switches so that for air-air communications the upper antenna of one aircraft is used with the lower antenna of the other aircraft. Thus the ground reflections tend to be blocked by the body of the aircraft with the upper antenna. In addition to using the antennas in this normal mode, two out-of-specification switching tests were made. One was to operate one aircraft in reverse so that the transmissions and receptions went from lower to lower and upper to upper. The other was to lock one aircraft into either the upper or lower antenna only and allow the other aircraft to be operated normally.

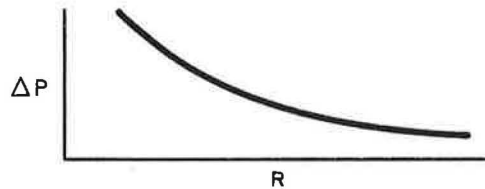
Specular reflections were measured for intensity and time displacement. These results can be reasonably well explained on the basis of simple geometry. Assume the ground to be a smooth reflecting surface. Referring to the diagram, where one aircraft



is at altitude h_1 and the other at altitude h_2 , if ΔP is the difference in path length between the indirect and direct paths, then we have

$$\begin{aligned}\Delta P &= \text{Indirect} - \text{Direct} \\ &= \sqrt{(h_1 + h_2)^2 + R^2} - (h_2 - h_1) - R \\ &= \sqrt{R^2 + 4 h_1 h_2} - R.\end{aligned}$$

The graph of this function is of the form

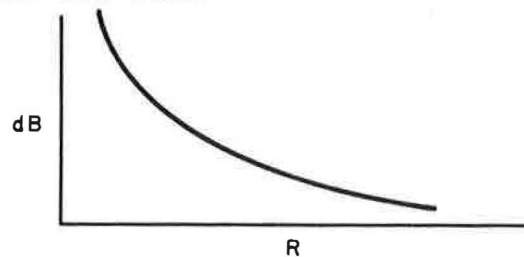


Dividing ΔP by the speed of light gives the time displacement. The observed time displacement data correlated well with the calculations.

The relative power difference in dB between the direct and indirect signals due to free space attenuation is

$$\begin{aligned}
 \text{dB} &= 10 \log \frac{(\text{Indirect})^2}{(\text{Direct})^2} \\
 &= 10 \log \frac{(R^2 + 4 h_1 h_2)^2}{R^2}
 \end{aligned}$$

The actual measured difference will be somewhat greater than this because of energy absorption by the ground. The graph of this function is of the form



No power difference data were reported from these tests.

Note that the ΔP and power difference for the two aircraft at different altitudes h_1, h_2 is the same as for two aircraft at the same altitude $\sqrt{h_1 h_2}$.

Some measurements were also made of the effectiveness of the single parity bit error checking technique (see message format in the ATA-CAS discussion). These data however did not reveal the detailed effect of multipath on digital transmissions. The data did indicate that the single bit parity check was ineffective - a conclusion in line with that generally held by coding specialists for this kind of channel. There is a clear indication from this that further study of error control coding techniques is called for. Such a study should include some carefully designed experimental measurements.

APPENDIX C

ANTIMULTIPATH CODING

The Reed-Solomon (RS) codes were proposed in the ATCAC report (Ref 6, Vol 2, Pages 241-251) to counteract the derogatory effects of multipath reflections. These codes are based on an advanced level of mathematics and the discussion in the above report is probably too technical and too specialized to be of much use to persons concerned with designing ATC communications systems. In an attempt to increase the understanding of RS codes and to pinpoint why they are effective against multipath, we will explain them in relatively simple terms. We present this Appendix in the spirit of how one might "turn the crank" to produce these codes. A specific code is constructed in detail in the belief that it is easier to extend this understanding to the general case than it is to apply the general mathematical RS formalism to a specific case.

We start by letting N represent both the number of symbols in an RS code word and the number of elements in the symbol set. We restrict N so that $N = p^n$, where p is a prime number and n is a positive integer. We construct a first-order RS code with $p^n = 2^3 = 8$. That is, the code will be a set of sequences of 8 elements, each element being a member of a set of 8 symbols.

We construct a Galois field (GF) of 2^3 elements using the "irreducible" polynomial $x^3 + x + 1 = 0$. That is, neither of the elements of $GF(2) = \{0, 1\}$ satisfy this equation mod 2. If α is a root of this equation, the elements of $GF(2^3)$ can be presented modulo $\alpha^3 + \alpha + 1$ as follows:

$$0$$

$$\alpha$$

$$\alpha^2$$

$$\alpha^3 = 1 + \alpha$$

$$\alpha^4 = \alpha + \alpha^2$$

$$\alpha^5 = \alpha^2 + \alpha^3 = 1 + \alpha + \alpha^2$$

$$\alpha^6 = \alpha + \alpha^2 + \alpha^3 = 1 + \alpha^2$$

$$\alpha^7 = 1.$$

Let $P(x) = a_0 + a_1x$ where a_0 and a_1 are elements of $GF(2^3)$. The code that we seek is the set of 8-tuples $[P(0), P(\alpha), \dots, P(\alpha^7)]$ allowing $\{a_0, a_1\}$ to take on all 64 "values" from $GF(2^3)$. For convenience we use the mapping

$$\begin{aligned} 0 &\leftrightarrow 0 \\ 1 &\leftrightarrow \alpha \\ 2 &\leftrightarrow \alpha^2 \\ 3 &\leftrightarrow \alpha^3 \\ 4 &\leftrightarrow \alpha^4 \\ 5 &\leftrightarrow \alpha^5 \\ 6 &\leftrightarrow \alpha^6 \\ 7 &\leftrightarrow \alpha^7. \end{aligned}$$

Then the entire first order RS code becomes:

$P(x) = a_0 + a_1x$	$[P(0), P(\alpha), \dots, P(\alpha^7)]$
0	0 0 0 0 0 0 0 0
αx	0 2 3 4 5 6 7 1
$\alpha^2 x$	0 3 4 5 6 7 1 2
$\alpha^3 x$	0 4 5 6 7 1 2 3
$\alpha^4 x$	0 5 6 7 1 2 3 4
$\alpha^5 x$	0 6 7 1 2 3 4 5
$\alpha^6 x$	0 7 1 2 3 4 5 6
x	0 1 2 3 4 5 6 7
α	1 1 1 1 1 1 1 1
$\alpha + \alpha x$	1 4 7 2 6 5 3 0
$\alpha + \alpha^2 x$	1 7 2 6 5 3 0 4
$\alpha + \alpha^3 x$	1 2 6 5 3 0 4 7
$\alpha + \alpha^4 x$	1 6 5 3 0 4 7 2

To see that this code forms a group, we observe that code words are added on a symbol-by-symbol basis modulo $\alpha^3 + \alpha + 1$. For example, $4 + 6 = \alpha^4 + \alpha^6 = \alpha^3 = 3$. The eight integers 0,1,2,3,4,5,6,7 can be thought to be a symbolic representation of bursts of RF energy of eight different frequencies, making the symbol set orthogonal. It is a property of this code that no two code words are identical in more than one place (the code is said to have at most one overlap). Thus the code is nearly orthogonal: the cross correlation between any two code words is zero or nearly zero.

To get the code with the favorable antimultipath property, delete the first symbol and form a subset of the remaining code words consisting of a word for each fixed value of a_0 , providing $a_1 = 0$. A resulting code then could be

```

1 2 3 4 5 6 7
2 6 5 3 0 4 7
3 7 6 4 0 5 1
4 1 7 5 0 6 2
5 2 1 6 0 7 3
6 3 2 7 0 1 4
7 4 3 1 0 2 5
0 3 6 1 5 4 2

```

Since the original RS code had at most one overlap, the above code will likewise have at most one overlap. And noting the cyclic nature of the truncated RS code, any code word in the above code will have at most one overlap with a cyclic shift of itself or any other code word. Thus the key coding property, in addition to the near-orthogonality one, is that any code word will have low correlation with a shift of itself or any other code word in the code. This shift would be due to the time delay of the multipath reflection.

Observe that the conventional binary PN sequences (also called simplex codes) do not quite do the job. They have near-orthogonality property and low autocorrelation values. But they are deficient in that a time-delayed code word may extend into and exactly match an adjacent word, thus producing a high correlation.

One should be very careful in trying to use these truncated RS subset codes in practice. Many questions have to be answered before it can be concluded that this kind of code, among the many competing techniques, is appropriate for any given application. It is not our purpose here to discuss the many engineering problems that need to be considered.

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