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MULTIFUNCTION DATA LINK FOR AN ADVANCED AIR-TRAFFIC MANAGEMENT SYSTEM

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16. Abstract

This report evaluates the requirements relating to a multifunction data link for an advanced Air Traffic Management System. A two-way time ordered data link is postulated to accomplish the communication and control function. Several candidate modulation schemes and methods for obtaining a time reference are also discussed. The availability of a suitable time reference could also serve as the basic ingredient of an integrated communication, navigation, and surveillance system.

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PREFACE

The work described in this report was performed at TSC under PPA OS204, Advanced Air Traffic Management Systems under the sponsorship of the Office of the Secretary of Transportation, Office of Systems Engineering.

The overall and principal objective of the above program is to define and develop an advance systems concept for future air traffic. This report defines the basic requirements and structure of multifunctional time ordered data link for advanced air traffic systems as they apply to the future of air traffic control.

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1.0 INTRODUCTION

The basic requirements and structure of a multifunction time-ordered data link is presented herein for an advanced air-traffic management system. The multifunction data link makes possible two-way exchange of information between the ground system and a large number of operating aircraft. Such a link may be required to accommodate the flow of air traffic, projected in the 1990's, by automatizing the communication, command, and control functions.

A time-ordered data link requires a time reference. Such a reference might be available from a navigation system based on measurements of the time-of-arrival of signals from known source positions; thus, providing a common element for an integrated communication and navigation system. Availibility of a time reference can also aid the surveillance function, such as the beacon-interrogator system, by time-ordering the beacon replies, and thus alleviating a major problem associated with fruits, garbled replies, and system saturation.

For computational purposes, 4,000 instantaneous operating aircraft were postulated, as might be expected, in dense terminal areas. The derived requirements can be readily modified for other operating conditions such as might be encountered for enroute operations.

2.0 MULTIFUNCTION DATA LINK

A basic function of a multifunction data link is to provide for two-way exchange of information between a ground system and perhaps several thousand aircraft, for automatic closed loop communication, monitoring, collision avoidance, and command and control of air traffic. Figure 2-1 illustrates such an envisioned operation in a functional form, where several sources provide the required information for navigation and air-traffic control. The source of data may be ground derived, air derived or pre-stored information.

a. Ground derived data may be acquired by active sensors such as radar, beacon or trilateration system which measure aircraft's position and velocity.

b. Air derive data may originate from passive navigation sensors, barometric altitude measurements or from aircraft sensors.

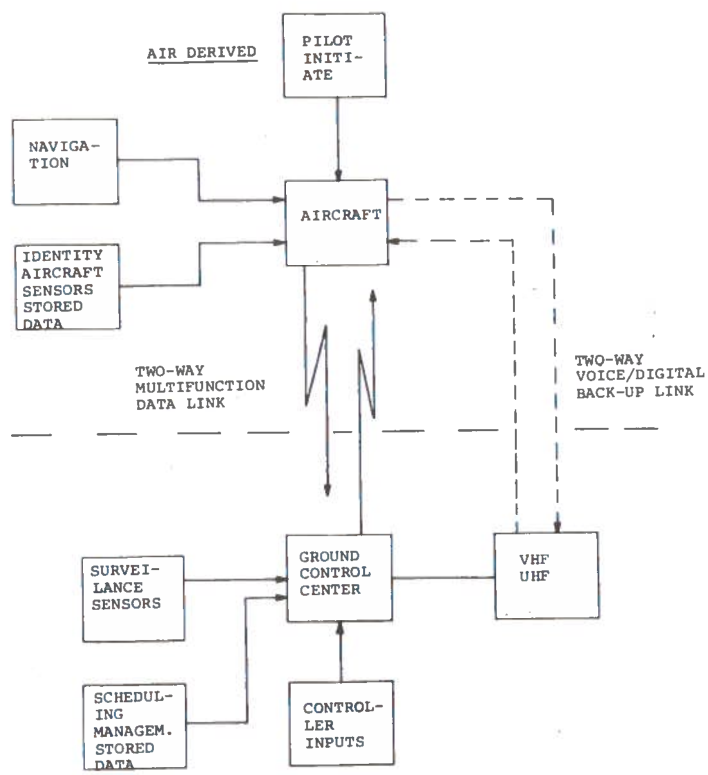


Figure 2-1. Multifunction Data Link - Functional Representation

c. Instructions, requests or commands generated by the pilot or controller and pre-stored supplementary data.

2.1 ATC FUNCTION

With a two-way data link a closed loop communication, command, and control functions can be provided. In high density terminal areas and enroute, the following type of information is required.

a. ATC data such as position, speed, heading, identity.

b. Advisory and instructional.

c. Command and control for separation assurance and collision avoidance.

2.2 ASSUMPTIONS

The following additional tentative assumptions are made on operational requirements:

a. The system surveillance in terminal areas shall accommodate 4,000 aircraft instantaneously per unit time T, where T is the up-date rate.

b. The aircraft shall be addressed in a discrete mode of operation.

c. The data link shall operate over a 100 mile range.

d. The link will operate at L-band. The up-link and down-link will operate on separate frequencies.

e. A two-way voice link will serve as a back up mode. The voice links will operate at either L-band or VHF.

f. Pilot and controller shall have random access to message data, display, commands or requests.

3.0 COMMUNICATION REQUIREMENTS

To determine communication requirements for such a multifunctiona data link, the following information is needed: (a) type of message data, (b) up-date rate, and (c) modulation type.

3.1 MESSAGE DATA

The type of data to be sent up-link or down-link is still not firmly established. However, in a dynamic air traffic control (ATC) situation a steady flow of positional information is required. For the moment let's postulate the following basic requirements for ground-air-ground data transmission.

Up-Link		Down-Link	
Address	30 bits	Idenity	30 bits
Synch	11 bits	Synch	11 bits
Azimuth	12 bits	Altitude	12 bits
Range	12 bits	Range	12 bits
Velocity	6 bits	Heading	12 bits
	71 bits	Speed	6 bits
			83 bits

To provide effective communication, additional instructional information, requests, and, most important, command and control information for collision avoidance would be required as noted in paragraph 2.2. The Appendix of this report outlines a tentative message content for ground-air-ground transmission which could provide all the ATC positional and related functions. The outline was prepared by the North American Working Group for the Second Meeting of the Automatic Data Interchange System Panel of the International Civil Aviation Organization, Montreal, Canada, April 27 through May 15, 1970, where it is stated that these messages could be accomplished with at most 10 alphanumeric (α-n) characters.

One of the more specific tentative suggestions made on the type of messages and formats to be sent up-link was outlined by ARINC in circular letter 121. The tentative outline proposes the use of alphanumerics for display of messages with a minimum of seven characters and a maximum of 14. The tentative outline of messages and format is shown in Tables 3-1 and 3-2. It is assumed here that 10 alphanumeric characters will be sufficient to accomplish this function.

Accepting this assumption, the number of bits/message can be readily evaluated. The no. of bits/message is:

$$\text{no. of bits/message} = (\text{no. of } \alpha\text{-n characters}) \times (\text{no. of bits/charact.}) \qquad (3\text{-}1)$$

There are 26 letters in the alphabet and 10 numerics. By clever composition one could use 32 characters. Each character could then be represented by 5 bits. One could also envision a set of 32 or 64 predetermined messages, each of which could be represented by five and six bits respectively thus considerably reducing the data rate. The assumption is made here that the data format will conform to the American standard code for information exchange (ASC 11). In this format each character is represented by seven bits and one bit is used for parity. Thus, 80 bits are required per message. In addition, an address code plus synch code may be added to the message. A lower and upper bound of 100 and 200 bits respectively is postulated.

- Lower bound = 100 bits: (a) Positional information + identity routing or request information, or (b) Identity + message
- Upper bound = 200 bits: Combined (a) plus (b) (3-2)

TABLE 3-1. SEVEN CHARACTER POSITION DISPLAY

Ground-to-Air Message	Suggested	Alternate
Altitudes		
Climb to (ALT)	↑ 280	↑28000
Descend to (ALT)	↓ 190	↓19000
Climb Immediately to (ALT)	↑↑ 280	↑↑28000
Descend Immediately to (ALT	↓↓ 190	↓↓19000
Maintain (ALT)	ALT 280	M 28000
Headings		
Turn Right to (DEG)	→ 245°	→245
Turn Left to (DEG)	← 039°	←039
Turn (DEG) Right	→ 20°R	→20R
Turn (DEG) Left	← 110°L	←110L
Maintain Heading (DEG)	HDG047°	M 047
Speed		
Increase Speed to (KTS)		↑250KTS
Decrease Speed to (KTS)		↓190KTS
Maintain Speed at (DTS)	250 KTS	M250KTS
Frequency Changes		
Contact Center (FREQ)	C21.250	
Contact App. Control (FREQ)	A23.050	
Contact Tower (FREQ)	T24.700	
Reporting		
Report Reaching (FIX)	RR ESR	ATA ESR
Report Leaving (FIX)	RL ESR	ATD ESR
Request Estimate to (FIX)	ETA ESR	
Hold (FIX)	HLD ESR	HLD@ESR
Cleared to (FIX)	CLR ESR	CLR→ESR
Arrive over (FIX) at (TIME)		
Report Reaching (ALT)	RR 280	
Report Leaving (ALT	RL 190	
Report Present Altitude	RPT ALT	

TABLE 3-1. SEVEN CHARACTER POSITION DISPLAY (CONTINUED)

Ground-to-Air Message	Suggested	Alternate
Collision Avoidance		
Climb Immediately	CLIMB	↑↑↑↑↑↑↑
Dive Immediately	DIVE	↓↓↓↓↓↓↓
Don't Change Altitude	LEVEL	FLY LVL
Level Off	LEVEL	LVL OFF
Turn Right Immediately	TURN→R→	→→→→→→→
Turn Left Immediately	TURN←L←	←←←←←←←
Don't Turn	NO TURN	
Climb Immediately (RATE)		↑↑↑1500
Dive Immediately (RATE)		↓↓↓1000
Turn Right Immediately(NEEDLE)		→→→HALF
Turn Left Immediately (NEEDLE)		←←←FULL
Miscellaneous		
Repeat Last Message	REPEAT	RETRANS
Test Message	TESTING	
Altimeter (PRESS) at (FIX)		
NOT UNDER SURVEILLANCE	NO SEE	
UNDER SURVEILLANCE		I SEE U

TABLE 3-2. FOURTEEN CHARACTER POSITION DISPLAY

Ground-to-Air Message	1st Seven	2nd Seven
Frequency Changes		
Contact Center on (FREQ)	NY CTR	121.250
Contact Approach Control (FREQ)	DCA APP	122.050
Contact Tower on (FREQ)	DCA TWR	120.700
Reporting		
Report Reaching (FIX)	RPT ATA	ESR
Report Leaving (FIX)	RPT ATD	ESR
Request Estimate (FIX)	REQ ETA	ESR
Hold (FIN) (PATTERN)	HLD ESR	SW 1M R
Arrive Over (FIX) at (TIME)	ARR ESR	10103
Report Reaching (ALT)	RPT ARR	280 ALT
Report Leaving (ALT)	RPT DEP	200 ALT
Climb to (ALT) RPT. Reaching	↑ 280	RR 280
Climb to (ALT) RPT. Passing (ALT)	↑ 280	RP 200
Climb to (ALT) RPT. Leaving (ALT)	↑ 280	RL 150
Collision Avoidance		
Climb Immediately (FEET)	CLIMB	500 FT
Dive Immediately (FEET)	DIVE	1000 FT
Don't Change Altitude	FLY	LEVEL
Level Off	FLY	LEVEL
Turn Right Immediately (DEG)	TURN R	90°→NOW
Turn Left Immediately (DEG)	TURN L	90°←NOW
Don't Turn	DO NO	TURN
Miscellaneous		
Repeat Last Message	REPEAT	LASTMSG
Test Message	TESTING	MESSAGE
Altimeter (PRESS) at (FIX)	ESR ALT	29.95
Not Under Surveillance	NOT ON	RADAR

3.2 UP-DATE RATE

The up-date rate is the rate at which new information is acquired concerning the aircraft. In a ground based radar or beacon acquisition system, the up-date rate is determined by the scan rate. The scan rate is a function of the PRF and the required number of data points per dwell time.

The dwell time T_d is given by:

$$T_d = \frac{(\text{scan rate}) \times \theta}{360} \qquad (3\text{-}3)$$

In the present radar beacon system, $\theta=4°$, the scan rate = 4 sec.; therefore, the dwell time per aircraft is about 45 msec.

The PRF is limited by the desirable unambiguous range. If it is desired to have n interrogations per aircraft per dwell time then the scan rate is determined by:

$$(n + 1) = (\text{dwell time}) \times \text{PRF} = \frac{(\text{scan rate})\ \theta \times \text{PRF}}{x\ 360}$$

$$\text{therefore scan rate} = \frac{(1 + n) \times 360}{\theta \times \text{PRF}} \qquad (3\text{-}4)$$

Suppose, that as in the present beacon system, a 200 mile unambiguous range is desired. The PRF is then approximately:

$$\text{PRF} < C/_{2R} \;\; <450 \qquad \text{for 200 mile range} \quad (3\text{-}5)$$

Thus for PRF = 400, the up-date rate is

for n = 2 { up-date rate = 1.4 sec.; dwell time/aircraft = 8 msec.

for n = 3 { up-date rate = 1.8 sec.; dwell time/aircraft = 10 msec.

where, n is the number of bits per scan, θ is the beamwidth of the scanning beam, and PRF, is the pulse repetition frequency.
Assuming:

a. PRF = 400 (to provide a 200 mile unambiguous range)
b. $\theta = 2°$ (contemplated for up-dated third generation system)
c. n = 3 (for detection, interpolation, PRF sweep to sweep correlation) then

$$\text{The up-date rate} = T = 2 \text{ seconds} \tag{3-6}$$

For other acquisition or navigation systems the rate at which new information is generated may be different, and the up-date rate needs to be adjusted accordingly.

3.3 COMMUNICATION RATE

The communication rate or bit rate is given by

$$\text{Bit rate} = \frac{(\text{no. of aircraft}) \times (\text{no. of bits/message})}{(\text{up-date rate})} \tag{3-7}$$

For the postulated conditions,

a. no. of aircraft = 4000
b. no. of bits/message = $\begin{cases} 100 \text{ lower bound} \\ 200 \text{ upper bound} \end{cases}$
c. up-date rate T = 2 seconds

$$\text{The bit rate} = \begin{matrix} 200 \text{ Kb/s lower bound} \\ 400 \text{ Kb/s upper bound} \end{matrix} \tag{3-8}$$

The required bit rate varies with the up-date rate as 1/T.

3.4 BANDWIDTH REQUIREMENT

The bandwidth requirement is given by

$$B = \frac{(\text{bit rate}) \times (\text{modulation type})}{\text{coding rate}} \tag{3-9}$$

Assuming

a. bit rate $= 400$ Kb/sec.

b. coding rate $= 1/2$ (one redundant bit for each information bit)

c. modulation $= 1$ to 2 (PSK or FSK)

$$\text{Bandwidth} \approx 0.8 \text{ to } 1.6 \text{ MHz.} \tag{3-10}$$

The bandwidth requirements could increase considerably if:

a. A smaller fraction of time is available for message transmission;

b. More sophisticated coding is required to provide good reliability.

c. More sophisticated modulation is required to overcome the problem of fruits and multipath.

For example, in multitone modulation several transmission frequencies are used to represent a "1" or a "0", (to provide frequency diversity) expanding the bandwidth by the number of available frequencies. In M-ary Frequency Shift Keying (FSK) the word is encoded into 2^n orthogonal code words or levels where n is the number of bits in the word. The number of frequencies is 2^n and the bandwidth expansion factor $2^n/n$.

The choice of modulation must be judicious. The eventual choice will be determined from functional requirements, complexity, signal integrity, cost and spectrum utilization.

4.0 COMMUNICATION MODES

Three basic communication modes are available: frequency division multiplexing (FDM), time division multiplexing (TDM), and code division multiplexing (CDM) as well as hybrids of the above. The modes are explained in detail below.

a. FDM: In FDM each user is assigned a separate channel for a time duration t. During the time t the user has exclusive use of that channel. FDM is simple and reliable but requires many narrow band channels, is susceptible to interference and suffers from low channel capacity utilization.

b. TDM: In TDM the data is sent serially. Each user is assigned a time slot during which the entire operational bandwidth is available to the user. TDM has high channel utilization and messages can be received from many subscribers without interference. However, TDM requires precise timing and synchronization, and is susceptible to multipath.

c. CDM: In CDM each user is assigned a coded waveform usually with TW product > 1 and shares the entire available channel bandwidth with other subscribers on a continuous basis. In CDM, spectrum spreading provides protection against interference and multipath. On the other hand CDM is more complex than TDM. There may be a lack of "good" codes with orthogonal properties, more bandwidth is required, proper timing and synchronization must be maintained for code correlation and the equipment is more complex.

The choice of modulation is complex. However, in a multitarget environment and burst type operation, TDM appears to be attractive. If the timing requirement or multipath present severe problems, one might operate in a FDM-TDM mode where the increase in the number of subcarriers is traded for an increased time slot interval and reduced efficiency. In TDM the total time interval T is divided among

M subscribers or a time interval of T/M seconds per subscriber. If T=2 seconds and M=4000 aircraft as postulated, the time interval per subscriber is 500 μsec. long.

4.1 MODE OF OPERATION,COMMAND AND CONTROL

We now postulate a time ordered communication system for ATC, where the messages are transmitted and received on a time ordered basis as shown in Figures 4-1 and 4-2. Two operational phases are envisioned, (a) acquisition, identification, time slot assignment, (b) discrete addressing, communication, command and control. In the acquisition phase the time slot and identity code are assigned to the aircraft as it enters the airspace; or if the identity and time slot are pre-assigned, they are obtained through a logical interrogation or polling procedure. With the aid of Figures 4-1 and 4-2 the time ordered operation is as follows:

a. Assign a time slot and discrete address to each aircraft entering the airspace under surveillance, or obtain through polling procedures.

b. When discretely addressed, the aircraft identifies its address and activates the message decoder. The decoded message is displayed or routed for automatic response of selected air-derived data and pilot-initiated requests. The aircraft replies in its assigned time slot with identity and aircraft generated data, via the data link.

c. The ground received message is correlated for aircraft identity. Knowing the time of transmission and range to the aircraft messages are received on a time ordered basis. The message data is routed to compute, appropriate sensors or displays.

d. Ground computed ATC data, requested information, controller initiated commands and instructions are formatted and transmitted to a particular address via the data link. Thus, a closed-loop communication, command and control operation is established. (Note: If the aircraft knows the up-link transmission time and range to the station, it could also receive message on a time ordered basis.)

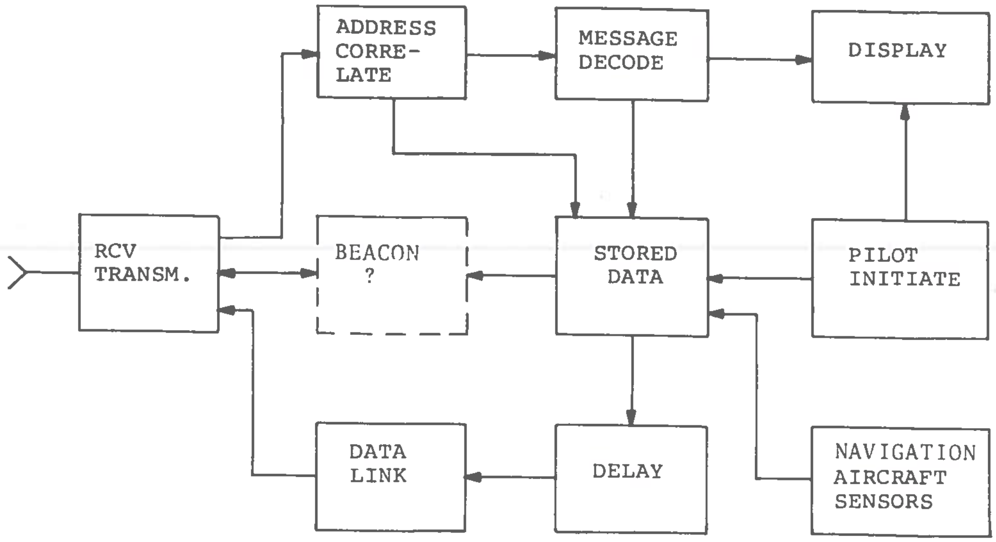
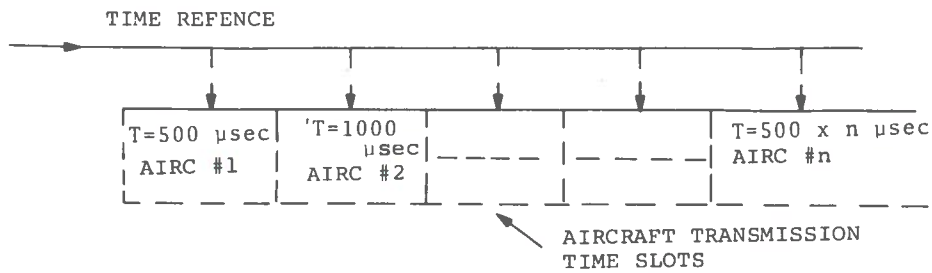


Figure 4-1. Airborne Discrete Address Mode of Operation



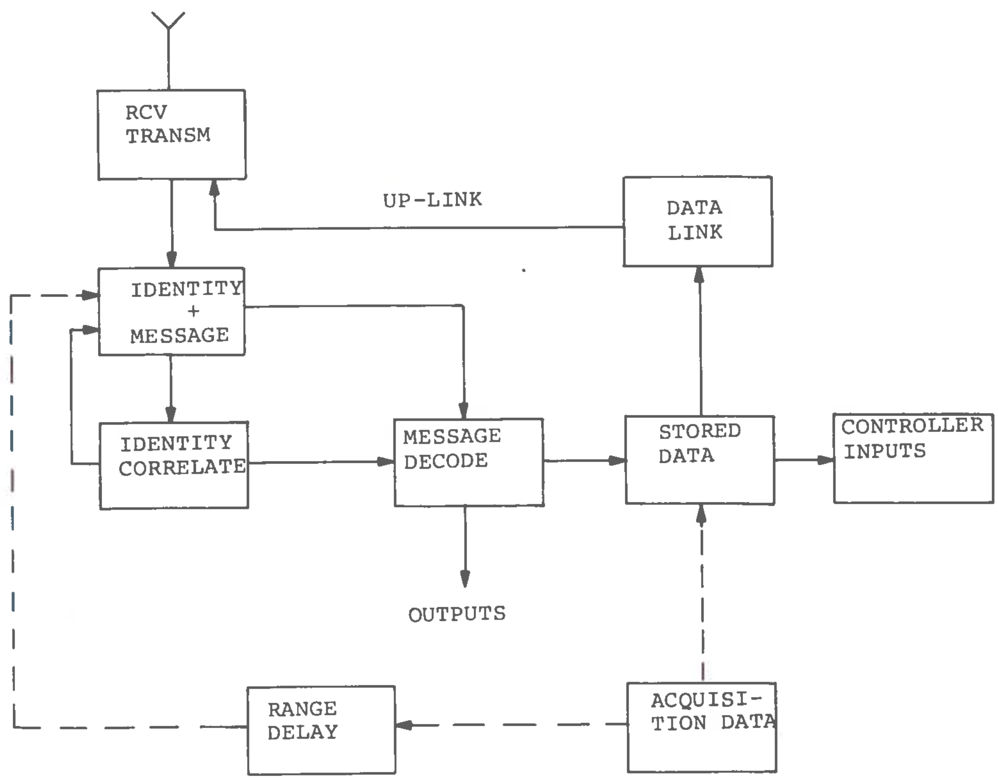


Figure 4-2. Functional Representation of Ground Time Ordered Mode of Operation

4.2 DISCRETE ADDRESS CODES

In the postulated operation each aircraft will be discretely addressed. An ideal discrete address code should have unique properties such that each code, when correlated with itself, is maximum or when correlated with any other address code is zero. In mathematical terms we can describe such a code as:

$$C_i \otimes C_i = L \qquad C_i \otimes C_j = 0 \tag{4-1}$$

where C_i is a code work, L is the code length, $\otimes$ is the correlation, and C_j is a code work different from C_i.

A less stringent but still very desirable characteristic would be of the form:

$$C_i \otimes C_i = L \qquad C_i \otimes C_j = \pm 1/L \tag{4-2}$$

The length L should be minimum to minimize the data rate and bandwidth requirements. Thus, if the number of aircraft is M, the minimum length of the code is given by:

$$M = 2^L \tag{4-3}$$

If M= 4096, then L = 12. In practice it is difficult to find such codes and L would be greater than 12. For instance, there exist orthogonal codes with the ideal property, but of length L given by:

$$L = 2^M \tag{4-4}$$

and hence not practical for large M. Thus, it may be more practical to use a limited number of such code words or coded conventional binary numbers in conjunction with frequency or time division multiplex system.

From operational consideration or electronic complexity, it might be advantageous to label an aircraft with some permanent number. In this case instead of assigning one of n addresses to the aircraft by the controller, the interrogator interrogates the aircraft for the address. In such a case, however, the minimum number of required bits, n, per aircraft would be on the order of:

$$M = 2^n \tag{4-5}$$

where M is the total number of projected aircraft. (For example if $M > 10^6$ then $n > 20$).

The assignments could be made in terms of alpha-numerics. Should alpha-numeric representation be used and a total of 36 characters is available (26 letters, 10 numerals) the number of permutations or addresses is given by:

$$P(n,r) = \frac{n!}{(n-r)!} \tag{4-6}$$

where n is the total number of characters and r is the number of characters used for a label. Thus, for n = 36, and r = 4 the total number of addresses is 1,437,720.

On the other hand if it is desirable for display purposes to use letters first and then numerals, the number of permutations or addresses is given by:

$$\frac{L!}{(L-m)!} \times \frac{N!}{(N-S)!} \tag{4-7}$$

where L = 26 is the number of letters, N = 10 is the number of numerals, m is the number of letters used in the label and S is the number of numerals in the label. Thus, for m = 3, S = 2, the number of available addresses is 1,404,000. To represent 36 characters with binary numbers requires six bits. Thus, in the first case 24 bits would be required and in the second case 30 bits to obtain over a million addresses in alpha-numeric representation.

The drawback of simple binary designation is that such addresses would not have the unique desirable characteristics outlined above and be susceptible to errors, a very undesirable feature in a multitarget environment. Some coding would probably be desirable so that even more binary bits per address would be required. At this time it is not clear whether such an approach would be desirable and acceptable.

5.0 MODULATION, MESSAGE FORMAT, SYNCHRONIZATION

5.1 MODULATION

The choice of modulation is complex because of conflicting requirements relating to implementation complexity, spectrum utilization and reliability of signal transmission. In Table 5-1 several preferable digital modulation modems, (frequency shift keying (FSK)), coherent phase shift keying (PSK) and differentially coherent phase shift keying (DPSK), are compared with respect to bandwidth requirements and achievable probability of error (P_ε).

TABLE 5-1. COMPARISON OF SEVERAL MODULATION SCHEMES

MODULATE TYPE	APPROX. IF+ BANDWIDTH	PROBABILITY OF ERROR (P_ε) OR SNR
FM (ANALOG)	$2\ f_m\,(M+1)$	$SNR = \frac{3}{2} M^2 \frac{B_{IF}}{f_m} \frac{C}{N}$ THRESHOLD $\approx$ 6 to 10 db
FSK	$4/T_b$	$P_\varepsilon = 1/2\varepsilon^{-E/2N_o}$
COHERENT PSK	$2/T_b$	$P_\varepsilon = 1/2\ \varepsilon^{-E/N_o}$
DIFFERENTIALLY COHERENT PSK	$2/T_b$	$P_\varepsilon = 1/2\ (1-\varepsilon rf(\sqrt{E/N_o}))$

LEGEND

f_m = modulation frequency
M = modulation index
T_b = bit length
C/N = IF SNR
E/N_o= SNR(energy/bit per unit bandwidth)

Note: P_ε for PSK is less than 1 db when compared to DPSK for $E/N_o \geq 10$

For comparative purposes expressions for the bandwidth requirements and signal to noise ratio for analog FM is also given. Coherent PSK and differential PSK require least bandwidth. In coherent PSK, for a probability of error $P_{\varepsilon} = 10^{-5}$, the required SNR is about 9.6 db. In differential PSK the probability of error is higher but for E/No > 10, the difference is less than 1 db. In FSK about 3 db more signal power is required than in coherent PSK. Even though coherent PSK is the most efficient of the three digital modulator modems, DPSK is often preferred because of equipment simplicity. On the other hand, if a coherent carrier is required, for instance, for accurate velocity measurements, coherent PSK may be a preferable mode of operation.

Implementation wise, coherent PSK is most complex and FSK least. In coherent PSK it is necessary to reconstruct a reference carrier at the receiving terminal for coherent demodulation. Figure 5-1 shows, in diagramatic form, a typical receiver structure for coherent PSK signals. The incoming modulated carrier is mixed with a coherent reference, generated by means of the VCO at a lower

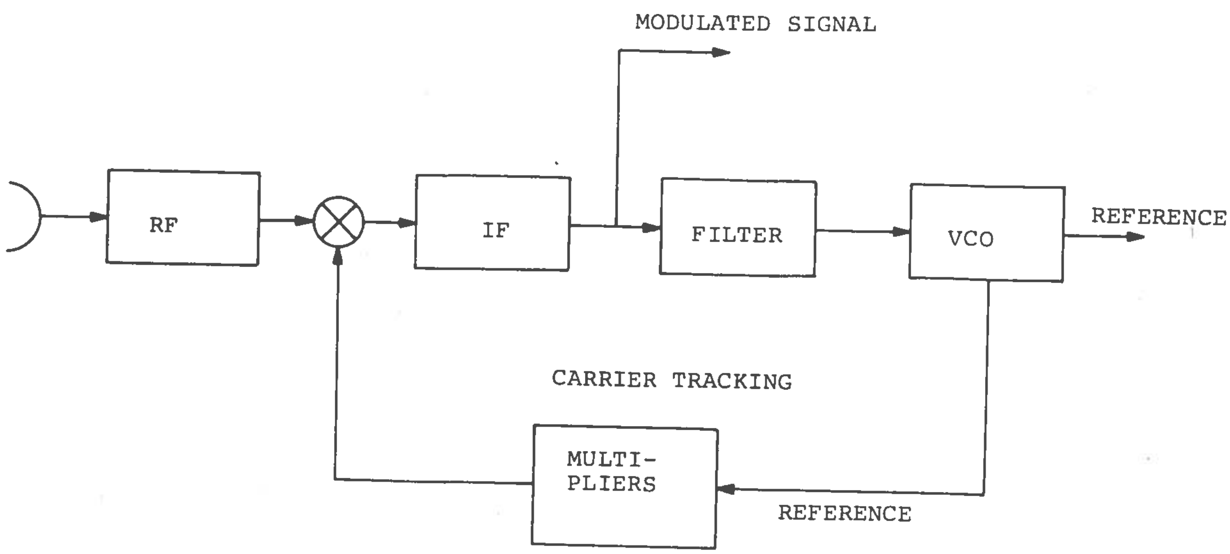
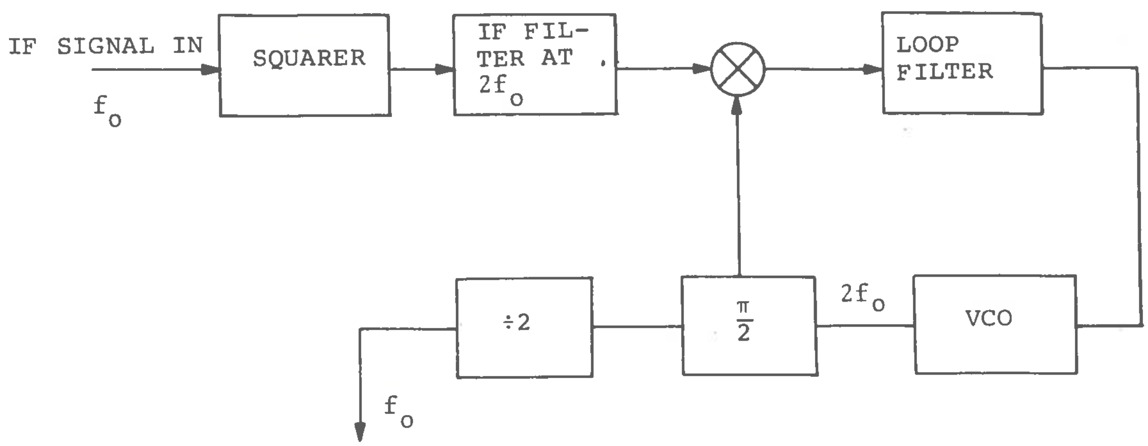


Figure 5-1. Coherent Receiver Representation

SQUARING METHOD



COSTAS LOOP METHOD

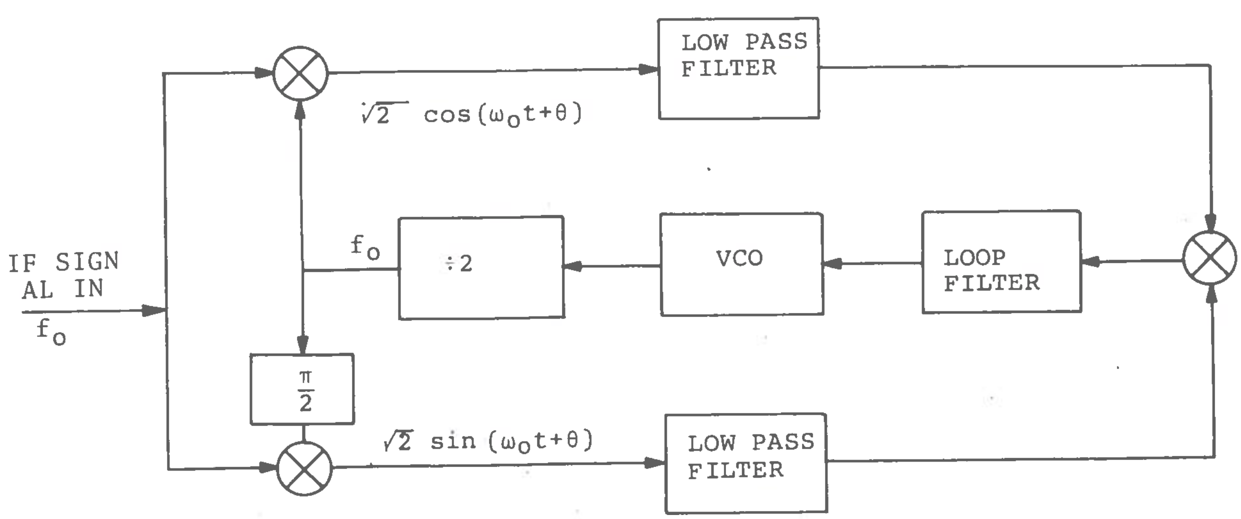


Figure 5-2. Reconstruction of Reference from Coherent PSK Signals

frequency and multiplied as indicated, to establish a carrier tracking loop. Figure 5-2 shows two general methods, the squaring and costas loop techniques, for generating the references at IF frequencies. The generated reference signal can then be used to demodulate the data, synchronization and doppler or velocity tracking and estimation.

Figure 5-3 shows the general receiver structure for DPSK. In contrast to coherent PSK, it is a much simpler configuration. No coherent tracking is required. The data is demodulated by delaying the signal by 1 bit, at an IF frequency, and phase detecting as shown. Each preceding bit serves as a reference signal for the next incoming bit.

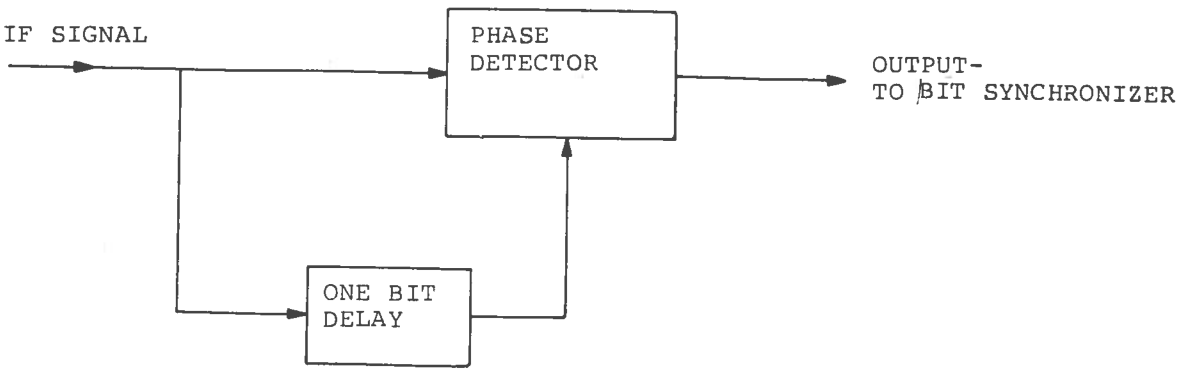


Figure 5-3. Detection of Differentially Coherent PSK Signals

Frequency shift keying is even simpler than DPSK. Even though 3 db more signal power is required for the same comparative performance and almost twice the bandwidth, FSK is a popular modem for many applications where the other two factors, signal power and bandwidth are not critical. Figure 5-4 shows two schematic representation of receiver structures for the reception of FSK signals, one using a discriminator and the other matched filter detection. The detection is incoherent and instrumentation sample. The receiver using a discriminator can be used in a dual role: (a) for detection of FSK signal: (b) for analog FM voice or other broad-band analog signals depending on the system bandwidth.

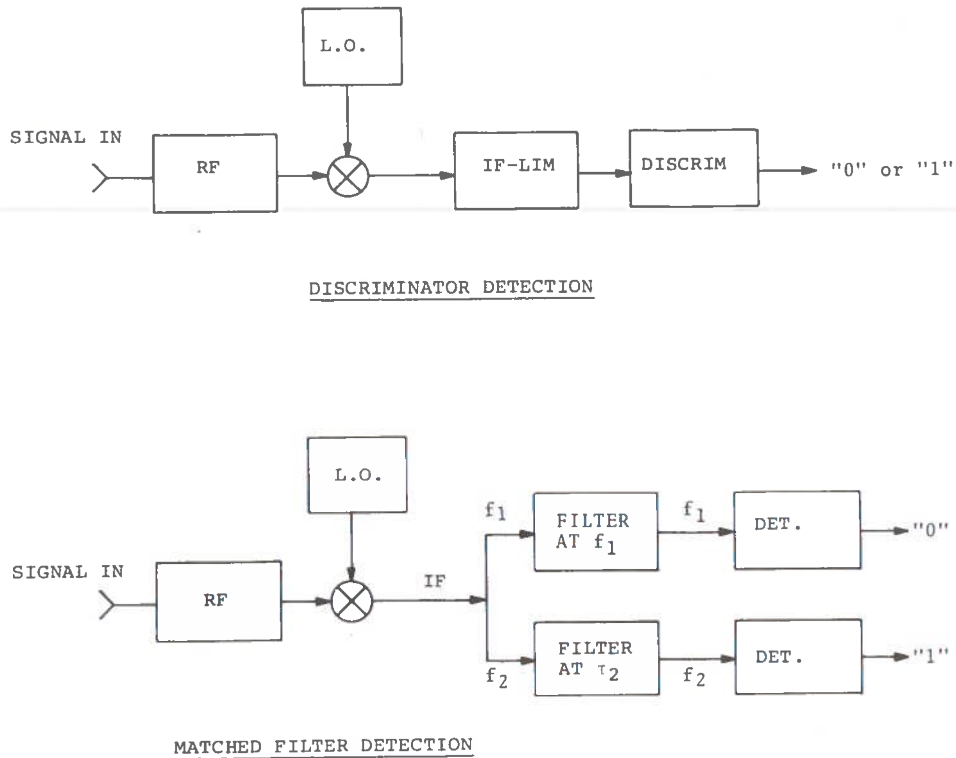


Figure 5-4. Reception of FSK Signals

The above discussion did not take into account severe fading or multipath which may be present in the operational environment. In such a case sophisticated coding or time-frequency diversity may have to be utilized. A meaningful discussion of this topic and techniques is beyond the scope of this report and must be reserved for follow-up studies. However, most of the more sophisticated schemes will in all likelihood include one of the three digital modulation schemes as basic ingredients of the operational modems.

5.2 MESSAGE FORMAT

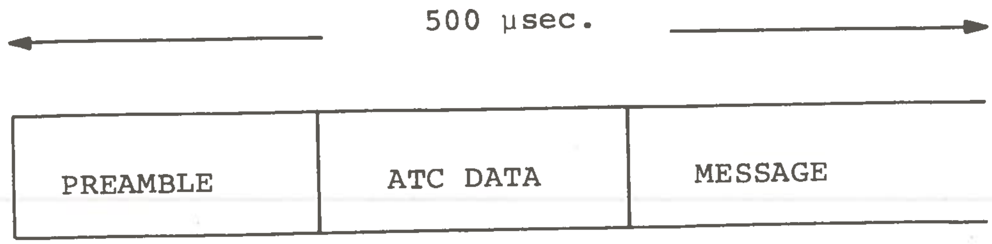
In a time ordered system the information will be transmitted in bursts, where the burst length is T/n, T being polling cycle and n the number of available time slots or subscribers. In our case, the duration of the time slot was postulated to be 500 μsec. long and will be referred to as a frame. The frame format will ordinarily contain a preamble, ATC data and perhaps a message as illustrated in Figure 5-5a. The preamble shown in Figure 5-5b provides the acquisition and execution function; it prepares the system to receive ATC and message data. The preamble contains at least the guard time, carrier recovery, synch and the address. The carrier recovery is required for synchronous systems such as coherent PSK unless provided separately by a synchronizing subcarrier; about 30 bits may be required for carrier recovery.

In differentially coherent PSK, the carrier recovery bits may be replaced by a short duration unmodulated carrier to serve as a detection and timing pulse. The synch and address establish the beginning of ATC data and routes the message to a particular subscriber. Tentatively, 11 bits is assumed for synch and 30 bits for address or aircraft identity. The particular format is similar to the Air Transport Association (ATA) data format for collision avoidance.[1] The pertinent characteristic of this data format are shown in Figure 5-6.

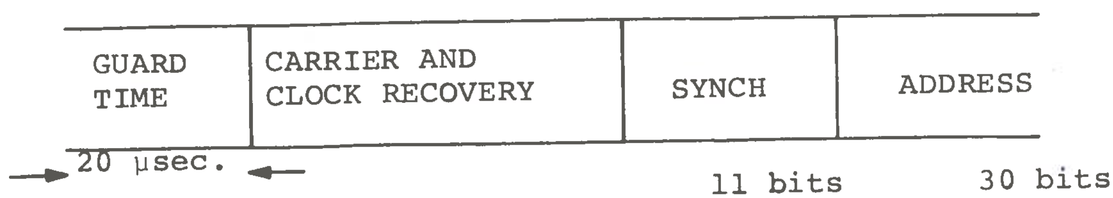
The exact format for the ATC data has not been yet established. The routing instructions and positional data may eventually use a non-standard form to minimize the required number of bits. For the message data we have tentatively postulated 10 alphanumeric characters to achieve flexibility in providing advisory and command and control information. The character format is an ASC II code as shown in Figure 5-5c. Under the stated conditions of 200 maximum number of bits per frame and 500 μsec. time slots, the bit duration will be on the order of 2.5 μsec. More generally, the bit length T_b will be on the order of:

$$T_b = \left(\frac{T}{n}\right) \left(\frac{R}{m}\right) \qquad (5\text{-}1)$$

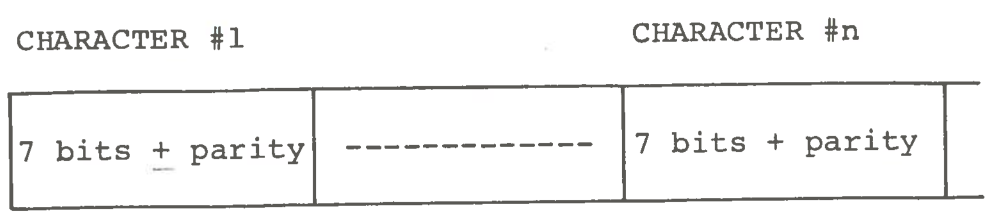
where T is the polling cycle, n the number of subscribers, m is the number of information bits per frame and R is the coding rate.



a. Frame Format

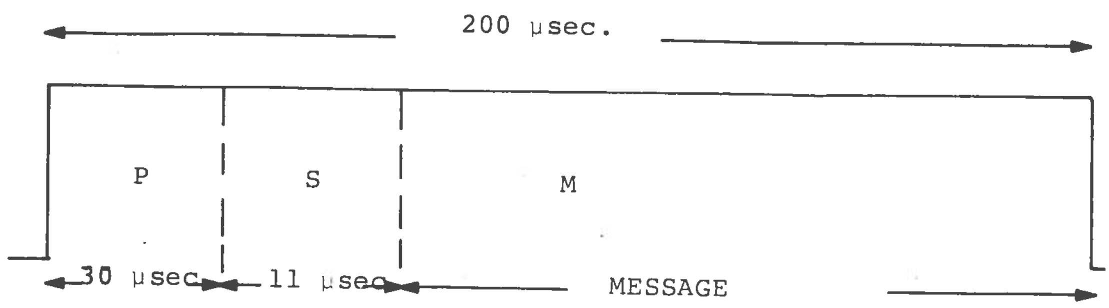


b. Preamble



c. Character Format for Message Format

Figure 5-5. Message Format



P - Preamble (unmodulated carrier)

S - Message start or synch burst

(biphase modulated, 11 pulse inverse Barker Sequence

M - Differentially coherent bi-phase modulated - 2 μsec. per data bit

Figure 5-6. ATA Recommended CAS Data Format

5.3 SYNCHRONIZATION

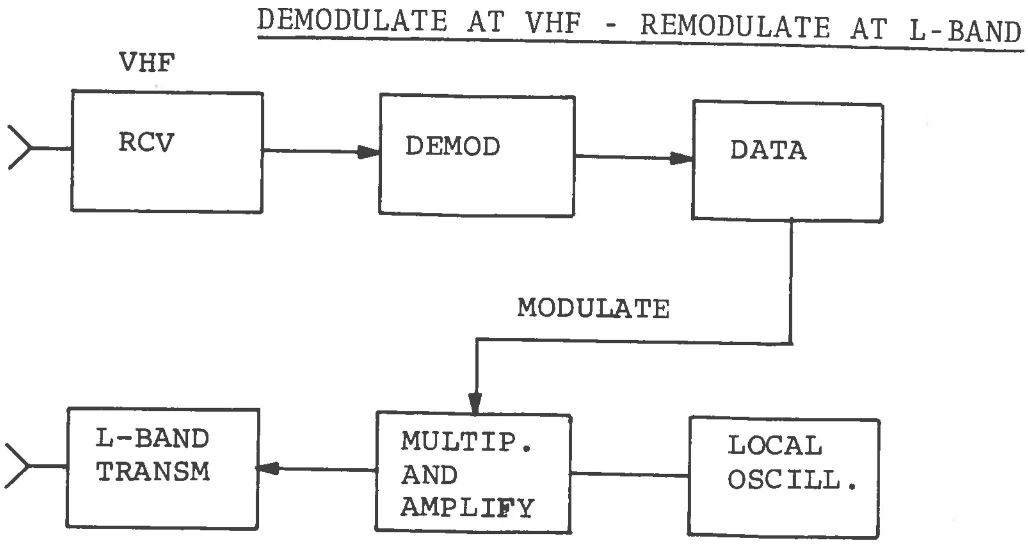
To decode a digital message a synch signal must be acquired to establish the beginning of a message and timing for word decoding. If a single channel is available, the synchronizing pattern is inserted in the message channel.. The important criteria is that the synch be distinguishable and not be a part of a data sequence. The Barker Code used for synch in the ATA data format for collision avoidance has such desirable properties. The sequence when correlated with itself is maximum and when correlated with a cyclic permutations of the sequence is equal or less than unity.

The timing or synchronizing signals can be transmitted on a separate channel where the synch pattern period is related to the word and frame duration. The interesting fact is that by establishing a synch with respect to a time reference, basic elements for ranging also become available. Such integrated modes of signal formats need to be given attention in follow up studies.

6.0 COMPATIBILITY WITH VHF

The multifunction data link was assumed to operate at L-band frequencies with VHF voice/digital back-up link as shown in Figure 2-1. Whatever operational mode is eventually chosen for different classes of aircraft, it would be desirable to provide compatibility between these two subsystems. The VHF channels are assumed to remain the same with the provision that they will be capable of handling either analog voice or digital data. To achieve compatibility, provisions must be made to up-convert from VHF to L-band to VHF. In Figure 5-7 are shown two modes for up-conversion. In direct up-conversion, the received VHF signal is merely translated to L-band and retransmitted to proper destination. In the second method, the information is first demodulated and then remodulated on an L-band carrier. On board generated data may be added to the demodulated data, formatted and transmitted directly or via satellite to a control center.

In Figure 5-8 are shown two methods for inverse process of down-conversion from L-band to VHF. In translating from L-band to VHF the problem arises of matching the information bandwidth. The L-band channel is expected to be wide, while the VHF channel is narrow. As far as voice is concerned no serious problem is expected since the VHF channels can accommodate FM voice. On the other hand the digital rate at VHF may be on the order of kilobits, while at L-band, especially in burst transmissions, it may be on the order of megabit. This implies that to retransmit L-band high rate data, provisions would have to be made for storing such data and then retransmitting at VHF at a slower rate.



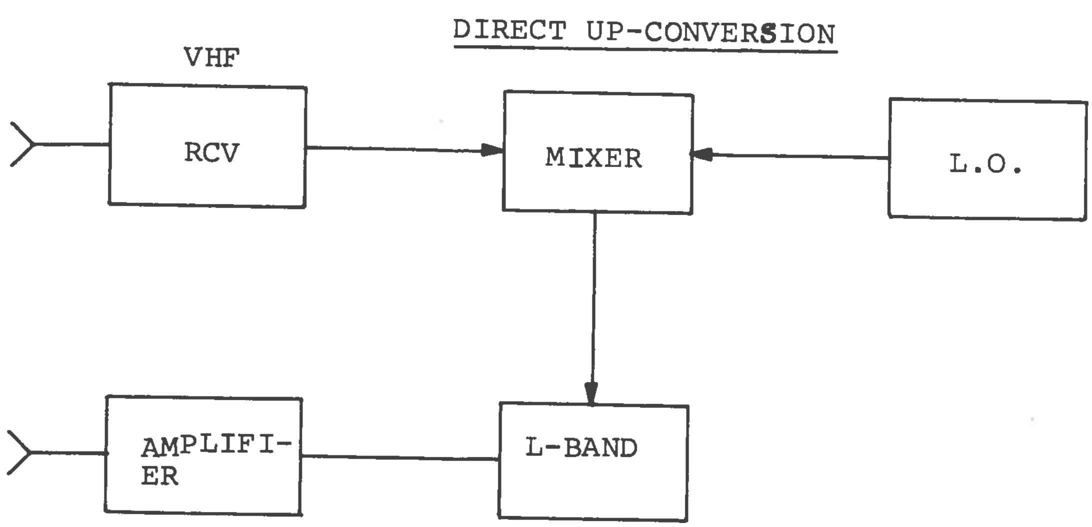


Figure 5-7. Up-Conversion from VHF to L-Band

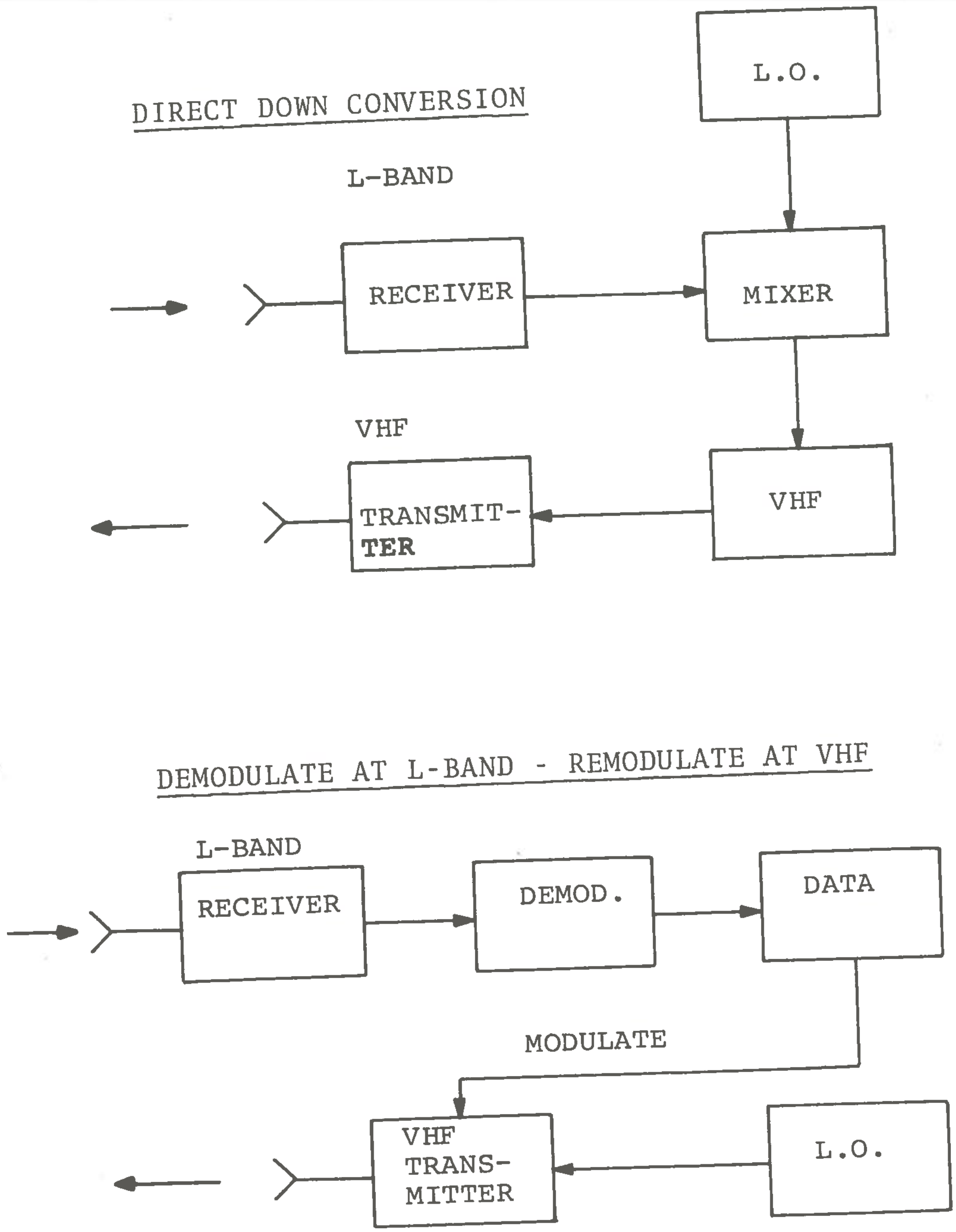


Figure 5-8. Down-Conversion from L-Band to VHF

7.0 TIME REFERENCES AND TIME DISSEMINATION

Time ordered systems are attractive if proper timing and synchronization can be provided: it is a major problem in time ordered systems. In the above postulated operation each aircraft transmits in an assigned time slot of 500 μsec. duration. The following additional informational elements are required for proper operation:

a. Zero time reference or epoch start;
b. Guard time between slot times;
c. Message synchronization.

The zero time reference provides the system with a common reference from which the time slots or time of transmission is measured. The guard time provides isolation between time slots or transmissions and message synchronization is required for demodulation of message data. The latter will depend on the type of modulation and information that needs to be extracted. Time references may be classified into:

a. Absolute:
b. Relative or local time:
c. Disseminated to user from a central standard.

7.1 ABSOLUTE TIME

Absolute time implies a clock aboard the aircraft which is precisely calibrated and runs at the same rate as a universal standard clock. By providing an epoch start, the time intervals can be measured precisely. With such a clock one way range measurements are possible if the position of the transmitting source and plus start time is known. Clocks, however, are not stable and usually must be synchronized. The time accuracy Δt of a clock is given by:

$$t = \left(\frac{\Delta f}{f}\right) t \qquad (7\text{-}1)$$

where $\Delta f/f$ is the frequency stability and t is the counting time. (Note that each microsecond error in Δt, corresponds to a range uncertainty of about 1000 ft.) The clock stabilities are assumed to be as follows:

crystal oscillators.......10^{-8} to 10^{-9}
(stabilized)
atomic.................... 2×10^{-11}
(cesium clock)

For air carriers and especially general aviation, it would be desirable to have simple, low cost clocks. Thus, if we assume a crystal osciillator with 10^{-9} stability, and a flight time of only 10,000 seconds, the timing accuracy $\Delta t = 10^{-4} = 10$ μsec. and an implication that every few hours the clock would have to be recalibrated. Unless, there is a scientific breakthrough, relative time references and synchronization will be required.

7.1.1 Relative Time

In relative time reference systems, the airborne clock is synchronized to a local clock or station such as might be located in a terminal area or enroute control center. Each aircraft entering such an area must synchronize its clock with reference to the local clock. Typically, synchronization is achieved by means of a master-slave type operation, where either master or slave transmit a coded time reference and one of the participants adjusts its clock rate with reference to the other. Several techniques are available.[2] The question that still must be answered relates to the complexity of receiving equipment and cost, synchronization, up-date interval, and trade-off of attainable timing accuracies.

7.2 TIME DISSEMINATIONS

Precise time for time ordered system can in principle be disseminated to users from a central standard such as located at the Naval Observatory, Washington, D.C. by means of satellites of navigation systems such as Omega or Loran. Thus, an entire Air Traffic System would be locked to a Standard Time. In Table 7-1 below some of the possible means of precise time and time interval dissemination are tabulated[3], which are or could be expected in the near future.

TABLE 7-1. PRECISE TIME DISSEMINATION

MEANS OF DISSEMINATION	ACCURACIES	
1. Portable Clock	1/2 μsec. Global	
2. VLF - Omega	5 μsec. (timing capability) Global 1-3 μsec. (phase track-relative)	
3. Loran-C	1/2 μsec. Covers Northern Hemisphere except Western U.S.	
4. Satellites:		
a. DSCS	0.1 μsec. (Trunk line)	2 way
b. TacSat	0.5 μsec. (Intermediate)	2 way
c. Transit	10 μsec. Global	passive
d. DNSS (Timation)	0.1 μsec. Global	passive

As seen from Table 7-1 using Omega and Loran-C time could be disseminated with timing accuracies of ±5 μsec. and ±0.5 μsec. respectively. The attractive feature is that this dissemination as an incidental fallout from the navigation system. By some modification of transmitter an incorporation of time code, time can be promulgated to the user with some minor receiver modification. If satellites are used to relay time, special equipment may be required. In all probability the time would have to be relayed to the user via central stations in the air traffic system.

The problem of equipment complexity, up date interval, net arrangement, reliability and cost still remain to be resolved.

7.2.1 Timing Accuracies

The required timing accuracies depend on the systems functional and operational requirements. In the postulated system with 500 μsec. long time slots, we may allocate slot guard times of say 5% corresponding to a timing accuracy of 25 μsec., with small loss in efficiency. Such a requirement could possibly be met by an Omega navigation systems provided the epoch time measurement interval is not too excessive. However, if, for instance, range measurements are to be based on the delay of a pulse from epoch time, use of Omega would restrict the accuracy to ±5000 ft. For 100 ft. range resolution, timing accuracies on the order of 0.1 μsec. would be required. Loran-C is considerably more accurate than Omega, but also expensive and may not be economical for general aviation.

8.0 MULTIFUNCTION DATA LINK APPLICATIONS

8.1 THE INTERROGATOR-BEACON SURVEILLANCE SYSTEM

The utilization of a multifunction data link is discussed below with reference to the up-dated interrogator-beacon surveillance system proposed by the Alexander Committee for the third generation air traffic system.[4] The tentative proposed characteristic of the interrogator-beacon surveillance system are as follows:

a. Discrete addressing and data link
b. 4096 distinct codes as potentially available in present day beacons
c. Range accuracy = 100 ft.
d. Interrogator beamwidth = 2°
e. Angular accuracy - 1-2 mils (monopulse)

Accuracy for 2 mils = 1000 ft at 100 miles
100 ft at 10 miles.

Presently, the beacon, in response to modes 3A and C interrogations replies with a 12 digit identity burst or an automatic 12 digit altitude report burst. As noted in a. above, discrete addressing plus data link is a main requirement for increasing the level of automation in future air traffic systems. However, the signal format and mode of operation of such a data link is, so far, still undertimed. The outlined time ordered data link could be adopted to operate with an advanced beacon system as a prime ground surveillance system. Figure 8-1 shows a possible integrated airborne mode of operation. The beacon is tentatively assumed to retain the 4096 identity codes even though the eventual number and structure of the identity codes may be different. As illustrated in the diagram, the identity codes could be used to specify the slot time assignment for individual aircrafts. Assignments of a code is linked automatically to a transmission time slot measured from zero time reference. The slot duration would be on the order of T/m where T is the polling cycle and n the number of available addresses.

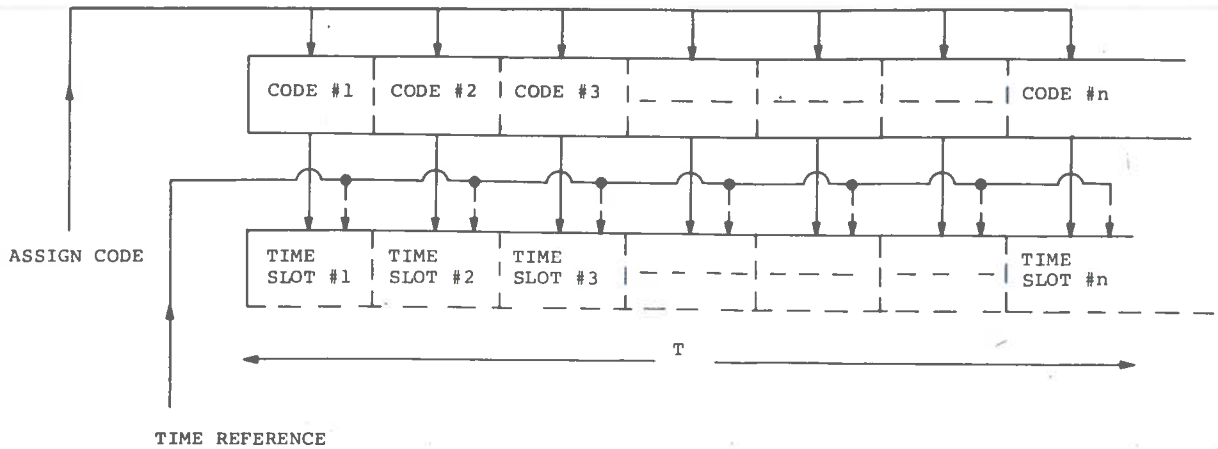


Figure 8-1. Up-Dated Beacon Airborne Time Ordered Mode of Operation

8.2 NAVIGATION

With the aid of a multifunction data link, the position data acquired by the aircraft navigation system can be provided to the ground system, if so required. Similarly, the ground system can provide navigation data to the aircraft in case of a malfunction in the navigation system or for validation of data. In 4D type area navigation, correctional information may have to be supplied periodically to the aircraft, as computed by the ground system, to maintain its (x,y,z,t) flight plan and schedule.

8.3 INTEGRATED COMMUNICATION AND NAVIGATION

In a hyperbolic navigation system such as Loran or Omega, the aircraft determines its position by measuring the differences in the arrival time of distinct pulses from a master and two slave stations; the stations transmit at different frequencies and at known times. By comparing the differences in the signal arrival time from two pair of stations, the aircraft determines its position. The above measurements are relative, and no absolute clock is required aboard the aircraft. A satellite-aided navigation system could similarly provide the required position information. By incorporating a time code on one of the transmitted carriers, precise time can be established aboard the aircraft that would permit transmission and reception of signals in the assigned time slots and rapid synchronization. If precise time becomes available aboard the aircraft, one could also consider the use of one-way ranging and all the related ramifications.

The above discussion clarifies the fact that the key elements in an integrated communication and navigation system is an accurate time reference. The time-ordered data link requires such a reference which basically could be obtained from navigation systems that measure time-of-arrival of signals from a known reference source. However, in each terminal area a relative time reference could be supplied by a separate ground station.

9.0 CONCLUSION

This report discussed the requirements and uses of a multi-function data link for an advanced air traffic system. A time ordered data link was postulated from a two-way exchange of data, command and control, between the ground and several thousand air-crafts. A key element in a time ordered communication link is a time reference or synchronization which, in principle, could be obtained from the navigation system. Thus, a time ordered data link contains the basic ingredients for an integrated air traffic system.

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APPENDIX

DISCUSSION PAPER NO___
NORTH AMERICAN WORKING GROUP
ADIS PANEL

<u>Message Content for an Aeronautical Mobile Digital Communications System</u>

(Retyped from original copy specifically for this report)

Submitted by the United States

RD-232: WP-5/70
Original Issue
Copy No:______

WORKING PAPER
Project 232-002-01C

Message Content for
An Aeronautical Mobile Digital Communications System

(Text of a Working Paper presented to the Second Meeting of the Automatic Data Interchange Systems Panel of the International Civil Aviation Organization, Montreal, Canada, April 27--May 15, 1970)*

27 May 1970

FAA, Systems Research and Development Service, Washington, D.C. 20590

*Courtesy of V. Rogers of the FAA

MESSAGE CONTENT FOR AN AERONAUTICAL MOBILE DIGITAL COMMUNICATION SYSTEM

An aeronautical mobile digital communication system to be fully effective, must be capable of handling the following types of messages:

1. ATC Control Information
2. Advisory (non-control) information, such as weather
3. Requests for information and assistance
4. Acknowledgements
5. Emergency messages
6. Company operational messages

In the following paragraphs, present thinking as to the content and extent of messages in each category are discussed.

1. ATC Control Information

The transition from manual to automated air traffic control, which is presently getting underway and will continue for many years, seems certain to have an appreciable, perhaps drastic effect upon operational procedures. Changes in operational procedures will inevitably produce changes in the nature, quantity, and general character of control communications between control authority and aircraft. Therefore, it is not practical at this time to specify precisely the number, form, and content of these messages.

For planning purposes, a repertory of 32 equiprobable air-to-ground messages, and an equal number of ground-to-air messages, each of which can be expressed in approximately 10 or fewer alphanumeric characters, is presently being postulated.

Messages which presently appear to be necessary or desirable include:

a. Ground-to-Air

(1) You are under surveillance

(2) Climb (to altitude)

(3) Descent (to altitude)

(4) Turn left (to heading)
(5) Turn right (to heading)
(6) Maintain heading
(7) Maintain altitude
(8) Contact ground station on voice
(9) Fly (coded route structure)
(10) Fly (specific heading)
(11) Arrive over (fix) at (time)
(12) Repeat last message
(13) Increase speed (to knots)
(14) Decrease speed (to knots)
(15) Maintain speed
(16) Clearances
(17) Changes
(18) Etc.

b. Air-to-Ground

(1) I acknowledge your command
(2) I have executed your command
(3) Request voice communications
(4) Repeat last message
(5) I refuse your command
(6) Altitude rate
(7) Heading
(8) Speed
(9) Etc.

2. <u>Advisory (non-control) information</u>

The nature, quantity, direction, and general character of advisory information passing between ground station and aircraft are dependent upon the basic philosophy of the air traffic control system being employed. If strict ground control is exercised (the so-called "tactical" approach), very little advisory data need be sent to the airplane--the ground control will make all the decisions.

However, in order to make optimum decisions, much more information on aircraft status may have to be "telemetered" to the ground. On the other hand, if ground control is very liberal (the so-called "strategic" approach) or if an electronic "see and be seen" philosophy is employed, then the aircraft pilot must be supplied with a considerable amount of advisory information on which to base his decisions.

Assuming a more or less "middle of the road" system, not appreciably different from today's system, the messages listed in the following paragraphs will probably be required.

a. Ground-to-Air

(1) Enroute Weather Message

(a) Ceiling

(b) Clear air turbulence

(c) Icing levels

(d) Wind shear

(e) Ozone advisory

(f) Radiation level advisory

(g) Etc.

(2) Terminal Weather Message

(a) Altimeter Setting

(b) Runway Conditions

(c) Runway temperature

(d) Runway Visual Range

touchdown

mid-point

roll out

(e) Sky condition

(f) Turbulence

(g) Wind direction and speed (surface)

b. Air-to-Ground

(1) Automatic Upper Air Weather Report

(2) Outside air temperature, wind speed and direction, humidity.

(3) Automatic Aircraft Status Report

Reports of unusual or out-of-tolerance conditions which -

a. might affect the ability of the airplane to operate in the air traffic control environment

b. might assist the operating agency in maintaining efficient and economic operation of the aircraft

3. Requests for information and assistance

a. Ground-to-Air

It is envisioned that most ground-to-air requests will be machine to machine with little or no human intervention at either terminal. Some possible request messages might be:

(1) Request for air derived position (x,y,z, time)
(2) Request for weather report
(3) Request for voice communication

b. Air-to-Ground

Most air-to-ground request will probably be man-to-machine (pilot initiated) and will deal with out-of-the-ordinary facets of operation. Some possible requests may be:

(1) Request for weather at alternate airport
(2) Request for weather along alternate route
(3) Request for ground based position fix (for update of on board navigation equipment)
(4) Request for voice communications
(5) Request for retransmission of a faulty message
(6) Etc.

4. Acknowledgments

Three types of acknowledgments will probably be required in the system.

a. Technical acknowledgment - A "Technical acknowledgment" is an acknowledgment that a message has been received without any technical deficiency, such as parity errors, essential portions missing, etc.

b. Message understood and accepted - This type of acknowledgment indicated that the man or machine to which the message is directed understands the meaning of the message and is prepared to take the necessary action described in a message.

c. Action completed - This acknowledgment indicates that the action described in a message has been taken.

5. Emergency Messages

Emergency messages to be of practical use should be automatically initiated and transmitted since personnel involved will most probably be fully occupied in taking immediate corrective measures. Voice messages declaring emergency situations will undoubtedly be sent, but due to the time lags associated with human reaction time and human tendency to defer declaration until at least some corrective actions are taken, the automatic digital message may be more timely (provided efficient and reliable sensors and decision elements can be provided).

The following emergency message may be required to be handled:

a. Ground-to-Air

Collision Avoidance Commands

(1) Turn right immediately (rate)
(2) Turn left immediately (rate)
(3) Climb immediately (rate)
(4) Descend immediately (rate)
(5) Don't turn
(6) Don't change altitude
(7) Level off
(8) Etc.

b. Air-to Ground

(1) Major electrical system failure
(2) Major loss of engine power unable to maintain altitude
(3) Major structural failure
(4) Major loss of pressurization
(5) Serious fire
(6) Etc.

6. <u>Company operational messages</u>

Company operational messages include:

a. Status of aircraft (go-no go)
   - (1) Power plants
   - (2) Airframe

b. Status of subsystems
   - (1) Passenger services
   - (2) Communication
   - (3) Navigation
   - (4) Weather radar
   - (5) Flight controls

c. Position Reports - Flight progress
   - (1) Time out
   - (2) Time off
   - (3) Time on
   - (4) Time in

d. Weather
   - (1) Icing
   - (2) CAT
   - (3) Other hazardous

e. Special services
   - (1) Ambulance
   - (2) Doctor
   - (3) Etc.