AD-759 709

HF COMMUNICATIONS IMPROVEMENT FOR NAVAL AIRCRAFT

J. M. Horn

Naval Electronics Laboratory

Prepared for:

Naval Air Systems Command

2 January 1973

NELC / TR 1857

NELC / TR 1857

HF COMMUNICATIONS IMPROVEMENT FOR NAVAL AIRCRAFT

Antenna and signal processing systems revealed as key to improved aircraft communications

J. M. Horn

Research and Development

2 January 1973

D D C
MAY 14 1973
C

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

NAVAL ELECTRONICS LABORATORY CENTER
SAN DIEGO, CALIFORNIA 92152

24

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
Naval Electronics Laboratory Center
San Diego, California 92152

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
HF COMMUNICATIONS IMPROVEMENT FOR NAVAL AIRCRAFT

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Research and Development July 1971 through September 1972

5. AUTHOR(S) (First name, middle initial, last name)
J. M. Horn

6. REPORT DATE
2 January 1973

7a. TOTAL NO OF PAGES
22

7b. NO OF REFS
2*

8a. CONTRACT OR GRANT NO.

b. PROJECT NO NAVAIR W3243 (NELC B705)

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TR 1857

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Approved for public release: distribution unlimited

11. SUPPLEMENTARY NOTES
*Also includes bibliography

12. SPONSORING MILITARY ACTIVITY
Naval Air Systems Command

13. ABSTRACT

Research pinpoints techniques that promise improvement in aircraft hf communication system design. Approaches discussed include:

1. Adaptive hf antenna array including antijam
2. Miniature passive and active antenna elements
3. Adaptive phase equalization/predetection combining
4. Polarization diversity
5. Mode averaging diversity combiner
6. Antenna mathematical modeling techniques

Two techniques show promise for diversity reception improvement – Villard mode averaging and predetection/phase equalization combining.

Improved aircraft antenna systems are the key to improved aircraft communications. Mathematical modeling shows promise for designing aircraft antennas. Hf adaptive antennas may be feasible for both beam and null steering.

DD FORM 1 NOV 65 1473 (PAGE 1)
0102-014-6600

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Hf communications						
Aircraft antenna systems						
Polarization diversity						
Frequency diversity						
Modems						
Combiners						
Adaptive antenna arrays						
Miniature antenna elements						
Active antennas						
Passive antennas						
Receive antennas						
Transmit antennas						

UNCLASSIFIED
Security Classification

PROBLEM

To improve hf aircraft communications on the platform without significantly increasing weight, size, and power.

RESULTS

The research reported here has pinpointed techniques that promise to overcome some of the problems in aircraft hf communication system design. The approaches that are discussed are:

- Adaptive hf antenna array, including antijam
- Miniature passive and active antenna elements
- Adaptive phase equalization/predetection combining
- Polarization diversity
- Mode-averaging diversity combiner
- Antenna mathematical modeling techniques

CONCLUSIONS

1. The Villard mode-averaging technique shows promise for diversity reception improvement.

2. The predetection/phase equalization combining technique also shows promise for diversity reception improvement.

3. Improved aircraft antenna systems are the key to providing improved aircraft communications.

4. Mathematical modeling shows promise for designing aircraft antennas.

5. Hf adaptive antennas on aircraft may be feasible for both beam and null steering.

ADMINISTRATIVE INFORMATION

Work was done by the Radio Technology Division under NAVAIR W3243 (NELC B705) from July 1971 through September 1972. The report was approved for publication 2 January 1973.

The author extends appreciation to W. M. Chase and R. L. Goodbody, NELC, for their valuable contributions to this report.

CONTENTS

TABLES

1.0 INTRODUCTION

The purpose of this task is to provide studies and design recommendations relating to improvements in hf communications for Naval patrol aircraft over ranges to 2000 miles. This requirement presents severe design problems to the communications and antenna system designers because of the vagaries of hf propagation and the difficulty of providing an adequate communication system design in the limited space on aircraft. One of the fundamental communications problems on the aircraft is to determine (in real time) the best frequency to transmit on. This is both a circuit management problem and an aircraft communication system design problem. This report considers both of these aspects of the problem in relation to the design of patrol aircraft communications and control systems.

2.0 PROPAGATION FACTORS THAT AFFECT AIRCRAFT COMMUNICATION SYSTEM DESIGN

Many propagation phenomena affect the receivability of the transmitted signal in the hf range. The receive system should be designed to minimize the deleterious effects of the following:

- Multipath propagation
- Polarization shifting
- Atmospheric noise

Multipath propagation causes nulls to occur in the information passband spectrum of the receiver due to the interference of two or more modes of differential time delay. These nulls occur periodically in frequency at a reciprocal of the differential time delay. A time delay of 2msec (not normally exceeded) results in a spectrum null every 500Hz (Villard, et al 1972). Additionally, the different propagation modes can undergo a differential frequency shift in the ionosphere which causes the resultant received signal to undergo a periodic time fading. The differential doppler can be typically 0.1 to 1Hz, which causes the received signal to have a time fade with a period of 1 to 10 seconds. These temporal time fades do not occur simultaneously across the passband spectrum, but propagate across it.

The polarization shifting observed at the receive site is caused by wave splitting in the ionosphere due to the presence of the earth's magnetic field. The resultant two waves are circularly polarized with opposite sense and propagate with different phase velocities. The two waves combine at the receive site to form the resultant field. (The field is a randomly polarized elliptical wave that may be slowly rotating due to the difference of the distinct wave velocities.)

The aircraft receive system must be designed to minimize these propagation effects while not introducing more weight and power requirements. Atmospheric noise is important to the design of the receive system, since it establishes the upper limit on receiving system noise figure allowed.

3.0 FREQUENCY MANAGEMENT CONSIDERATIONS

The patrol aircraft has a few hf circuits assigned for reception and transmission of command control communications and for transmission of sensor data. The proper frequency for transmission to a designated remote site must be determined just prior to selection and usage. The desirable frequency for usage, FOT (frequency of optimum transmission), changes gradually throughout the day. The raw error rate of an hf circuit is minimized when this frequency is used, because the multipath situation is minimal. Thus, it is important that the communication system on the aircraft be designed to incorporate frequency management, including detecting the necessity to shift frequencies.

The remote site may transmit with one or more transmitters with the same traffic. The patrol aircraft normally transmits on one data channel and may have a separate transceive channel for command control.

4.0 RECEIVE SYSTEM DESIGN TO COUNTERACT PROPAGATION AND PLATFORM EFFECTS

The receive system on the aircraft should be designed to overcome certain of the propagation effects. The traditional techniques used are the following:

- Polarization diversity
- Frequency diversity
- In-band frequency diversity

(counteract propagation effects)

- Majority logic (counteracts both propagation effects and pattern nulling)
- Pattern diversity (counteracts radiation pattern nulling due to platform effects)

Of these, only polarization diversity has not been deliberately designed and implemented on Navy aircraft.

4.1 THEORETICAL DIVERSITY IMPROVEMENT

Diversity* combining is employed at hf to reduce the error rate obtainable in a single channel at a given signal-to-noise ratio (SNR). Space, polarization, or frequency (but not pattern) diversity combining provides a capability – in real time – to significantly overcome the effects of fading. The combiner produces a composite signal which does not have fades as deep or as numerous. There are many combining techniques which can be employed in the combiner (modem). All of them can be expected to provide the maximum obtainable diversity improvement when the correlation coefficient between the antennas is zero.

---

*The terms adopted in this report are diversity and quadversity for two- and four-channel combining, respectively. All forms of diversity, except space, are applicable for utilization on aircraft to reduce the raw, or nondiversity, error rate.

Sifford (1965) states that negligible deterioration in performance occurs for a signal correlation coefficient up to 0.6 as compared to zero. Thus, the correlation coefficient of the signals from antennas which are collocated but which have differing polarization ellipsis can provide significant diversity action. In fact, obtainable data in Grisdale et al (1956) and Schwartz et al (1966) show that a signal correlation coefficient of up to 0.8 yields diversity action within a couple of dB relative to that obtainable with uncorrelated signals. The signal correlation coefficient is identical with the correlation coefficient between the two antenna polarization ellipses. The performance of selection diversity action in an FSK system with a Rayleigh-fading signal and no multipath interference can be seen in table 1. This table is obtained from data in Akima et al (1969, 1970). The table is for a V_d = 4dB (V_d is the ratio of rms to average of the noise envelope voltage). A minimum acceptable binary bit error rate (ber) is usually considered to be 10^{-2}. Table 1 shows that this requires a SNR of about 10dB. At a SNR of 25dB, the diversity improvement in ber is over one order of magnitude. Quadversity provides 1.5 orders of magnitude improvement at 15dB SNR over single-channel reception.

TABLE 1. SNR FOR DIVERSITY SCHEMES.

SNR, dB	No Diversity	Diversity	Quadversity
10	3.0×10^{-2}	1.1×10^{-2}	1.1×10^{-2}
15	7.0×10^{-3}	4.5×10^{-3}	4.0×10^{-3}
20	3.0×10^{-3}	9.0×10^{-4}	4.0×10^{-4}
25	1.0×10^{-3}	1.5×10^{-4}	3.5×10^{-5}
30	3.5×10^{-4}	2.5×10^{-5}	1.0×10^{-6}

The previous discussion leads one to the conclusion that an order of magnitude ber improvement should normally be obtainable on aircraft whose antennas have polarization correlation coefficients of as high as .8 where normal diversity action is obtainable. Quadversity provides more than an order of magnitude improvement relative to single-channel reception.

The preceding results are valid only where there is little adjacent channel interference due to differential phase shifting and differential multimode delays. When this situation occurs, the error rate becomes (SNR) irreducible.* That is, the bit error rate is not limited by SNR but by the level of diversity employed.

Figure 3 of Heritage (1970) shows the effect of particular multipath and doppler conditions. It shows that diversity can be used to achieve an improvement of 10^{-3} to 10^{-5} ber in the region in which the error rate is SNR irreducible. Other pertinent theoretical and measured diversity performance data can be found in Dickson (1970), Heritage (1969), and Johnson and Francis (1969). Horn and Gustafson (1971) show the relative importance of antenna pattern shape on statistical hf communications performance in terms of ber and time availability.

---

*"(SNR) irreducible" error rate means the error rate will not be reduced by further increases in SNR for that level of diversity.

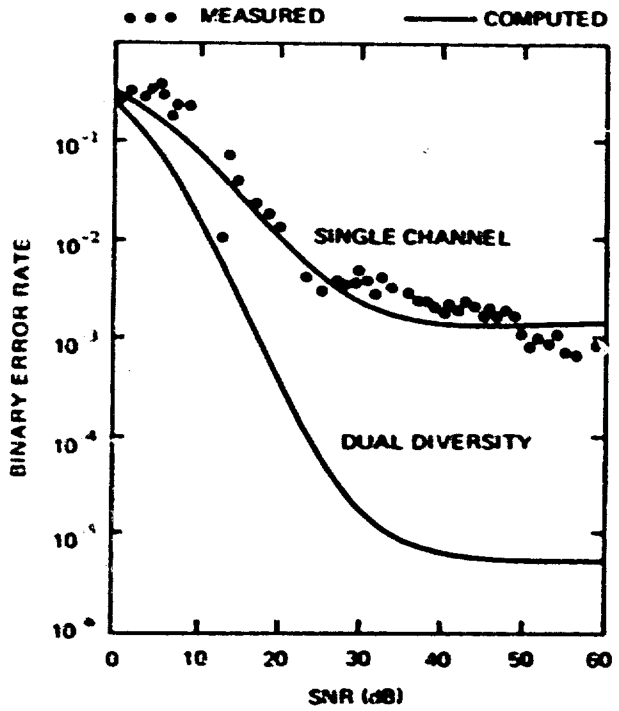

Figure 1. Measured data versus SNR for particular multipath and doppler conditions (fig. 3, NELC/Report 1686).

Many documented hf antenna studies have been conducted, such as those described in Hendershot (1967), Emberson and Knox (1968), and reference 1. These reports discuss various miniature hf antennas and antenna system design techniques. Basically, these are antennas that couple to either the magnetic or electric current.

4.2 ANTENNA SUBSYSTEM

The antenna system must be designed to provide the maximum decorrelation possible between the antennas used in diversity for acceptable diversity action.

4.2.1 RECEIVE ANTENNA SUBSYSTEM FOR POLARIZATION DIVERSITY

The hf receive antennas installed on Navy aircraft are usually of the wire type that are a significant portion of a wavelength in length. The wire

---

[1] Ohio State University Electroscience Laboratory, *High Frequency Aircraft Antenna*, Final Technical Report 2235-5, 3 May 1968

antenna can be of the bent (dogleg), straight (longwire), or trailing configuration. A particular aircraft receive antenna system may be comprised of a few of these antenna types. It is normally desired that the antenna patterns be complementary or decorrelated; that is, the pattern nulls should not be coincident.

The antennas of a particular aircraft installation should be designed to provide appreciable polarization diversity at frequencies from 2 to 30MHz. The antennas should be located on the aircraft to respond to decorrelated polarizations. The antenna pair should, in proper combination, provide adequate polarization diversity action when properly located. However, adequate decorrelated polarizations will be better obtained with miniature antennas due to the increased flexibility for antenna location. These antenna elements could be tunable multiturn loops, such as in Flaig (1968). The miniature antenna element could also be a broadband (2–30MHz) or narrowband tunable active antenna. A number of miniature antenna elements could be judiciously located on the aircraft to give at every frequency a pair of antennas that together provide polarization diversity.

A novel antenna has been reported (Campbell et al, 1971) that was designed to provide orthogonal polarization. It is a dual-mode symmetrical hf antenna that was developed for helicopters. The antenna pair used is similar to the "dogleg" antenna used by the Navy. The dual-mode antenna can be used to provide polarization diversity or can be used for simultaneous receive and transmit on separate frequencies. The dual-mode antenna is obtained by using a "hybrid" circuit and connecting the receiver and transmitter to the sum and difference ports or vice versa. The average isolation of the ports is 30dB. (For more detail, see the Campbell report.) This is greater than the space isolation between two hf antennas on aircraft in most instances. This dual-mode antenna approach works best when the antennas are mounted on the aircraft in a symmetrical manner. The dual-mode antenna provides vertical polarization in the sum mode and horizontal polarization in the difference mode. This can be useful in cases in which the horizontal noise field is much less than the vertical noise field as well as for implementation of polarization diversity.

4.2.2 PATTERN DIVERSITY

Pattern diversity provides improvement to the SNR only, and only for those portions of the coverage sphere at which the antennas have disparate antenna gains.

The pattern nulls, however, have less significance at high SNRs because the receive field, with the multipath situation, does not exhibit the normal ber-versus-SNR curve. The curve reaches an (SNR) irreducible error rate for single channel at some modest SNR, as seen in figure 3 of Heritage (1970). (When frequency or polarization diversity or both of them are used, the (SNR) irreducible error rate level is significantly less than in the nondiversity case.)

4.2.3 HF ADAPTIVE ANTENNA ARRAY

Adaptive antenna array technology has been developed at uhf frequencies for aircraft (Compton, 1971 and 1972). Adaptive antenna arrays provide the capability of both beam and null steering of n-1 beams plus nulls, where n is the number of antenna elements. The null steering can be performed by transmitting a pseudorandom noise (PRN) code and correlating on it in the receive system. This null steering approach is appropriate in a jamming environment. The adaptive receiving antenna system serves to maximize the signal-to-jammer ratio. Null steering can also be implemented via calibrated software prediction techniques. The beamsteering essentially is performed by coherent rf or i-f combining; that is, the beam is formed by maximizing the SNR, which is typical of a predetection combiner approach. Thus, the adaptive array provides an improved SNR through better gain.

The prospect of an hf adaptive array is a promising one for larger aircraft, even though the largest extent of the aircraft is small in terms of a wavelength, because the antenna elements, active or passive miniature, can be located optimally with minimum interaction. The antenna array that is formed can best be described as a superdirective array.

The adaptive array may also be constructed over some of the hf range to match the receive antenna system polarization ellipse to the receive wave ellipse. The improvement due to diversity reception needs to be investigated when an hf adaptive antenna array is used. This hf adaptive antenna array is at present only a design concept and needs to be investigated in a research effort.

4.3 DIVERSITY RECEPTION COMBINING AND SIGNAL PROCESSING SUBSYSTEM

The hf receive situation can be improved by employing a combination of polarization, pattern, frequency, and in-band diversities. These techniques are implemented by such devices as combiners, modems, and majority logic units. A combination of combining and error reduction approaches is desirable, because each method tends to remove different types of errors that have occurred in the received signal.

4.3.1 POSTDETECTION COMBINING

Hf polarization, antenna pattern, frequency, and in-band frequency diversity combining can be implemented with postdetection combining techniques. Diversity is obtained by combining two independently fading signals in a combiner. Two receivers are required to supply the modem with the two independent baseband signals except in the in-band frequency diversity case. The modem can combine both channels of 2400-baud serial bit stream. Quadversity is obtained when "in-band" frequency diversity is utilized with frequency or polarization diversity in a four-channel modem combiner. Quadversity gives, roughly, a two-order-of-magnitude improvement at 30dB SNR in processed error rate as compared to single-channel or "raw" error rate with no multipath interference.

4.3.2 PREDETECTION COMBINING

The previous section describes the traditional approach to implementing polarization diversity or any other type of diversity at hf. That technique is postdetection combining, which is done in the modem. Predetection coherent combining can be done at uhf but does not yield diversity improvement, because the correlation bandwidth is less than the actual bandwidth. At hf, however, a coherent predetection combiner (combining performed at the i-f level) could provide a simple technique for achieving pattern diversity. The predetection combiner could also provide improvement for errors that occur due to flat fading – that type that has a deep null across the entire 3kHz passband. The flat fade of one polarization is temporally uncorrelated with the flat fading of the other. However, predetection combining will not provide diversity improvement for the situation in which the ionospheric transfer functions on the orthogonal polarizations are uncorrelated.* This statement means that, roughly speaking, the differential phase shifts across the passbands, obtained from antennas of orthogonal polarizations, are different. Thus, upon combining coherently, at a single frequency, the two signals will only be in phase at a few frequencies. Fades and nulls will occur at frequencies in between. That is, the two signals "beat" together when the propagation transfer functions are uncorrelated.

An important point must be made here: experience shows that the propagation transfer functions of signals received from widely separated antennas are uncorrelated. However, the correlation of the transfer functions of signals obtained from orthogonally polarized antennas is unknown. The degree of correlation may be quite good. (This does not mean to imply that the spectral fades of such signals are correlated.) The relative decorrelation of the spectral nulls and temporal nulls of signals is a fundamental necessity in order to obtain diversity improvement. Thus, polarization diversity combining alone may or may not be feasible in a predetection combiner to provide diversity improvement.

A summary of the improvements to be obtained with predetection combining for implementing polarization diversity is as follows:

- Automatic "best" antenna pattern selection actually implements a two-antenna adaptive array
- Diversity performance is improved during periods of flat fading
- Diversity performance is improved during periods or cases of propagation transfer function correlation

Frequency diversity cannot be implemented with this predetection combiner, because the propagation transfer functions will almost certainly be decorrelated on the separate frequencies.

---

*"Uncorrelated" here refers to the phase portion of the transfer function, only.

4.3.2.1 ADAPTIVE PHASE EQUALIZATION/PREDETECTION COMBINING

The predetection combining may not work in all cases for polarization diversity without adaptive phase equalization. Predetection combining certainly does not work in the frequency diversity case. However, the total ber improvement is not solely due to predetection combining. The improvement in ber due to the adaptive phase equalization can be quite significant.

The problems associated with the reception of hf propagated signals stem from the propagation transfer function. This has associated with it a nonlinear differential phase shift and spectral nulling. The phase shifting problem causes adjacent channel interference of the multichannel FSK or DPSK signals. The transfer function does not preclude predetection combining if the transfer functions of the two signals are identical (with respect to phase). Thus, a technique is required to readjust the overall system transfer function in the receiver in cases in which it is necessary, in order to provide predetection combining that results in diversity improvement.

Such a technique is an adaptive communications system (Morgan, 1971) that employs spectral lines to sample the propagation transfer function across the passband. The lines are separate channels that are detected in the adaptive receive system and used to adjust adaptive filters. They require little of the overall transmitted power. The function of the adaptive filters (implemented at the i-f level) is to synthesize an inverse transfer function of the propagation transfer function. This technique provides an equalized signal that, when combined with another equalized signal, should provide satisfactory diversity improvement in either the polarization or frequency diversity case.

This hybrid technique of adaptive equalization/predetection combining provides quadversity level of error rate improvement performance. The important features to notice are that the modems do not need to be redesigned to handle quadversity, and that one receiver, rather than two or four receivers, is required. One receiver is eliminated in the case of polarization or frequency diversity. Three receivers are eliminated in the case of quadversity. Preselectors and down-converters are required for each rf channel. However, the preselectors are not required when simultaneous transmission is not required.

4.3.3 MODE-AVERAGING DIVERSITY COMBINER

This section presents a new technique (Villard et al, 1972) that is very promising for aircraft application.

The Villard mode-averaging diversity combining technique is rather simple in concept. The separate propagation modes combine at the receive site. However, each of these modes arrives at a different incoming angle. The incoming modes combine externally to the antenna in a constructive and destructive manner that causes nulls to be distributed in frequency and in time. There exists also a polarization null occurrence due to combining of circularly polarized waves of the same sense but 180° out of phase. The polarization null itself rotates at an infrasonic rate due to the distinct phase velocities at which the waves propagate.

The Villard combining technique utilizes two antennas that form an array. The array is designed to form a null in the elevation plane. This null can be swept over the angles of interest of the incoming modes. Such nulls can be formed by two antennas in close proximity, such as a loop and a probe.

The pair of antennas is swept in phase at a 45kHz rate – or at least a frequency higher than the highest spectral component of interest. This process serves to sweep the null(s) successively through each incoming mode and to prevent instantaneous interference with the other mode. Thus, the null(s) in frequency and in time is reduced greatly. The amount of adjacent channel interference is also reduced. The Villard article does not treat the impact of this new technique upon the channel error rate. However, the error rate should be markedly improved.

This technique is implemented with dual receivers with different i-f's that are spaced 45kHz apart. The two i-f's are then fed to a detector and a low-pass filter to yield the audio output with the mode-averaged baseband signal. This technique should be superior to polarization diversity postdetection combining on an aircraft from a weight standpoint, because a second modem is not required. Of course, the improvement obtainable with the Villard technique on an aircraft is not known and can only be determined by measurement or by computer simulation.

The Villard article restricts its attention to the improvements obtainable by reducing multipath effects. However, an important design parameter on aircraft (and ships) is to minimize the effects of the antenna null. Clearly, one of the benefits of the Villard technique is that the pattern nulls have been averaged out; that is, the pattern standard deviation is less. Thus, we note that the Villard technique provides significant pattern improvement as well as diversity reception improvement.

4.3.4 MAJORITY VOTING

The odd-channel majority logic combining approach operates on a bit-by-bit basis and is useful because it is an inexpensive combining technique for implementing diversity. The majority voting technique also is useful in that it allows diversity reception of separate signals from separate transmission sites. (The majority vote unit must have correlation circuitry for bit sync.)

The majority logic combining can also be done on three 2400-baud serial data streams from three DPSK modems. The three channels can be used to implement triversity. Triversity can be obtained by having two receivers for polarization diversity and one for frequency diversity. This latter possibility is in effect a simple EDAC code. The code rate is 1/3 for three-channel majority voting. The majority voting technique offers inexpensive but significant improvement over sophisticated and costly modem redevelopment programs.

The majority voting concept can also be utilized on separate frequencies and in those cases in which the transmitters are located on separate shore sites. This allows path diversity as well as the other types of diversity. This form of diversity works quite well to overcome the well known sunrise/sunset fadeouts.

5.0 RF/ANTENNA SYSTEM DESIGN RELATED TO PLATFORM/EMC CONSTRAINTS

5.1 RECEIVE SYSTEM

Hf aircraft receive antennas are difficult to design due to the severe operational and electromagnetic environment. This is especially true if the receive antenna must be operational while the transmitter antenna is transmitting. Of course, all antennas on the aircraft are very closely coupled. (Sections 6 and 7 deal with the various aspects of common transmit/receive antenna design on aircraft.) Thus, special care must be taken to protect the receiver from overloading, crossmodulation, and desensitization due to simultaneous transmission. The receive antenna system must be designed to receive from 2 to 30MHz and remain atmospherically noise limited (Gustafson and Chase, 1970); that is, the receive system noise figure must be less than the atmospheric noise figure by 5dB to ensure that the receive system sensitivity is not reduced by more than 1dB. With no requirement for simultaneous transmission and reception, the active or passive miniature receive antenna is attractive for many reasons:

- Reduced size
- Conformal mounting
- Less induced static noise
- Less vulnerability to lightning effects
- More desirable location from a performance point of view
- Superior performance in an array because of optimized locations

Active receive antennas of two types are feasible — narrowband and broadband. The first is useful for single-frequency, the second for multifrequency reception. The broadband active receive antenna is the more desirable, because reception is desired on more than one frequency. The broadband active antenna can be used in the receiving system in two ways. One method is to use a single broadband antenna. The second is to use the broadband antenna in an adaptive array; that is, to carefully locate on the aircraft many miniature passive or active broadband antenna elements. Thus, an array can be formed at each desired frequency. The same antennas, probably from two to four elements, could also be so designed to provide polarization and pattern diversity. These antennas for polarization diversity can be utilized by any of three combining techniques — postdetection modem, the Villard approach, and the adaptive phase equalization/predetection approach. These antennas have an rf system attached that receives at a number of frequencies, usually two frequencies for frequency diversity. The antennas, of course, can also be comprised of the active or passive narrowband tuned antennas that are miniature for single-frequency reception.

The hf adaptive array technique proposed in section 4.2.3 is not feasible unless implemented with the miniature passive or the active antenna elements. The real problem with implementing this approach is to determine the best antenna array locations on the aircraft. The procedure and techniques that can be used to locate antennas on aircraft are discussed in section 7.

The practical problem associated with the active antenna is that the active device must be protected from narrowband high-power sources nearby that induce energy into the active antenna. This protection can be provided with a tuned high-Q notch filter. The insertion loss of the filter amplifier, the noise figure, and the receive system should be designed to provide, barely, an atmospherically limited noise figure (Gustafson and Chase, 1970). Of course, the tuned frequency of the notch is that of the transmitter. When more transmit frequencies than one are present, multiple ganged notches may be utilized.

One of the problems that arise with the use of miniature antennas on aircraft is that it is desirable to receive on more than one frequency per antenna. This can be done with an antenna currently being developed at Ohio State University. This antenna is to have multiple ports whose basic element is the multiturn loop. This antenna would allow simultaneous reception on more than one frequency. Thus, this type of antenna would be necessary for a multiple-frequency hf array.

The dual-mode antenna (Campbell et al, 1971) is useful because it provides an average of 30dB isolation even though the antennas are close together. This antenna is discussed in section 4.2.1.

5.2 TRANSMIT SYSTEM

The most common existing requirement specified for minimum receiver/transmitter frequency separation on aircraft is 10%. The design problem is to obtain the required isolation at 10% frequency separation to guarantee that the performance of the receiver(s) is not degraded. The transmit and receive systems on Navy aircraft are placed on separate antennas to give maximum transmitter/receiver isolation. This is done because design parameters that would ensure satisfactory simultaneous transmit/receive operation in the transmit system are difficult to achieve. This situation exists even with the largest possible separations on Navy aircraft.

Thus, an important factor in successful simultaneous hf transmission and reception at 10% frequency separation is the control of broadband noise from a transmitter on receive frequencies. Transmitter noise power must be held to a level at least 5dB below minimum atmospheric noise at the receive system input if receivability degradation is to be held below 1dB. Total attenuation of transmitter noise is obtained from the combination of transmit antenna tuner and transmit filter rejection with receive/transmit antenna isolation at the receive frequency which equals or exceeds the minimum of 10% separation from the transmit frequency.

Transmitter noise power data are available at three typical hf frequencies for both ARC-132 (Collins) and ARC-142 (RCA) equipments in a 3kHz bandwidth 10% away from the transmit frequency. Calculations comparing transmitter noise with quasi-minimum* atmospheric noise yield the required total attenuation necessary. These data are presented in table 2.

---

*Essentially an average minimum that is usually below the actual minimums.

The information presented in table 2 was obtained from Gustafson et al (1972). The total attenuation required to result in simultaneous transmitter/receiver operation (antenna isolation, transmit tuner attenuation, plus additional transmit system attenuation at the receive frequency) is given in table 2 at 10% spacing. The table shows that the transmit system attenuation requirement with the AN/ARC-142 is much more severe than that with the AN/ARC-132 — by a factor of 36dB. The total attenuation required by the AN/ARC-132 ranges from 25 to 44dB. The maximum space isolation between two antennas on an aircraft is probably not more than 20dB at 10%, not including the receive antenna mismatch. (Receive antenna mismatch is not part of the total attenuation requirement of table 2.) The antenna isolation data used here were obtained from reference 2.

TABLE 2. ATTENUATION REQUIREMENTS.

Freq. MHz	Transmit Noise, dBM	Quasi-min Atmos Noise, dBm	5dB Below Atmos Noise, dBm	Total Attenuation Required, dB
AN/ARC-132				
2.5	-69	- 89	- 94	25
11.0	-74	-107	-112	38
25.0	-78	-117	-122	44
AN/ARC-142				
2.5	-31	- 89	- 94	63
11.0	-38	-107	-112	74
25.0	-40	-117	-122	82

The total attenuation requirement at 10% frequency spacing is almost met at 2.5MHz, but is short by at least 20dB at 25MHz. This attenuation requirement shortage can be met by increasing the attenuation at the receive frequency by:

a. reducing the broadband noise from the high-power amplifier,

b. increasing the filtering in the antenna tuner,

c. providing a transmit filter, or

d. increasing the frequency spacing to 15% or so.

The point must be restated here that these calculations are based on the AN/ARC-132. The transmit filtering requirement with the AN/ARC-142 is 37dB more severe. Also, the broadband noise level of the AN/ARC-142 tapers off at frequency offsets of 10% or more whereas that of the AN/ARC-132 does not.

---

[2] Naval Air Test Center, WST-183R-71, *Report of Test Results*, 30 December 1971

6.0 ANTENNA MATHEMATICAL MODELING DESIGN TECHNIQUES

The procedure for designing hf antennas for aircraft has been traditionally restricted to scale modeling approaches with miniature models. This procedure lends little insight into the cause-effect relationships of the antenna(s) with the model. Thus, the designer does not come to understand the delicate interrelationships of the basic antenna design and the antenna locations on the aircraft - it is impossible to take voluminous enough data and to correlate them to allow conclusions on these interrelationships to be drawn.

Mathematical modeling on aircraft is currently feasible and has been used to develop both antennas and antenna array locations on the aircraft at hf (Burke, 1971). There exists a concept of aircraft antenna analysis that utilizes a detailed knowledge of orthogonal current modes and their respective current distributions. The mathematical modeling approach can be used to determine the current modal distributions due to an incident plane wave on the aircraft. The proper location of an individual antenna element is assumed to be at a maximum of a current mode. However, for array design purposes the locations of all elements are dictated by the overall system design goals. It may be desired that the antenna pattern of the array be omnidirectional and have a steerable null.

The design philosophy of the array is also different if the actual array at a particular frequency is formed from a subset of all the elements of the array. For example, a total of eight elements may be used in the array with only two or four of these being utilized at a given frequency in the actual operating array. The antenna pair that is used at a certain frequency is that which couples best to the current distributions while satisfying the basic requirements of the signal processing system of interest.

7.0 SOME ADAPTIVE AIRCRAFT COMMUNICATIONS SYSTEM DESIGN APPROACHES

It would be advantageous to have an automatically selectable capability to transmit on the antenna which has the best pattern for the desired direction. This approach might be implemented with the use of a read-only memory (ROM) to store the antenna patterns. The proper transmit antenna would be selected by consulting an ROM with the desired frequency and azimuth. The ROM would correspondingly contain the desired transmit antenna selection. This technique would allow the aircraft-to-shore link to be improved in areas in which nulls occur on the primary transmit antenna.

A different approach would be to utilize an adaptive receive/transmit hf antenna array (see also section 4.2.3). This would require the use of miniature transmit antennas and receive antennas, the phases of which are controlled in an adaptive manner to form both a receive and a transmit beam in the direction of propagation. The receive and transmit systems should probably be time shared on the same frequency. The antennas would be either dual unilateral or single bilateral types to be used in the array. This approach has a further advantage in that the transmit amplifier can be provided at the antenna. Thus, a high-power transmitter amplifier is not needed. A still further advantage is that frequencies received simultaneously have a lower transmit power level.

This aircraft adaptive communications system performs optimally when used in a certain manner. The remote site can determine when the transmit signal (frequency) becomes unsatisfactory and can request the aircraft system to switch frequencies. The best approach on the aircraft would be to utilize two transmitters on separate frequencies. The second transmitter would be tuned to a higher frequency than the first if the received ber on the shore/ship was better on the higher receive frequency. On the other hand, if the lower receive frequency was better, a new transmit frequency would be chosen that was lower than the original transmit frequency. The remote site would compare the reduced error rate on both its receive channels. (This assumes that during this adaptive process the aircraft is transmitting on two frequencies and using a known sequence.) The remote site would report back whether or not the new channel (frequency) met the criterion (better than a certain error rate). The remote site would also report back whether or not the new channel error rate was improved over the other channel. This adaptive (or automatic) frequency selection process is repeated until the remote site receives an adequate signal (based upon a certain minimum ber). When this transmit frequency selection process is completed, the second transmitter on the aircraft is turned off. This adaptive control technique requires that the remote site have the capability to monitor and compare error rates. The aircraft also must be designed to interact in this manner with the remote site to adapt the frequency to the channel as the FOT changes throughout the day. These discussions assume that an adequate list of frequencies is available. The receivers and transmitters for this circuit management technique must be controlled by a processor. The assumption made here is that the existing equipment automatic configuration capability is adequate. Otherwise, control and processing functions have to be added.

8.0 SYSTEM DESIGN PHILOSOPHY AND SYSTEM MODELING

The approach to the actual implementation of the new techniques presented in the previous sections depends upon the aircraft, its size and capability, and the functional communications requirements. Of course, the implementation plans discussed in this section reflect a desire to maintain a generalized approach for all Navy aircraft. The R&D efforts to be conducted will, by necessity, be structured to guarantee a maximum of applicability to most aircraft situations. The general approach is to improve and upgrade Navy hf communications to reflect the latest state of the art.

The hf design approaches for Navy aircraft recommended in the previous sections require a systems approach towards implementation. Thus, the different subsystems and systems have to be compared to each other on a cost-versus-performance basis. The best medium for comparison is a statistical communications mathematical model. Such models have more validity than the "build and measure" concept, because the experiment is largely random and too many vital system parameters are otherwise left unvaried. The parameters left unvaried are the various propagation factors such as multipath delay spread, differential doppler shift, and polarization splitting and rotation. The problem associated with the research and development of a new communications system is that the complex natural "environmental" factors such as propagation cannot be separated from the design parameters in a set of measurements. The use of a statistical model is most appropriate because of the desire to reduce costs. In fact, not only is the best system approach determined by use of the mathematical model concept but also the optimum subsystem trade-offs are made, to yield a maximally advanced system improvement.

The statistical mathematical model that is to be utilized is comprised, in part, of an exact model of the antenna system performance. This is obtained by using an antenna mathematical modeling technique in which the appropriate structural geometry detail for the frequency is used. Boundary matching is performed to obtain closed-form solutions of sufficient accuracy. The model obtains accurate results for polarization, pattern, impedance, and antenna intercoupling. All these parameters are of interest in a communications system modeling analysis. Further, they can be translated into statistical terms. The statistical terms of the antenna subsystem that are of importance are the following

- Antenna Pattern Amplitude Probability Distribution (APAPD)
- Joint Antenna Pattern Amplitude Probability correlation distribution
- Antenna polarization probability distribution
- Joint antenna polarization probability correlation distribution
- Weighted antenna impedance distribution (weighted refers to the desirability to minimize VSWR versus frequency)
- Joint antenna isolation

These statistical parameters are readily incorporated into an overall system model. The model includes the propagation statistics, both the channel and the noise. The evaluation of separate competing hf system improvement approaches in the area of antenna arraying/signal processing must be done from such a statistical communications system model. This is because the different approaches tend to improve the raw ber, or grade of service, but are radically different, and their performance is not now known. The design trade-offs that must be made to optimize the design are also unknown. Thus, prudence dictates the mathematical modeling technique.

9.0 SUMMARY

The previous sections contain many approaches to improving aircraft hf communications. They apply to a wide variety of Naval communications requirements. The particular approach selected should be based on requirements and functional analysis. It will most likely be different for different sizes and speeds of aircraft. This is particularly true of the antenna design area.

A large variety of techniques has become available in the last couple of years that promise to substantially improve aircraft hf communications. As an example, the tunable notch filter may allow active antennas to be used in a transmit environment.

These new concepts and approaches should be pursued to determine their individual and collective merit. Generally, implementation would start with a communications requirements analysis, a functional analysis, and an antenna system design approach. Then an effort would be conducted to locate antennas on the aircraft by use of modeling techniques, either hardware or software. The modeling data and systems analysis would determine the degree to which the antenna design met such functional requirements as beam steering, null steering, isolation, efficiency, gain, polarization, and mode-averaging diversity. Once the performance of the antenna system design (including aircraft installation) is determined, it is necessary to proceed with the design and development of the signal processing hardware. (Many competing signal processing approaches are available for consideration, and thus a trade-off analysis must be performed.) The signal processing hardware should then be tested and analyzed for system performance

10.0 RECOMMENDATIONS

1. Develop miniature hf antennas for aircraft   active, passive, narrowband tunable, and broadband.

2. Perform research, using a mathematical modeling antenna approach, to determine optimum locations for coupling antenna elements to the different current modes. Also, determine the best antenna elements to excite the different modes for the different applications. The applications are polarization diversity, mode and antenna pattern averaging diversity, beam steering, and null steering.

3. Perform research to determine the feasibility of hf adaptive arrays to be used for diversity (pattern, polarization, and mode averaging), antijam, and antiintercept.

4. Conduct a requirements functional analysis and systems performance analysis to determine which signal-processing-technique/antenna-system-approach pair is optimum to meet the functional requirements.

5. Develop a prototype antenna system to install on an aircraft to interface with the selected signal processing approach.

6. Develop a performance simulation model of the adaptive phase equalizer/predetection combiner. Evaluate the results and make recommendations.

7. Implement majority voting approaches in cases in which extremely low error rates and high time availabilities are desired, particularly if shore station transmission diversity is available.

BIBLIOGRAPHY

Akima, H., Ax, G. A., and Beery, W. M., *Required Signal-to-Noise Ratios for HF Communication Systems*, ESSA Research Laboratories/ TR 131, August 1969

Akima, H., *Modulation Studies for IGOSS*, ESSA Research Laboratories/ TR ERL 172-ITS 110, June 1970

Burke, C. J., *Mathematical Modeling of Aircraft Antennas and Supporting Structures*, January 1971

Campbell, D. V., Arnold, J., Inslerman, H., and Wilson, T., ECOM, *Dual-Mode Symmetrical High-Frequency Antenna for Airborne Use*, March 1971

Compton, R. T., Jr., *Adaptive Antenna Arrays for Aircraft Communication Systems*, Interim Technical Report 3098-1, Contract N00014-67-A-0232, 0009, July 1971

Compton, R. T., Jr., *Adaptive Antenna Arrays for Aircraft Communication Systems*, Final Report 3098-2, Contract N00014-67-A-0232-0009, January 1972

Dickson, R. L., *San Diego to Key West HF Test*, Naval Electronics Laboratory Center Report 1695, 24 March 1970

Emberson, W. C., and Knox, R. M., ECOM, *Aircraft Antenna Requirements Study*, March 1968

Flaig, T. L., Ohio State University Electro Science Laboratory, *The Impedance and Efficiency of Multi-Turn Loop Antennas*, 3 April 1968

Grisdale, G. C., Morris, J. G., and Palmer, D. S., *Fading of Long-Distance Radio Signals and a Comparison of Space and Polarization Diversity Reception in the 6–18 MHz Range*, Proc. IEEE, v. 104, Part B, p. 39-51, January 1956

Gustafson, W. E., and Chase, W. M., *Shipboard HF Receiving Antenna System: Design Criteria*, Naval Electronics Laboratory Center Technical Report 1712, 2 June 1970

Gustafson, W. E., Potthoff, J. R., and Meenan, J. P., *Applicability of HF Aircraft Radio Equipments to Shipboard Systems*, Naval Electronics Laboratory Center Technical Report 1816, 2 February 1972

Hendershot, J. H., *Compact HF Aircraft Antennas*, Final Report, Report No. 4, Contract No. DA 28-043-AMC-00477(E), Martin Marietta Corp., August 1967

Heritage, J. L., *Error Rate of High Frequency Multi-Channel Fleet Broadcast System*, Naval Electronics Laboratory Center Report 1620, 27 March 1969

Heritage, J. L., *Error Control in the HF Fleet Broadcast System*, Naval Electronics Laboratory Center Report 1686, 10 February 1970

BIBLIOGRAPHY (Continued)

Horn, J. M., and Gustafson, W. E., *HF Shipboard Antenna System Design and Utilization Criteria*, Naval Electronics Laboratory Center Technical Report 1808, 1 December 1971

Johnson, G. B., and Francis, G. P., *Error Rate Observed on HF Multichannel Fleet Broadcast System*, Naval Electronics Laboratory Center Report 1620, 27 March 1969

Morgan, L., *Optimum Signal Processing for An Adaptive Communications System*, Teledyne Micronetics Report, Contract No. N00019-71-C-0112, December 1971

Naval Air Test Center, WST-183R-71, *Report of Test Results*, 30 December 1971 (reference 2)

Ohio State University Electro Science Laboratory, *High Frequency Aircraft Antennas*, Final Technical Report 2235-5, 3 May 1968 (reference 1)

Schwartz, M., Bennett, W. R., and Stein, S., *Communication Systems and Techniques*, Inter-University Electronics Series, McGraw-Hill, 1966

Sifford, B. M., Shaver, H. N., Daly, R. F., and Felperin, K. D., *HF Time and Frequency Dispersion Effects-Experimental Validation of an FSK Error-Rate Model*, SRI Project 4172, TR 4, March 1965

Villard, O. G., Jr., Comasney, J. M., Kawachika, N. M., *A Mode-Averaging Diversity Combiner*, IEEE Transactions on Antennas and Propagation, v. AP-20, no. 4, p. 463-469, July 1972