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MULTIPLEXED ECCM
ADAPTIVE ANTENNA

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1.0. INTRODUCTION AND SUMMARY

1.1. Background

The past few years have seen several new programs arise to add antenna and modem ECCM capability to tactical air communications and navigation. Many of these programs are large ones with lengthy development times (e.g., JTIDS, SEEK TALK, LOSTFCS, GPS). Their objective is to provide a high degree of ECCM using adaptive array (AA) techniques as well as other sophisticated signal processing methods. These programs involve a total revision of the aircraft communication system from the antennas through the cabling to the radio set itself.

The program proposed herein adopts a "quick fix retrofit" approach to the tactical airborne ECCM problem. Its objective is to provide a more modest amount of jam resistance for the interim using existing antennas, cabling, and radio sets. The ECCM technique to be used in the proposed program is adaptive antenna processing for spatial nulling of jammers. The proposed approach can be incorporated as an appliqué into existing systems and is compatible with a slow frequency-hop spread spectrum waveform.

It should be recognized, however, that the results of this program may have longer term applicability. The resulting system will provide a wide variety of Navy aircraft with a choice of a low cost, modest ECCM system.

Recently the vulnerability of certain adaptive arrays to dual-polarized ECM was first demonstrated experimentally at Rome Air Development Center by Andrew E. Zeger. In 1977 he demonstrated that a two element adaptive array at C-band could effectively null a single dual-polarized jammer as long as the two linearly polarized elements were perfectly aligned. If one of the elements were rotated with respect to the other, the AJ capability of the adaptive array in question was severely degraded. The addition of another adaptively weighted and properly polarized antenna permitted the array processor to null the dual polarized jammer.

1.2. Description of the Problem

Adaptive receiving requires signals from two or more distinct antennas; however, many aircraft radio systems already have more than one antenna, for example a top and bottom. There is then some algorithm used to determine the antenna from which to receive, and the signal at the other antenna is ignored. With the known benefits of adaptive processing, it is only natural that one should want to use both (or all) antenna signals in an adaptive receiver. A reasonable solution is to replace the antenna RF selector switch with a currently available adaptive receiver. This solution is acceptable given the following conditions: 1) The size, weight, and power constraints at the location of the antenna RF selector switch do not prohibit the replacement of the switch with an adaptive receiver. 2) The location is easily accessible for normal maintenance of the adaptive receiver, and 3) the location is not environmentally severe, for the adaptive receiver is a complex and rather sensitive piece of electronics.

The problem is then one of implementing adaptive processing in cases where a current adaptive receiver cannot replace the antenna RF selector switch.

The solution is to replace the switch, instead, with a signal multiplexer. A unit that is designed to be minimal in size, weight, and power consumption, as well as complexity, to minimize or eliminate maintenance. It would also be designed to operate in severe environments. The multiplexer would place onto the cable, to the radio, the multiplexed signals. At the other end, before going into the radio receiver, the signals are sent to a unit which first demultiplexes and then adaptively processes the signals and produces an AJ output that is then sent into the radio receiver (See Figure 1.1.).

1.3. Adaptive Arrays

In a typical airborne system each receiver operates with its own antenna. Thus when it came to providing ECCM to protect an airborne receiver, it naturally followed that one should provide a separate antenna array and adaptive control unit for each receiver. Adaptive nulling arrays have received much attention during the past six years and the literature contains numerous theoretical and experimental results (2,4,8,9) . Here we briefly summarize the structure and subsystems of an adaptive array (AA) so that this report can stand on its own.

Figure 1.2. illustrates an N element array employing the Least Mean Squares (LMS) adaptive control algorithm. The processing of each receiving antenna's output is the same so only the n-th channel is shown. The AA consists of four subsystems:

1) The array of antennas
2) The beamformer subsystem
3) The adaptive control subsystem
4) The wavefront sampling subsystem

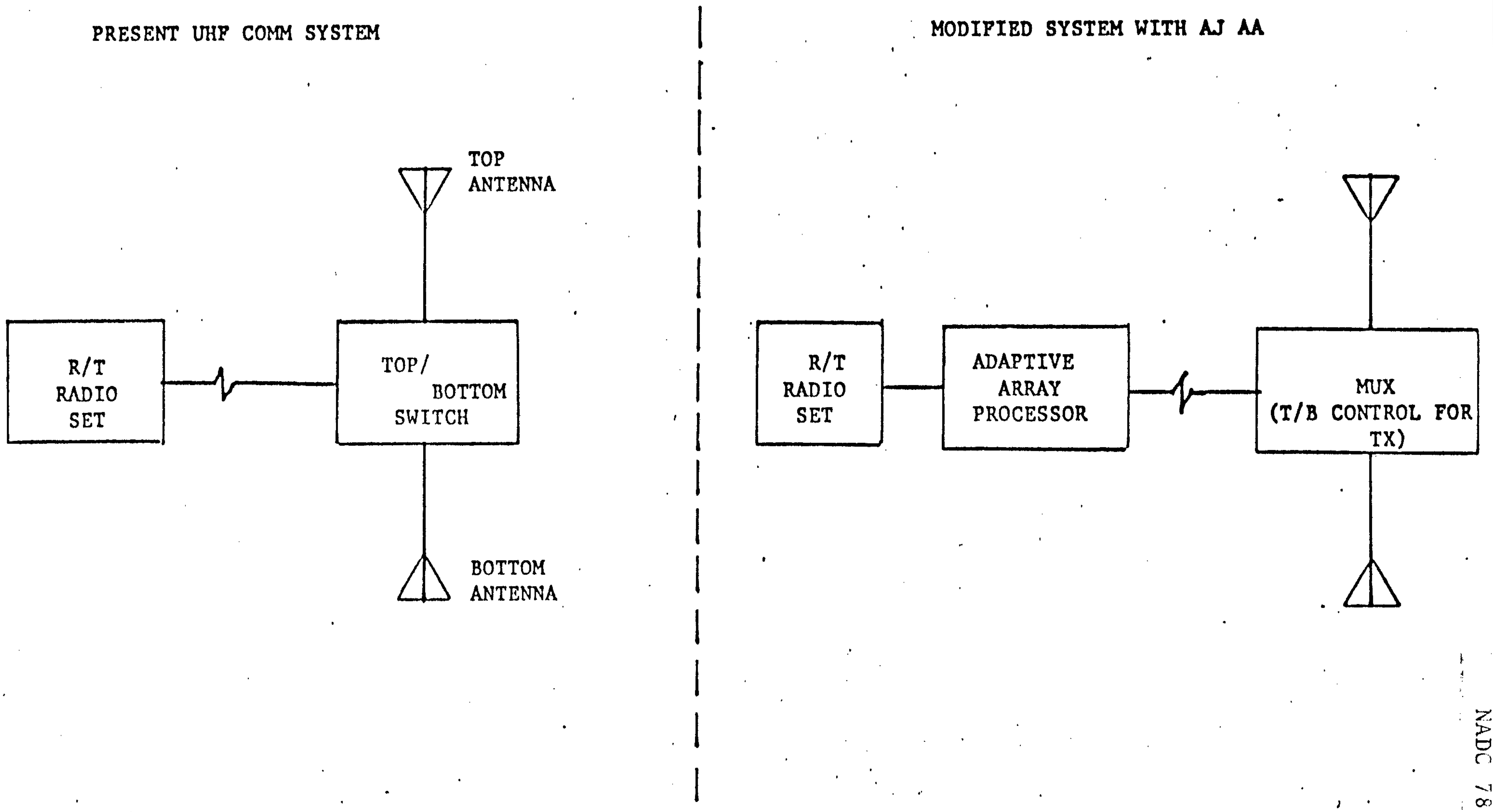


Figure 1.1.

AJ PROTECTION USING EXISTING ANTENNAS & CABLING

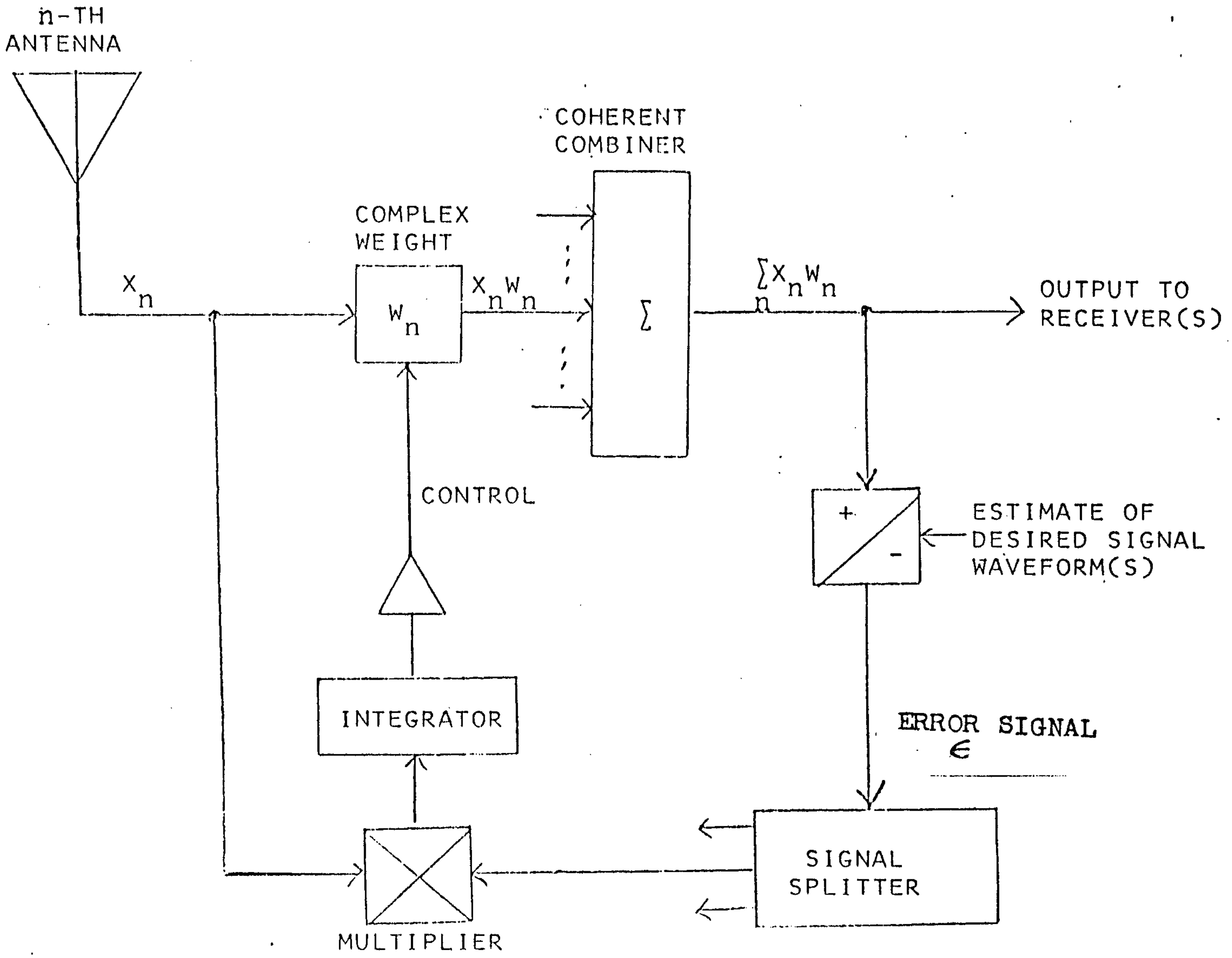


FIGURE 1.2. ADAPTIVE NULLING ARRAY EMPLOYING THE LEAST MEAN SQUARES (LMS) ALGORITHM

The antennas are the transducers between the incident waves in free space and the RF transmission lines leading to the receiver. In an N element array the spatial pattern can be independently specified in at most N-1 distinct directions. Thus a four element array is required to null three independent jammers.

The beamformer consists of N complex weights (phase and amplitude adjustment of the N received waveforms) and an N-way coherent summer. The power pattern (antenna spacial response) is established at the bemaformer output. Beamformers can be implemented at RF, IF or baseband. Beamformers can be distributed (complex weights located with antennas), or compact (transmission lines bring the antenna signals to a central processor).

The adaptive control unit adjusts the beam pattern by varying the N complex weight values in the beamformer in response to the electromagnetic environment incident upon the array and upon an algorithm (prescribed course of action based upon a goodness criteria such as maximum signal-to-noise ratio).

The wavefront sampling system makes the N received signals $X_1, \ldots, X_N$ available to the adaptive control unit. For the LMS algorithm (a steepest descent approach), the time derivative of the n-th weight is proportional to the correlation of X_n and the error signal ε. As seen in Figure 1.2. ε is the difference between the beamformer output and an estimate of the desired signal waveform. As the error signal is driven toward zero by the N feedback control loops the jammers are nulled in the beamformer output and the desired signal is forced to the level of the estimated desired signal (reference waveform level).

A drawback of this system is that an estimate of the desired signal must be formed.

If we set the estimate equal to zero, so that the adaptive loop then tries to drive the output equal to zero. This can obviously be done by setting all the complex weights equal to zero. However, if one of the complex weights is fixed to a non zero value, or more simply if that antenna input is left unweighted, then the rest of the complex weights are forced to a nontrivial solution (See Figure 1.3.). A working adaptive adaptive array using this technique has been built and tested successfully

1.4. Signal Multiplexing

The main objective in signal multiplexing is to send 2 or more signals simultaneously over a single communication channel, and by demultiplexing at the other end, be able to separate the original signals without any loss of information.

The general method for multiplexing signals is illustrated in Figure 1.4. The signals $X_1(t),\ldots,X_N(t)$ are base band and band-limited with bandwidth B. The time functions $f_1(t),\ldots,f_N(t)$ are periodic of period T, and mutually orthogonal; i.e.:

$$\int_{t_o}^{t_o + T} f_i(t) f_j(t)\,dt = 0, \quad i \neq j$$

where $T < \frac{1}{2B}$.

The lowpass filters have a cutoff frequency at B. By specifying the form of the time functions $f_1(t),\ldots,f_N(t)$, it is possible to obtain the familiar systems of time division multiplexing (TDM), frequency division multiplexing (FDM), and code division multiplexing (CDM), (See Figure 1.4.).

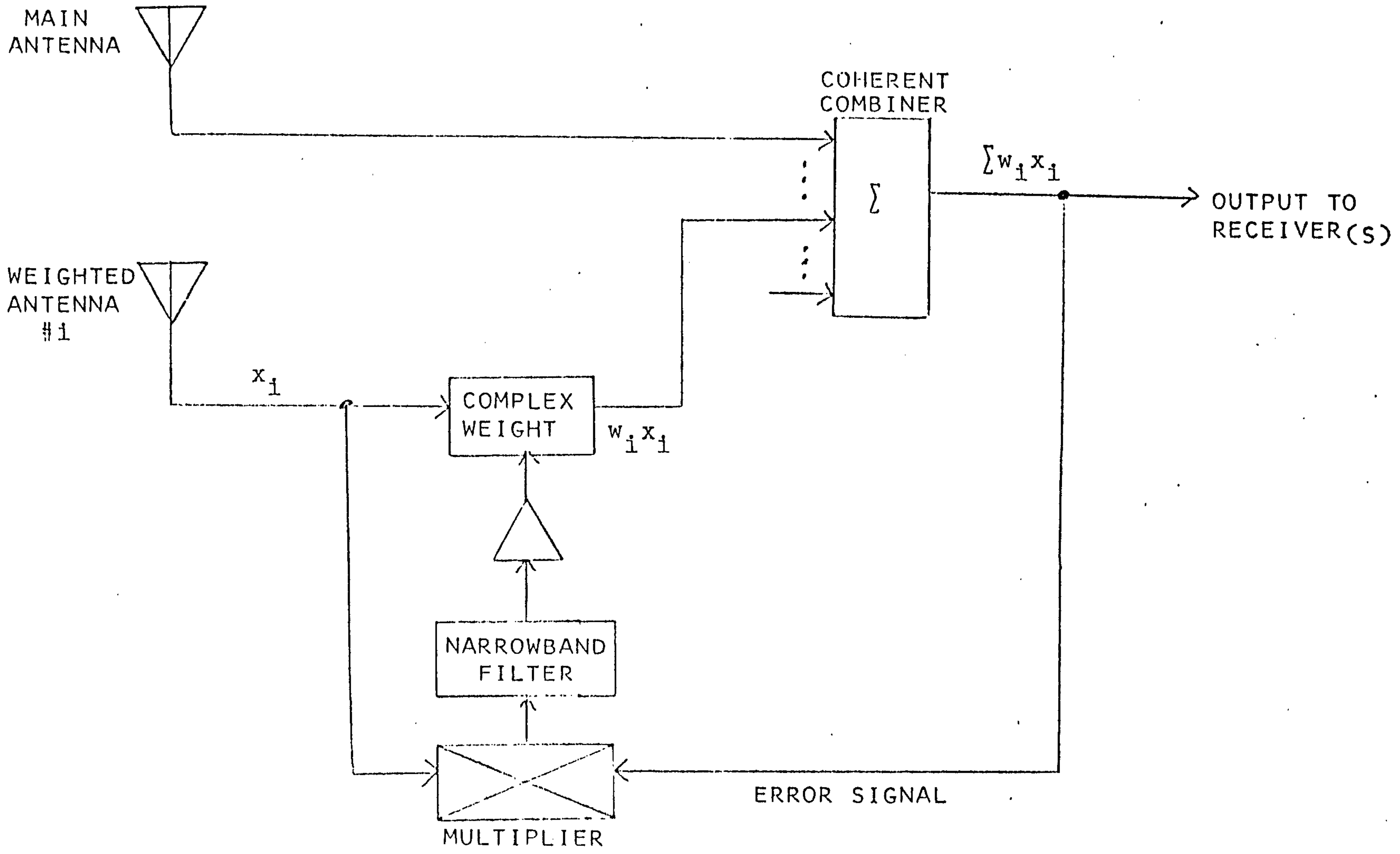
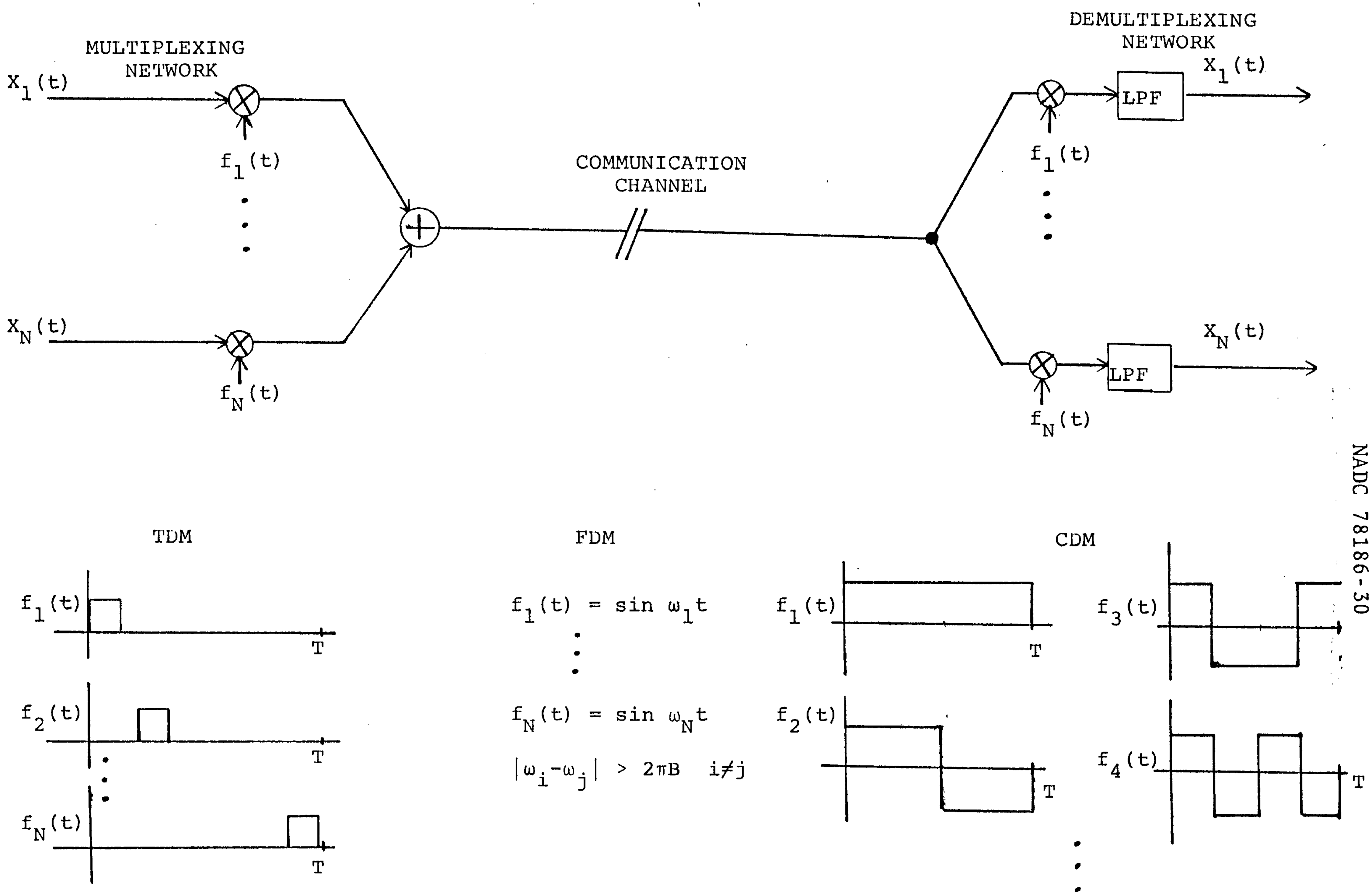


FIGURE 1.3.

BLOCK DIAGRAM OF MODIFIED LMS ADAPTIVE ARRAY



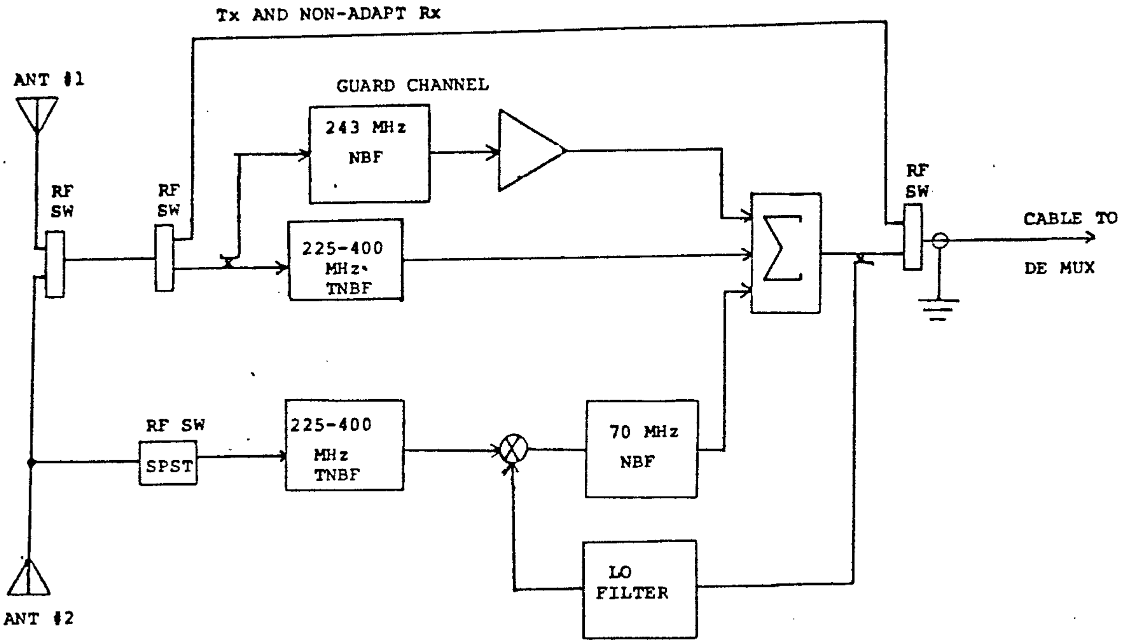
GENERAL SIGNAL MULTIPLEXER

FIGURE 1.4.

1.5. Overview of the Recommended Design

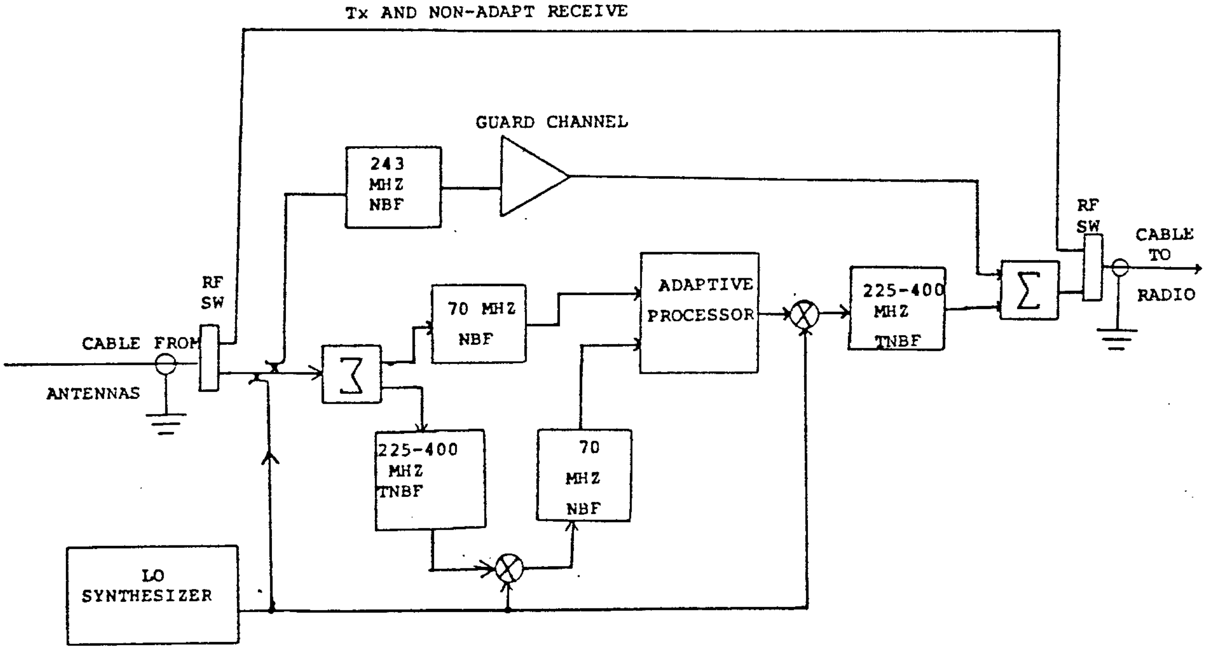
The recommended design is a two unit frequency multiplexed adaptive array system for UHF communication with two antennas. One unit would replace an outboard antenna selector and frequency multiplex both antenna signals onto the existing coaxial cable. At the other end the second unit would demultiplex the signals, adaptively process them and feed the output directly into the existing radio receiver. Modifications to the design to include VHF processing as well as suggested use of the design in systems that have more than two selectable antennas are considered in Sections (4.2.) and (4.3.) respectively.

A block diagram of the recommended design is shown in Figure 1.5. For transmitting and non-adaptive receiving, the signals are routed by switches to completely bypass the multiplexer and adaptive array. For adaptive receiving the signals are processed as follows. In the outboard multiplexer, one of the antenna signals is converted to a fixed IF of 70 MHz by a tunable LO sent outboard on the cable. The signal of the other antenna is sent on the cable after some narrowband filtering, but without frequency translation. The guard channel is tapped off of one of the antenna signals, filtered and amplified, and is added back to the line later to prevent it from getting lost in the filtering of the other signals. At the other end, the signal is split and filtered again to obtain the 243 MHz guard channel, the 70 MHz IF signal, and the unconverted RF signal. The RF signal is now converted to 70 MHz by mixing with the LO. The two 70 MHz signals are then input into an adaptive processor. The output is reconverted back to the original RF, combined with the guard channel, and sent to the radio receiver.



OUTBOARD MULTIPLEXER

1.5.a



INBOARD DEMULTIPLEXER

1.5.b

RECOMMENDED SYSTEM BLOCK DIAGRAM

FIGURE 1.5.

1.6. Expected Performance

The proposed multiplexed adaptive array design would operate transparently as far as the radio controls are concerned, except for an additional adapt/non-adapt receive switch.

In adaptive receiving, the proposed design would achieve 30 dB cancellation of the strongest interference ± 25 KHz of the center frequency in the narrowband mode and ± 50 KHz in the wide mode.

1.7. Recommended Future Work

Construction of a multiplexed adaptive array feasibility model is recommended as the next step in the system development. Both inboard and outboard units would need to be constructed to adequately test the system. Feasibility model construction and testing is at this point the most effective way to verify the system design, or to expose areas which need further work.

2.0. ANALYSIS OF ECCM FOR AIRBORNE UHF/VHF RECEIVERS

2.1. Existing Antenna, Cables, and Airframes

The main objective of this design is to obtain AJ adaptive array processing with a minimum of alterations to the current radio-antenna systems. For this design, it is assumed that the current location of the antennas, as well as the cable runs, are unalterable. The only things that can be changed, (size, weight, and power permitting) are the devices to which the cables are connected. Hence, the current antenna and cable configurations greatly affect if and how AJ adaptive array processing can be achieved for a particular radio system.

The first requirement of a radio system, in order to allow AJ adaptive array processing, is that the receiver in some manner has access to more than one antenna. The information provided to Zeger-Abrams by NADC on 28 November 1978, showed that this is the case for the UHF communication radio system on all the aircraft of interest: F-14, F-4, A-7E, A-6E, and E-2C. Information on the VHF radio systems was not included; however, an analysis of the inclusion of various VHF configurations is given later in Section 4.2.

Since there is more than one antenna, but the receiver can use only one signal at a time, there must be an antenna selector switch in the cable network. If that switch is in the electronics equipment bay near the receiver, then it is recommended that AJ capabilities be achieved with a straight adaptive array, without multiplexing, placed in the equipment bay. Such arrays are currently available electronic items. This is the case for the UHF communication band on the A-6E and A-7E aircraft.

If the antenna selector switch is not in the electronics equipment bay, and is in a location that for space, weight, power, maintenance, or environmental reasons, an adaptive array cannot be placed, then it is recommended that the proposed multiplexed adaptive array be used to obtain AJ capabilities. This is the case for the F-4 aircraft for reasons of space and power.

Information on the UHF cable locations in the E-2C and F-14 was not furnished, however, a similar analysis of these systems can be made based on the location of the antenna selector switch. One must note that both the E-2C and F-14 have more than two UHF communication antennas. Use of a two element adaptive array (multiplexed or unmultiplexed) with such a network is described in Section 4.3.

2.2. Adaptive Array Processing

2.2.1. Number of Nulls

An adaptive array with N weighted elements has N degrees of freedom, which can be distributed to allow jammer nulling or as constraints for desired signal maintenance. If all N elements are weighted, then at least one constraint is needed to prevent the weights from all going to zero, so that the array can form up to N-1 independently steerable nulls. If there is an unweighted main antenna, with N weighted elements, no constraint is required to prevent the all-zero solution, so the array can form up to N independently steerable nulls.

2.2.2. Adaptive Arrays Controlled by the LMS, Gradient Control Algorithm

The LMS algorithm (1) employs feedback control to adjust the array weights to minimize the mean square error ε between the array output and a desired signal response. With $\vec{W}$ representing the complex weight vector, the system equation is

$$\dot{\vec{W}} = -k \vec{\nabla}_W |\varepsilon|^2 = -2k \varepsilon \vec{x}^*$$

where k is a gain (or step size factor) and $\vec{\nabla}_W$ represents the gradient with respect to $\vec{W}$, and $\vec{x}^*$ is the complex conjugate of the vector of signals received at each weight input.

A block diagram of an LMS adaptive array was given in Figure 1.2., a modified LMS adaptive array was also sketched in Figure 1.3. in which a main antenna input replaces the desired signal reference, and the integrator is replaced by a narrowband filter.

2.2.3 Complex Weight Implementation

The complex weight may be implemented in polar coordinates with a variable attenuator and 360° phase shifter, or in rectangular coordinates as shown in Figure 2.1. This implementation is preferred because both control inputs (W_I and W_Q) are processed identically. The RF or IF input is split into two quadrature channels, each of which is adjusted in amplitude by a real bipolar

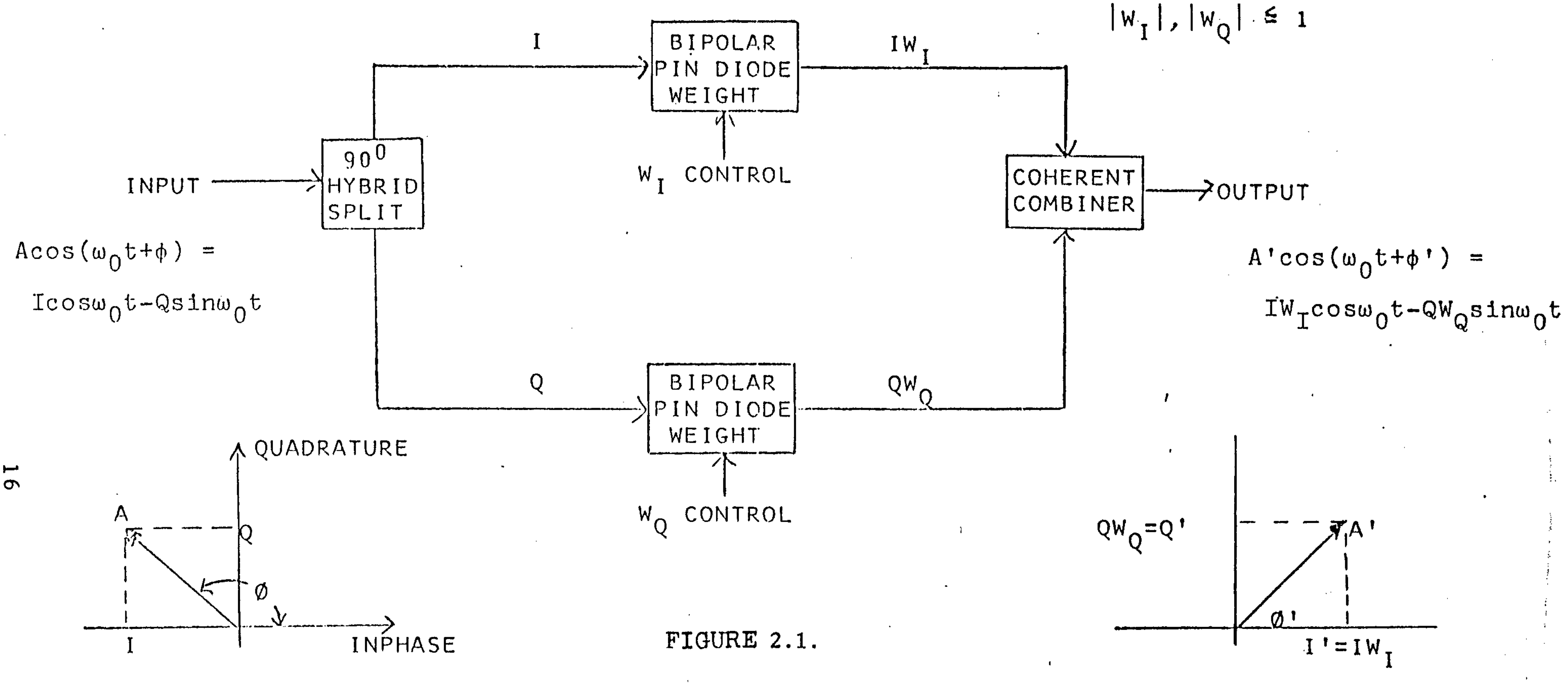


FIGURE 2.1.

COMPLEX WEIGHT IMPLEMENTATION

weight (bipolar in the sense that the sign can be + or -), the outputs of which are combined in phase to form the complex weight output. A PIN diode implementation of the bipolar attenuator allows it to be built with low intermodulation distortion.

2.2.4. Nulling Characteristics of Adaptive Array - N Curve

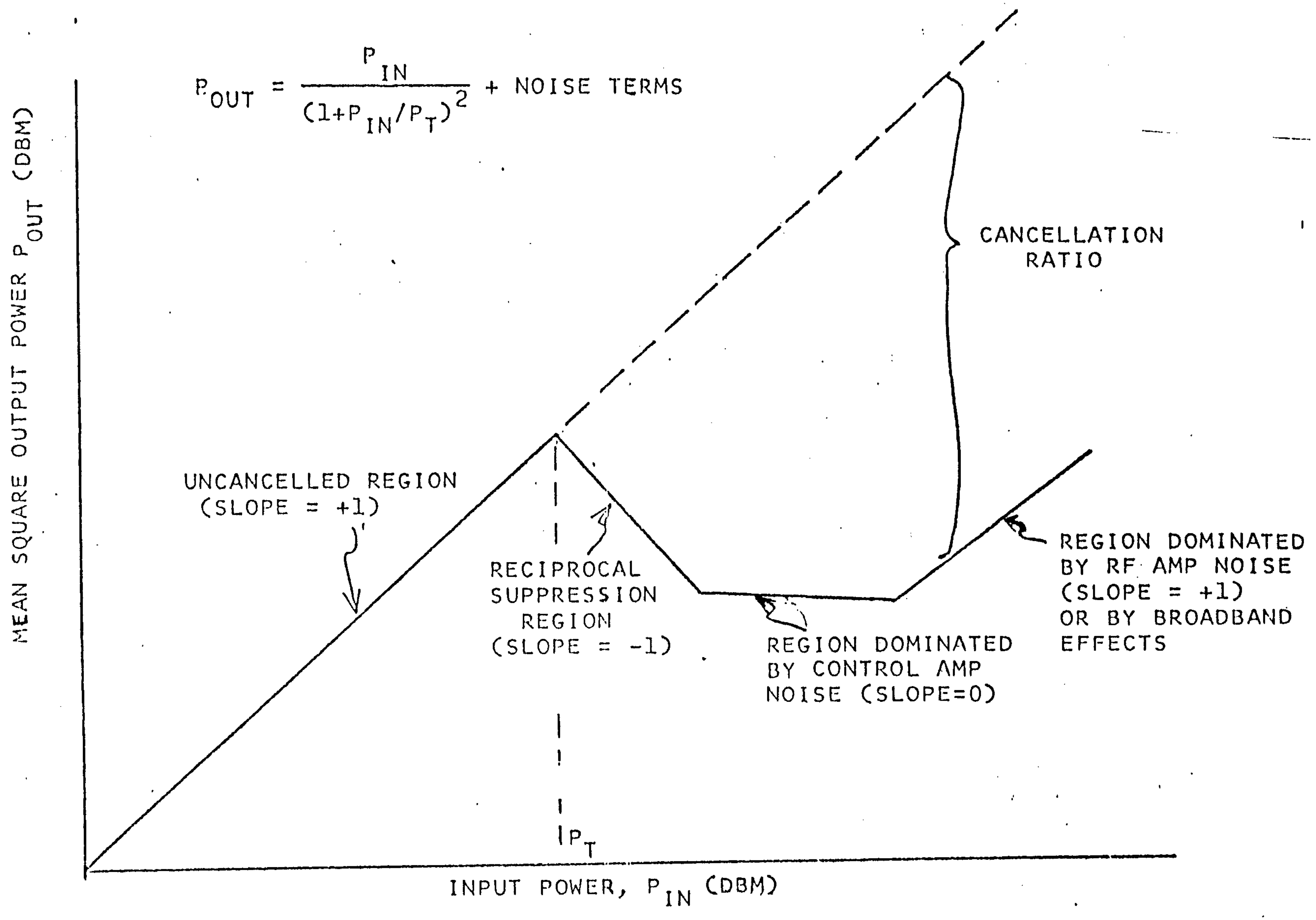
The adaptive array nulling behavior is characterized by the N-shaped curve given in Figure 2.2. It is derived in (2) for a single jammer scenario with a two-element array with one element unweighted, and with a narrowband filter in the control loop. A low level input is not nulled. When the input level exceeds a threshold power level P_T, nulling begins. This is due to the fact that an input level below P_T produces a feedback loop gain below unity, so the LMS feedback loop does not respond.

The closed loop voltage gain is equal to P_{in}/P_T, so that for $P_{in} > P_T$, a stronger input actually comes out weaker in the reciprocal suppression region of the N curve. This region is eventually terminated by noise effects in the loop amplifiers, or by broadband null depth limitations. Thus, the loop gain is one of the limits on null depth.

Although derived for a specific case, the N-curve represents an approximation to behavior under other conditions as well. If the loops contain perfect integrators instead of narrowband filters, then P_T is determined by the front end noise level (3). If the adaptive array is overconstrained in that there are n incident jammers at varying power levels but there are only k degrees of freedom ($k < n$), then P_T is determined by the $(k + 1)$-th strongest jammer. In multiple jammer scenarios, the N-curve approximates the nulling behavior of the

FIGURE 2.2.

NULLING CHARACTERISTIC OF ADAPTIVE ARRAY



$$P_{OUT} = \frac{P_{IN}}{(1+P_{IN}/P_T)^2} + \text{NOISE TERMS}$$

adaptive array on each jammer individually in most cases. Data for 2 jammers is shown in Figure 2.3. and in (4).

2.2.5 Bandwidth Limitations on Null Depth - M effect

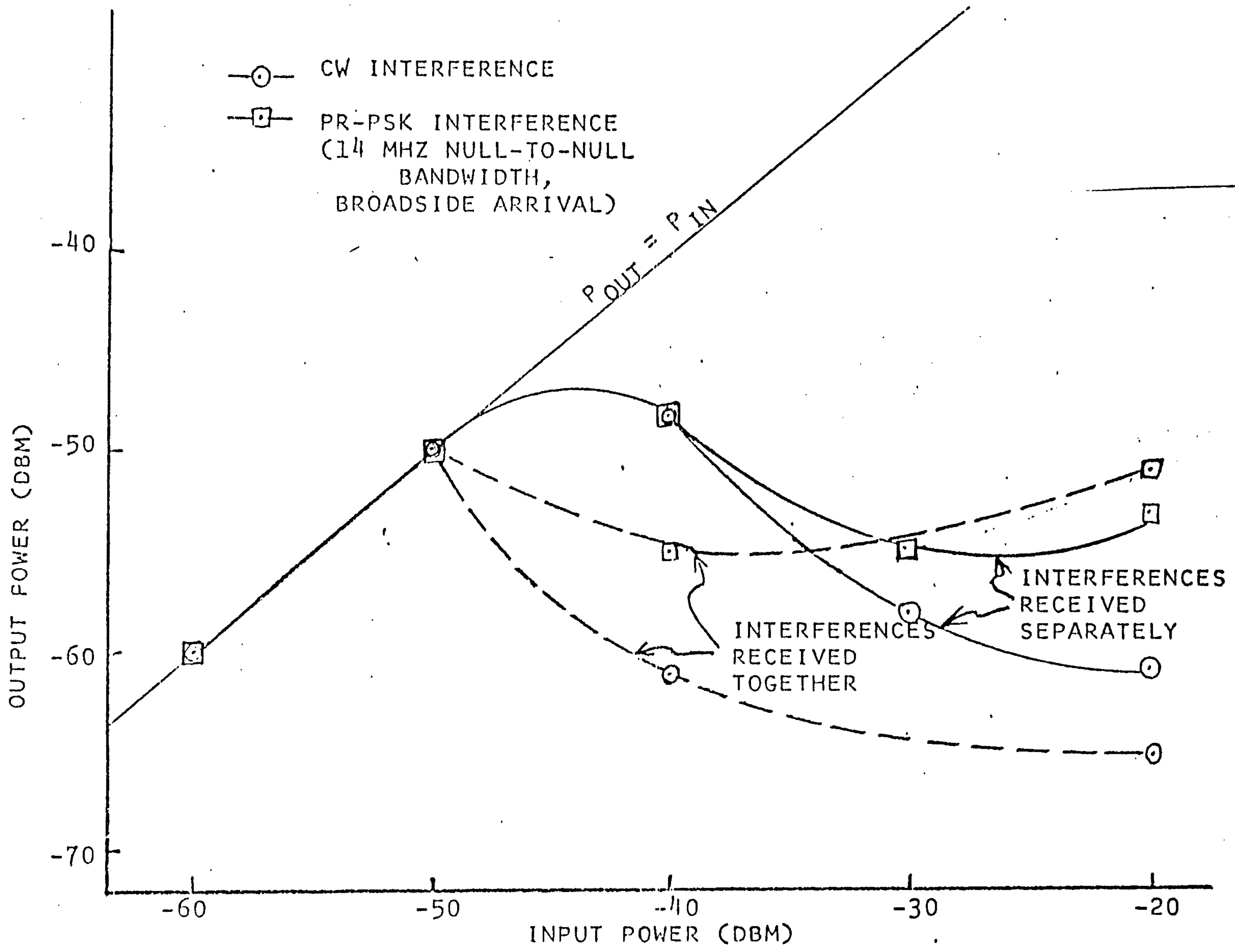
A broadband jammer may not be received simultaneously at all elements of an adaptive array, corresponding to different phase vs. frequency slopes in the various array channel transfer functions. The complex weight attempts to compensate for these variations by a frequency-flat phase shift, which is correct at only one frequency and has ever increasing phase error as a function of offset from that frequency.

This limitation has been analyzed in (2) for a two element array. The assumed jammerpower density spectrum is shown in Figure 2.4a., and the power density spectrum after nulling is shown in Figure 2.4b. Because of the spectral shape in Figure 2.4b., the null depth limitation is termed the "M effect". The ratio of power level in the output spectrum of Figure 6b to the power level in the spectrum of Figure 6a has been computed in (2) for endfire arrival on a two element array with interelement spacing d. These results are graphed in Figure 2.5.

Broadband null depth can be maintained at the expense of hardware complexity if the array channels each pass through an equalizing network (5), such as an adaptive tapped delay line equalizer on each element as described in (1).

FIGURE 2.3.

NULLING PERFORMANCE OF A THREE-ELEMENT ADAPTIVE ARRAY



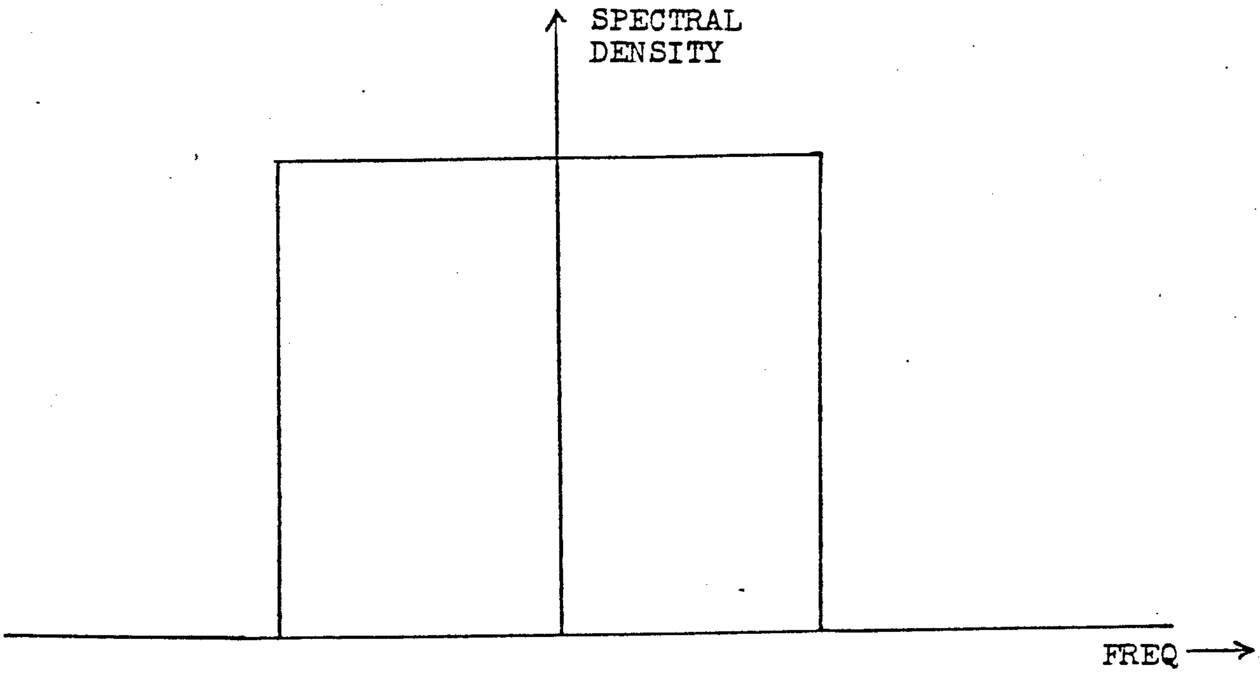


FIGURE 2.4a.

BROADBAND JAMMER POWER SPECTRAL DENSITY

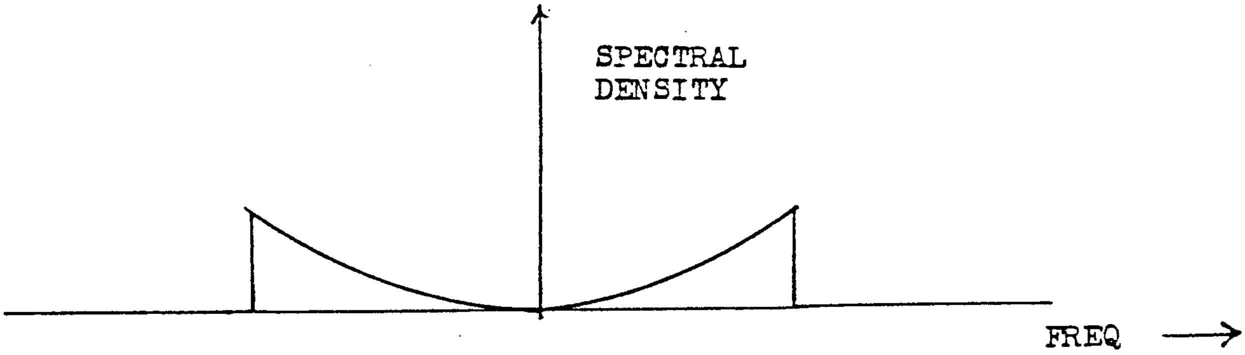


FIGURE 2.4b.

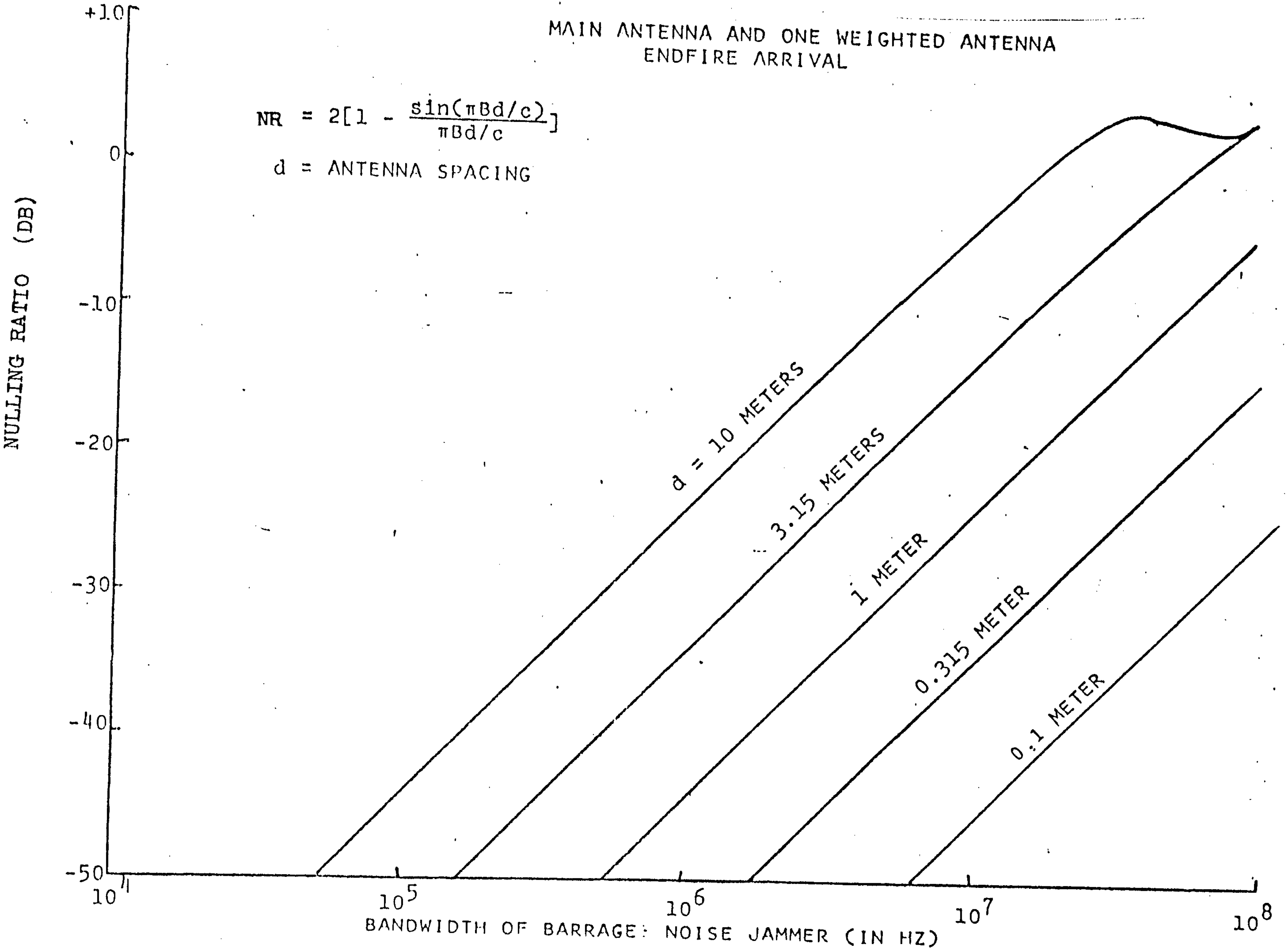
POWER SPECTRAL DENSITY AFTER NULLING

"M" EFFECT

FIGURE 2.4.

FIGURE 2.5.

ACHIEVABLE NULLING RATIO VS. JAMMER BANDWIDTH



MAIN ANTENNA AND ONE WEIGHTED ANTENNA
ENDFIRE ARRIVAL

$$NR = 2\left[1 - \frac{\sin(\pi Bd/c)}{\pi Bd/c}\right]$$

d = ANTENNA SPACING

2.2.6 Noncancellation Regions with a Main Antenna Adaptive Array

The use of a desired signal reference in Figure 1.2. prevents the weights from seeking the all-zero solution by requiring that the desired signal be maintained at a fixed level. The main antenna system of Figure 1.3. also prevents the all zero solution, but it will null any jammer or signal above its threshold (see Section 2.3.4) within the capability of its degrees of freedom. It is most useful for desired signals whose received level is below the nulling threshold.

Another drawback of the main antenna adaptive array is pointed out in (2) in that there are certain jammer geometries for which nulling cannot be achieved even though the number of jammers equals the degrees of freedom of the array. This occurs when there is a linear dependence between the jammers as received at the weighted elements. As shown in (2) for the case of an array with two weighted elements and one unweighted, two jammers cannot be cancelled if the angle formed by the intersection of their propagation vectors is bisected by the line joining the two weighted elements. If the third element were weighted, nulling of the two jammers would be achieved by the third weight going to zero.

2.2.7 Acquisition Time

Because of the dependence of loop gain on jammer strength, and because of the dependence of the response time of a feedback loop on its loop gain, acquisition time depends on jammer strength. An analysis is done in (2) for a two element adaptive array (one element unweighted) of the jammer acquisition time (to within 3 dB of the final value) as a function of jammer strength. The result is given here in Figure 2.6.

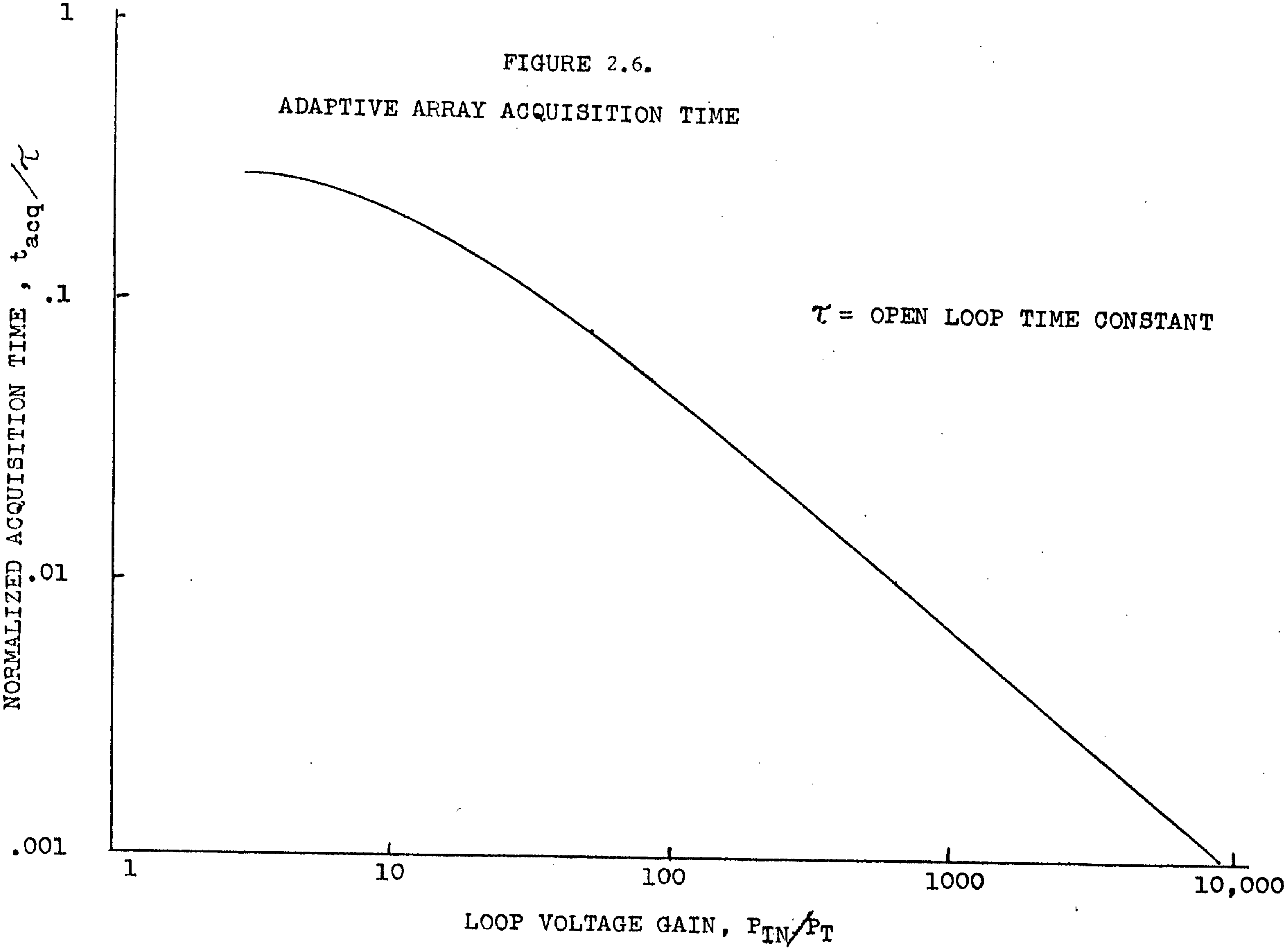


FIGURE 2.6.

ADAPTIVE ARRAY ACQUISITION TIME

When multiple jammers are incident on an adaptive array, the stronger ones will in general be nulled fastest. However, Figure 8 does not apply strictly to each jammer individually because the system behavior to any one jammer is not independent of the others. This is most clearly seen by a system analysis in terms of its normal modes (6) in which the weight vector is transformed onto a set of orthonomal coordinates so that the input correlation matrix is diagonalized. The time constant associated with each mode is determined by its eigenvalue, which in turn is related to the jammer power levels and the geometry of their distribution with respect to the array element locations.

A trade-off of null depth vs. acquisition time is analyzed in (6) and (7) . Faster acquisition causes greater variance in the output error signal about its mean value, which is reflected in the mean square measurement of null depth.

2.2.8 Adaptive Array Techniques for Frequency-Hopped Receivers

Frequency-hopped spread spectrum receivers are a special case of wideband receiver as far as the design of a complementary adaptive array is concerned. This is because the full bandwidth is not occupied instantaneously but on a frequency-hopped basis over time. At any instant of time the receiver bandwidth is the signal bandwidth about each individual hop frequency.

Such a receiver can be likened to a so called "narrowband" radio receiver that is pseudo-randomly tuned across a wide band of frequencies. It would be unwise to attempt to design an adaptive array for an airborne UHF radio that provides AJ at all times across the 225-400 MHz band when only one 25 kHZ channel is in use at any time. A much more effective way is illustrated in Figure 2.7., where the signals from each antenna are frequency converted to a fixed IF for bandlimiting about the desired channel before adaptive array processing is applied. The nulling capability of the adaptive array is thus concentrated in the desired signal channel instead of being dispersed throughout the RF band or deteriorated by broadband null depth limitations.

The main distinction in the analogy between a frequency-hopped spread spectrum receiver and a tunable "narrowband" receiver is the hopping speed, which then imposes a requirement on the speed of null formation of the adaptive array processor. Each time a new frequency is used, the adaptive array processor must readapt itself to combat the new jammer scenario. For such an adaptive array to be effective, it must be adapted in a time short compared to the hop dwell time.

The faster that an AA can adapt to a new frequency hop (FH) the faster the allowable FH rate and hence the more difficult for an enemy to construct a FH following jammer. The block diagram of an AA for a FH spread spectrum (SS) receiver is illustrated in Figure 2.8. where only the n-th antenna channel is shown. The wideband RF preamplifier establishes the system noise figure. The FH LO from the SS receiver converts the wideband FH signal from RF to a common IF (e.g., 70 MHz). An IF strip filters the reduced bandwidth signal to its psuedo-noise (PN) bandwidth (e.g., 5 MHz) and an AGC adjusts the signal to a level which is suitable for the AA nulling threshold. The AGC must be as fast as the FH rate since jammers in "time-adjacent" frequency slots

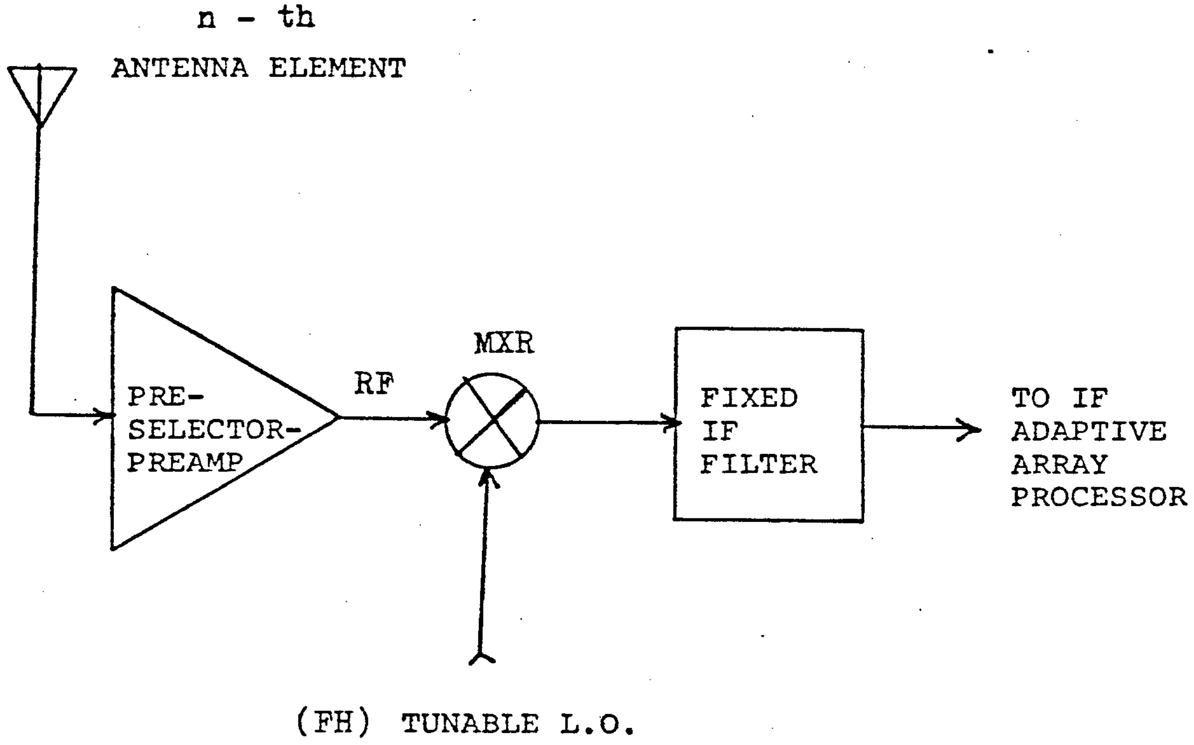


FIGURE 2.7.

FRONT END FOR EACH ADAPTIVE ARRAY CHANNEL IN A TUNABLE (FH) RECEIVER may be of different strengths. The rest of the AA in Figure 2.8. is a conventional LMS loop (discussed in Sections 2.3.1-.3.7) and a signal reference loop.

When the AA of Figure 2.8. is fast enough to readapt in a fraction of the time between hops the nulling bandwidth is 5 MHz. Consider an interference that covers the entire FH band (e.g., 100 MHz). Suppose the band is located at 1 GHz and array elements are separated by $\lambda/2$ ($\lambda = 0.3$ meters).

In a conventional AA without dehopping and re-adaption, the results of Chapter 1 show that the null depth on a 100 MHz wide interference at endfire would be less than 20 dB. The fast AA would need only null that 5 MHz wide portion of the 100 MHz wide interference that lies in band at any instant and would be able to achieve up to a 46 dB null at endfire.

Against narrowband or spot interference the fast FH AA offers a different advantage over a conventional AA. An N element AA can only form N-1 independent nulls at a time. Thus, the fast AA can null up to N-1 distinct sources of interference in each 5 MHz FH slot while the wide-open conventional AA can null N-1 interferences in the entire (100 MHz) FH band. In a severe interference environment, the conventional broadband AA will rapidly exhaust its degrees of freedom.

2.3.0 Multiplexing Antenna Signals

Signal multiplexing was introduced in Section 1.4. The theory here expands upon those characteristics of concern to a multiplexed adaptive array, by the technique of time division multiplexing (TDM), code division multiplexing (CDM), and frequency

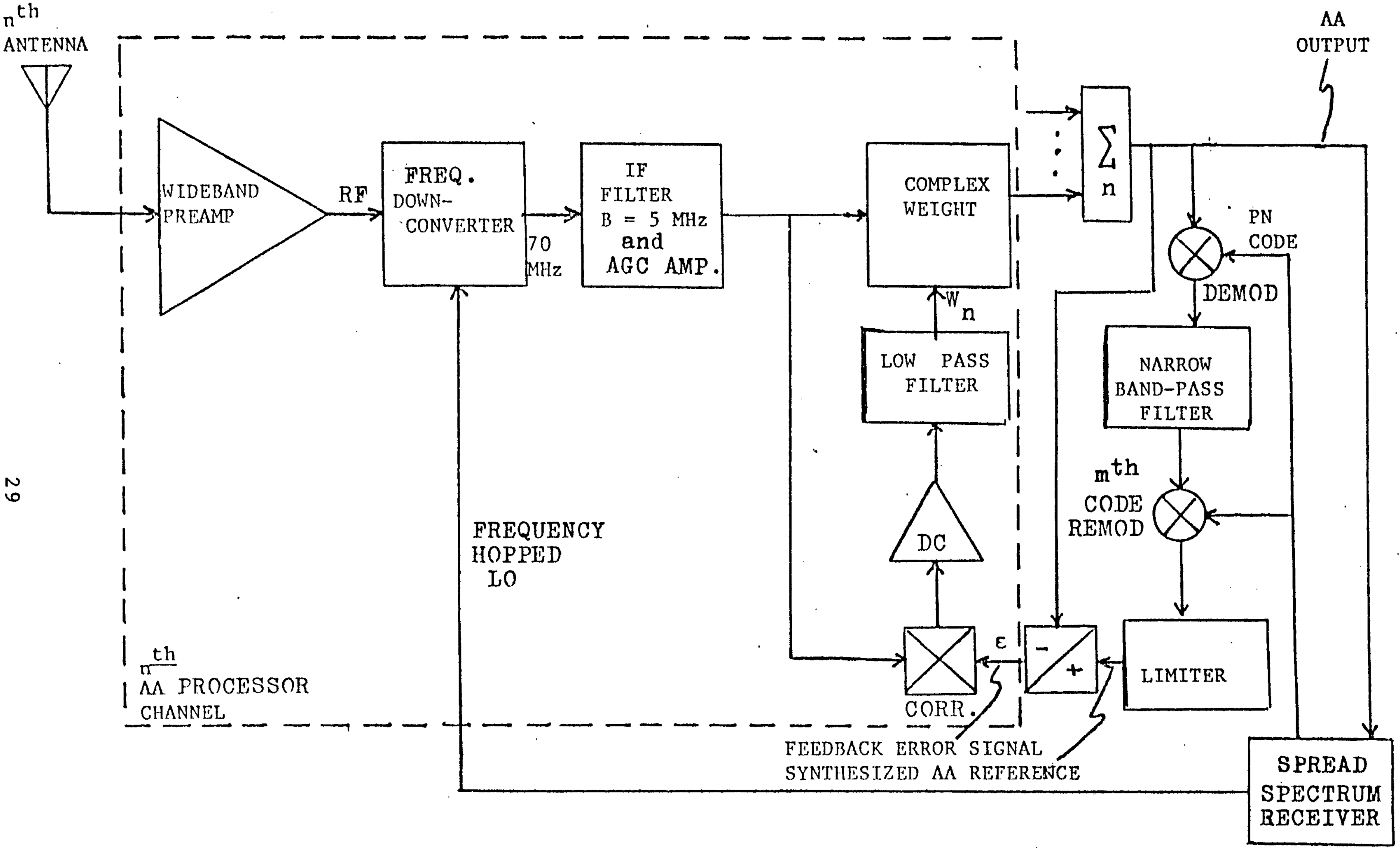


Figure 2.8.

AA FOR FREQUENCY HOPPED TDMA COMMUNICATIONS division multiplexing (FDM).

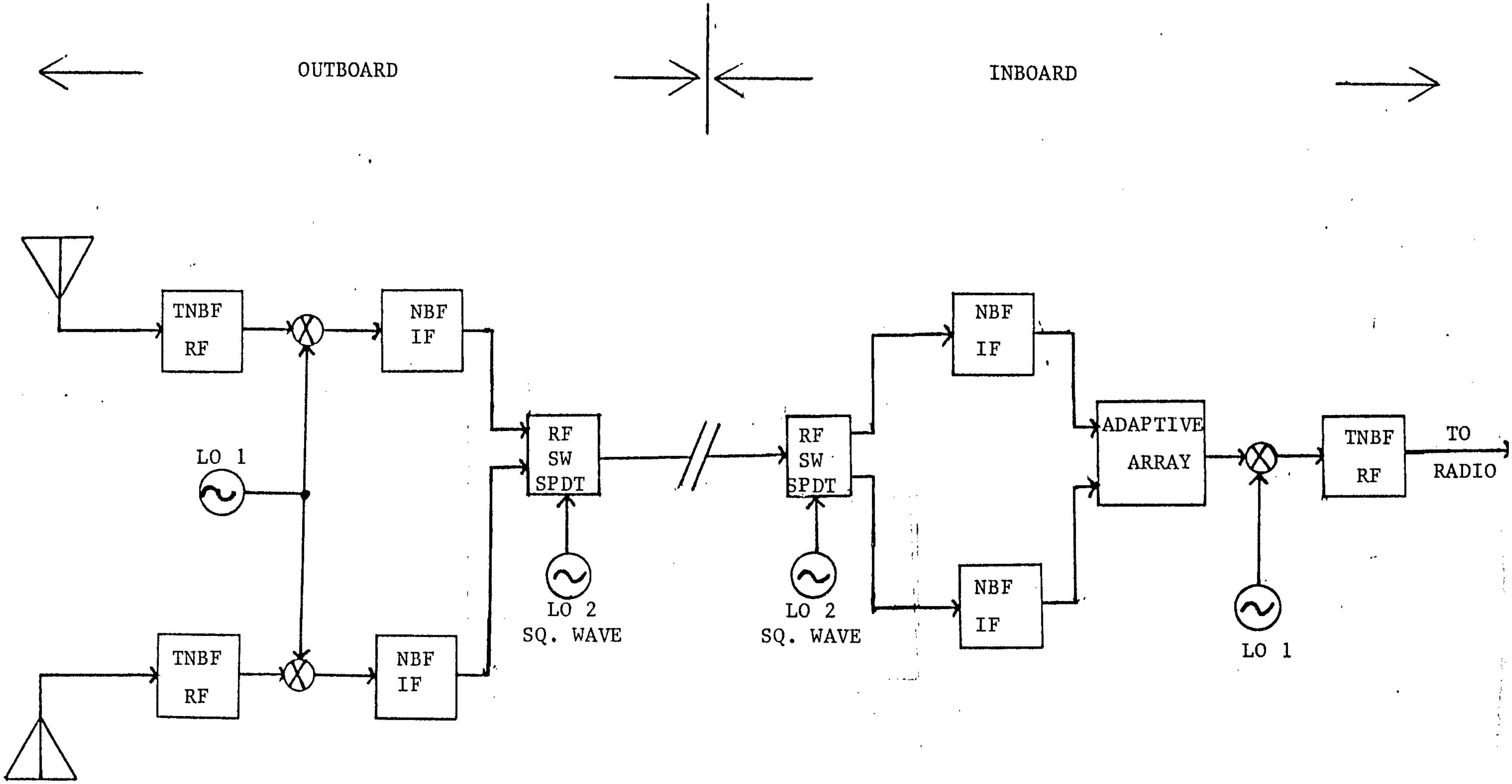
2.3.1 Time Division Multiplexing

In TDM, a single communication channel is used to transmit more than one signal by dividing the total transmission time into distinct time slots which are alternated amongst the desired signal lines.

A block diagram of an inboard/outboard TDM adaptive array for a two antenna system is illustrated in Figure 2.9. Each antenna signal is brought down to a constant IF by LO1, which is tunable and dependent on the selected frequency channel. These IF signals are then narrowband filtered, with strong rejection of any signal out of the passband. Any signal outside of the filter passband will cause aliasing upon demultiplexing at the other end. This initial filtering must be done on both signals and is almost identical to the filtering done in the first stages of a receiver. LO2 must be a coherent source to both ends of the cable. It would probably be generated inboard and sent outboard along the cable to the outboard system.

Furthermore, it may be that the SPDT switch will not provide enough isolation between the two signal lines, particularly during transistions. This problem can be solved by using a SP3T switch, where the third position is simply open or grounded. LO2 is then a clock which drives a control signal network that drives the switch as 1-3-2-3-.....

To expand the system to N antenna signals, one would add N-2 throws to the switch as well as generating a new set of switch control signals.



TDM

FIGURE 2.9.

The disadvantages of TDM are that one needs to convert all signals to an IF, and heavily filter the signal outside the passband of the multiplexing network. The multiplexing network is active and requires a coherent signal at both ends. The advantage of TDM is that signal lines require a minimum of additional hardware.

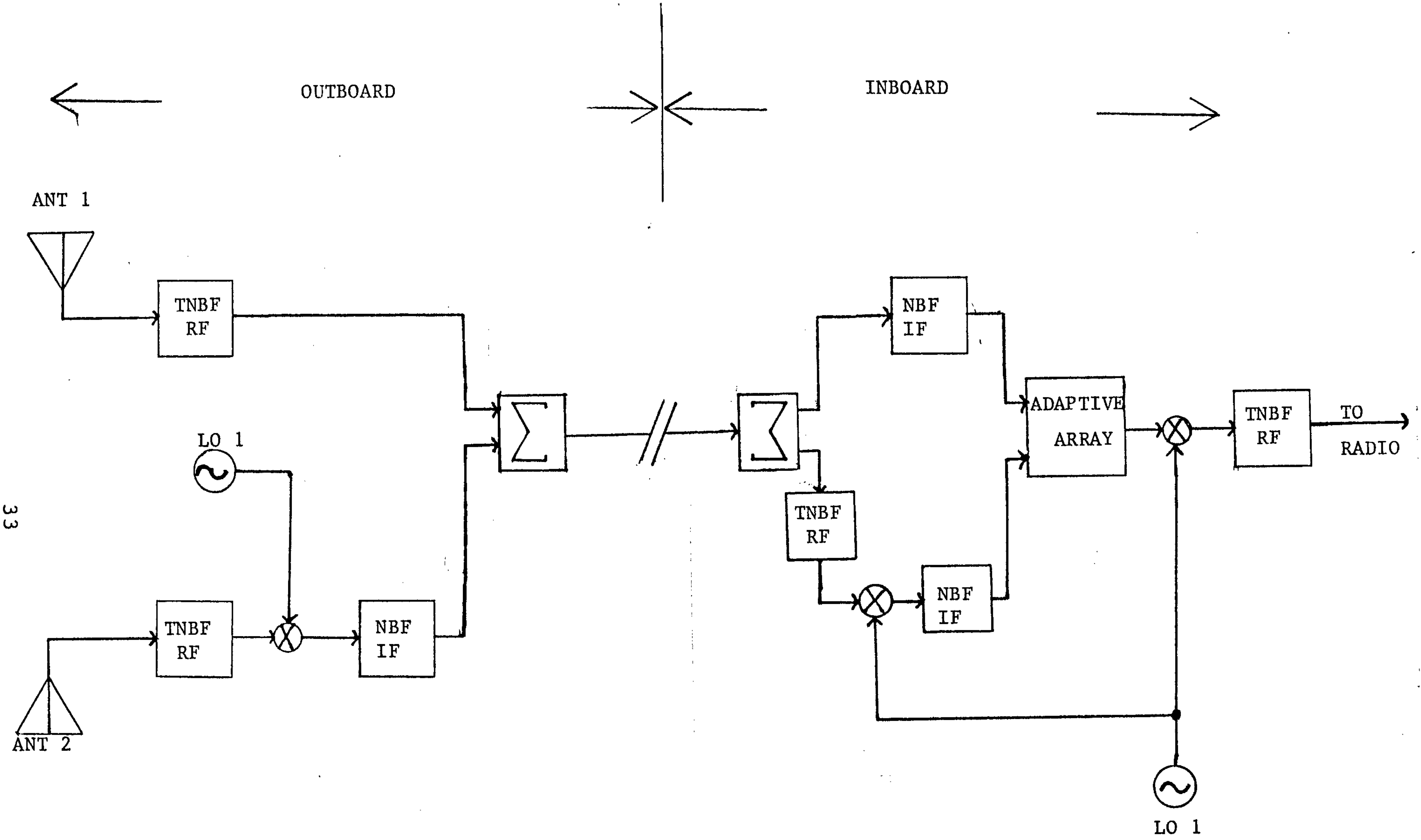
2.3.2 Frequency Division Multiplexing

In FDM, more than one signal is sent down a single communication channel by converting the signals to disjoint frequency bands and then transmitting them down the channel simultaneously.

A block diagram of an inboard/outboard FDM adaptive array, for a two antenna system is illustrated in Figure 2.10.

In comparing the FDM diagram in Figure 2.10. to the TDM diagram in Figure 2.9., we notice a significant reduction in the components necessary outboard. The reasons for this are: 1) Only one of the two antenna signals need to be converted by a local oscillator. 2) The filtering of the signals need only be enough to make sure no spurious signals of either line fall directly on either desired signal. Rejection of all signals outside a given bandwidth about the desired signals, is not necessary because there is no aliasing problem. 3) The two signals are multiplexed passively in a signal combiner as opposed to the TDM active switch and necessary control signals generating network.

One must also note that the need for a second oscillator has been removed; however, LO1 must now be coherent both inboard and outboard. This means that LO1 would be generated inboard and



FDM

FIGURE 2.10.

shipped down the cable outboard. In practice, this would probably not be an addition to the design over TDM, because LO1 is a high stability, tunable oscillator. Such an oscillator would be a rather large device and use considerable power. So that in TDM where outboard space and power constraints force LO1 inboard, as well as in FDM where a coherent inboard/outboard LO is a necessity, the practical design calls for LO1 to be generated inboard and shipped outboard.

FDM is at a disadvantage to TDM for systems with several signals to multiplex. Each additional signal requires another coherent oscillator at each end, as well as additional different filters to multiplex and demultiplex. TDM simply requires another throw to the switch, modification to the control signals, and another line filter identical to all the others. For systems with only two signals to multiplex, FDM is usually the favored method. For systems with three signals, FDM and TDM are about equal in complexity and the specific signal format requirements on the input and output of the multiplexing network, i.e., which is more convenient to use, will probably be the basis for a decision for either method. For systems that will multiplex four or more signals, TDM would probably be the favored method.

The case at hand concerns the multiplexing of two antenna signals, for which FDM essentially requires no outboard components that are not also used in TDM, while TDM requires many components that are not needed outboard in FDM. It is on this point that the recommended design, put forth in Section 3, uses FDM.

2.3.3 Code Division Multiplexing

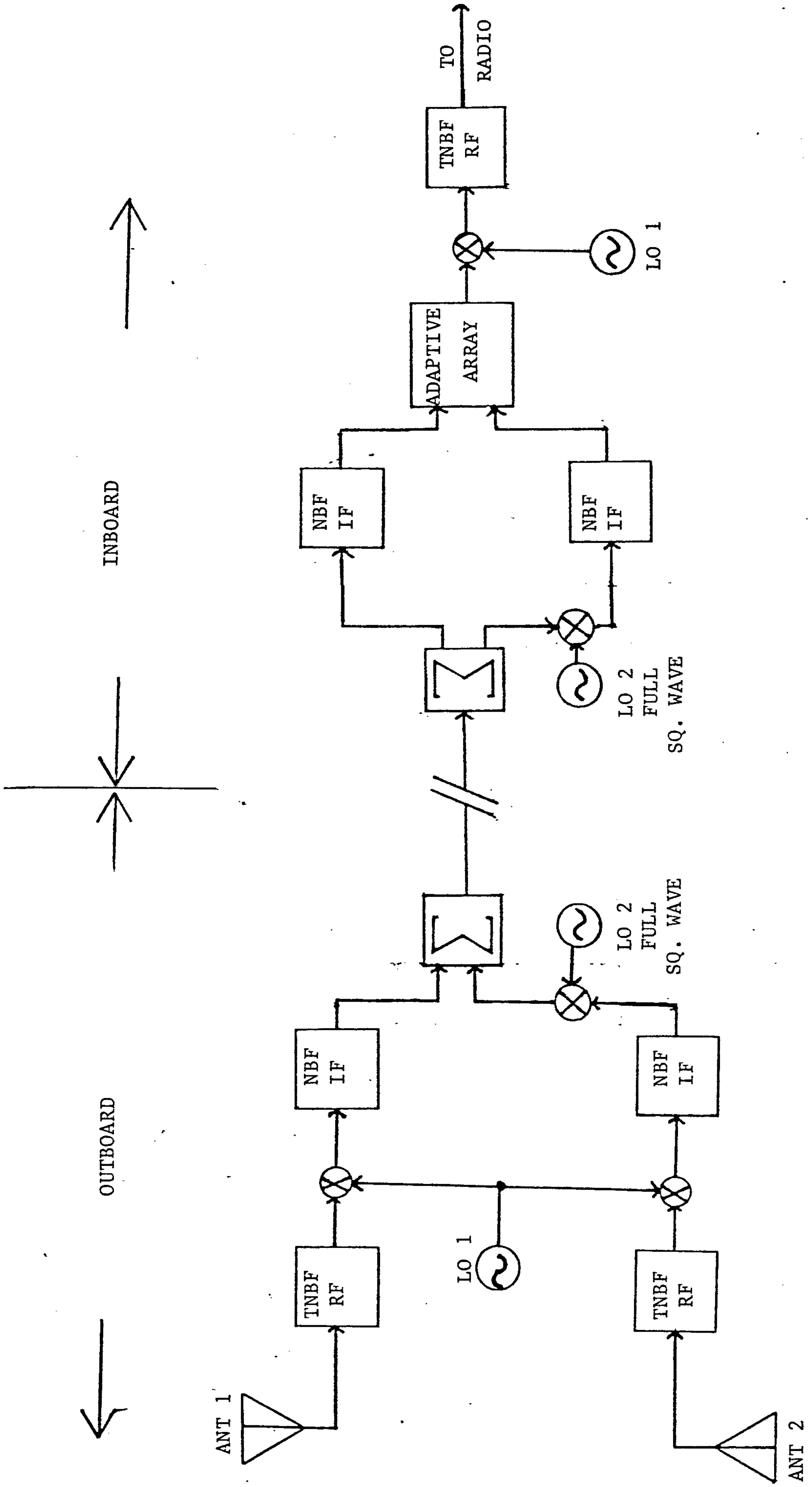
Code division multiplexing is somewhat of a cross between FDM and TDM. A block diagram for a CDM system is illustrated in Figure 2.11. All signals must be converted to a given IF to be narrowband filtered. As in TDM, there is a problem of aliasing during multiplexing and demultiplexing, so complete narrowband filtering is necessary. After multiplying each signal by the appropriate multiplexing function, the signals are passively combined as in FDM.

The CDM block diagram in Figure 2.11., corresponds to a two signal system from Figure 1.4. with $f_1(t) = 1$ and $f_2(t)$ = a full square wave. To add another signal line would require the generation of another multiplexing function, another mixer, and expanding the combiner. For ease of expansion, CDM lies somewhere between TDM and FDM. The main use of CDM is in communication channels where security is desired. The multiplexing functions $f_1(t)$, $f_2(t)$, etc., can be based on a pseudo-random sequence that is available at both ends of the communication channel.

The multiplexed adaptive array being considered does not have a need for secure transmissions, so CDM was not considered a viable approach to the problem.

2.4 Dual Polarized Jammers

A dual polarized jammer emits simultaneously two uncorrelated waveforms with orthoganal polarizations. Such a signal impinging on an adaptive array whose element antenna polarizations are perfectly parallel, would cause no problem. In reality, however, the element polarizations are not perfectly parallel, and a



CDM

FIGURE 2.11.

dual polarized jammer would degrade the performance to a degree dependent on how much the element antennas are out of line.

There are two methods to reduce or remove this effect. One is to realign all the element antennas, so that they are as parallel as can be achieved. An alignment of 3° or better is necessary. This may require the redesign of some antennas as well as the mounting platform, however, this does not change the number of antenna nor alter their cable runs. This method is totally compatable with the proposed design.

The other method of combatting the effect of a dual polarized jammer is to add extra antennas to the system, where the new antennas are orthogonally polarized relative to the old ones. This solution, however, requires altering the airframe, adding cable runs, and increasing the amount of adaptive processing. This approach is not consistent with the "quick-fix" object of this design.

3.0. THE RECOMMENDED DESIGN

3.1. System Configuration and Performance Objectives

The system architecture will meet the following configurational and performance objectives:

(i) The outboard subsystem will connect via existing cables to 2 UHF antennas and via an existing cable to the inboard subsystem which is also connected directly to the UHF receiver.

(ii) The combined system will operate transparent to the radio receiver and transmitter, and require operator control only via an "Adapt/No Adapt" selector switch.

(iii) Will form -30 dB nulls on interference within ±25 KHz of the desired frequency in narrowband mode and ±50 KHz of the desired frequency in wideband mode.

(iv) The system will change modes, from Adapt to No Adapt, and vice versa, within 65 ms; and change frequencies within a mode in 4 ms.

(v) The system will have a maximum of 1 dB in non-adaptive transmit power or receiver sensitivity and no effective loss in non-adaptive received power in the recommended design. An alternative design that does not have this loss in non-adaptive receiving is also discussed.

(vi) The system will generate no spurious signals greater than -113 dBM within ±100 KHz of the center frequency, no spurious signals greater than -43 dBM within 1 MHz of the center frequency and no spurious signal greater than -33 dBM anywhere else in band.

(vii) The power of any reradiated signals during receiving shall be within acceptable levels (See Section 3.2.4.).

(viii) The adaption time constant is 15 ms.

3.2.0 The Outboard Subsystem

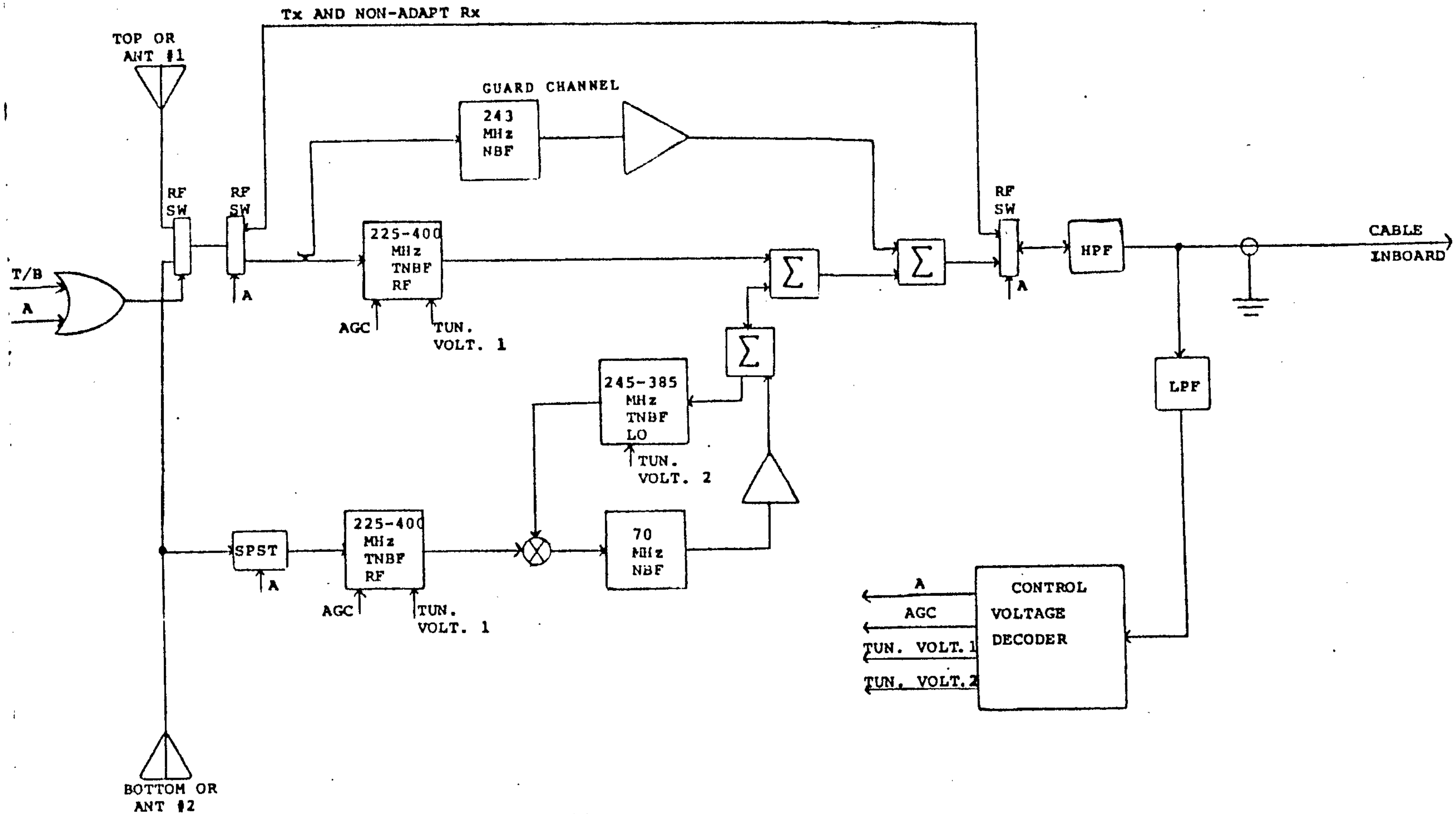
The recommended outboard subsystem, drawn in Figure 3.1., shall take the two antenna signals and do the necessary premultiplex filtering. It will FDM the signals together by converting one of the signals to a different frequency and then combining them.

The signal that is converted, is done so with a variable LO that is sent outboard on the cable link. The LO will convert that signal to a constant IF, that is 70 MHz in the recommended design. Alternative IF's are discussed in Section 3.3.5.

Both antenna signals will be filtered by tunable narrow-band filters, composed of varactor diodes. The recommended design would use the varactor diode filters. To control these filters, two signals must be sent outboard along with the LO. These are the tuning voltage, necessary to select the desired frequency, and the automatic gain control, (AGC), to the amplifiers in the filters.

3.2.1 Operating Mode Selection

There are four RF switches in the diagram of Figure 3.1. These switches control the signal paths. One of these switches performs the same function as the existing antenna selector, or Top/Bottom switch, that the outboard subsystem replaces. The switch is



OUTBOARD DESIGN

FIGURE 3.1.

called the Top/Bottom switch because most two antenna systems have one antenna on top of the aircraft and one underneath. The signal "T/B," in Figure 3.1., is the existing Top/Bottom switch control signal. For discussion, it is assumed to be high or "1" for selecting the top or #1 antenna, and low or "0" for selecting the bottom or #2 antenna.

One method of operation of the existing Top/Bottom switch, is to toggle the switch at a very slow rate until it detects a signal that breaks squelch. Then it stays in that position until squelch is reinstituted, when it resumes the toggling operating. The last position held during an unsquelch is remembered and selected for transmitting. This position selection is done inboard. The "T/B" signal merely represents the decision.

The other signal that controls the switches is "A" for Adapt. "A" is high or "1" for adaptive processing and low or "0" for non-adaptive processing. "A" is generated inboard and sent outboard along with the control voltages.

In the recommended design, the new Top/Bottom switch would be controlled by the old "T/B" signal when "A" is low, but is forced into the Top position when "A" is high. This is represented in Figure 3.1. by logically OR-ing "A" and "T/B" as the input into the Top/Bottom switch.

However, if "A" simply represented the position of the operator Adapt/No Adapt selector switch, then it would interfere with the antenna selection for transmitting, as described above. Therefore, "A" is generated inboard by a logical AND operation of the signal from the Adapt/No Adapt operator switch and a de-squelch signal from the radio receiver.

All the other RF switches are operated by the signal "A." When "A" is high, both antenna signals are processed by the multiplexer and sent on the cable link. When "A" is low, the antenna signal selected by "T/B" is sent onto the cable, by passing the multiplexer. These two cases are illustrated in Figure 3.2.

In a similar manner, the signals will bypass the inboard subsystem when "A" is low. The addition of these four switches to the transmit and non-adaptive receive path accounts for the 1 dB loss in performance in these operational modes. An alternative approach which has no effective signal loss is discussed in Section 4.1.

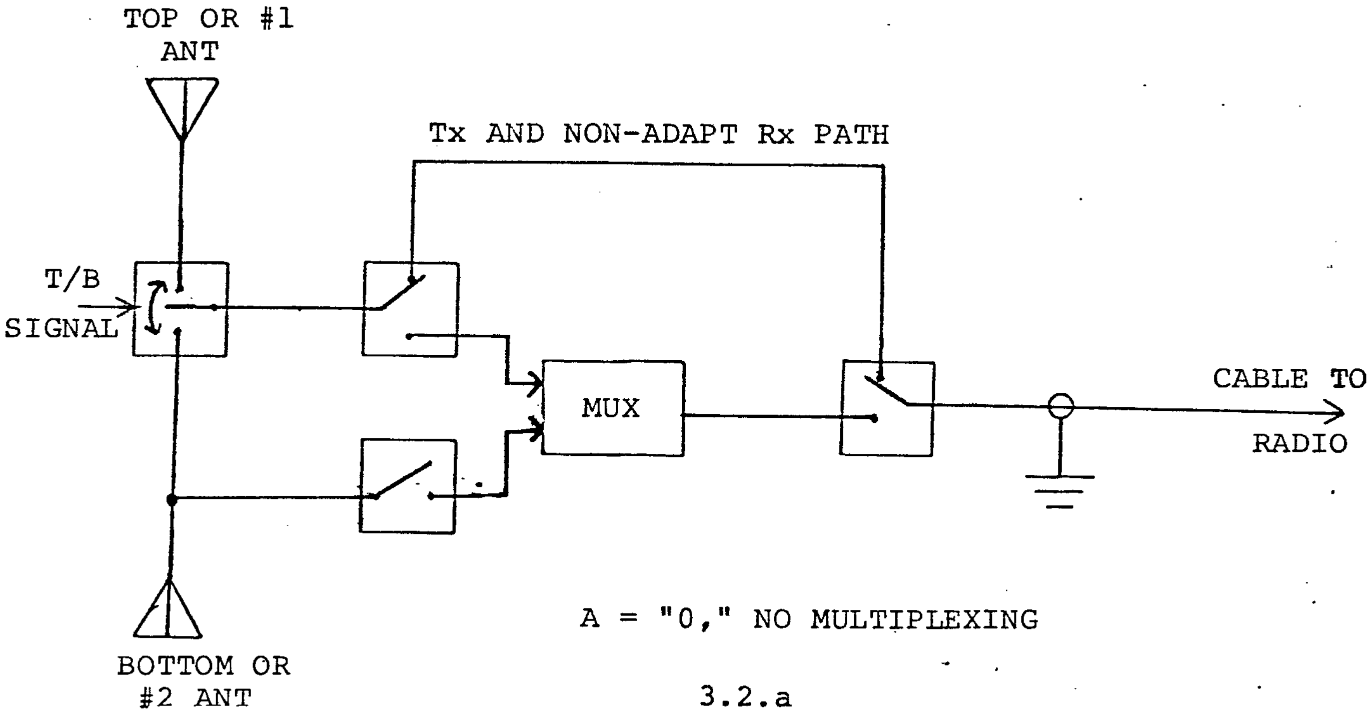
3.2.2 A dB Analysis

Figure 3.3., shows a signal level and isolation analysis of the multiplexing network. This analysis is based on the following assumptions:

(i) The incoming desired RF signals have a dynamic range of -103 dBM to +7 dBM and incoming out of channel undesired RF signals have a maximum strength of -36 dBM.

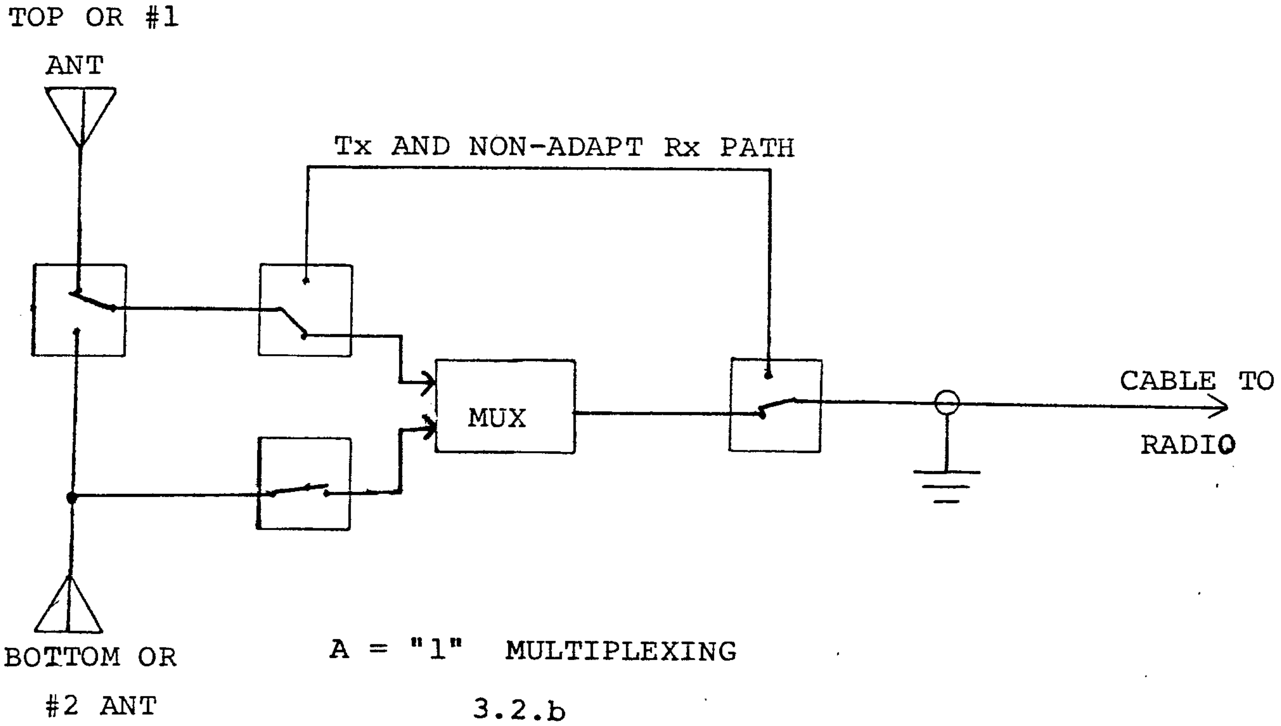
(ii) The tunable narrowband filters have variable gain of -37 dB to +26 dB, and have a bandwidth of 4-7 MHz over 225-400 MHz or ≃ 1.7% of center frequency. These are 3 pole filters.

(iii) There is 20 dB isolation between the sum ports on the combiners and 25 dB isolation from the LO to the RF port on the mixer.



A = "0," NO MULTIPLEXING

3.2.a

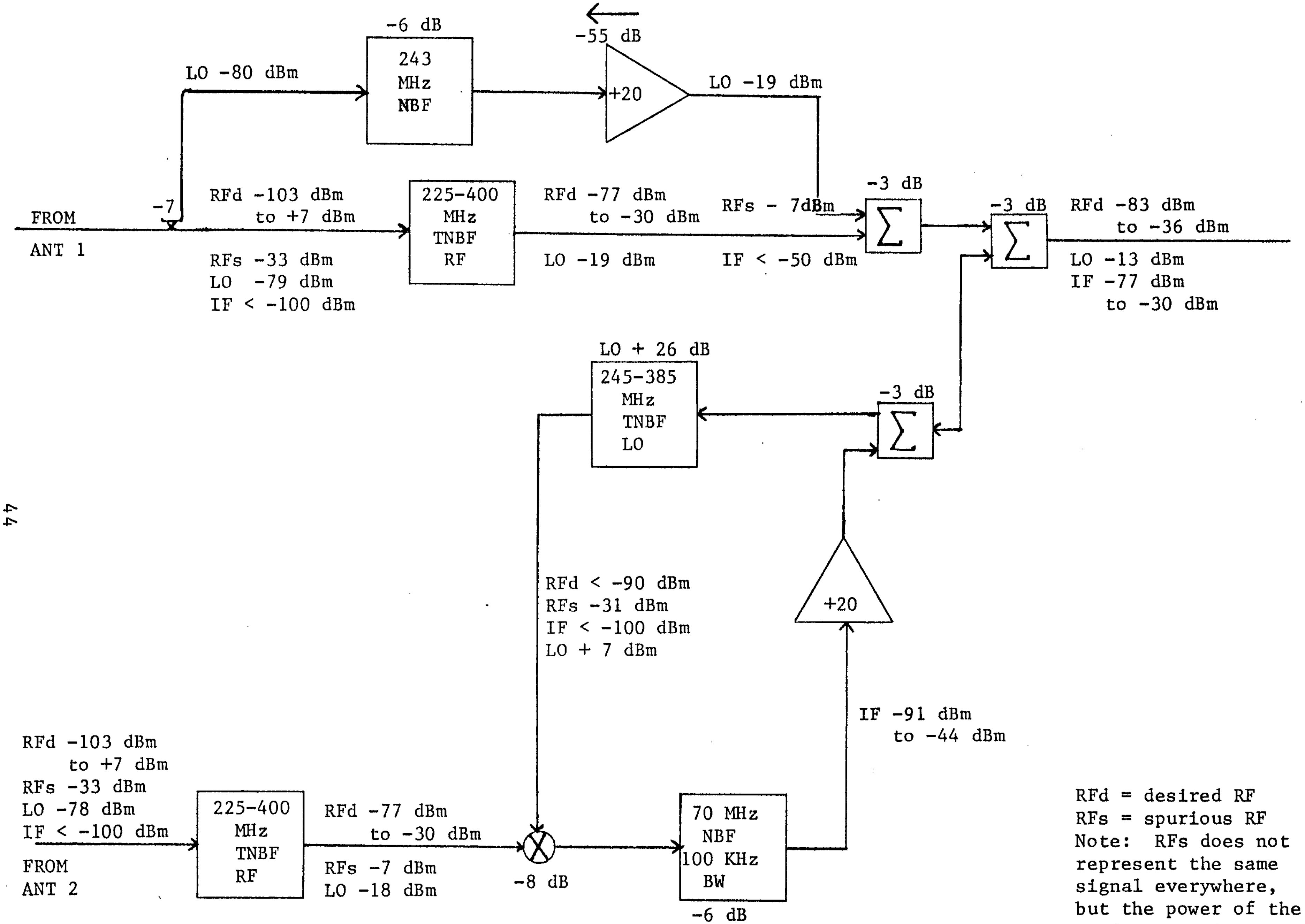


A = "1" MULTIPLEXING

3.2.b

OUTBOARD SIGNAL PATH

FIGURE 3.2.



RFd = desired RF
RFs = spurious RF
Note: RFs does not represent the same signal everywhere, but the power of the maximum spurious RF that can appear at the point which each is given.

dB ANALYSIS

FIGURE 3.3.

The guard channel is preserved by tapping off part of the top signal with a 7 dB directional coupler. This signal is sent through a 243 MHz narrowband filter, and then a low noise amplifier. The gain of the amplifier is enough to establish the noise figure over all the remaining losses in the line.

Consider now the reverse RF feedback loop on the guard channel. There is up to +26 dB gain in the TNBF, then -20 dB in isolation of the combiner inputs, -55 dB in reverse isolation of the amplifier, and -27 dB isolation in the directional coupler. This adds up to a neglible feedback of -76 dB.

The tunable narrowband filters are 3 stage filters with a bandwidth of 7 MHz or less. This means at 70 MHz array, there is 78 dB rejection. Thus, the filters tuned to the LO reject the desired RF by 78 dB and vice versa.

But isolation between ports on a device of greater than 60 dB is hard to achieve. The combined rejection gain product of any device shall not be less than -60 dB. For example: 1) TNBF rejection of 78 dB and an AGC gain of 26 dB means a final rejection of 52 dB. 2) TNBF rejection of 78 dB and no AGC gain means a final rejection of 60 dB.

The value of 78 dB is also the minimum attenuation through both TNBF's for any RF signals coming from antenna 1 to the LO port of the mixer. It is, however, possible that such a signal would pick up +26 dB gain through both TNBF's, allowing the full 78 dB rejection. Finally, such a signal would be isolated and attenuated 26 dB through the combiners. Add all this up with a maximum spurious RF signal of -33 dBM and arrive at a maximum spurious RF signal into the LO port of the mixer of -49 dBM.

Consider also the isolation of the mixer LO port from the desired RF of antenna 1. The maximum signal level of the desired RF out of the TNBF at that RF is -30 dBM. There is 26 dB of loss and isolation in the combiners and 60 dB isolation in the LO TNBF. This leaves a desired RF at the LO port of -90 dBM.

Similarly, the desired and spurious RF signals from antenna 2, which leak through the mixer, are removed by the LO TNBF or the 70 MHz IF filter. The IF is kept from the LO mixer port by the LO TNBF.

In actual construction, care has to be taken to isolate connections and ports. This is necessary to insure that the rejections described in this Section will be obtained.

3.2.3 Reradiation Protection

First, one must obtain an estimate of safe reradiated power levels. The situation to consider is when one wants to receive signals, but maintain radio silence, that is, not reradiate any spurious signals that would be detectable by the enemy. It is determined in the Appendix that this power is -55 dBM. In the recommended design, the reradiated power is the sum of the powers of the IF and LO at both of the antennas.

From Figure 3.3. this is essentially the sum of the LO appearing at both antennas, for the IF is comparatively negligible. The sum of the LO powers is approximately -75 dBM, well below the calculated allowed power.

3.2.4 Control Signals

There are a few control signals for the outboard subsystem that must be sent outboard from the inboard subsystem. These are 1) the "A," or "start adapt" signal, which must be sent with each change of operation mode, 2) the DC tuning voltages for the TNBF's, one for the RF TNBF's, and another for the LO TNBF, updated with each frequency change and 3) the AGC control loop voltage, which is a continuous low pass signal.

The recommended design digitizes the "A" signal and the tuning voltages and sends these down the cable when necessary. The line is then switched to the continuous AGC voltage.

The RF outboard components will be isolated from the control signals by capacitive coupling and the control lines will be isolated from the RF by an inductive choke. Stronger filtering will be used if found necessary.

The digitized signals are in the diphase form or Manchester code. This is a synchronous code where a bit is transmitted with every clock pulse. Every data pulse, however, has a transition in the middle of it. A "1" pulse might start high and switch low, where as a "0" pulse would then start low and switch high (See Figure 3.4.). This transition is a way of simultaneously transmitting the clock and data.

To transmit a diphase signal, one would start by sending a string of all "1" or all "0" to allow the phase lock loop on the other end to synchronize it's clock. This string of "1"s or "0"s would be followed by a special string of bits, called a "sync code," which the outboard processor would recognize as a start code, meaning the data would be following.

The sync code in the recommended design would convey the "A" signal. There would be two codes, one to start adaptive processing and one to stop it. If the sync code represents "A" high, then immediately following it are the digitized DC tuning voltages. As soon as the digitized voltages are received, the outboard system sends the same bits back for verification inboard. If the data received back inboard is incorrect, the inboard system will transmit the right data again. In the absence of a second message, the outboard system will switch the line over to the AGC circuits. The line is still monitored; however, to detect a signaled change in operation (See Figure 3.5.).

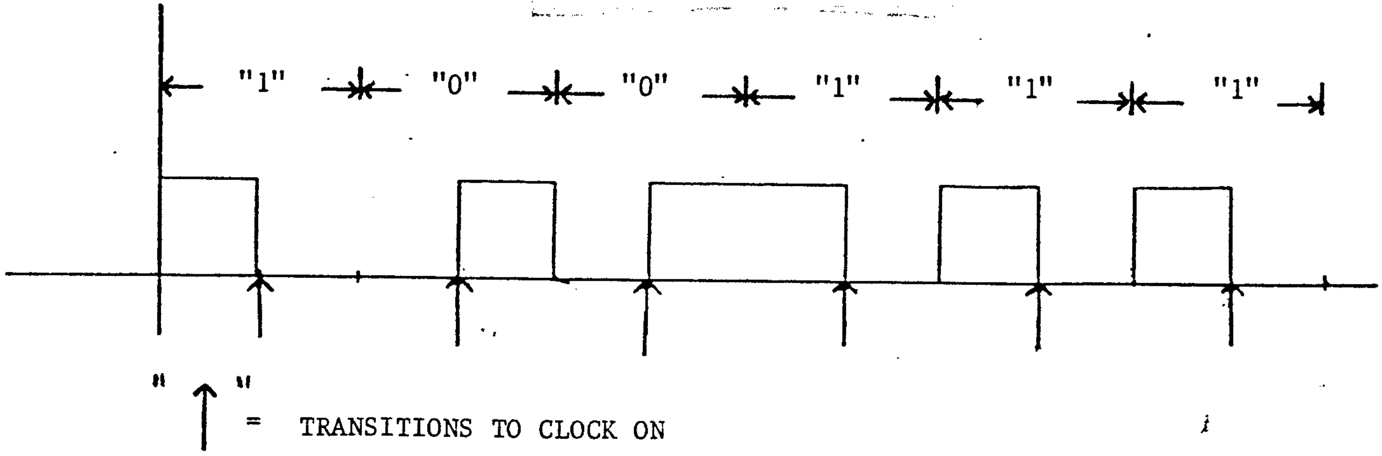
3.3.0 The Inboard Subsystem

In the adaptive mode, the inboard subsystem will demultiplex the signals and then adaptively process them at the IF frequency of 70 MHz. There are two sets of 70 MHz filters to allow for both narrowband voice and wideband secure operation. After the adaptive loop, the signal is mixed with the LO to convert it back to RF (See Figure 3.6.).

3.3.1 Operating Signal Paths

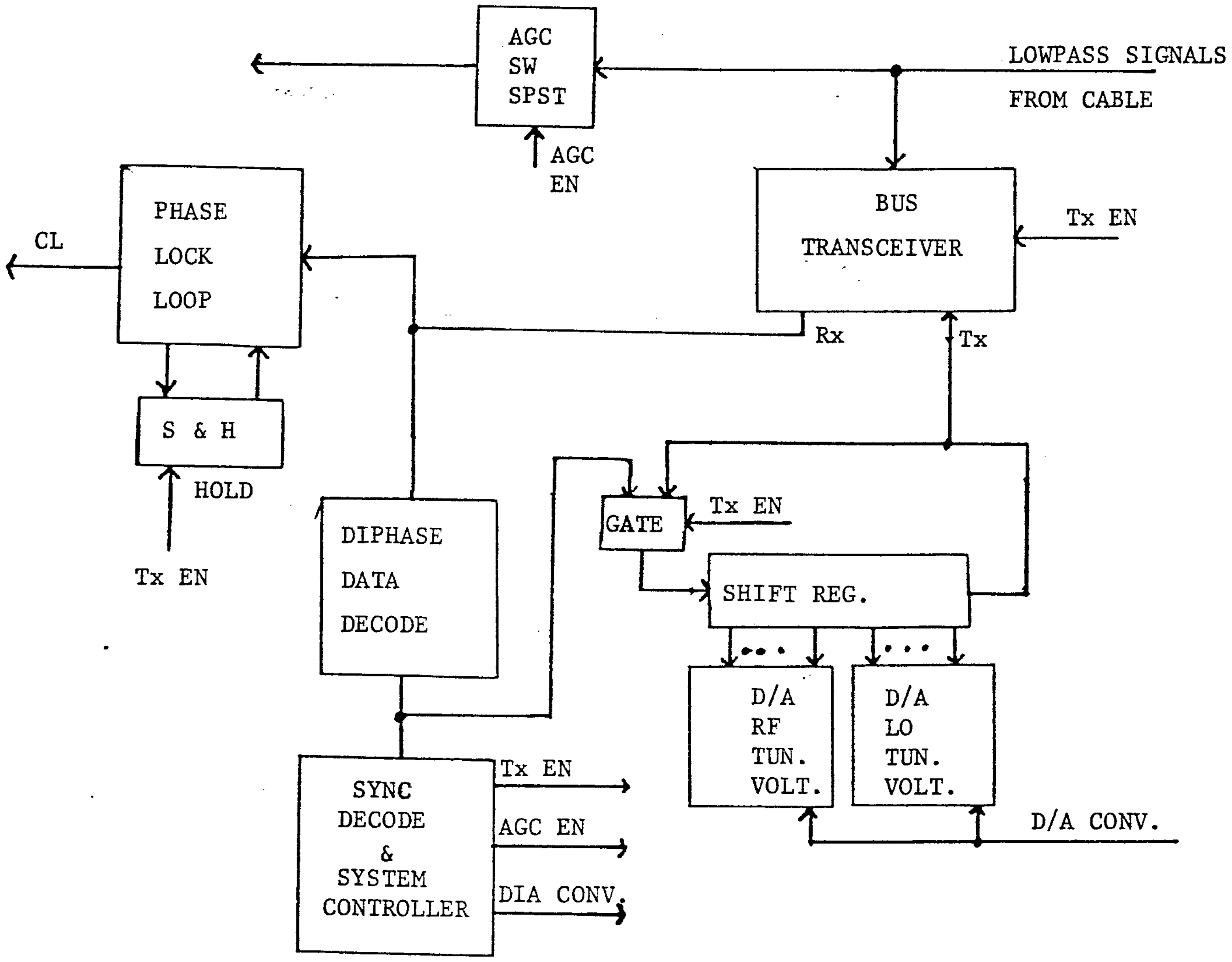
There are two high power RF switches inboard. These operate a bypass circuit for signals while transmitting or non-adaptive receiving. These switches are controlled by the same "A" signal that is sent outboard.

The generation of "A" is accomplished by the control signal network, which has as it's inputs: signal from the operator Adapt/No Adapt switch, and signals from the radio which tell transmit/receive, squelch/no squelch, the desired frequency, and voice/secure.



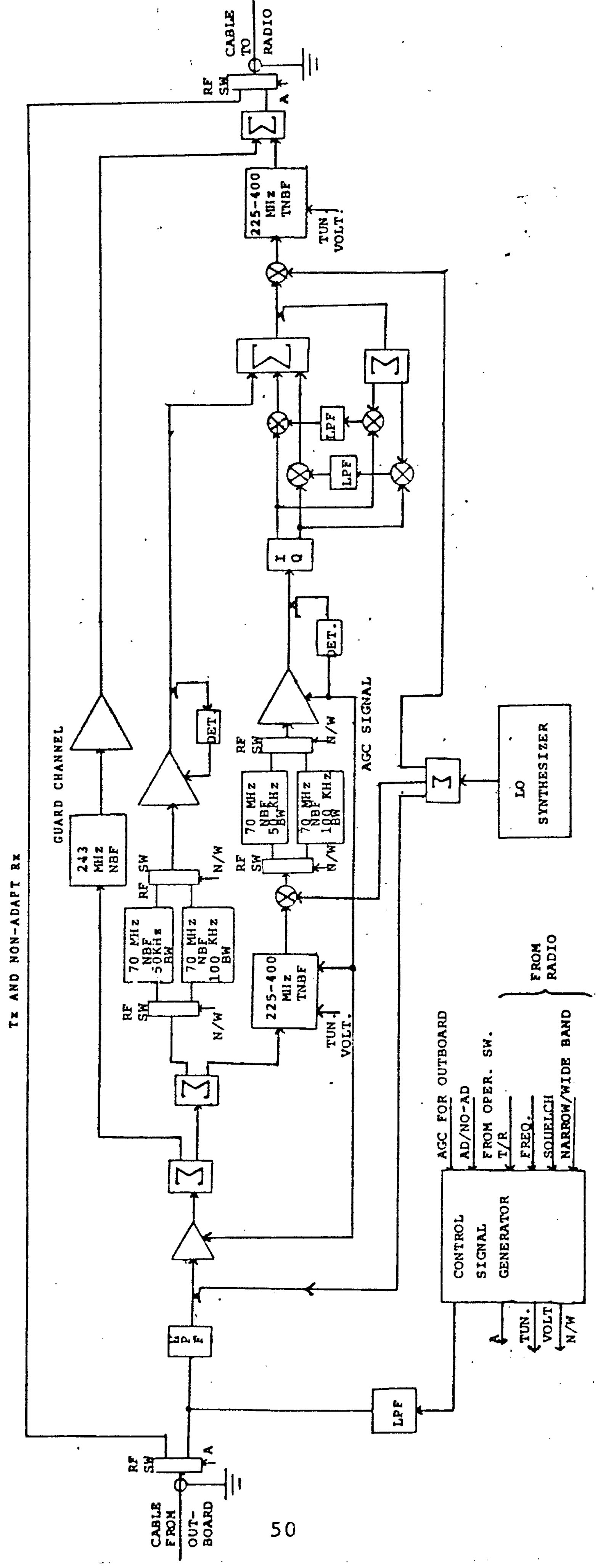
DIPHASE CODING

FIGURE 3.4.



CONTROL SIGNAL DECODER

FIGURE 3.5.



INBOARD DESIGN

FIGURE 3.6.

3.3.2 The Demultiplexing Network

Upon traversing the length of the cable, the signals may have lost up to 6 dB, depending on the aircraft and the length and type of the cable. Therefore, after the T/B switch and a high pass filter to keep out the control signals, the signal will go into a wide band, low noise, variable gain amplifier. The gain of this amplifier will be controlled by the AGC signal but it will not allow attenuation, which might degrade the guard signal.

After the low noise amplifier, the signal goes through a 3 dB splitter to obtain a signal for the guard channel. This signal is filtered by a 243 MHz narrowband filter and then amplified.

The other output of the splitter is divided again by another 3 dB splitter. These two lines are then frequency demultiplexed by passing one through a 70 MHz narrowband filter to obtain the IF signal of antenna 2, and passing the other through a TNBF, centered at the RF frequency, to obtain the RF signal of antenna 1.

The 70 MHz narrowband filter is actually a switched pair of 70 MHz filters. During narrowband voice operation, the signal is passed through a 70 MHz filter with a 50 KHz bandwidth, while during secure voice operation, the signal is switched through a 70 MHz filter with a 100 KHz bandwidth. Another switch also directs the correct back output onto the line.

The RF signal, from antenna 1, is converted to 70 MHz by the variable LO. It too is then switched to one of a pair of 70 MHz narrowband filters, just as the IF line was.

Both antenna signals are now at 70 MHz. These signals are passed through a last variable gain stage that is intended to input the signals into the adaptive loop at a set power level. This makes the stability control of the adaptive loop easier. The AGC loop for these and all the variable gain amplifiers are described in the next Section, Section 3.3.3.

3.3.3 Automatic Gain Controls

There are two AGC loops in the combined inboard-outboard system (See Figure 3.1.). The first, and major, AGC loop controls all the variable gain amplifiers outboard as well as all but one of those inboard. This AGC loop is designed to bring the power of the signal that goes into the weight channel of the adaptive array to a set level.

The other AGC loop operates only on the amplifier, in the unweighted adaptive array channel that just precedes the adaptive array.

The major AGC loop acts on both signal lines with the amount of gain on attenuation necessary to bring signal line 1, the weighted input, to the set level. The second AGC loop then takes care of the differences between the signals themselves.

3.3.4 The Adaptive Loop

The techniques of adaptive arrays were presented in Section 2.2. We note here the special points of applying those techniques to the recommended design.

The adaptive array of the recommended design consists of two inputs and one weight. Thus, a multiplexed weight was not considered.

This implementation of an adaptive array, requires a moderately fast weight. To have a fast weight requires the bandwidth of the adaptive loop to be large. The larger bandwidth causes weight jitter, reducing the eventual amount of cancellation that can be achieved. An optimal trade off was decided upon and used in the recommended design. That is a goal of 30 dB cancellation in 15 ms.

3.4. Physical Characteristics

The recommended design could be built as a feasibility model with the following estimated physical demands:

(i) Power @ +28 D.C.; 15 W, outboard
40 W, inboard

(ii) Size (not including connectors);
75 in^3 outboard ≈ 6" x 4" x 3.25"
240 in^3 inboard ≈ 6" x 4" x 5".

Note that these estimates are for a feasibility model and some reduction in these demands could be achieved for a production model.

4.0. ALTERNATIVE DESIGNS

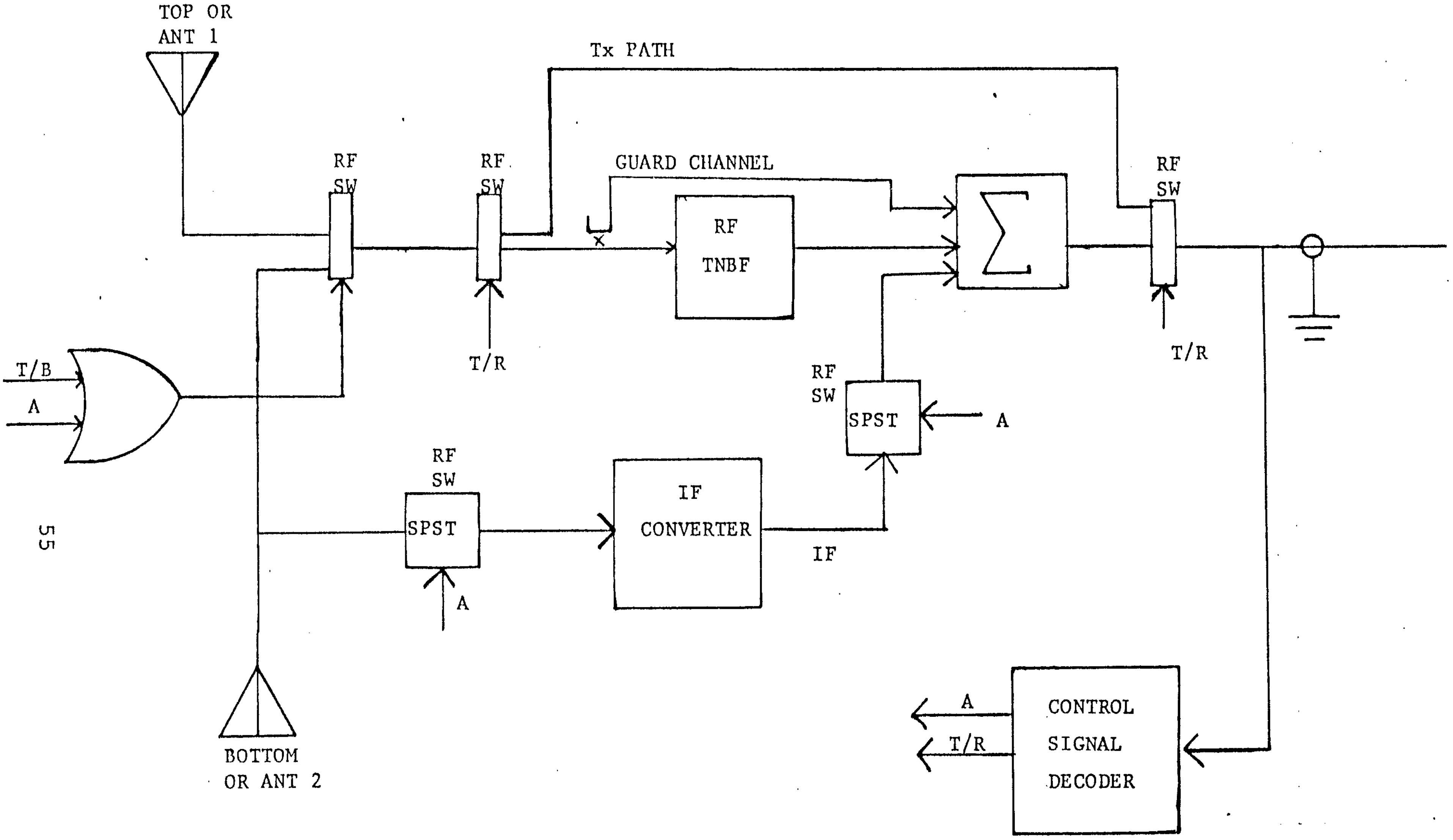
4.1. Signal Gain in Non-Adaptive Receiving

In the proposed design, there is about 1 dB of signal loss in non-adaptive operation. To regain this loss during transmitting would require the use of a high power amplifier. The use of such an amplifier for only 1 dB of gain is highly impractical. Therefore, one focuses on reducing the loss during non-adaptive receiving.

The loss comes from the addition of four RF switches to the signal path with about 0.25 dB of loss through each switch. The proposed alternative design would use the same method of operation as already described for transmitting and adaptive receiving. However, in non-adaptive receiving, the signal would be sent through the unconverted channel of the outboard multiplexer (See Figure 4.1.). In this case, the noise figure gets established by the amplifiers in the varactor diode tuning networks. The effect on S/N will depend on the amount of loss in the cable to the radio. If the loss is small, then the S/N will be reduced very slightly. If the cable loss is up to several dB, then there would actually be an improvement in S/N, because of the gain early in the line.

The alternative design would require another SPST RF switch outboard, as well as another control signal being multiplexed down the cable outboard.

The control signal could be sent outboard by the use of a third sync word. The three sync words would then be translated to two control signals: "A," same as before, and "T/R," high on



ALTERNATIVE DESIGN FOR IMPROVED S/N IN NON-ADAPT RECEIVE

FIGURE 4.1.

transmit. The three modes of operation are then represented by the following control signal levels:

1.) transmit, T/R = high, A = low

2.) non-adaptive receive, T/R = low, A = low

3.) adaptive receive, T/R = low, A = high

See Figure 4.1. as to how these signals would control the RF switches.

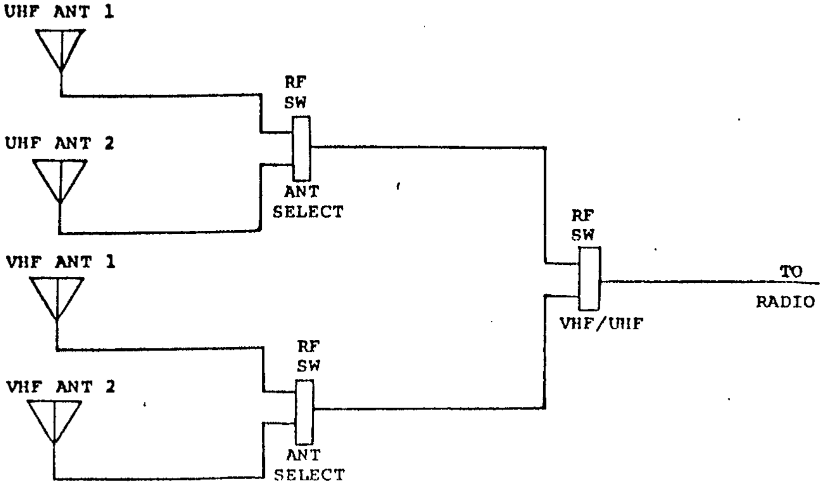
In the inboard subsystem, the signals would be routed as described in the proposed design.

4.2. VHF/UHF Operation

Many communication radio sets are being built or modified to allow VHF and UHF operation.

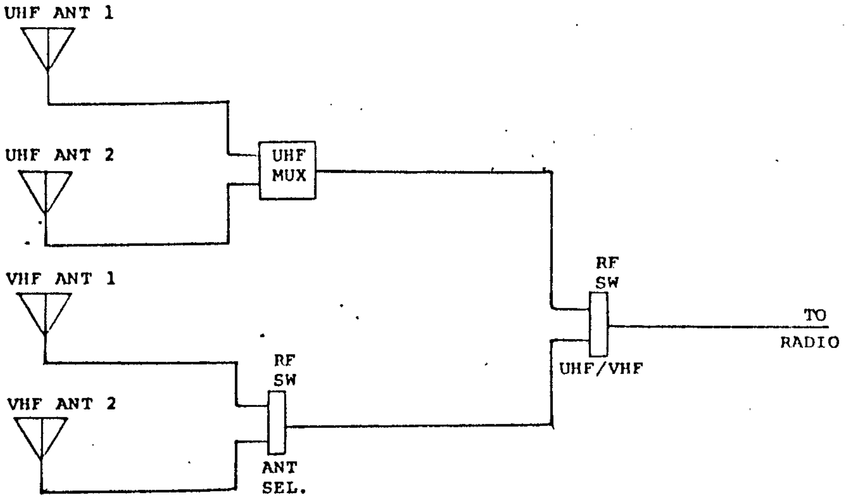
But VHF signals must be sent and received through different antennas than the UHF signals are. This is most simply implemented by having a UHF/VHF selector switch somewhere on the cable between the radio and the UHF antenna selector switch, (See Figure 4.2.a.). If such is the case, then a UHF multiplexed adaptive array as proposed could be used without interfering with VHF operation by putting it into "transmit" mode when using VHF, (See Figure 4.2.b.).

This method, however, does not allow for adaptive processing in VHF, assuming there are two or more VHF antennas. There are several ways to achieve adaptive capabilities in VHF. The simplest way requires that the selector switch for the UHF antenna and the switch for the VHF antenna be located near each other in the plane, such that a single device can replace both of them without requiring major cable modifications.



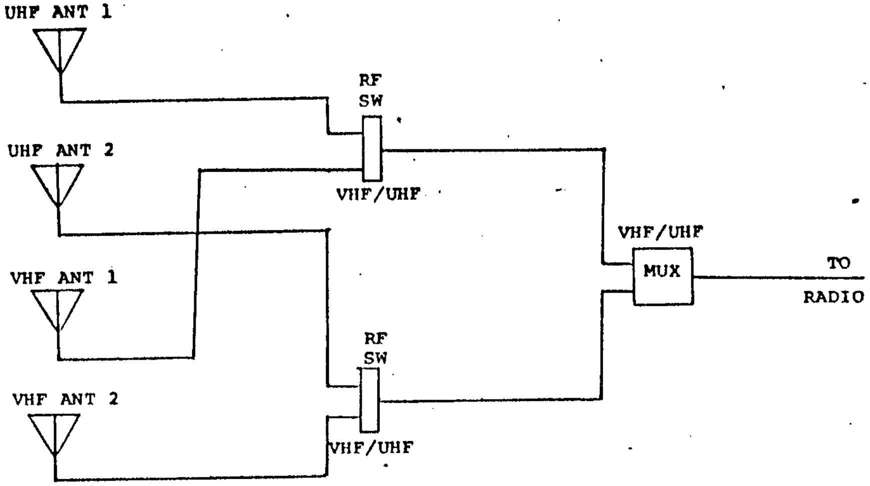
NO MULTIPLEX

FIGURE 4.2.a.



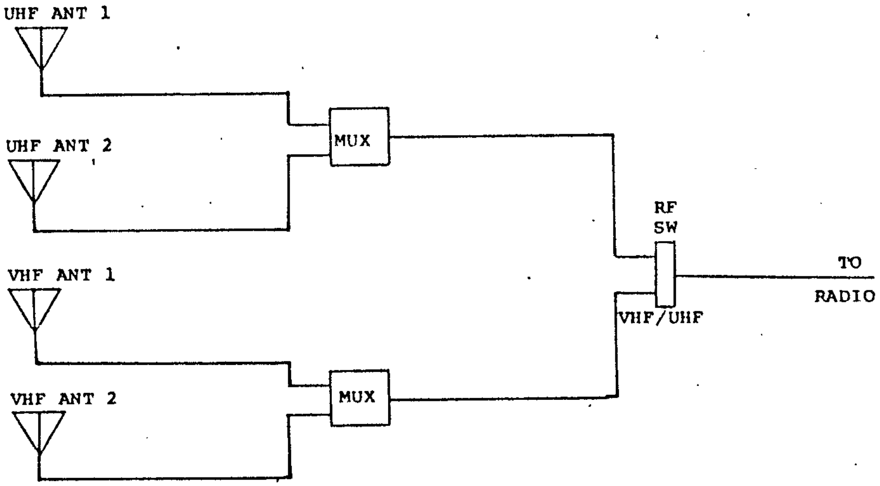
MULTIPLEX UHF ONLY

FIGURE 4.2.b.



ONE MULTIPLEXER, SWITCHED INPUTS

FIGURE 4.2.c.



TWO MULTIPLEXERS, SWITCHED OUTPUTS

FIGURE 4.2.d.

VHF/UHF OUTBOARD MULTIPLEXER NETWORKS

FIGURE 4.2.

one to form a null in either VHF or UHF, whichever the radio is listening to at the time, (See Figure 4.2.c.).

If the selector switches are not located sufficiently near each other, and one still desires adaptive processing on both channels, then it is necessary to have two outboard multiplexers, one for each band. However, with a slight modification of the control signals, still only one inboard unit would be necessary (See Figure 4.2.d.).

4.3. Systems of More Than Two Antennas

For systems with more than two antennas, it is recommended that two antennas be chosen to be used with the proposed design. During non-adaptive operation, the desired antenna would be selected as usual. During adaptive operation, the signals from the two selected antennas would be multiplexed and sent inboard to be adaptively processed. This method uses the proposed design and is consistent with the "quick fix" approach of this project.

If it is desired to multiplex more than two signals in order to form more than one null in the adaptive array, then one might consider the following approaches. For multiplexing three signals, it is recommended that two of the signals be converted to an IF, and then one of the IF's further sidestepped by maybe 20 MHz. The signals are then frequency multiplexed down the cable.

If more than three signals are needed to be multiplexed, it is recommended that all the signals be converted to an IF and then to time multiplex them.

4.4. Multiplex Only

One final alternative approach is to design and build a new system which only multiplexes the signals and the adaptive processing is done inboard with a currently available adaptive array. This is not recommended because the adaptive processing must be done at an IF. The separate adaptive array would have RF input and output, requiring two unnecessary frequency conversions. These are unnecessary because the adaptive processing can be done at the IF in the demultiplexor as in the proposed design.

5.0. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

For those applications where the RF antenna selector switch is in a location where size, power, maintenance, or environmental constraints prohibit the use of a current adaptive array model; it is recommended that a multiplexed adaptive array be employed.

It was determined that a two channel frequency multiplexed system was the simplest design. Furthermore, such a two channel system could provide moderate AJ capabilities in nearly all configurations, with minor modifications. These included applications to VHF/UHF systems and systems with more than two antennas.

It is recommended that a feasibility model of the proposed design be constructed and tested. If some of the alternative features, or others yet to be proposed, are desired; these can be added to the design once feasibility of the basic model has been established.

APPENDIX

In this Appendix, an estimate is obtained of the maximum allowable power of a spurious signal radiated through an antenna. This level is determined by determining the minimum level detectable in the following scenario. A plane, flying under radio silence, is emitting a certain level of a spurious signal. An enemy unit in the area is listening with a frequency sweeping receiver. The following variables are defined:

P_T = spurious power transmitted

P_R = power received

A_R = area of the receiver

η = efficiency of the receiver

G_T = gain of the antenna in the direction of the receiver

r = distance between the plane and the receiver.

These quantities are related by

$$P_R = \frac{P_T G_T A_R \eta}{4\pi r^2} \quad . \qquad \text{A1}$$

Equation A1 can be solved for P_T to obtain

$$P_T = \frac{4\pi P_R r^2}{G_T A_R \eta} \quad . \qquad \text{A2}$$

It is necessary to determine the minimal P_R needed to be detected. This power can be obtained as the product of the minimal necessary signal to noise ratio (S/N) and the noise power of the receiver. A S/N of at least 1, (0 dB), is a reasonable minimum. Let N be the noise power.

$$N = (kT)FB \qquad \text{A3}$$

where F = noise figure of receiver

B = receiver channel bandwidth

kT = thermal noise level

Substituting A3 into A2 yields:

$$P_T = \frac{4\pi(S/N)(kT)FBr^2}{G_T A_R \eta} \quad . \qquad \text{A4}$$

Known or reasonable limiting values for the variables are

$kT = 4 \times 10^{-18}$ mW/Hz = (-174 dBm/Hz)

$S/N = 1$ = (0 dB)

$F = 10$ = (10 dB)

$B = 3$ kHz

$r = 1.5$ km $\simeq$ 1 mi.

$G_T = 2$ = (3 dB)

$\eta = \frac{1}{2}$ = (-3 dB)

$A_R = 1\ \text{m}^2$

With these values, the allowed spurious radiated signal power, P_T, is calculated to be

$P_T = 3 \times 10^{-6}$ mW = (-55 dBm).

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