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ADAPTIVE ARRAYS FOR SATELLITE COMMUNICATIONS

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16. Abstract (Limit: 200 words)

A feasibility study of suppressing interfering signals in a satellite communication system is presented. Adaptive arrays are used to suppress interference at the receive site. Since it is required that the interference be suppressed to very low levels, a modified adaptive circuit is used which is shown to accomplish the desired objective. Techniques are also explored for the modification of the transmit patterns to minimize interference with neighboring communication links.

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OBJECTIVE

The objective of this grant was to study the feasibility of accomplishing the following goals:

1. Provide interference protection to receiving earth stations from signals originating from satellites other than the desired source satellite. The satellites producing the undesired signals may be located at arbitrary angular separations from the satellite generating the desired signal and their locations may change with time. The spectral characteristics and modulation of the desired and undesired signals are similar. The carrier-to-noise ratio of the desired signal is expected to be approximately 15 dB. The undesired signals are initially at 10 to 30 dB below the desired signal level and are to be further suppressed by up to 30 dB. The number of interfering sources may be equal to or larger than two.

2. Control the radiation patterns of earth station transmit antennas such that only the targeted satellites receive signals of detectable level. This objective is to be accomplished by providing steerable broad nulls in the transmit pattern. The number of such nulls should be at least two.

3. Provide protection to satellites from interference emanating from stations. The interfering ground stations are at arbitrary angular locations. The spectral characteristics and modulation of the desired and undesired signals are similar. The carrier-to-noise ratio of the desired signal is expected to be approximately 15 dB. The interference signals are at 10-30 dB below the desired signal level and are to be further suppressed by up to 30 dB. The number of interfering signals may be equal to or larger than two.

4. Provide control of satellite transmission patterns to assure that only targeted service areas receive detectable signals. This objective is to be accomplished by providing steerable broad nulls in the transmission pattern. The number of such nulls should be at least two.

5. Provide control of the radiation pattern of a spot beam switching satellite antenna to assure that only targeted service areas receive detectable signals. Provide at least two transmit nulls in arbitrary directions when the beams are switched to different positions. The beam and null switching to accommodate high beam hopping rates.

The objectives as outlined above fall naturally into two categories. One involves receiving systems and aims at suppressing signals arriving at the receiving terminal from sources other than the desired signal source and thus termed interference or jammers. The other category involves the control of the transmit pattern to assure that the transmitted signal does not aim (inadvertently) excessive amounts of power at unintended receiving stations. The first category involves the first and third items dealing with earth and satellite receive systems, respectively. The second category involves the second, fourth and fifth items dealing with transmitting earth and satellite stations. Because of the commonality of the problems and the solutions within each of these two categories, the study below addresses the various issues by category rather than by item to avoid duplication.

I. INTRODUCTION

A major problem in satellite communications is the interference caused by the transmission from adjacent satellites whose signals inadvertently enter the receiving system and interfere with the communication link. The same problem arises in the earth to satellite part of the link where transmission from nearby ground stations enter the satellite receiver through its antenna sidelobes. The problem has recently become serious because of the crowding of the geostationary orbit. Indeed this interference prevents the inclusion of additional satellites which could have been allowed if methods to suppress such interference were available.

The interference can be suppressed at the originating station, either space or earth, by reducing the sidelobes of the transmit antenna in the direction where receiving systems are located when such locations are known. Alternatively, the interfering signals may be suppressed at the receiving site. Both approaches are examined in this report.

For the transmit case, methods are explored for the inclusion of small auxiliary antennas that would produce broad radiation pattern nulls in specified directions where interference is either known to exist or is expected to be caused. With regard to the receive case, it would appear that the suppression of interference can be readily handled by the use of adaptive arrays [1-5] where the objective is interference suppression. Adaptive antenna arrays have been thoroughly investigated over the last decade. One difficulty, however, arises in that adaptive arrays are ideally suited for high power jammers where the interference to desired signal ratios are large and the interference to noise ratio is even larger. In the present case, the undesired signals are significantly weaker than the desired signals and in fact may even be below the noise level by several dB. Although weak, these signals because of their coherent nature and their similarity to the desired signal, do cause objectionable interference and must be suppressed. Conventional adaptive arrays are shown to be incapable of suppressing such signals. A modification of the adaptive array is then proposed which appears to overcome this difficulty and accomplish the desired objective.

In Section II, the receive case is investigated. Section III discusses the transmit problem and Section IV contains conclusions and recommendations for future work.

II. EARTH STATION OR SATELLITE RECEIVE ANTENNA SYSTEMS

In this section, we will discuss the interference protection provided by adaptive antenna arrays to an earth station or satellite receive antenna from signals originating from sources other than the desired ones. The undesired signal sources may be located at arbitrary angular separations from the desired signal source. The spectral characteristics and modulation of the desired and undesired signals are similar. The carrier-to-noise ratio of the desired signal is expected to be 15 dB. The undesired signals are initially at 10-30 dB below desired signal level and are to be further suppressed by up to 30 dB.

Adaptive antenna arrays have been used to provide protection to radar and communication systems from undesired signals. Undesired signals may consist of deliberately generated electronics counter measures signals, unintentional RF interferences, clutter scatter returns and natural noise sources. An adaptive array automatically steers nulls onto sources of undesired signals while attempting to retain the desired main beam characteristics in the desired signal's direction and thus maximizes the output signal-to-interfernece-plus-noise ratio (SINR). The output SINR is optimized in real-time, making adaptive arrays useful in a changing interference environment. In the case of earth stations, or satellite receive antennas, the exact location of interfering sources are a priori unknown and may change with time. Therefore, an adaptive array is suitable to provide interference protection.

An adaptive array is a system consisting of an array of antenna elements and a real-time adaptive receiver-processor. It samples the current signal environment and then automatically adjusts the element weights to optimize the output SINR in accordance with a preselected algorithm. The selection of the algorithm is based on the information available about the desired signal. This information may consist of either the signal characteristics such as its waveform or spectrum or alternatively its arrival angle. If the spectral characteristics and/or modulation of the desired signal are known and are different from that of interfering sources, one can use the least mean square (LMS) algorithm of Widrow, et al [1]. When the angle of arrival of the desired signal is known, one can use the steered beam algorithm [2]. Since in the case of earth station or satellite receive antennas, the desired signal source location is known and the spectral characteristics and modulation of the desired signal and undesired signal are similar, steered beam type adaptive arrays are used to provide interference protection.

Figure 1 shows a typical steered beam adaptive array. The main antenna is highly directive and is steered in the desired signal direction. Auxiliary antennas are relatively low gain antennas and may have uniform radiation patterns in the given sector. Note that the configuration looks exactly like a sidelobe canceller [6] except that a control signal is used in the weight control network. The control signal is used to prevent the cancellation of the desired signal component (the auxiliary antennas also carry the desired signal) and is generated from the knowledge of the desired signals direction and its strength at various antennas. We will refer to this configuration as a sidelobe canceller.

In Figure 1, the output of each auxiliary antenna is multiplied by a complex weight, w_i, and is then subtracted from the output of the main antenna. Figure 2 shows a typical feedback loop used to control the

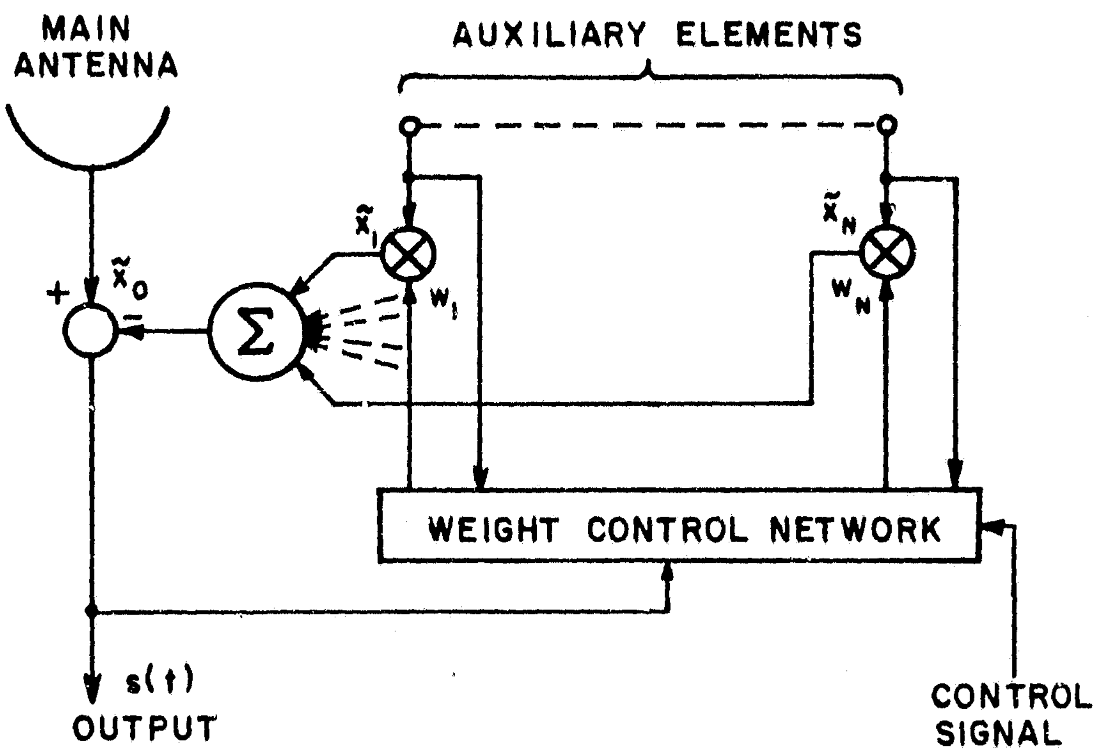

Figure 1. A steered beam adaptive array.

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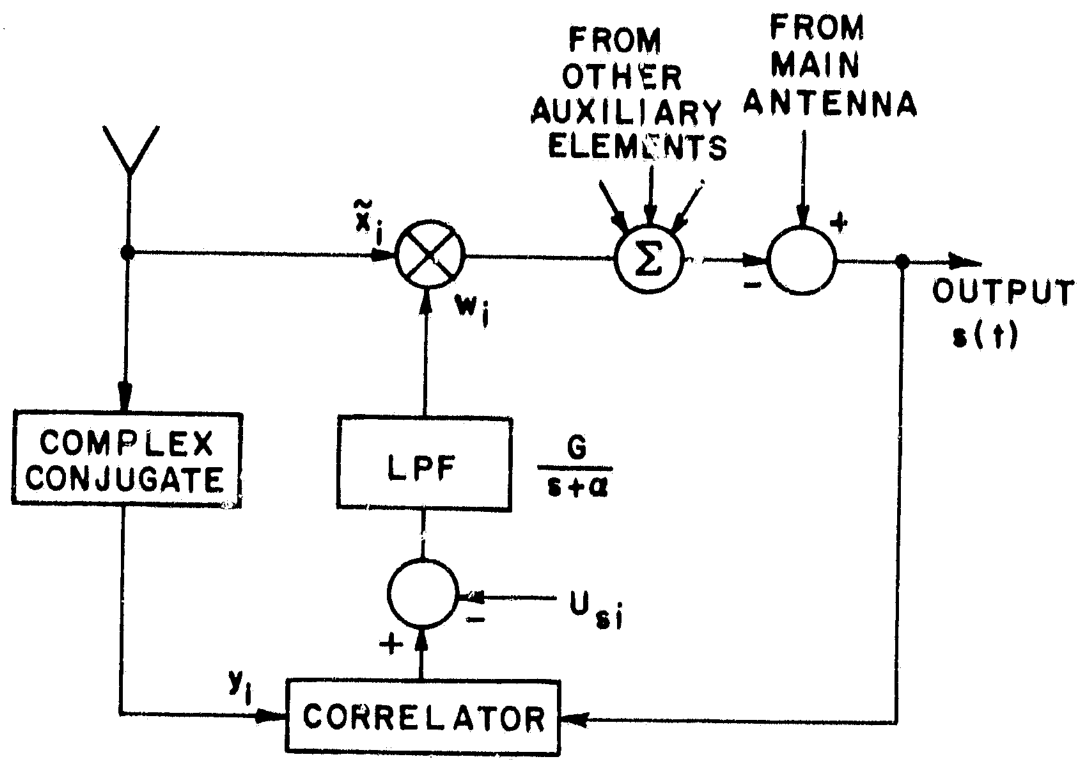

Figure 2. A typical feedback loop of a steered beam adaptive array.

weight of an auxiliary antenna. There are N such loops, where N is the number of auxiliary antennas. In Figure 2, U_{si} is the control signal. From Figures 1 and 2

$$\frac{dw_i}{dt} + \alpha w_i = G[y_i(x_o - X^T W) - U_{si}] \tag{1}$$

where α is the pole position of the low pass filter and controls the bandwidth of the low pass filter, G is the loop gain, superscript T denotes transpose, $\tilde{x}_0$ is the signal in the main antenna, X is an N × 1 column vector defining the input signals in various auxiliary antennas, W is an N × 1 column vector defining the weights of various auxiliary antennas and

$$\tilde{y}_i = \tilde{x}_i^* \tag{2}$$

where $\tilde{x}_i$ is the signal in the i^{th} auxiliary antenna and superscript * denotes complex conjugate. In this work, analytical signal representation is used. For all auxiliary antennas, the differential equation governing the antenna weights (1) can be written in vector form

$$\frac{dW}{dt} + \alpha W = G[\mathbf{X}^*(\tilde{x}_o - X^T W) - U_s] \tag{3}$$

where U_s is the control signal and will be called the steering vector. Assuming that the signals present in the antennas are ergodic processes and the weights of an adaptive array follow relatively slow changes in the signal scenario, (3) can be approximated as

$$\frac{dW}{dt} + \alpha W = G[R - \Phi W - U_s] \tag{4}$$

where

$$R = E\{X^{*}\tilde{x}_0\} \tag{5}$$

is the correlation vector defining the correlation between the signal in the main antenna and the auxiliary antennas,

$$\Phi = E\{X^{*}X^{T}\} \tag{6}$$

is the covariance matrix defining the correlation between the signals present on the auxiliary antenna and $E\{\cdot\}$ denotes ensemble average. From (4)

$$\frac{dW}{dt} + (\alpha I + G\Phi)W = G(R - U_s) \tag{7}$$

where I is an $N \times N$ identity matrix. In steady state,

$$\frac{dW}{dt} = 0 \tag{8}$$

and from (7),

$$(\alpha I + G\Phi)W = G(R - U_s) \quad . \tag{9}$$

Knowing the signal scenario, one can compute the correlation vector R and covariance matrix Φ and the steady state weights can be found. In practice, the analytic signal $\tilde{X}_i(t)$, i=0, 1,2....N consists of a desired signal, interfering signals and uncorrelated noise (sky noise and/or internal thermal noise). Assuming that the various signals incident on the antennas are uncorrelated with each otner and the noise, and the noise voltages in various antennas are uncorrelated with each other and are zero mean Gaussian with variance σ^2, one can rewrite (9) as

$$[\alpha I + G(\sigma^2 I + \Phi_d + \sum_{i=1}^{M} \Phi_i)]W = G[U_d + \sum_{i=1}^{M} U_i - U_s] \tag{10}$$

where Φ_d is the covariance matrix due to the desired signal present at various auxiliary antennas, Φ_i is the covariance matrix due to the i^{th} interfering signal, U_d and U_i are the correlation vector due to the desired signal and i^{th} interfering signal, respectively, and M is the total number of interfering signals. From (10)

$$[I + \frac{G}{\alpha}(\sigma^2 I + \Phi_d + \sum_{i=1}^{M} \Phi_i)]W = \frac{G}{\alpha}[U_d + \sum_{i=1}^{M} U_i - U_s] \quad . \tag{11}$$

Let the steering vector be chosen so that

$$U_s = U_d \quad . \tag{12}$$

Note that one should know the desired signal direction and its amplitude at the various antenna elements to choose a proper steering vector. In the case of ground station or satellite receive antennas, the location of the desired signal source is known and one can find the desired signal amplitude at the various antenna elements by knowing the gain of the various antennas in the desired signal's direction. Substituting (12) in (11), one gets

$$[I + \frac{G}{\alpha}(\sigma^2 I + \Phi_d + \sum_{i=1}^{M} \Phi_i)]W = \frac{G}{\alpha}\sum_{i=1}^{M} U_i \quad . \tag{13}$$

Using (13), the steady state weights of the adaptive array can be computed and its performance can be evaluated. The desired signal power at the output port is

$$S_d = \frac{1}{2}|\tilde{x}_{do} - X_d^T W|^2 \tag{14}$$

where $\tilde{x}_{do}$ is the desired signal in the main antenna and X_d is an $N \times 1$ column vector defining the desired signal in the various auxiliary antennas. The interference power at the output port is

$$S_j = \sum_{i=1}^{M} \frac{1}{2} \mid \tilde{x}_{io} - X_i^T W \mid^2 \tag{15}$$

where $\tilde{x}_{io}$ is the i^{th} interfering signal in the main antenna and X_i is an $N \times 1$ column vector defining the i^{th} interfering signal in various auxiliary antennas. The noise power at the output port is

$$S_n = \frac{1}{2} (\sigma_0^2 + \sigma^2 W^T W^*) \tag{16}$$

where σ_0^2 is the noise power in the main antenna.

Figure 3 shows the output jammer power of an adaptive array consisting of four auxiliary antennas. The main antenna is assumed to be a linear array of ten isotropic antennas and is steered along broadside (the desired signal's direction). The interelement spacing is half of a wavelength. The auxiliary antennas are also assumed to be isotropic radiators with interelement spacing of half a wavelength. This particular distribution is chosen to demonstrate the basic principle and represents a satellite communications system where the interfering signals are nearly planar with the desired signal. In practice, the main antenna may be a reflector antenna or it may be an array of directive antennas. The same is true for the auxiliary antennas.

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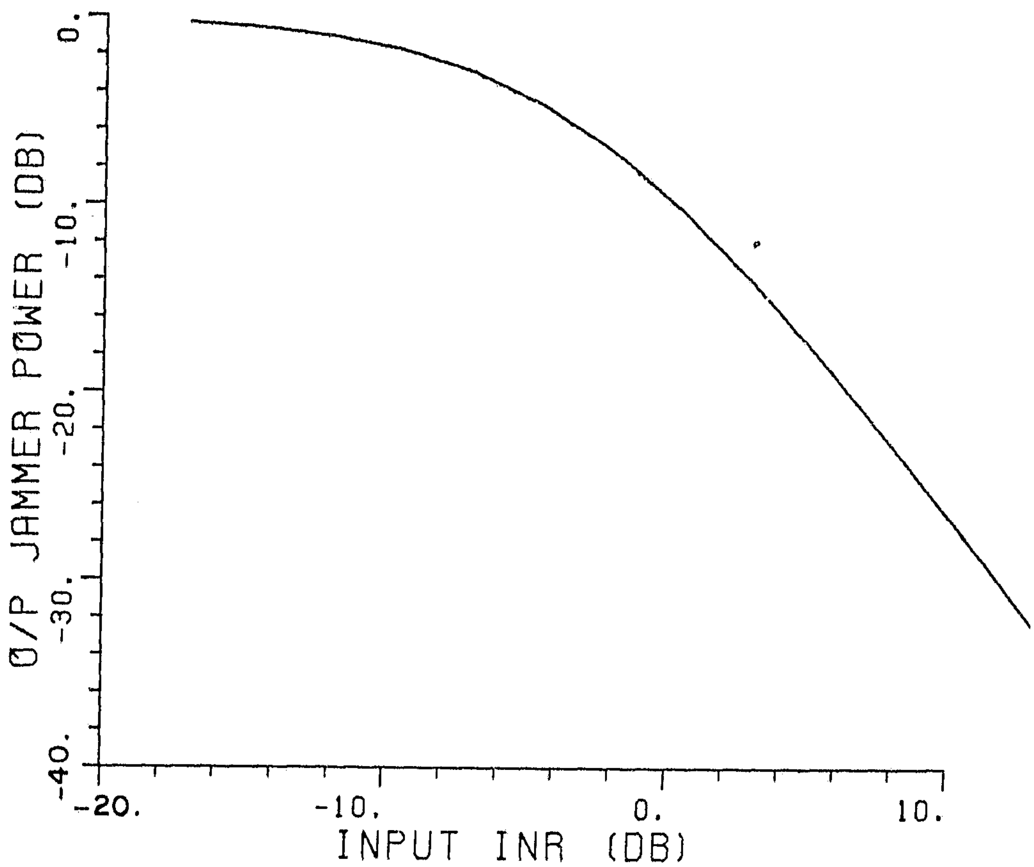

Figure 3. Normalized output jammer power of an adaptive array vs. the input INR in the main channel. $\theta_d = 90°$, $\theta_i = 60°$, SNR (main antenna) = 20 dB, SNR (auxiliary antenna) = 0 dB, $G/\alpha = 100$.

The desired signal amplitude at each antenna is one unit and the thermal noise in the main antenna as well as the auxiliary antenna is one unit. Thus, desired signal-to-noise ratio (SNR) in the main antenna is 20 dB while it is 0 dB in the auxiliary antenna†. The ratio G/α is chosen to be 100. In practice, this ratio is quite large (a very narrowband filter is used in the feedback loop and the feedback loop gain is quite high). For large G/α, Equation (13) can be approximated as

$$[(I + \frac{G}{\alpha}\sigma^2)I + \frac{G}{\alpha}(\Phi_d + \sum_{i=1}^{M} \Phi_i)]W$$

$$\approx [\frac{G}{\alpha}\sigma^2 I + \frac{G}{\alpha}(\Phi_d + \sum_{i=1}^{M} \Phi_i)]W = \frac{G}{\alpha}\sum_{i=1}^{M} U_i$$

or,

$$(\sigma^2 I + \Phi_d + \sum_{i=1}^{M} \Phi_i)W = \sum_{i=1}^{M} U_i \quad . \qquad (17)$$

Thus, the steady state weight vector is independent of the ratio G/α and $G/\alpha = 100$ is a reasonable number for the above approximation. The interfering signal scenario consists of a single CW jammer incident from 30° off broadside to the main antenna. The main antenna has a -17 dB sidelobe in this direction, i.e., if the desired signal is incident from this direction, its SNR in the main antenna will be 3 dB instead of

†The noise is assumed to consist of receiver noise only. Thus, the SNR in the main antenna is 20 dB. If external noise is dominant, the SNR in the main antenna will be 10 dB.

20 dB. The input INR to all antennas is assumed to be the same and is varied between -20 to 10 dB (the input INR to the main antenna varies between -17 to 13 dB). The output jammer power is plotted versus the input INR in the main antenna. Normalized jammer power (normalized with respect to the jammer power at the input of the main antenna) is plotted. Note that for weak interfering signals (INR < -10 dB), the jammer power at the array output is approximately the same as that at the main antenna input. Thus, the interfering signal is not suppressed by the array. This can be explained as follows.

For weak interfering signals, the thermal noise is the main source of degradation in the output signal-to-noise-ratio. Since the noise in the main antenna is uncorrelated with the noise in the auxiliary antennas, it can not be cancelled with the noise in the auxiliary antennas. Thus, the only way for the array to minimize the noise at the array output and consequently maximize the output SNR, is to shut off the auxiliary antennas, i.e., make $w_i=0$, $i=1,2, \dots N$. This choice of weight vector minimizes the noise. However, the interfering signal remains unsuppressed.

In Figure 3, as the interfering signal power increases, the interference power at the array output decreases. Thus, the auxiliary antennas are cancelling the interfering signal. For strong interfering signals (ξ_i > 5 dB), the interfering signal goes through a power inversion (the output jammer power is inversely proportional to the input jammer power). The steered beam adaptive array, therefore, suppresses strong interfering signals. In the case of earth station or satellite receive antennas, the input INR is -15 to 5 dB and the interfering signals are to be further suppressed by 20-30 dB. Thus, one must suppress relatively weak interfering signals. To accomplish this, the feedback loops must be modified.

In Figure 2, the correlator in each feedback loop correlates the signal from the auxiliary antenna with the array output S(t). If the noise component of the signal $\tilde{y}_i(t)$ is correlated with the noise component of the output signal, then the thermal noise in the feedback loop will be large and will have a dominant effect on the array weights (assuming that the interfering signals are quite weak). However, if the noise voltages in the two signals are uncorrelated, then the noise power at the input to the low pass filter will be small and thus the interfering signals alone will affect the array weights. One can use different techniques to decorrelate the noise in the two signals. One can use two different amplifiers (Figure 4), two different antennas (Figure 5) or a band pass filter (Figure 6) in one of the branches of the feedback loop.

When two different amplifiers are used in the feedback loop, the internal thermal noise in the two signals (the output signal and the signal $\tilde{y}_i(t)$) will be uncorrelated. Thus, the noise power at the input to the low pass filter will be reduced. This technique is, therefore, useful when the receiver noise is the main source of the noise.

When every feedback loop is connected to two different antennas (Figure 5), the external noise as well as internal thermal noise in the two signals will be uncorrelated. Thus, the noise power at the input to

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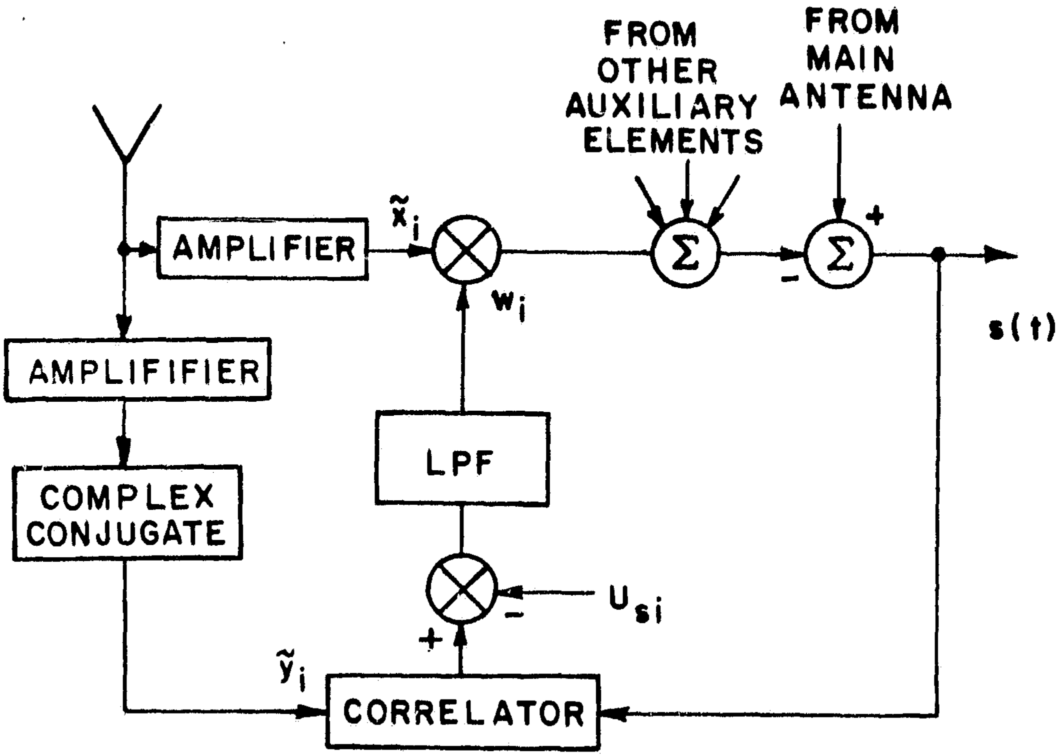

Figure 4. Feedback loop with two amplifiers.

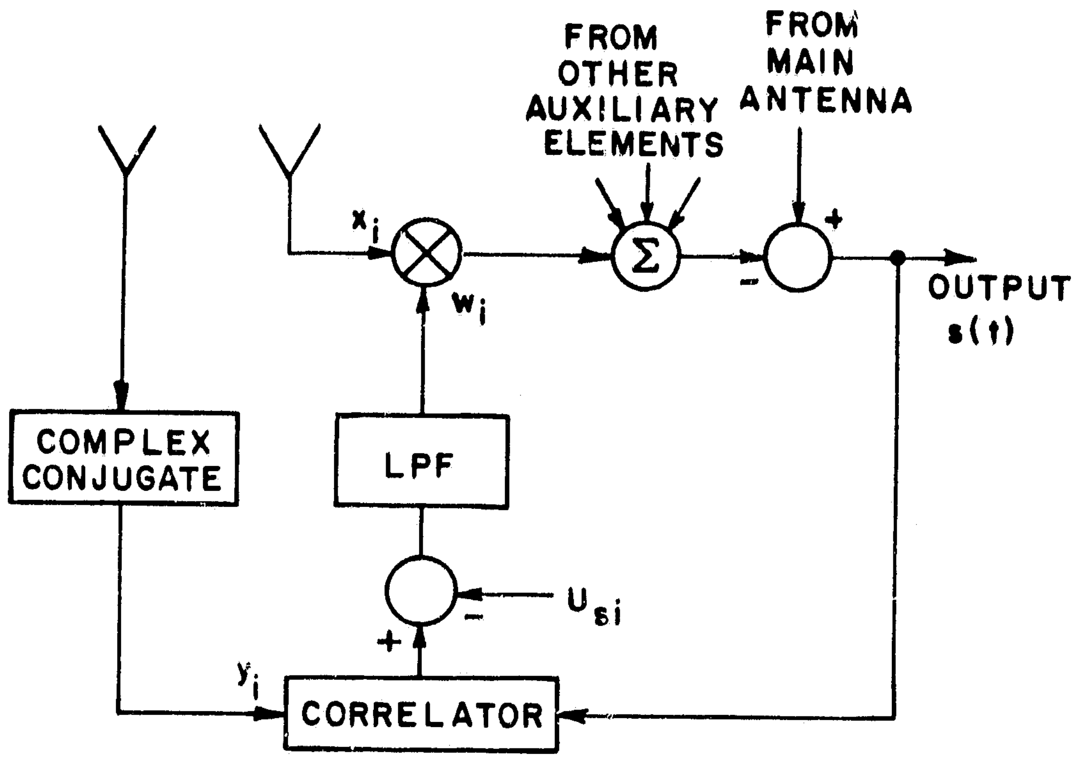

Figure 5. Feedback loop with two antennas.

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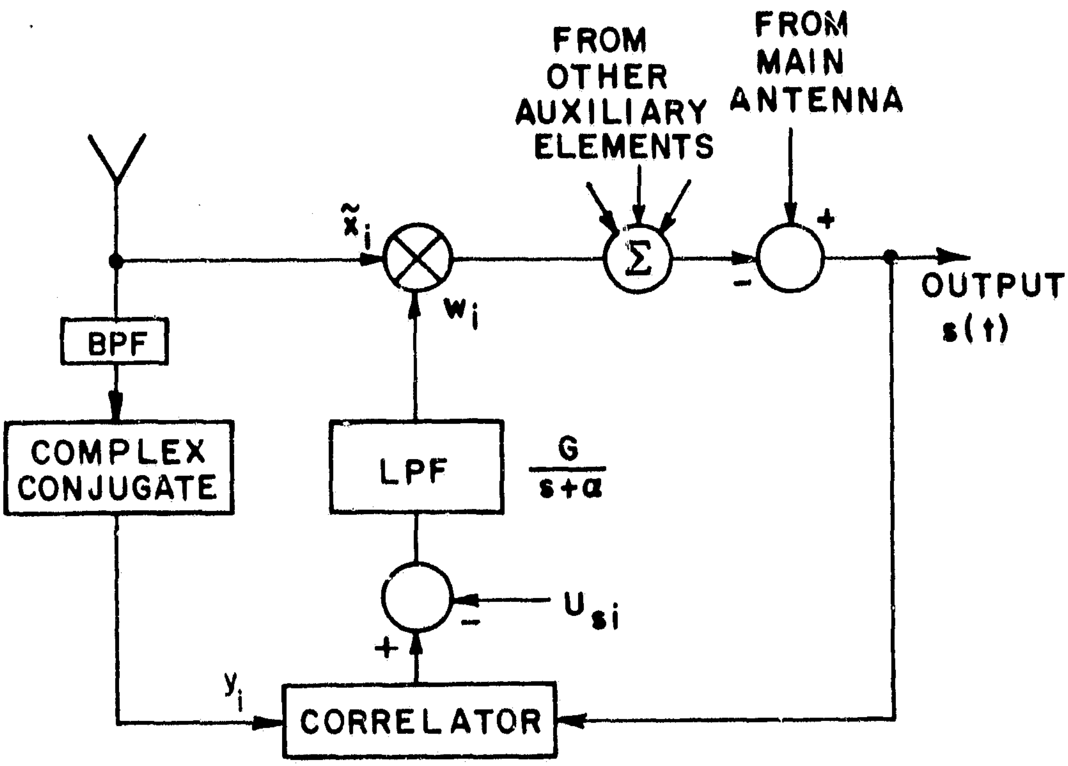

Figure 6. Feedback loop with a band pass filter.

the low pass filter will be reduced significantly. However, this scheme requires a lot more hardware than the previous one (two different amplifiers). Therefore, this technique is recommended when the external noise is the main source of noise.

By using a bandpass filter in one of the branches of the feedback loop, one can reduce the correlation between the noise in the two signals. However, the correlation between the directional signals (desired and interfering signal) should be maintained. Thus, this technique is useful when one is dealing with small bandwidth signals.

Let us assume that the noise voltages in the two signals have been decorrelated. Then the steady state weight vector (13) of the adaptive array is given by

$$[I + \frac{G}{\alpha} (\Phi_d + \sum_{i=1}^{M} \Phi_i)]W = \frac{G}{\alpha} \sum_{i=1}^{M} U_i \quad . \tag{18}$$

Note that the term due to the thermal noise is missing from the left hand side. Comparing (17) and (18), one can see that the steady state weight vector of the modified array depends on the ratio G/α. The larger this ratio, the more effect the directional signals (desired as well as undesired) have on the array weights. Thus, for large values of this ratio (G/α), even weak interfering signals can be suppressed.

Figure 7 shows the output interference power of an adaptive array consisting of four auxiliary antennas. All the parameters are the same as in Figure 3 except that the new feedback loops are used to control

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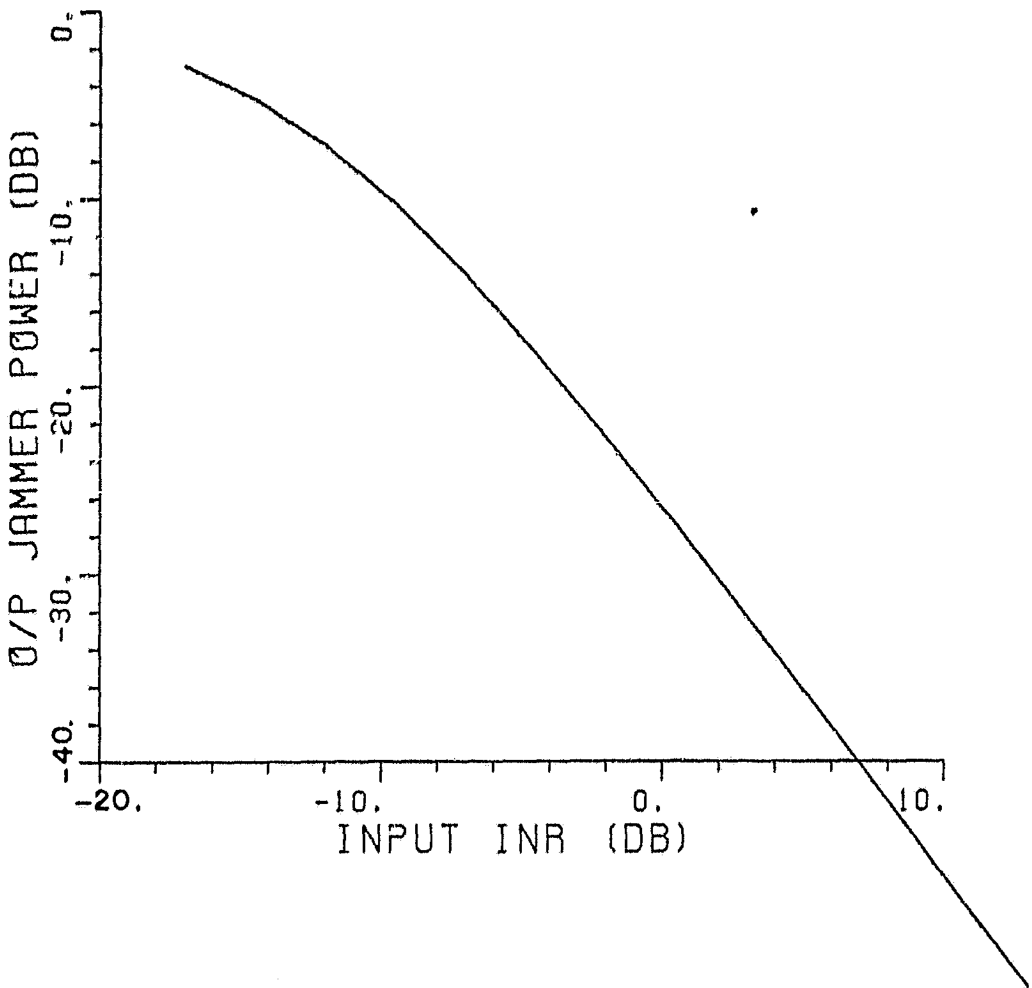

Figure 7. Normalized output jammer power of an adaptive array vs. the input INR in the main channel. $\theta_d = 90°$, $\theta_i = 60°$, SNR (main antenna) = 20 dB, SNR (auxiliary antenna) = 0 dB, $G/\alpha = 10$.

the weights of the auxiliary antennas. The ratio G/α is chosen to be 10 in the plot. Note that the auxiliary antennas are active even for weak interfering signals and the output interference power is less than the input interference power for all values of the input INR. Figures 8 and 9 show the output interference power when the ratio G/α is increased to 50 and 100, respectively. Note that the jammers are further suppressed. Thus, the new feedback loops are capable of suppressing relatively weak jammers.

Figures 10 and 11 show the radiation pattern of the array for various interference scenarios. G/α is selected as 100 in these plots. Note that the array has steered deep minimas in the direction of arrival of the interfering signals. Thus, the new feedback loop can provide the desired interference protection to earth station or satellite receiver antennas.

In this section, interference protection provided by a sidelobe canceller to earth station or satellite receive antennas was studied. It was found that the sidelobe canceller was unable to provide any significant interference suppression for the specified signal-interference scenario. The feedback loops controlling the weights of the sidelobe canceller were, therefore, modified. The modified loops provided the desired interference suppression and are recommended for earth station as well as satellite receive antennas. Earth station and satellite transmit antennas are discussed next.

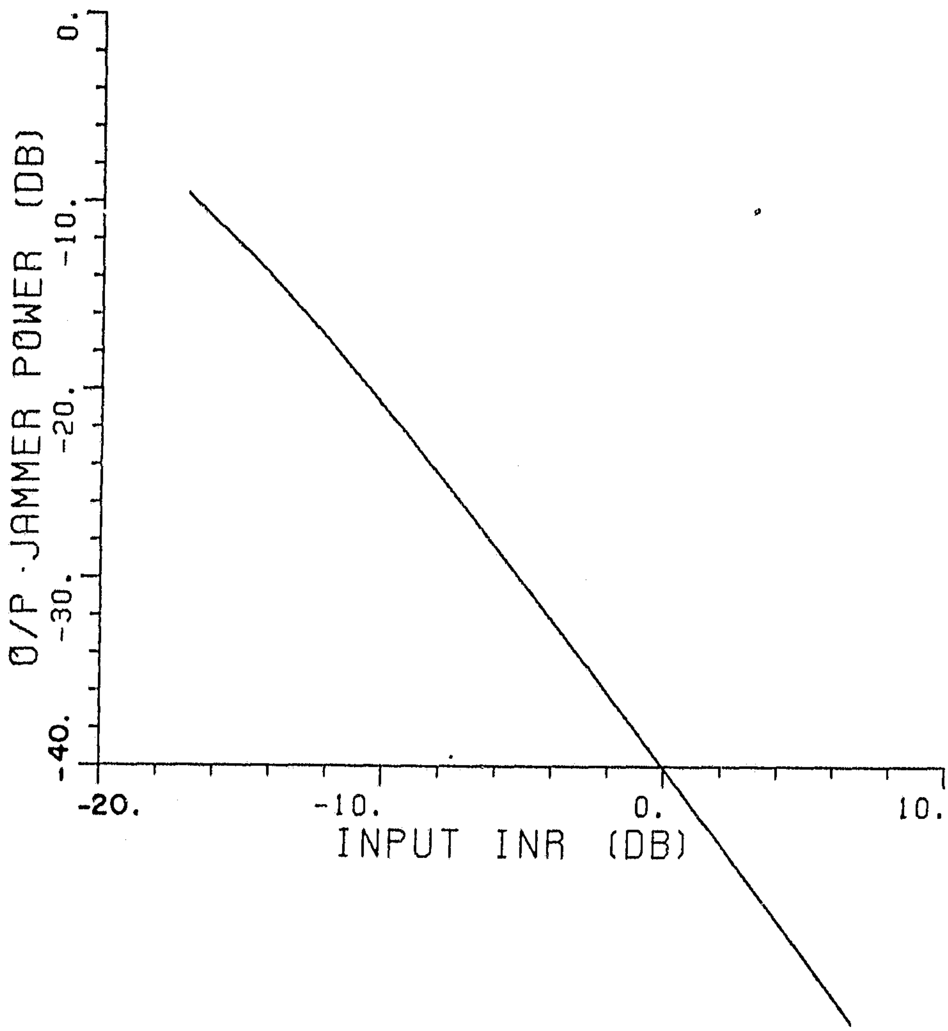

Figure 8. Normalized output jammer power of an adaptive array vs. the input INR in the main channel. SNR (main antenna) = 20 dB, SNR (auxiliary antenna) = 0 dB, $G/\alpha = 50$.

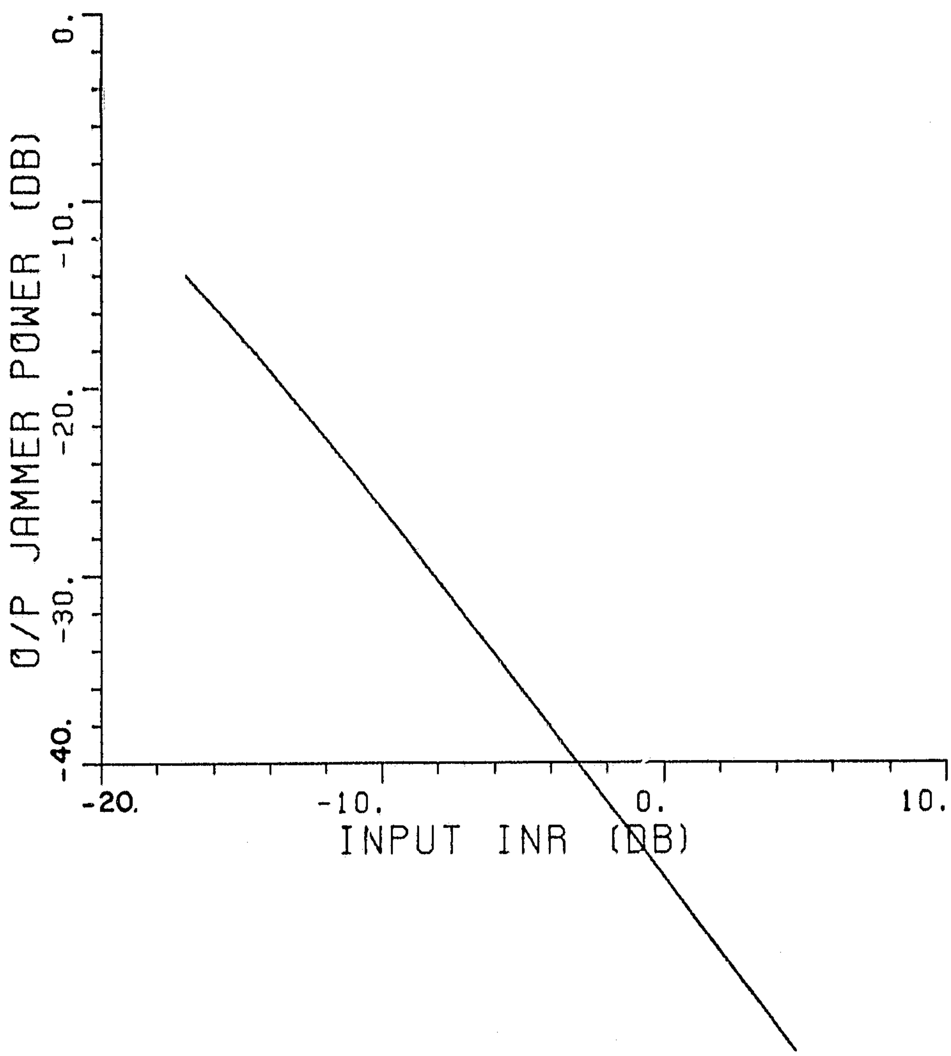

Figure 9. Normalized output jammer power of an adaptive array vs. the input INR in the main channel. SNR (main antenna) = 20 dB, SNR (auxiliary antenna) = 0 dB, G/α = 100.

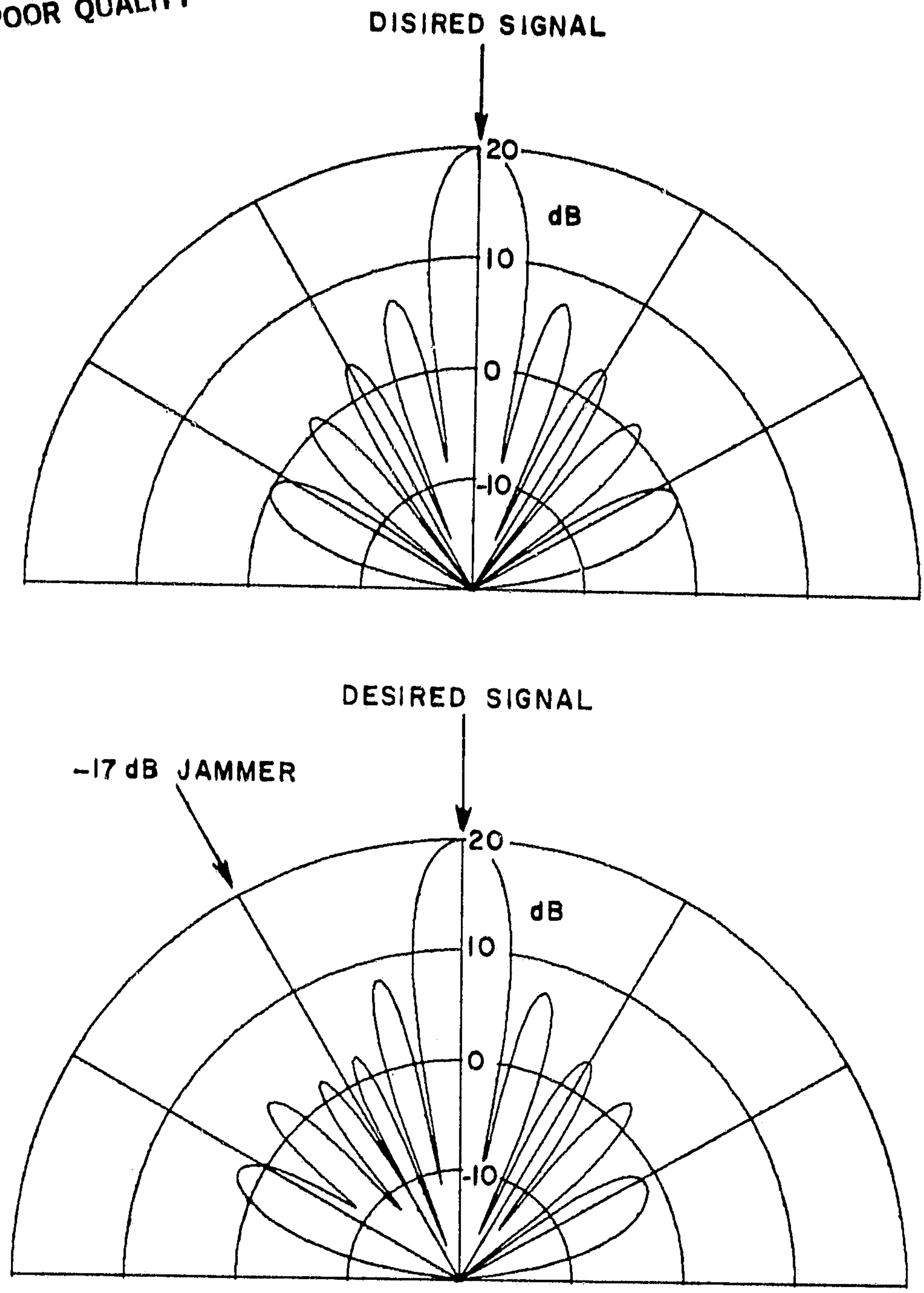

Figure 10. Adaptive patterns of an adaptive array with four auxiliary elements. Main antenna is an array of 10 isotropic elements. SNR (main antenna) = 20 dB, SNR (auxiliary antenna) = 0 dB, INR (auxiliary antenna) = -20 dB, $G/\alpha = 100$.

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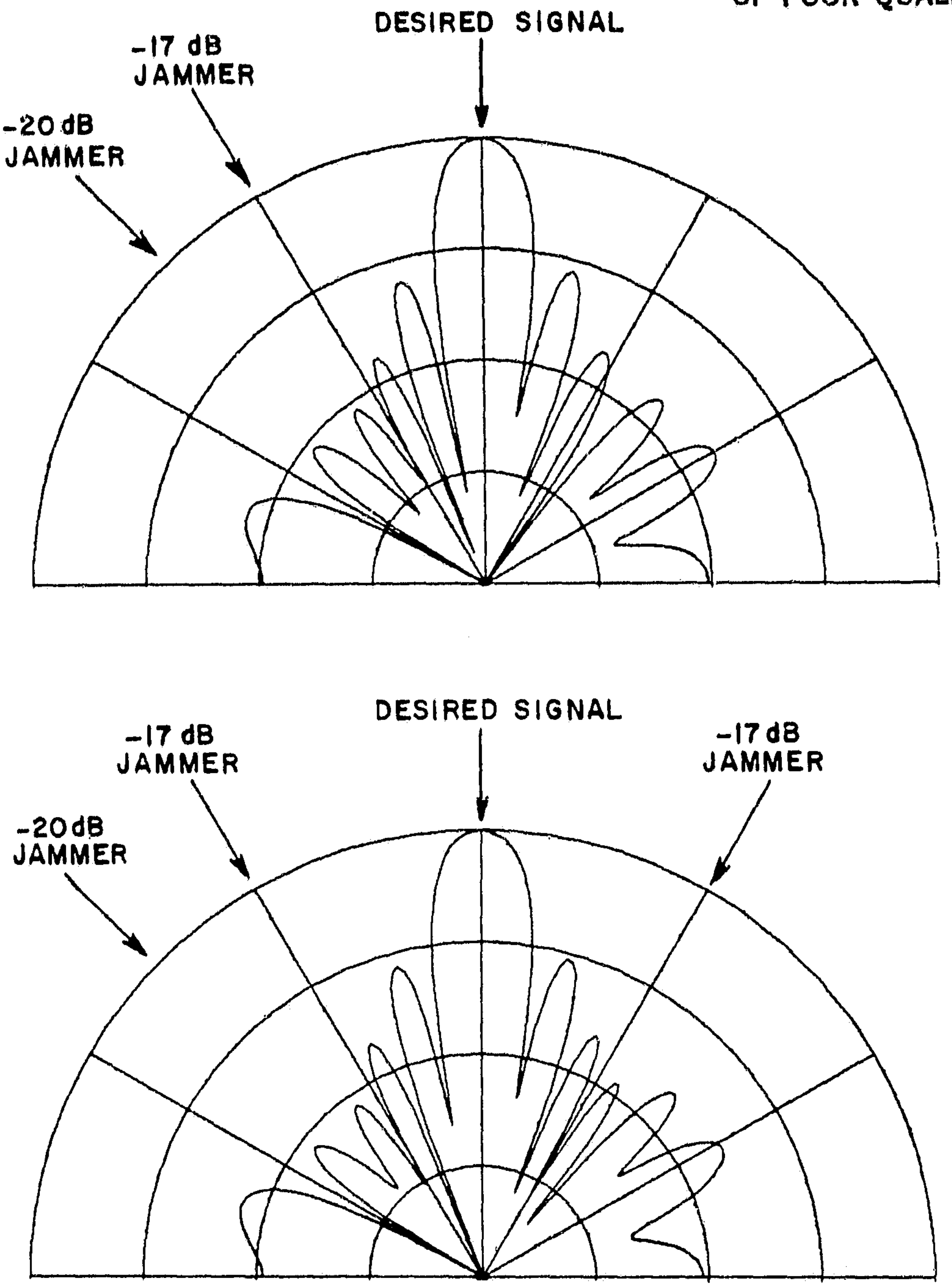


Figure 11. Adaptive patterns of an adaptive array with four auxiliary elements. Main antenna is an array of 10 isotropic elements. SNR (main antenna) = 20 dB, SNR (auxiliary antenna) = 0 dB, INR (auxiliary antenna) = -20 dB, $G/\alpha = 100$.

III. EARTH STATION OR SATELLITE TRANSMIT ANTENNAS

In this section, methods are discussed for the control of radiation pattern of earth station or satellite transmit antennas such that only the targeted service areas receive signals of detectable level. This is accomplished by pointing nulls along the affected areas (areas other than the targeted areas which are receiving signals of detectable level). To point the nulls along the affected areas, one must know the directions of affected areas. This information may or may not be available and accordingly the problem can be divided into two groups:

A. directions of affected areas are approximately known,

B. directions of affected areas are not known.

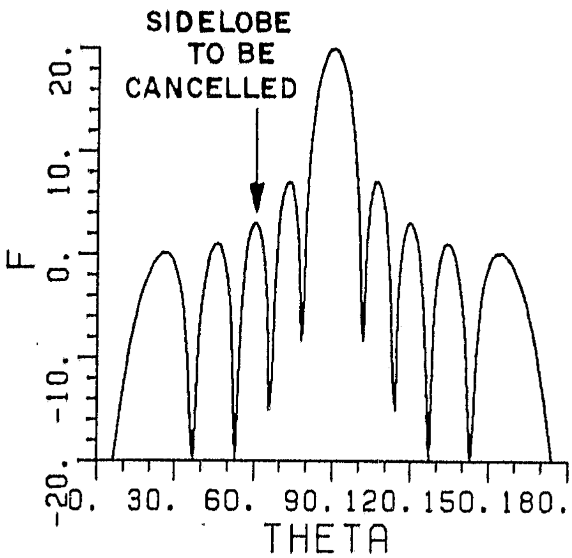
Methods to control the radiation pattern in each case are discussed below.

A. DIRECTION OF AFFECTED AREAS ARE APPROXIMATELY KNOWN

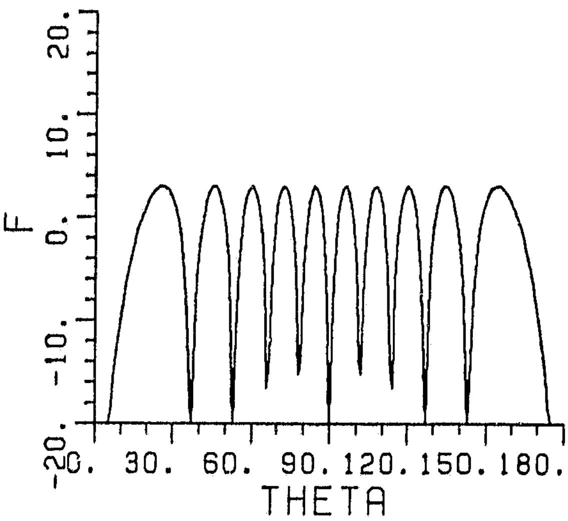
When the directions of affected areas are known only approximately, one should produce broad nulls in those directions so that the affected areas do not receive signals of detectable level. This can be accomplished using two auxiliary antenna elements. The auxiliary antennas are relatively low gain antennas and are spaced at such a distance that the width of a lobe of the interferometer formed using the auxiliary antennas is equal to the width of a sidelobe of the transmit antenna. The two auxiliary antennas are pointed in the direction of the sidelobe whose level is to be reduced and their excitation is adjusted to cancel the sidelobe. Since the interferometer's lobe is equal to the sidelobe of the main antenna and it is radiating out of phase from the main antenna, the neighboring sidelobes will also be reduced by the auxiliary antennas and a broad null will be produced in that direction.

For example, let the main antenna be an array of 10 isotropic elements. The interelement spacing is one half of a wavelength and the array is steered along broadside. Figure 12a shows the radiation pattern of the antenna. If one wishes to reduce the sidelobes of this antenna using two auxiliary antennas, the spacing between the auxiliary antennas should be five wavelengths (the width of a lobe of the interferometer formed using the auxiliary antennas should be equal to the width of a sidelobe of the transmit antenna). Figure 12b shows the pattern of the interferometer formed by the auxiliary antennas. The auxiliary antennas are assumed to be isotropic radiators and are excited to cancel the sidelobe along 60°. Figure 12c shows the radiation pattern of the total array (main + auxiliary antennas). Note that the radiation level in the range $50° < \theta < 70°$ is quite low (less than -20 dB) and the neighboring sidelobes have also been reduced. Thus, one can use two auxiliary antennas to produce broad nulls.

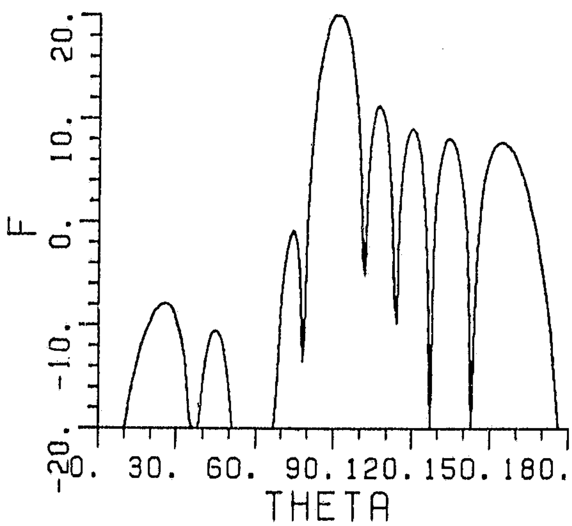
Comparing the radiation patterns in Figures 12a and 12c, one can see that though the sidelobes in the region $0° < \theta < 80°$ have been reduced, the sidelobe level in the region $100° < \theta < 180°$ has been



(a)



(b)



(c)

Figure 12. Radiation patterns in dB (F) of a) the main antenna, b) auxiliary elements, c) the total array. Main antenna is an array of ten isotropic elements and auxiliary antennas are two isotropic antennas.

increased. The reason for this increase in the sidelobe level is that in this region the auxiliary antennas are radiating in phase with the main antenna. Therefore, to avoid this problem, one should use directive antennas as auxiliary antennas and these antennas should be pointed to the region where the sidelobes are to be reduced.

Figure 13 shows the various radiation patterns when the auxiliary antennas are one wavelength long dipoles. A one wavelength dipole is sufficiently directive and this can be seen from its radiation pattern in Figure 13b. The dipole is oriented such that its main beam is along 60°. Note that the dipole does not have any significant radiation (less than -20 dB) in the range $110° < \theta < 180°$. Figure 13c shows the interferometric pattern of the two auxiliary antennas while Figure 13d shows the radiation pattern of the total array (main antenna and auxiliary antennas). Note that the radiation in the angular range $30° < \theta < 70°$ is insignificant and other sidelobes in the angular vicinity of this region have also been reduced. The radiation pattern in the range $100° \leq \theta < 180°$ is unaffected by the addition of the auxiliary antennas.

Figures 14-17 show the radiation patterns of the array when auxiliary antennas are pointed and excited to cancel the sidelobes along 26°, 45°, 120° and 135°, respectively. Note that the radiation levels in these directions are very low and the sidelobes in the angular vicinity of these directions have also been reduced. The radiation in other directions has not changed much. Thus, auxiliary antennas can be used very effectively to decrease the sidelobes in any given sector.

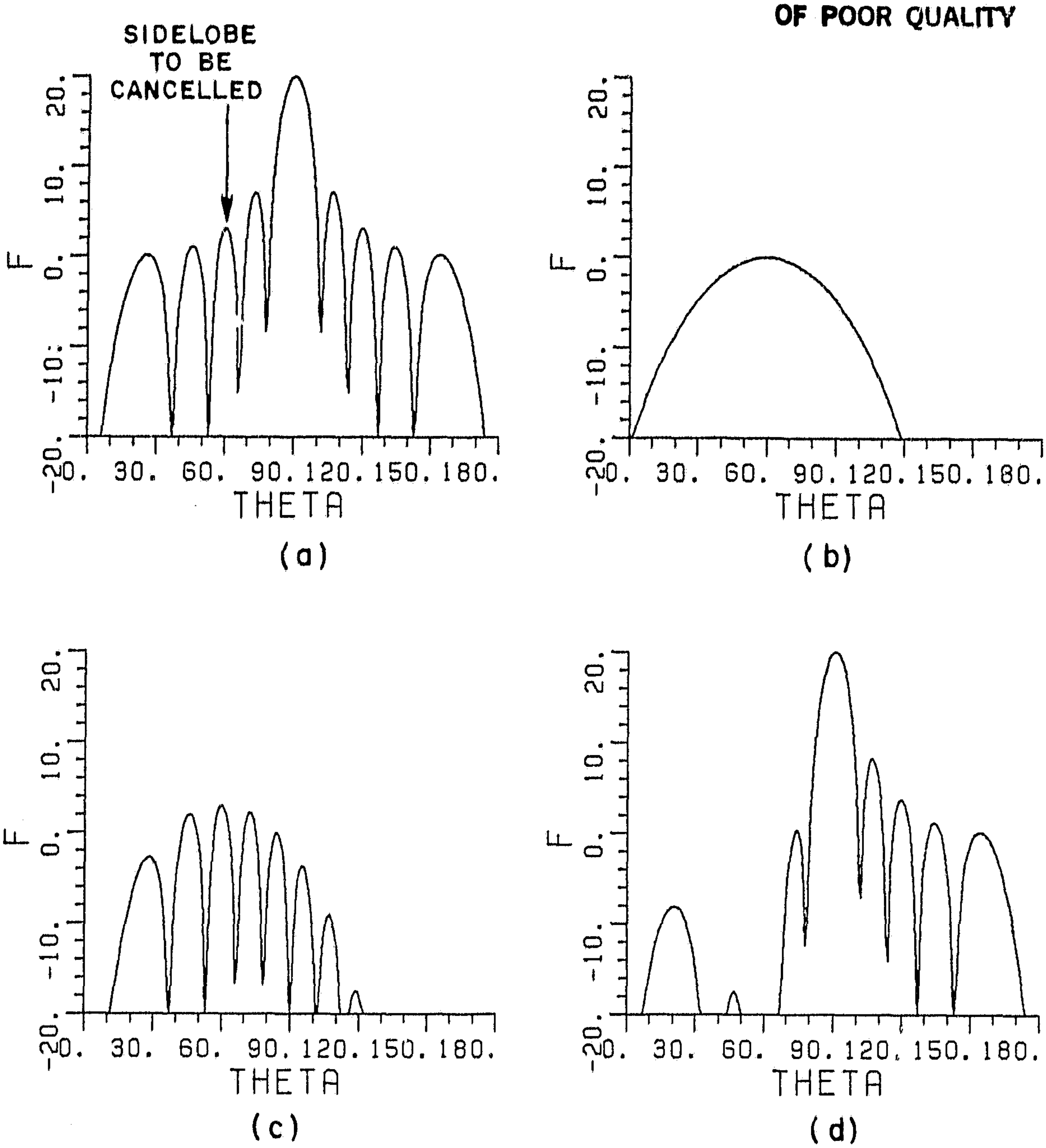


Figure 13. Radiation patterns in dB (F) of a) the main antenna, b) an auxiliary antenna, c) two auxiliary antennas, and d) the total array. Main antenna is an array of 10 isotropic antennas and auxiliary antennas are one wavelength dipoles.

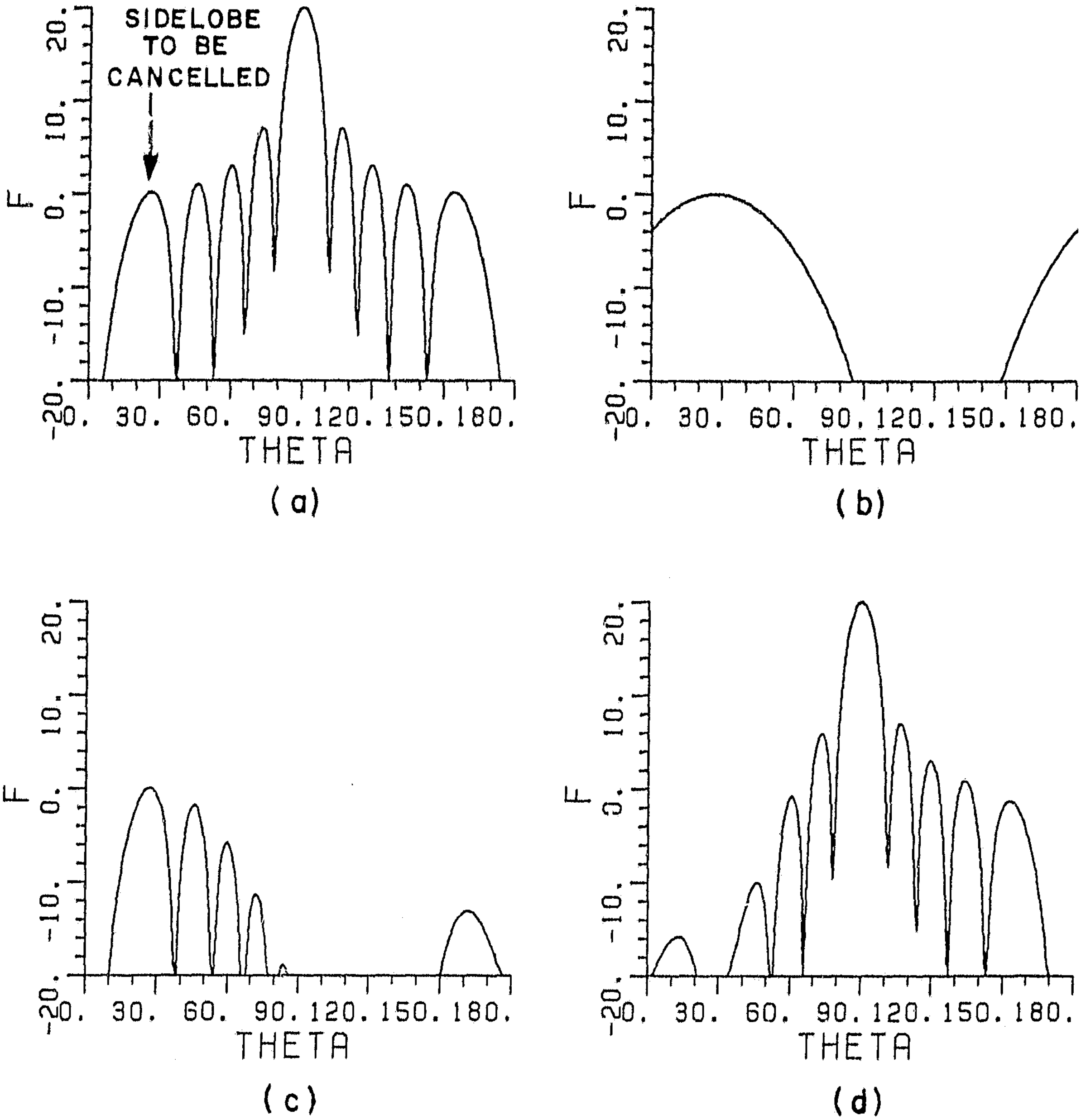


Figure 14. Radiation patterns in dB (F) of a) the main antenna, b) an auxiliary antenna, c) two auxiliary antennas, and d) the total array. Main antenna is an array of 10 isotropic antennas and auxiliary antennas are one wavelength dipoles.

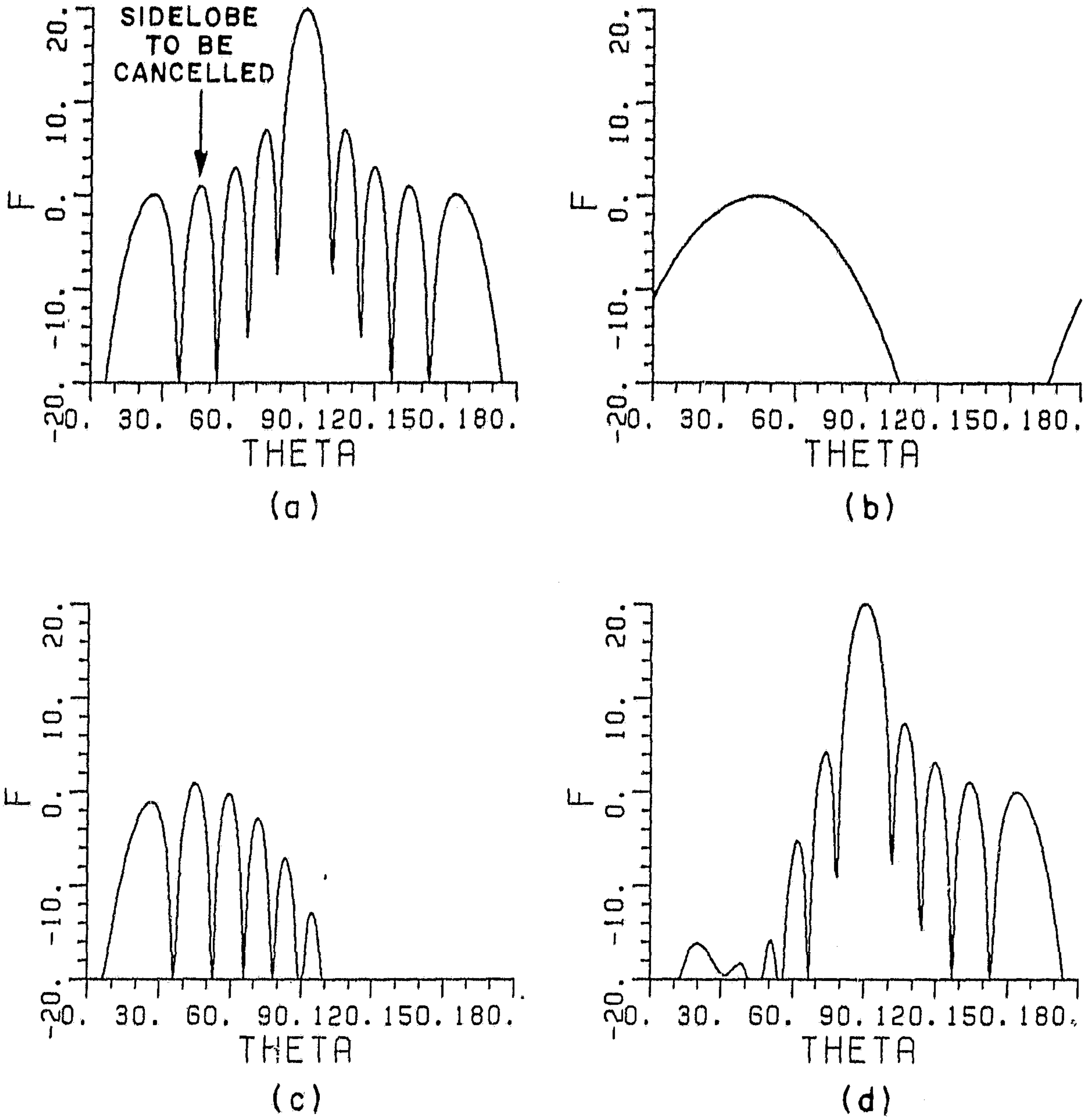


Figure 15. Radiation patterns in dB (F) of a) the main antenna, b) an auxiliary antenna, c) two auxiliary antennas, and d) the total array. Main antenna is an array of 10 isotropic antennas and auxiliary antennas are one wavelength dipoles.

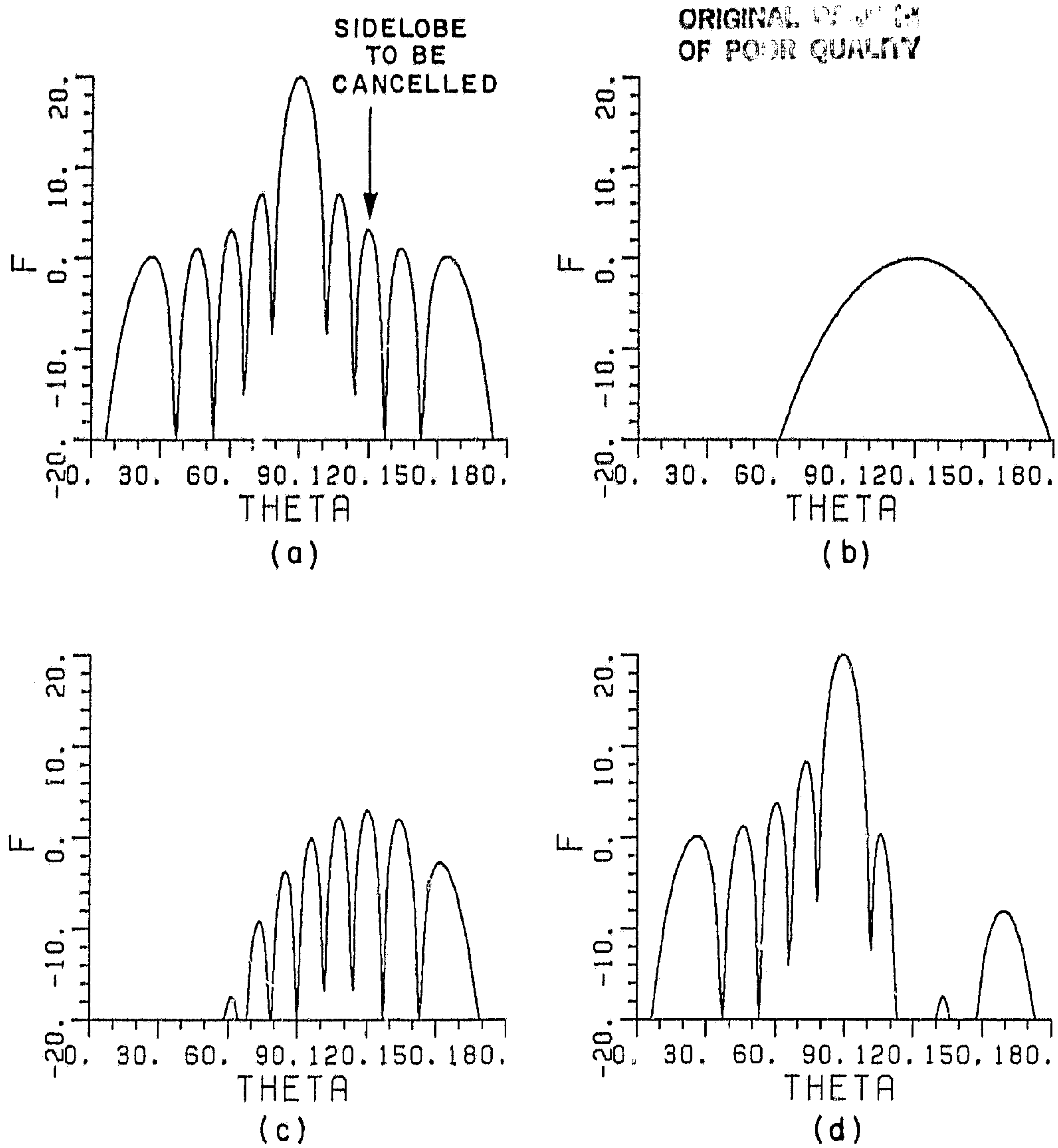


Figure 16. Radiation patterns in dB (F) of a) the main antenna, b) an auxiliary antenna, c) two auxiliary antennas, and d) the total array. Main antenna is an array of 10 isotropic antennas and auxiliary antennas are one wavelength dipoles.

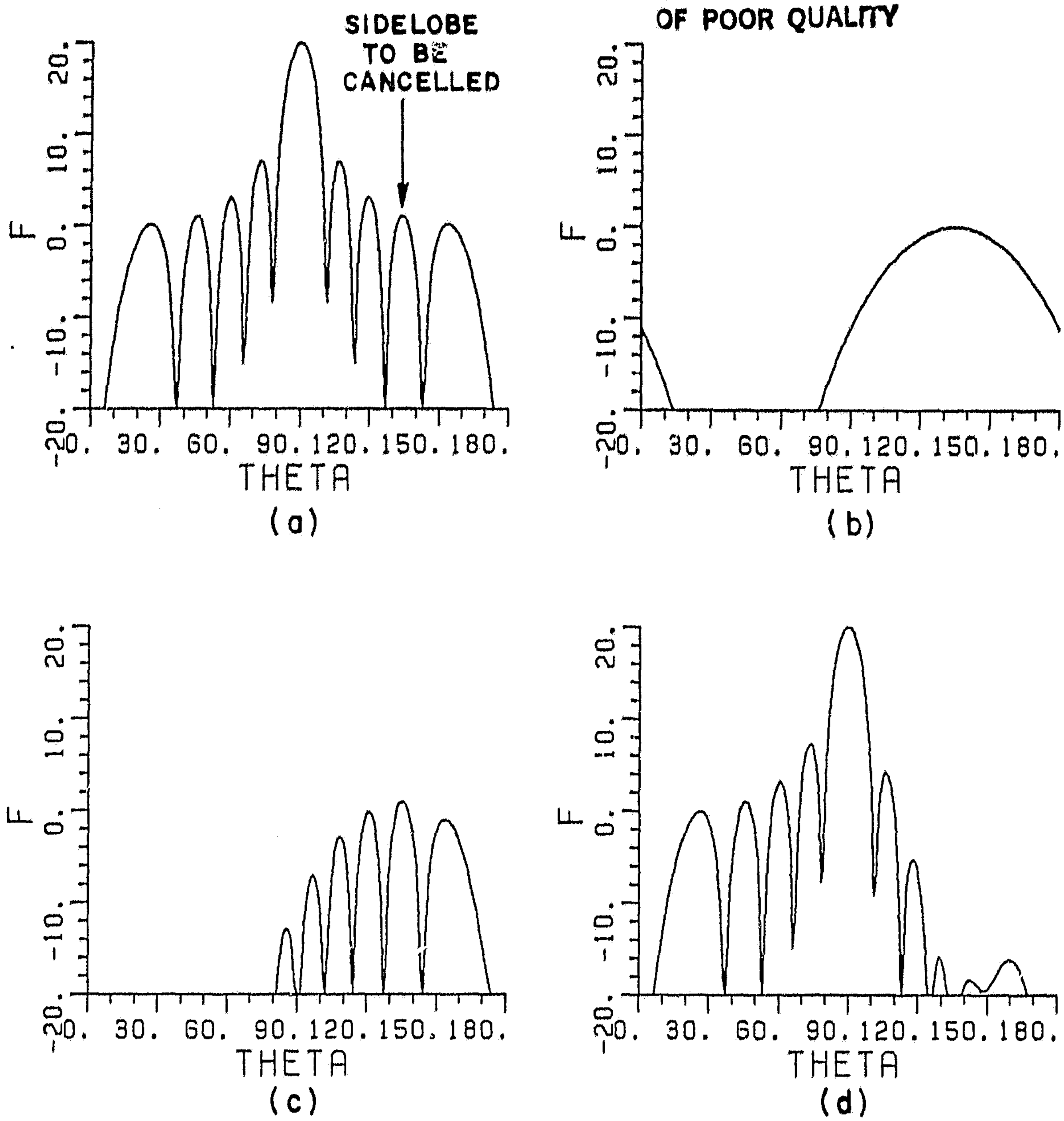


Figure 17. Radiation patterns in dB (F) of a) the main antenna, b) an auxiliary antenna, c) two auxiliary antennas, and d) the total array. Main antenna is an array of 10 isotropic antennas and auxiliary antennas are one wavelength dipoles.

However, if one wants to produce broad nulls in more than one angular region, several pairs of auxiliary antennas will be needed. As a rule of thumb, the number of auxiliary antennas is twice the number of nulls required. The presence of additional auxiliary antennas may affect the overall radiation pattern of the array (unless the auxiliary antennas are highly directive). Therefore, a detailed study is recommended for this case.

In the above discussion, the main antenna was chosen to be an array of 10 isotropic elements. This was done to illustrate the basic principle. One can use auxiliary antennas to produce broad nulls even when the transmit antenna is either an array of directive elements or a reflector antenna. In the case of reflector antennas, one can also use offset feeds to produce nulls in given directions. This is particularly suitable for beam switching transmitting antennas where one has an array of feeds. However, the nulls produced by offset feeds will be quite narrow and therefore one should know the directions of affected areas fairly accurately.

B. AFFECTED AREAS ARE A PRIORI UNKNOWN

In the above discussion, directions of the affected areas were assumed to be known approximately. If such is not the case, one should either modify the transmit antenna such that all the sidelobes are reduced or one should locate the affected areas and produce nulls in those directions.

The sidelobes of an antenna can be reduced by modifying its aperture illumination. An antenna with uniform aperture illumination has higher sidelobes than an antenna with tapered aperture illumination. Thus, by proper excitation of the elements of an antenna array, its sidelobe level can be reduced. In the case of a reflector type transmitting antenna, the same can be accomplished by using an array feed instead of a single feed. Most of the sidelobes in a reflector antenna are due to diffraction from the rim of the antenna. By shifting to the tapered aperture illumination, the total diffracted energy is reduced and thus the sidelobes are reduced. Another method to reduce the diffracted energy is to reduce the diffraction coefficient of the rim edge. This can be accomplished by using a corrugated rim or a roll-over type of reflector.

However, if the modification of the transmit antenna is not possible, one should determine the location of the affected areas and produce nulls in those directions. One can use adaptive arrays for this purpose. Again one needs some auxiliary antennas. These auxiliary antennas along with the main antenna (transmit antenna) are used periodically as adaptive receive antennas while various receiving antennas are used as transmit antennas transmitting narrowband signals (CW signals) at the carrier frequency of the communication link. The weights of the adaptive array (transmit antenna plus auxiliary antenna) are adjusted such that the SNR of the signal arriving from the targeted service area is maximized. The weights can also be adjusted to suppress the signals arriving from service areas other than the targeted service area (see Section II). Thus, the adaptive array will steer nulls in the directions of affected areas. These weights are stored and are used as excitations in the transmit mode (the main antenna and auxiliary antennas are transmitting). In the transmit mode, radiation levels along the previously affected areas will be low (adaptive array has steered nulls in those directions). Thus, service areas other than the targeted service areas will not receive signals of detectable levels.

In this section, methods to control the radiation pattern of an earth station or satellite transmit antenna such that only the targeted service areas receive signals of detectable level were discussed. Situations where the directions of affected areas are known (approximately) as well as situations where such information is not available were considered. Auxiliary antennas to produce broad nulls were used in the first case while adaptive arrays were recommended for the other case. Future work in these areas is recommended in the next section.

IV. CONCLUSIONS AND RECOMMENDATIONS

Various methods have been considered in this study for the reduction or elimination of interference in satellite communications. The study considered both the receive and transmit aspects of interference. For receiving systems, adaptive arrays were proposed to provide interference protection. It was found that conventional adaptive arrays were unable to provide any significant interference suppression for the specified signal-interference scenario. The reason was that the interfering signals were rather weak (carrier-to-noise ratio of interfering signals was less than 0 dB). To overcome this difficulty, the feedback loops controlling the weights of the adaptive array were modified. Using computer simulations, it was shown that the modified loops provide the desired interference suppression.

The reason for the effectiveness of the modified loop is that it reduces the noise level in the feedback loop which in turn leads to further suppression of the interfering signals. The noise level is reduced by reducing the correlation between the noise components of the two inputs of the loop correlator. Various techniques to decorrelate these noise components were discussed. The relative effectiveness of these techniques, however, require a critical evaluation for varius signal-interference scenarios. In particular, the study must consider the two main conditions. One is an earth station where the external noise would be rather small looking into the sky and the other a satellite terminal where the antenna is pointed toward the earth and absorbs a significant amount of thermal noise. The proportions of external and internal noise and their effects on the interference suppression should be evaluated.

A comparative study of the performance of the system when the main antenna is a reflector antenna and an array of small antennas is recommended. In the case of an antenna array, the feasibility of using some array elements as auxiliary elements should be studied. In the case of reflector antennas, the possibility of using offset feeds as auxiliary antennas should be considered. The total number of auxiliary antennas and their radiation characteristics for various scenarios should be determined.

Regarding the transmit problem, various methods of controlling the radiation patterns of earth and satellite transmit antennas such that only targeted service areas receive signals of detectable level were studied. It was shown that if directions of affected areas are known (approximately), one can use pairs of auxiliary antennas to produce broad nulls in those angular regions thus reducing or eliminating the radiation into those regions. A detailed study is required, though, of the number, the types and the locations of auxiliary antennas. The performance of the system should be evaluated when the main antenna is a reflector type antenna as compared to an array antenna. In the case of reflector type antennas, the use of offset feeds should be considered.

When the directions of the affected areas are unknown, adaptive antenna arrays are recommended to locate the affected areas and produce nulls in those angular regions. To use adaptive arrays, transmit antennas might be periodically used as receiving antennas while the receiving antennas would be used as transmitting antennas. A feasibility study of accomplishing this task should be done and effectiveness of adaptive arrays in producing nulls along affected areas should be determined. Alternatively, small, special purpose antennas co-located with the receiving antennas might be used as very low level transmitters to pinpoint the location of the receiving antennas.

Although not representing the characteristics of the actual receiving antenna, it could provide at least its location. Other methods of determining the affected areas should be sought and evaluated.

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