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Automated Steerable Nulling Antenna Processor (SNAP) Model

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This report describes an adaptive antenna computer model that simulates the behavior of a steerable-nulling antenna processor (SNAP) in a jamming or interference environment. The model predicts the signal-to-(interference-plus-noise) ratio as a function of antenna parameters and interference environment. The model can be used to demonstrate the application of antennas with the SNAP for obtaining increased spectrum utilization or improved performance in an interference or jamming environment.

Key words: adaptive antennas; interference nulling; steerable-nulling antenna processor

1. INTRODUCTION

An adaptive antenna computer model has been developed to simulate a steerable-nulling antenna processor (SNAP). This model is intended to be used to evaluate the spectrum conservation potential of an antenna with a SNAP. Multiple point-to-point communication links with conventional antenna systems must operate on separate radio frequencies to avoid interfering with each other. Each of the links containing an antenna with a SNAP will be permitted to operate on the same radio frequency by virtue of the multiple nulls formed by the SNAP in the directions of interference.

A SNAP antenna system consists of an array of radiating elements and a real-time adaptive receiver processor. This SNAP antenna system is but one type of an adaptive antenna array. The model discussed in this report specifically addresses a linear antenna array, but a SNAP or an adaptive array can have either linear, conformal, or circular antenna element geometry.

When given a beam-steering command, the system will simultaneously sample the current environment for interference and jamming. The system then proceeds to adjust the element control weights in phase and amplitude to attain one form of optimum condition such as maximum signal-to-(interference-plus-noise) ratio using a particular adaptive algorithm. The optimum weighting condition produced via this algorithm usually forms some degree of nulling in the directions of interference. This is termed adaptive interference

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nulling. The complete operation of the adaptive antenna array is equivalent to a spatial filter. The algorithm used for this simulation is a modified Howells-Applebaum algorithm (Applebaum, 1976), which optimizes output signal-to-(interference-plus-noise) ratio, by forming nulls in the directions of interference in the adaptive pattern.

The adaptive weight adjustment is determined by sensing the correlation between antenna element signals (Compton, 1988). The antenna elements contain the signal, noise, and interference environment.

The SNAP implementation of the adaptive array is capable of forming n-1 nulls where n is the number of array elements of the antenna. It is possible to null more than n-1 interferers when either multiple interferers are located at the same angular direction or the interferers possess symmetries in angle (Compton, 1988). This depends on the scenario, which in general will not provide these conditions most of the time. An N element antenna has N degrees of freedom. Assuming a worst case scenario, one of these degrees of freedom is required to form the main beam and the remaining N-1 degrees of freedom can be used to form N-1 nulls in the directions of interference.

The SNAP implementation of the adaptive array will hereafter be referred to as simply the adaptive array. This report will first describe the operation of the adaptive array. A description of the algorithms used in the computer simulation will follow. An explanation of the simulation will be included along with a procedure for using the simulation. An example will also be given.

2. DISCUSSION

The adaptive antenna computer model begins with an interference environment generator, which requires the interference amplitudes and location angles in space of each interference source. These are entered by the user. The first part of the model takes these amplitudes and generates a simulation of the amplitude variation as a function of time so that the occupied spectrum in the frequency domain represents the environmental variation of the interference sources. The total interference environment is then sampled in the time domain and the resultant covariance matrix is computed for each time sample.

The eigenvalues and eigenvectors are then computed for each covariance matrix for each time sample. The eigenvectors of this matrix are then used to determine the adaptive weights of the antenna elements. The result is an adaptive pattern at each time sample.

The magnitudes of the eigenvalues, the receiver bandwidth, and the adaptive processor integration filter bandwidth determine the transient response of the adaptive control loops and, hence, the transient response of the entire antenna array. The magnitudes of the eigenvalues are determined by the instantaneous magnitudes of the interference sources in the environment.

The antenna pattern is computed only at the desired signal angular location and the angular locations of each of the interference sources to save computation time. These pattern computations are all that are needed to determine the composite signal-to-(interference-plus-noise) ratio versus time. The signal-to-(interference-plus-noise) ratio is the final output of the SNAP antenna simulation. This can be further integrated into a complete communication simulation model with propagation effects for a total system analysis.

2.1 Adaptive Antenna Description

The adaptive antenna array automatically senses the direction of the interference sources by processing the signals due to interference and noise from each of the array receiving elements. This can be represented as a matrix column vector where each matrix element in the column is the total interference plus noise from each antenna element. Each column entry is in general, a complex number. The product of the complex conjugate and the transpose of this matrix vector results in a square N by N matrix where N is equal to the number of antenna elements in the array. The adaptive array processor forms this matrix. It is called a covariance matrix and represents the cross-correlation of all element signals in the array.

The eigenvalues and eigenvectors of this matrix are computed and used to form the retrodirective receiver antenna beams in the directions of interference. These are the retrodirective receiver antenna beams for the adaptive array. The retrodirective beams are subtracted from the unadapted (quiescent) antenna pattern to form the adapted antenna pattern containing "nulls" in the directions of interference. The unadapted (quiescent) antenna pattern is the antenna beam formed with the appropriate interelement phases such that its maximum amplitude is in the direction of the desired signal. The net result is spatial filtering of the interference sources in the environment.

A retrodirective receiver antenna beam is the beam formed when the phase of each element of the array is delayed (with respect to phase of a given reference element) by exactly the same amount that the incoming signal was advanced. This is the requirement of phase conjugacy on the antenna elements for retrodirective beams (Gabriel, 1976). The retrodirective beam phases for each element are the conjugate of the element phases of the incoming signal. The adaptive array processor determines the phase conjugate element relationship for a multitude of interference sources from the covariance matrix. The covariance matrix is the cross-correlation of the receiver antenna element signals with a receiver reference signal. The reference is usually the array output, which is the summation of all the element signals.

The simplified block diagram of an adaptive antenna array in Figure 1 illustrates the relationship of the antenna elements and the adaptive control loops for a four-element array. There is an adaptive control loop for each antenna element. A signal from each antenna element is first amplified by a preamp. The preamp in each channel is used to establish the noise figure of the antenna array. Each element signal V_L is then converted to its complex conjugate V_L^* and then fed to a cross-correlation mixer. This cross-correlation mixer forms the product of each conjugate element signal V_L^* with a reference signal. The reference signal is the array output, $\sum_{i=1}^{4} F_i V_i$. The mixer output for each element represents one column of the covariance matrix. The signal is then amplified and applied to an adaptive integration filter, which has approximately one-tenth the bandwidth of the receiver to allow adequate signal integration time. The cross-correlation filter must have excellent phase stability to properly integrate the cross-correlation mixer signal output.

The cross-correlation filter output C_L is then subtracted from the element beam steering signal B_L^*, and the result, F_L, is multiplied by the original element signal V_L using a mixer. All of the adaptive control loop signal outputs for each element are then summed together to form the final adaptive array output $\sum_{i=1}^{4} F_i V_i$. Each adaptive control loop is similar to a Type-0 servo-control loop. For an N-element array, the solution of N simultaneous linear differential equations is required to compute the necessary adaptive weights, F_L, for the array. The solutions to these N simultaneous equations are the eigenvectors of the covariance matrix. This will be

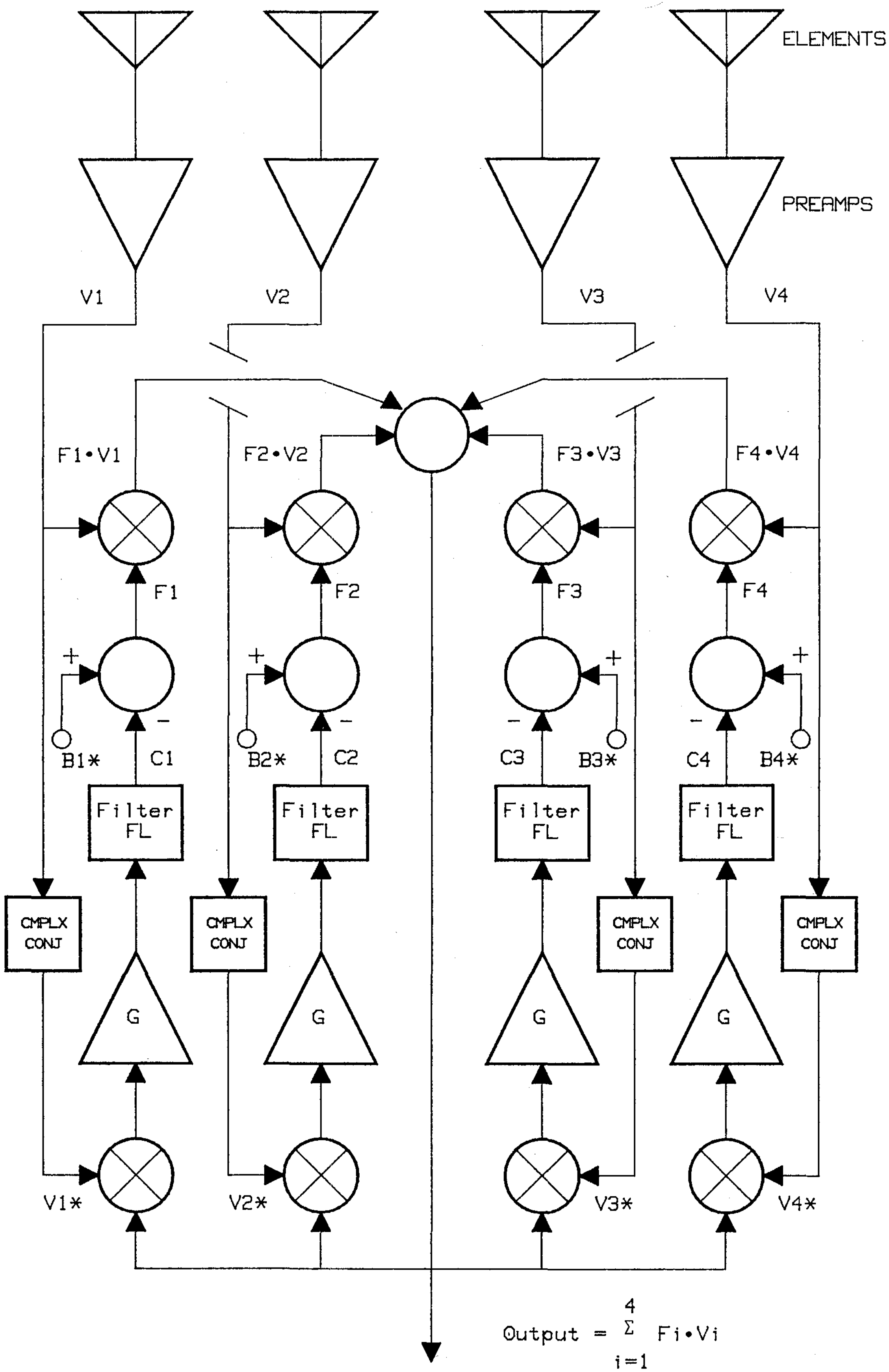

Figure 1. Adaptive Array Block Diagram.

discussed in more detail in section 2.2. The output of the array is the adaptive array pattern containing nulls in the directions of interference. The algorithms for an adaptive array will be discussed in the next section.

2.2 Algorithms For An Adaptive Antenna

The algorithms for the adaptive antenna simulation model will be described in the form as they appear in the computer program for ease in identification. Each variable will be explained as it occurs. The total adapted pattern must be computed before determination of the composite signal-to-(interference-plus-noise) ratio. The total adapted pattern GT(T,K) is

$$GT(T,K) = GQ(K) - GAD(T,K), \qquad (1)$$

where GQ(K) is the quiescent antenna pattern without adaptation,
GAD(T,K) is the sum of individual adapted patterns retrodirective beams necessary to null each interference source,
K is an angular index for Theta (θ), the azimuth angle, and
T is an index representing time.

The subtraction indicated in (1) forms a total adapted antenna pattern with nulls in the directions of each interference source.

The quiescent antenna pattern is the azimuth pattern obtained for an array with the required phasing necessary to steer the main beam to the desired position. The quiescent pattern is

$$GQ(K) = \sum_{L=1}^{N} AK(L) \cdot e^{j\cdot\pi\cdot D\cdot(\sin\theta(K)-\sin\theta(1))\cdot(2L-N-1)}, \qquad (2)$$

where L is the radiating element index,
AK(L) is the amplitude of the L^{th} radiating element,
$\theta(K)$ is the azimuth angle of the $(K-1)^{th}$ interferer in degrees for K=2, through R with respect to the array normal,
R is the number of interferers IR plus one,
$\theta(1)$ is the azimuth angle of main beam in degrees with respect to the array normal,
N is the total number of radiating elements, and
D is the antenna interelement spacing in wavelengths.

This summation can be interpreted as the vector inner product $\vec{S}^t(K,L)\ \vec{E}(L)$ (Hudson, 1981). $\vec{E}(L)$ is a column vector representing the array element weights, and $\vec{S}^t(K,L)$ is the transpose of a column vector $\vec{S}(K,L)$ representing element signal levels of unit amplitude with superscript t denoting the transpose. The result is a scaler quantity defined by the summation of (2). The individual expressions for the vectors $\vec{E}(L)$, $\vec{S}(K,L)$, and $\vec{S}(L)$ are

$$\vec{E}(L) = \vec{AK}(L) \cdot e^{-j \cdot \pi \cdot D \cdot (\sin \theta(1)) \cdot (2L-N-1)}, \qquad (3)$$

$$\vec{S}(L,K) = \vec{S}(L) \cdot e^{j \cdot \pi \cdot D \cdot (\sin \theta(K)) \cdot (2L-N-1)}, \qquad (4)$$

and

$$\vec{S}(L) = [S(1),\ S(2),\ \ldots\ S(N)]^t. \qquad (5)$$

Each element amplitude S(i) of $\vec{S}(L)$ equals 1 for i=1 to N. This concept becomes important when considering the adaptive component of the array and the adjustment of weights for obtaining the adapted antenna pattern.

When (2) is expressed as a vector inner product, then

$$GQ(K) = \vec{S}^t(K,L) \cdot \vec{E}(L). \qquad (6)$$

The sum of the individual adapted patterns is

$$GAD(T,K) = \sum_{M=1}^{N} (1 - e^{-ALPHA(M) \cdot TIME(T)}) \cdot \left(\frac{MU(M) - MU(1)}{MU(M) + 1}\right) \cdot EW(M) \cdot ES(M,K), \qquad (7)$$

where TIME(T) is the time variable indexed in increments of T samples,
ALPHA(M) is the decay factor representing the transient response of the adapting antenna beams, and
M is an index denoting the M^{th} eigenvalue or eigenvector.

The expression for decay factor ALPHA(M) is

$$\mathrm{ALPHA(M)} = \frac{[1 + \mathrm{GAIN} \cdot \mathrm{W(M)}] \cdot \mathrm{BW} \cdot \pi}{\mathrm{IBWR} \cdot (1 + \mathrm{GAIN} \cdot \mathrm{EMAX})} , \qquad (8)$$

where GAIN is the conversion loop gain of the adaptive control loop of each element, and is assumed identical for all loops,

W(M) is the M^{th} eigenvalue,

BW is the receiver bandwidth in Hertz,

the symbol π is the constant 3.14159265,

IBWR is the integration bandwidth ratio of the adaptive control loop equal to the ratio of the receiver bandwidth to the adaptive integration loop bandwidth,

EMAX is the largest eigenvalue which is equal to W(N), the N^{th} eigenvalue for the computation technique (Smith et al., 1976) used in this model,

MU(M) is the product of the GAIN defined above and the M^{th} eigenvalue represented by W(M), and

MU(1) denotes the product of GAIN and the smallest eigenvalue W(1), which represents a quiescent condition with only noise present in all channels.

The term in (7) involving MU(M) will cancel out all eigenvector beams for all eigenvalues equal to the quiescent eigenvalue. Only the unique eigenvector beams are formed as retrodirective antenna beams.

The term EW(M) is the vector inner product of the complex conjugate of the M^{th} eigenvector, $\mathrm{EIG\vec{V}C(L,M)}$ a row vector, and the quiescent element weight vector $\vec{E}(L)$, a column vector. The result is a scaler:

$$\mathrm{EW(M)} = \mathrm{EIG\vec{V}C(L,M)}\ \vec{E}(L) \qquad (9)$$

$$= [\mathrm{EIGVC(1,M)}, \mathrm{EIGVC(2,M)}, \ldots, \mathrm{EIGVC(N,M)}] \begin{bmatrix} E(1) \\ E(2) \\ \cdot \\ \cdot \\ \cdot \\ E(N) \end{bmatrix} .$$

The equation expressed as a summation is

$$EW(M) = \sum_{L=1}^{N} EIGVC(L,M) \cdot E(L). \qquad (10)$$

The term ES(M,K) is a vector inner product of the M^{th} eigenvector, $\vec{EIGV}(L,M)$, a row vector, with a column vector, $\vec{S}(L,K)$ representing signals with unit amplitude:

$$ES(M,K) = \vec{EIGV}(L,M) \cdot \vec{S}(L,K) = [EIGV(1,M), EIGV(2,M) \ldots, EIGV(N,M)] \begin{bmatrix} S(1,K) \\ S(2,K) \\ \cdot \\ \cdot \\ \cdot \\ S(N,K) \end{bmatrix} . \qquad (11)$$

The equation expressed as a summation is

$$ES(M,K) = \sum_{L=1}^{N} EIGV(L,M) \cdot S(L,K). \qquad (12)$$

If a signal voltage column vector $\vec{V}$ is defined in which the L^{th} element component V_L consists of a quiescent receiver channel noise voltage N_L plus a summation of voltages associated with IR external interference sources of amplitude JA(K,T) and physical angular position θ(K) with respect to the normal to the array, then for an array with N antenna elements the transpose of vector $\vec{V}$ is

$$\vec{V}^t = [V_1, V_2, V_3, \ldots, V_N]. \qquad (13)$$

One component of this vector is

$$V_L = N_L + \sum_{K=2}^{R} JA(K,T) e^{jD \cdot \pi \cdot (2L-N-1) \cdot \sin \theta(K)} , \qquad (14)$$

where the interference sources JA(K,T) are assumed to be statistically independent,

JA(K,T) is the amplitude of the K^{th} source, and

$\theta(K)$ is the angular position of the K^{th} source with respect to the array normal.

The adaptive control loops are built into each antenna element channel. Each adaptive loop contains a cross-correlation mixer and RC filter that computes the average covariance between all the antenna element signals of the antenna array. A matrix differential equation describes the behavior of the adaptive control loops. The solution of the matrix differential equation determines the behavior of the adaptive array element weights. The solution contains both a transient and steady-state solution. The theory describing the behavior of adaptive control loops and its practical application to adaptive antennas is described in several references (Compton, 1988; Gabriel, 1976; Widrow and Stearns, 1985). The following discussion is based on the work of Gabriel (1976) and Compton (1988).

If the adaptive weight associated with the L^{th} element is designated as F_L, then from Figure 1 the adaptive weight is

$$F_L = B_L^* - C_L \quad . \tag{15}$$

The L^{th} correlation mixer output voltage Z_L is given by the product of the L^{th} element signal V_L^* and the summed output of the array:

$$Z_L = CNVF \cdot (V_L^* \cdot \sum_{i=1}^{N} F_i \cdot V_i), \tag{16}$$

where CNVF is the adaptive control loop conversion factor for each mixer, and is assumed to be the same for all N elements.

The output voltage of the L^{th} correlation filter, C_L will obey the differential equation of an RC integrating filter. If the input voltage is designated by $X_L(t)$, then the differential equation is given by

$$RC \cdot \frac{dC_L}{dt}(t) + C_L(t) = X_L(t). \tag{17}$$

The L^{th} correlation filter input in the adaptive array is

$$X_L = G \cdot FL \cdot CNVF \cdot (V_L^* \cdot \sum_{i=1}^{N} F_i \cdot V_i), \tag{18}$$

where G is the post-mixer amplifier gain,
FL is the filter loss factor, and
the other terms were defined previously.

The differential equation that determines the response of the adaptive control loops can therefore be written as

$$TO \cdot \frac{dC_L}{dt} + C_L = G \cdot FL \cdot CNVF \cdot (V_L^* \cdot \sum_{i=1}^{N} F_i \cdot V_i). \tag{19}$$

The overall time constant TO is dependent on receiver bandwidth, filter loss, integration bandwidth ratio, conversion gain, and the maximum eigenvalue:

$$TO = \frac{IBWR}{\pi \cdot BW} \cdot [1 + GAIN \cdot EMAX]. \tag{20}$$

All of the independent variables in (20) were defined previously.

For L = 1 to N, (19) contains N unknowns and must be solved as N simultaneous linear differential equations. This equation may be revised and stated in terms of the element adaptive weights F_L using (15):

$$TO \cdot \frac{dF_L}{dt} + F_L = B_L^* - GAIN \cdot (V_L^* \cdot \sum_{i=1}^{N} F_i \cdot V_i). \tag{21}$$

GAIN is the product of G, FL, and CNVF defined previously and represents a combined amplifier gain, mixer conversion factor, and filter loss constant.

If a conversion is made to matrix vector notation for convenience, then (21) becomes

$$TO \cdot \frac{d\vec{F}}{dt} + \vec{F} = \vec{B}^* - GAIN \cdot (\vec{V}^* \cdot \vec{F}^t \cdot \vec{V}), \tag{22}$$

where $\vec{F}$ is an adaptive weight column vector,
$\vec{F}^t$ is the transpose of $\vec{F}$,

$d\vec{F}/dt$ is the time derivative of $\vec{F}$,

TO is an overall time constant for the adaptive control loop,

$\vec{B}$ is the beam steering column vector required to steer the beam to the desired angular location, and

$\vec{V}^*$ is the complex conjugate of the vector $\vec{V}$ defined previously.

Matrix multiplication rules allow rearrangement of the matrix multiplier in (22) to arrive at

$$\vec{F}^t \cdot \vec{V} = \vec{V}^t \cdot \vec{F} = \sum_{i=1}^{N} F_i \cdot V_i, \qquad (23)$$

and

$$\vec{V}^* \cdot \vec{F}^t \cdot \vec{V} = [\vec{V}^* \cdot \vec{V}^t] \cdot \vec{F}. \qquad (24)$$

The average product of the conjugate of the signal column vector $\vec{V}^*$ and its transpose $\vec{V}^t$ results in a matrix whose components represent the correlations between the various element channel signals, which is the covariance matrix of the set of system inputs (Gabriel, 1976).

Substituting (24) into (22) results in the final form of the differential equation for the adaptive control loops of the adaptive array.

$$TO \cdot \frac{d\vec{F}}{dt} + \vec{F} = \vec{B}^* - GAIN \cdot (\vec{V}^* \cdot \vec{V}^t) \cdot \vec{F}. \qquad (25)$$

The solution to the vector differential equation governing the behavior of the adaptive control loop response of the entire antenna is the set of eigenvectors of the covariance matrix A. The average product of the conjugate of the signal column vector $\vec{V}^*$ and its transpose $\vec{V}^t$ results in a square matrix whose components represent the correlation between the various element channel signals. This is the covariance matrix A of the set of system inputs.

The matrix product of $\vec{V}^{*}\cdot\vec{V}^{t}$ is

$$A = \overline{(\vec{V}^{*}\cdot\vec{V}^{t})} = \begin{bmatrix} V_1^* \\ V_2^* \\ V_3^* \\ \cdot \\ \cdot \\ \cdot \\ V_N^* \end{bmatrix} [V_1, V_2, V_3, \ldots, V_N] \tag{26}$$

$$= \begin{bmatrix} \overline{V_1^*V_1} & \overline{V_1^*V_2} & \overline{V_1^*V_3} & \cdots & \overline{V_1^*V_N} \\ \overline{V_2^*V_1} & & \cdot & & \\ \overline{V_3^*V_1} & \cdots & \overline{V_x^*V_y} & & \cdot \\ & & & & \cdot \\ & & & & \cdot \\ \overline{V_N^*V_1} & \cdots & & & \overline{V_N^*V_N} \end{bmatrix} . \tag{27}$$

Each element of the matrix is the average correlation of the product $\overline{\vec{V}^{*}\ \vec{V}^{t}}$, where the overbar will be used to denote the averaging operation.

Each element of matrix A is by (14):

$$\overline{V_L^{*}\cdot V_P} = \sum_{K=2}^{R} \overline{|JA(K,T)|}^{2} \cdot e^{j2\cdot D\cdot\pi\cdot(P-L)\cdot \mathrm{Sin}\theta(K)} \text{, for } L\neq P, \tag{28}$$

and

$$\overline{V_L^{*}\cdot V_P} = \overline{|V_L|}^{2} = \overline{|N_L|}^{2} + \sum_{K=2}^{R} \overline{|JA(K,T)|}^{2} \text{, for } L=P. \tag{29}$$

The mathematical operations indicated by the multiplications in (28) and (29) have zero cross-multiplication terms, because of the noise and interference in each channel being uncorrelated for each case.

The eigenvectors of matrix A are used to compute the adaptive array element weights for the purpose of forming nulls in the directions of interference. The eigenvalues of matrix A control the time response of the antenna system. A large eigenvalue causes a fast time response, and a small eigenvalue causes a slow time response. In the case of no interference, there are N eigenvalues proportional to the noise in each channel. For equal noise in the channels and no interference, the adaptive beam component is zero, and the antenna pattern is the original pattern formed by the input element phase and amplitude.

The eigenvalues and eigenvectors are computed and then substituted into (7), (2), and (1) to determine the adaptive antenna pattern with the magnitude of the null depths in the directions of the interference sources.

The signal-to-(interference-plus-noise) ratio STIPN(T) is then computed using the main beam maximum and null depth magnitudes:

$$STIPN(T) = \frac{PR \cdot AGT(T,1)}{\sum_{I=1}^{N} |NOISE\ (I)|^2 + \sum_{K=2}^{R} |JA(T,K)|^2 \cdot AGT(T,K)}, \tag{30}$$

where Noise (I) is the noise voltage for the I^{th} channel which is equal to N_L when L = I, and

PR is the received signal power level and is determined by the user input signal-to-noise ratio STN in decibels:

$$PR = 10^{.1 \cdot STN}. \tag{31}$$

JA(T,K) is the voltage amplitude of the interference determined by the user-input interference-to-signal power-ratio JTS(K) in decibels and the environment simulation as a function of time:

$$JA(T,K) = (\text{time variation}) \cdot PR \cdot 10^{.05 \cdot JTS(K)}. \tag{32}$$

The time variation for the interference environment simulator modifies the user input amplitudes at each angular location for each of the interference sources. An environmental simulator uses these amplitudes and generates an interference magnitude fluctuation as a function of time. Thus the occupied spectrum in the frequency domain represents the measured environmental variation of the interference sources. The measured environment parameters require that the spectrum be 3 dB down at 22 Hz and 10 dB down at 50 Hz with respect to the maximum amplitude at zero Hz. This resulted in a time domain risetime (0 to 100 percent amplitude) of .0147 seconds. These parameters can be changed in the model or the model can be completely replaced by another model.

AGT(T,K) is the adaptive antenna pattern amplitude as a function of time for the main beam signal and the nulls at each interference location. It is the absolute value of GT(T,K) given in (1). AGT(T,1) is the main beam amplitude and AGT(T,K) is the null amplitude for the K^{th} interference source. The final signal-to-(interference-plus-noise) ratio in decibels is

$$STNI(T) = 10 \cdot \log [STIPN(T)] \quad (33)$$

This signal-to-(interference-plus-noise) ratio is computed as a function of time and is the final output of the adaptive antenna model. Time T = 0 is the instant that the interference sources are turned on in the environment. The adaptive antenna (SNAP) response is determined by the receiver bandwidth, the adaptive loop conversion gain and integration bandwidth ratio, the amplitude and number of interference sources, and the interference environment fluctuation.

2.3 Using The SNAP Antenna Model

The SNAP antenna model has been copied onto one 360-kilobyte 5¼" floppy disk. The FORTRAN 77 code (SNAP8.FOR), object code (SNAP8.OBJ), and an executable code (SNAP8.EXE) are on this disk. The executable code resides in approximately 290 kilobytes of memory. This executable version of the program should run on most personal computers with 512 kilobytes of RAM. The FORTRAN 77 source code can be transferred to any computer using FORTRAN 77 and then compiled on that machine. A math coprocessor is recommended, but not required.

To run the personal computer version on the floppy disk, the user types "SNAP8" and enters a carriage return. The user will then be asked questions to supply the required input data necessary to run the program. A carriage return with no data entry typed by the user will enter the default value indicated in each question. The questions will now be described in the order that they appear. If the user enters data that is out of the range indicated with each question, the program will ask the question again until the user makes a data entry within the range specified. Table 1 contains the permissible range of values and defaults for each of the user-input variables.

TABLE 1. Definitions of User Input Variables

Name	Description	Range	Default
N	Number of Antenna Elements	2 to 8	6
IR	Number of Interferers	0 to N-1	N-1
MAXT	Maximum Observation Time	.0001 to .250 s	.250 s
D	Antenna Element Spacing	.25 to 1.00 wavelengths	.50 wavelengths
AK(L)	L^{th} Antenna Element amplitude	.01 to 10.0	1.0
THETA(1)	Antenna Main Beam Direction	0 to 360 deg	0 deg
THETA(K+1)	K^{th} Interference Source Angular Location for K=1, to N-1	0 to 360 deg	30, 60, 90, 150, 180, 190, and 200 (for 8 elements)
JTS(K+1)	Interference-to-Signal Ratio for K^{th} Interference Source	-30 to +50 dB	+30 dB
BW	Receiver Bandwidth	1 Hz to 50 MHz	100 kHz
GAIN	Conversion Gain	.001 to 1,000	1.0
STN	Desired Signal-to-Noise Power-Ratio in Absence of Interference	-30 to 100 dB	10 dB
IBWR	Integration Bandwidth Ratio	1 to 100	10

The number of antenna elements (N) is the actual number of antenna radiating elements present. The present limitation is a maximum of eight, but this may be changed to a larger number by editing the program. This limitation was imposed so that the executable code would fit on most personal computers with 512 kilobytes of RAM. The program has been used successfully on a personal computer with 16 elements, but this program completely filled the available 640K RAM when a maximum observation time of .250 seconds was used for a program run.

Dividing the number of antenna elements by two in the parameter statement of the FORTRAN 77 code will divide the RAM required by a factor of approximately two. Dividing the maximum observation time dimension MAX in the parameter statement by two will reduce the RAM required by a factor of approximately six-tenths.

The number of interferers (IR) is the number of interference sources present in the environment. It has been limited to the number of radiating elements minus one in accordance with the discussion on the number of degrees of freedom in an adaptive array. This limitation can be changed also by editing the FORTRAN 77 code, but this procedure is not recommended, because the algorithm is not valid for the case where the number of interferers exceeds the number of degrees of freedom for the array minus one.

The maximum observation time (MAXT) in seconds is the upper limit of time interval that the user wishes to observe the response of the adaptive antenna. The time interval starts at time equals zero when the interferers are first turned on. The antenna element spacing is the interelement spacing between adjacent radiating elements in wavelengths. The elements of the array are all equally spaced.

The input antenna element amplitudes are the individual radiating element amplitude excitations and are proportional to a current or voltage. In most cases the amplitudes are equal for a uniform distribution, but the user may put in any amplitude desired for each element. This allows input of tapered distributions to reduce antenna sidelobes if desired. The user will be asked for each antenna element amplitude until all N elements have been assigned an amplitude.

The antenna beam direction is the angle of the antenna main beam with respect to a vector normal to the array surface in the azimuth direction measured clockwise. If the user selects a number that is not 0 or 360 degrees, then the program automatically computes the quiescent phase necessary for each radiating element that is required to steer the beam to the user selected beam direction. The adaptive antenna beam amplitude will be computed at this angle for calculation of the signal-to-(interference-plus-noise) ratio. The antenna beam direction is identified as THETA(1) in the program.

The selected interferer angles are the angles of interference sources measured clockwise with respect to the array normal. They are identified as angles THETA(2) through THETA(IR+1).

The interference-to-signal ratios JTS(K) in decibels are the ratios of the individual interference powers to the signal power. The index number in parentheses of JTS(K) for K=2 through IR+1 corresponds to the angular locations of the interference sources of THETA(K) entered previously. The receiver bandwidth (BW) is the actual receiver bandwidth in Hertz. The conversion gain (GAIN) is a numeric ratio and is the voltage gain of the cross-correlation mixer and preamp combination in the adaptive loop of each element. The symbol (STN) is the input signal-to-noise ratio in decibels, desired for proper operation in the absence of interference sources.

The integration bandwidth ratio (IBWR) is the numeric ratio of the receiver bandwidth (BW) to the adaptive loop integration bandwidth. A value of 10 is recommended for proper operation of the adaptive antenna. Values of less than 10 provide less time for proper integration in the adaptive signal processing, but result in faster response times. Values greater than 10 provide plenty of integration time, but may be sluggish for environmental conditions with rapid signal variations.

All of the input ranges and default values given in Table 1 and discussed previously can be modified according to user preference by editing the source code. The ranges and defaults were originally selected to provide useful limits for analysis of SNAP antenna behavior. After all data have been entered, the words "Computation In Progress" appear and the program is executed with the input data.

The output data are printed out in two separate arrays. The time array is printed first by rows, each read from left to right in sequence. The signal-to-(interference-plus-noise) ratio array is then printed by rows again each read from left to right in sequence. The signal-to-(interference-plus-noise) ratio of one row and column entry corresponds to the same row and column in the time array.

2.4 The Operation Sequence Of The SNAP Antenna Model

The main program SNAP8 first asks the user for the input data required to perform the computation. This is done by a question-and-answer sequence that asks the appropriate questions, checks the form and range of input data, and assigns the necessary input variables.

The main program then calls subroutine IST. Subroutine IST uses the input data pertaining to the interference environment and simulates the interference environment time variation. Subroutine IST also calls subroutine ATE at appropriate intervals of time. This simulates a time sampling of the interference environment. Subroutine ATE first sets up the covariance matrix describing the interference environment at each instant in time. Subroutine ATE then calls subroutine CH which subsequently calls subroutines HTRIDI, TQL2, and HTRIBK. Subroutine CH (Smith et al., 1976)** and the three subroutines that it calls compute the eigenvalues and eigenvectors for the covariance matrix at each instant of time. These values are then returned to subroutine ATE. Subroutine ATE calls subroutine STNDP which uses all relevant input data and the eigenvalues and eigenvectors to compute the adaptive array antenna pattern versus time for the SNAP. Subroutine STNDP completes the computation by forming the signal-to-(interference-plus-noise) computation versus time and writes these data on the screen.

2.5 Sample Computation

A sample computation will demonstrate the performance of the adaptive array model. All of the necessary parameters to describe this example are given along with the results of Table 2. When the interference sources are initially turned on (t=0 s), the signal-to-(interference-plus-noise) ratio is at 10 dB, because the interference sources are all initially at zero amplitude for that instant. As time progresses the signal-to-(interference-plus-noise) ratio degrades at different rates depending on the adaptive loop integration-bandwidth ratio (IBWR). The IBWR = 20 run shows that the adaptive antenna cannot keep up with the rapidly fluctuating environment. The IBWR = 10 run performs somewhat better, but the best signal-to-(interference-plus-noise) ratio is still negative. The IBWR = 5 run is able to respond to the interference environment fluctuation rate to achieve a respectable signal-to-interference-plus-noise) ratio of 8.64 dB. The interference-to-signal ratio of 30 dB from four different interference sources is a severe environment. If the

**The eigenvalue subroutines used in this model are public domain routines modified from their original form in EISPACK.

TABLE 2. Signal-to-(Interference-Plus-Noise) Ratio S/I+N versus Time with Parameter Integration Bandwidth Ratio (IBWR) for a Time Varying Interference Amplitude, JTS

t(sec)	JTS (dB)	IBWR = 20 S/I+N (dB)	IBWR = 10 S/I+N (dB)	IBWR = 5 S/I+N(dB)
$.000 \times 10^{-2}$	0.0	10.00	10.00	10.00
$.147 \times 10^{-2}$	3.1	-3.91	4.67	9.26
$.294 \times 10^{-2}$	6.0	-6.82	2.47	9.19
$.441 \times 10^{-2}$	8.8	-8.55	1.01	9.12
$.588 \times 10^{-2}$	11.7	-9.78	-.07	9.05
$.736 \times 10^{-2}$	14.8	-10.74	-.94	8.98
$.883 \times 10^{-2}$	17.9	-11.52	-1.67	8.91
$.103 \times 10^{-1}$	20.9	-12.19	-2.29	8.84
$.118 \times 10^{-1}$	23.7	-12.76	-2.83	8.77
$.132 \times 10^{-1}$	26.4	-13.27	-3.31	8.71
$.147 \times 10^{-1}$	30.0	-13.73	-3.74	8.64
$.162 \times 10^{-1}$	26.4	-13.27	-3.31	8.71
$.147 \times 10^{-1}$	23.7	-12.76	-2.83	8.77
$.197 \times 10^{-1}$	20.9	-12.19	-2.29	8.84
$.206 \times 10^{-1}$	17.9	-11.52	-1.67	8.91
$.221 \times 10^{-1}$	14.8	-10.74	-.94	8.98
$.235 \times 10^{-1}$	11.7	-9.78	-.07	9.05
$.250 \times 10^{-1}$	8.8	-8.55	1.01	9.12
$.265 \times 10^{-1}$	6.0	-6.82	2.47	9.19
$.279 \times 10^{-1}$	3.1	-3.91	4.67	9.26
$.294 \times 10^{-1}$	0.0	10.00	10.00	10.00

Parameters: N = 6, IR = 4, BW = 100 kHz, AK(L) = 1., D = 1/2 wavelength, GAIN = 1.0, JTS(K) = 30 dB, (0.0147s rise time)

interference environment fluctuates at a slower rate, then the adaptive antenna could achieve respectable signal-to-(interference-plus-noise) ratios with a larger IBWR or less receiver bandwidth. These two parameters can be used to trade-off both antenna and system performance. Increasing receiver bandwidth would increase the system noise level, but it would allow increasing the IBWR to a larger number for longer and more stable adaptive antenna loop integration times. If this antenna were in a tracking loop for a radar or communication system, a too short integration time (IBWR too small) could cause track loop oscillations. In this case, it may be beneficial to increase the receiver bandwidth and tolerate the increased noise, so that IBWR can be increased. The relationship between IBWR and BW in (22) shows that they are directly proportional to each other. If it is desired to double IBWR, then BW must be doubled. This model predicts only adaptive antenna performance. It can be integrated as a subroutine into a tracking loop or other closed loop system model to predict overall system performance.

3. CONCLUSIONS AND RECOMMENDATIONS

The model provided for simulation of SNAP antenna behavior in an interference or jamming environment can be used as a stand-alone computer program, or it can be easily integrated into a larger computer program as a subroutine. The larger computer program would contain the additional communication simulation models required for a total communication simulation model. The SNAP model subroutine could be called by the larger program in locations needing the SNAP simulation such as multilevel SNAP implementations in a complex communications network. The SNAP model could also predict performance and stability of tracking loops when integrated into a closed-loop computer program that simulates a tracking system.

The SNAP model runs well on most compatible personal computers. The SNAP model can also be made to run on larger mainframe computers to circumvent the memory limitations of personal computers incurred for antenna arrays of greater than 16 elements.

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5. REFERENCES

Appelbaum, S. P. (1976), Adaptive Arrays, IEEE Trans. Ant. Prop. 24, No. 5, pp. 585-598.

Compton, R. T. (1988), Adaptive Antenna, Concepts and Performance, (Prentice Hall), pp. 6-73, pp. 81-93.

Gabriel, W. F. (1976), Adaptive arrays, Proc. IEEE 64, No. 2, pp. 239-272.

Hudson, J. E. (1981), Adaptive Array Principles, (Peter Peregrinus Ltd.), pp. 27-58.

Smith, B. T., J. M. Boyle, J. J. Dongarra, B. S. Garbow, Y. Ikebe, V. C. Klema, and C. B. Moler (1976), Matrix Eigensystem Routines - EISPACK Guide, Lecture Notes In Computer Science, Vol. 6 (Spring - Verlag), pp. 19-23, p. 235, pp. 349-352, pp. 357-363, pp. 468-474.

Widrow, B., and S. D. Stearns (1985), Adaptive Signal Processing (Prentice Hall), pp. 368-454.

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This report describes an adaptive antenna computer model that simulates the behavior of a steerable-nulling antenna processor (SNAP) in a jamming or interference environment. The model predicts the signal-to-(interference-plus-noise) ratio as a function of antenna parameters and interference environment. The model can be used to demonstrate the application of antennas with the SNAP implementation for obtaining increased spectrum utilization or improved performance in an interference or jamming environment.

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