MULTIBEAM ADAPTIVE ARRAY FOR RPV ANTIJAM COMMUNICATION

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1.0 INTRODUCTION

An application using a multibeam adaptive array for the simultaneous communications of command control, and telemetry data from 20 Remotely Piloted Vehicles (RPV's) to a command station is investigated. It is assumed that the RPV's are on tactical mission beyond FEBA as typically shown in Figure 1, and that communication links must be established to and from each RPV in the presence of many airborne and/or surface based jammers. The RPV's are assumed to be on data collection missions out to a maximum range of 100 km and must data link the sensor information (including digitized video of 20 Mbps) back to the tactical RPV control center. The data link will be operated at C-band. Other system parameters are summarized in Figure 2.

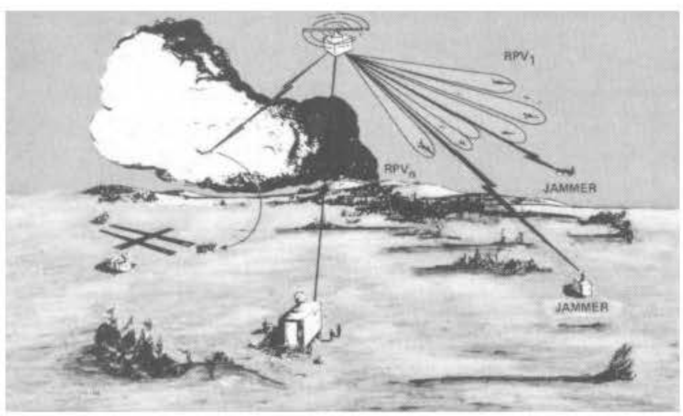


Figure 1. Typical Operational Scenario

The concept evaluated employs an airborne array but locates all of the complex beam forming and adaptive antijam processor functions for each RPV on the ground; hence its name Adaptive Ground Implemented Phased Array or AGIPA. Although a tethered rotor vehicle is shown in Figure 1 for the relay platform, the basic multibeam antijam concept presented herein is applicable whether the array is remotely suspended in space (aircraft, helicopter, tethered rotor vehicle, or spacecraft) or surfaced based (land or sea). The advantage of locating the array on an elevated platform is to extend the usable support

RELAY VEHICLE	• AIRCRAFT, HELICOPTER–TETHERED ROTOR PLATFORM • ATTITUDE: ±1 DEGREE • ALTITUDE: 1000 FT
RPV	• NUMBER OF: ≤ 20 • RANGE: ≤ 100 km • ALTITUDE: 0 - 5000 FT

DATA

LINK	FREQ (GHz)	DATA RATE
• COMMAND	4.4	≤ 10 kbps
• RETURN	5.0	≤ 20 Mbps OR 10 kbps

Figure 2. System Parameter

range for the RPV as shown in Figure 3. Obviously, it is desirable to place the array at as high an altitude as possible. This paper assumes a tethered rotor platform at an altitude of 1000 ft.

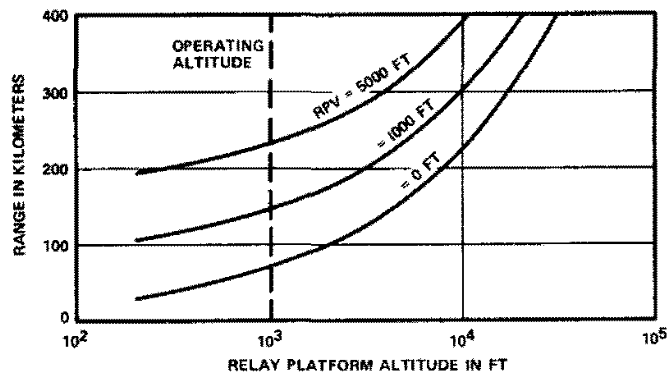


Figure 3. Range Extension With Relay Platform

The signal environment is shown in Figure 4 which shows the susceptibility to jammers of the receiver on the RPV as well as the receiver on the relay platform. The jammer has the option of disrupting either the individual RPV command and control receive link, or to jam the common return telemetry link receiver on the relay platform that receives the multiple access signals from all RPV users or both. Of the two, the relay receiver is more critical since it is the central focal point for the command, control and telemetry to and from all RPV's. This paper addresses only the antijam protection for this return link.

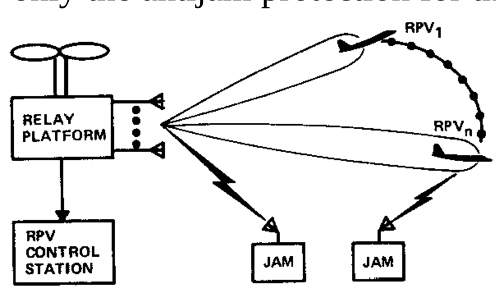


Figure 4. Signal Environment

2.0 SYSTEM APPROACH

To protect the relay receive link an adaptive array is used which optimizes the output signal-to-jammer plus noise ratio S/(J+N), by placing jammers in spatial pattern nulls while similtaneously placing the peak of the antenna beam on the desired user. More specifically, the array is mounted on the airborne relay platform to extend the range of coverage to the RPV's, but all of the complex beam forming and adaptive processing networks for each beam formed are located on the ground. In addition, in order to form multiple beams, each one customized for the individual RPV, unique pseudorandom codes are employed to identify each RPV signal, providing code division multiple access (CDMA) system on the return link. Figure 5 summarizes the highlights of the antijam approach to be employed, and Figure 6 shows the basic components essential to the implementation of the AGIPA approach. The array is located on the relay platform and each element of the array is essentially connected to the ground-based beam forming and adaptive antijam processors through a multichannel repeater and long transmission lines (or alternatively, by way of a radiating link). Both hardware and radiating links have been evaluated and will be described later. On the ground, a multichannel beam forming network and adaptive antijam processors are employed for each multiple access RPV user.

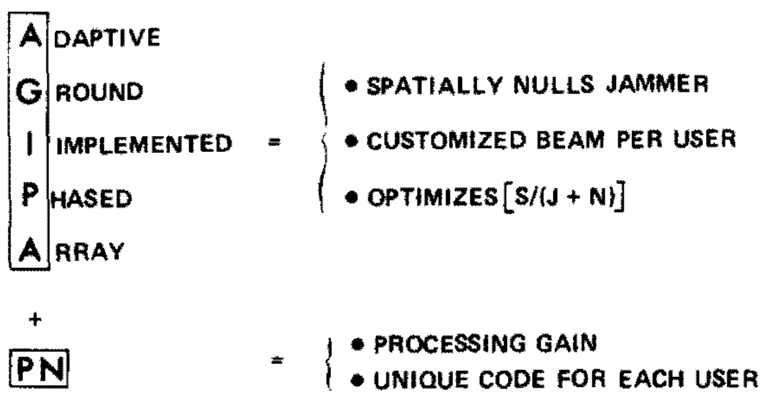


Figure 5. Antijam Approach

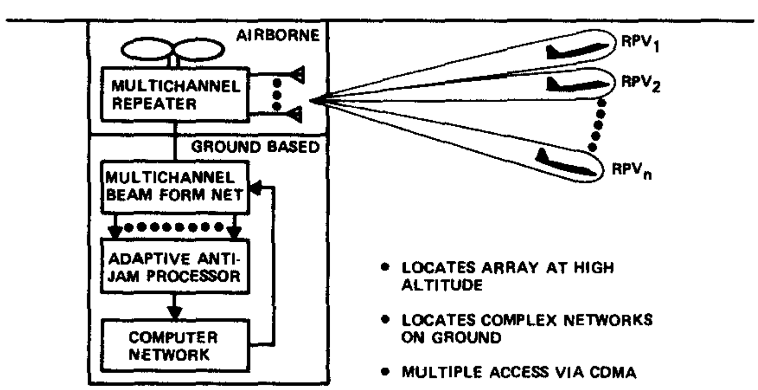


Figure 6. AGIPA Implementation

The acquisition and track procedure is summarized in Figure 7. Two approaches are presented, either using the known signal waveform (unique PN code), or the known direction of arrival (DOA) of the desired RPV signal. In the initial approach, the beam is initially pointed in the approximate direction of the desired RPV, and the PN generator is scanned to search for the desired user FIN code. After PN lock, the adaptive process is initiated to optimize the S/(J+N). After adaption, the AGIPA processing algorithm will automatically track the desired user.

KNOWN SIGNAL WAVE FORM	KNOWN RPV DOA
• INITIALLY POINT BEAM TO RPV	• INPUT RPV SIGNAL DOA
• ACQUIRE PN CODE	• ADAPT ON JAMMERS
• START ADAPTION	• ACQUIRE PN CODE
• AUTOMATIC TRACK	• ADAPT ON SIGNAL AND JAMMER
	• AUTOMATIC TRACK

Figure 7. Acquisition and Track

In the alternate approach, using known RPV DOA information, the desired user DOA data (obtained through other navaid techniques) could be inserted into the computer program, and the computer can use this input to contrive an adapted solution, forcing the adaptive processor to null jammers based on this software injected RPV signal. This approach is very valuable since the adaptive process can be directed to spatially null jammers, even before the desired RPV signal is received. After the jammers are nulled, the PN code is acquired, and the adaption process is initiated on the actual received RPV signal as in the initial approach.

The return signal path is a tandem link composed of an air-to-air link in cascade with an air-to-ground link. The overall carrier-to-noise ratio (CNR), Q_0 requirements for tandem link can be expressed as:

$$Q_o = \frac{Q_1 \, Q_2}{Q_1 + Q_2 + 1}$$

where,

Q_1 = CNR required in air-to-air link

Q_2 = CNR required in air-to-ground link and the equation is plotted in Figure 8 as a function of the allowable CNR degradation (Δ Q= Q_0 /Q_1) in the relay repeater. To achieve an output received signal power density per bit-to-noise density (E_b/N_o) of +7.4 dB for digitized video will require an output CNR Q_0) of - 7.8 dB where:

Q_0 - E_b/N_o - Bandwidth process gain - Array gain = +7.4 - 5.2 - 10.0 = - 7.8 dB

and where,

PG = RF bandwidth/information bandwidth
= 66.7 Mbps/20 Mbps = +5.2 dB

Array
Factor = G_{array} /$G_{element}$ = +10.0 dB

Therefore, if we allow a CNR degradation (Δ Q) of 1 dB in the airborne multichannel repeater, the resultant CNR (Q_1) required in the air-to-air link is -6.8 dB; from the curves in Figure 8, the required CNR (Q_2) in the air-to-ground link is +6.9 dB.

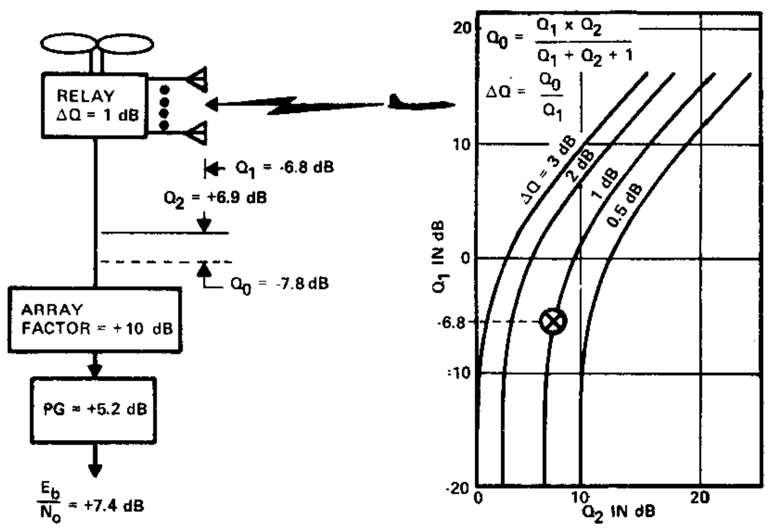
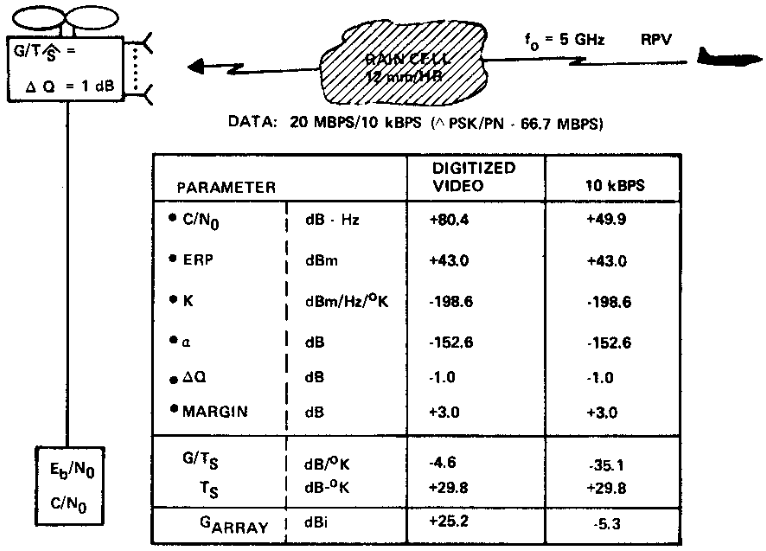


Figure 8. Tandem Link CNIR Requirement

In order to determine the number and type of antenna elements required for the air-to-air return link, Figure 9 shows the link budget used to size the array requirements on the relay platform. This air-to-air link operates at 5 GHz over a maximum range of 100 km. Over this range, it is also assumed that a rain cell of 18.5 km with a precipitation rate of 12 mm per hour is encountered, representing a propagation absorption loss of 2.2 dB. In addition, an array pointing loss of 1 dB as well as a polarization loss of 3 dB has been used to allow for relative attitude variations of approximately ±45 degrees between the element on the RPV and relay platforms.



PARAMETER		DIGITIZED VIDEO	10 kBPS
• C/N_0	dB · Hz	+80.4	+49.9
• ERP	dBm	+43.0	+43.0
• K	dBm/Hz/°K	-198.6	-198.6
• α	dB	-152.6	-152.6
• ΔQ	dB	-1.0	-1.0
• MARGIN	dB	+3.0	+3.0
G/T$_S$	dB/°K	-4.6	-35.1
T$_S$	dB-°K	+29.8	+29.8
G$_{ARRAY}$	dBi	+25.2	-5.3

Figure 9. Air-to-Air Return Link Power Budget

The link budget shows the results of returning digitized video (20 Mbps) or 10 kbps of telemetry data. The return data is delta phase shift key (Δ PSK) modulated and PN spread using a chip rate of 66.7 Mbps. For an RPV effective radiated power (ERP) of +43 dBm, the resultant relay receiving system array gain-to-system noise temperature (G/T_s) of -4.6 dB/K is required for video reception to achieve an output E_b/N_o of +7.4 dB. For data, a BER of $10^{-5}$is assumed, requiring an output E_b/N_o of +9.9 dB and a G/T_s of -35.1 dB/K. If we use an available bipolar transistor low noise preamplifier with a noise preamplifier with a noise temperature of +400 K, a system noise temperature (T_s) of +955 K or +29.8 dB/K can be achieved, resulting in an array gain requirement of +25.2 and -5.3 dBi for video and data reception, respectively. The relay array will be designed for more stringent case of video reception.

The array of the relay platform shall provide a gain of at least +25.2 dBi over a 120-degree field-of-view (FOV) in the azimuth plane as shown in Figure 10. In the elevation plane, the array must track RPV's at mission altitudes from 0 to 5000 feet. Including attitude stabilization errors of ±1 degree in roll and pitch, the array must have an elevation beam width of approximately 3.6 degrees, requiring a vertical aperture of approximately 18 wavelengths. In order to minimize the number of array elements and consequently the number of repeater channels on the relay platform, each element will be designed to provide a half -power beam width (HPBW) of 3.6 degrees in elevation and 160 degrees in azimuth. This will result in an element gain (G_{e1}) of approximately +16.5 dBi on boresight and +14.9 dBi at the desired ±60 degree scan limits. Using the approximation:

$$G_{array} = n \times G_{el}$$

10 elements are required to achieve the desired array gain of +25.2 dBi at scan limits. This is the minimum number of elements that can be used to provide adaptive nulling in the azimuth plane. Since the elevation beam width is narrow, no elevation null steering is provided.

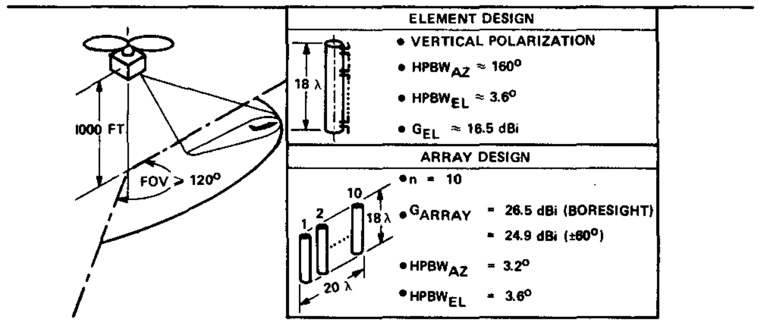


Figure 10. Antenna Design

Figure 10 shows the design for the element as well as the array. The element is a collinear array of 36 dipoles, mounted on a one wavelength diameter cylinder, providing a wide cardiod shaped azimuth pattern with a HPBW of approximately 160 and 3.6 degrees in elevation. The elements can be designed to provide either vertical, horizontal, or circular polarization. Vertical polarization is preferred, however, because:

- Linear polarization is much simpler to implement

- Relative polarization between the two RPV's will probably be less than 45 degrees since both vehicles must maintain relatively level attitude during their mission functions, and the loss due to nonalignment will be less than the cosine of 45 degrees, or 3.0 dB if both relay and sensor RPV are vertically polarized

- If circular polarization is used at one terminal and linear polarization at the other, the loss can be up to 6 dB

- Vertical is preferred over horizontal polarization since vertical polarization produces less multipath interference signal as a function of grazing angle

Therefore, vertical polarization is recommended at both sensor RPV and relay vehicles. Ten such elements are arrayed in the azimuth plane with approximately two wavelength separation between elements. The resultant HPBW's of the array are approximately 3.2 and 3.6 degrees in azimuth and elevation plane, respectively.

The repeater design is functionally shown in Figure 11 and employs a multichannel RF front end using low noise bipolar transistor amplifiers to minimize the receiver noise. Each of the 10 channels are frequency division multiplexed (FDM), downconverted, and transmitted to the ground for processing. It may be necessary to break this band into several smaller bands in order to minimize the RF bandwidth linearity requirement on the transmitter amplifier.

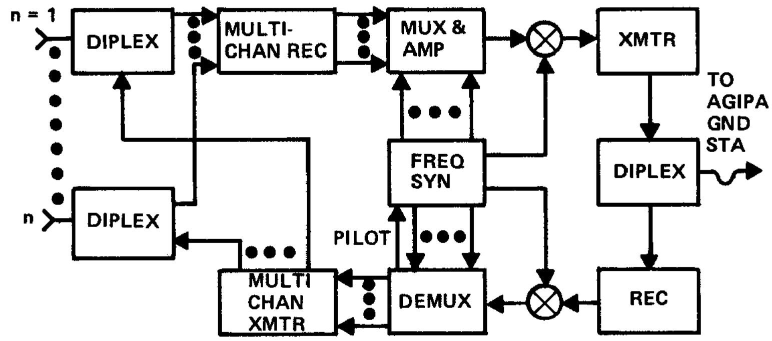


Figure 11. Repeater Design

The repeater system weight and power has been estimated as shown in Figure 12, including the command link requirements as well as the frequency synthesizer.

ITEM	WEIGHT, LBS	POWER, WATTS
ANTENNA ARRAY	75	•
RETURN LINK	55	48
COMMAND LINK	80	348
FREQUENCY SYNTHESIZER	10	50
TOTAL	220	446

Figure 12. Summary of Weight and Power

In the air-to-ground return link, the amplified output from the 10 array elements are frequency division multiplexed (FDM) for return to the ground station. Each channel requires approximately 100-MHz RF bandwidth (BW ≈ 1.5 x PN chip rate). If we conservatively include 50-MHz guard band between each channel, a total RF bandwidth of approximately 1500 MHz is required.

Two alternative approaches were evaluated for this air-to-ground link, namely hardwire versus radiating links. For the hardwire link, three possible operating frequency bands were considered as summarized in Figure 13. Band 2 was selected as a best compromise between bandwidth ratio and input power required. Within this band, the channelizing filters would be reasonably similar in construction complexity and performance. In addition, the maximum channel RF power for this band can easily be met by available solid-state amplifiers. A single wideband amplifier could not cope with the power frequency slope, nor produce a suitably low intermodulation product level when handling 10 channels simultaneously. The band I filter would have widely varying characteristics, while the RF power required for band 3 operation is unattractively high.

	BAND 1	BAND 2	BAND 3
FREQUENCY RANGE, MHz	100 - 1600	500 - 2000	1000 - 2500
BANDWIDTH RATIO	16:1	4:1	2.5:1
Δ RANGE dB	15 - 65	30 - 80	50 - 100
RF INPUT PWR, dBm	-50 TO +0	-35 TO +15	-15 TO +35
CHANNEL RF PWR, dBm	-60 TO -10	-45 TO +5	-25 TO +25

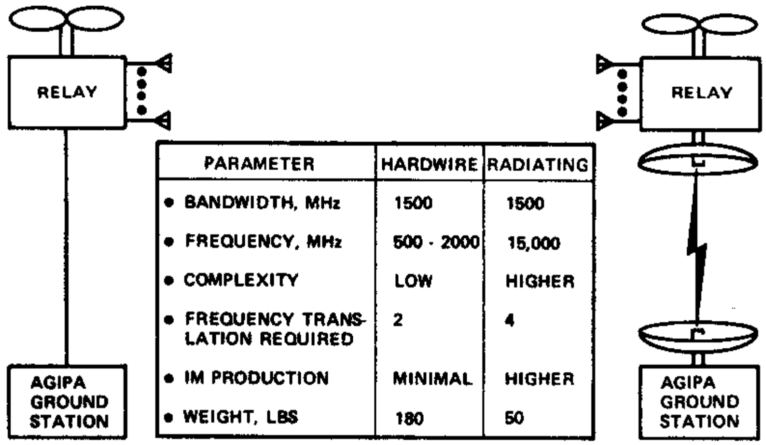
Figure 13. Performance of Hardwire Links Versus Operating Frequency

Consideration for a radiating air-to-ground link begins with the 1500-MHz bandwidth requirements. Direct use of the 500 to 2000 MHz band is technically feasible but impractical for a radiating link due to spectrum pollution and ease of interception.

A more reasonable approach to implement a radiating link is to use a 1500-MHz band located in the K_u-band region, say about 15 GHz. The 10-percent bandwidth can be handled with highly directional antennas andrepresents reasonably efficient spectrum utilization. The available antenna gain (30 dB for a 1-ft dish), would produce a net path loss of 47 dB. The receiver performance would be reduced somewhat (NF = 15 dB) and the per channel transmitter power would be about -20 dBm (-10 dBm total). This level could be provided directly from the output of individual channel solid-state upconverters using a passive multiplexing filter network to drive the common antenna. However, the multiplex requirements would be stringent and a multiple frequency LO source at K_u-band would be required.

A more promising approach would be to use a 4-ft antenna on the ground to reduce the total transmitter power by 10 dB to about -20 dBm (-30 dBm per channel). This level could be obtained by linearly amplifying the output of a single K_u-band upconverter which would operate on a 1500-MHz wide multiplexed signal centered at 3 GHz. The filter requirements would be softened and the multiple frequency source would now be at a much lower frequency, thereby being more efficiently realized.

In summary, for the short path (1000 ft) and wide bandwidth (1500 MHz) of this application, a hardwire data link provides a simpler, lower cost solution than does the alternative radiating link operating at Ku-band. The relative merits of the two approaches are given in Figure 14. Clearly, the only advantage to the radiating link is the reduction in cable weight from an estimated 180 lb and down to 50 lb.



PARAMETER	HARDWIRE	RADIATING
• BANDWIDTH, MHz	1500	1500
• FREQUENCY, MHz	500 - 2000	15,000
• COMPLEXITY	LOW	HIGHER
• FREQUENCY TRANSLATION REQUIRED	2	4
• IM PRODUCTION	MINIMAL	HIGHER
• WEIGHT, LBS	180	50

Figure 14. Hardwire Versus Radiating Link

At the ground, the inverse process is performed as shown in Figure 15. The signals from "n" array elements which were multiplexed for transmission to the ground are now demultiplexed into "n" separate channels. Since each element may contain code division multiple access (CDMA) signals for "m" number of RPV users, the outputs from the demultiplexer are divided into "m ways". For each "m" user, a separate adaptive processor is employed to provide a customized beam that nulls his particular jammers and optimizes his particular S/(J+N), using the unique PN code to recognize and separate the desired user signal. A common computer network has been assumed for the "m" number of RPV users.

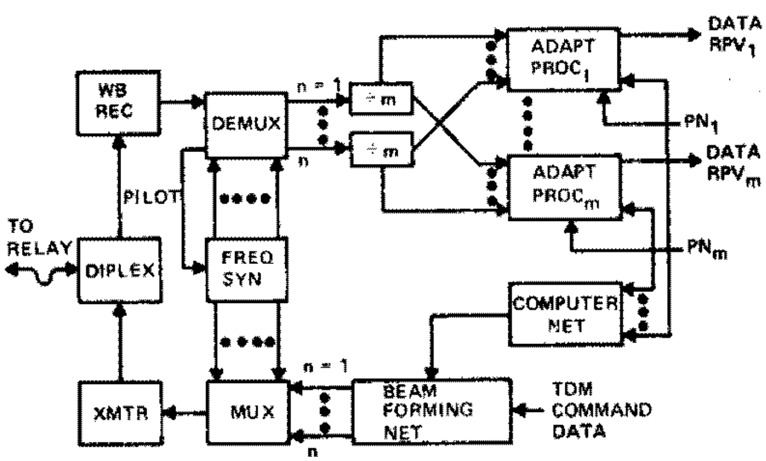


Figure 15. AGIPA Ground Processor Design

A typical AGIPA adaptive processor is shown in Figure 16 which employs an adaptive algorithm that optimizes the S/(J+N) on the basis of knowing the desired signal waveform. In the approach presented herein, a PN code is used to uniquely define each multiple access RPV signal waveform. This knowledge is used to separate the desired user signal from other unwanted interference signals (jammers as well as other users) for the sum output as well as for each received channel. The resultant desired and interference signals from the sum channel are cross correlated with the resultant desired and interference signals from the individual channels to provide the steering information necessary to compute the amplitude and phase adjustments required in each channel in order to place the jammers in pattern nulls while simultaneously optimizing the output S/(J+N). However, the process to achieve the optimum solution is an iterative process and cannot be achieved in a single step. Therefore, a computer is employed to calculate the desired step size and direction based on the correlator outputs as well as measured signal ($|V_s|^2$) and interference ($|V_i|^2$) power levels. This optimization process is referred to as plunge routine, convergence or accelerated convergence processes. The iterative process is shown in Figure 17 for a two-dimensional case. The dark line superimposed on the family of concentric error ellipses shows the steps (size and direction) necessary to achieve the optimum S/(J+N) solution in the center. The rectangular graph (dB versus number of steps) shows the resultant performance of the desired signal (S) in the presence of two jammers (J1 and J2) as a function of each iterative convergence process. In this computer-simulated example, it is seen that the optimum signal-to-interference ratio (SIR) has been achieved in approximately 10 steps, and the jammers have been effectively suppressed by approximately 50 dB. This optimization process can be completed in a few milliseconds.

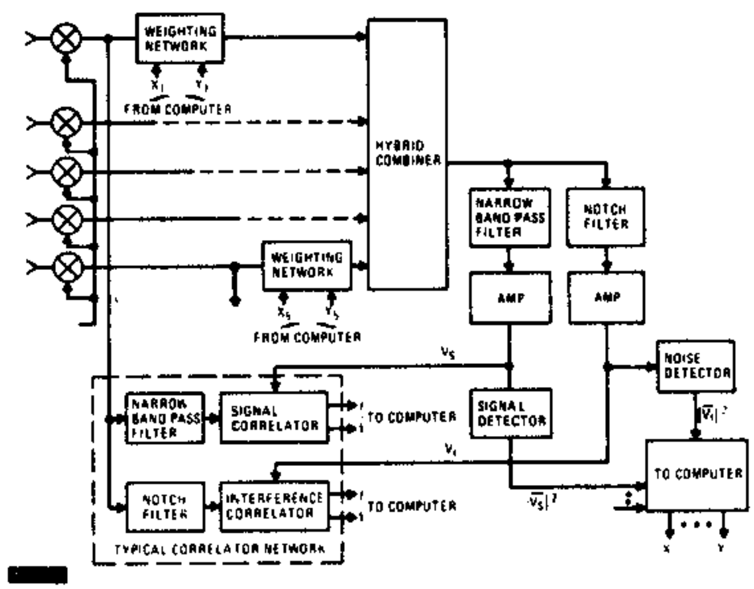


Figure 16. AGIPA's Adaptive Processor

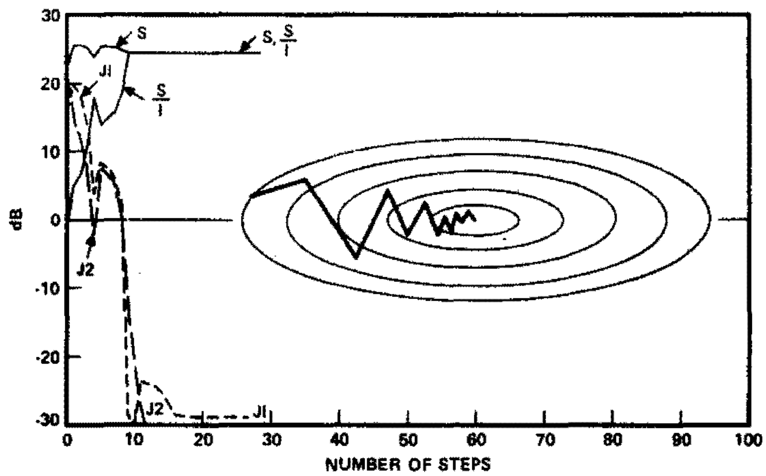


Figure 17. Accelerated Convergence Process

Computer simulations have been used extensively to evaluate the antijam performances of adaptive arrays using various signal environments as typically shown in the three-dimensional antenna contour plot of Figure 18. The relative contour levels with respect to the peak of the beam pointed on boresight is shown above the plot. The computer run shows the effectiveness of the adaptive algorithm to locate the desired signal “ D ” in the peak of the beam while placing the five jammers “ J ” in pattern null to optimize the S/(J+N).

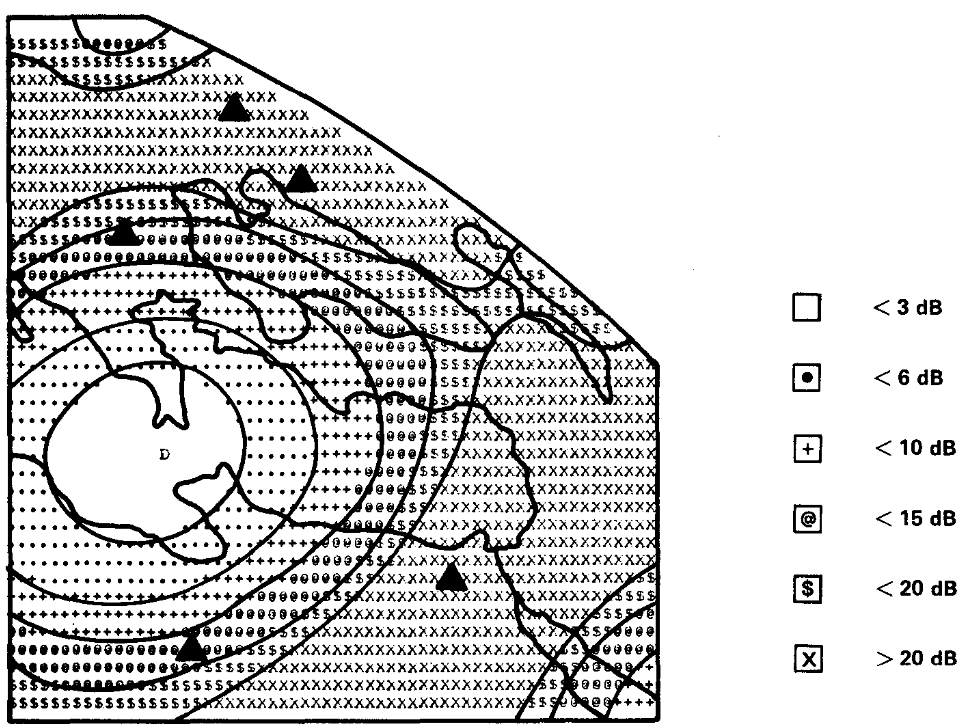


Figure 18. Typical Computer Simulation

AIL has to date fabricated several multibeam adaptive arrays using this AGIPA concept, two for NASA and one for the Navy. A typical 32-element array designed for NASA's MRS S-band multiple access link is shown in Figure 19. This system used a hardwire link back to the adaptive processors. Typical results are given in Figure 20 showing the adaptive antijam performance in a single jammer and two jammer environment. It is interesting to note how the beam is steered to spatially null the jammer, but also how the beam shape is changed to null the jammers while keeping the peak of the beam on the desired signals. These tests have shown jammers to be spatially suppressed in excess of 40 dB, limited only by the noise level of the demonstration system.

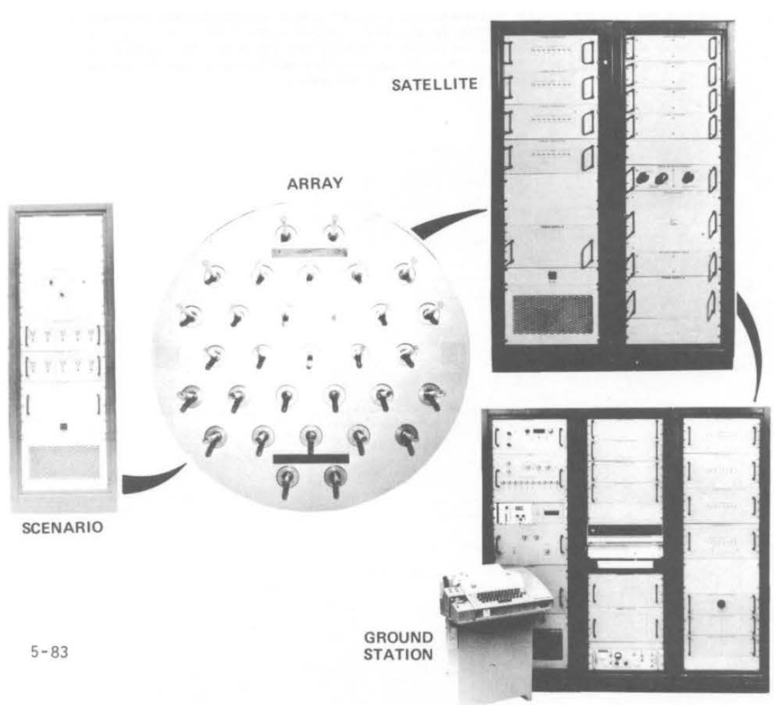


Figure 19. Demonstration Setup

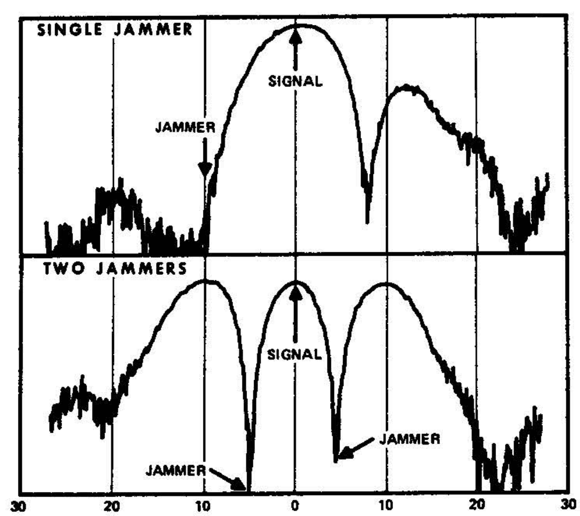


Figure 20. Antijam Performance