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FOLIAGE PENETRATION RADAR: HISTORY AND DEVELOPED TECHNOLOGY

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This report documents the USA Land Warfare Laboratory's Foliage Penetration Radar program including the historical aspects, the technology developed and four resulting systems that saw combat in Southeast Asia. Application of the FOPEN technology to intrusion detection systems, airborne FOPEN radars, swimmer detection systems, and a radar capable of detecting low flying aircraft concealed by foliage are presented.

A review of signal processing techniques and tradeoffs for ground surveillance

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radars and a summary of propagation research concludes the report.

SUMMARY

The report documents the US Army Land Warfare Laboratory's Foliage Penetration Radar Program from its start in May 1966 to June 1974. The history of these developments, which have become known as the FOPEN Technology, is traced with important decisions that spun off such systems as the Automatic Alarm for the PPS-4 and -5 Radar documented.

The program began after two University of Rochester students (one the author) submitted a proposal entitled "ORCRIST, An Anti-Guerilla Detection System" to the Army in October 1965. The proposal presented the results of field tests performed (by the authors) with a 143 MHz CW Radar in which detections were made of personnel concealed by foliage.

Continuing the program at LWL, a noncoherent pulsed system was fabricated at 140 MHz and tested in various foliated areas. Signal processing investigations resulted first in an adaptive signal processor (later applied to the PPS-4 and -5 radar) and later resulted in conversion to a coherent system. Six man-portable and two base station systems were fabricated and evaluated in Vietnam. These evaluations resulted in a statement of need for this type of radar and led to development of the second generation, Multipurpose FOPEN (M-FOPEN) Radar. Concurrent investigations included different forms of signal processing and transmitted modulation and were applied to the M-FOPEN.

In March and April 1973 the 25th Infantry Division conducted a User Evaluation of the M-FOPEN and found that the shortcomings encountered with the ORCRIST systems had been corrected and that its performance was significantly more reliable than the AN/PPS-5 radar. The M-FOPEN was used in an exercise in a town and demonstrated a capability to penetrate buildings and power lines and automatically detect personnel and vehicles. In addition, the M-FOPEN demonstrated a capability to detect aircraft flying nap-of-the-earth.

From this program have emerged many new applications for this technology. Section V describes each of these applications in detail and presents the significant test results. The significant achievements of this program are reviewed in Section VI along with a critical reappraisal of two systems, and their failure to make it into the system.

PREFACE

Current equipment that employs FOPEN technology owes much to the evolutionary process which marked its development. An idea conceived at a university by two students in September 1964 started an LWL program in early 1966 which resulted in the fielding of three new types of ground surveillance radars, an automatic signal processor for the PPS-4 and PPS-5, and established the feasibility for an airborne foliage penetration radar, building surveillance and swimmer detection radars as well as other systems.

Persons who made significant contributions to this program are:

Mr. G. M. Foster, fellow student (1965), co-inventor, ORCRIST, who materially assisted with both the ground based and airborne FOPEN radars.

Mr. Jack Wenig, Chief, Applied Physics Branch, USALWL, whose timely support for unconventional concepts and flexible guidance and supervision, contributed greatly to the success of this program.

Dr. Andrew Longacre, Member, Army Scientific Advisory Panel, whose timely trip to Panama in 1967 and subsequent support enabled the program to continue.

Mr. James Rodems, Chief, Defense System Laboratory, Syracuse University Research Center (SURC), led the team which fabricated the original manportable and base station ORCRIST radars and later the airborne FOPEN system. Other members of this team include Mr. William Emeny, SURC Project Engineer for both the ground and airborne systems as well as the Vietnam tech rep for the ORCRIST manpack systems, Mr. Scott Bowen, who served as Vietnam tech rep for the base station FOPEN and worked on the airborne FOPEN radars, and Mr. Paul Harris who contributed advances in transmitter and signal processing.

Mr. Aaron Galvin, Vice President, Aerospace Research, Inc., devised the adaptive processor for the early non-coherent FOPEN radar (this later became the automatic alarm for the PPS-4 and PPS-5), and designed and fabricated the first hardened balanced adaptive signal processors, the first target identification processor, and the phase monopulse radar.

Mr. John Dunlavy, President, Antenna Research Associates, provided VHF antennas which always exceeded our performance expectations.

Dr. Theodor Tamir, Consultant to LWL, Polytechnic Institute of New York, provided invaluable assistance by developing a model against which our radar data could be compared and assisted with many illuminating discussions of propagation methods. He prepared the review of propagation research included as Appendix D and performed the calculation presented in Appendix E on the detection of helicopters in nap-of-the-earth flight.

Mr. Cary Weigel, Task Officer, LWL, did much valuable work with the FOPEN radars, led the development of the L-band PPS-14 and ultrasonic intrusion alarms, and provided the basis for the vehicle classification data discussed herein.

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I. INTRODUCTION

In creating the advances that have led to the current state of the art in foliage penetration radar technology, we have had to bargain with the laws of nature and to choose design parameters in such a manner that a given goal is met by trading among a series of characteristics, for example antenna size vs. lower transmitted frequency. Many old concepts have fallen by the wayside during this program not because we have uncovered any new truths but because we have taken data from a new perspective and that has shown assumptions based on previous data to be incorrect. The system to be discussed fits into a well-ordered evolutionary process which was accelerated because of the needs of Vietnam, and which was necessary to make up for the 20-year lag in ground surveillance radar development which preceded the present decade.

The purpose of this paper is to review the development of FOLIAGE PENETRATION (FOPEN) hardware and technology, with emphasis on specific critical experiments performed and their impact on the program. These will be somewhat general in nature, with additional data and references being contained in the appendices.

The current third generation FOPEN radar, the M-FOPEN, will be described along with the results of the user evaluation conducted in Hawaii during March and April 1973.

Section V is devoted to the nine new unique applications to radar technology developed during the course of the LWL program.

The significant achievements of this program and a critical reappraisal of the FOPEN technology conclude this paper.

II. HISTORICAL BACKGROUND OF THE LWL FOPEN RADAR PROGRAM: THE ORCRIST EXPERIMENTS

A. The Original Idea

In September of 1964, two University of Rochester students attempted to apply fundamental concepts in physics to the problem of discriminating between civilian and military targets. Attentions were focused on those techniques which might enable the detection of personnel concealed in a jungle and the identification of those carrying weapons. A chance observation of the distortion to VHF FM radio reception inside a building suggested that some sort of resonant detection technique might enable the penetration of buildings and foliage and the discrimination between armed and unarmed personnel. A calculation of the cross section of a cylinder[1] and a few measurements of the effect of a resonant dipole in the field of an FM receiving system suggested the validity of a concept for a detection system where the rifle would act as a resonant dipole. Thus began a project which has spanned nine years and from which evolved ten fundamentally new radar concepts.

B. The Concept of Color Applied to Radar

In physics, color is identified in optical phenomena with radiation at different wave lengths. In particular, color (frequency) discrimination occurs when radiation interacts with a system of atomic electrons which have certain resonant frequencies or normal modes determined by the charge of the atom and its environment. For practical radar wavelengths (i.e., $\lambda > 0.1$ cm), there are no resonances of this type, but a similar effect exists based on a different physical principle. It is possible to excite a resonance of purely electromagnetic origin if the physical size of an object is made almost equal to a wavelength, this being the classic Rayleigh curve. As an illustration, Figure 1 shows the radar cross section of a conducting sphere as a function of the radius to wavelength ratio.[2] It is suggested by this curve that one can choose a wavelength to maximize the return from the target (if the target is a sphere or other simple geometry like a dipole) and yet choose a frequency that would minimize the return from unwanted targets such as trees. Since clutter in the case of foliage may be assumed to come from a large number of objects having a random distribution of sizes and orientations, the clutter cross sections of a given region should then be a fairly smooth function of wavelength. If the resonant curve of a given target were known in advance, and if the clutter cross section was reasonably independent of frequency, it might be possible to distinguish the target from the clutter by detecting the cross section variation in the target with a multiple frequency radar. This, in effect, would add the dimension of "color" to the radar.

NOTE: Superscript numbers denote references which will be found at the end of the report.

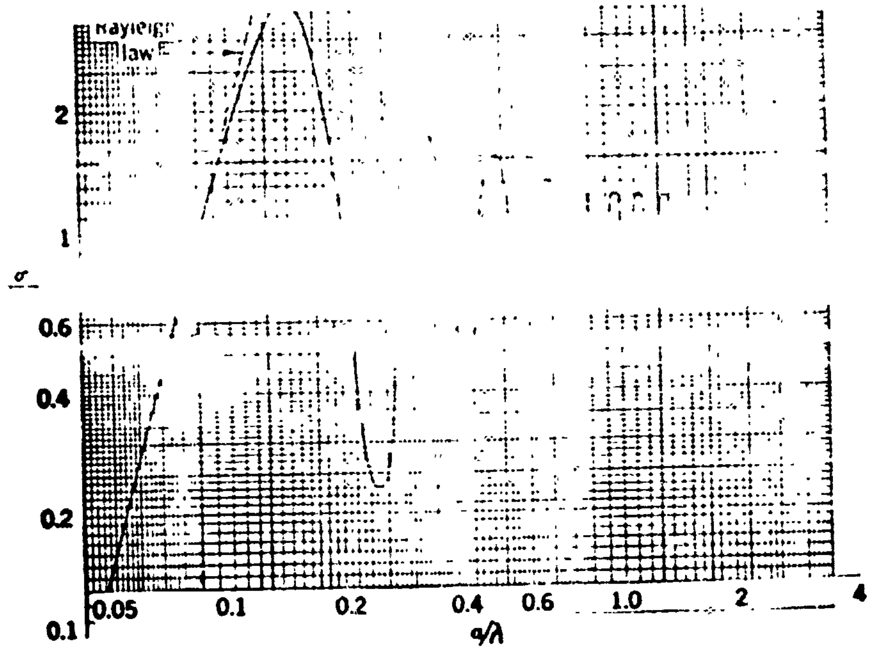


Figure 1. Back Scattering from a Metallic Sphere. In the Region Where the Line is Shown Dotted, No Calculations Have Been Made.

C. The ORCRIST Experiments

Based on the above reasoning, a simple resonant detection system was built to perform sufficient measurements to demonstrate the practicality of the theory.

The radar named ORCRIST* was a bistatic system fabricated from two military surplus transceivers. The transmitter was crystal controlled, having a 0.15 watt power output at 148 MHz and modulated with a 1,000 Hz note. The transmitting and receiving antennas were both six-element yagi arrays with a gain of 8 dB and a beamwidth of 45°. Two receivers were utilized: one, a simple RF voltmeter with a sensitivity of 1 millivolt was used for radar cross section measurements; the other was a superheterodyne receiver having a sensitivity of one microvolt.

Extensive field tests were performed from January to August 1965. Radar cross section data was recorded for vegetation, individual trees, and targets including men with and without weapons and dipoles of various lengths and aspect angles.

The following conclusions were based on these measurements:

1) The radar cross section at 140 MHz of bushes, vines, tall grass, etc., is negligible, while that of a large tree may be as much as a square meter.

2) The plane of polarization of the wave was rotated by backscatter from vegetation.

3) Cross section measurements performed from an elevated position with a dipole target in dense foliage yielded signal strengths for the dipole greater than those obtained over bare ground.

4) Cross section measurements of a free space dipole made as the length was varied confirmed that cross section fluctuations existed. These fluctuations were also observed with a man holding the dipole.

D. The ORCRIST Proposal

During September 1965, a document was prepared detailing the experiments performed and suggesting a design for an airborne foliage penetration system. On 5 October 1965, the document called "ORCRIST, An Anti-Guerrilla Detection System" [3] was presented to Mr. Deitchman, Special Assistant (Counterinsurgency),

*A glowing sword from J. R. Tolkien's "Trilogy of the Ring".

in the Office of the Defense Director of Research and Engineering. Mr. Deitchman referred the document to the Department of the Army. It was then forwarded to the Limited War Laboratory (now the Land Warfare Laboratory) (LWL) and a task established to evaluate the technique as a possible limited war system.

The fundamental concept of this proposal was the combining of three factors, which in themselves were not singular, but which together formed the basis for a unique radar system. These factors are:

1) The use of low frequency transmission for the dual purpose of penetrating foliage and for maximizing the return from a rifle barrel.

2) The use of horizontal polarization for transmission and reception.

3) The rejection of any cross-polarized returns.

In May 1966, the author was employed by LWL to continue development of the "concept" towards a militarily useful system. No restrictions were placed on the form that the final system was to have, only that it detect targets concealed by vegetation, either from the ground or the air. As will be seen, this philosophy enabled the program to proceed while establishing realistic goals along the way and retaining a capability to explore new avenues. A contract was awarded in the Fall of 1966 to the Georgia Institute of Technology to perform confirming experiments which would result in design parameters for a future system.

III. EVOLUTION OF THE FOPEN PROGRAM: PART I

A. General

It was recognized, prior to starting the LWL program in 1966, that several factors would have to be considered before the construction of a prototype radar for operational use. The most serious of these was the urgent need for data on foliage penetration, and foliage and target cross sections. The intent of the experimental program, therefore, was to perform those minimum experiments that would establish trends and establish design parameters for a simple detection system. No attempt was made at the outset to define the types of targets or ranges of detection. It was assumed that this would be a ground based system at first with the airborne application to follow, and the data collection program was slanted towards gathering data for both applications.

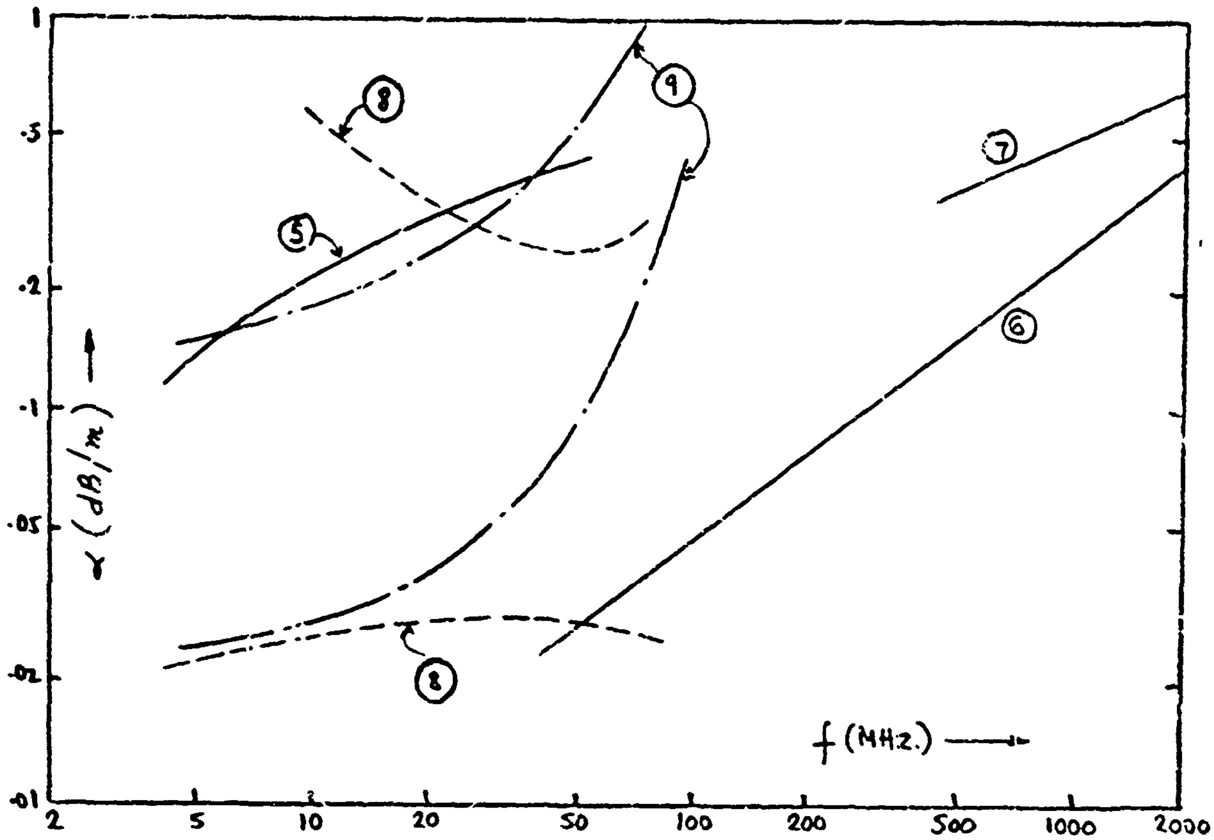
Writing this section with some degree of hindsight, however, it is obvious that if we had used all the then current information at our disposal to set the basis for the program, we would not have started. Much of the propagation data was misunderstood and would have prevented our believing that a VHF radar could actually penetrate foliage and detect targets. At that time, in early 1966, the primary source of radio wave propagation data was the SEACORE Project, sponsored by ARPA for communication purposes. Before this project was initiated, it had always been assumed that energy radiated by a transmitter antenna could reach an observation point in the forest only by means of a straight "line-of-sight" path. The attenuations previously reported at 100 MHz ranged from 0.02 to 1.0 dB/m depending on the source, type of foliage and method of measurement. (See Figure 2 for reported values of attenuation in dB/m versus frequency, with references.)

As a result, the detection of personnel through foliage by radar was deemed impossible over any but very short distances. However, measurements carried out by Jansky and Bailey under the SEACORE Project showed that the actual propagation mechanism was not along a line-of-sight path but that the energy travelled by skipping across the tree tops. This seemed to indicate that penetration of foliage in the frequency range of 100 MHz was possible, and provided some confirmation of the results obtained in the original ORCRIST experiments.

In addition to the direct effect of frequency on attenuation through foliage, the choice of frequency has significant bearing on the target cross section, doppler spectra of the target (and clutter), and requirements for antenna size and height above ground. The remainder of this section will discuss the results of the experiments which led first to the fabrication of a non-coherent VHF pulse doppler radar and then to the fabrication and field development of a fully coherent system.

B. Basic Experiments

The contract was begun in September 1966 to perform those experiments necessary to build a simple man-portable system. These were designed to provide data from which a model predicting target-to-clutter ratio for a radar system could be derived. The tests were divided into three broad categories:



5. S. Krevsky, "HF and VHF Radio Wave Attenuation Through Jungle and Woods", IEEE Trans on Atnennas and Propagation, Vol. AP-11, pp. 506-507; Jul 63.

6. J. A. Saxton and J. A. Lane, "VHF and UHF Reception - Effects of Trees and other Obstacles", Wireless World, vol. 61, pp. 229-232; May 1955.

7. L. G. Sturgill and Staff, "Tropical Propagation Research", Jansky and Bailey Engineering Dept., Atlantic Research Corp., Alexandria, VA, Final Report, Vol. I, June 1966.

8. H. W. Parker and G. H. Hagn, "Feasibility Study of the Use of an Open-Wire Transmission Line, Capacitors and Cavities to Measure Electrical Properties of Vegetation", Stanford Research Inst, Special Tech Report 13; August 1966.

9. H. W. Parker and W. Makarabniromya, "Electric Constants Measured in Vegetation and in Earth at Five Sites in Thailand", Stanford Research Inst, Special Tech Report 43; December 1967.

Fig. 2. Measured values for the foliage attenuation α as a function of frequency. Numbers inside circles indicate references from which curves were extracted; when two curves appear for the same reference, they refer to maximum and minimum values measured.

Clutter and target return measurements, propagation measurements and fluctuation spectra for targets and clutter.

A pulsed, non-coherent 140 MHz radar was fabricated for the field tests. The use of pulsed transmission enabled discrimination for close and distant targets on the basis of propagation time and reduction of the amount of clutter competing with the target in the radar cell. A non-coherent design was chosen because of its simplicity. In addition, a C.W. system was fabricated to provide one way path loss measurement at 140, 500, and 1000 MHz.

1) Target and Clutter Measurements - Measurements of target and clutter (foliage) backscatter were made using the 140 MHz non-coherent radars and two linearly polarized log periodic antennas. The radar antennas were placed both in the foliage and at the edge of the foliage looking in. Three important observations were made.[3] First, the backscattered energy from the foliage with the antenna in or near the trees followed no simple rule which would allow polarization discrimination between foliage and static targets. Second, the backscatter from foliage appeared to be minimized when using horizontally polarized transmission, while at the same time use of horizontal transmission gave lower one-way path losses and reduced the doppler spectra of the clutter. Third, the target of interest, a man with weapon, did not depolarize the incident energy (for either polarization). The static radar cross section of a fixed rifle was too complex to detect with simple equipment. The cross section of the weapon varied from 6 dB below a square meter to 3 dB above depending on orientation, aspect angle and polarization. The cross section of a man carrying a weapon in foliage was 1/2 square meter under most conditions. Strangely, larger target cross sections were observed in denser foliage.

2) Early Propagation Experiments

a) One-Way Path Loss - Propagation through foliage was measured with the C.W. field strength equipment at 140, 500, and 1000 MHz to determine the one-way path loss between the radar and the target, at a range R, which is assumed to have a cross section σ and an effective height of 1 meter above the ground in foliage. If the two points were in free space, the ratio between received power Pr and transmitted power Pt would be given by:[3]

$$Pr/Pt = \frac{G_1 \, G_2 \, \sigma^2}{(4\pi)^2 R^2}$$

where G_1, G_2 respectively the gains of the radar antenna and a probe antenna when the antennas are located in foliage. The above equation must be multiplied by a factor which represents the additional losses due to the effect of the ground and attenuation of the medium (foliage). It was anticipated that the one-way path loss would have a $1/R^4$ dependence due to the ground effect plus additional losses due to foliage. Although this was true under some circumstances, we were able to create a situation in which the losses were much less than anticipated. This occurred when the transmitting antenna was located near or above the tops of the trees, even in fairly dense foliage with trees of at least 30 feet in height, and the receiving probe at a height of 1 meter.

In Figure 3 the loss between the transmitter output and field strength meter input is plotted versus log range in meters. The solid line with a slope of -20 dB per decade of range is the loss that would have been measured in free space with antennas of known gain. Clearly, departures from this line are due primarily to the effects of ground and foliage. The dashed line with a slope of -40 dB per decade of range represents the predicted loss by the plane conducting earth interference model of propagation for the antenna and probe heights used.

Figure 3 shows a greater loss with range observed with a 2-meter high transmitter antenna than the 13-meter high antenna. Figure 4 shows, for the 13-meter transmitter height, a fixed, 20 dB loss over and above free space propagation from the measured one day path loss. We called this 20 dB "loss defect"; it was the first confirmation we had that lower loss propagation modes existed in foliage for certain antenna heights (i.e. 13 meters) and that these might be used to advantage in a Foliage Penetration System.

b) Field Distribution in Foliage - The distribution of the radar field strength near the ground is of great importance to the detection of personnel concealed by vegetation. Variations of the field strength both in range and height above the ground affect both the absolute return from the target and its time signature. Two primary observations were made. The first showed that, if a target walked through the radar range gate, when the gate was set in foliage, the target amplitude return was a reproduction of the transmitted wavelength; i.e., at 140 MHz (λ = 2 meters) a radial moving target went through a maximum and minimum every two meters.

The second observation demonstrated the strong height dependence of a target at about ground and one meter above it. The difference between a walking man at 1 meter height versus a crawling man at 0.1 meter height was a 28 dB reduction in received power. This ruled out the detection of crawling targets at 140 MHz except at close ranges or at high angles of illumination. As a result, additional experiments were conducted with CW equipment at frequencies of 500 and 1000 MHz to determine the losses at these frequencies and determine the variation in field strength above the ground for both frequencies. For an antenna located at or below the tree tops, the losses were too great for the long range detection of crawling men at either 500 or 1000 MHz. However, at 1000 MHz and low antenna heights, one-way path losses were not prohibitive over short distances (less than 100 meters) for crawling man detection.

3) Doppler Spectral Measurements

Motion of the target was observed with the non-coherent measurement radar during cross section tests even through one to two hundred meters of foliage. Therefore, it was decided to concentrate the remainder of the effort on building a simple doppler man-portable foliage penetration radar breadboard. (NOTE: The results of these experiments did not establish that a system to detect static targets was not feasible; rather, a static

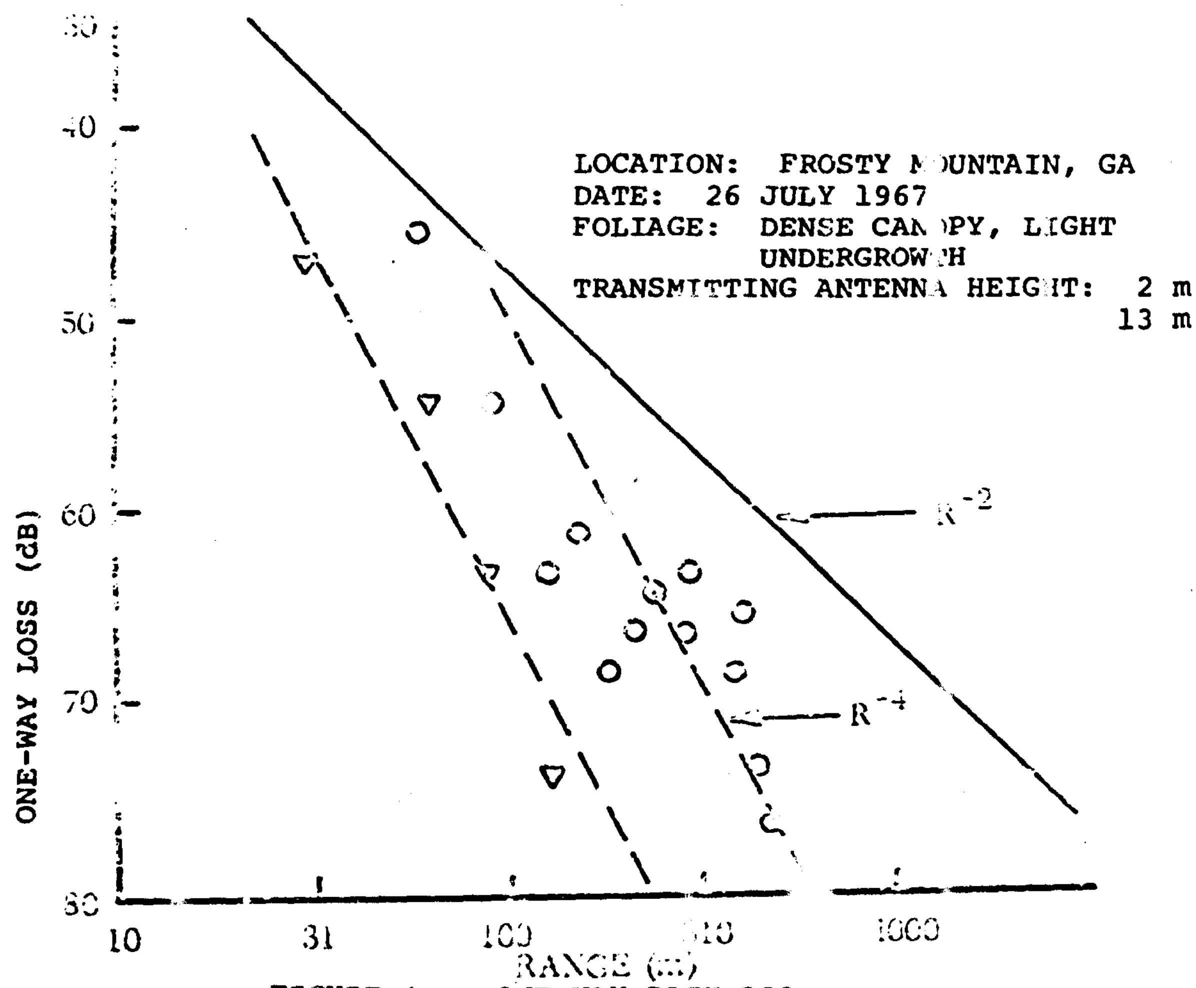


FIGURE 3 . ONE-WAY PATH LOSS

The next graphs show the difference between the esperi-mental data and the $1/R^2$ curve.

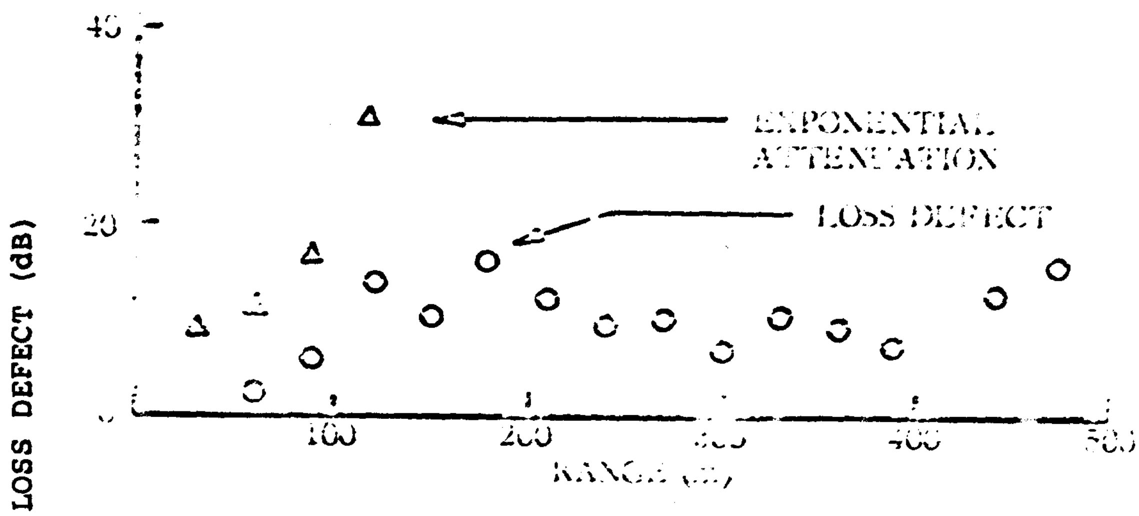


FIGURE 4 . PROPAGATION LOSS FACTOR

detection system could not be built without further investigation whereas a simple doppler system could.)

Although the motion of a target through the range cell could be readily detected by displaying the output of the sample and hold circuit on a chart recorder, additional data was necessary to convert the low doppler frequencies (1 to 5 Hz at 140 MHz for a moving man) to the audio band for aural detection.

Approximately 500 non-coherent doppler signatures were recorded[6] for spectral analysis by Honeywell, Inc.[4] of both targets and targets plus clutter. A wide variety of target configurations, ranges and foliage conditions were used. A digital comb filter (DCF) was used to analyze the data, which consisted of recordings of the sample and hold outputs. The distinguishing characteristics of the target were determined to be its frequency, amplitude, and time in the range cell.[5] Figures 5 and 6 indicate the general type

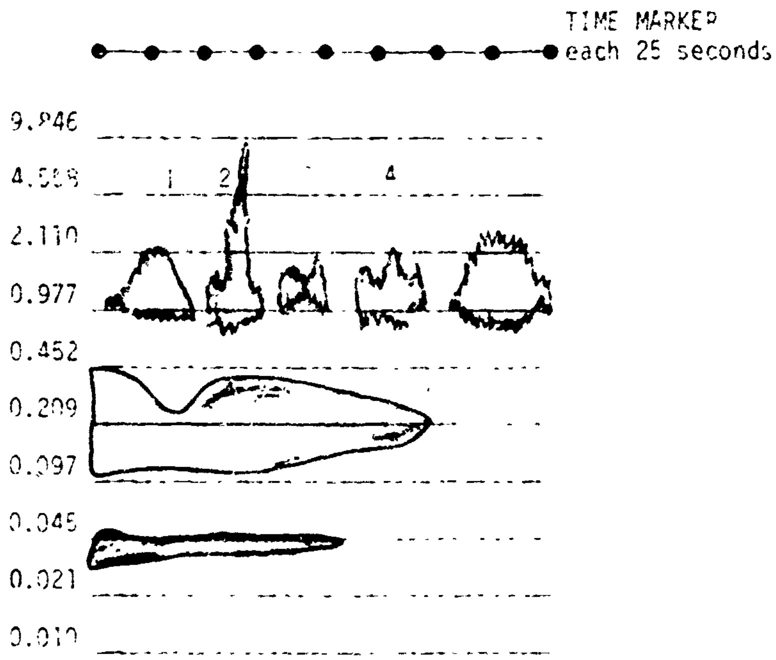


Figure 5. Features of the Digital Comb Filter Output

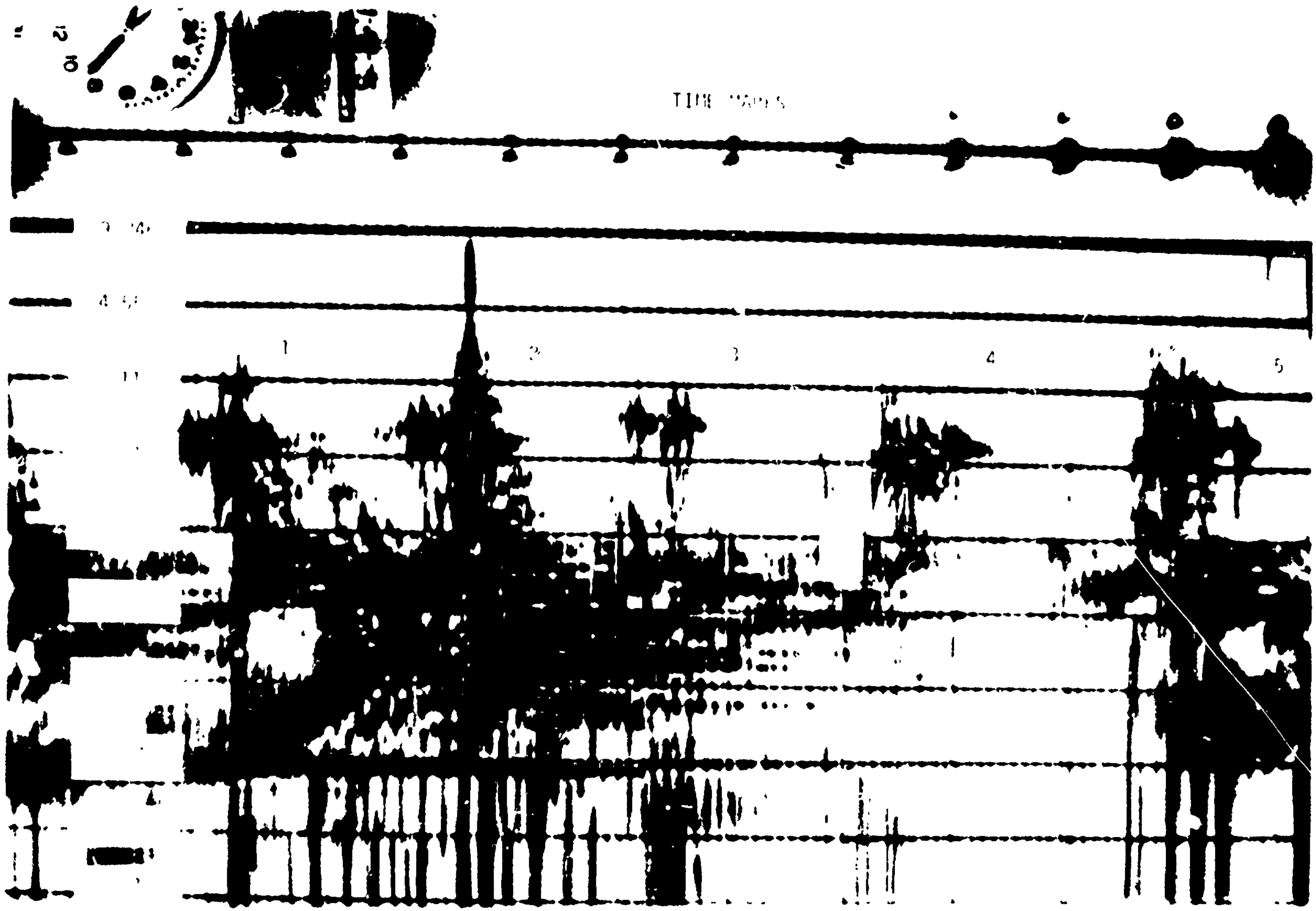


Figure 6. Digital Comb Filter Output

of features observed. The dots immediately below the top line indicate real-time increments of 25 seconds. The identified features in the DCF output are listed below:

a) Features 1 to 5 are target signatures for five separate target runs. These appear to be centered slightly above the 0.977 Hz line.

b) The background clutter produces a wide variety of features occurring in the lower frequencies, primarily below the 0.452 line. The two low frequency "lines" indicated as features 6, 7 are one type of persistent clutter characteristic related to the tree sway period.

A major feature of the DCF output display is the array of "exponential" triangles shown in Figure 6. These are caused by transient build-up and decay as new frequencies are put to the filter bank. The leading edge of a "transient envelope" defines the onset of the transient and the tail indicates the frequency. The "width", "duration", and number of the transient envelopes are useful features for comparing target responses.

The clutter return for a given cell fluctuates over a wide range in high winds with a standard deviation of the order of 5 dB. Even in low winds, the standard deviation is seldom less than 1 dB over a period of several seconds. The amplitudes of target signature fluctuations are typically smaller than these levels so that the target is distinguished from the clutter fluctuations by the rate of these fluctuations. The moving target, in general, produced a smaller amplitude but higher frequency fluctuation than that inherent in the clutter.

Regardless of the exact spectral shape for the clutter, the spectrum falls off rapidly with increasing frequency, so that a high-pass filter with correctly chosen cut-off frequency and cut-off shape will reject a major portion of the clutter fluctuation and pass most of the doppler frequencies associated with walking men. The choice of the filter cut-off frequency and slope are affected by the details of the clutter spectrum.

In summary, the magnitude of the fluctuation of clutter is dependent on wind speed and the limitation may be as small as a couple of decibels for low wind speeds to as high as about 10 dB with a spread associated with the Rayleigh distribution. The spectrum of clutter fluctuation at 140 MHz in <u>low winds</u> is such that most of the energy lies below 0.4 Hz, so that high-pass filters can be used to distinguish the return of moving men from the effects of wind on the clutter under those conditions.

<u>C. The Prototype Radar</u>

1) <u>Description</u> - The experiments described formed the basis for choices of radar parameters for the prototype system. These choices were influenced by the following trends:

a) <u>Frequency</u>: The choice of 140 MHz was made to give the radar maximum range through foliage based on two limitations: The antenna would never be higher than the tops of the trees and the target was an upright man.

b) Polarization: Horizontal transmission and reception was chosen to minimize the backscatter from the clutter, reduce the foliage doppler clutter spectrum, and enhance the return from a man carrying a weapon (horizontal).

Since these choices were similar to those used in the non-coherent 140 MHz breadboard radar, it was repackaged into a battery operated system with the following parameters:

a)	Frequency	140 MHz
b)	Pulse length	0.1 microsecond
c)	Transmitter power	50 watts peak
d)	PRF	15 KHz
e)	Azimuth beamwidth	45 degrees
f)	Antenna gain	9 dB
g)	Displays	audio (frequency translated doppler), chart recorder (sample and hold output), threshold cycle counter

A block diagram of this system is shown in Figure 7, and a photograph of its components are shown in Figure 8. With this system, detections were made at ranges from 100 to 800 meters depending primarily on antenna height, terrain shape, and foliage density. Specific instances where detections were studied will be discussed later. In general, it was observed that when the wind speed over the foliage was low (less than about 5 mph), the minimum detectable target-to-clutter ratio was large enough to allow reliable detection of upright walking men in all types of foliage out to ranges of 300 meters, and, when the terrain shape was sufficiently concave, or antenna located above the canopy, out to 800 meters. At higher wind speeds the clutter fluctuations increased in amplitude so that a simple high pass filter no longer allowed detection of walking men with the system. Targets were detected but the clutter doppler spectra was confused with target motion. This prompted investigation into self-adaptive doppler filters.

2) Significant Field Tests - The radar was tested at Eglin AFB during the summer and fall of 1967, and Panama in the spring of 1968. Although targets were readily detected through foliage beyond 300 meters under periods of low wind, aural detections were impossible when the wind speeds picked up.

We drew many conclusions from the trends established during these tests. Although some of them have been shown later to be incorrect they became the basis for the system fabricated for the Vietnam tests. These conclusions are presented below. [6,7]

When a horizontally polarized VHF radar is operated with the antenna immersed in jungle vegetation below the canopy, the range of the system is limited by the attenuation of the foliage and by near field effects of the moving

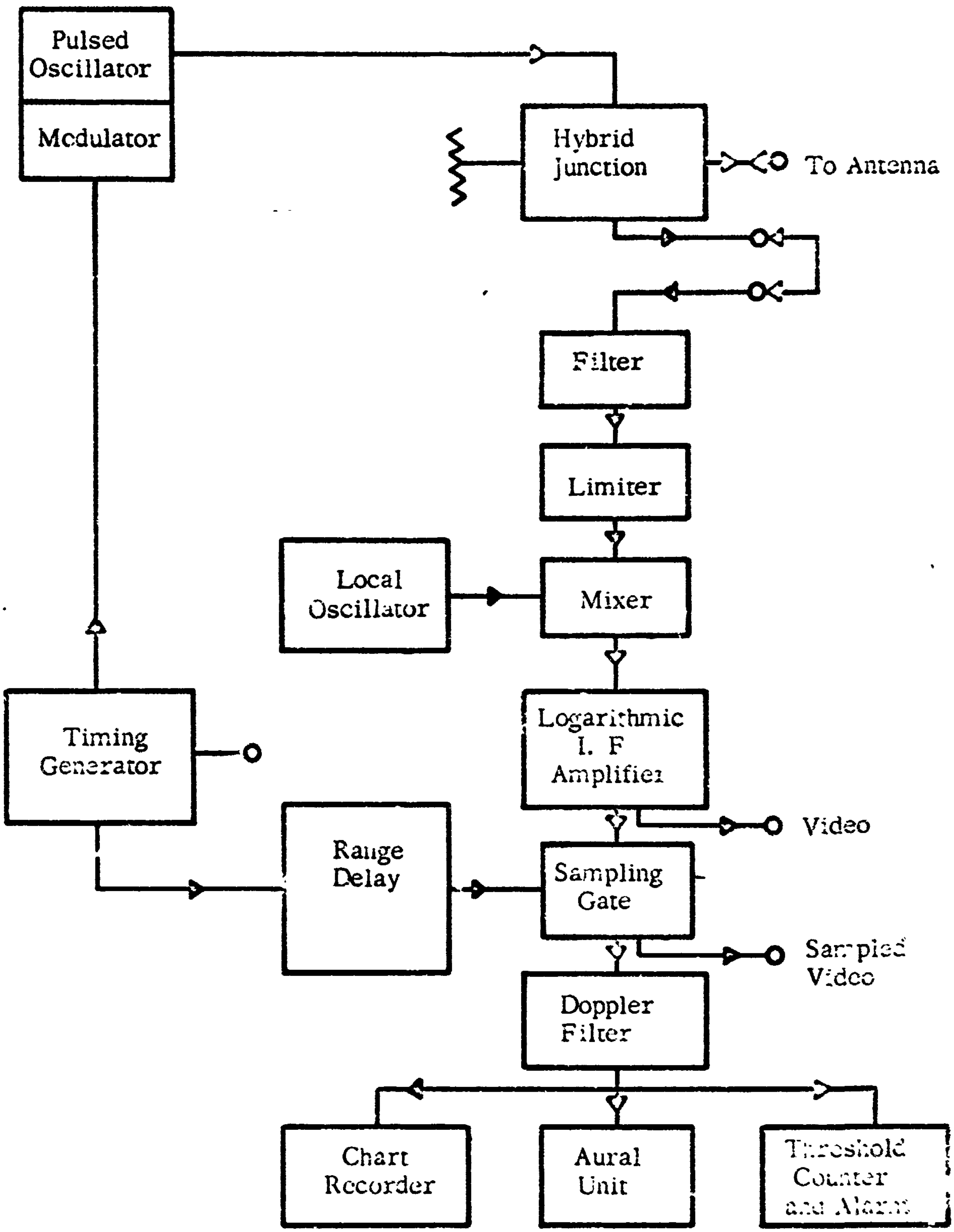


Figure 7. Block Diagram of Breadboard Noncoherent Radar

Figure 8. Man-Portable Breadboard Radar

foliage on the antenna. Raising the height of the antenna so that it is near or slightly above the canopy level, substantially increased the range of the system. This appears to be a result of more efficient launching of the lateral wave mode of propagation, and less path length through foliage.

Wind-induced clutter motion causes signals which can mask targets. Measurements of the characteristics of the wind returns have showed that, although they are of larger amplitude, they occur at a lower frequency than the target returns.

When the horizontally polarized VHF radar was operated over tall grass (10 to 12 feet), propagation conditions were more favorable than in a forest. This is possible because of dielectric nature of the grass, reflection coefficient of the ground, and the fact that target-to-clutter ratios were higher due to a lack of tree trunks. Range twice that in jungle were possible through tall grass.

The effect of wind blowing through the grass was not a problem. Whereas wind speeds in excess of 10-15 mph in dense vegetation caused target marking and false detections with a simple bandpass filter used to filter the aural data, no false alarms were obtained with wind speeds in excess of 15 mph in tall grass. This is due to the small size of the scatterers (maximum diameter of the grass was approximately 1-1/2 inches) with respect to a wavelength (6 feet).

When the system was operated from the 50 foot tower over 100 meters of bare ground into vegetation, detections were made through 300 meters to 350 meters of vegetation.

The use of a 140 MHz radar for a Long Range Fixed Installation system appeared practical, with a narrow beam antenna system, and sufficient antenna height.

Experience with the breadboard system demonstrated the need for a small, short range system to detect crawling targets. Preliminary path loss investigations indicated that short range detection through foliage would be possible with a 1000 MHz system and that use of higher frequencies would reduce the losses due to ground lobing and enable lower antenna heights to be used. Thus a parallel program described in Section VII was begun to fabricate a small 1000 MHz prototype.

D. With a Little Help from our Friends

The future of the LWL FOPEN program was to have been determined by the outcome of the Panama tests. There were, at this time, two FOPEN radar programs, the other being the larger Camp Sentinel system under development by MIT Lincoln Labs (later pursued by Harry Diamond Laboratories.)

On 15 February 1968, prior to the Panama tests, the Army Scientific Advisory Panel Ad Hoc Group on Foliage Penetration Radar Systems was briefed on the LWL approach. At this meeting Dr. Andrew Longacre, Chairman of the committee shared the enthusiasm for a simple man-portable foliage penetration radar and he was invited to observe the Panama tests.

During the third week of field tests in Panama, Dr. Longacre and James Rodems, Director of Defense Systems Laboratories, Syracuse University Research Corporation, visited the jungle test site and observed a series of detection experiments. Dr. Longacre's conclusions, excerpted from the Panel Report[8], were as follows:

a) The LWL Foliage Penetration equipment did have quite reliable detection of moving men out to 600 plus feet through dense rain forest.

b) There was evidence of tropical field deterioration of the equipment and an insufficiency of test gear to readjust the equipment. The equipment did not seem to be in a field-worthy configuration. Also, it seemed to need better tropicalization.

c) Using one or another of the four data outputs (A-scope, chart recorder, modulated aural tone, and a light) there seemed to be a 75% probability of detection and a 50% probability of a false alarm.

With these conclusions and the recommendations of the ASAP Panel, Emergency Funds were made available to fabricate six engineering prototypes correcting as many of the deficiencies as possible while expediting delivery to the field (Vietnam).

E. The Decision to Go Coherent

In May 1968, a contract was awarded to Syracuse University Research Corporation to build six man-portable systems with two base station conversion kits consisting of a power amplifier and 12° beamwidth antenna. October 1968 found us back in Panama with a non-coherent prototype system. The objective of this test was to return to the same test areas of the previous test, and determine what improvement we had made in the equipment. It should be pointed out that the electronics boxes, antennas, and base station modules had been fabricated and that this was only a check of the electonics prior to fabricating the circuits in hardened form. In keeping with our original assumption that the radar should not interfere with a man's other senses. Mr. Aaron Galvin of Aerospace Research Corporation provided an adaptive automated alarm for use with the non-coherent system. This device sampled the amount of clutter energy in the doppler band (See Appendix A), and adjusted the low frequency response of the doppler detection band for minimum false alarms and maximum detection sensitivity. The October 1968 Panama field tests were disappointing to us, even though the automatic alarm enabled reliable detections with the non-coherent VHF system. It was obvious that certain properties of the environment interacted with the principles of operation of the non-coherent radar to limit its effectiveness.

Briefly these were:[9]

a) Proximity effects of moving trees near the antenna caused amplitude modulation of the transmitted signal due to change in antenna parameters. To a non-coherent system this modulation appeared as clutter causing the adaptive processor to desensitize.

b) Wind blown foliage in the radar's range cell also caused the adaptive processor to desensitize.

c) Reflection from close-in trees caused saturation in the receiving system with a resulting loss in sensitivity.

d) Wind motion of the antenna looked like "clutter" to the radar, resulting in a reduction in processor sensitivity.

e) Radio frequency interference caused by communications equipment proved to be a source of false alarms.

After much discussion of these observations, it was decided in October 1968[10] that the only solution was to build a coherent radar with balanced processing. (See Appendix B for a complete description.)

A property of vegetation is that the primary scatterus (vertical tree trunks) move back and forth but with no average relative motion to the radar. This characteristic lends itself to the balanced approach of processing or the Kalmus technique,[11] in which the clutter is averaged over several periods so that only targets with net motion to the observer are processed as targets.

In February 1969, we were back in Panama with the first coherent 140 MHz with balanced processor. These tests were successful and indicated we had overcome the limitations imposed by the non-coherent system.

The period between February 1968 and August 1969, the date of RVN deployment, was used to complete fabricating of eight man-portable ORCRIST systems, two of which were converted to base station radars with the addition of a High Power Amplifier (20 kw), high gain 12° beam width antenna and "A" scope display.

F. The Final ORCRIST System

The Backpack ORCRIST

The man-portable ORCRIST system shown in Figures 9, 10, and 11, consisted of a homodyne system, including a transmitter and receiver duplexed with a common antenna, coherent detectors for target direction measurement, a balanced audio signal processor for automatic detection, suitable operator controls and indicators, antenna and mast hardware, and carrying packs for man-portability. The transmitter-receiver consisted physically of a small 4 pound box for mounting at the top of the mast, close to the antenna, to minimize RF power losses in cables. The Signal Processor/Control and Battery Box weighed 6 pounds, and included alarm lights and a head phone for operator discrimination of target type; i.e. man, animal, vehicle, etc.

The pulse doppler coherent radar, Figure 12, starts with a crystal controlled oscillator, multiplying the crystal frequency up to 140 megahertz. This stable radio frequency source is applied to a pulsed power amplifier producing an output peak power of 50 watts. This power is applied to a hybrid rf duplexer for routing to the antenna. The radar return signal from clutter

Figure 9. Man-Portable Radar Components

Figure 10. Man-Portable Display Box

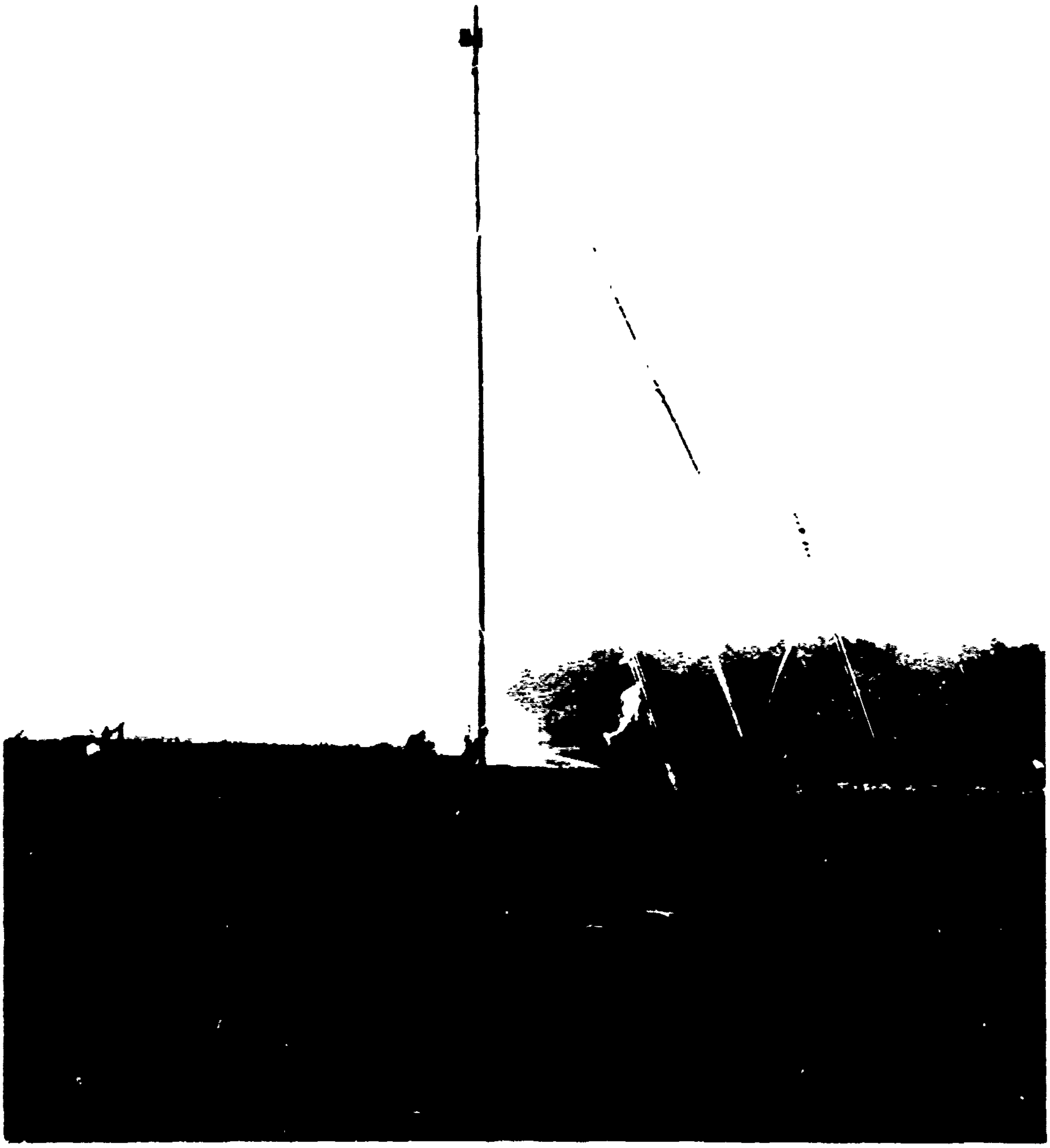


Figure 11. Man-Portable Antenna Deployed

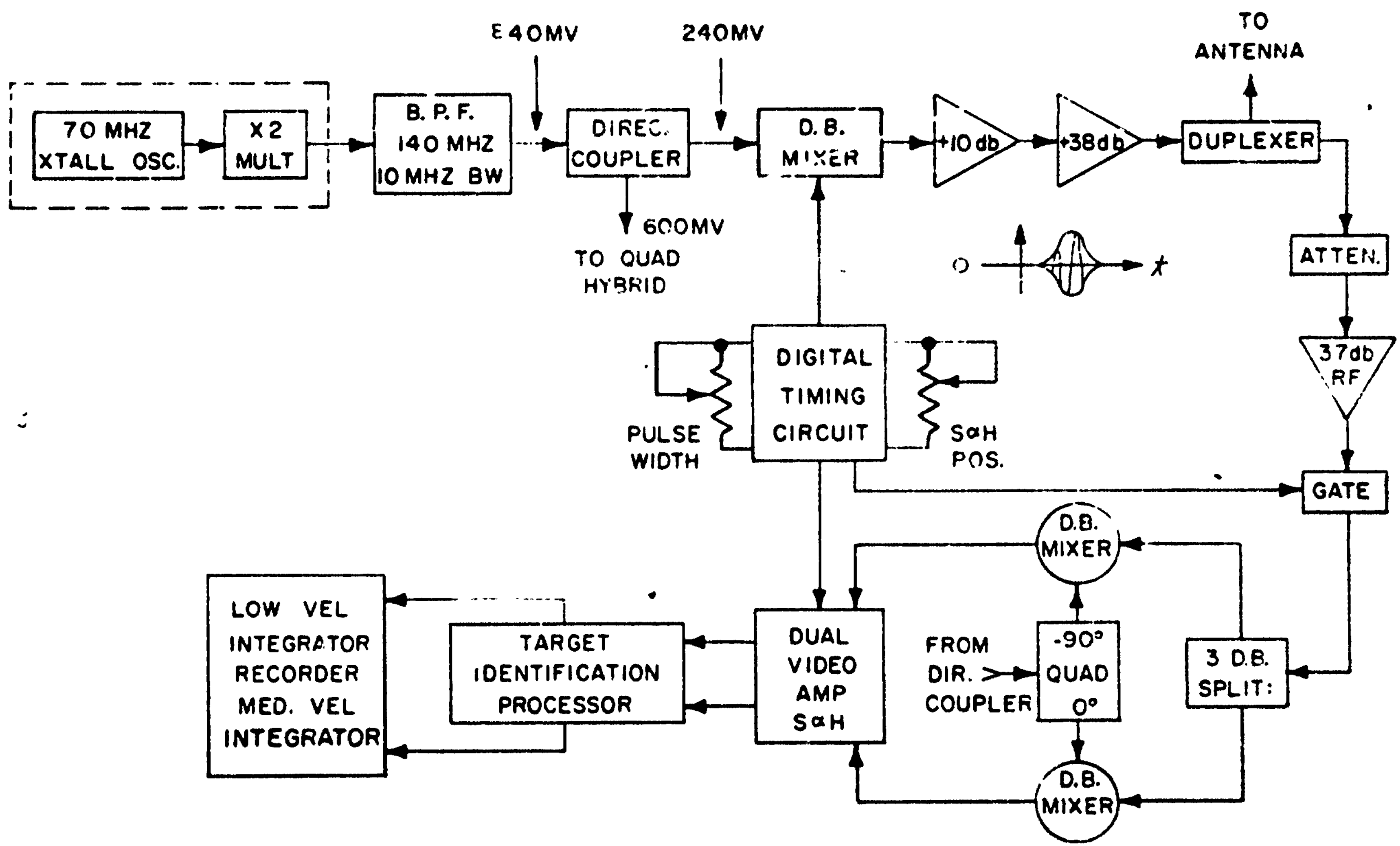


Figure 12 Block Diagram, 140 MHz Coherent Radar

and targets is routed through the same duplexer to an rf amplifier whose center frequency is tuned to 140 megahertz, resulting in zero IF or homodyne operation. A portion of the 140 megahertz cw signal of the transmitter is connected to two phase detectors with 90 degrees of phase difference between the two. The output of the rf amplifier is then detected in the phase detectors, with the cw signal providing the coherent reference. This produces video which is then range gated at the ranges of interest, which are operator adjustable in range out to 1000 yards in increments of 1.0 meter. The antenna beamwidth of 60 degrees defines the other dimension in azimuth of the geometric ground patch under surveillance. This establishes the target-to-fixed-and-moving clutter ratios. The range sampler essentially translates the doppler shifted target and clutter motion from video to audio, with a scale factor of 0.4 hertz per mile per hour. The signal exists on two lines or wires with a phase difference of 90 degrees, and vector rotation clockwise or counter-clockwise depending on whether the detected motion is toward or away from the radar. These two audio signals are applied to the balanced Kalmus type signal processor described in Appendix B whose bandwidths and target integration times are designed to cancel any vibratory motion and detect any net motion. Since the audio signals are in the frequency range of 0.5 to 10 hertz, it was necessary to modulate a 500 hertz oscillator in amplitude and frequency so the operator's hearing acuity could be used for target type discrimination. The doppler processor filters were divided into three contiguous bands; crawling, walking and running man velocities. Further, the low band contained most of the foliage motion energy, and was used as a gain control of the processor to avoid false alarms in the presence of gusty winds. The automatic alarm lights also indicate target direction, i.e. inbound or outbound. Further discussion of this type of coherent signal processing is included in Appendix B.

The Base Station ORCRIST

Portability, antenna size and power output of the man pack ORCRIST forced limitations on detection range of a maximum of 500 to 600 meters. The base station system shown in Figures 13 & 14, succeeded in increasing that range to 1500 to 2000 meters by narrowing the antenna pattern from 60 to 12 degrees and by increasing the transmitter peak power from 50 watts to 10 kilowatts. The implications of such a change are significant in antenna size and weight, mast weight and prime power. The antenna had switchable lobes between the two beamwidths. In essence the back pack system simply was built-in to the base station equipment, all of its basic parameters and functions being retained.

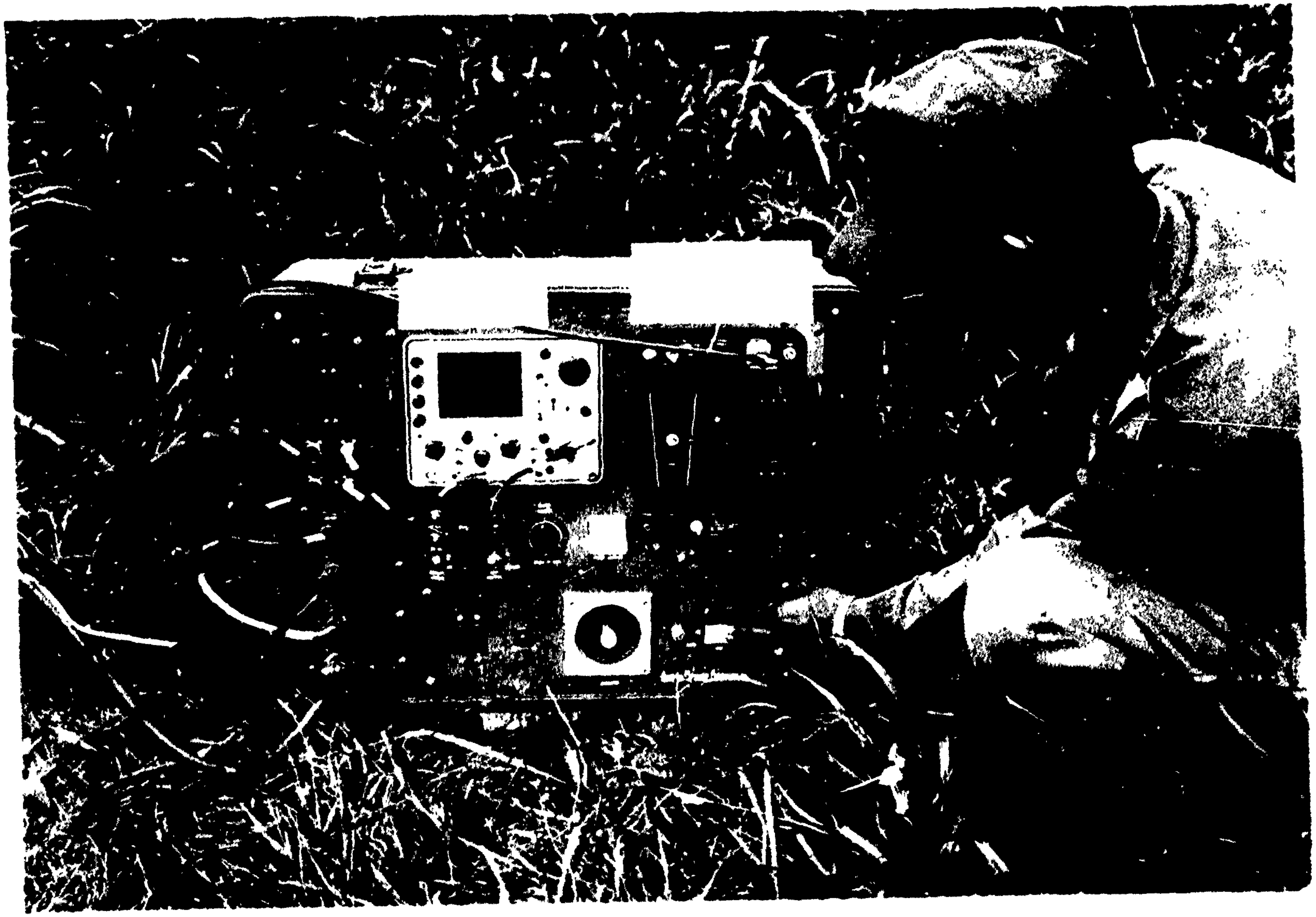


Figure 13. Ground Control Unit Base Station Radar

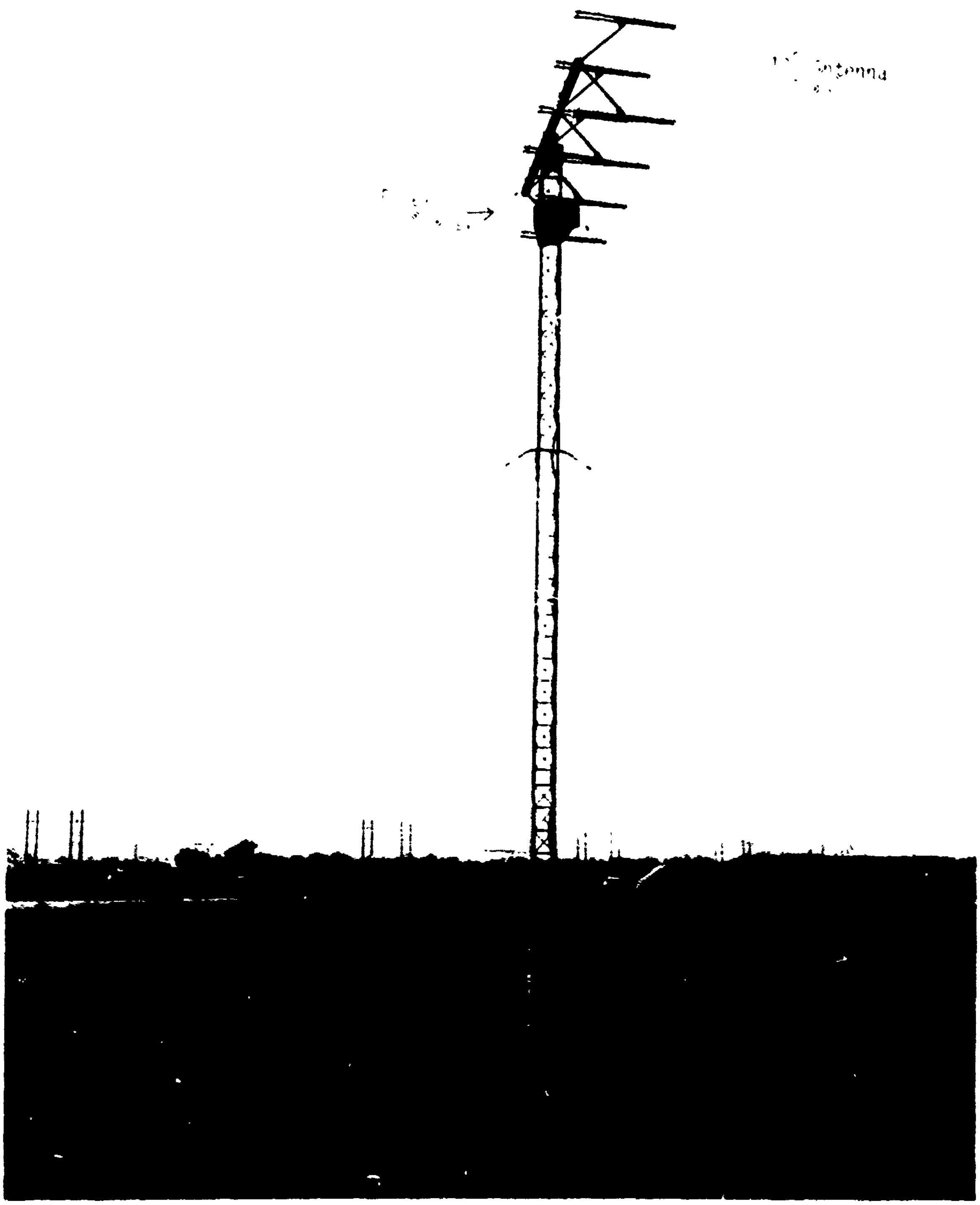


Figure 14. Antenna, Base Station Rajar

IV. EVOLUTION OF THE FOPEN PROGRAM: PART II

A. General

The conclusion of the first part of the FOPEN radar program came with the Vietnam evaluation of the man-portable and base station ORCRIST systems.

Before describing the results of the evaluation,[12,13] it should be noted that during the period between finalizing the Vietnam-bound systems and their actual delivery, certain improvements to these systems were obvious. This resulted in a parallel development program, started prior to the RVN evaluation, to provide the technical basis for improvements to these systems. Thus, when the evaluation was completed, we were prepared to correct the (Vietnam-reported) shortcomings reported by the Army Concept Team in Vietnam (ACTIV) and start fabrication of the second generation multi-purpose FOPEN system.

B. The Vietnam Evaluation

1) Man-Portable Radar - Six man packs were evaluated by the Logistics Electronic Division of ACTIV. The sets were used for 12 weeks under normal field conditions by two combat divisions in the Third Corps area. Three sets were issued to the First Division and three sets to the Twenty-Fifth Division. One set was made available to a U.S. Navy river patrol boat unit for a short period of time.

The sets were used as intrusion detectors at ambush patrol locations and fire support bases (Figure 15) on river patrol missions (Figure 16), for night defensive positions (Figure 17), and for the surveillance of infiltration routes and roads.

During the missions the antenna was erected to heights of up to 30 feet by two men; the most used antenna height was 18 to 20 feet. Ranges varied out to 400 meters.

During the evaluation, approximately 90 target detections were made at ranges of 70 to 400 meters. Twenty seven detections were confirmed. The confirmation of target detections at ranges of 70 to 400 meters demonstrated the capability of the radar to detect targets through various types and densities of foliage.

The radar was always employed where it could be used to penetrate foliage. In one instance, it was used to protect the blind areas of the AN/PPS-4 and AN/PPS-5 radars. Numerous friendly ambush patrols were seen by the ORCRIST but not by the other surveillance gear in the area.

The Vietnam tests concluded[12] that the ORCRIST would effectively penetrate foliage and detect targets, that the sets were not effective during periods of high winds and heavy rain because wind motion of the antenna and foliage caused an excessive false alarm rate. It was also deemed desirable to improve the azimuth resolution capability of the set so that it would not only provide warning but also enough directional information to permit reaction to the threat.

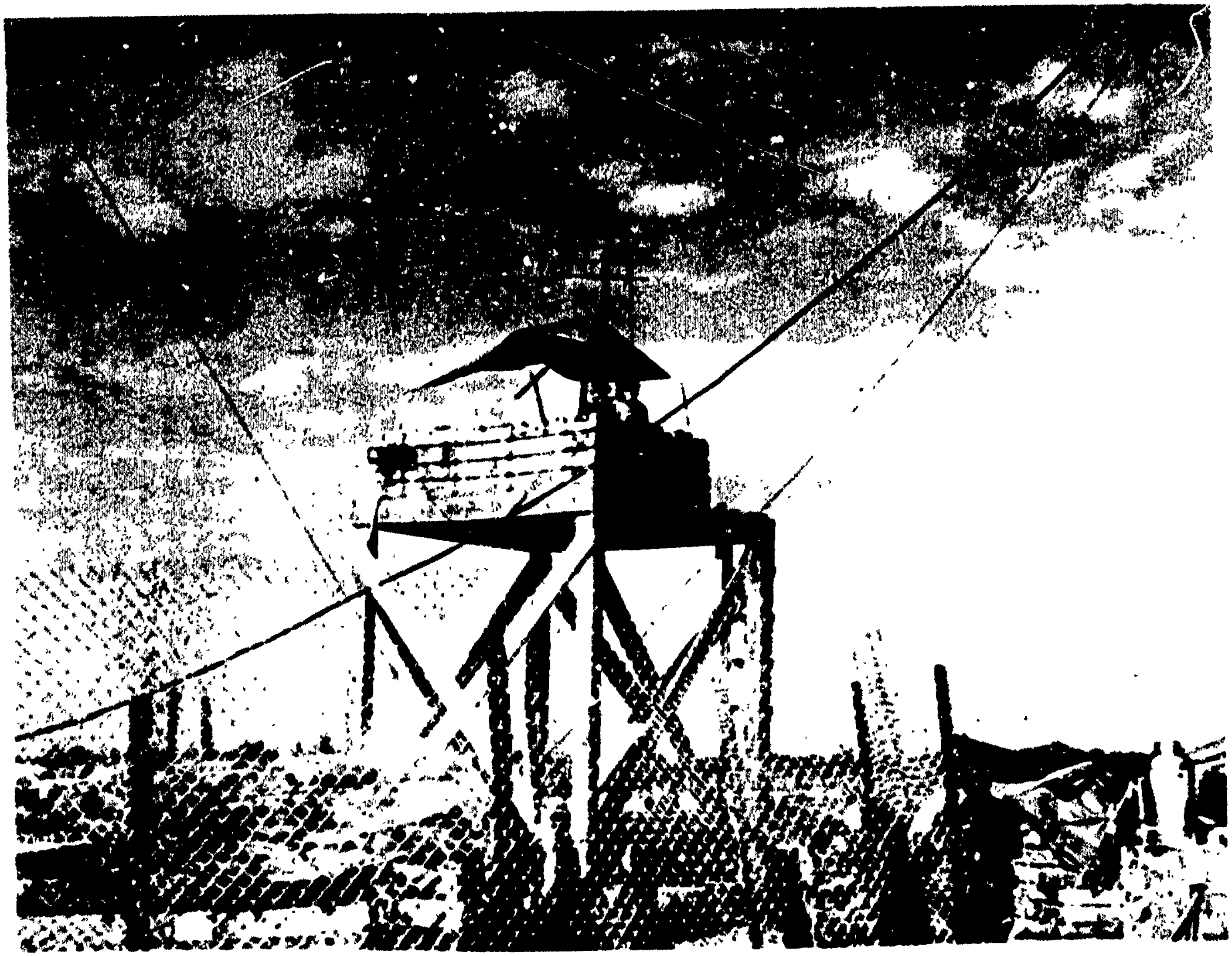


Figure 15. Man-Portable Radar at Perimeter of Fire Support Base

Figure 16. Man-Portable Radar at Night Defensive Position Near Small Town

Figure 17. Area in Which Man-Portable Radar was Used on River Patrol Boats

The man-pack sets were found not to be sufficiently rugged for the Vietnam environment, one of the primary problems being moisture. One other problem was shock; presumably because of their small size the man-pack sets received rougher handling than the base station systems.

2) Base Station Radar - Two ORCRIST base station radars were evaluated by ACTIV for four months in FY70. Both these systems were deployed to the 25th Division. The radars were used as intrusion detectors at a Fire Support Base (Figures 18 & 19) and two base camps (Figure 20). The radar was operated primarily in the wide beamwidth (70^{o}) to obtain maximum coverage. When greater foliage penetration was desirable, the narrow beamwidth (12^{o}) was selected.

The antenna height was limited to 50 feet to enable erection at smaller bases, such as a Fire Support Base. After an initial trial and error setup, it was noted that the entire radar system could be dismantled, loaded into either a 6 x 6 truck or Chinook Helicopter, and reassembled within one day. Since the radar was needed and used at night, site changes could be accomplished during a period of normal downtime.

The only major mechanical difficulty was defective antenna tower construction. The gin pole used to raise and lower the antenna system was weakened to the breaking point by the magnitude of the forces on the end of the gin pole.

Downtime for the four month evaluation due to maintenance problems was kept to a minimum. It is noted that one system was never inoperational and that the second set logged only 24 hours of downtime. Confirmed target detections were made with the base station radar, to 1200 meters through rubber tree forests. The Vietnam tests proved that the ORCRIST base station radar would effectively penetrate foliage and detect targets. It was also concluded that each radar system should be equipped with two Army 3 KW generators in order to provide continuous operation. Improvement in azimuth resolution would be a desirable capability to improve target location. There were no reported shortcomings in the ruggedness of the base station equipment.[13]

C. Initial Development Toward New Generation

During our participation in the final field testing of the ORCRIST radars in summer 1969 and the subsequent Vietnam evaluation, it was obvious that there were three major shortcomings in the radars:

1) The relatively short range of the man-portable system, i.e., 300 meters.

2) The false alarm rate of both systems, although good, needed improvement under high wind conditions.

3) The angle resolution of both the radars, 60^{o} for the man pack and 12^{o} for the base station, was not sufficient to direct fire effectively.

To solve these obvious limitations in the ORCRIST equipment, several areas were investigated in parallel. These included propagation studies, increasing the power transmitted by the radar, changes to the signal processing

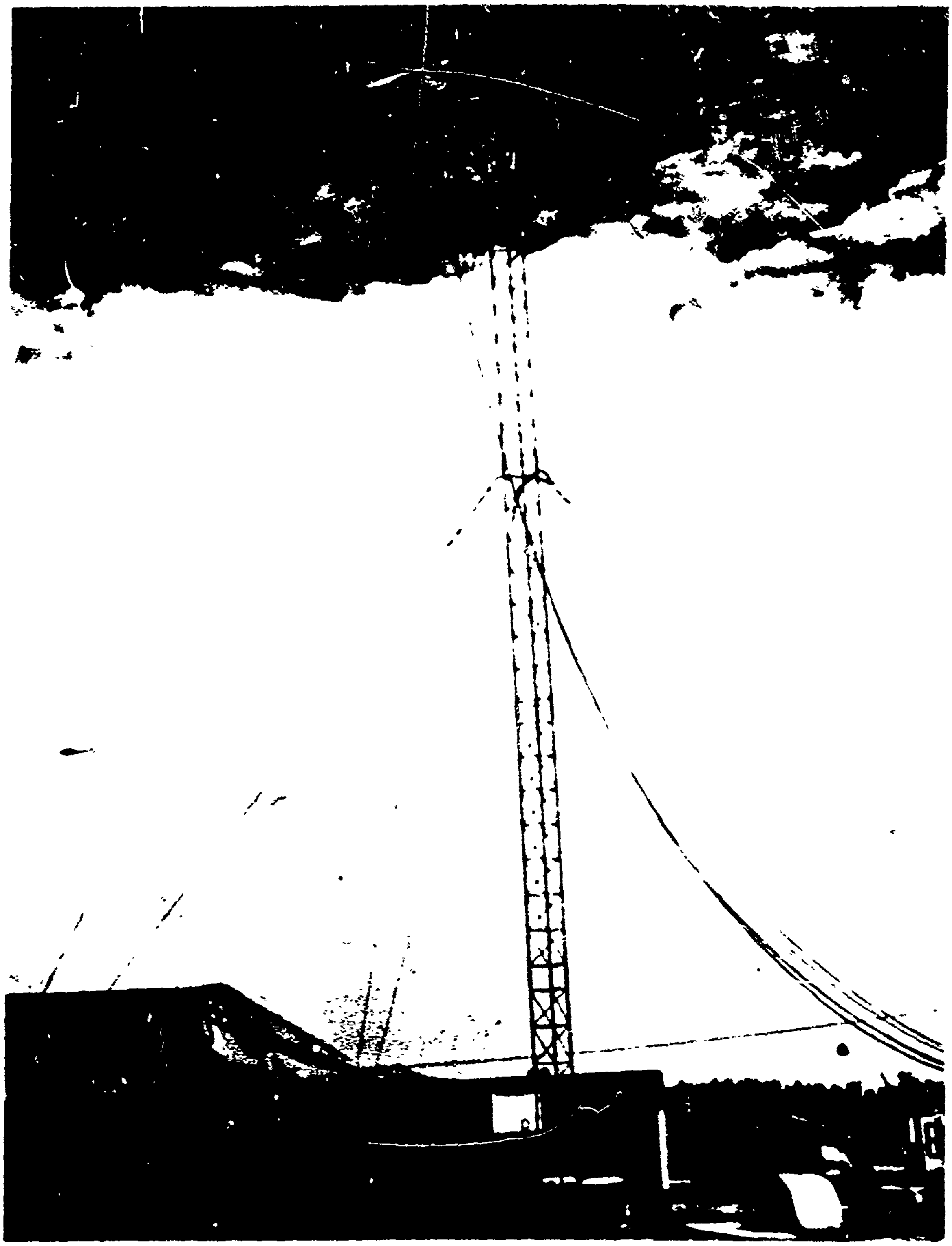


Figure 18. Base Station Radar at the Edge of a Fire Support Base

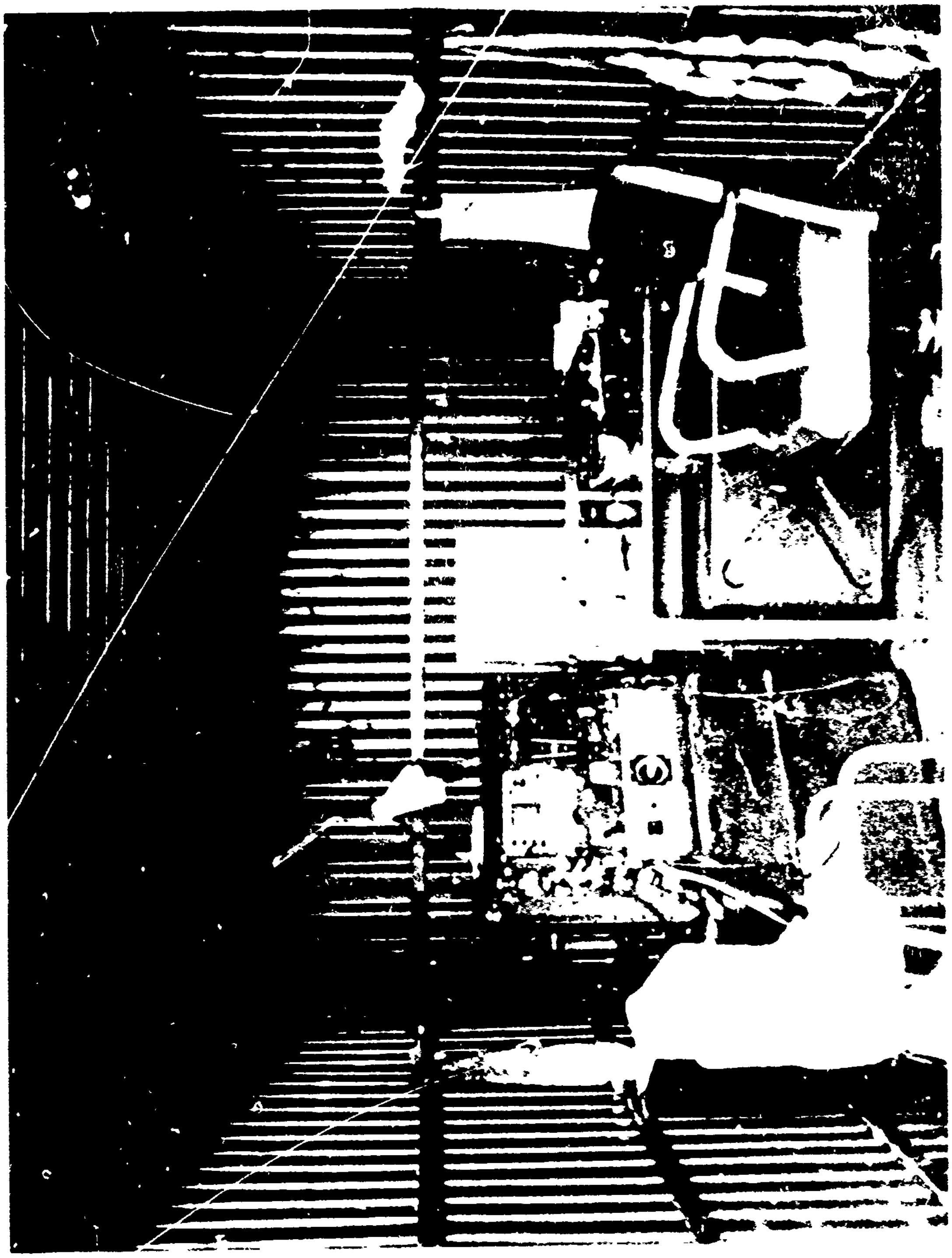


Figure 20. Foliage & Terrain Around the 9th Infantry Division Base Camp

and techniques to improve the angular resolution.

At this time the adaptive alarm which had been tried with the PPS-4 radar in Panama was modified to work with either the PPS-4 or PPS-5 and a program started to fabricate units for Vietnam and Korea evaluations (see Section V.)

RANGE EXTENSION

a) Propagation Studies - Two approaches were taken to extend the detection range of the FOPEN radars. The first was a detailed investigation of the propagation mechanisms relating to the site location of the radar antenna. Dr. Tamir, who was the first to identify the lateral wave mode of propagation, was asked to evaluate the detection ranges achieved through foliage with the radar in light of current propagation data. Appendix D summarizes these results in detail. These confirm the choice of frequency for a detection system operating with its antenna at or below tree top height. Dr. Tamir's work provides insight into the effect of changing the frequency or other radar parameters on detection range.

After understanding this propagation mechanism, it is possible to obtain loss predictions for a variety of circumstances. These predictions have been obtained by describing the forest environment in terms of a lossy dielectric layer which is characterized by an equivalent homogeneous dielectric constant ε_1. Because of these losses, this constant is complex such that

$\varepsilon_1 = \varepsilon' - j\varepsilon''$, (with $1.01 < \varepsilon' < 1.1$) The forest-slab model has enabled path losses to be calculated over the frequency range from 100 to 1000 MHz, with no systematic experiments to verify this behavior. However, losses expressed in dB/meter account for only the real part of the complex loss factor and do not enable accurate range predictions. With the results of Dr. Tamir's analysis,[14,15] however, it is possible to choose the frequencies, antenna heights, and transmitted powers required to penetrate a specified amount of foliage. As may be seen by Appendix D, lower frequencies and higher antennas are required to increase the detection range.

b) Increasing the Transmitted Power - During the course of the work that Aerospace Research, Inc. carried out for the U.S. Army Land Warfare Laboratory, a high power, 1 kilowatt, solid-state VHF RF amplifier was designed, fabricated and field tested.

This amplifier provides increased range capability, particularly in heavy foliage, by increasing the 50 watt peak FOPEN transmitter output power to a 1 KW peak operating level; included also is a mode in which the length of the RF pulse is increased by a factor of 13 in duration and is binary phase code modulated by a 13 bit Barker code to give detection capability equivalent to a 13 KW peak level transmitter when the signal is decoded upon reception. This is done without extending the basic size of the radar's range-resolution cell. The particular code was chosen to yield the maximum of control in the range sidelobes of the autocorrelation function: i.e., the sidelobes would be down in voltage by a factor of 13, which is the number of individual segments in the sequence.

Although the field results showed that this high degree of sidelobe control was achieved, it nevertheless fell short of what is required to avoid having ambiguous target situations show up when operating through dense foliage.

When the system was operated against personnel moving in the clear, the targets always appeared at their prescribed ranges. This was because the range sidelobes never appeared at the sample-and-hold input at a sufficiently high level to exceed the alarm threshold. Had the threshold been exceeded, a wrong-range "ghost" target would have appeared.

When operating through dense foliage, however, with the system's sample-and-hold positions set for a position deeply imbedded in the dense foliage, range sidelobes from large targets at ranges shorter than several hundred meters would cause "ghost" targets to appear. The problem is caused by the fact that when operating through dense foliage, a reasonably strong sensitivity-time-control (STC) increasing gain versus range must be applied in order to normalize the strength of the expected target return. This, in effect, causes the range sidelobes to be amplified by the differential STC gain, which, in general, is a large factor. As a result, the sidelobes can appear at a level which is quite comparable to a level of a normal expected return, and thereby cause the ambiguous range situation.[16]

As a result of the tests that were carried out, it was decided to configure the multipurpose FOPEN radar with a range-sidelobe free signal; i.e., a high-repetition-frequency sequence (40 RHz) of simple rectangular pulses, 1 KW in peak power. Other codes were also considered at this time but even 25 dB of sidelobe suppression available with some more sophisticated techniques would not be sufficient to prevent range sidelobe problems. This applies primarily to the case where the path from the radar to the targets is through foliage for most ranges and may not be as severe when the antenna is elevated substantially above the tree tops as in the Camp Sentinel System (which operates at 100 feet antenna height.)

REDUCTION OF FALSE ALARMS: SIGNAL PROCESSING INVESTIGATION

Under conditions where the radar is operating in foliage under high wind conditions, sufficient clutter energy (due to moving foliage and moving antennas) will enter the low velocity filters to cause the automatic gain control to reduce processing sensitivity for targets of all velocities (See Appendix A and B for a complete description of this type of processor.) Because of the time constants associated with the AGC action, the processor would false alarm under high winds with gusts.

To reduce the difficulties associated with clutter energy in the low velocity channel, an adaptive filter was added to each quadrature audio input. The low velocity cutoff frequency of the filter is set by the amount of clutter residue in each low velocity channel. Therefore, as wind conditions increase, the adaptive corner of the high pass filter adjusts in frequency by reducing the sensitivity to targets moving at low velocities while maintaining maximum sensitivity over the rest of the doppler band.

A prototype of this processor was fabricated and tested with the 1 KW RF amplifier and Barker code unit.[17] Because of the reduction of the amount of clutter energy by the adaptive filter, the gain of the audio signal processor was substantially increased, resulting in a 25% increase in detection range for the basic radar. No false alarms were experienced with this system even under wind conditions up to 40 knots in heavy foliage.

The results of this investigation were two-fold. First, the balanced adaptive processor was added to the L-band Listening Post Surveillance Radar then under fabrication by Aerospace Research, Inc. (See Section V). Second, the design and breadboarding of a second generation system was completed (except for angle resolution improvement) prior to the conclusion of the Vietnam evaluation. This system had twice the detection range of the existing ORCRIST man-pack and almost no false alarms. Also as part of this program, criteria were developed[18] which form a basis of comparison of different types of signal processing. These criteria are discussed in Appendix C.

INCREASING ANGULAR RESOLUTION

In the initial phase of the investigation, leading to the design of the second generation multipurpose FOPEN radar, a number of types of target angle measurement subsystems were examined. These included:

a) Amplitude comparison monopulse based on two angularly squinted radar beams formed by mechanically skewing two antennas.

b) Amplitude comparison monopulse based on an electronically formed beam-left beam-right sequential lobing, the two beams being produced by an RF matrixing of two antennas, both pointed in the same direction.

c) A phase comparison monopulse system based on a sequential measurement of the target phase as measured by two independent antennas, both observing the entire field of view.

At first, it appeared as though the beam-left beam-right,sequential lobing, amplitude approach would be the best one to use, because it did not require that phase stability be maintained throughout the entire receiver and signal processing subsystems, and only depended on amplitude stability which is easier to obtain. Further study of the operation of this type of system in a densely foliated environment, particularly one in which the foliage is non-homogeneous in azimuth, showed that this type of system would yield large azimuth measurement errors. This is caused by the fact that the left beam is generally viewing a completely different foliage and multipath situation than the right beam and, as a result, the instantaneous target amplitude measurement taken in each of these beams would have a different multipath component, causing large amplitude errors which in turn would result in large angle measurement errors. Therefore, the third technique described above was selected.

Figure 21 shows a simplified diagram of the angle-estimation system currently being used in the multipurpose FOPEN radar. Two antennas, each with an approximate 60° beamwidth, are mounted on the same tower, closely spaced and both pointing in the same direction into the field of coverage of the radar.

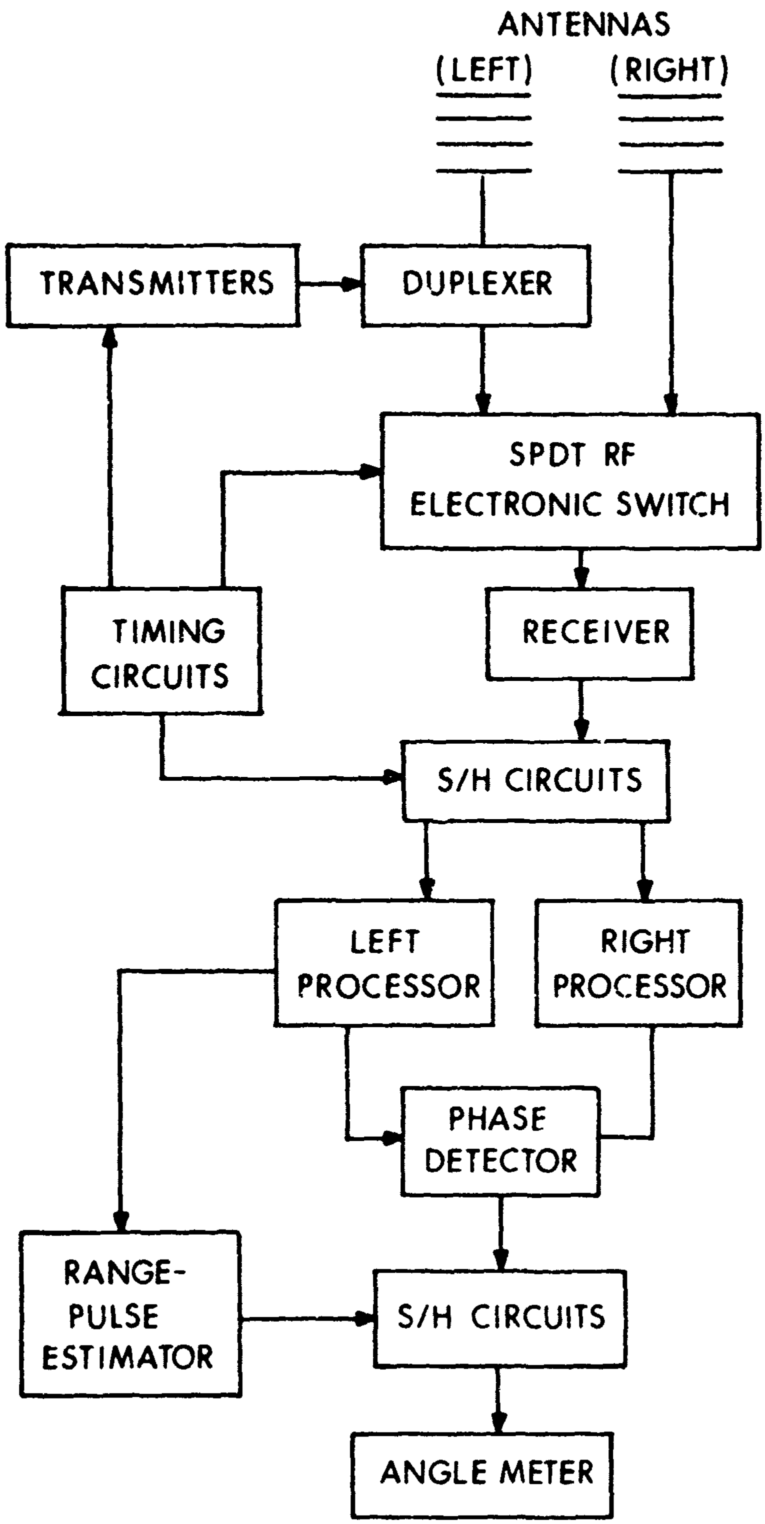


Figure 21. Simplified Diagram of Multipurpose FOPEN Angle-Estimation System

The left antenna is utilized for both transmitting and receiving, while the right antenna is used for receiving only. By utilizing a single-pole-double-throw RF electronic switch and a pair of sample-and-hold circuits, the system is able to utilize a single receiver, on an alternating repetition period basis, to operate on the information obtained from both antennas.

The output of the sample-and-hold circuits go to a left-antenna signal processor and a right-antenna signal processor, both of which supply the required adaptive balanced rejection of clutter. These processors are designed to obtain a very high degree of phase stability even through such devices as dual five-pole adaptive highpass filters.

When a target is detected, the range-pulse estimation circuit provides a trigger at the correct time for reading out the phase difference between the left and right target returns from the processor, which contains the information as to the off-boresight angular position of the target. This reading is presented to the angle meter and held for a ten second period beyond the last angle estimation. A target moving through the range cell, particularly if the return is scintillating strongly, will yield several angle estimations.

Field experience has shown that this angle estimation system consistently produces a target angle which is within five degrees of the true angle even in dense and highly non-homogeneous foliage environments.

D. The Multipurpose FOPEN Radar (M-FOPEN)

In June 1970, funds were approved to correct the shortcomings indicated by the Vietnam evaluation and to produce six additional systems for further evaluation, possibly as part of the "cross fertilization" program whereby the ARPA-sponsored Vietnamese Combat Developments Test Center (CDTC) was evaluating certain development items. In addition, a feasibility program was started to mount the FOPEN radar on a truck, boat, and aircraft. A contract was awarded to ARI in December 1971 to fabricate six man portable radars, two to become base station systems. One base station radar was furnished to Syracuse University Research Corporation for use in the Moving Platform FOPEN Radar Study. Section V describes this program in detail. The basic multipurpose FOPEN radar shown in Figure 21 and described in Appendix F, utilized the 140 MHz transmitter with a 1 KW peak power, 8 watts average power, and the improved signal processing with the angle determination system. We required that the system meet the applicable military specifications with respect to vibration and cold and hot weather storage and operation. Certain difficulties were experienced in the fabrication and testing of the first production unit. These included: low temperature effects when transistors operating in starved current modes to save battery power did not have sufficient internal heating to function, components supplied by vendors that did not meet performance specifications, and C.W. and pulse leakage from operation of the high peak power transmitter in the same box as the receiver.

The difficulties were overcome and resulted in the development of a basic radar system called the Multipurpose Foliage Penetration Radar (M-FOPEN). The M-FOPEN has three specific implementations: the Man-Portable Radar (MPR), Figures 22 to 26, the Intermediate Range Radar (IRR), Figure 27, and the

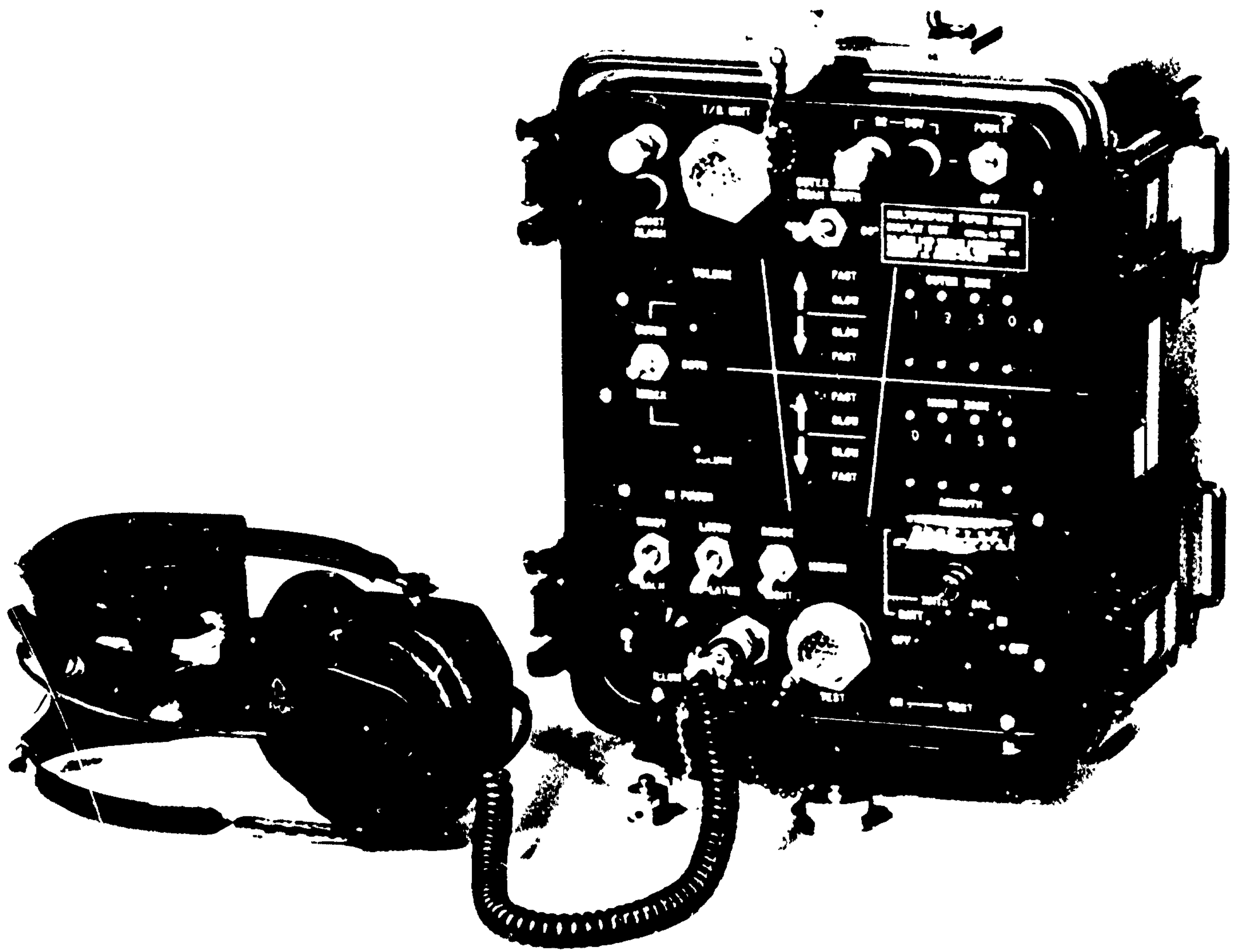


Figure 22. I-FOPEN Display Box and Headset

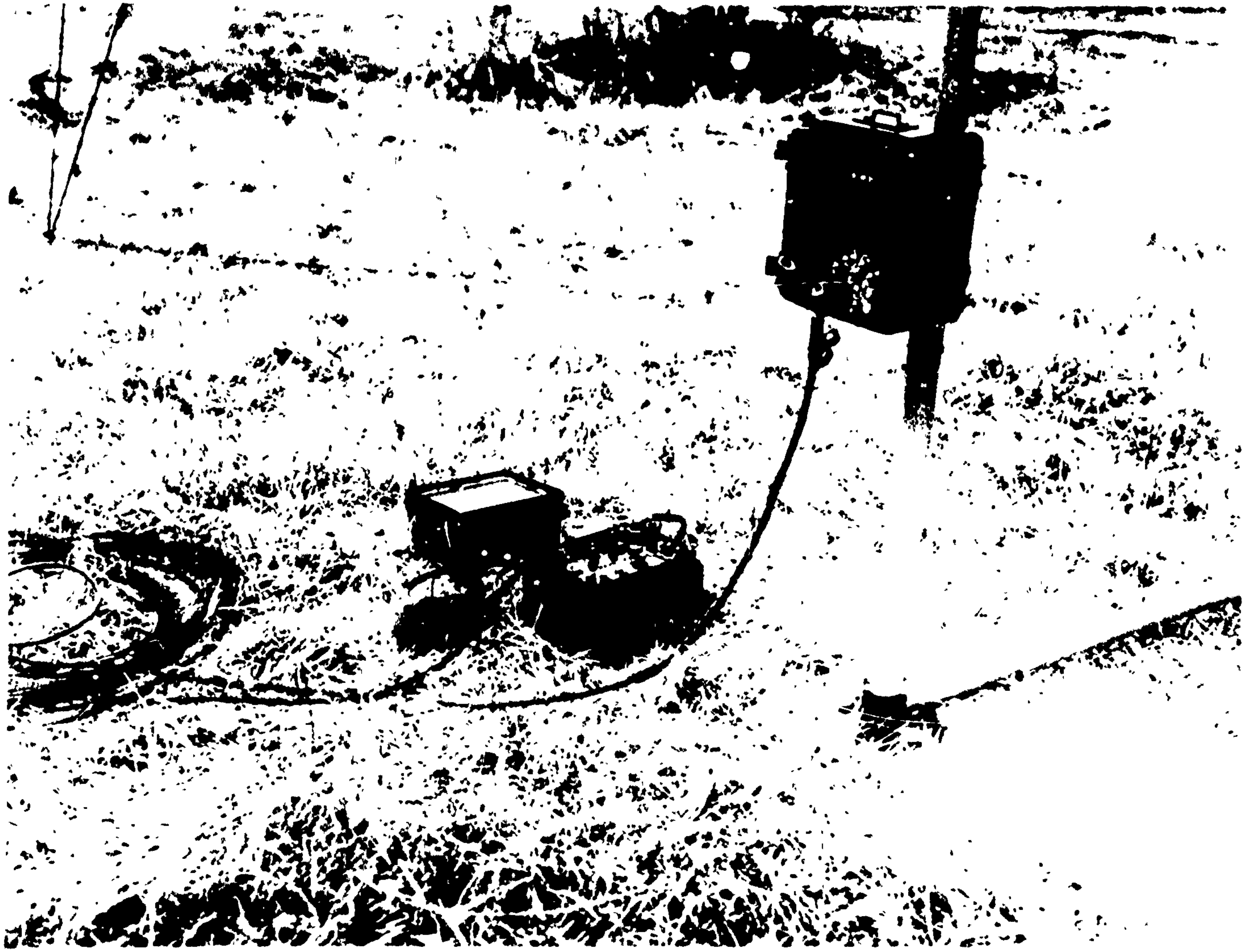


Figure 23. H-ROPEN Components at the Base of the Fiberglass Antenna Mast

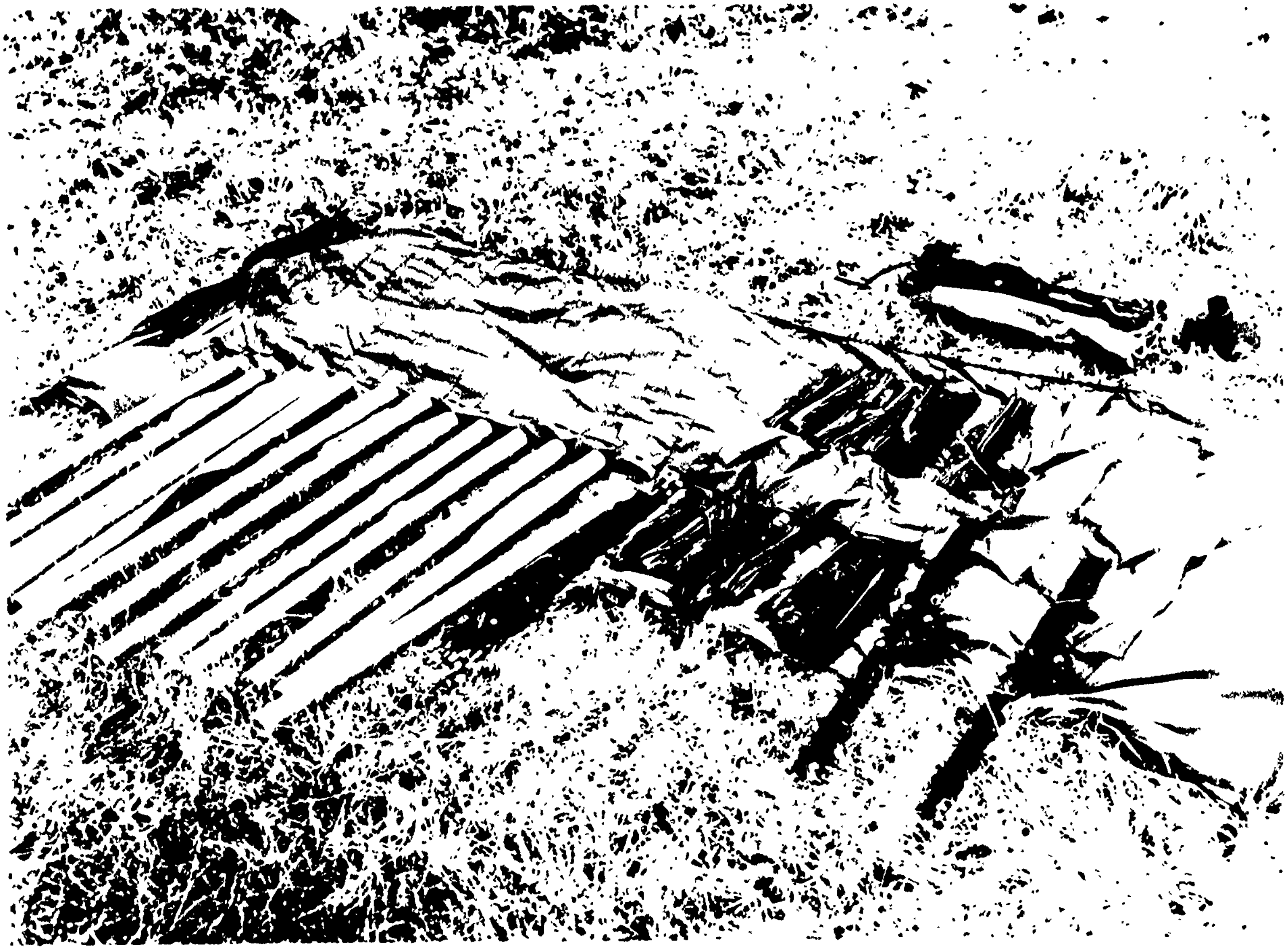


Figure 24. M-FOPEN Light Weight Antenna Mast Components

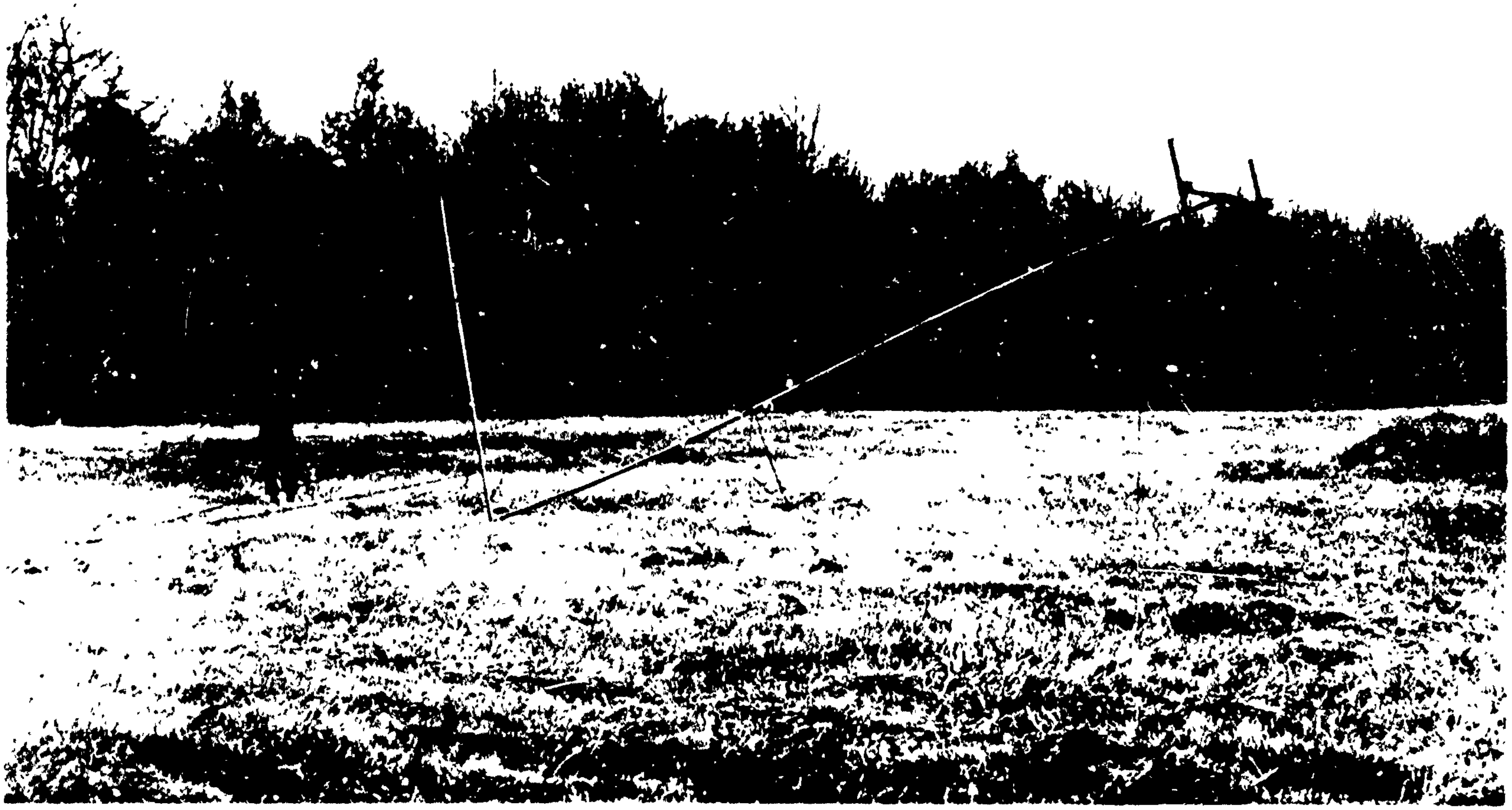


Figure 25. Antenna Mast Being Raised into Position

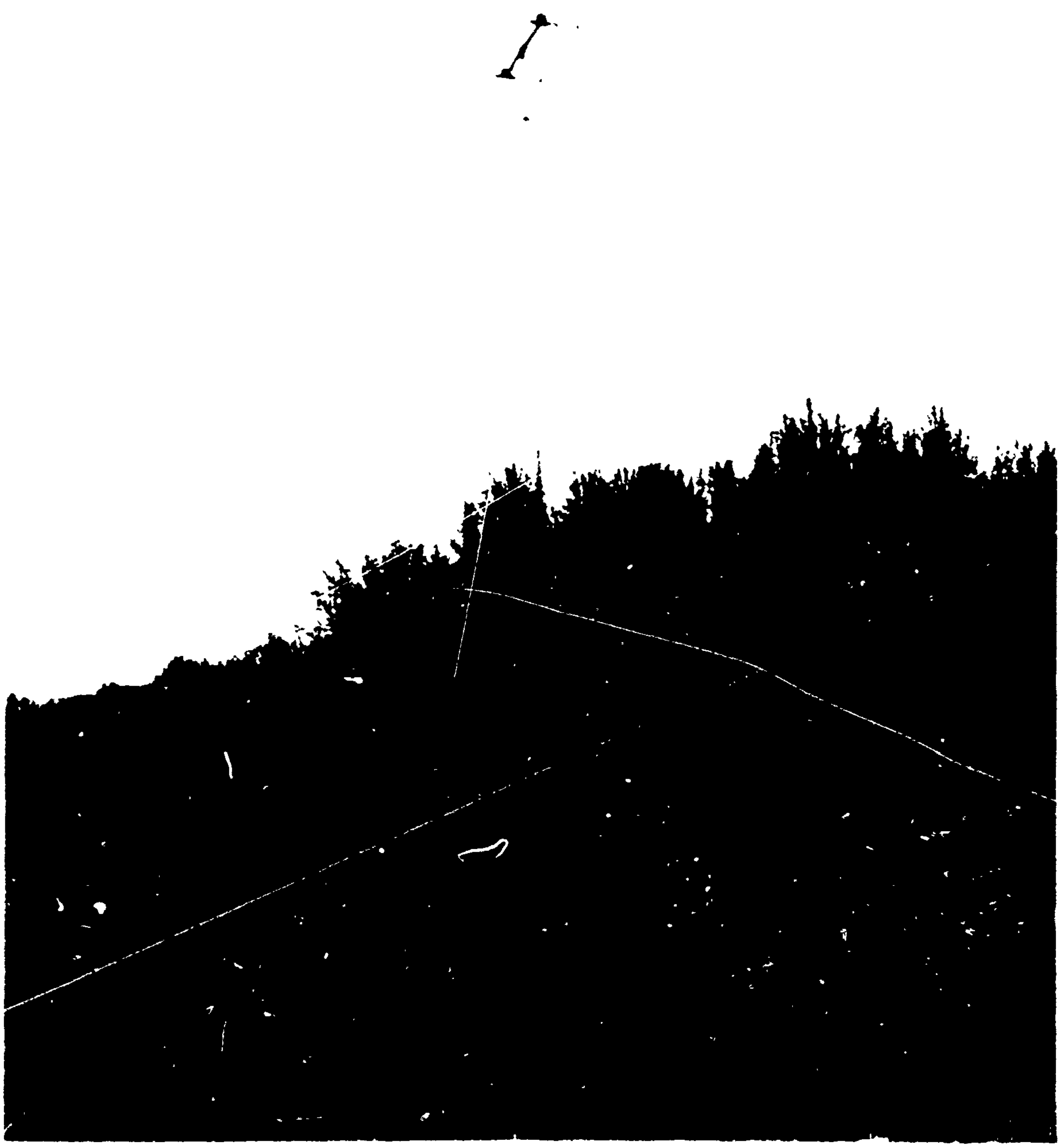


Figure 26. M-FOPEN Antenna Mast with Delta-Loop Antennas

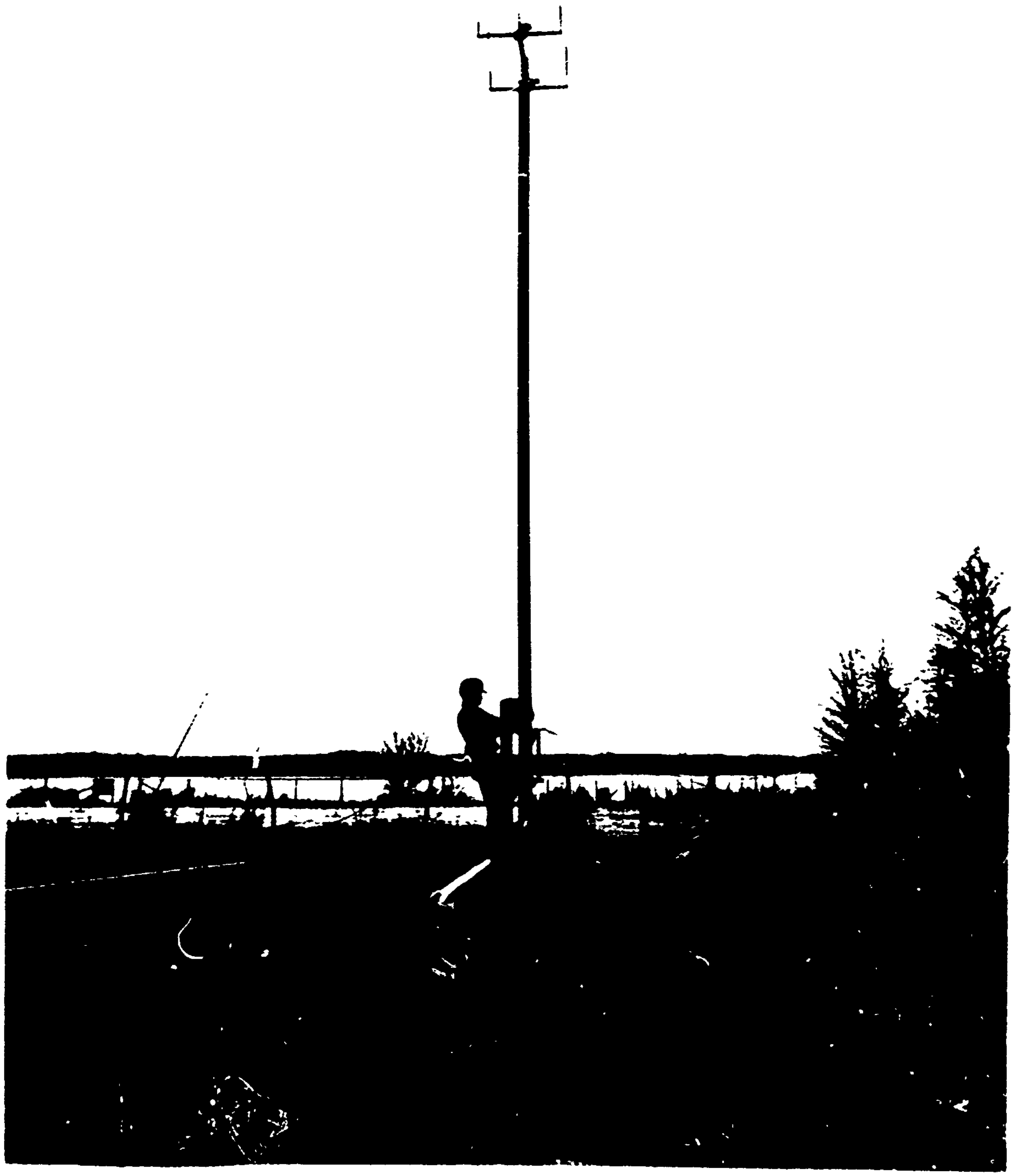


Figure 27. AB-577/GRC Antenna Mast Used to Extend the Range of the Man-Portable Radar

Base Station Radar (BSR), Figures 28 and 29.

E. Evaluation of the M-FOPEN Radar - General

The evaluation of this radar was originally scheduled for MASSTER at Ft. Hood, TX, but a delay in equipment availability and a lack of personnel and suitable test areas at Ft. Hood prevented MASSTER from testing the FOPEN Radar. On 1 September 1972, it was proposed to the Commander-in-Chief, U.S. Army Pacific, that a User Evaluation be conducted by the 25th Infantry Division, and a proposed evaluation plan was provided. The 25th Infantry Division agreed to perform this evaluation during the third quarter of FY74.

The M-FOPEN system was designed to be issued to the Ground Surveillance Section of the Infantry Battalion for use in conjunction with other battlefield surveillance and target acquisition equipment in areas where other systems are limited by vegetation, weather, terrain, detection range or portability. Thus, the M-FOPEN was issued to the Ground Surveillance Section of the 1st Battalion, 5th Infantry, 25th Division to conduct the evaluation. Appendix F describes the major components of the M-FOPEN radar. For this evaluation, the IRR was not considered. However, the MPR was used with the AB-577/GRC antenna mast (the Intermediate Range Configuration) to extend the range of detection and provide data at different antenna heights.

F. Test Objectives

The purpose of this user evaluation was to determine if the item was ready for production in operational quantities, or if not suitable, to specifically identify those shortcomings in design and performance which make it unsuitable. The specific test objectives were:[19]

1) Objective 1: To determine the performance characteristics of the M-FOPEN (MPR and BSR configurations):

a) Ranges at which detection occurs (ROD) for various targets and at different antenna heights.

b) False alarm rate (FAR).

c) Estimated amount and type of foliage penetrated.

d) Target recognition capability by the operator.

e) System range and azimuthal resolution.

f) Percentage of true targets detected and recognized.

g) Susceptibility to simple countermeasures (ECM).

2) Objective 2: To investigate the utility of the remote capability.

3) Objective 3: To investigate the reliability characteristics of the M-FOPEN, the logistical support requirements to properly maintain the M-FOPEN, and to determine the human engineering deficiencies associated with the

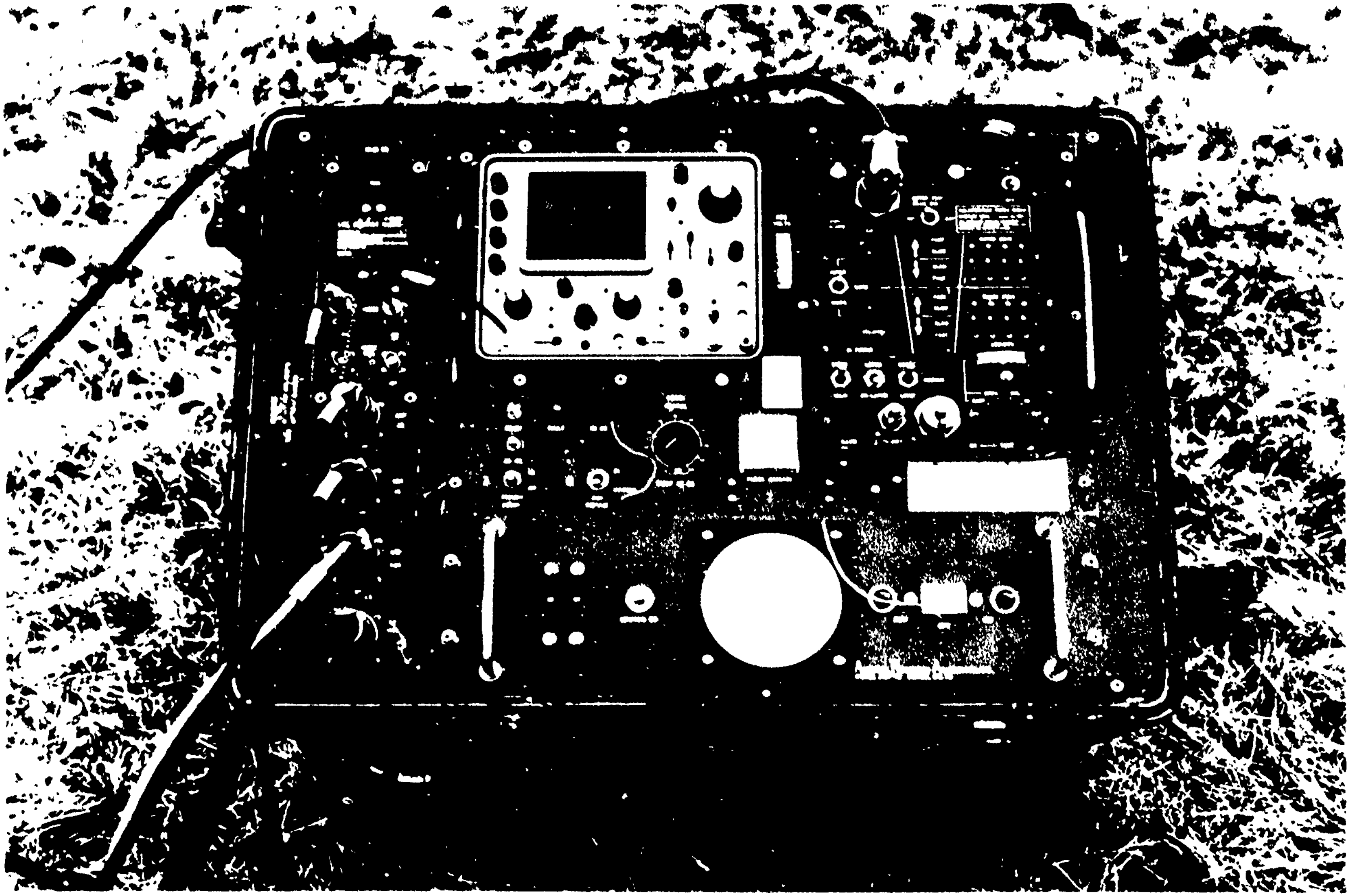


Figure 28. Base Station Ground Control Unit

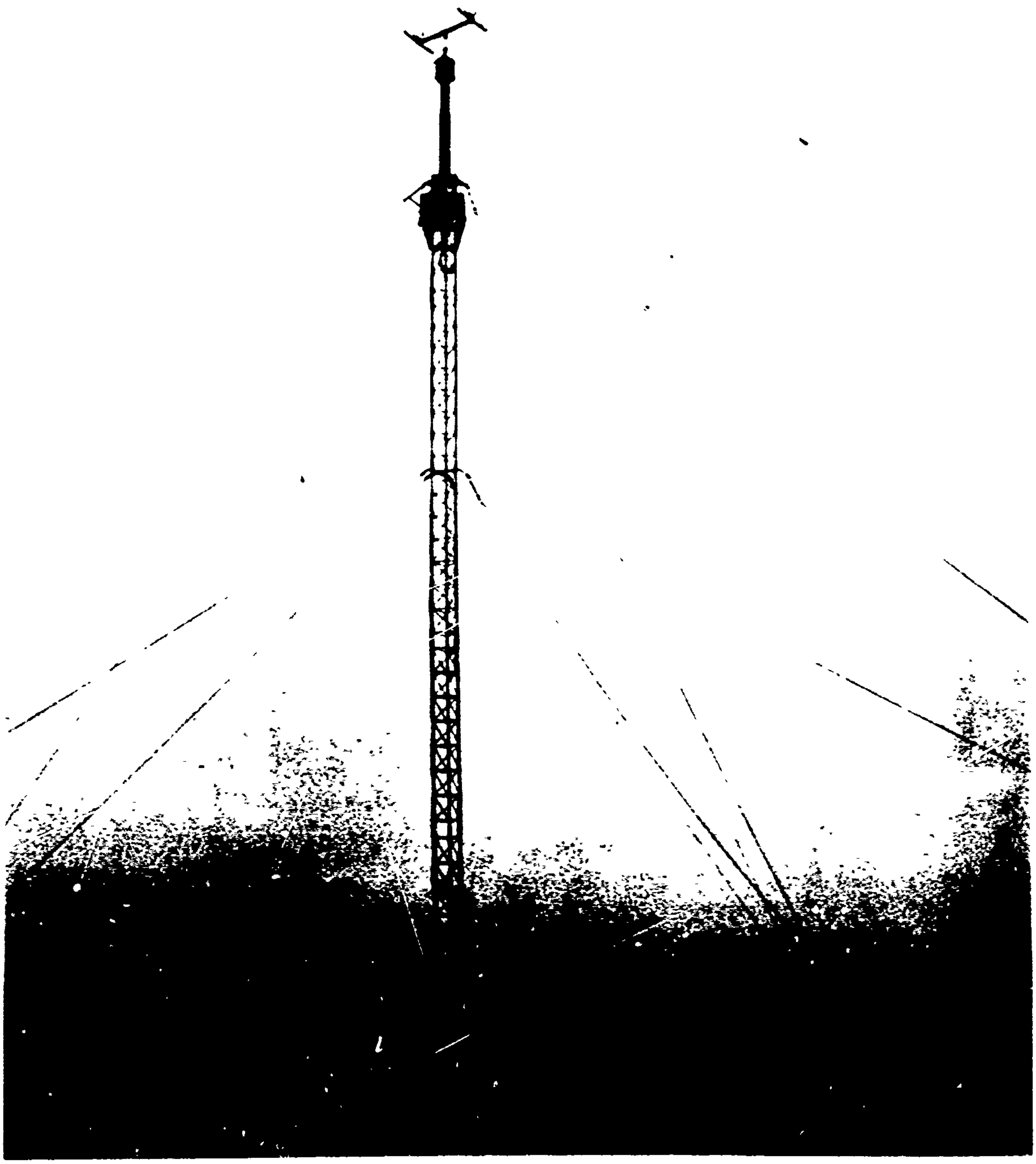


Figure 29. Base Station Tower with Delta-Loop Antennas

operation and employment of the M-FOPEN.

4) Objective 4: To determine the training requirements to operate the M-FOPEN properly.

G. Tests and Results

1) Base Line Testing - The purpose of this subtest was to determine under controlled conditions the operational performance characteristics of the M-FOPEN against various targets and the maximum range of detection for targets in the open and in foliage.

The MPR on the AB-577/GRC antenna mast (this mast was used to facilitate maximum range of detection (ROD) experiments to be performed at different antenna heights) and the BSR were set up on one end of the range. Range markers were placed at 50-meter intervals from the radar location out to the maximum range available.

To enable baseline testing to be accomplished under as wide a variety of terrain and foliage conditions as practical, three major test areas were utilized:

a) Open area baseline tests were conducted in an area called "McCarthy Flats." A maximum straight-line path of 1400 meters was available.

b) Densely foliated baseline experiments were conducted to the South Range Test Area on the edge of the Schofield Barracks Forest Reserve. The area is slightly elevated from the surrounding terrain and exposed to all prevailing winds. The tops of the trees normally move in the trade winds which pervade the area. During gusts or high winds, significant tree motion was induced in the top portions of the trees. Extensive limb motion was induced on the ground and intermediate levels. At this side, two locations were used; one with the antenna immersed in the trees, the other with the radar removed 30 meters from the edge of the trees.

c) Medium to light foliage and open mixed baseline tests were conducted at Makua Gulch. There is a slight terrain mask directly in front of the radar. Terrain limitations prevented detection experiments at ranges beyond 750 meters for light foliage, 450 for medium/dense foliage, and 1100 meters on the open road. The M-FOPEN was deployed on the Farrington Highway side of the Gulch with a 38 foot high hillock with the antenna approximately 10 feet above the M-FOPEN antenna.

The results of open baseline testing are shown in Table 1 and discussed below:[19,20,21]

There were no false alarms for either the MPR or BSR in this phase of testing during which 594 separate targets were presented to the radars.

Operators were able to identify single and multiple personnel and vehicular targets presented by their distinctive audio presentation, relative speed as they traversed through a range gate, and the duration and intensity of the

Ranges of Detection for Type Target vs Terrain. First range given is for > 95% probability of detection, second is for maximum detection range.

	Open Baseline Ranges						
	Flatland (McCarthy Flats)				Rising Terrain (Makua Valley)		
Targets	MPR 20'	MPR 30'	MPR 50'	BSR 57'	MPR 20'	MPR 30'	MPR 50'
Single Man	550 / 650	700 / 800	-	850 / 900	550 / 700	800 / 800	900 / 900
Three Men	-	-	-	-	-	900 / 900	900 / 900
Five Men	750 / 750	800 / 1100	1200 / 1300	1200 / 1250	750 / 750	1050 / 1050	-
1/4 Ton Vehicle	750 / 850	-	1200 / 1200	1200 / 1200	1100 / 1100	1100 / 1250	1100 / 1100

TABLE 1. *Summary of Bareground Baseline Data*

signal indicated on the FOPEN Test monitor.

The system range accuracy was determined to be within ±5 meters of the actual range as determined by the target controller using range markers.

The azimuthal resolution of the M-FOPEN for bare ground was better than ±3 degrees as compared with an advertised accuracy of ±5 degrees.

The direction of target motion inbound or outbound was always (100%) accurate.

The operators could determine when the radar was subjected to RFI (see preceding discussion) by listening to the audio. The extent to which the RFI effected the radar, i.e, reduced detection range could also be determined by the AGC/AFC* readings in the test monitor box.

On three occasions, light rain fell during testing with no apparent effect on radar performance.

It was determined that the Base Station configuration (BSR) did not offer any significant advantage over the man-portable radar when the man-portable antenna was used at 50 feet in height, using the AB-577/GRC antenna mast. Testing of the BSR was therefore terminated after completion of the Bare Ground Baseline Tests.

Densely foliated baseline experiments were performed with the MPR set up in the 65 to 70 foot trees at both 30 and 50 foot antenna heights. The antenna was within 2 meters of major tree limbs. Under these conditions, high AFC readings were induced in the radar by tree motion close to the antenna. This extremely high AFC condition precluded the detection of personnel targets beyond 150 meters because of the low frequency desensitization of the radar. This further confirmed empirically derived effects of operating a radar too close to the foliage. When the system was moved into an open area approximately 30 meters from the edge of the foliage, the detection ranges improved significantly as illustrated by Table 2. One hundred target iterations were performed at this location using the MPR with a 30 foot antenna height. Because prevailing winds at this location moved the foliage continuously, some degree of AFC control (i.e., low frequency desensitization) was always present. However, although this limited the detection ranges to 450 meters for personnel, vehicles could still be detected through 800 meters of continuous foliage.

*Defined as: AGC = Signal Processor Automatic Gain Control
AFC = Signal Processor Automatic Frequency Control

Ranges of Detection for Type Target vs Terrain. First range given is for > 95% probability of detection; Second range given is maximum range of target detection.

Targets	Foliated Baseline Ranges					
	Light (Makua Valley)			Dense (Makua Valley)		Very Dense (South Range)
	MPR 20'	MPR 30'	MPR 50'	MPR 30'	MPR 50'	MPR 30'
Single Man	-	650 / 750	650 / 750	450 / 450	450 / 450	450 / 450
Three Men	-	650 / 750	670 / 750	450 / 450	450 / 450	-
Five Men	700 / 750	700 / 750	710 / 750	450 / 450	450 / 450	430 / 450
1/4 Ton Vehicle	700 / 750	700 / 750	700 / 750	450 / 450	450 / 450	800 / 850

TABLE 2. Summary of Foliated Baseline Data

Detection ranges for open baseline with rising terrain are given in Table 1. The results of the light foliage testing limited to 750 meters by terrain, is shown in Table 2. Signal levels for group personnel and vehicular targets were often twice threshold. The results of medium/dense foliage baseline tests are also shown in Table 2. ROD were limited by terrain to 450 meters. Signal levels for most targets were two to three times alarm threshold.

The resolution of the radar was found to be within the ±3 degree accuracy previously determined over bare ground.

2) Tactical Exercise and AN/PPS-5 Comparison (24 - 27 April 1973) - The M-FOPEN and AN/PPS-5 radars were colocated at one end of the Makua Gulch test site, both scanning essentially the same presentation of terrain and foliage. Both antennas were approximately the same height above ground, i.e., 30 feet (Figure 30), with the AN/PPS-5 radar located on top of a 30' hillock behind the M-FOPEN position. The area of surveillance was a 60^0 fan centered on an avenue of approach into the area. Operators were separated so they could not observe or hear each other's activities. This portion of the evaluation was conducted by the 25th Division Project Officer. The results of this part of the evaluation are presented in Table 3.

The range gates were deployed according to varying simulated tactical situations with which both radars were confronted; variations of terrain, foliage, and target avenues of approach. Random single and multiple targets were injected separately and simultaneously into both radar areas of surveillance with tactical dispersion distances used for multiple personnel targets.

A total of 34 separate target runs were presented to both radars during this phase of testing. A target run consisted of the movement of a target between two predetermined points.

The M-FOPEN (MPR at 30 feet antenna height) detected, manually tracked, and correctly identified 31 out of the 34 target runs presented. Of the three missed targets, one was a lateral target at the maximum range, 750 meters. The second occurred during a 5-minute period in which the batteries had dropped below the minimum operating voltage. Despite operator training that each battery should be charged after ten hours of use, the battery had not been charged for 3 days. The third miss occurred during the first evening of the exercise when a second group of targets were inserted after a previous group had moved out and stopped. The operators had tracked the first group of targets until they stopped, then placed the range gates (inner and outer) 50 meters either side of that location. During further movement the second group did not traverse either range gate. Subsequent discussion of the results of the first night's testing with both groups of operators resulted in the M-FOPEN operators deciding to keep one range gate at 150 meters as a guard ring and track with the outer gate only. A repeat of the multiple target experiment on the second evening resulted in both groups being detected and tracked. During the conduct of the tactical exercise, only once was a target called in to test control by the M-FOPEN operators during a period in which there were no controlled targets in the area. The operators reported this as a grazed threshold which could not be tracked, in contrast with all other targets which could be tracked in range, identified by type,

Figure 30. Test Configuration for the AN/PPS-5 Comparison Test and Tactical Exercise. Photograph taken from 30' Hillock Behind M-FOPEN Antenna.

TABLE 3. Tactical Exercises and AN/PPS-5 Comparison Test

Radar	Total Targets Presented	# Detected During Day	# Detected During Night	Probability of Detection	# False Detections
M-FOPEN	34	11	20	91.2%	1
AN/PPS-5	34 (19 in field-of-view)	4	2	17.8%	Stopped recording after 30, too numerous to mention

and located in azimuth. On the second evening of the practical exercise, the operators assembled the MPR on the AB-577/GRC mast in total darkness in one hour.

The AN/PPS-5 radar which was performing surveillance on the same area, detected only six out of the 34 targets presented. Of the 34 targets, 19 of the 34 targets crossed open areas visible to the PPS-5 and should have been detected. Four of the six detections were in daylight hours. One of the two evening target detections was a vehicle, the other, a group of ten men on an open road. Neither was tracked for any significant distance, only the vehicular target could be identified as such, and the azimuth information provided was, for the most part, in error by $\pm 20^{\circ}$. The PPS-5 radar was operated from vehicular power with the inverter because its battery would not run the radar more than 20 minutes when the remote indicator was used. During both evening portions of the test, numerous false targets were called by the AN/PPS-5 operators to test control. Apparently these were caused by wind motion of the foliage within and at the edge of the field-of-view of the AN/PPS-5 radar. On the second evening the AN/PPS-5 was shut down due to wind motion of the foliage which rendered the set unusable.

3) In-Town Test - As an adjunct to the tactical exercise, the MPR was disassembled and taken to the town of Makaha where it was assembled in 20 minutes in a backyard. Controlled personnel targets were tracked and identified out to 400 meters and vehicles out to 650 meters. Targets could not go beyond 650 meters on the road because of highway traffic. This was accomplished in spite of much uncontrolled personnel and vehicular activity in the area. To make these detections, the M-FOPEN signal had to traverse through numerous houses, trees, powerlines, and telephone poles, as shown in Figure 31.

This test clearly demonstrated the capabilities of the M-FOPEN to penetrate buildings and suppress clutter, such as moving powerlines, while detecting targets.

4) Helicopter Detection Test - These detection experiments were performed at Makua Valley. One of the three M-FOPEN radars was modified so that helicopters could be tracked and their doppler spectra measured. UH-1 and AH-1G helicopters participating in a live fire demonstration downrange were used as targets.

Using the A-scope and chart recorder with the modified MPR at 30 feet antenna height, helicopters were tracked at 2,990 meters, the maximum range of the FOPEN track capability. At the top of a hill, 1160 meters from the radar, two AH-1G Cobras landed and shutdown their engines. The range gate was positioned over the aircraft and data recorded during approach, hover, and engine shutdown. A unique signature was recorded for each type of aircraft activity which clearly showed the rotation of the main rotor blade and doppler signal received from the moving aircraft fuselage. When the pilot shutdown his engine, the main rotor was observed to slow down and stop on the chart recorder. The energy received from the aircraft was 27 times the background noise at 1160 meters in range even though light foliage and a slight rise in the ground blocked the aircraft from the FOPEN radar.

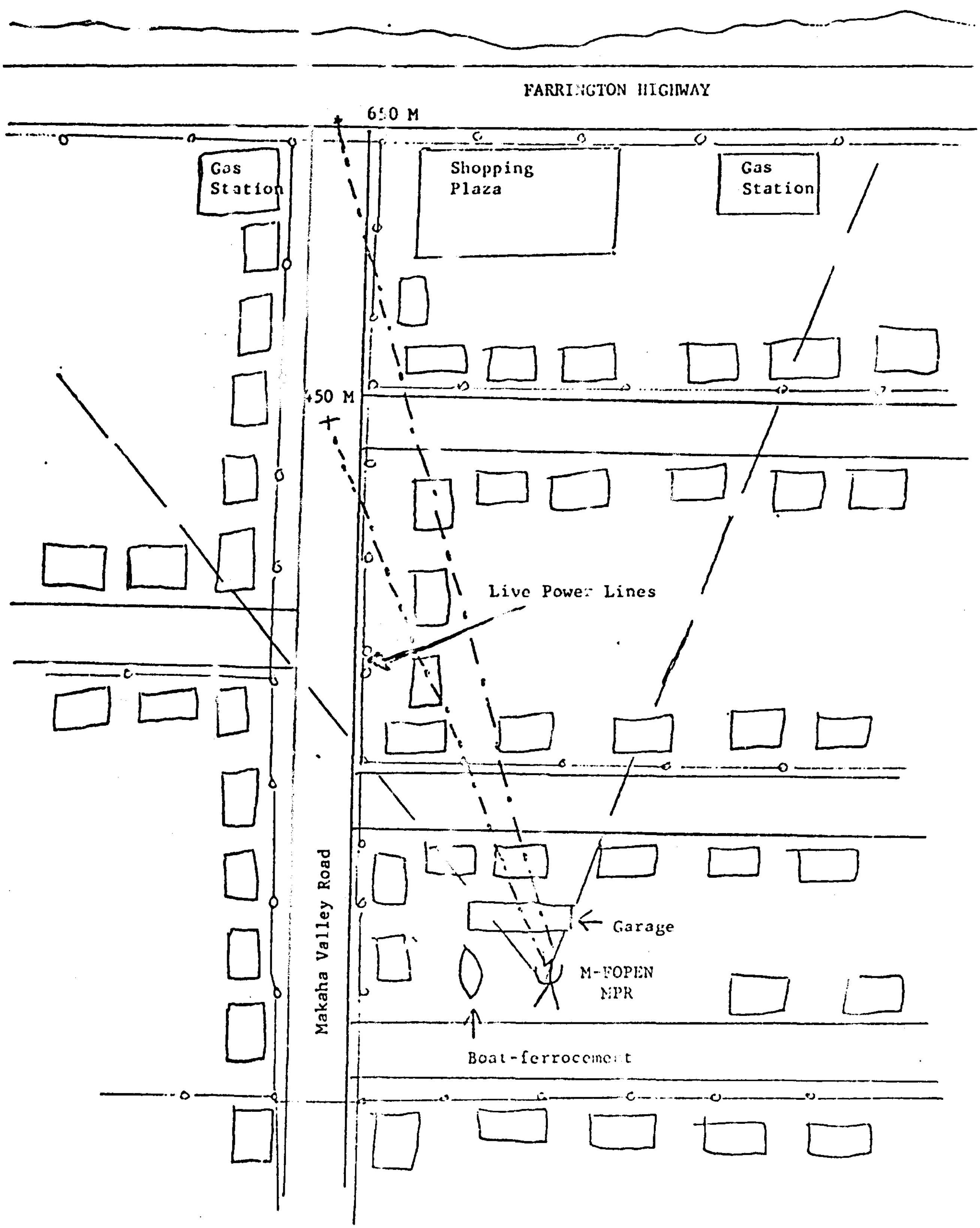


Figure 31. Makaha Intown Test With the M-FOPEN Radar

The results of this test were provided to the AVSCOM and resulted in a task being originated at LWL to further study the detection of helicopters with low frequency radar. Section V describes this program.

5) Countermeasures Test - During this test, which was completed at the end of the tactical exercise, the effects of simple field expedient countermeasures and the electronic vulnerability of other radiating sources, and the effect of standard military FM equipment on the M-FOPEN radar were investigated. Two types of passive, field expedient target imitators were used against the M-FOPEN. Random motion of the targets were induced by test personnel shaking the targets. During this countermeasure exercise, targets were inserted along pretested paths and the difference in detection capability recorded.

a) Simple field expedient countermeasures which were installed in a heavily foliated area 400 meters from the radar consisted of aluminum foil targets and communications wire - WD-1. When suspended in the trees and shaken either manually or by the wind, they did not cause the M-FOPEN to alarm.

b) Personnel were detected when they emplaced and activated the countermeasures.

c) During the period the countermeasures were activated, 1, 2, and 4-man targets were detected at 400 meters with only slight degradation due to a small AFC/AGC buildup caused by the countermeasures.

d) The countermeasures could be located in range by moving out the range gate until a buildup in AGC/AFC was noted.

e) Operation of standard FM radios, both man-pack and vehicular types, at subharmonics of the M-FOPEN frequency at distances of ten feet from the radar had no measurable effect. FM radios were used for all phases of the evaluation with no measurable effect on the system performance.

6) Maintenance of M-FOPEN - There were no electronics, cable, or battery failures during the six weeks of this evaluation. No maintenance was performed on the M-FOPEN systems other than operator maintenance consisting of cleaning and charging batteries. Two mechanical field modifications to the AB-577/GRC antenna mast and antenna bracket were done by the Ground Surveillance Section during the test. These consisted of making nylon guylines to replace the metallic cable guylines used with the AB-577/GRC and fabricating a plywood antenna mount to raise the antenna above the metallic support. These modifications were necessary to reduce the movement of metal items in the near field of the antenna.

H. Conclusions

The following conclusions are based on the results of the M-FOPEN User Evaluation.[19]

1) The M-FOPEN has demonstrated a capabil·· to detect military targets

over bare ground and through foliage with greater than 95% probability of detection as shown in Tables 1 and 2.

2) The M-FOPEN has demonstrated an extremely low false alarm rate, i.e., two false alarms for 1,2 5 target iterations in six weeks of testing.

3) The M-FOPEN (MP) has demonstrated a capability of penetrating foliage not possible with conventional ground surveillance radars such as the AN/PPS-5.

4) The MPR has demonstrated a capability of penetrating the following amounts of vegetation to detect targets:

a) 450 meters of dense foliage (60 to 75 foot mahogany trees) to detect personnel, 800 meters to detect vehicles.

b) 750 meters of light foliage to detect both personnel and vehicles.

5) Operators were able to identify targets by their distinctive doppler audio presentation, relative speed through the range gate, and amplitude of the signal as displayed on the test monitor box.

6) The tactical utility of the MPR configuration was demonstrated during the tactical exercise in which 91% of the targets were detected, tracked, and identified with sufficient information to enable the targets to be engaged and neutralized.

7) The standard Army ground surveillance radar, the AN/PPS-5, is not capable of detecting or locating targets when any portion of the intervening field-of-view of the radar contained foliage.

8) The M-FOPEN is not significantly affected by or subject to false alarm by wind at any test location.

9) The M-FOPEN is not false alarmed or significantly affected by simple field expedient countermeasures although the system is slightly desensitized. Targets were detected prior to and during the emplacement of the countermeasures.

10) The mechanically complicated tower and related assemblies of the M-FOPEN provided only slightly greater detection range which did not warrant their installation under tactical conditions.

11) The M-FOPEN MPR when used with the AB-577/GRC mast provides a target detection capability similar to that of the BSR at a significant savings in size, weight, and complexity.

12) It was determined during tests at McCarthy Flats that target height is an important factor in the detection of the target. This was observed when the target walked in a depression which reduced the return from the target at that range. Increasing the antenna height from 30 to 50 feet reduced this effect.

13) The detection and tracking of rotary wing aircraft, even those concealed by foliage has been demonstrated and shown to be practical using the M-FOPEN radar. The signatures are so unique that a simple discrimination circuit could be added to the M-FOPEN to enable the automatic discrimination between helicopters and other types of targets.

14) The feasibility of using an M-FOPEN MPR radar in builtup residential areas to see through buildings, power lines, etc., to detect moving target, has been demonstrated.

15) The fiberglass antenna mast used with the MPR configuration shows general military potential and application. It appears superior, particularly more durable, than the standard RC-292 antenna masts currently in Army-wide use. It was easier to assemble and disassemble, stronger, more flexible and capable of providing greater mast height than the RC-292.

16) The maintenance requirements of the M-FOPEN radar were found to be minimal. Normal operator maintenance consisting of cleaning was sufficient to maintain the radar for extended periods.

17) The test monitor box was determined by operators to be an invaluable adjunct to the operation of the radar. It provided the operators with additional information with which to determine target characteristics.

18) The AB-577/GRC antenna mast is preferred over the fiberglass antenna mast when vehicular transport is available.

19) The M-FOPEN alarm indicators (audio, lights, beeper and wrist alarm) are nonfatiguing and more than adequate to alert the operator under all conditions.

20) The remote capability of the M-FOPEN display box and the wrist alarm are very desirable features.

21) One week of training is sufficient to train most operators; however, two weeks with emphasis on tactical experience is preferable.

V. APPLICATIONS OF FOPEN TECHNOLOGY RESULTING FROM THE LWL FOPEN RADAR PROGRAM

A. Summary

In addition to the two generations of Foliage Penetration radars previously discussed, several other radar systems and system concepts evolved from this effort. Fortunately, the structure of LWL has enabled many of those areas to be pursued further.

1) The airborne FOPEN radar, Part B of this Section and Appendix G, began with a request from Vietnam to examine the possibilities of mounting a FOPEN radar on a moving platform such as a truck. This stemmed from the successful use of the man-pack FOPEN on a patrol boat (at rest) to provide security when the vessel was hiding in the shore line.

2) The need for a small, light-weight false alarm-free sensor to be used on a listening post or ambush was well known. It was the combination of two separate investigations of propagation and signal processing that resulted in the 1200 MHz coherent radar with balanced processing, which became the PPS-14 (see Part C of this section).

3) While using the PPS-4 radar in conjunction with the early non-coherent FOPEN, an adaptive processor designed for the FOPEN was tried with the PPS-4. The success of a nonfatiguing aural presentation and the addition of an automatic alarm feature for this radar led to a separate program to fabricate adaptive alarm systems for the PPS-4 and PPS-5. Ten months later alarm units were employed in an operational evaluation in Vietnam and Korea. (See part D of this section.)

4) It was suggested in June, 1971, that perhaps the motion of the treads of a tank, which move at twice the velocity of the vehicle, could be used as a means to discriminate between tracked and wheeled vehicles. A modified FOPEN radar (140 MHz) and PPS-14 (1200 MHz) were obtained from the contractor, Aerospace Research, Inc. (ARI), and data was developed to demonstrate the concept. (See part E of this section.)

5) In the late 1960's there were a large number of intrusion alarms on the market intended for indoor applications. Many of these devices used ultrasonic energy for detection. Most of these were coherent devices and all depended on simple filter and threshold crossing for the alarm mechanism; as a result, they are prone to false alarms from moving fans, swinging drapes, etc. Two organizations, Syracuse University Research Corporation (SURC) and ARI applied the technology gained with the FOPEN radars to these acoustic systems. ARI now produces three series of ultrasonic and microwave intrusion detectors that are sold commercially. These were evaluated by LWL and incorporated into the Army's Physical Security program. (See part F of this section.)

6) While in Korea in April 1971, the author was shown supposedly secure air defense sites and army depots at which a high degree of pilferage was being experienced. It was obvious that some sort of cheap, low-false-alarm perimeter coverage was necessary. A feasibility program was submitted in

the FY72 budget but was not funded. A year later, Dr. James Rodems of SURC became interested in the idea and connected an L-band indoor intrusion detector to a Goubau transmission line (consisting of two launchers and 400 feet of #12 wire) and demonstrated detections of personnel up to 6 feet away from the wire. A GNI (generation of new ideas) program was established at LWL which later formed the basis for the current program described in part G of this section.

7) Tests of the PPS-14 L-band FOPEN radar by MASSTER at Ft. Hood and by LWL in Florida with the Defense Communications Planning Group (DCPG) demonstrated the capability of this radar to detect swimmers on the surface of the water. A program was established in 1971 to evaluate the application of FOPEN type systems to the swimmer detection problem. The results are described in part H of this section.

8) The AN/PPS-14 was also tried as a building surveillance radar; however, its wide fixed-range gate precluded discrimination and location of targets. Subsequently the swimmer detection radar, the high resolution L-band (915 MHz) system with a 5-foot range gate was used to detect personnel in buildings through brick and concrete block walls. These tests are described in Part I of this section.

9) Based on tests of the X-FOPEN radar in Hawaii against helicopters, a program was established with AVCOM to establish parameters of detection of helicopters flying nap-of-the-earth by VHF radar systems. This program is described in part J of this section.

B. Airborne FOPEN Radar

Work on the airborne FOPEN radar began with a study phase in the fall of 1970 in which data from various target types was collected from three types of moving platforms. These platforms included a truck, a boat, and an aircraft. The radar data was digitized and stored on magnetic tape; processing and analysis of the data was accomplished through the use of a general purpose computer.

The radar system was basically a dual channel ORCRIST Base Station Radar with a cross polarized antenna capable of receiving both horizontal and vertical polarizations simultaneously. Six doppler channels plus range and gain data were converted to 12 bit digital words and recorded on magnetic tape. The field data was later reformatted, demultiplexed and recorded on permanent data tapes for subsequent computer analysis.

The radar and instrumentation system was mounted in succession on a truck, a boat and an airplane (Figures 32 and 33). Data was collected from both open fields and wooded areas. Both moving and fixed targets, which were located through the use of a beacon, were considered.

Analysis of the data was centered around a Univac 1206 digital computer with an interactive keyset/CRT system. Processing techniques including power spectrum and cross power spectrum programs, spectrum mapping programs, and special filtering programs were developed.

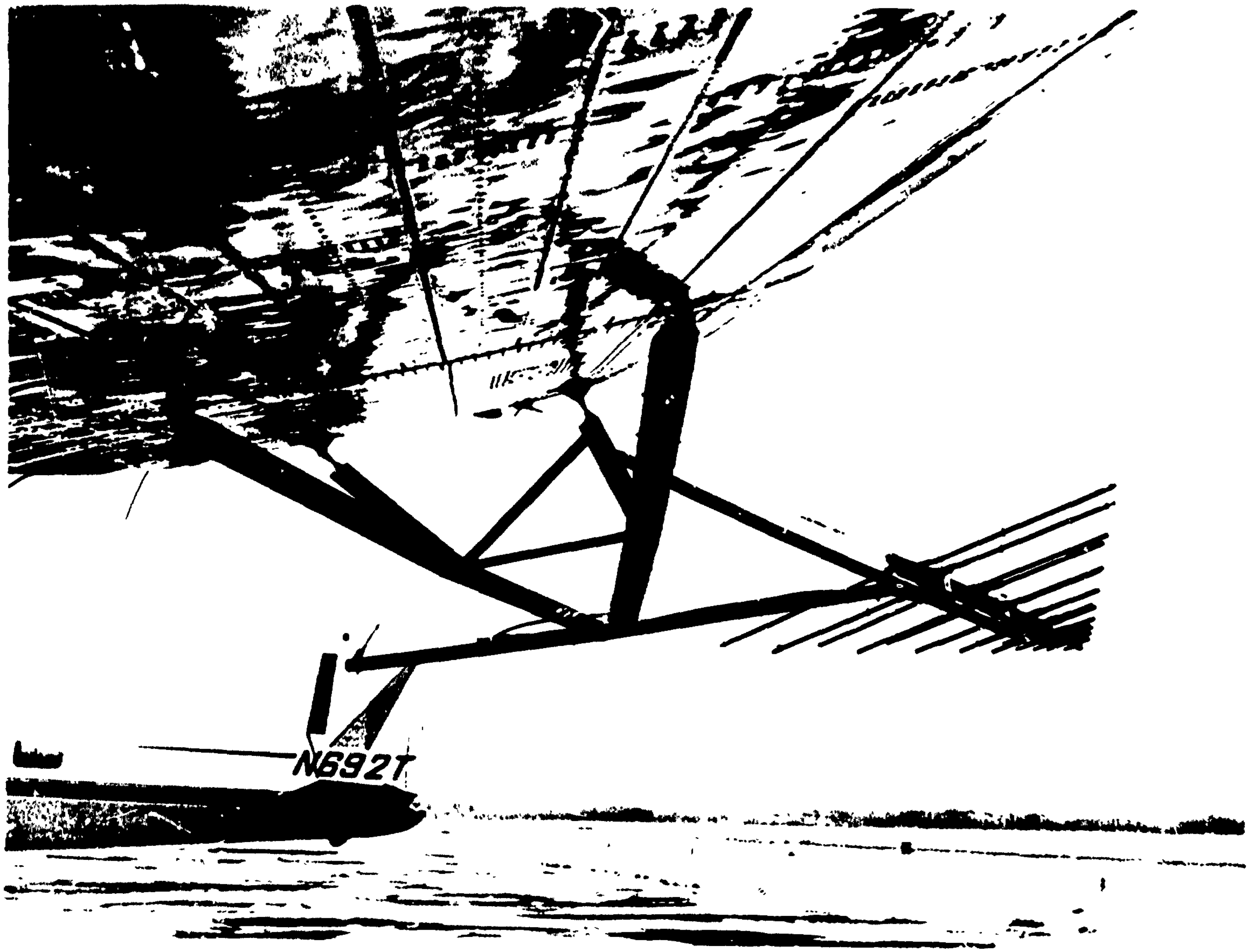


Figure 32. VHF Airborne FOPEN Radar Antenna on the Wing of the DC-3 Aircraft

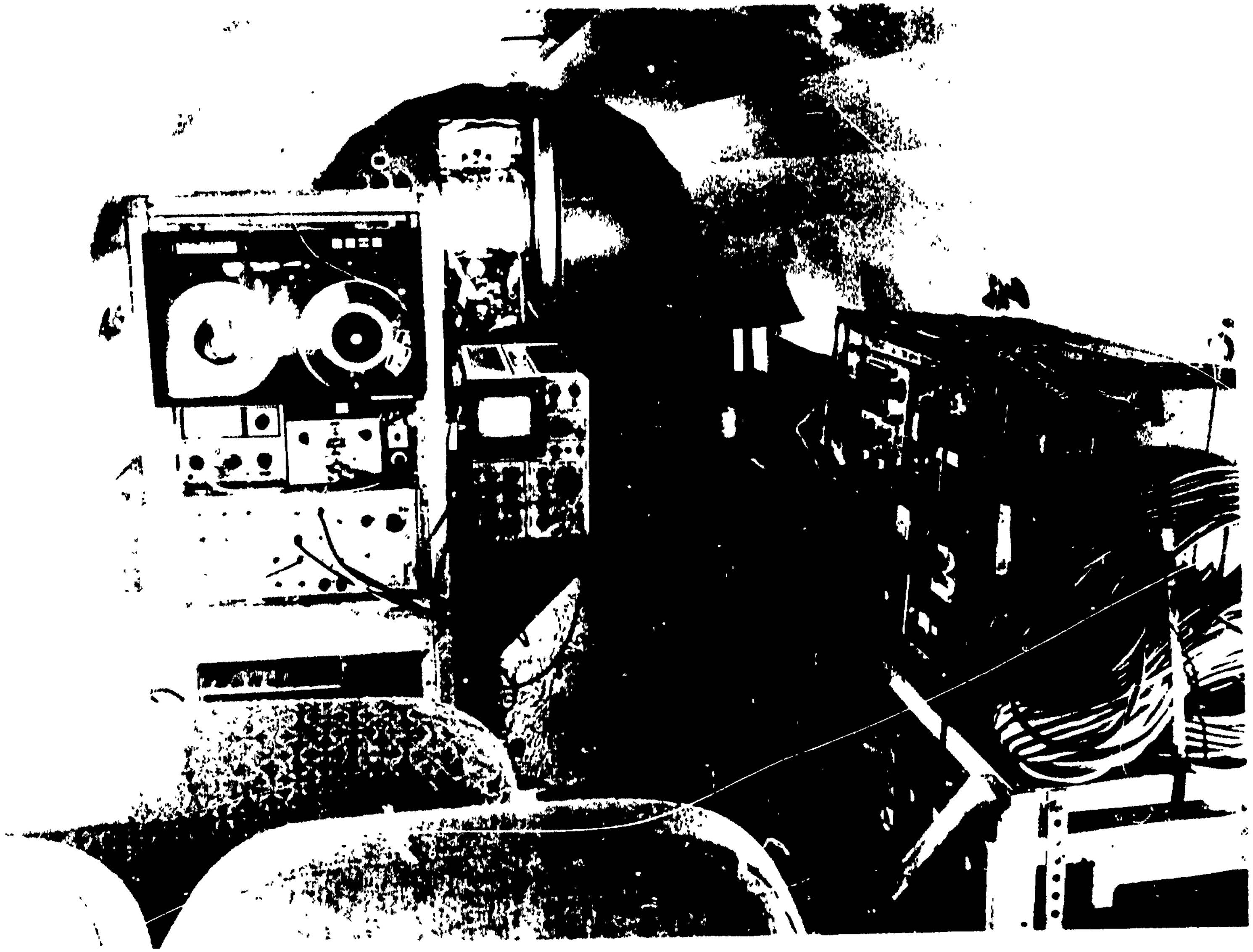


Figure 33. Airborne FOPEN Radar and Data Recording System in the DC-3 Aircraft

One of the primary and most significant results of the program was the development of a process that eliminated, to a large extent, the doppler return from the platform motion. Based on the premise that the clutter was stationary for short terms, a frequency filter was developed based on past clutter history. This filter continually adapted to the clutter environment, and significantly reduced the doppler response due to the platform motion. It was found that fixed as well as moving targets could be identified using this frequency discrimination technique.

As a result of the Moving Platform Study,[22] a hardware development phase was initiated with the objective of providing a fieldable airborne FOPEN radar, see Figure 33, to further test the techniques developed during the study phase.

The developmental processor uses a mini-computer, a hard-wired Fast Fourier Transform (FFT) and a Cathode Ray Tube (CRT) display, Figure 34.

The hard-wired FFT developed by SURC can output a 256 complex point transform at the rate of 150 per second. This enables real-time processing and displaying of the radar data. One of the outputs of the processor is a radar map; the processor also has the ability to display all the spectra and the filtered spectra as they are processed.

The CRT display, shown in Figure 34, also developed by SURC, presents a display frame of 256 by 256 picture elements. Each picture element displays eight levels of gray scale. The entire display frame can be rotated to allow entering of new display data at the top and the discarding of the oldest data at the bottom.

In parallel with the hardware development additional data was collected from an airborne platform. A corner reflector with a 176 square meter cross-section was used as a primary target. Data from the corner reflector was gathered and its empirical cross-section determined through a computer analysis and compared with its theoretical cross-section. The results indicated that the measurement technique was valid and the cross-section of a given area of object could be determined experimentally, thereby laying the basis for target detection predictions in given types of clutter areas.

Data for the development phase was collected from the same basic radar as during the first phase, with the exception that the radar antenna was side looking and horizontally polarized. Two range gates were added to the radar making a total of three range gates rather than one as in the previous testing. Data was collected over water, open fields and heavy forests.

It was determined that the radar cross-section of the foliage was too large to permit reliable detections of concealed targets for the resolution of the measurement system, and a decision made to reduce the operating frequency to 50 MHz. Modifications were made to the data recording system, radar, and antenna, after which additional clutter and calibrated target (a dipole) measurements were made. The results showed a dramatic reduction in clutter cross-section and indicate that a simple static target detection system is feasible.

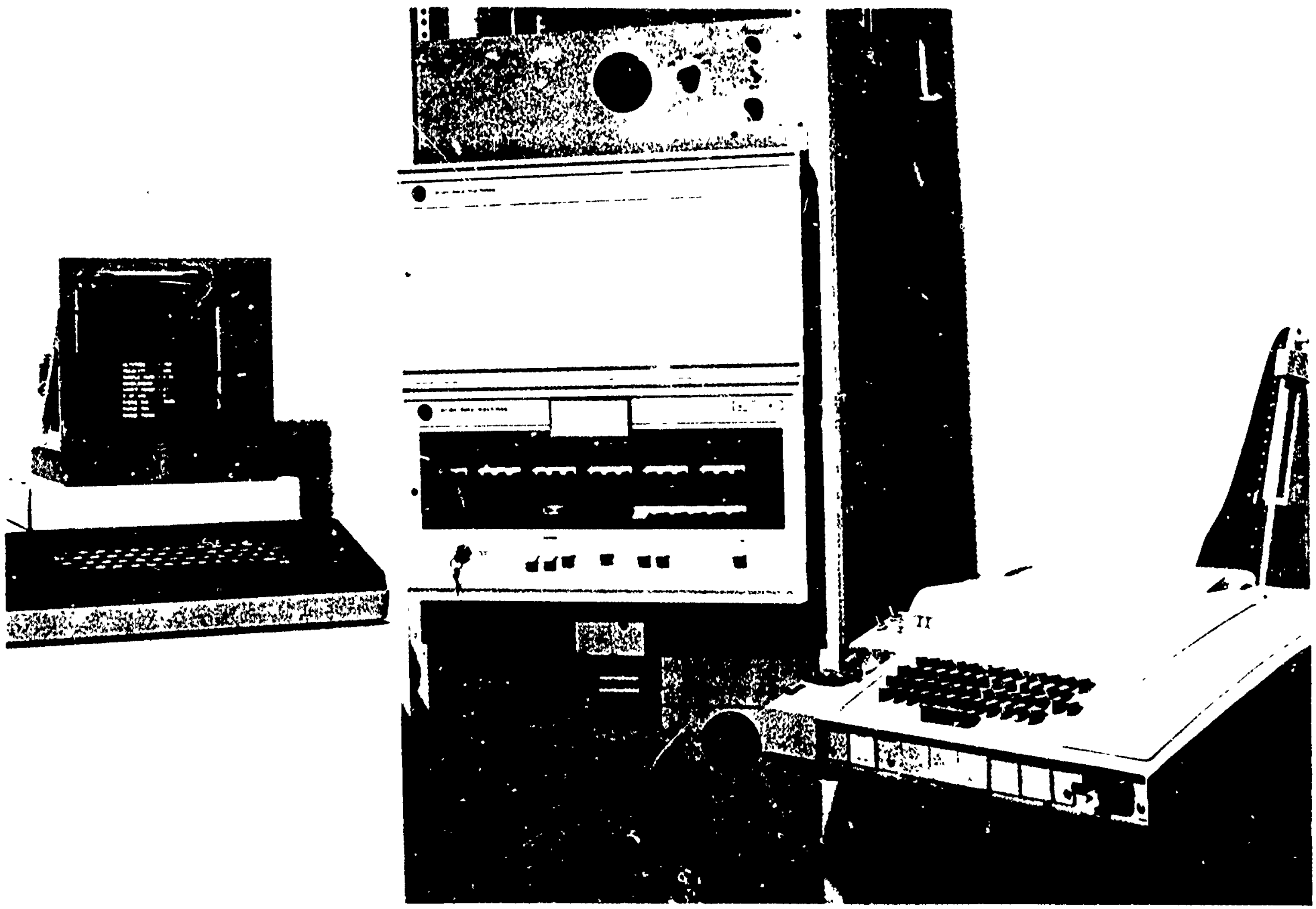


Figure 34. Computer Processing Unit for the Airborne FOPEN Radar

The significant results and conclusions are summarized below:

1) The data gathered at both 140 and 50 MHz was sufficiently reliable and repeatable to enable the measurement of the radar cross-sections of both point targets and distributed targets.

2) Within the parameters of the simple 140 MHz system, sufficient resolution was not available to detect targets concealed by foliage without false alarms.

3) The detection of static targets concealed by foliage has been demonstrated at 140 MHz and sufficient data is available to show the practicality of such a system if the resolution cell were reduced from 100' x 100' to 15' x 15'.

4) Reducing the radar frequency from 140 MHz to 50 MHz effectively reduced the energy received from the clutter by 15 dB.

5) A simple, unfocused, side looking radar is feasible and could be demonstrated with nominal changes to the existing 50 MHz radar. The existing computer signal processor, and display could be flown to demonstrate this radar with only a small programming change.

C. The PPS-14: L-Band Intrusion Detector

To provide surveillance protection against crawling targets at short ranges, experiments were conducted using a CW 1,000 MHz doppler radar system. Tests showed that over bare ground, the maximum detection range was limited only by:

1) Antenna height (ground lobing effect)

2) Average power

3) System resolution (antenna gain, aperture, range cell size)

In foliage, however, two additional limitations are placed on the system; attenuation and clutter. At L-band (1,000 MHz) the attenuation due to foliage is approximately 0.5 dB per meter, which represents a total two-way attenuation through 25 meters of foliage of 25 dB.

These experiments confirmed that, at frequencies much above 140 MHz, the attenuation of the foliage became a critical factor. Even for a high power, high resolution system penetration of more than 50 to 100 meters of foliage becomes impossible.

The Listening Post Surveillance Device PPS-14, Figure 35, is an L-band doppler radar. The range of frequency chosen was such that a degree of foliage penetration could be obtained while realizing a fair trade-off for antenna height and size. The nucleus of the system is the signal processing, both adaptive and balanced, described in Appendix A, which enables the radar to cope with moving foliage. Using this processing scheme, good detection under both high and low wind conditions can be obtained.

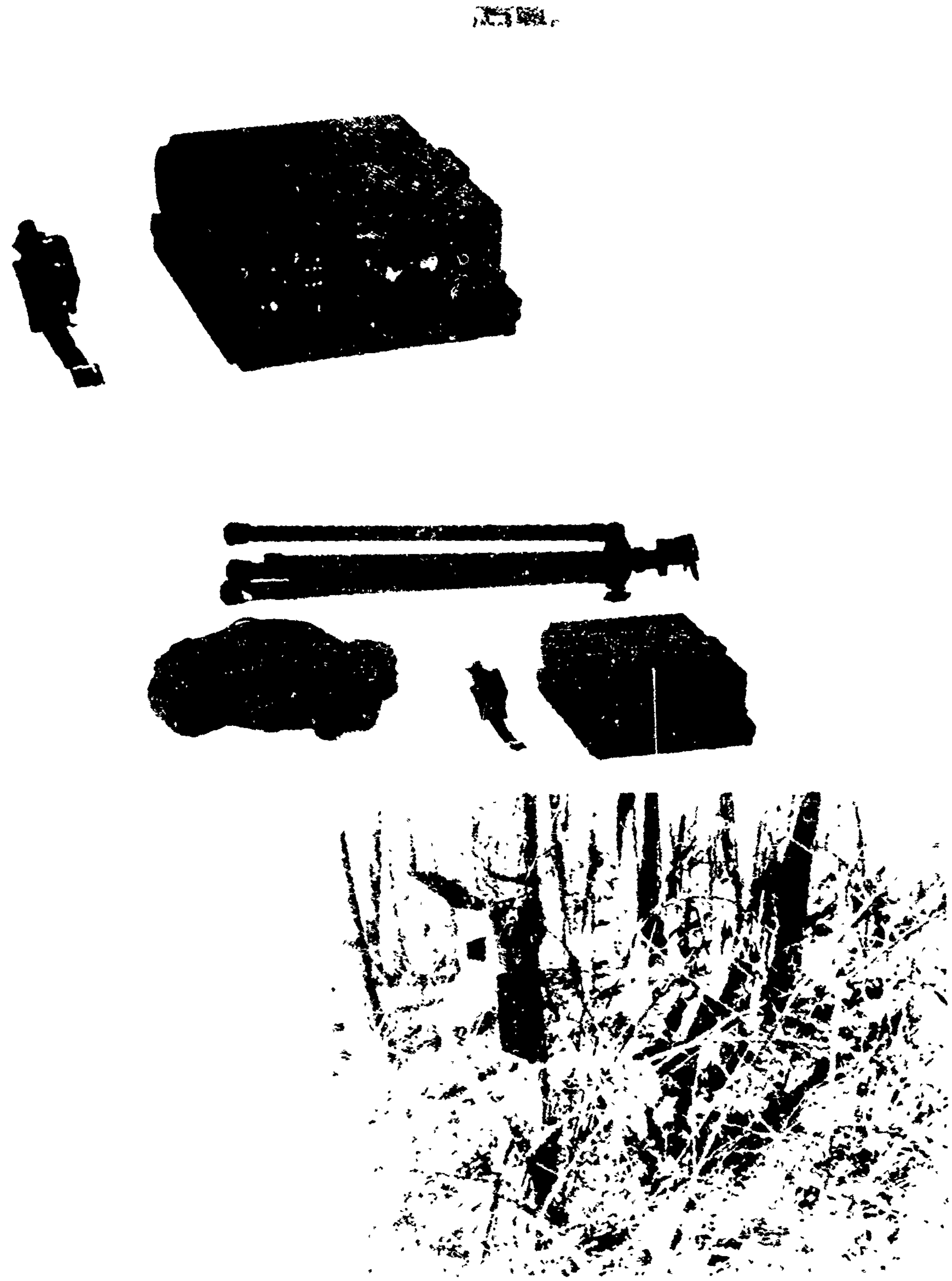


Figure 35. [illegible]

Operationally, the PPS-14 consists of a single unit which can be tree mounted with the stretch cord provided in the carrying pack, supported by an optional tripod, or supported by any convenient means at the discretion of the operator. For best performance the radar should be placed as high as practical (at least 7 to 8 feet preferred), but, in any case, between 4 and 15 feet off the ground. The zone of surveillance is approximately a 60 degree fan-shaped area ranging from approximately 25 to 150 meters. The desensitized zone around the unit is essential to minimize effects of operator motion which could cause false alarms. This zone extends to approximately 25 meters. The system can be deployed and put in operation in about one minute. There are no sensitivity, calibration or threshold controls to complicate usage. The operator pulls upon the antenna reflectors, turns the switch to the ON position, and the radar is in full operation. Complete system and battery test is accomplished by activating a test switch if desired. Battery life is rated at 10 hours continuous use. The total package weighs about ten pounds, including batteries. The alarm has been designed specifically to be consistent with the concept of use. Gallium arsenide lights concealed within the control panel of the unit display the presence and direction of targets without compromising operator position. A wrist alarm is supplied which visually displays target presence and direction while alerting the operator by its vibration. This device is for remote use with WD 1/TT standard Army field wire.

Basic capabilities and limitations of the system have been established as a result of LWL field tests and the MASSTER and Vietnam Evaluations. Maximum range data obtained to date indicates that a walking man can be detected through about 40 meters of heavy brush and out to 100 meters in the open. Maximum range data for a crawling man vary from 20 meters to 40 meters, depending on environmental conditions. Slowly moving vehicles can be detected at maximum ranges from 50 to 130 meters depending on environmental conditions. Canoes have been detected moving up to 50 meters from the system. Multiple targets will enhance detectability under any conditions.

The PPS-14 was tested by MASSTER, Ft. Hood, TX in June 1970. A 98% probability of detection was achieved with no false alarms.[23] Subsequently, it was evaluated in SEA as an intrusion detector[24], and more recently, as a building surveillance device.

D. Automatic Alarm for the PPS-4 and PPS-5 Radars

The non-coherent signal processing study was published in April 1969.[5] As a result, Mr. Aaron Galvin of Aerospace Research, Inc. came forth with a new signal processing concept, which enabled automatic detection of moving targets when used with either a coherent or non-coherent radar.

Under high clutter conditions experienced when targets are to be detected in vegetation and in which the clutter spectrum is variable, it is possible to help the situation considerably by introducing adaptive filtering. In adaptive filtering, the cutoff frequency of the highpass filter is variable and is set in a feedback system by the amount of clutter residue energy which appears at the filter output. Instead of requiring the permanent sacrifice of low-velocity target detection, this type of processor rejects low velocity targets for only those portions of time where the wind is blowing severely. As soon as the wind subsides, the cutoff frequency of the filter decreases to a lower value, which reintroduces high sensitivity to low velocity targets. If the parameters of the system are chosen properly, it is possible to perform good detection of targets while maintaining a very low false alarm rate.

The Model AU-1040 Adaptive Signal Processor was developed by ARI and supplied to the Land Warfare Laboratory. The device contains two processing channels, one of which is built around a three-pole electronically variable active highpass filter, Figure 36, and is used in a feedback arrangement shown in Figure 37, to provide normalization of the filtered clutter residue. The other channel uses a five-pole filter feeding an optimal time-on-target integrator followed by a latching threshold and alarm. The filter response pair can track over a doppler frequency range somewhat in excess of an order of magnitude. The use of a lower-slope filter response (18 dB per octave) in the adaptive control loop provides increased clutter energy (because the major portion of the clutter energy is at a lower frequency) for the operation of that loop and provides a high degree of protection for the 30 dB per octave highpass detection channel against effects of time-varying wind-excited clutter motion. A moving target can only stay in a range resolution cell for a limited amount of time; hence, that target will cause only a small amount of filter adaption -- not enough to cause a significant amount of self-cancellation and resultant loss in target detectability; the time constant of the clutter-residue integrator is much longer than that of the detection channel. If there is a normal buildup of wind, however, the clutter energy will gradually redistribute itself in doppler frequency in such a way as to produce greater energy at higher frequencies. This is a situation in which the adaptive filter will continuously adjust itself to provide a low clutter residue for the detection channel and, hence, a low false alarm rate is obtained. If the wind subsides, the higher frequency portion of the clutter energy is reduced and the filter retunes itself to a lower cutoff frequency to provide very low velocity target detection.

The adaptive processor was tested extensively with the non-coherent 140 MHz radar system. Although the radar was able to detect targets automatically and maintain a very low false alarm rate, certain limitations in the design of non-coherent radars forced a change to a coherent system. As a result, the adaptive processor without modifications was tried with the PPS-4 radar during the Panama test in September 1968, (the PPS-4 is a microwave -- X-Band -- non-coherent ground surveillance radar which had been obtained for comparison purposes). Personnel and vehicular targets were automatically detected with the alarm even when the range gate of the PPS-4 contained some foliage.

As a result of these tests, a separate task was established for the purpose of fabricating six hardened systems for operational evaluation. Three each, Figures 38 and 39, with the characteristics of Table 4, were evaluated in the fall of 1969 in RVN and Korea. During the six-month evaluation, none of the units required maintenance. In all cases, the alarm's detection capability was the same as or better than a well-trained operator. In Vietnam, the alarm actually increased the range at which detections were made, due to a substantial reduction in operator fatigue.

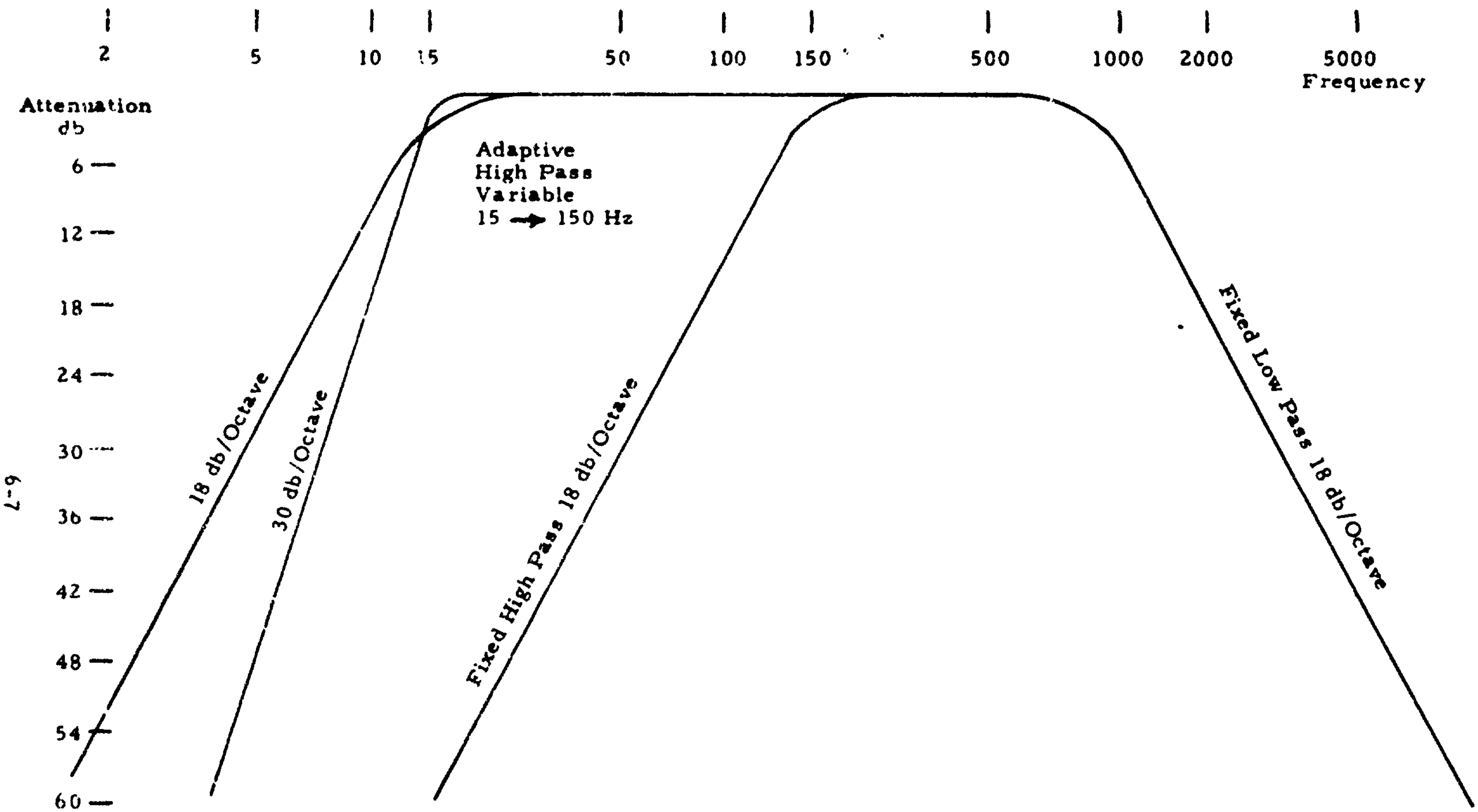


Figure 36. Adaptive Processor Filter Characteristics

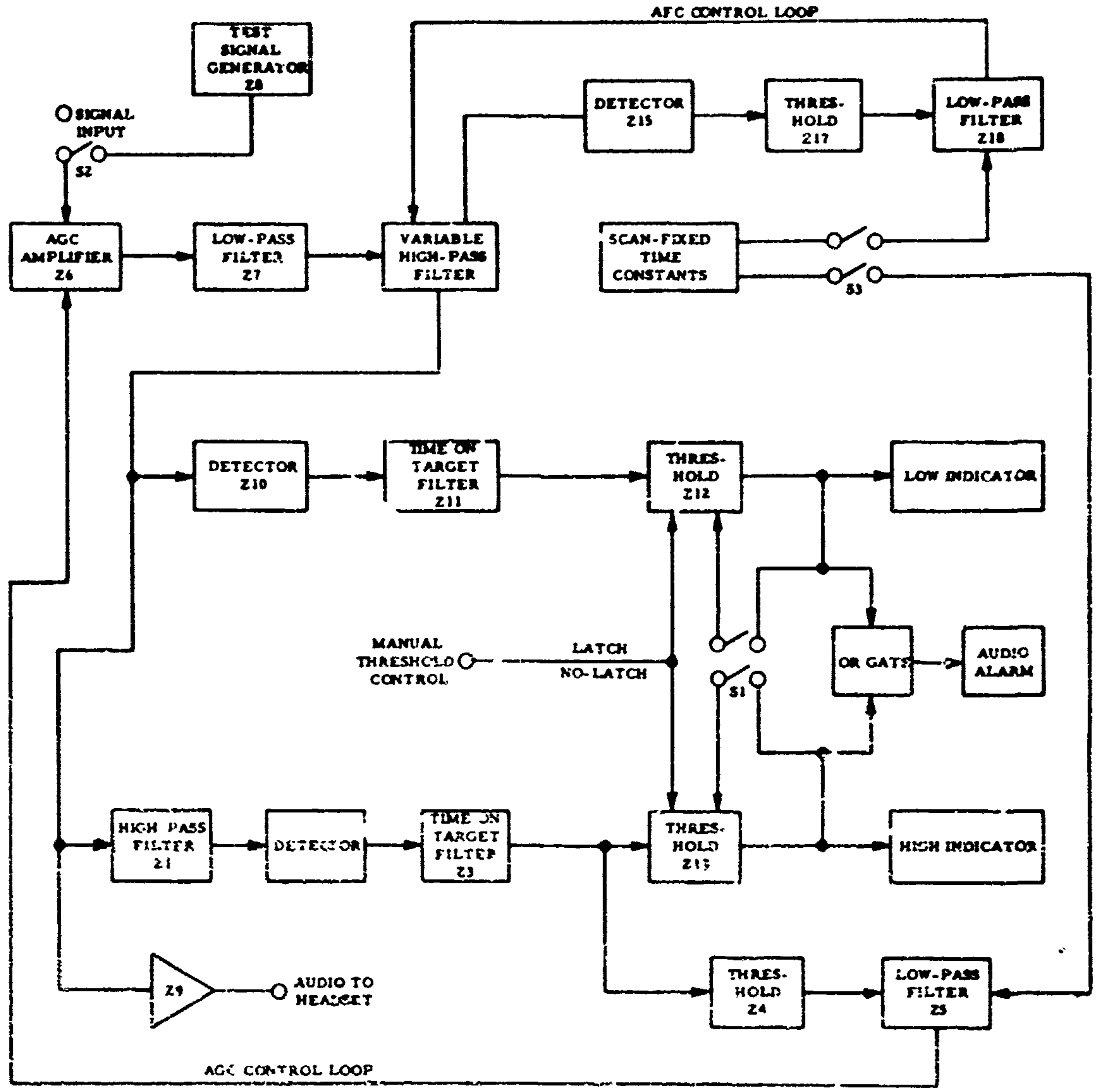


Figure 37. Automatic Alarm Block Diagram

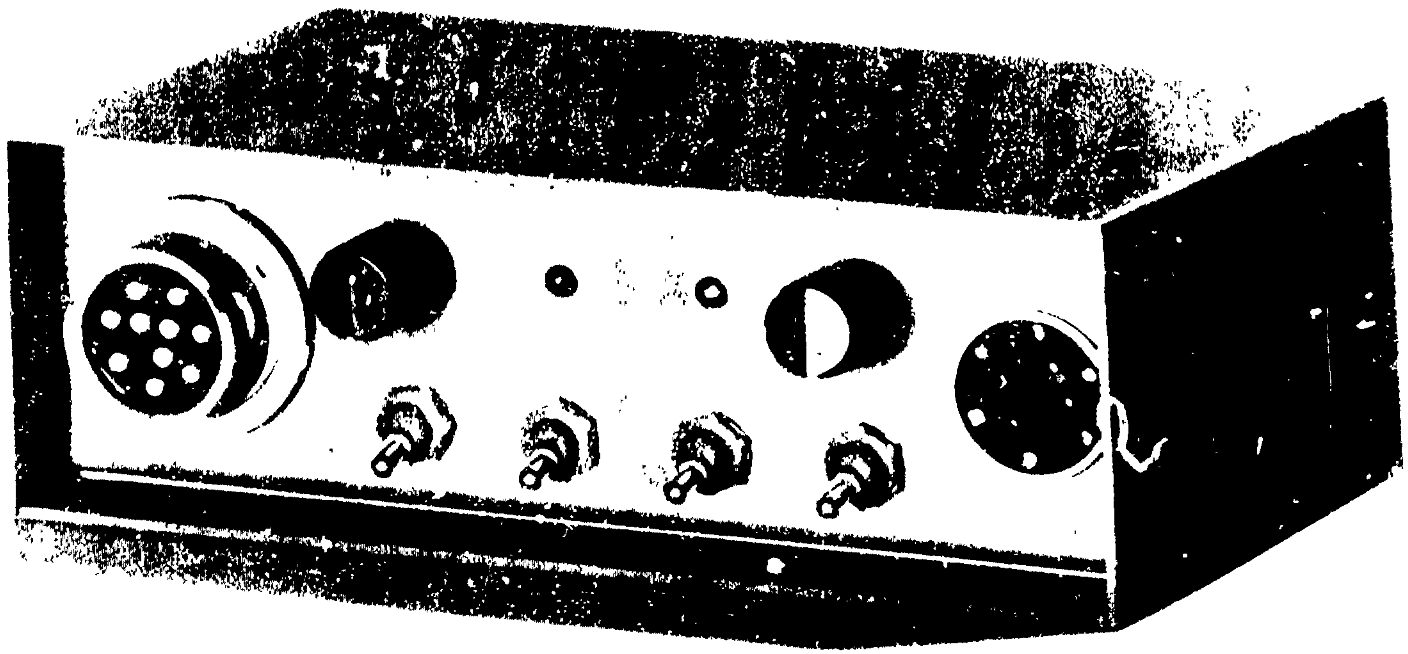


Figure 38. Basic Automatic Alarm for the AN/PPS-4 or -5 Radars

TABLE 4. ADAPTIVE PROCESSOR SPECIFICATIONS

Input:	Inband signal for alarm, 7.8 mv peak
Outputs:	Audio alarm High and low velocity indicator lights Processed signal to headphones
Thresholds:	Target threshold 1V Clutter residue thresholds (8 dB below target threshold) 0.4 V
Inband Gain:	42 dB 12 dB (with full 30 dB AGC)
Low Pass Filter:	Three-pole Butterworth with KHz cutoff frequency
Adaptive Filter:	Three and five-pole Butterworth with cutoff frequency normally 15 Hz, controllable to 150 Hz
High Pass Filter: (High Velocity Channel)	Three-pole Butterworth with 150 Hz cutoff frequency
Power:	30 ma @ +6 V 30 ma @ -6 V
Size:	2" x 4" x 6" HWD
Temperature:	$-55^{o}C$ to $+55^{o}C$

The PPS-4 has two basic modes of operation: a stationary range-gate mode and a scanning range-gate mode (in the scanning mode there are actually two modes, one short scan of 200 meters and another longer scan of 500 meters.)

The automatic alarm demonstrated its ability to detect walking man targets either when they were in a clear area or in an area in which a considerable amount of blowing foliage occupied the same resolution cell as the target. In all cases when foliage in the cell was blown by the wind, operator detection by earphone became nearly impossible. Under the same conditions, the automatic alarm adapted to the background conditions and still provided reliable detection. The foliage penetration capability of the radar is, of course, limited because of the greater-than-4 dB per meter of attenuation that would be experienced.

E. RADPAVE: Discrimination Between Tracked and Wheeled Vehicles

LWL has been continuing experiments to gather data on the radar cross-section of various targets so that technology developed in low frequency radar could be furthered. In examining the return at L-band from wheeled vs. track vehicles, certain higher frequency components were present in the doppler spectra of the tracks. It was determined that these components resulted from motion of the treads of the vehicle. Since the treads move forward at a speed twice that of the vehicle, the return signal from the treads appears at precisely the second harmonic of the base doppler frequency. A PPS-14 was modified with two harmonically related doppler bandpass filters located at the output of the sample-and-hold circuit. Figure 40 shows a portion of audio data recorded of an M-60 tank moving through the range cell at 5 mph radial velocity and 45^{o} incidence to the radar. Channel one is the basic doppler return; from the fundamental filter, channel two is the output of the second harmonic filter designed to remove the fundamental frequency with 20 dB voltage gain over channel one.

The results dramatically indicate the presence of a second harmonic type signal. No such signal was present for wheeled vehicles or test targets. These results fit our original criterion in that the tread size is approximately equal to one wavelength. This concept is being pursued both as an adjunct to a ground surveillance radar and as a remote discrimination sensor.

F. The Ultrasonic Radar

A large number of ultrasonic intrusion devices have been developed principally for indoor intrusion detection. These systems are generally ultrasonic radars without balanced signal processing. They are prone to false alarms from vibrating walls, drapes, blinds, the displacement of air from rotating fans and ultrasonic noise interference. A typical system consists of a 20 to 40 kilohertz ultrasonic source, microphone detectors, receiver/audio amplifier, rectifier and integrator, and an automatic threshold alarm circuit.

During the development of the signal processing for the FOPEN radars in 1968, Aerospace Research, Inc. (ARI) demonstrated the significant improvement to ultrasonic radar systems obtained with the addition of balanced signal processors. The effect is the same as that obtained in the FOPEN radars, namely, that of cancellation of vibratory motion in the field-of-view when there

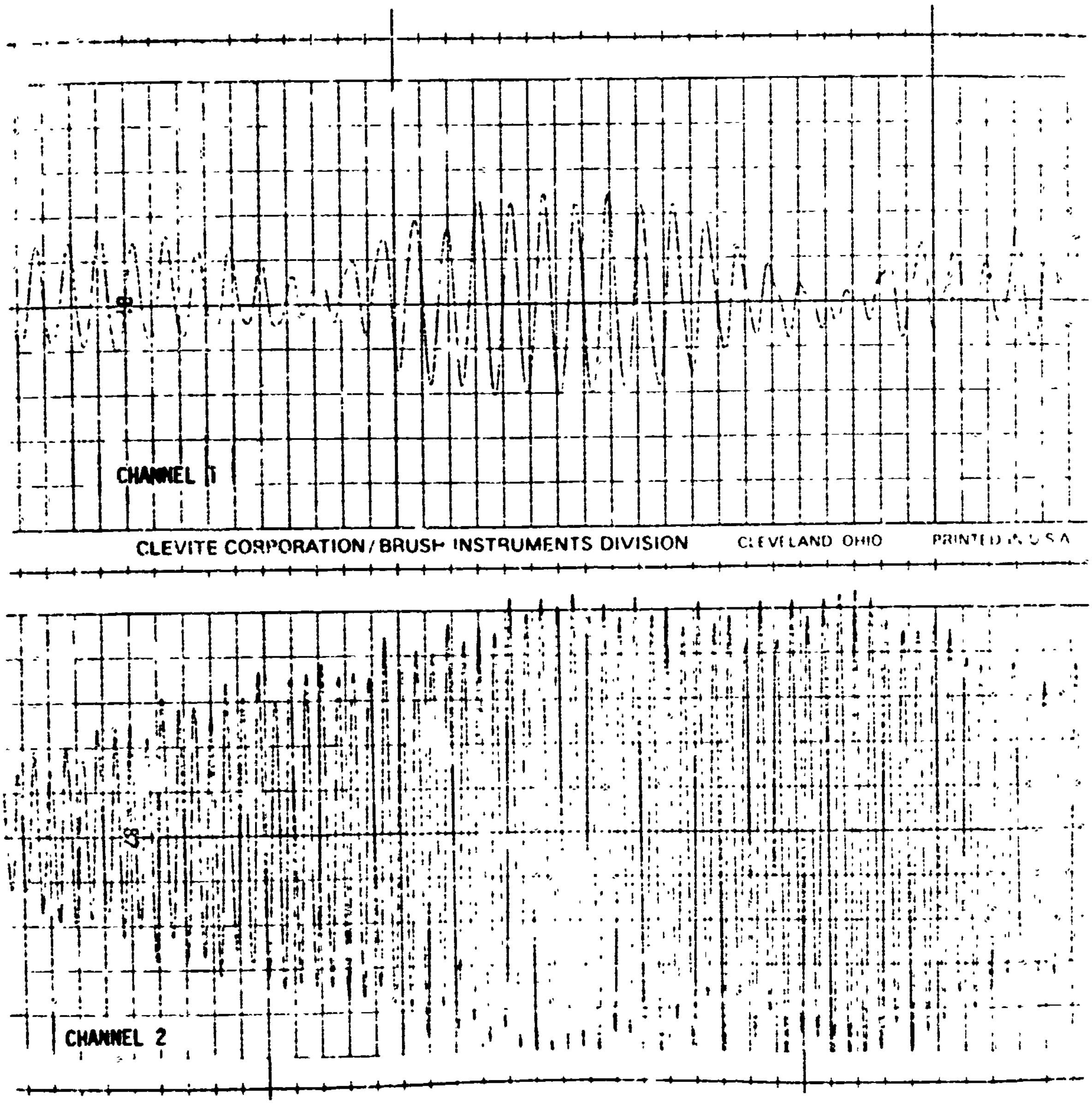


Figure 40. Harmonic Doppler Return from a Tracked Vehicle

is no net motion over the duration of the signal integration time. Thus, the real intruder target has a greatly increased probability of detection, and false alarms are virtually eliminated.

LWL initiated a program in 1968 to pursue the commercial ADVISOR V produced by ARI as an interior intrusion detector. The objective of this program was to evaluate a basic intrusion detection system for arms room protection. "Volume coverage" (as opposed to monitoring only doors and windows) was considered essential for this system; ultrasonic radar was selected as the primary detection mode that would best provide this type coverage. Based on these initial guidelines, the ADVISOR V ultrasonic motion detector was chosen as the detector component for the Arms Room Security System (ARROSE). An additional advantage of ultrasonics over electromagnetics is that ultrasonics are reflected from windows and walls, thus bounding the sensor inside the structure or room. Electromagnetic systems (radars) can penetrate the walls of the facility and cause false alarms from legitimate outside activity.

Various other components such as battery chargers, local and remote alarm units, system arming time delays, etc. were either purchased or built at US Army Land Warfare Laboratory (USALWL) and combined into a security system capable of reliably detecting and relaying intrusion information. The complete ARROSE system provided a means of evaluating the ADVISOR V detector.

ARROSE systems were installed for test and evaluation in two locations at Aberdeen Proving Ground (APG) and in three locations at Danang, Vietnam. Both systems at Aberdeen and two of the systems at Danang performed excellently. They were simple to install and could be maintained with a minimum of training. The systems at APG had no failures in over two years of operation. The third system at Danang had to be returned to USALWL because of intermittent malfunctions. Those malfunctions were later assessed, based on laboratory tests, to be caused by frequent power failures at the installation site, which resulted in a gradual degradation of the backup batteries.

The AN/FSS-8 (ADVISOR V) shown in Figure 41, is an ultrasonic doppler motion detector which contains a unique type of signal processing to minimize false alarms. This unit can be used with up to twenty transceivers for either single or multiple room installations. Tamper circuitry is provided to reduce vulnerability of the installation. The ADVISOR V operates on 16 VAC and has a 4-hour rechargeable battery back-up supply. The output from the unit is either a normally open or normally closed switch. This switch activates the Alarm Control Module to relay the alarm information to local or remote monitor points.

The transceiver unit, shown in the figure contains transmitting and receiving transducers and operates at a frequency of 26 KHz. They are normally mounted on walls or partitions and positioned (aimed) to protect a given area. Each transceiver provides an elliptically-shaped volume of coverage approximately 30 feet wide and 40 feet long, when properly installed in an area relatively free of air turbulence. The most effective protection is provided in areas within line-of-sight of the transceiver.

The Alarm Control Module, shown in the figure contains a timer, two transformers, batteries and relays. The module provides control circuitry for battery

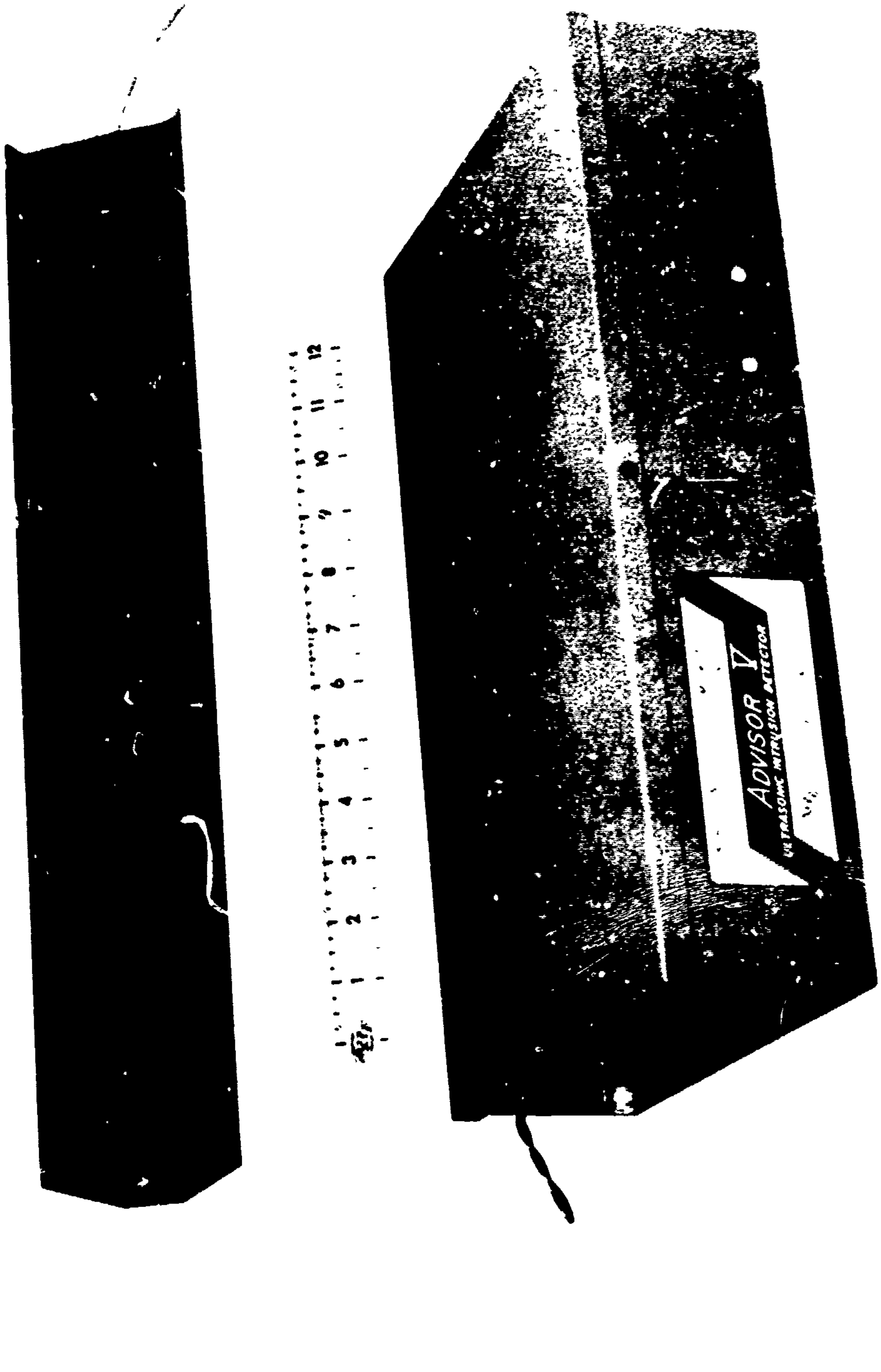


Figure 41. The Advisor V Ultrasonic Radar

charging, desk monitor operation and system arming, as well as a local alarm to alert personnel in the immediate area of an intrusion condition. Mounted on one end of the module is the arm switch and two fuze holders. The fuzes are in the 110 VAC line and the battery control circuit.

The arm switch and timer allows the operator to turn the system ON and then leave the protected area without causing an alarm. The operator has approximately two minutes to vacate the area before the alarm system becomes operational.

G. Line Intrusion Detector (LID)

The Line Intrusion Detector concept evolved from a need observed at a NIKE site in Korea for a low-cost line sensor that could be used around the perimeter of a building, fence, or installation and yet be bounded so as not to detect targets more than a fixed distance away. This is not possible with conventional radars; and seismic detectors detect, not only a man 20 feet away, but also a truck or train a mile away. Hearing of the problem, Dr. James Rodems of SURC decided to build a prototype detector using a Goubau transmission line and an L-band intrusion detector. The prototype was then tested by LWL under the Generation of New Ideas (GNI) Program and a formal follow-on program was initiated.

The Goubau line is a single wire transmission line which can be used as a means of propagating a non-radiating wave. The surface wave transmission line (SWL) goes back to 1898 when Sommerfield[26] derived the field of a non-radiating wave which is guided by a single wire of finite conductivity. In 1907, Harms[26] applied Sommerfield's theory to an insulated wire in order to explain why the resonant wavelength of an antenna made with insulated wire is greater than that of plain wire. Subsequent experiments with a wire connected to a transmitter showed no evidence of a surface wave; only the radiating wave was excited. More recent work has shown that both radiating and non-radiating waves exist simultaneously; their presence may be derived, theoretically, from Maxwell's equations by satisfying the boundary conditions on the wire and the mutual orthogonality relations between radiating and guided (non-radiating) fields.

In order to excite predominately the surface (guided) wave, a launching device must be used which preshapes a field to match the field distribution of the surface wave. The launching can be done by means of a metal cone which is connected to the outside conductor of a coaxial feed line. The outer diameter of the cone is gradually increased until it is so large that it no longer affects the field significantly. This results in a field distribution at the end of the cone that approximates that of the surface wave along the wire. The amount of energy lost over the wire (including launchers) consists of four parts: conductivity loss in the wire; loss in the dielectric coat; radiation losses resulting from a partial excitation of the radiating wave by the launcher, and parasitic losses, such as those due to bends in the wire or metal near the wire.

The initial experiments were performed with a 915 MHz continuous wave (CW) commercial radar because of its availability (see Fig. 42). Two foam-filled

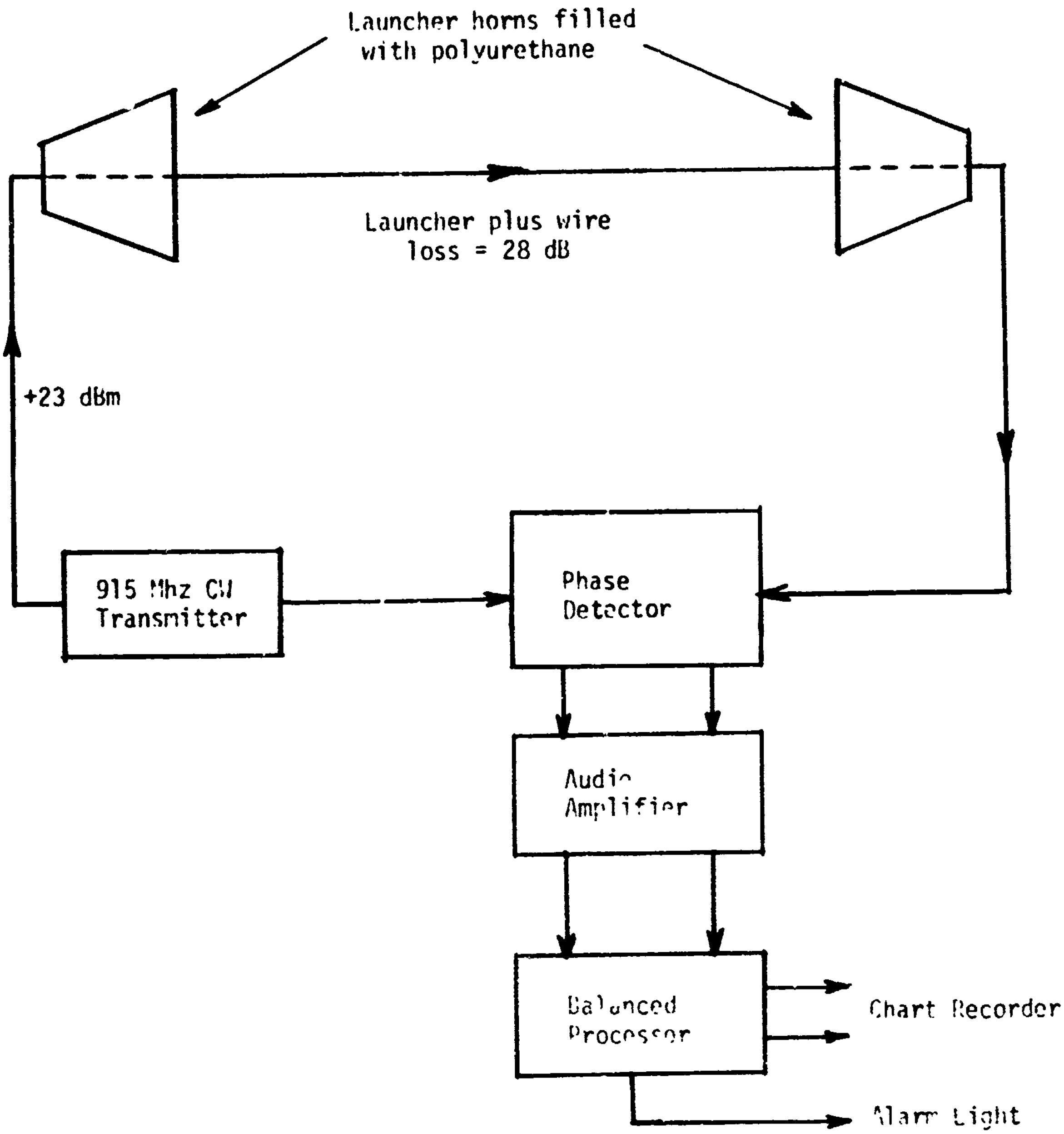


Figure 42. Block Diagram of the Line Intrusion Detector

horns with a type 'N' coaxial fitting were fabricated and 300' of #14 enameled wire was extended from the center conductor of one horn to the center conductor of the other. The losses measured from the input of one horn to the output of the other were 28 dB. This compares to data taken by Goubau showing 3dB/100' for 1000 MHzs and #12 wire and 2dB launch loss at each end, or 13dB total.

Detection experiments were performed with the configuration of Figure 43, with the wire suspended in a hallway using the 915 MHz Radar. Personnel were readily detected up to 6 feet away from the wire, with some increase in sensitivity noticed near the launchers.

Although there was no radar clutter in the standard sense, motion of the loosely suspended wire induced doppler energy into the system with the same characteristics of moving foliage. Since the radar was coherent, the energy was distributed about zero and was capable of being processed by the radar's balanced processor (see Appendix B for a description of balanced processing.)

Subsequent testing both indoors and with the wire suspended on wooden stakes outdoors has shown that the radiated energy is confined to a region within 6 to 8 feet from the wire. Personnel moving radially or tangentially (to the wire) could be detected up to a distance of 6 - 8 feet, however, vehicles moving 15 feet away were not detected. After the sensitivity and time constant of the balanced processor were adjusted, the unit was installed indoors at LWL, suspended from the ceiling by 18" plastic hooks. The system was operated 24 hours a day for 3 days, with no uncorrelated (false) alarms.

Based on the success of the preliminary tests, a program was established to fabricate a 1000' section of Goubau line with optimized launchers to overcome line losses and modify a commercial microwave intrusion alarm for the ARI ADVISOR X for the radar and balanced processing. The resulting system will be further tested for external perimeter protection at an Air Defense artillery site or similar area.

H. A Swimmer Detector System

Swimmer Detection tests were performed under the LWL Task 07-P-71 Detection of Submerged Targets by Aerospace Research, Inc.[27] to provide measurements of radar characteristics of targets (swimmers) and clutter (water surface) for use in the design of a swimmer detection radar system. Preliminary measurements using the LWL PPS-14 radar had indicated that swimmers could be detected under some conditions.

Initial measurements were made using two CW doppler radars, one operating at 140 MHz and the other at 915 MHz. Spectral characteristics of clutter return and target return characteristics under various water surface conditions were recorded.

The 915 MHz CW radar was then modified for operation as a high-range-resolution pulsed system. The introduction of a high-resolution signal resulted in swimmer return-to-clutter ratios sufficiently high for automatic detection.

Figure 43. Views of th[illegible] corridor

Figure 44 is a block diagram of the CW radar measurement system, Figure 45 the pulsed radar measurement system, and Table 5 a summary of the parameters of the three systems used.

Three basic types of measurements were made using both CW and pulsed radars. The first type consisted of spectral density plots of clutter return from water surfaces under various conditions of wind and wave activity. The second type of measurement consisted of signal return amplitude vs. time recordings from an 18-inch diameter spherical test target moving radially with respect to the radar antennas while suspended in free space from a wire and also towed on the water surface. The third type of measurement consisted of signal return amplitude vs. time recordings from swimmers moving radially with respect to the radar antennas both with and without SCUBA equipment.

Outdoor measurements of clutter spectra were made at a test site along the Charles River in Brighton, Massachusetts. The antenna was placed at the water's edge in an area free of vehicular and pedestrian traffic. Vegetation in the immediate vicinity of the radar was limited to low growing brush. The clear-water area extended well beyond the radar range for almost 180° in azimuth.

A second test site was used for calibration of the measurement system using the test sphere target in a "free space" environment. The target was suspended from a trolley which ran on a wire stretched between two trees. The radar antenna was mounted near one end of the wire and pointed along the target path. The target path was 8 - 10 feet off the ground. The target was manually towed along the wire.

Indoor tow tests and swimmer tests were conducted at the Boys Club swimming pool in Waltham, Massachusetts. The radar antenna was positioned six feet above the water surface and was directed across the pool with its line-of-sight pointed at the water surface at the midpoint of the pool. The test target was manually towed on the water surface along the antenna line-of-sight using a pulley and line arrangement which kept the operator out of the antenna beam. During swimmer detection tests, the swimmer moved along the same path.

A random wave pattern was generated in the pool by disturbing the water surface in one corner of the pool. Multiple reflections from the sides of the pool produced waves with amplitudes up to 4 inches in height.

Outdoor swimmer detection tests were conducted at the Massachusetts Institute of Technology Boathouse on the Charles River in Cambridge, Massachusetts. The radar was located on the boathouse dock with the antenna directed at the water surface 30 feet from the dock. The swimmer and test targets moved along a line extending from the antenna to a piling about 60 feet out from the edge of the dock.

The results of the tests provided the following information:

1) <u>Clutter Spectra</u>

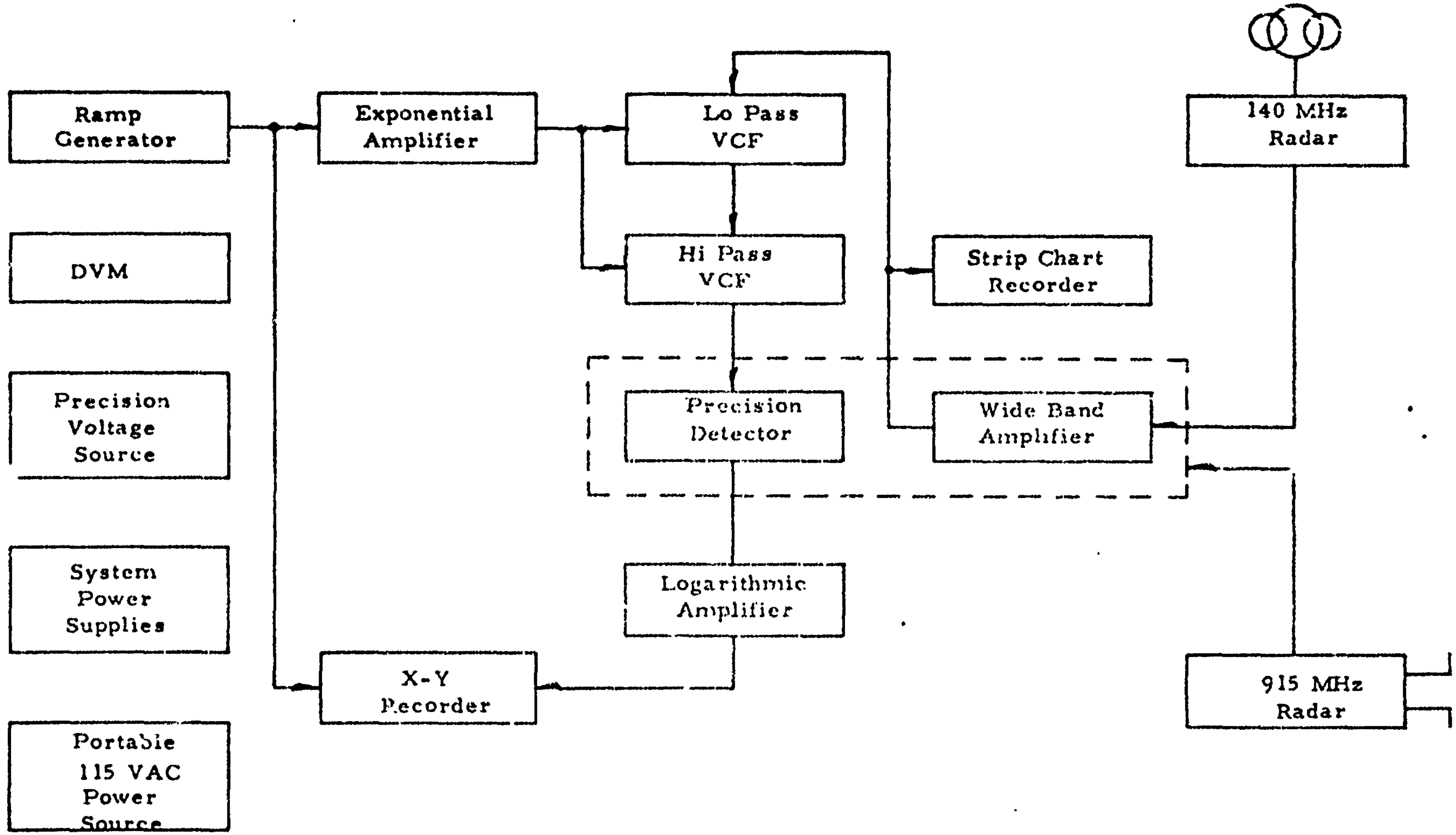


Figure 44. CW Radar Measurement System Block Diagram

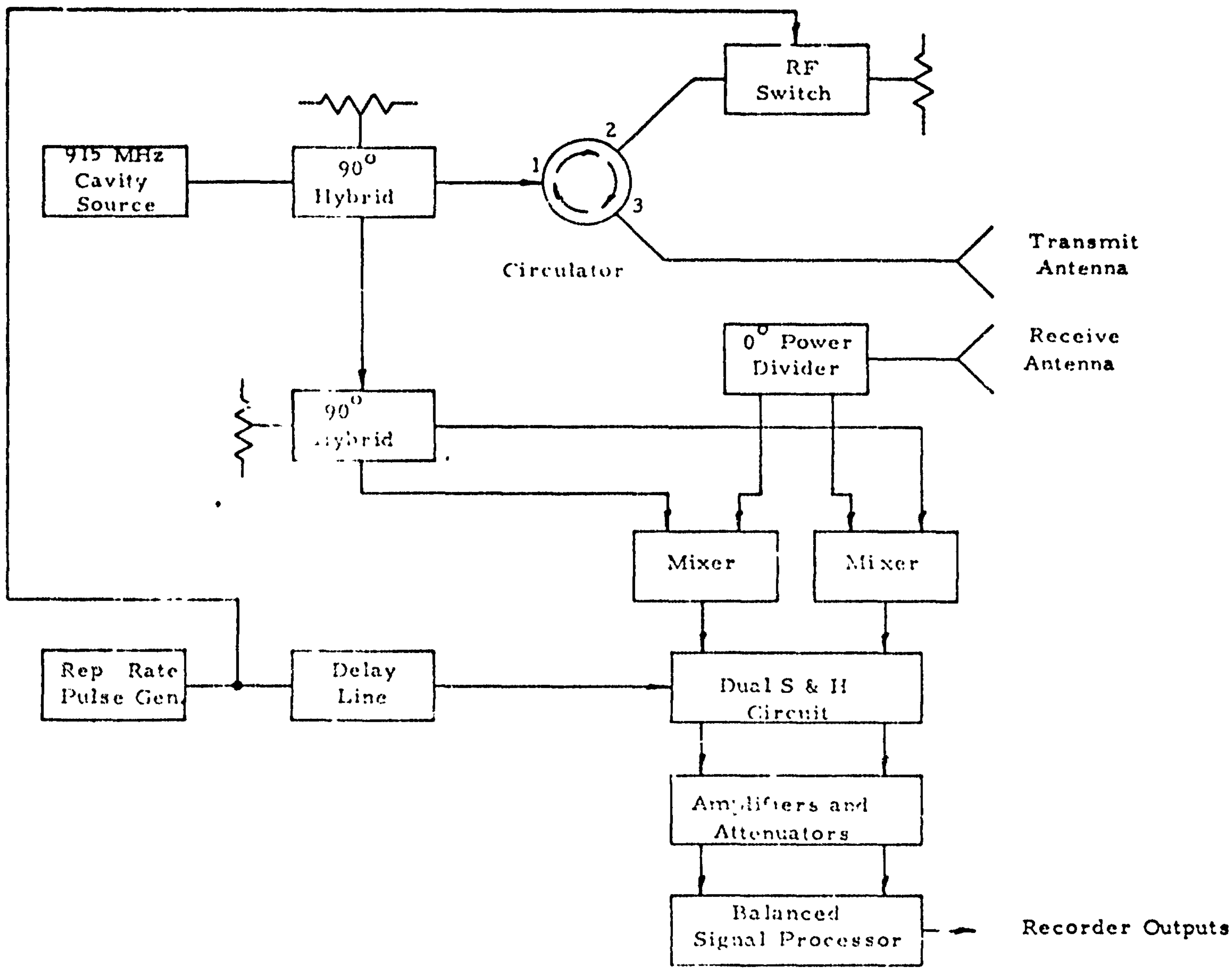


Figure 45. 915 MHz Pulsed Doppler Radar Block Diagram

TABLE 5. SPECIFICATIONS OF THE SWIMMER MEASUREMENT RADAR SYSTEMS

ITEM	SPECIFICATION	SPECIFICATION	SPECIFICATION
Type of radar	Coherent doppler with homodyne quadrature detection.	Coherent doppler with homodyne quadrature detection.	Pulsed coherent doppler with homodyne quadrature detection.
Operating frequency	915 MHz	140 MHz	915 MHz
Modulation	Continuous Wave	Continuous Wave	20 nsec pulse at 1 MHz rate
Average output power	150 milliwatts	20 milliwatts	150 milliwatts
Receiver gain (max)	90 dB	110 dB	90 dB
Signal processing	Balanced, non-adaptive, single velocity band	Balanced, non-adaptive, single velocity band	Balanced, non-adaptive, single velocity band
Antenna	Dual antenna, each a monopole plus three-plane reflector. One used for transmit, one for receive; gain = 8 dB	Single tri-loop antenna shared for transmit and receive; gain = 12 dB	Dual antenna, each a monopole plus three-plane reflector. One used for transmit, one for receive; gain=8dB(apx)
Range resolution	None	None	Determined by fixed delay line nominally set to 20 feet.

a) For water surface waves with amplitudes up to 4 inches, the clutter spectra exhibits a sharp peak within the doppler band of interest for swimmer detection at both 140 and 915 MHz. Most of the clutter energy lies in a very narrow band around the spectrum peak.

b) The peak frequency varies only slightly (less than 2 octaves) for a wide range of wave conditions.

c) The peak amplitude is a direct function of surface activity.

d) The vertically polarized return is stronger (by up to 20 dB) than the horizontal return for low angle grazing beams.

e) The velocity of windblown waves on the water surface appears to the radar as an unbalanced doppler return and may be detected as a target, whereas the return from a random wave pattern, i.e., waves with no net surface velocity, is suppressed somewhat by balanced processing.

f) The general character of the clutter spectra is the same as measured by both CW and pulsed systems.

2) Target Returns

a) The 140 MHz and 915 MHz CW radars were capable of detections of a swimmer on the water surface to a range of 30 feet under calm conditions, using either vertical or horizontal polarization.

b) The 915 MHz CW radar detected a SCUBA equipped swimmer 2 feet below the surface at ranges up to 15 feet under calm conditions using vertical polarization, although the detections may be based on a surface effect caused by the water displacement of the subsurface swimmer.

c) Reliable swimmer detections were not possible with either CW radar when the water surface was disturbed substantially.

d) The 915 MHz pulsed radar produced a much improved target to clutter ratio over either CW radar.

e) The 915 MHz pulsed radar was able to detect a surface swimmer in calm or moderately disturbed water at a range of thirty feet. This range was limited by the fixed range gate position of the radar. Detection should be possible at considerably greater ranges since the target to clutter ratio for the pulsed system varies roughly as 1/R.

f) An underwater SCUBA equipped swimmer was also detected in calm water at a 30 foot range by the pulsed radar using vertical polarization. The amplitude of the return appeared to be strongly dependent on the position of the swimmer's air tank.

g) Vertical polarization produced the strongest target returns and some apparent surface penetration.

h) Based on comparison with test target of known cross-section, a swimmer with head only above water has a cross-section of about 0.1 ft.^{2} at 140 MHz.

i) Based on comparison with a target of known cross-section, a swimmer with head only above water has a radar cross-section of about 0.8 ft.^{2} at 915 MHz.

Based on the total data gathered, the following can be concluded:

1) It appears that a system for the automatic detection of surface swimmers can be built.

2) The same system would have a limited capability to detect SCUBA-equipped swimmers under the surface, particularly under relatively calm surface conditions and at ranges under 30 feet.

3) The system which should be able to perform the swimmer detection best would operate at high UHF or low L-band, utilize vertical polarization and operate with a high range-resolution signal subsystem.

4) The signal processor would utilize balanced processing to suppress the random components of background fluctuations plus a form of automatic adaptive notch filter to suppress the peak unbalanced clutter component.

I. New Concepts in Building Surveillance

During LWL tests of a CW, 1000 MHz radar in June 1968, the capability of energy in this frequency region to penetrate buildings and detect targets was demonstrated. The system, which was tested, formed the basis for the PPS-14 (Listening Post Surveillance Device) which was ultimately evaluated by MASSTER, Ft. Hood, Texas and ACTIV in Vietnam, (see Section V, C.)

After the PPS-14 was developed, experiments were performed which again demonstrated that L-band energy is capable of penetrating walls. It was found, however, that the PPS-14 was not suitable as a building surveillance tool because of the following characteristics:

1) The wide range cell of 120 meters.

2) The lack of range control.

3) The wide azimuthal antenna pattern with poor sidelobe suppression.

4) The signal processing optimized for foliage penetration, i.e., long integration time constants.

Upon completing the swimmer tests in January 1973, the pulsed 915 MHz radar described in Section V, H. was made available by ARI for tests as a building surveillance radar.

Since the 915 MHz measurement radar was designed to overcome problems inherent in the detection of a swimmer, which were similar to those faced in surveillance of a building, and since a calibrated target was available, it was decided to perform a series of through-the-building detection experiments using the measurement radar (A block diagram is shown in Figure 45.). This system has the following characteristics:

1) Adjustable range with a 5-meter wide range cell.

2) An antenna beam width of 60 degrees, with good sidelobe suppression.

3) Single channel balanced processor with short time constants; i.e., the system is capable of making a detection in a much shorter time interval than the PPS-14 system.

The radar was set up looking at the side of a brick building. A measure of the two-way losses through the double brick wall was obtained by taking the ratio of the radar return from the calibrated target when inside, then outside the building. Figure 46 is a sample of the data recorded inside and outside the building. This loss was determined to be 26 dB.

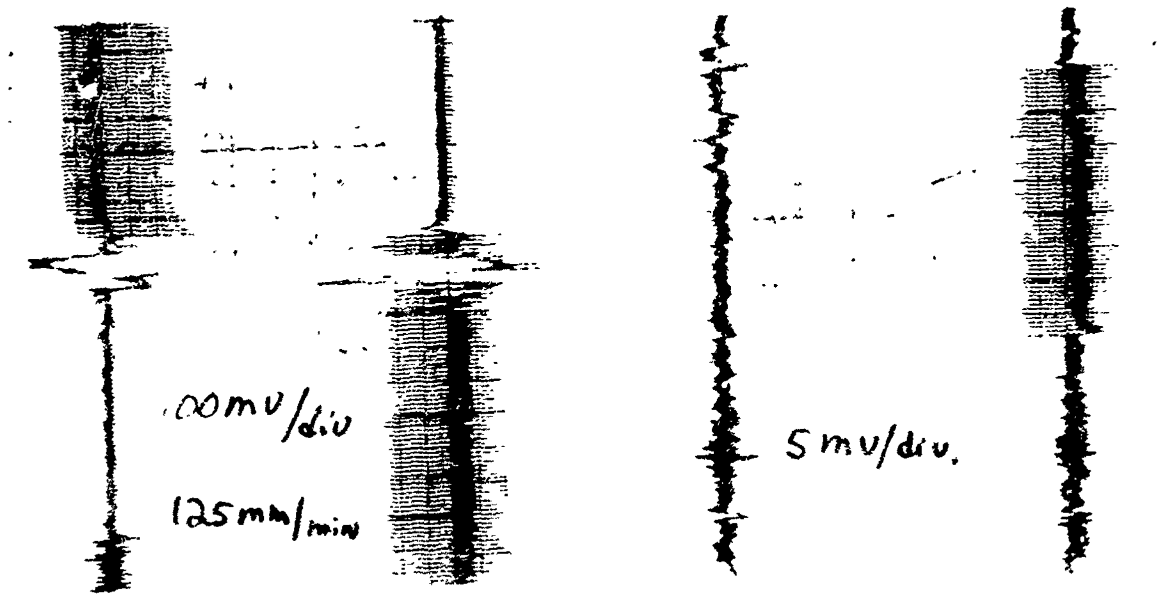
Two test areas were used. The wall was constructed of a double layer of brick with a metal roof. The first site was inside a storage area that had wooden shelves on the walls; the second inside a photo laboratory. The wall of the second site was the same as the first; however, between the radar and the target on the wall were an air conditioner, air vent, metal sink, metal tank and table, and numerous pipes. The target, one man, then walked at different velocities both radially and tangentially with respect to the radar, inside and then outside the building.

The results of these tests established that one man moving at any velocity from a very slow walk to a fast run could be detected even though the target was blocked from view of the radar by a double brick wall covered with metal obstacles. These results were repeatable at different distances behind the wall, at another test site, and with different target motions, from radial to tangential. A sample of the alarm integrator data which shows a target moving inside the building is included as Figure 47. In all cases, the target exceeded the alarm threshold by at least 3 times and an alarm occurred no more than one second after the target started moving.

Sufficient experiments were conducted to establish the detection capabilities of this type of system and the losses associated with penetrating a brick wall. To pursue this concept further, it would be logical to add an azimuth and elevation angle location capability to the existing swimmer measurement radar and perform an evaluation of this breadboard. The application of such a radar to urban warfare, as well as for police work, would be very valuable.

J. Helicopter Detection Experiments

Based on the Helicopter Detection Tests performed in Hawaii, AVSCOM, St. Louis, MO funded a short-term program to demonstrate the use of a FOPEN Radar for the detection of helicopters flying nap-of-the-earth (NOE). The program was also to determine the maximum detection ranges for radars operating in this frequency band, and to assess the effect on range caused by changing the radar cross-section of the helicopter. AVSCOM was concerned that certain

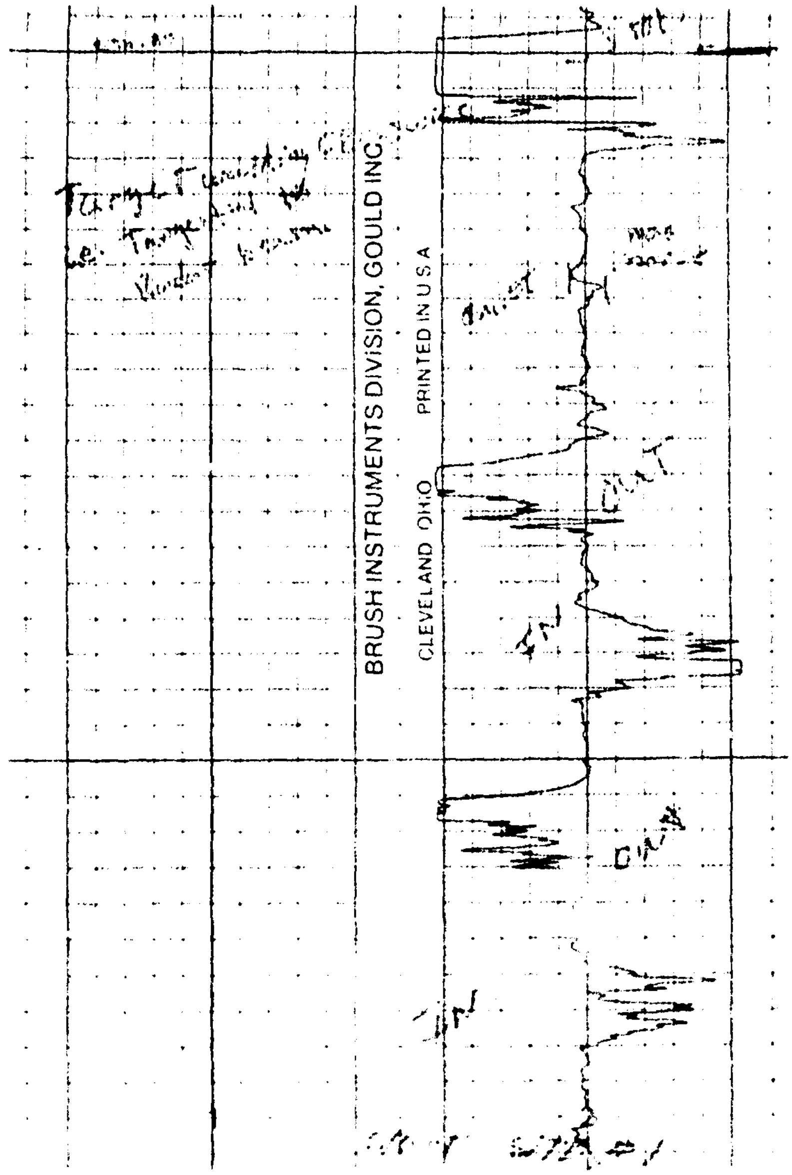


TEST TARGET OUTSIDE

TEST TARGET INSIDE SITE #1

20:1 ratio in voltage = 26 db power loss due to brick wall.

Figure 46. Sample of Chart Recorder Data (915 MHz Pulsed Doppler Radar) With Calibrated Target



Integrator data:

1 man walking inside site #1.

5 mv / div.

125 mm/min.

H Polarization.

Figure 47. Sample of Chart Recorder Data from Alarm Integrator with a Man as the Target

Soviet radars operating in the frequency region 100 to 1000 MHz could be adapted to the detection of helicopters at long ranges through foliage.

Experiments were performed at Aberdeen Proving Ground to establish the maximum range of detection for a UH-1 Helicopter under four conditions:

1) Hovering behind the trees

2) Flying behind a tree line

3) Flying just above the trees

4) Flying substantially above the trees at greater than 100' altitude

The M-FOPEN Radar was located at the edge of a tree line consisting of 50' - 60' hardwoods/pines along Bush River. The helicopter flew 3 paths; one along a radial line 10' over the tops of the trees, one along the edge of the foliage 10' above the water, and one 50' over the tree tops. Hover tests were conducted in cleared areas at ranges of 800 and 1300 meters from the radar.

The results summarized below indicate that the detection range through foliage is extremely dependent on target height and the amount of foliage being penetrated.

Target	Path	Altitude	Max. Range Detected
UH-1	Hover	2'	800 M
UH-1	Hover	50'	1300 M
UH-1	#1 along water	5' - 10'	1200 M
UH-1	#2	10' above trees	1400 M
UH-1	#2	100' above trees	2000 M

Subsequent analysis of these results (See Appendix E) has confirmed the maximum range values obtained. This model shows that the maximum theoretical detection range through foliage (i.e. total path through foliage) will vary between 420 and 1340 meters depending on the type of foliage and the radar cross-section of the aircraft. Since the rotor blade is at least 14 feet above the ground, has a large peak radar cross-section,[28] and moves at a precise number of revolutions (300 RPM) per minute, it is the primary contributor to the aircraft's doppler cross-section. If the M-FOPEN radar or other VHF Systems were optimized to detect helicopters, (i.e. spectral, balanced processing matched to the rotor blade), it would be possible to detect and locate the aircraft with a high degree of accuracy.

The radar range equation modified by Tamir (in Appendix E) for aircraft flying behind or just above the foliage has the form:

$$R_{max} = \left(0.13X10^{16} \quad \frac{P_t \quad G^2 \quad \tau^6 \quad \sigma}{B \; N_f \quad \theta_1 - 1 \; 4} \right) 1/8 \quad ,$$

Where P_t = Peak power in watts,

G = Gain of antenna (in area units),

τ = Wavelength,

σ = Aircraft cross-section,

B = System bandwidth,

N_f = Noise figure,

θ_1 = Equivalent

The analysis leads to the following conclusions. First, detection range goes as the 1/8th power of σ , the radar cross-section of the aircraft. Thus, to decrease the detection range by 1/2, it would be necessary to make a 2^8 or 256 times reduction in aircraft cross-section. Second, if one assumes that both σ and G vary as $1/\lambda^2$ over the frequency of interest, the detection range R_{max} goes as $\lambda^{1/2}$. Hence R_{max} decreases with increasing frequency, i.e., a 10 times increase in frequency (10 times reduction in wave length) will decrease detection range by approximately 3 times. Thus, to detect aircraft flying NOE, the choices of radar frequencies are heavily weighted towards 100 MHz. The existence of threats in this band indicate that additional work needs to be done to protect army aircraft. Further, the M-FOPEN radars have demonstrated an additional capability which could be provided friendly units for protection from hostile aircraft.

VI. SIGNIFICANT ACHIEVEMENTS/CURRENT STATUS

In discussing the significant achievements of this program, an attempt has been made to distinguish between real advances in technology and achievements which are, in fact, different applications of existing principles. It is concluded that the areas which represent a substantial advance in technology are: signal processing, propagation studies, and the airborne foliage penetration radar system. These areas are discussed in the following paragraphs.

A. Signal Processing

General: When USALWL started its FOPEN program in 1966, all Army tactical radars required an operator to listen to audio data or watch A or B Scope presentations, or both, in order to detect a target. This required a man to monitor the radar continuously and frequent replacements as the operators became fatigued. In writing the in-house requirement document which guided the development of the FOPEN radar, the Military Operations Division of LWL stated that the radar should automatically detect a target and alert the operator. Consequently, a substantial effort was started to gather target-to-clutter and spectral data which would enable such an automatic alarm to be designed and built. This program resulted in several major advances. The most significant are summarized below:

1) Noncoherent Signal Processing: The first successful attempt to automatically process ground surveillance radar data was accomplished with the adaptive processor built for LWL by Aerospace Research, Inc. (described in Appendix A) and used with the noncoherent FOPEN prototype. The system was able to adapt to the amount of clutter energy present in order to maintain a low false alarm rate, and demonstrated the significance of automatic signal processing for ground surveillance radars. Although the limitations inherent in a noncoherent radar required that a coherent system be used for FOPEN applications, the adaptive processor was successfully tested with other noncoherent systems in the inventory; the PPS-4 and PPS-5 Army radars, the PPS-6 Marine Corps radar, and the AN/PPS-10 system under development by General Dynamics for the Marine Corps. As a result of these tests, a separate program was established, (LWL Task 06-P-69), six hardened units were fabricated by Aerospace Research, and two separate OCONUS evaluations conducted, (Korea, Vietnam) in the fall of 1969. The evaluating Army and Marine Corps units reported favorably on the automatic alarm.

In a message from the US Army, Vietnam,[30] it was reported that the automatic alarm had resulted in increased detections and reduced time to locate targets, that operator efficiency was significantly increased and that the reduction in operator fatigue permitted a soldier to operate the radar efficiently for 40 minutes without rotation as opposed to the previous 20-minute rotation requirement. The CG, USARV recommended that the LWL automatic alarm be adopted as a standard item with the basis of issue of one per AN/PPS-5 radar.

A Marine Corps report[29] of a comparison test of several types of automatic signal processing with the AN/PPS-6 radar in September, 1969 stated that the automatic alarm supplied by Aerospace Research, Inc. (ARI) performed far better than any of its competitors. The test item consistently alarmed on moving targets with the highest degree of reliability and the lowest missed target rate and false alarm rate. The ARI item was the only device that gave an alarm on moving targets in heavy clutter and with a 14-knot wind with greater reliability and a lower false alarm rate than a human operator. The Marine Corps recommended that further development of alarm systems be terminated and that the ARI Model AU-1150 Adaptive Alarm be procured for evaluation and use with the AN/PPS-6 Radar.

Thus, by April 1970, the concept of automating ground surveillance radars with the LWL automatic alarm had been established and the Program turned over to the Parent Agency, ECOM. In July, 1970, AMC provided ECOM with sufficient funds to purchase several alarm units (or equivalent) for the purpose of prototyping these items with the PPS-5. The alarms at this time cost $1,000 each from Aerospace Research, Inc., were in hardened form and had survived three separate evaluations (Vietnam, Korea, the Marine Corps) without an electronics failure. The RFQ (request for quote) DAAB07-72-R-0359 was issued on a competitive basis on 2 June 1972. The final contract (DAAB07-73-C-0167) was awarded to General Dynamics on 10 April 1973 for the purpose of developing a prototype alarm system that could be used with the PPS-5 radar. More than four years after the Army in Vietnam had recommended adoption and issue of an existing alarm which satisfied all their requirements for the PPS-5 radar, action has regressed back to developing a prototype.

2) Coherent Signal Processing: To apply automatic processing to the FOPEN radars, a coherent radar with balanced processor was required. Originally proposed by Dr. Henry Kalmus of Harry Diamond Laboratories (HDL) in the 1950's, the first practical application was not until 1967 when engineers at MIT incorporated a processor as part of the Camp Sentinel Radar Program.

In October 1968, after tests demonstrated that coherency was required for FOPEN type radars, the choice was made to switch from a noncoherent to a coherent radar with balanced processing. The first system was fabricated and field tested in February 1969, and six units were delivered to Vietnam in August, 1969 for an operational evaluation. The success of the Vietnam evaluation clearly demonstrated the necessity for automatic detection for tactical radar systems. Balanced processing was subsequently refined and applied by LWL to many new radar systems including:

- Original ORCRIST FOPEN Radar
- Second Generation M-FOPEN Radars
- AN/PPS-14 Listening Post Surveillance Device
- ADVISOR V Ultrasonic Radar
- Line Intrusion Detector
- Swimmer and Building Surveillance Radar Prototypes

In addition to the use of signal processing for automatic detection, LWL's work with a balanced coherent radar led to two other new concepts. First, the very nature of a balanced coherent radar lends itself to extracting information about the characteristics of a target. As operators became familiar with the FOPEN radar it became readily possible to distinguish between tracked and wheeled vehicles, between rotary and fixed wing aircraft and between moving personnel and vehicles. It is now well within the state-of-the-art to equip coming generations of ground surveillance radars with this target discrimination capability. Second, in response to the requirement for azimuth resolution as stated in the ACTIV evaluation of the Base Defense Foliage Penetration Radar[13], a new technique applicable only to radar with balanced processing was devised. Using a pair of 65° azimuth beam width antennas with coincident antenna patterns, the angle of arrival of the energy from a target return is measured. The phase angle is then detected by the balanced processor and accuracies of plus or minus three degrees are achieved. This technique could readily be applied to other ground surveillance radars to provide an acceptable accurate azimuth without the use of mechanical scanners. To date, the advances in signal processing demonstrated by LWL's various detection systems are not being incorporated into Army radars.

B. Propagation

As part of the development of the family of radars described herein, a significant amount of electromagnetic data was taken, evaluated and compared with data available from other sources. This made it possible to develop a model[14,15] which enables the prediction of path losses for most radar frequency choices and foliage combinations, over the frequency range of 100 to 1000 MHz. Using these results, the frequency choices of 140 MHz and 1200 MHz for the ORCRIST and AN/PPS-14 tactical radar systems were confirmed and their design could be optimized. Later, the model was used to develop maximum detection ranges for Army aircraft flying nap-of-the-earth (NOE) using foliage for concealment. A report by the author to be published in June, 1974 titled: FOLIAGE PENETRATION (FOPEN) Radar Detection of Low Flying Aircraft, LWL Report No. 74-22 describes this effort in detail.

As a result of the LWL FOPEN Program sufficient data and analysis is available to enable choices of radar parameters (frequency, power, antenna size and height) to be made once the detection range is specified and the amount of foliage, or buildings existing between the radar and the target defined. The U.S. Army Intelligence School, representing the user has been made aware of this modelling capability and how it can be used to specify in requirements documents realistic detection ranges for ground surveillance radars. The data with which to continue the dialogue has been transferred to the ECOM, the designated Parent Agency.

C. The Airborne FOPEN Radar

The program to date as described in detail in Section V, has established the minicomputer as a signal processing device that can perform all the operations of the analog form of processing and display them in real time to the operator. One advantage of the computer processing technique is that this signal processing characteristics can be changed at will by the operator and thereby enable him to ask questions about the data (i.e., is it moving faster than 10 mph, etc.) or change the criteria for detection (i.e., rotary vs. fixed-wing aircraft, personnel vs. vehicles). Another advantage is the ability to construct a radar with continuous range coverage. This is economically impractical with analog processing since a separate signal processor is required for each range gate. Additionally, with a minicomputer one basic processing/display combination can be used for either airborne or ground based applications for ground surveillance, detection of aircraft or artillery, and remote radar sensors.

Flight tests of the airborne FOPEN radar have been completed and are being published in a contract report titled: "Moving Platform FOPEN Radar (New Techniques in Airborne FOLIAGE PENETRATION RADAR)," LWL Report No. CR-07-P-72, July 1974. Since ECOM has decided not to pursue this program and recommended other disposition of the radar and computer system, arrangements have been made to transfer this program intact to the Naval Weapons Center, China Lake, CA where it will be pursued for Marine Corps applications.

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APPENDIX A

VARIETIES OF SIGNAL PROCESSING

VARIETIES OF SIGNAL PROCESSING WHICH CAN BE USED

A. Nonadaptive, Unbalanced Processor

Under conditions in which the clutter situation is not severe, i.e., the target has a large cross-section or is moving at a high velocity, and the total clutter cross-section is not very large compared to the target and is, perhaps, made up of components which do not move in the wind, it is possible to get along with a relatively simple nonadaptive, unbalanced signal processor. In this kind of processor, the data from each resolution cell is filtered with a fixed cutoff highpass filter which rejects the major portion of the clutter spectrum, thus bringing the residual clutter level down to a point where it is much smaller than the normal target level. This would then be followed with a detector and post-detection filter (time-on-target integrator) before applying the output to an alarm circuit. Unfortunately, this relatively simple type of processing will not work well under severe clutter conditions (clutter which is driven by high winds and which is made up of a large number of scatterers) particularly when one is interested in detecting low-velocity targets such as a walking man. This type of processing also fails under severe interference conditions, because it is often possible to get enough interference energy in the doppler frequency band of interest to cause the alarm to be fired spuriously. It was this type of processing that was first tried with the breadboard noncoherent VHF radar with poor results.

B. Adaptive, Unbalanced Filtering

Under high clutter conditions in which the clutter spectrum is variable, it is possible to help the situation considerably by introducing an adaptive filtering in which the cutoff frequency of the highpass filter is varied by a feedback system governed by the amount of clutter energy which appears at the output of the filters (this is the principle used in the LWL Automatic Alarm or AU-1040 processor)[1]. Instead of requiring the permanent sacrifice of low-velocity target detection, this type of processor rejects low-velocity targets only for those portions of time where the wind is blowing severely. As soon as the wind subsides, the cutoff frequency of the filter will come down to a lower value, which re-introduces high sensitivity to low velocity targets. If the parameters of the system are chosen properly, it is possible to obtain good detection of targets while maintaining a very low false-alarm rate. This type of processing will work well provided that the basic radar does not produce a large amount of energy in the doppler passband associated with the targets of interest either by limiting, spurious antenna motions in the wind, amplitude modulation in the transmitter, etc. This processing also will be subject to false alarming in a high radio frequency interference environment; however, it does present the best overall performance that can be achieved in a non-coherent radar. This alarm was tested with the breadboard non-coherent ORCRIST radar in Panama in 1968 with good results except for false alarms caused by operation of a non-coherent system in and around foliage.

Greater success was achieved with the PPS-4 radar and a program was started to develop additional units.

C. Nonadaptive, Balanced Processing with Clutter-Residue AGC

The introduction of balanced processing immediately improves the MTI performance along the following lines: since the processor now looks at differences in the energy content of the doppler bands associated with incoming and outgoing targets, the processing is fundamentally less sensitive to the effects of interference represented by more-or-less constant energy which spans both doppler bands of interest. In addition, amplitude modulation on the transmitter or motion of the antenna generally produces a more-or-less symmetrical spreading of the clutter spectrum; again, a situation which will cause the system to false alarm. If there is correlation between the energy in the incoming doppler and outgoing doppler sidebands, which is the situation which exists when the clutter spectrum has been caused by the motion of foliage in the wind, the balanced processor can produce a degree of MTI performance which is on the order of 20 dB better than the maximum that can be obtained with unbalanced processing. Under extremely high clutter conditions, it is possible for even the balanced processor to false alarm. To overcome this situation, it is necessary that the system recognize an extremely high clutter condition (which can result from a large volume of clutter blowing strongly in the wind, or, alternatively, the gain being set much too high for the clutter cell in question) and provide a feedback. The feedback signal can control the gain on the processing channel and prevent this overly-high clutter level from causing false alarms. Under very severe and continuing clutter conditions, the overall reduction in the processing channel gain will result in reduced sensitivity to targets of all velocities; however, if this type of processor is configured properly, the clutter AGC will be needed only a small part of the time and, hence, the system sensitivity can be kept to a maximum under most conditions. This processor was incorporated with the coherent ORCRIST radar and utilized in the Vietnam evaluation models.

D. Adaptive, Balanced Processing

By using adaptive, balanced processing, i.e., processing in which each of the two quadrature audio input channels contain adaptive filters whose cutoff frequencies are set by a measure of the clutter residue in each particular channel, it is possible to avoid the uniform reduction in system sensitivity over the entire doppler band and instead only reduce the sensitivity to targets going at very low velocities when the wind conditions are severe. The adaptive, balanced processor should, under all clutter and wind conditions, produce the highest degree of MTI gain of any type of signal processor which is available today.

E. Requirements for Time-on-Target Integration

Each of the processors described above contain post-detection integration (time-on-target) filters. These filters serve three important functions:

1) Provide a non-coherent integration of the number of pulses contained within a time equal to the time-on-target, thereby raising the system sensitivity.

2) Provide protection for the threshold circuitry against transient signals which might normally alarm the system. (These transient signals arise from such things as a single, strong gust of wind, interference from communications equipment by virtue of a transmitter being keyed on or a carrier drifting through the doppler passband.)

3) Reduce the fluctuation level of the residue in much the same way as the filter reduces the fluctuation level of the noise (i.e., the post-detection filter treats the clutter residue much the same as noise, and allows a lower threshold than might be acceptable without the filter.)

APPENDIX B

BALANCED PROCESSING: A DESCRIPTION

Coherent Radars and Balanced Processing

The advantages of a coherent system are that its target doppler output is uncontaminated by the clutter spectrum, that directional information contained in the doppler shift is easy to implement, that lower transmitted power is required to achieve adequate target-to-noise ratio, and that lower receiver gain is required to drive the detectors.

The FOPEN balanced (quadrature channel) doppler signal processor provides a higher degree of subclutter visibility (SCV), particularly when operating against low velocity targets, than is possible to obtain utilizing an unbalanced adaptive (single channel) doppler processor. Since detection is based upon energy differences between two RF sidebands that are only a few Hz apart, the processor provides high rejection against effects of accidental (from communications equipment) or purposeful jamming.

The specific processor that is utilized is the Aerospace Research Inc., Model B-1140. As shown in the block diagram in Figure B-1, this processor accepts two inputs, which are sample/hold quadrature video, and provides as outputs an indication of when a target is detected and what is its sense (incoming, outgoing). The processor subjects the input signal plus clutter to the following operations before announcing a detection:

a) Filtering of the "man velocity" doppler band.

b) Separation of incoming from outgoing targets.

c) Separation of slowly walking, rapidly walking or running targets.

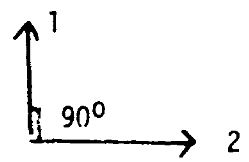
d) Balancing of incoming versus outgoing targets.

e) Matching to each expected Time-on-Target using post-detection filtering.

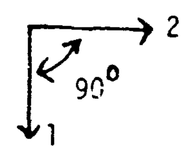
f) Application of the residue of this process to a bidirectional threshold.

The following vector relationships illustrate this process:

When the ORCRIST Radar (or a similar radar with Quadrature Detection) is viewing a moving target, the processor is fed two audio doppler signals which have one of the phase relationships shown as follows:



Incoming Target



Outgoing Target

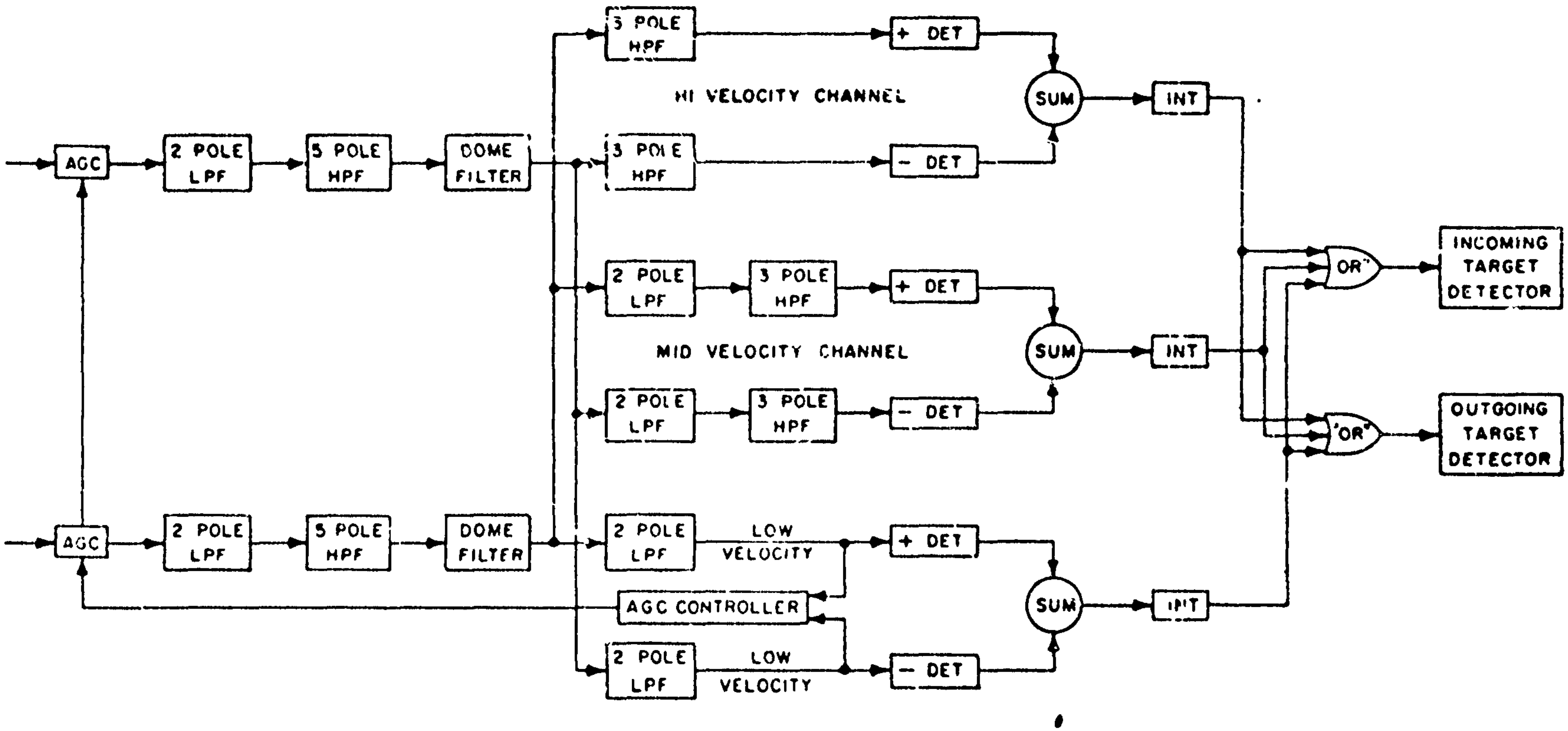


Figure B-1. Block Diagram of the Balanced Processor

APPENDIX C

SIGNAL PROCESSING: DETERMINING CRITERIA FOR COMPARISON

As work continued to improve balanced signal processors in parallel with the Vietnam Evaluation, it was obvious that a basis of comparison would have to be established. At this time it was fashionable to ask "what's your SCV? (subclutter visibility)" which was, of course, impossible to answer without certain additional information about the target and radar in question. The following criteria were developed in discussions with Aaron Galvin.[1]

Balanced Signal Processor Performance Comparison Tests

1) Minimum quadrature input signal for alarm (with no clutter).

a) For a given number of doppler cycles,

b) At all doppler frequencies of interest.

2) Maximum quadrature input signal which will still cause alarm.

a) For a given number of doppler cycles,

b) For all doppler frequencies of interest.

3) Maximum inband input double sideband signal which will not cause alarm.

4) Maximum out-of-band low frequency signal which will not cause significant required increase in minimum signal to alarm.

5) Signal-to-clutter outout/signal-to-clutter input ratio as a function of signal doppler and clutter characteristic frequency.

6) Increase in minimum signal to alarm with specific inband double sideband levels.

7) Maximum peak to peak input (for very low frequencies) relative to minimum alarm input signal.

8) Rate of recovery from saturation such as may be caused by operator range change.

To test these criterion specific measurements of performance criteria are provided in Table C-1 using the equipment setup of Figure C-1.

TABLE C-1. MEASUREMENT OF PERFORMANCE CRITERIA FOR NEW BALANCED SIGNAL PROCESSING SUBSYSTEMS

TEST ITEM	MEASUREMENT APPROACH (See Fig C-1)	PURPOSE
1. Minimum Quadrative Input Signal for alarm (for a specific number of Doppler cycles, for all Doppler frequencies of interest.)	Set tone-burst generator for appropriate number of cycles. Set attenuator at maximum and audio frequency at low end of band of interest. Decrease attenuation until processor shows alarm. Repeat with quadrature inputs reversed to check for opposite sense target. **Repeat** at all other Dopplers.	Find minimum automatically detectable signal across the target velocity band.
2. Maximum Quadrature Input Signal which will still cause alarm (for a specific number of Doppler cycles, for all Doppler frequencies of interest.)	Repeat above procedure, but start at much lower attenuator setting. Decrease attenuation until processor no longer shows alarm. Check opposite sense and all Dopplers.	Check for proper alarming under saturating target conditions.
3. Maximum Inband Input Double Sideband Signal which will not cause alarm.	Set balanced-clutter simulator for large inband component. Start with moderate attenuator settings and decrease until possible alarm results. Repeat for different (but always balanced) spectral inputs.	Check for protection against false alarming from RFI or large isolated clutter events.
4. Maximum Out-of-Band Low-Frequency Balanced Signal which will not cause substantial increase in minimum signal to alarm (with adaptive loops disabled and then with loops operative.)	Set balanced-clutter simulator for large out-of-band low-frequency component first well below the band and later closer in and finally into Doppler band. Repeat test #1 for all simulated clutter frequencies and amplitude. Put ultra-low-distortion oscillator into one quadrature input, measure pre-detection harmonics.	Check for effects of Harmonic distortion, small-signal suppression from large clutter, and proper operation of adaptive-frequency loop.

TABLE C-1. MEASUREMENT OF PERFORMANCE CRITERIA FOR NEW BALANCED SIGNAL PROCESSING SUBSYSTEMS (CONTD)

TEST ITEM	MEASUREMENT APPROACH (See Fig C-1)	PURPOSE
5. Signal-to-clutter Output/Signal-to-Clutter Input Ratio as a function of signal Doppler and simulated clutter characteristic frequency.	Apply simulated clutter input at a measured power level. After adaptive loops have stabilized, measure power in balanced-integrator fluctuations. Multiply this power ratio by the measured signal gain (at the peak signal point.)	Measure maximum target enhancement capability of processor.
6. Increase in Minimum Quadrature Signal to Alarm with Specific Inband Balanced Double Sideband Signals (with adaptive loops disabled and then with loop operative.)	Apply simulated clutter with substantial balanced in-band component. For a range of clutter amplitudes, measure minimum signal to alarm using audio oscillator and tone burst generator as described in Test #1. Repeat with adaptive loops enabled. Repeat for differing simulated clutter inband components.	Check for small-signal suppression effects such as might be caused by RFI, inband clutter transients or antenna sway.
7. Maximum Peak-to-Peak Clutter Signal Input for Very Low Frequencies Relative to Minimum Alarm Inband Quadrature Input Signal.	Apply ultra-low distortion input signal to one of the quadrature inputs at a frequency at least 2-1/2 octaves below the low end of the Doppler band. Increase this level until a substantial inband signal due to appearance of nonlinearities.	Check maximum dynamic range of signal processor.
8. Integrator Offset Amounts Caused by Broadband Noise Inputs.	Apply moderate amplitudes of breadboard flat noise to both quadrature inputs. Measure all integrator offsets as a function of noise level. Repeat with band-limited noise at various bandwidth settings.	Check accuracy of gain and frequency response balance of all active filters.
9. False Alarms or Offset Produced by very large transients.	Inject simulated step and impulse signals at varying amplitude and polarity into each of the two quadrature input channels. Check for offsets which might, under bad conditions, cause a spurious alarm.	Check nearness to false alarming caused by single step events such as caused by operator range switching.

TABLE C-1. MEASUREMENT OF PERFORMANCE CRITERIA FOR NEW BALANCED SIGNAL PROCESSING SUBSYSTEMS (CONTD)

TEST ITEM	MEASUREMENT APPROACH (See Fig C-1)	PURPOSE
10. Maximum Quadrature Inband Signal which will not alarm when signal contains less than 1/2 the Design Number of Doppler Cycles.	Adjust tone-burst generator for less than 1/2 the design number of Doppler cycles and repeat test #1, decreasing the attenuator setting until possible alarm results.	Check for protection against false alarms from large unbalanced clutter events or unbalanced RFI of short duration.

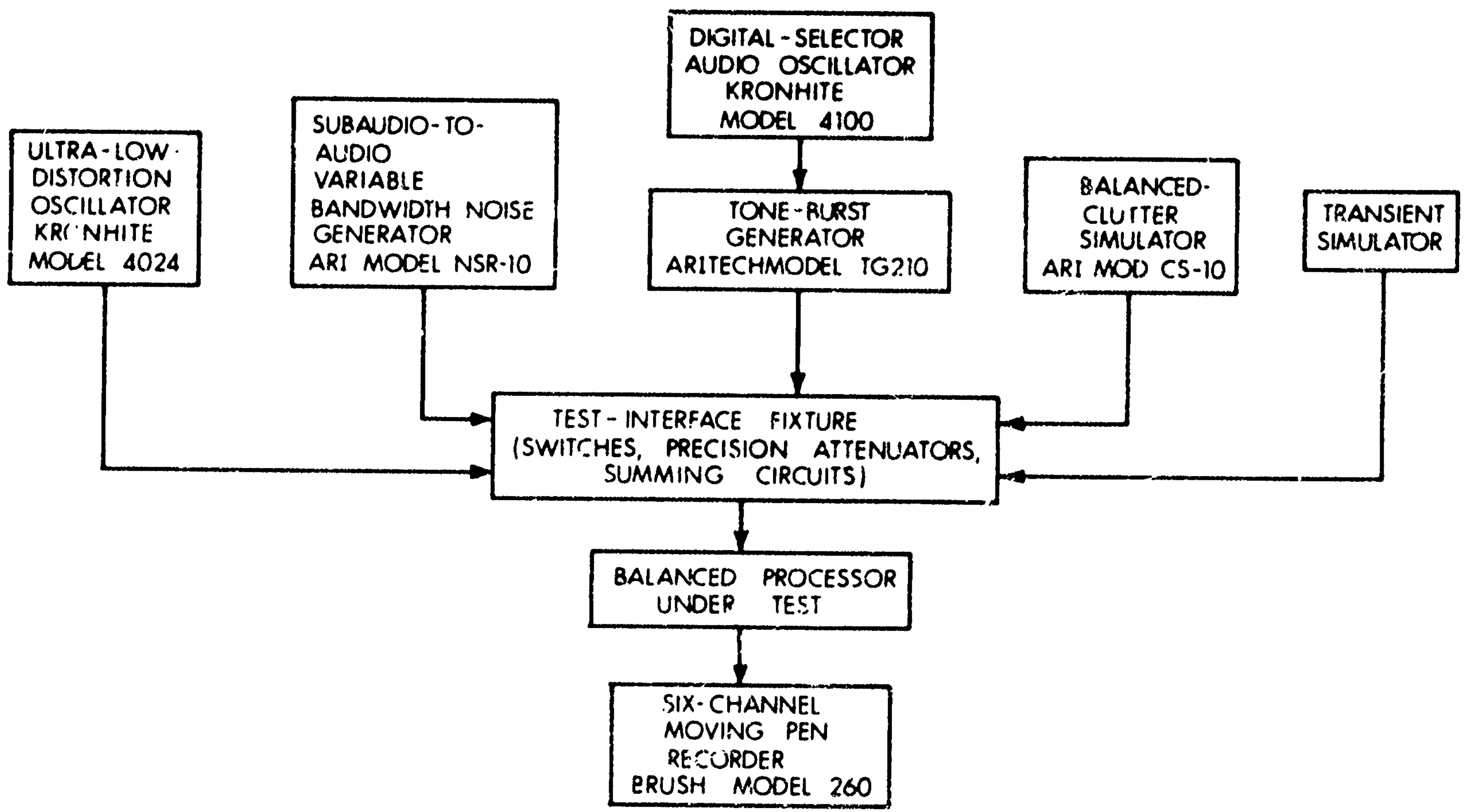


Figure C-1. Balanced Processor Setup.

APPENDIX D

REVIEW OF STUDIES ON WAVE PROPAGATION THROUGH VEGETATION

When utilizing radio waves to detect objects embedded in a forest environment, the vegetation medium produces propagation losses which may be so large that radio waves cannot effectively penetrate foliage if the electric path through vegetation is very long. Fortunately, however, the diffraction properties of waves permit them to establish a path of propagation such that the wave travels mostly in the lossless air region outside the forest and only a small distance is left to be traversed through lossy foliage. These specific diffraction properties have been investigated mostly in the context of long-range communication within forests and jungles rather than for short-range foliage penetration. To put the aspects of radio-wave propagation into proper perspective, we shall therefore briefly review these propagation studies.

The adverse effects of a rough terrain on the propagation of electromagnetic waves have been recognized already in the early stages of broadcasting and communication by means of radio waves. However, because the utilization of these waves had been at first restricted mostly to frequencies in the L. F., M. F. and lower H. F. ranges, these effects were not very significant. Consequently, propagation predictions could be made by adding terrain correction factors to a smoothly curved earth model. In those cases, the presence of trees or other dense vegetation was not considered to be very important in comparison with the presence of hills, mountains, rivers or other large geographical features. As the frequency of operation for short-range communication systems was raised to the V.H.F. range and higher, the effect of vegetation became increasingly more apparent and workers in the field became aware that a forest environment could no longer be accounted for by means of simple correction factors.

It is, therefore, not surprising that the first systematic efforts for studying the effects of wooded areas were initiated during World War II. It was then that requirements for short-range communication at frequencies in the HF spectrum and above became very important. At that time, a small-scale investigation at V.H.F. was carried out by the R.C.A. Corporation[1] while large-scale investigations were performed by Australian workers [2] in the jungles of New Guinea and, separately, by U.S. workers[3,4] in the jungles and rain forests of New Guinea and Panama. These efforts were carried out at various frequencies in the range of 2-100 MHz, with transmitter powers not exceeding a few watts and covering distances of not more than a few miles. Because of these restrictions, as well as because of the unsophisticated state of propagation theory at that time, it was concluded that a forest environment behaves as a lossy medium so that a wave traveling through this medium would suffer an exponential attenuation in the form $\exp(-\alpha d)$, where d is measured along the trajectory of the wave that links the receiving and transmitting antennas. Based on these conclusions, Herbstreit and Crichlow[4] recommended that the sky wave be utilized in preference to either the ground wave or a line-of-sight wave, if both receiver and transmitter are in the forest. The justification for this choice was that the sky wave would cross over only a small portion of the vegetation layer (essentially, for the sky wave: $d = 2h$, where h is the average tree height) whereas both the ground or the line-of-sight wave would traverse a much longer distance through vegetation (essentially, for these waves: $d = \rho$, where ρ is the distance between the receiving and transmitting antennas).

The exponentially decaying-wave approach, together with its implied preference for a sky wave propagation mechanism, have persisted until about 1964, at which time ARPA initiated a program (SEACORE) consisting of a major systematic investigation of radio-wave propagation through forest environments. In the intervening time, experimental studies had been concerned mostly with television reception[5-8] or with the utilization of communication equipment[9,13] whereas long-range theoretical considerations invariably assumed a propagation mechanism involving only the exponentially decaying wave.[10-12]

A considerable portion of the SEACORE effort was devoted to propagation measurements carried out in Thailand jungles by the Jansky and Bailey Engineering Department of Atlantic Research Corporation, Alexandria, Virginia, over the entire frequency range of 100 KHz to 10 GHz ; their short-range measurements confirmed from the start many of the previously observed phenomena.[14] Thus, larger radio losses were experienced in vegetation than over bare ground, and horizontal polarization showed smaller losses than vertical polarization for the antenna heights that were used. Also, the SEACORE measurements verified that an antenna-height gain occurs, in that radio losses decrease if either of the two antennas is raised. However, over longer ranges, these measurements showed some new and very interesting features that had not been observed by the investigations in the past, all of which had been restricted to much shorter ranges. In particular, it was found[14,15] that the field strength is proportional to ρ^{-2}, where ρ is the distance between the transmitting and receiving antennas; furthermore, the vegetation accounted for a loss that seemed to be independent of ρ, if ρ was more than a few wavelengths long.

Preliminary attempts were made to explain the above field-strength behavior with the distance ρ. Thus, several models for irregular terrains were adapted to a forest environment by Jansky and Bailey workers[14] but these models required the specification of empirical parameters that have little physical justification. By taking a better physical approach, Burrows[16] argued that the ρ^{-2} dependence of the field strength and the presence of an antenna height gain are accounted for by the ground-lobing effect; however, his model ignored the presence of vegetation and he had to introduce an empiric constant vegetation factor to account for the vegetation losses that are independent of ρ.

The investigations that have ultimately yielded a satisfactory model for estimating radio losses in forests were all based on a configuration that was first suggested by Pounds and Lagrone.[17] These investigators proposed to describe a wooded terrain in terms of a poorly conducting slab characterized by a homogeneous complex permittivity (representing the forest layer), which is placed on a highly conducting substrate (representing the ground). For frequencies in the HF range, an additional ionospheric layer could be introduced, as shown in Fig. D-1 In that form, the forest propagation problem appears as a particular case of the class of problems involving layered media, already considered in text books.[18,19] In fact, Sections 27 and 28 in Brekhovskikh's book[18] consider the specific general case of a slab bounded by two different media and the pertinent waves that are important in that case are discussed therein.

The specific case of a lossy (vegetation) slab has been examined by Tamir and Felsen[20] who noted that the principal propagation mechanism is due to diffraction and is characterized by a lateral wave, which propagates, by skimming along the (tree-top) slab boundary and leaking (continuously) energy back into the interior of the (forest) layer. The path of such a wave is shown by the broken line TABR in Figure D-2. Because it travels mostly in the lossless (air) region, this lateral wave does not incur the large exponential decay that is characteristic of a wave progressing through the lossy (forest) medium. However, Tamir and Felsen [20] did not relate their work to a forest environment and the initial specific work on forest slabs[21-22] did not take cognizance of lateral waves. It is, nevertheless, interesting to note that quite a few workers in the past had observed that the field seemed to arrive at the receiving antenna by diffraction from somewhere along the tree-tops. Thus, Trevor[1] noticed that "transmission of... signal... can be interpreted as showing reflection... from a level considerably above ground or near the top of the vegetation". Similarly, Head[6] asserted that "The signal in the presence of woods near the receiving antenna appears to be principally that diffracted over the trees...".

The identification of a lateral wave in a forest layer was first reported by Sachs and Wyatt[23] and Sachs[24] who gave a preliminary interpretation of Jansky and Bailey's measurements. Their work was followed by a detailed study into the significance of the lateral wave by Tamir[25,26] who showed that this wave explains clearly the antenna-height gain and yields the correct variation of both the field strength and the vegetation factor with the distance ρ. In addition, Tamir[25,26] also considered an ionospheric layer to account for the sky wave shown in Figure 2, and he evaluated that this sky wave may be dominant only in certain restricted cases. While acknowledging the lateral-wave character of the field in forests, Wait[27] considered a more sophisticated slab whose complex permittivity was different along the horizontal and vertical directions, thus accounting for anisotropic effects. However, no data on vegetation anisotropy is available and therefore, Wait's model has not yet been widely used.

To properly utilize the slab model, it is necessary to know the complex dielectric constant that describes the vegetation layer. Its determination was undertaken by Stanford Research Institute, Menlo Park, California, whose investigators have measured vegetation parameters in U.S. forests[28] and

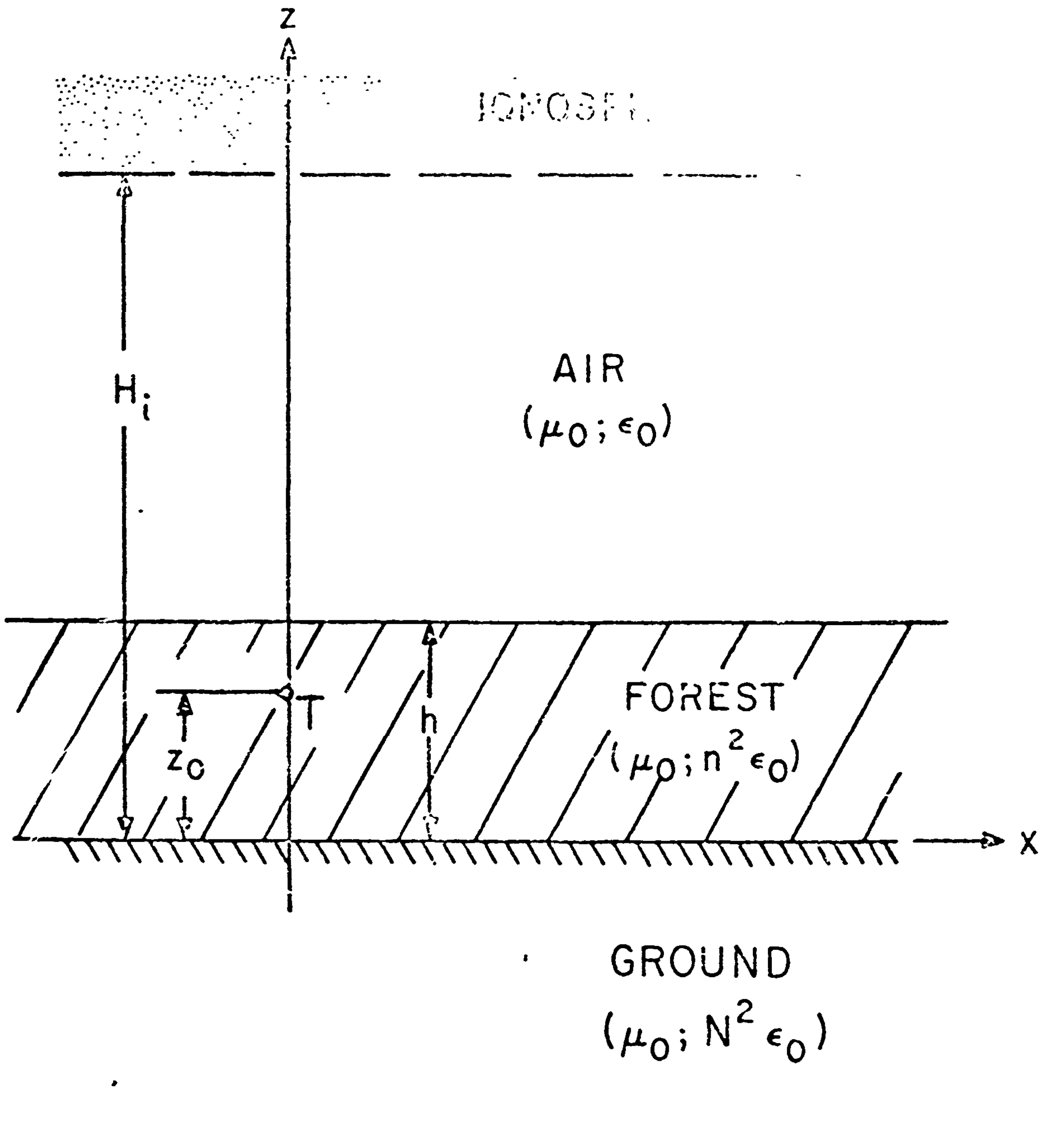


Figure D-1. Slab model of a forest environment. The refractive indices n and N for the forest and ground media, respectively, are complex quantities due to conduction losses. The ionospheric layer at $z = H_i$ is required only at frequencies in the range of 1-30 MHz., approximately.

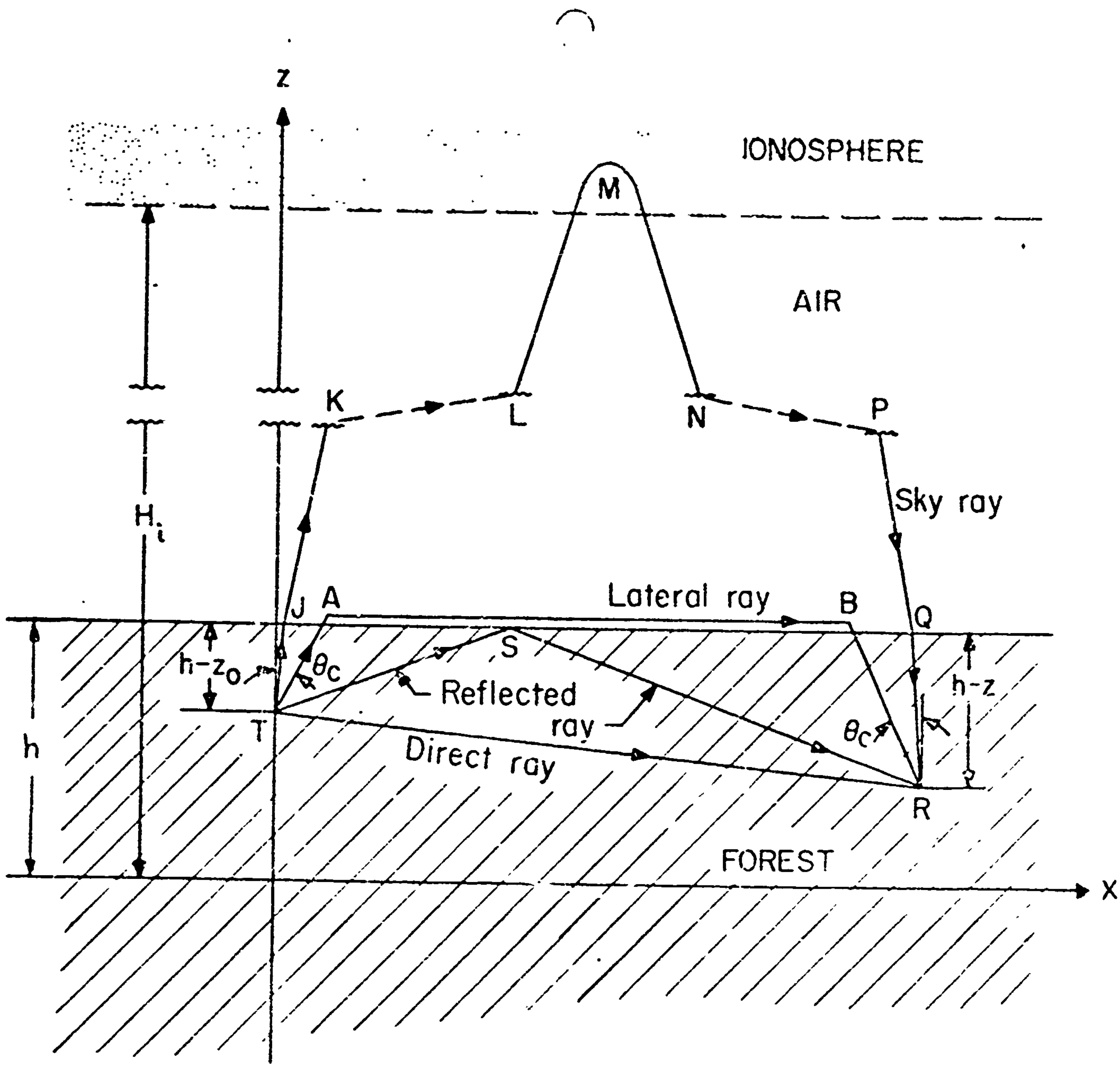


Figure D-2. Possible propagation paths within the forest, between a transmitter at T and an observation point (receiver) at R. For simplicity, the ground plane has been removed. Its presence adds additional propagation paths due to reflection, but these paths are usually of secondary importance.

performed measurements of vegetation and ground constants in several sites in Thailand jungles.[29,30] The fields scattered by isolated trees were also examined[31,32] and it was found that scattering is considerably stronger for vertical polarization than for the horizontal one. This effect is due to the presence of the vertical tree trunks, which form a substantial portion of the vegetation. Hence, the equivalent complex permittivity of the forest layer must actually be anisotropic, with the vertical direction possessing larger conductivity than the horizontal one. However, the degree of anisotropy could not be ascertained and no further work was reported on this point.

Using some of the Stanford vegetation data as guidelines, Hicks et al[15] have utilized a computer program to calculate radio losses in a forest-slab model and they have shown that the Jansky and Bailey propagation measurements were in very good agreement with theory. All of their calculations, however, were restricted to antennas that were sufficiently high so that the effect of ground proximity on the antenna input impedance was negligible. This restriction was removed in a study by Dence and Tamir[33,34] who showed that, if one or both antennas are very close to the ground, vertical polarization may be preferable to horizontal polarization at the lower frequencies. The lateral-wave propagation mechanism itself was verified experimentally under laboratory conditions by Tamir[35,36] who used a microwave set-up to simulate a lossy environment by means of an absorbing medium having a complex dielectric constant which was similar to the one measured by Parker and Hagn.[28]

Most of the above work has dealt with situations where both the observation point and the transmitting antenna were inside the vegetation or close to the tree tops. The derivation of electromagnetic fields at arbitrary heights above the forest slabs has been carried out by Tamir,[37] who showed that the lateral-wave regime extends only up to a small height H_c above the tree tops; at heights $H > H_c$, the fields are given by a refracted line-of-sight wave, which travels along a path as indicated by the trajectory TAR in Figure D-3. Similar results were also obtained by Rosenbaum and Bowles[38] who examined these features in the context of radar scattering in the presence of forests. A different situation was considered by Hicks et al[15] who examined the case where one antenna was inside a forest whereas the other one was located outside the wooded area, i.e., either in a large clearing or outside the region enclosing the forest. All of these situations involve propagation along mixed paths, in which case the straight line linking the transmitting and receiving antennas lies partly in vegetation and partly in free space (air). Measurements along such paths were reported by Hicks et al[15] for the 25-400 MHz range and by Barsis[39] at 410 and 4595 MHz; in addition, extensive measurements of radiation patterns were carried out by the Stanford Research Institute within the 3-1000 MHz range.[40]

Until about 1969, most of the work involving a slab model of forest environments had assumed that this model is valid only for frequencies below 200 MHz;

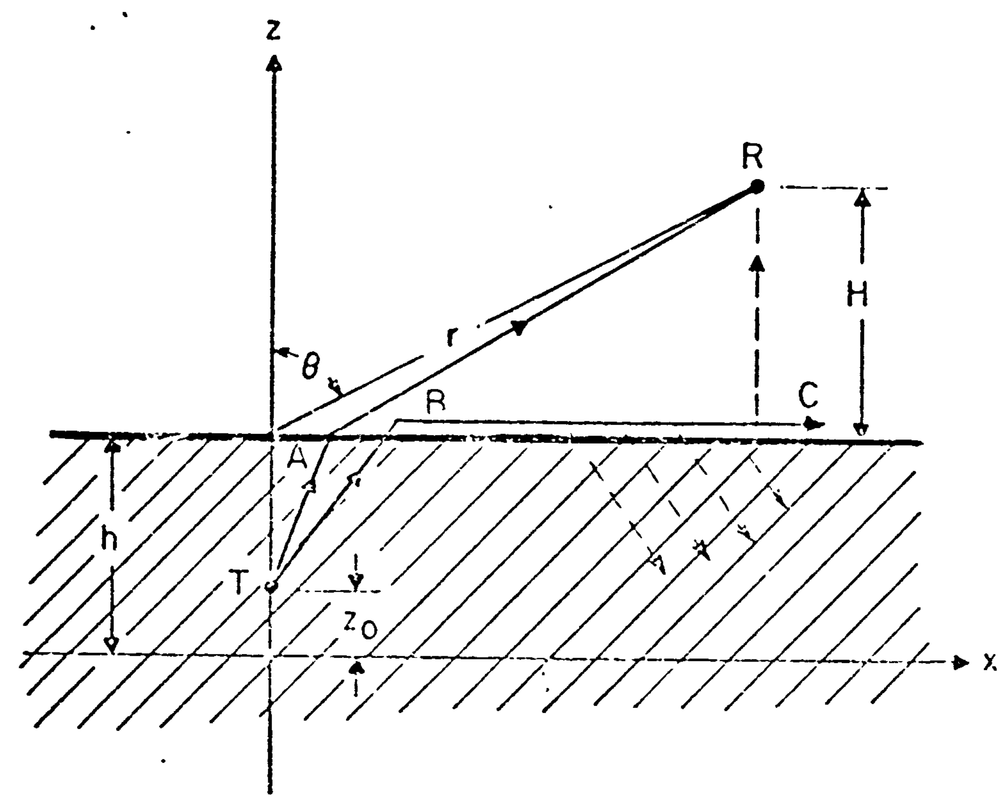


Figure D-3. Possible propagation path between a transmitter at T in the forest and an observation point at R in the air region above the treetops. (Due to reciprocity, R and T may be interchanged). For H small (about one wavelength or less) the lateral wave is dominant and propagates along the path TBCR; for larger values of H, the principal field contribution arrives along a refracted-line-of-sight path TAR. For simplicity, the ionosphere and ground planes have been omitted here.

this upper-frequency restriction has been discussed in detail by Tamir.[26] However, radar scattering work carried out at Lincoln Laboratories, Lexington, Massachusetts, has shown[41] that a forest slab may serve as a good model, at least as a background configuration, for frequencies as high as the L-band microwave range. These conclusions, based on extensive measurements carried out at 435 and 1300 MHz in Florida and Massachusetts wooded areas, have indicated that the forest slab model and the accompanying lateral-wave mechanism may have a range of application that is considerably wider than anticipated.

It was at this stage that the results of radio-wave propagation in forests were applied to the problem of foliage penetration by means of a radar system. Based on the M.I.T. results,[41] Tamir assumed that the slab model may serve up to frequencies as high as 1000 MHz. He then examined[42] the path losses that are produced by the presence of vegetation for a Doppler-radar system at 140 MHz. In particular, he calculated the additional losses produced by vegetation as compared to the losses in free space or over bare ground. His results show that these losses increase strongly with the average tree height, but they decrease rapidly if the height of either the antenna or the target is increased. In practice, he found that the vegetation losses are not prohibitive if the antenna is at treetop level or above, and if the range to be covered is of the order of one kilometer or less; however, unusually thick vegetation may substantially alter this estimate.

To obtain a comparative picture over a wider frequency range, Tamir[43] also examined the effect of operating frequency on the performance of doppler-radar systems. For this purpose, he compared two systems that operate at different frequencies in the range 100 to 1000 MHz by assuming that the two systems are similar and differ only in operating frequency; to take advantage of the larger antenna gain available at higher frequencies, he also assumed that the antenna apertures were the same at all frequencies. The results of this investigation show[43] that total radio losses generally increase if the frequency is raised; exceptions may arise if the antenna is well above the treetops and if the target is not too small. Figures D-4, D-5 & D-6 show relative losses experienced when the frequency is changed over the reference frequency of 100 MHz. However, Tamir pointed out (in Appendix A of reference 43) that his results are based on an empiric formula for the complex permittivity of vegetation. This formula was necessary because the available data[29,30] on permittivity is restricted to frequencies of 100 MHz and lower. Fully reliable results on the question of an optimum operating frequency are therefore dependent on measuring the permittivity of vegetation at frequencies above 100 MHz. This is, therefore, a measurement that should be undertaken in the near future. Otherwise, the slab model cannot be sufficiently reliable for frequencies above 100 MHz.

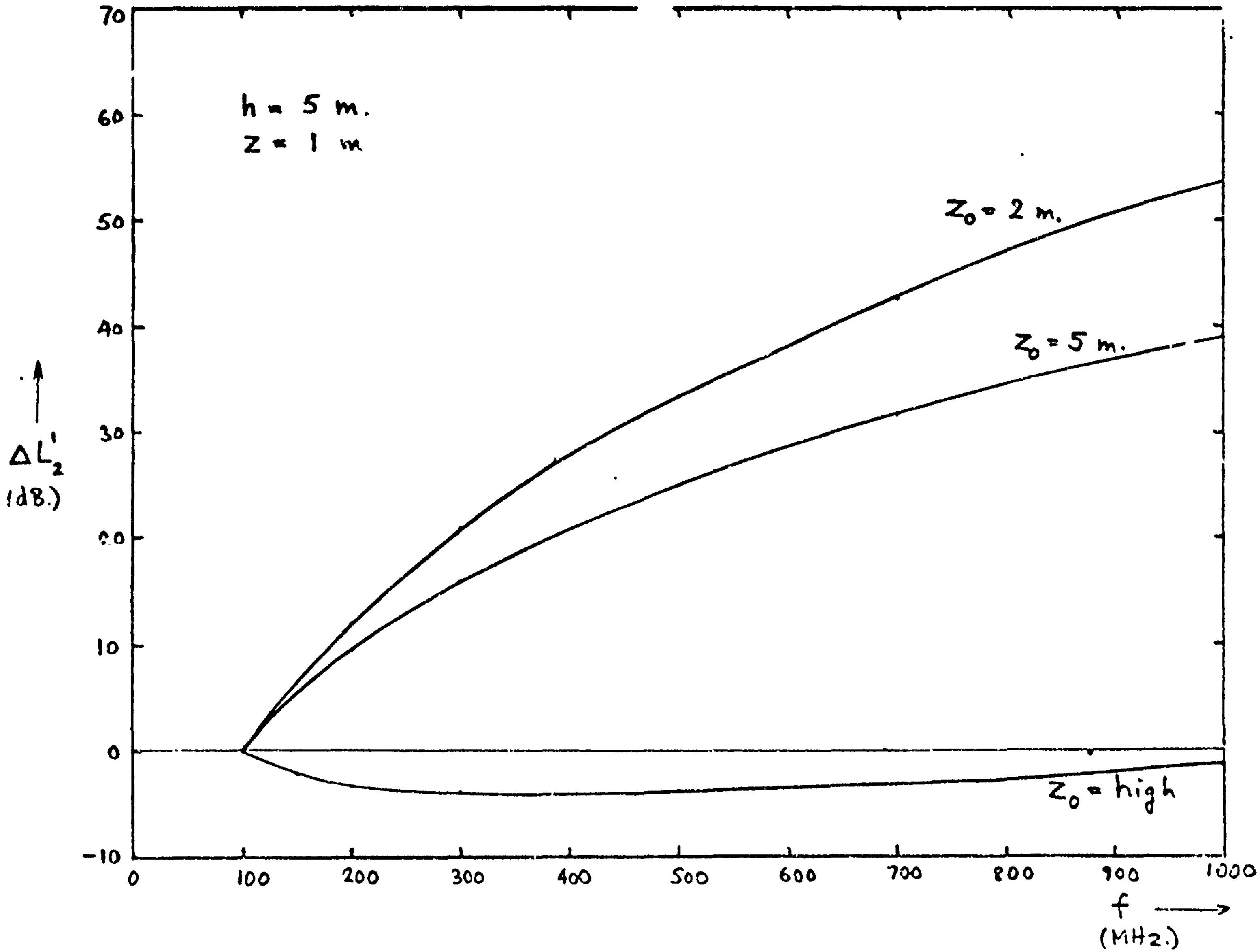


Figure D-4. Incremental loss $\Delta L_2'$ as a function of frequency for a forest with an average tree height h = 5 m. and a target height z = 1 m.

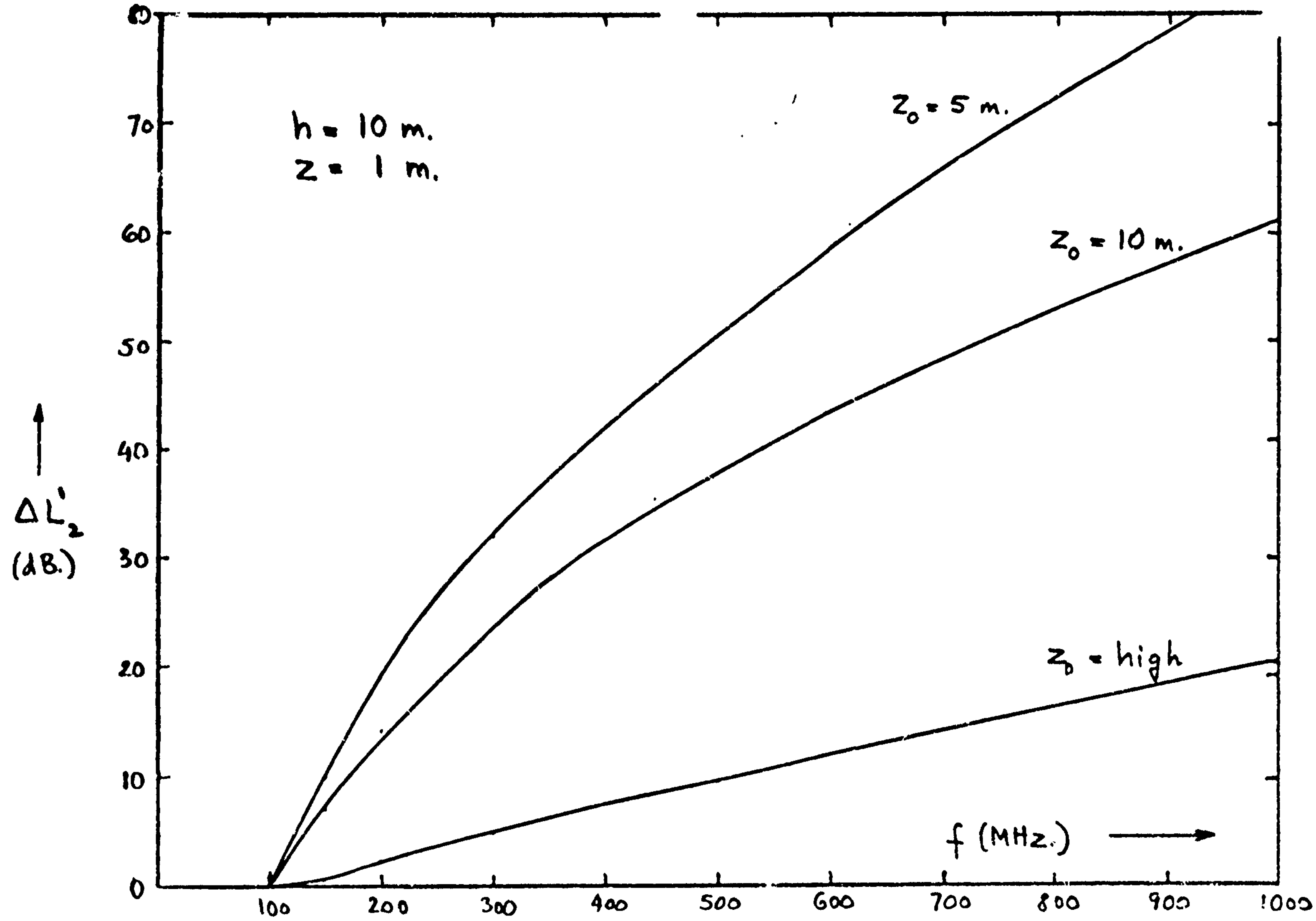


Figure D-5. Incremental loss $\Delta L_2'$ as a function of frequency for a forest with an average tree height h = 10 m. and a target height z = 1 m.

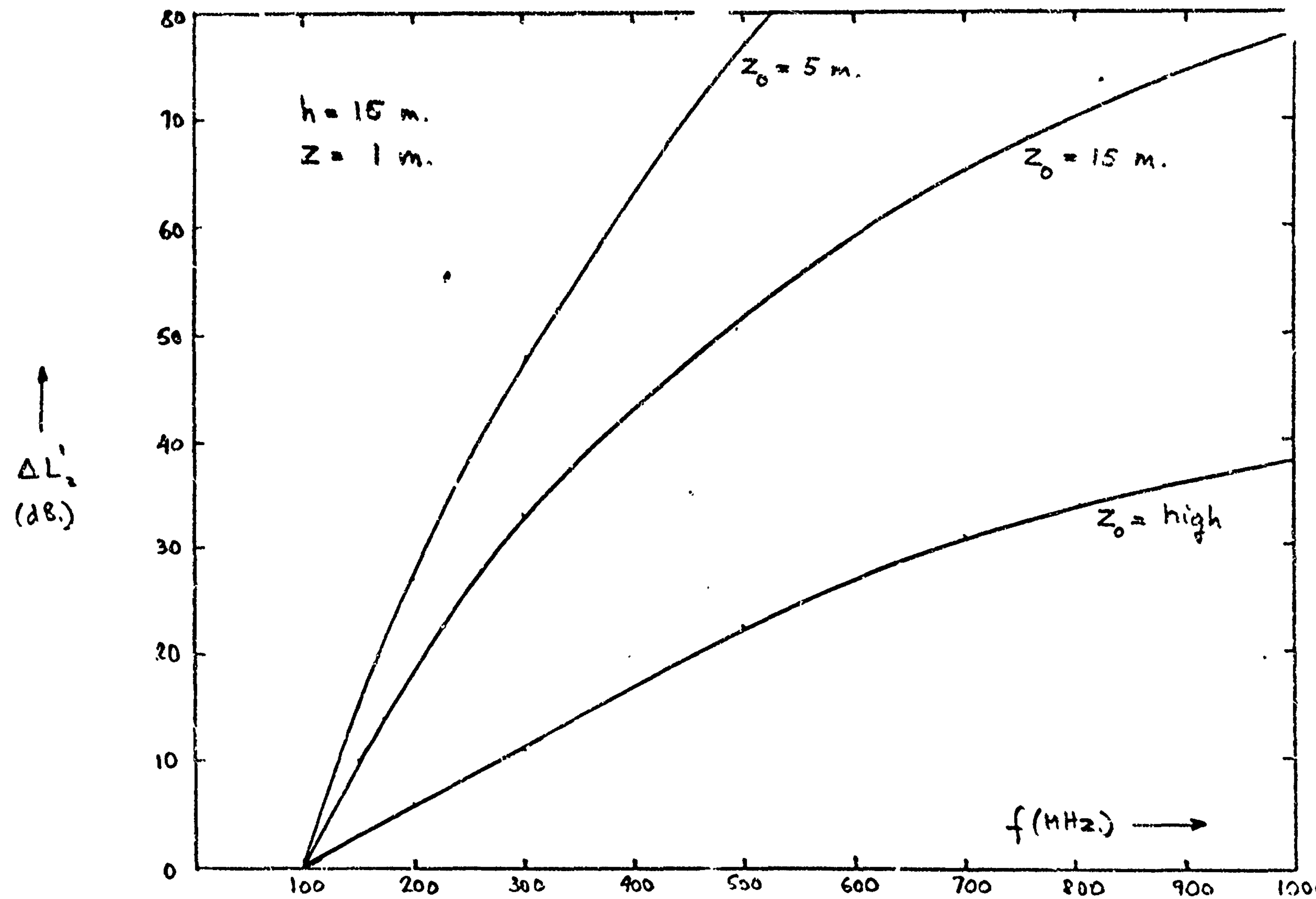


Figure D-6. Incremental loss $\Delta L_2'$ as a function of frequency for a forest with an average tree height h = 15 m. and a target height z = 1 m.

APPENDIX E

RADAR DETECTION OF HELICOPTERS IN NAP-OF-THE-EARTH FLIGHT

To assess the range of detection for helicopters flying nap-of-the-earth, we can use the radar equation in the form:

$$\frac{S}{N} = \frac{P_t\, G^2\, \lambda^2\, \sigma}{R^4\, B\, N_f\, L} \times 12.6 \times 10^{16}, \qquad (1)$$

where:

S/N = signal-to-noise ratio of receiver

P_t = transmitter power (in watts)

G = antenna gain

λ = wavelength (in meters)

σ = antenna cross-section (in sq. meters)

R = range (in meters)

B = receiver bandwidth (in c.p.s.)

N_f = noise figure of receiver

L = loss factor due to environment

As given, Eq. (1) is exactly Eq. (4.22) on pg. 116 of "Radar System Analysis", by D. K. Barton (Prentice-Hall, 1965), except that now all lengths are given in meters (rather than miles, etc.) and the factor 12.6×10^{16} is, therefore, different from that given in the book.

For low flying helicopters, the factor L will be rather important because the terrain introduces considerable losses so that free-space propagation conditions do not hold. We shall, therefore, examine two separate situations: (1) bare-ground conditions and (2) a vegetation (forest) layer covering the ground. For reasons that will be clarified later, we shall consider the latter terrain first.

1) Forest-Covered Ground - In this case, the transmitting antenna is at a height (40-60 ft) that is usually at about the same height as the average trees. The helicopter is close to or above the tree height. We may therefore use formula (36) on pg. 18 of "Effect of a Forest Environment on the Performance of Doppler Radar Systems", by T. Tamir (Interim Report issued by U. S. Army Land Warfare Laboratory, on December, 1971, hereinafter referred to as IR). Formula (36) is correct for the antenna height z_o and the helicopter height z being in the neighborhood of the tree height h, which is the case for maximum vegetation losses in the present case. If the helicopter rises well above the tree height h, the losses will be balanced, i.e., L in Eq. (1) will be smaller, so that the available range R will increase. Thus formula (36) will establish a lowest value for R under the

worst loss conditions.

As discussed above, R is found by taking $z = z_0 = h$ in formula (36) of IR, which yields

$$L_t = 20 \log \left| \frac{\pi(\epsilon_1 - 1)R}{\lambda} \right| , \tag{2}$$

where ϵ_1 is the complex permittivity of vegetation. Recalling that L_t is the one-way loss in decibels, we get

$$L = \left(\frac{\pi|\epsilon_1 - 1|R}{\lambda} \right)^4 , \tag{3}$$

so that Eq. (1) yields

$$\frac{S}{N} = \frac{P_t G^2 \lambda^6 \sigma}{B N_f |\epsilon_1 - 1|^4 R^8} \times 0.13 \times 10^{16} \tag{4}$$

For a signal/noise ratio of unity, the detectable range R_ν under fully vegetated conditions is therefore:

$$R_\nu = \left(0.13 \times 10^{16} \frac{P_t G^2 \lambda^6 \sigma}{B N_f |\epsilon_1 - 1|^4} \right)^{1/8} \tag{5}$$

The last result is easily evaluated for any given system. The vegetation factor ϵ_1 may be taken as

$$\underset{\text{(sparse)}}{0.01} \le |\epsilon_1 - 1| \le \underset{\text{(dense)}}{0.1} \tag{6}$$

As an example, consider:

$P_t = 1 \text{ KW} = 10^3 \text{ W}$

$G = 7.5 \text{ dB} = 5.6$

$\lambda = 2.14 \text{ meters}$

$\sigma = 5 \times 10^4 \text{ sq. ft.} = 4{,}500 \text{ m}^2$

$B = 10 \text{ MHz} = 10^7 \text{ c.p.s.}$

$N_f = 10 \text{ dB.} = 10$

Hence

$$R_\nu = \frac{1}{|\epsilon_1 - 1|^{1/2}} \left(\frac{0.13 \times 10^{16} \times 10^3 \times 31.4 \times 9.8 \times 4.5 \times 10^3}{10^7 \times 10} \right)^{1/8} = \frac{134}{|\epsilon_1 - 1|^{1/2}}$$

and, by introducing the values of Eq. (6), we get:

$$420 \leq R_\nu \leq 1{,}340 \text{ meters}$$

For temperate climates (U.S. and European), the vegetation is not so dense so that the higher value of $R_\nu = 1340$ m is probably more accurate. For dense jungles, the lower value of $R_\nu = 420$ is more likely to be correct.

Of course, for any other systems, Eq. (5) can be used to find the pertinent values of R_ν. It is interesting to note, however, that for fixed areas, both σ and G are inversely proportional to λ^2. Hence, the factor $G^2\lambda^6\sigma$ is independent of λ (or frequency) if the antenna and target cross-sections are kept fixed. However, as $|\epsilon_1-1|$ increases with frequency, Eq. (5) indicates that the lowest practical frequency should be used for radar systems under the present (vegetation) conditions. It is also interesting to observe that, as long as $z \approx z_0 \approx h$, the result for R_ν is independent of the three (antenna, helicopter and tree) heights. Hence, R_ν can be regarded as a characteristic (maximum) range length for any particular radar system required to detect low-flying helicopters.

2) Bare Ground - In this case, the pertinent terrain loss is due to the ground lobing effect on the antenna. By using Eq. (47) of IR, we find that the one-way loss in decibels due to this effect is

$$L_{gr} = 20 \log \frac{R\lambda}{4\pi\, z\, z_0} \quad , \tag{7}$$

Where the practical assumption was made that R is much larger than either z or z_0. Again using the fact that L_{gr} is in dB for one way, the two-way loss L in Eq. (1) is now given by

$$L = \left(\frac{R\lambda}{4\pi\, zz_0}\right)^4 \tag{8}$$

Introducing this into Eq. (1), we get:

$$\frac{S}{N} = \frac{P_t G^2 \sigma}{B\, N_f\, \lambda^2}\left(\frac{z\, z_0}{R^2}\right)^4 \times 31.4 \times 10^{20} \tag{9}$$

Again, taking S/N=1 and defining a geometrical figure of merit by

$$F = \frac{R_{bg}^{\;2}}{z\, z_0} \quad , \tag{10}$$

Where R_{b_g} is the maximum range detectable, we find

$$F = \left(31.4 \times 10^{20} \frac{P_t G^2 \sigma}{B N_f \lambda^2}\right)^{1/4} \tag{11}$$

Thus, for the example discussed on p. E-2, we find

$$F = \left(31.4 \times 10^{20} \frac{10^3 \times 31.4 \times 4.5 \times 10^3}{10^7 \times 10 \times 4.6}\right)^{1/4} = 1.77 \times 10^5 \tag{12}$$

In practice, z_o is fixed, so that we may write

$$R_{b_g} = \sqrt{F z z_o} \;, \tag{13}$$

so that, for z_o = 50 ft. = 15 m., we get

$$R_{b_g} = \sqrt{1.77 \times 10^5 \times 15} \sqrt{z} = 1630 \sqrt{z} \;, \tag{14}$$

where we recall that z is the height of the helicopter above ground (in meters).

Equation (13) and (14) permit a simple graphic presentation of R_{b_g} versus z and z_o for any given system, which is itself given by the figure of merit F. Thus, in Figure E-1, for $F = 1.77 \times 10^5$ of the above example, R_{b_g} is shown as a function of z, for true values of the antenna height z_o. A different graph would be needed for other values of F, i.e., for different system characteristics.

To continue the example, let us assume that $z = z_o$ = 50 feet = 15 m. We then find that R_{b_g} = 6.3 km. This is larger than R_J = 1.34 km for a forested region. For a terrain that is only partially covered by forests, we therefore expect that the maximum range would lie between these two limits, i.e., $1.34 < R_{max} < 6.3$ km. In this manner, suitable estimates may be obtained for any system and terrain conditions. The only restriction employed here is that the terrain must be reasonably flat so that the equations, which are accurate for flat ground, may be assumed to be sufficiently accurate.

The foregoing considerations for bare-ground conditions also hold for ranges that cross the sea. In the present context, we recall that G and σ are

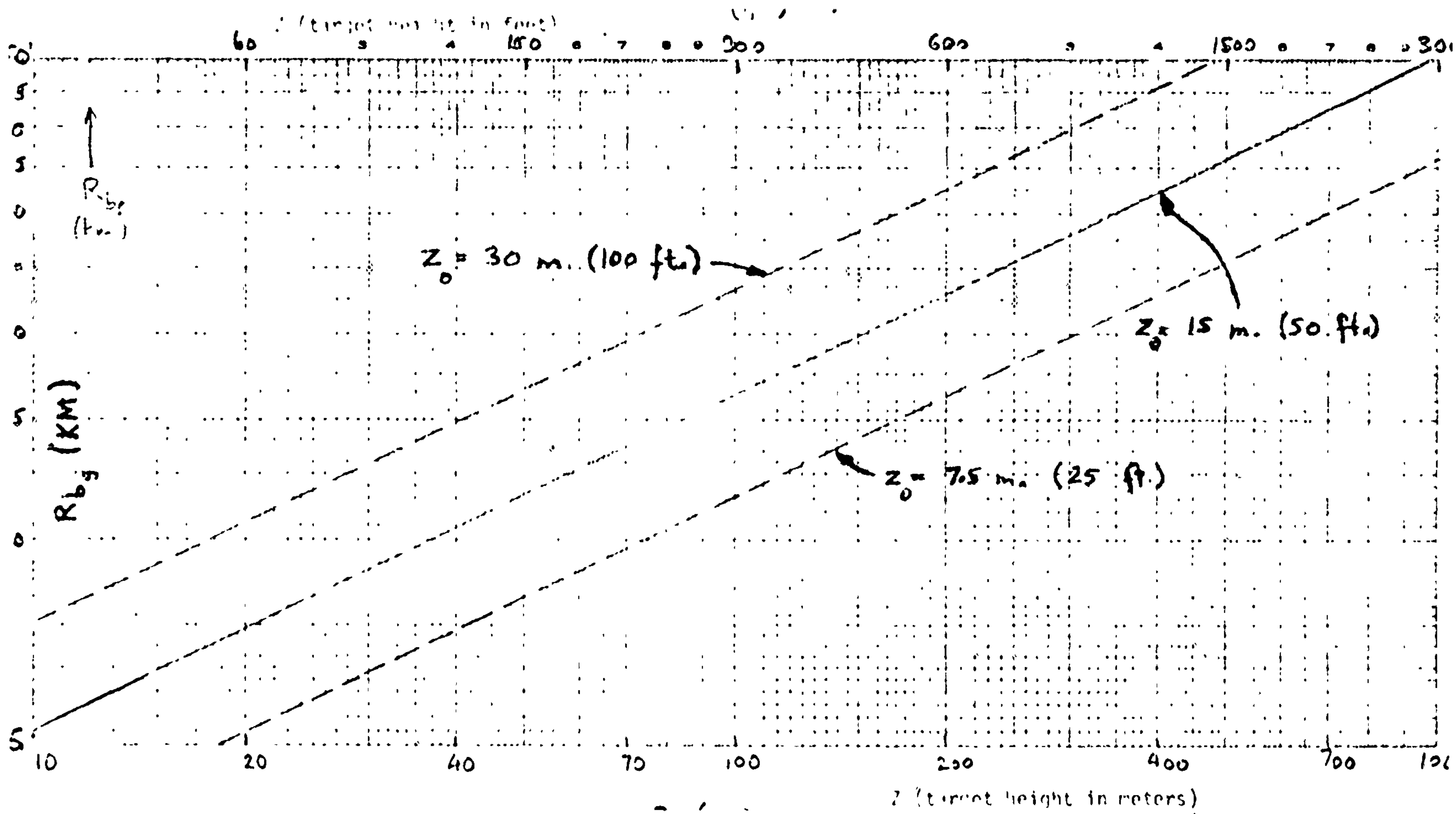


Figure E-1. Maximum Detection Range (R_{b_g}) as a Function of Target Height, Antenna Height inversely proportional to λ^2 so that the factor $G^2\sigma/\lambda^2$ in Eq. (11) is proportional to λ^{-8}, i.e., F is proportional to f^2, where f denotes frequency. Hence, R_{b_g} in Eq. (13) is proportional to frequency, unlike R_ν which was independent of frequency for constant antenna and target cross-sections. However, as R_ν is the limiting range in the case of foliage, this factor may be more restrictive in design considerations.

APPENDIX F

DESCRIPTION OF M-FOPEN

General

The M-FOPEN is a low frequency 140 MHz (VHF) ground-to-ground radar designed to provide the user a foliage independent, all-weather battlefield surveillance capability. It is a coherent, pulse doppler, moving target indicator (MTI) radar, which processes doppler returns with or without fixed returns as a reference. The set incorporates a 60° electronic scan that can be rotated 360° manually or remotely, and a multiple target detection capability. Two operators are required for the man-portable system (MPR), and base station (BSR) configuration. Six personnel are required to assemble and erect the BSR telescoping antenna tower. Major components of the two radar configurations are as follows:

(1) Man-portable Radar:

(a)	Display Box (Operator controls, azimuth readout, etc)	16 lbs
(b)	Transmitter/Receiver Box (Contains all RF circuitry)	16 lbs
(c)	Antenna (Two required for azimuth readout)	20 lbs
(d)	Fiberglass Antenna Mast, 30 Feet, w/Hardware	60 lbs
(e)	Control Cable (provides for operation up to 75' from antenna base), Antenna cables and batteries	30 lbs

(2) Base Station Radar: The electronics portion of the radar is incorporated into a display console, and a 20-kw power amplifier is used with the transmitter. The electronics portion is identical to the man-portable and intermediate range configurations.

(a)	Display Console (Control box, A-scope display, power amplifier controls, antenna rotator, speaker, power supplies and cable connections)	100 lbs
(b)	Power Amplifier (Connected to the output of the transmitter/receiver unit)	100 lbs
(c)	100-foot Cable (Remotes display console from power amplifier)	
(d)	2 Antennas and 50-foot Tower	400 lbs
(e)	Generator, 2-1/2 kw, 60-cycle, 110 VAC, 1 phase	

Technical Characteristics:

(1) Operating Frequency - 140 MHz

(2) Pulse Width (meters) - 20

(3) Peak Output Power

(a) Man-Portable Radar - 1 kw

(b) Base Station Radar - 5.0 kw

(4) Average Power Output

(a) Man-Portable Radar - 8 W

(b) Base Station Radar - 40 W

(5) Target Velocity Limits - 0.7 to 25 mph (40 mph with reduced sensitivity)

(6) Maximum Range - 200 to 1500 meters, depending on geometry, foliage, and wind conditions.

(7) Minimum Range - 75 meters

(8) Antenna

(a) Man-Portable Radar - Array of two log periodic antennas, horizontally polarized

(b) Base Station Radar - Array of two log periodic antennas, horizontally polarized

(9) Mast Height

(a) Man-Portable Radar - 30-75 feet depending on type of mast

(b) Base Station Radar - 50 feet

(10) Range Gates - Two, independently selectable, 20 meters wide

(11) Azimuth Coverage - 60° for both inner and outer gates; 40° available for outer gate only

(12) Target Angle Azimuth Readout - Angle Meter Readout on inner gate only

(13) Azimuth Readout Accuracy - Better than ± 5°

14) Supply Power

a) Man-Portable Radar - 22 to 30 V unregulated dc, 36 watts

b) Base Station Radar - 120 V, 60 Hz, ac power, 1.5 kw

Control/Display Console

The display box of the man-portable radar contains all operator controls, azimuth readout, target detection alarms, and headset capability. The operator sets each of two range gates, individually adjustable at ranges from 75 meters (150 meters for Base Station) to the maximum range of the radar for that location, typically 300 to 1500 meters depending on the antenna configuration, and environment. The range gates are 20 meters deep in a fixed 60° horizontal azimuth beam width which can be rotated 360° manually or remotely (for the BSR). The inner gate is equipped with an azimuth angle computer which provides the operator with the angle in mils left or right of the antenna direction to the target. The automatic visual and audio alarms are supplemented by the operator's headset which can monitor either or both range gates. Moving targets are presented by their characteristic doppler sounds in the headphones corresponding to the number, size and relative radial velocity of the target. The display box is incorporated into the display console of the base station system which also contains the "A" scope display, power amplifier controls, antenna rotator, speaker, power supplies and cable connections. The "A" scope can be used for range gate positioning, target identification, determining additional information on target motion, RFI jamming analysis, and trouble-shooting the radar.

Power Supply

The man-portable system requires an external power source providing 22-30 VDC (24 volt vehicle battery recommended for 24 hours continuous operation). The base station system requires 110-120 VAC, 60 cycle, 1 phase (1.5 kw required) which is supplied by the 2.5 kw generator accompanying this system. The power amplifier (20 kw pulse) of the base station system is connected to the output of the multipurpose radar transmitter/receiver unit, mounted at the base of the 50-foot tower providing the voltages necessary to operate the electronic and electrical/mechanical elements of the set.

Transport/Antenna Tower Assembly

Transport of the man-portable system and assembly of the system including the 30-foot tower can be accomplished by two men. The base station system requires transportation by 2-1/2 ton truck and five personnel for setting up the system. The telescoping tower is erected manually and incorporates the two antennas from the other systems. The power amplifier and transmitter/receiver unit are mounted near the base of the 50-foot tower. An AB-577 antenna mast used with the CORPS level TRC-110 radio equipment may be used instead of the 50-foot tower for a base station or fixed installation. This mast can be erected up to 75 feet and extend the range of either the man-portable or base station systems.

APPENDIX G

AIRBORNE FOPEN RADAR THEORY

A demonstration of the feasibility of a processing technique based on digital spectral analysis to detect man-made targets in foliated areas from a moving platform has been completed.[1] Using the Fast Fourier Transform as a basic processing tool, a technique has been developed that will cancel the majority of the clutter spread caused by the motion of a radar, allowing the detection of targets normally hidden by the clutter. These techniques can easily be implemented in a portable radar system containing a basic foliage penetration radar (illustrated in Fig. G-1) and a minicomputer (Fig. G-2).

The fundamental process used in analyzing doppler data involves a transformation of the sampled time signal to the frequency domain. For a given segment of the data the output from a spectrum analysis algorithm is similar to what would be obtained if the signal were processed through a bank of narrow-band filters. This estimate, using only one data set, is referred to as the power spectrum. It is simply the Fourier Transform of the autocorrelation function. The cross spectrum is also a power spectrum, but involves two separate data sets. It is the Fourier Transform of the cross correlation function, and measures the degree of linear correlation between the two signals as a function of frequency.

Both the power spectrum and the cross spectrum, as applied to real data, are estimates of theoretical quantities. In both estimates there is a certain amount of freedom in choosing certain parameters so that the estimate is not only a close approximation in a mean value to the theoretical values, but also a stable quantity in the sense of statistical variation. Statistical stability requires that the variance of the estimate be relatively small so that spurious frequency peaks are not likely to be confused with targets.

The coherency of the radar signal is useful but not essential to the success of this processing technique. All returns, targets and clutter alike, are shifted by the relative doppler velocity of the moving platform. As long as the platform is moving faster than the desired moving targets, all doppler returns due to the moving targets will be greater than the transmitted frequency, and they will not be folded over due to the homodyne operation in the radar receiver. Furthermore, significant fixed targets located at an off-boresight angle can be detected due to the platform's own doppler return. The doppler spread, due to platform motion, is one-half what it would be in the noncoherent case, improving the velocity resolution capability in the main-lobe clutter region. Finally, the use of a coherent signal provides in-phase and quadrature-phase components which can be used as the input to a cross spectrum algorithm. The main effect of using this technique is a significant reduction in noise over the ordinary power spectrum calculation.

The use of spectral analysis techniques really involves an estimation of the power or cross power spectrum. Several parameters have to be chosen in the software program, which averages a series of short-term spectrums to form

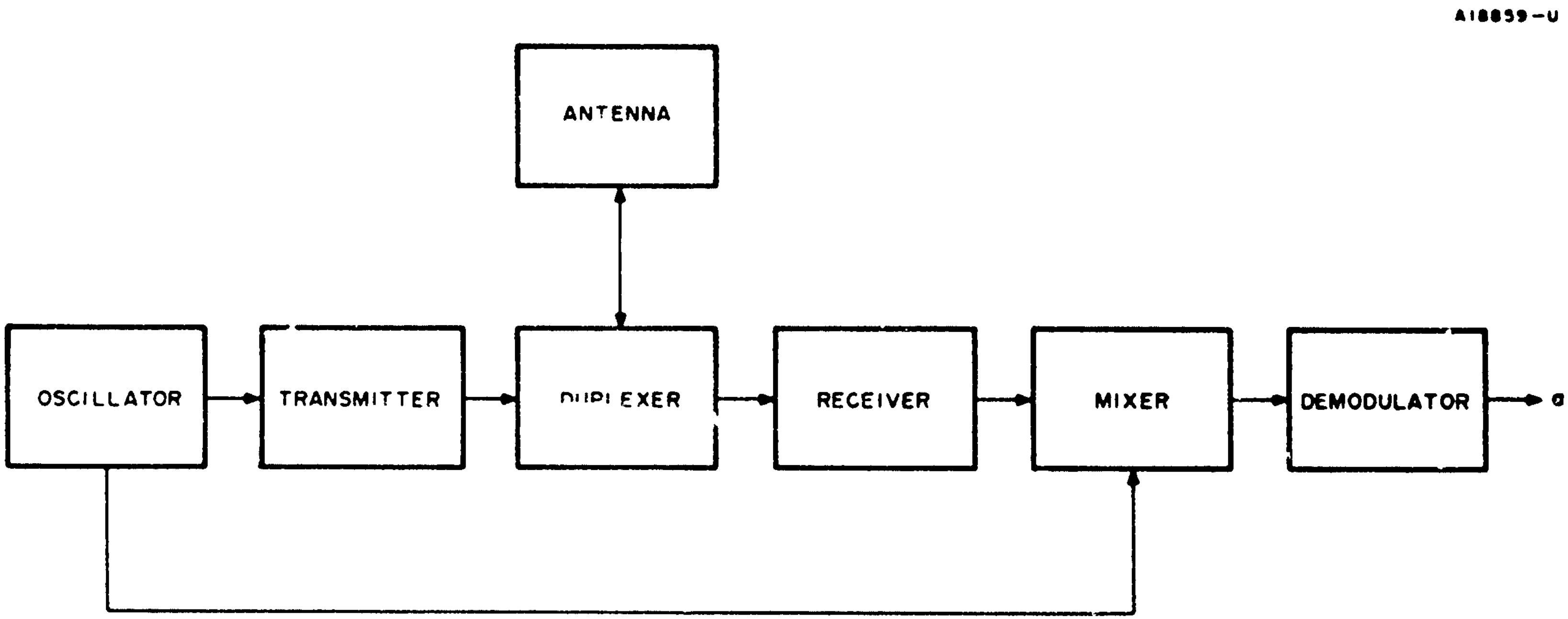


Figure G-1. Coherent Radar Block Diagram

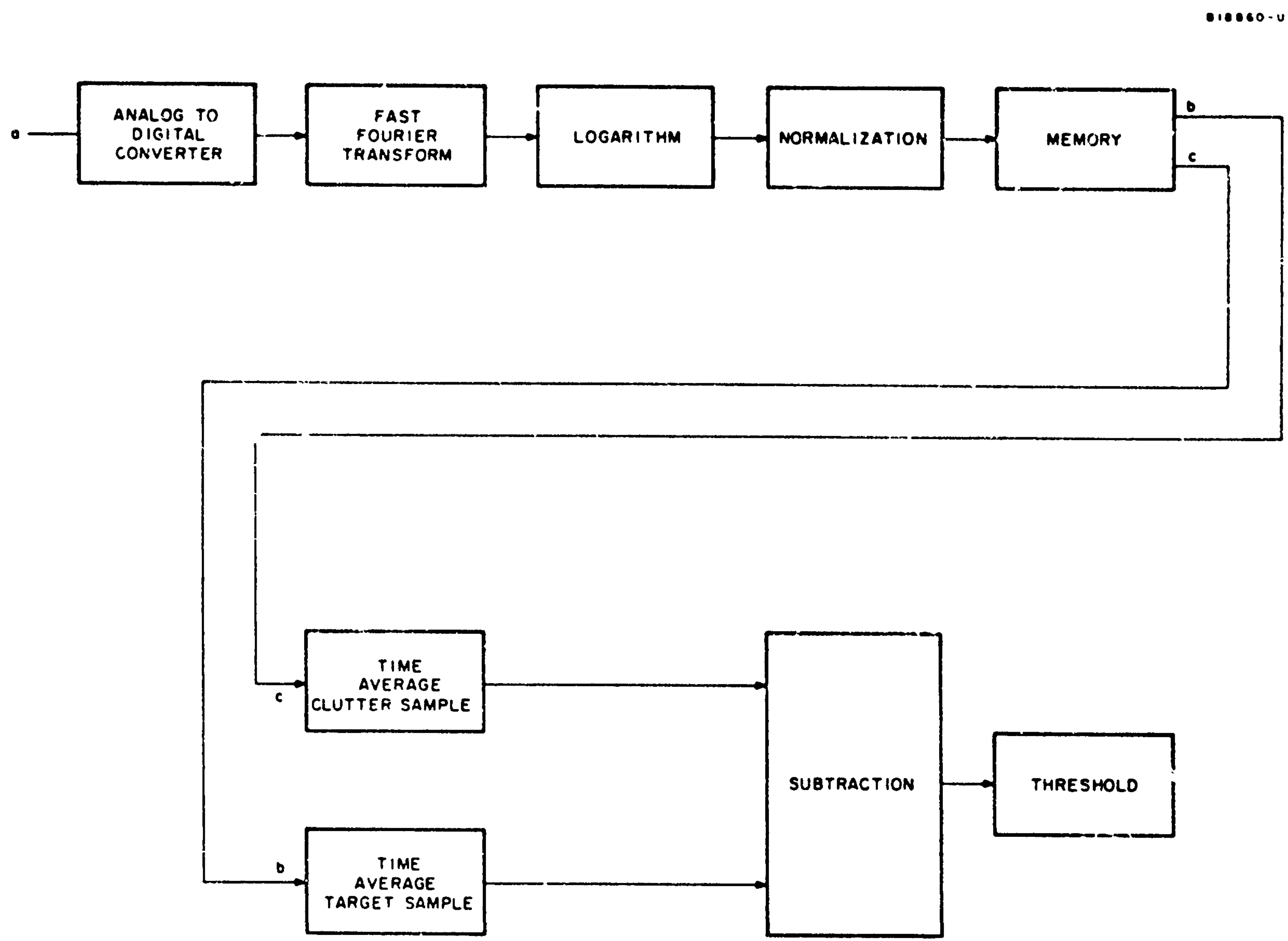


Figure G-2. Signal Processing Scheme

a stable estimate of the desired spectrum. Each component of that average should involve an interval of data approximately equal to the time on-target, and this, in turn, determines the basic processing resolution. High velocity platforms, such as an aircraft, collect fewer data points than the slower moving platforms. On the other hand, the averaging effect is likely to reduce the target-to-clutter ratio in this case. A truck-mounted radar requires more points in each component so that the higher resolution obtained will aid in separating the relatively close doppler frequencies. In this case, the increased time-on-target should improve the target-to-clutter ratio, and will tend to increase the detection probability.

The basis of the processing technique developed is the Fast Fourier Transform algorithm which is used to form a suitably smoothed power spectrum estimate. With only minor additional complexity, a cross-power spectrum analysis can be employed resulting in noise reduction. A fundamental characteristic of the signal processing scheme, Fig. G-2, is that the clutter filter uses an actual clutter sample rather than an assumed mathematical clutter model. The appropriate clutter sample is subtracted from a suspected target-plus-clutter situation to yield an output which can be threshold-detected for the presence of target doppler information. A further important realization is that doppler information is derived from fixed targets, as well as moving targets, and this return can be utilized to detect these targets under certain conditions.

Spectral analysis performed on the time sequence of doppler data has the effect of transforming that data to the frequency domain where doppler returns are easily identified. The particular algorithms used were predicted on two fundamental assumptions: The first is that a time series analysis of the data is equivalent to an average over many realizations of the fundamental random processes. This is known as the ergodic property, and is required so that one experiment under a given set of conditions is sufficient to characterize the statistical quantities to be estimated. Just as important is the condition that the estimates be independent of the time reference. This is the stationarity condition which is never realized ideally in practice but is often fundamental to the signal processing that the stationarity condition hold over a reasonable time period covering the duration of an experiment. Hence the name: short-term stationarity.

The requirement for short-term stationarity is that the power spectrum estimates of sequential data segments over a period of about five seconds remain substantially the same.

Generally, the signal processing in an MTI radar is done either at IF frequencies or by using video information directly. No matter what particular scheme is used, it can be interpreted as a filter in the frequency domain whose function is to suppress the expected clutter return. An attempt to implement this filter digitally imposes severe requirements on the processing system since high data rates will result due to the large bandwidths involved. Hence, the sampling hardware will be complicated and expensive, and will require sufficiently fast data storage hardware to record the data. The job of processing that data using a general purpose digital computer would be immense due to the large amount of data involved. No semblance of real-time operation could be expected. Thus, special purpose digital hardware would be required, and the resulting system would be both cumbersome and expensive.

The hardware and software restrictions discussed above can be significantly lessened if the information data rate is lowered. At frequencies in the audio and sub-audio range, the hardware requirements can be handled by off-the-shelf components and systems, and the software problem is easily handled by a general purpose computer or minicomputer. This condition is met if the low frequency doppler information is processed directly, after having been demodulated by analog circuits in the radar. The audio and sub-audio doppler frequencies lend themselves nicely to digital processing due to the low information rate and the narrow bandwidths involved.

The doppler data derived from the radar return signal can be considered to be a mixture of deterministic and random processes. The conditions of ergodicity and short-term stationarity discussed previously ensure that certain mathematical operations on the data will be descriptive of the underlying processes involved. It should be realized, however, that a fixed computational algorithm applied to random data will result in an output that must also be considered in the sense of a statistical average. Yet, it is the discrimination between the primarily random returns from the clutter and the partially deterministic returns from targets that form the basis of the processing.

The average frequency spectrum derived from clutter alone will not change much unless a physical clutter boundary is traversed by the range gate. However, the time-on-target for a particular target of interest is likely to be on the order of one-half second. The clutter adaptation filter utilizes this principle in attempting to find the target detection characteristics. In particular, a set of data is bracketed as containing clutter information only, and an estimate of the power spectrum is calculated and stored for later use. For a different data set, displaced in time from the clutter set, in which a target return is suspected to exist, the spectrum is estimated, and the clutter spectrum subtracted. This process is illustrated in Fig. G-3. The objective is to cancel the clutter returns leaving a residual noise component and a peak corresponding to the target return. The most pronounced effect is the elimination of the mainlobe clutter due to the platform motion itself.

This technique is labelled "store and cancel". Sample results of this technique appear in Fig. G-4. The success of filtering out the clutter spectrum components caused by the platform motion is the significant result of this processing technique.

The technique is similar, in principle, to the delay line canceler found in conventional MTI radars. However, since the processing is done on the basis of a statistical average, the software requirements are not nearly as stringent as the hardware requirements in the delay line canceler. For example, the PRF stability is not a sifnigicant factor in the store and cancel technique, but is crucial to a successful delay line canceler.

As implemented in the software, the store and cancel technique forms the basis of the signal processing scheme. Because the clutter sample is always

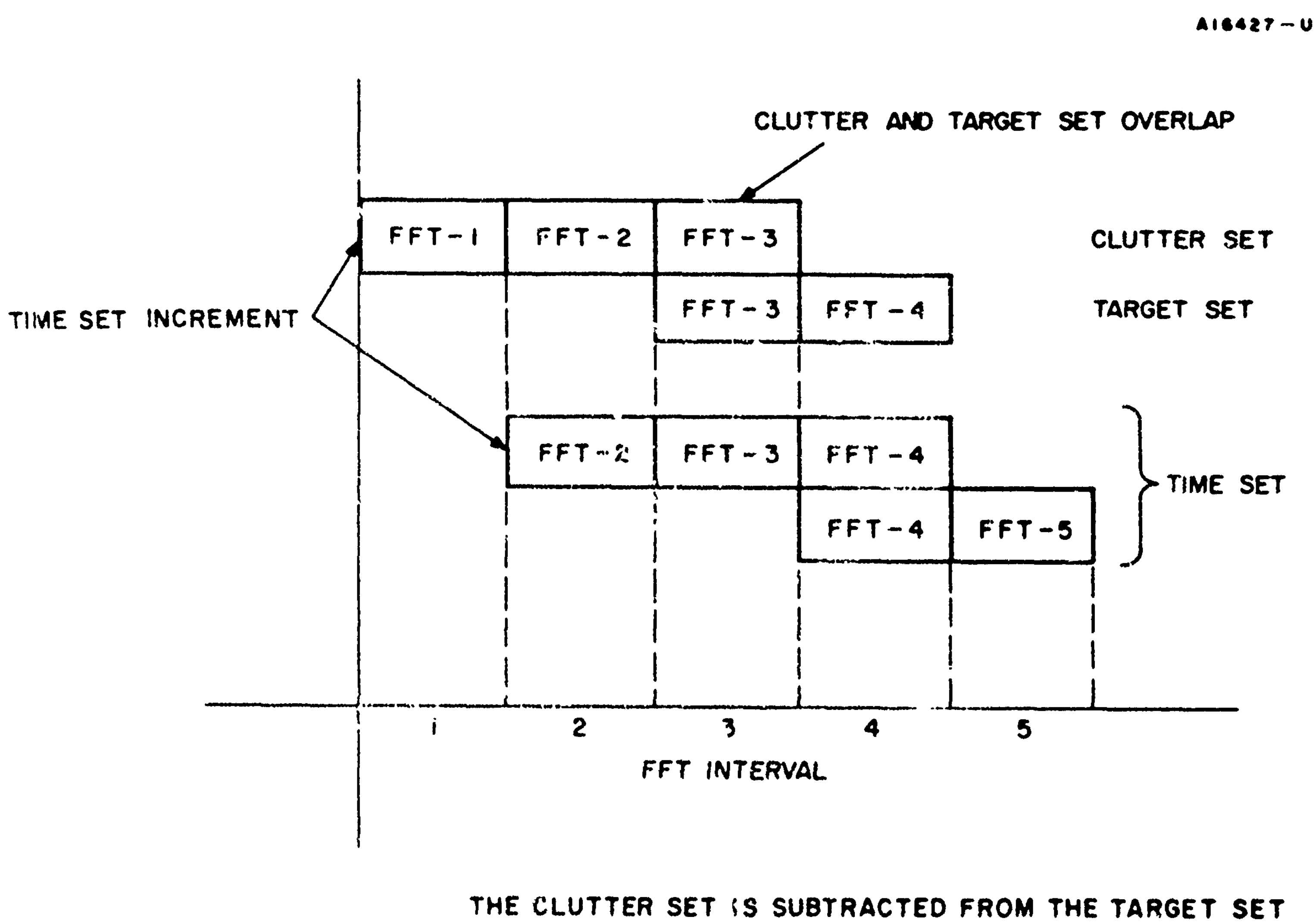


Figure G-3. Store and Cancel Processing Parameters

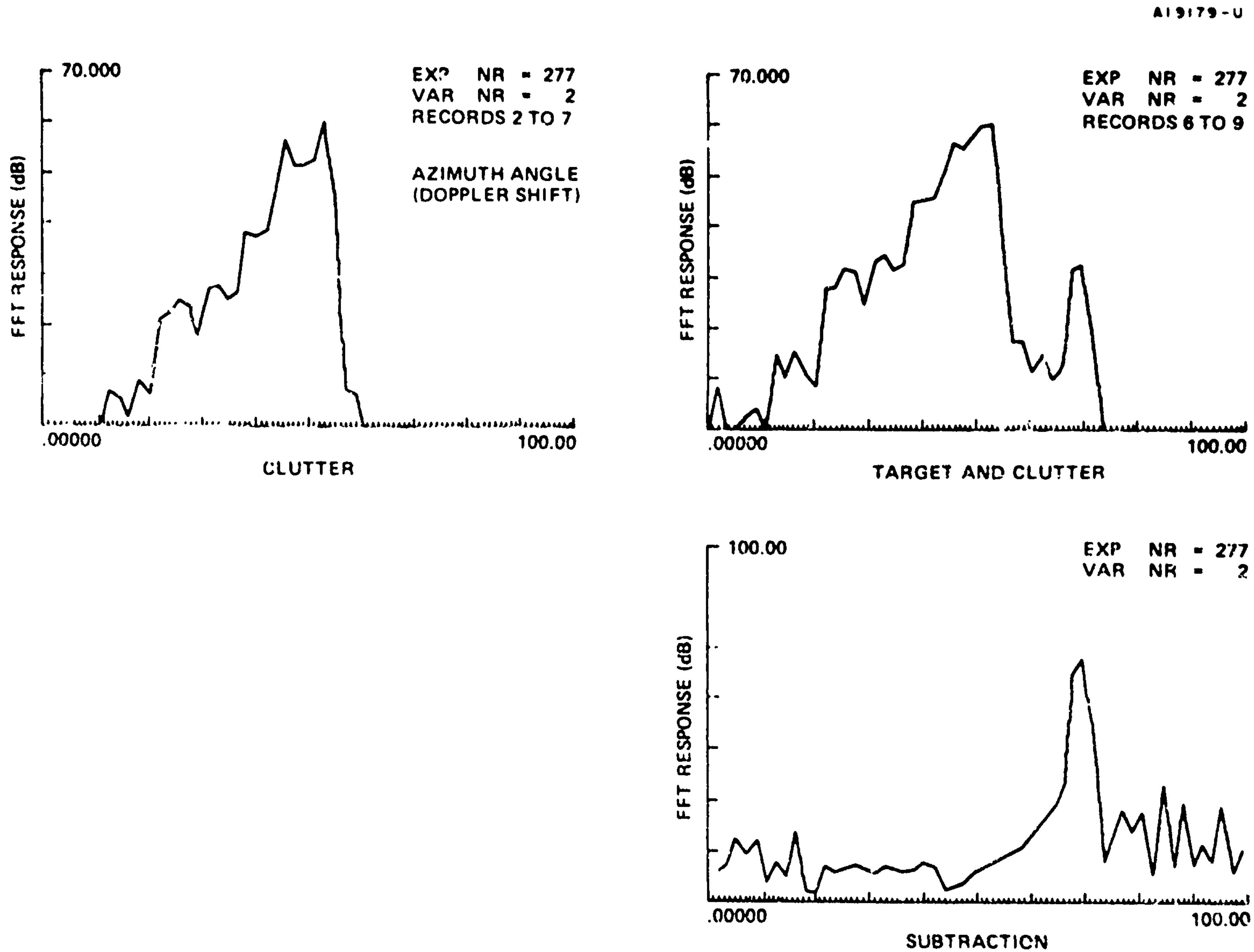
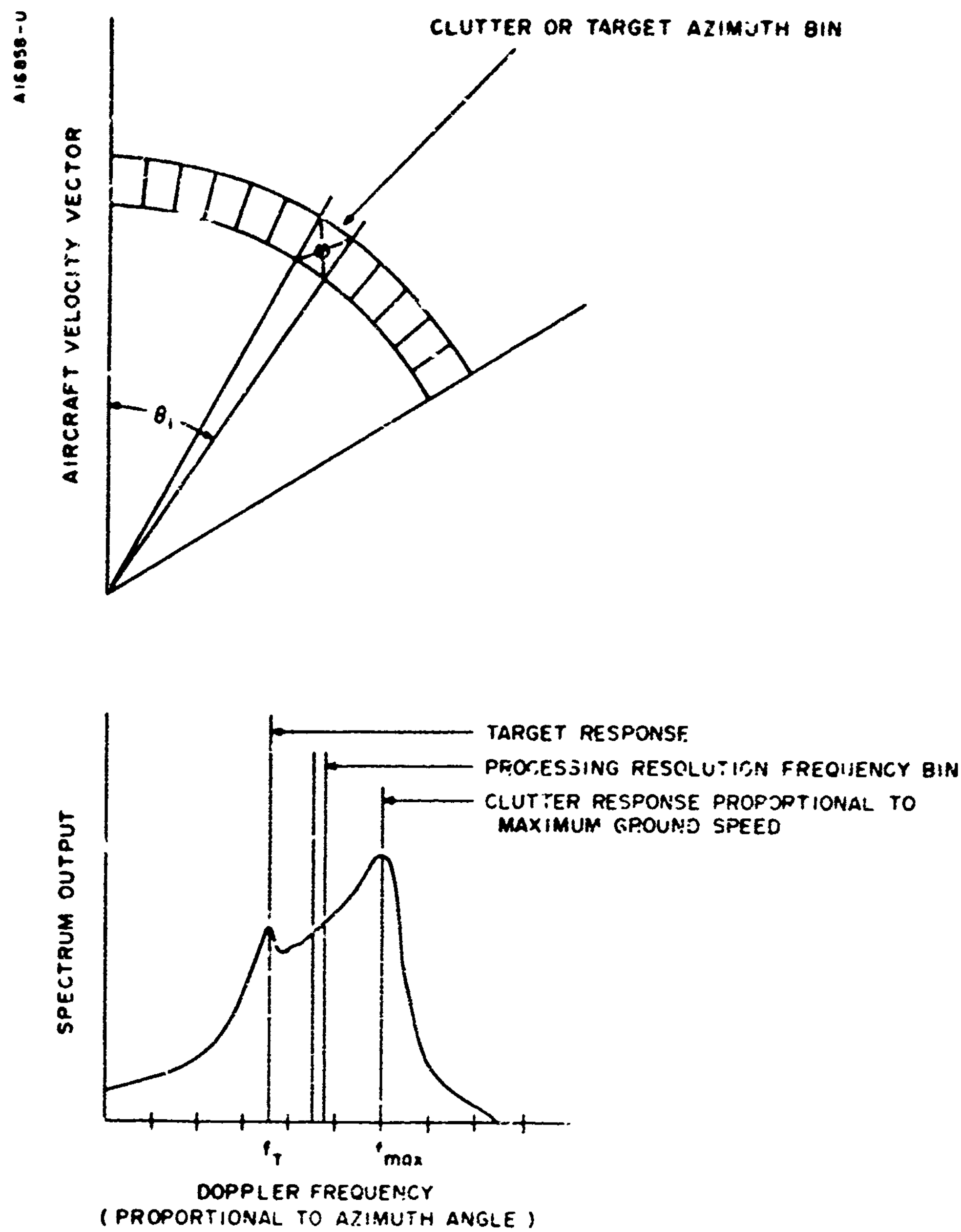


Figure G-4. Results of Subtraction Technique Showing Reduction of Ground Clutter and Enhancement of the Target from the same data run as the target sample, it is adaptive in the sense that no preconceived clutter model is needed.

This processing can also be considered as a frequency filter. Subtraction of the logarithmic power spectrum is equivalent to division in the linear domain. Treating the clutter estimate as an inverse filter, we have multiplication in the frequency domain which corresponds to linearly filtering the input data through the inverse clutter filter. Given the discrete nature of the spectral estimates, we can look at this as the equivalent of a finite bank of narrow band filters, each of whose gain is adjusted according to the past history of the clutter data. Processing of the airborne data has indicated that static target detection is possible under certain conditions.

The types of fixed targets that can be distinguished from clutter are those which present a greater radar cross-section than the surrounding clutter. Due to the wavelength of a VHF radar, this condition is likely to be a frequent occurrence since military targets of interest, such as vehicles and small metal structures, often have metal components on the order of a wavelength. Besides having a larger radar cross-section, we require some frequency dependent condition to hold. Targets located off the boresight of the moving platform contribute a given amount of energy to the total doppler spectrum. Since the target is off boresight, the doppler return is at a lower frequency than the main lobe clutter since the relative radial velocity between the platform and the target varies as the cosine of the azimuth angle (see Fig. G-5). Given the assumption that the target presents a larger return than the nearby clutter, it can then be recognized as a peak in the frequency domain. However, with the antenna boresight along the aircraft velocity vector, an ambiguity exists as to the target's azimuth position. Also, there is a problem in distinguishing it from a receding moving target.

Since the secondary peak in the frequency domain resulting from a static target off boresight is similar to that caused by a moving target, the store and cancel technique can be used to enhance the probability of detection. As with moving targets, the fundamental phenomenon being exploited is the stationarity of the general clutter as opposed to the one-time return from a prominent target. It is the change in the apparent clutter characteristics that alerts the operator to the target embedded in the frequency domain data.



$$f_d = \frac{2V}{\lambda} \cos \theta$$

f_T = TARGET FREQUENCY

Figure G-5. **Relationship of Fourier Transform to Azimuth Angle**