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ELECTROMAGNETIC PULSE SIGNAL CLASSIFICATION AND IDENTIFICATION OF NEARBY SFERICS IN THE HIGH ALTITUDE NUCLEAR DETECTION STUDIES (HANDS) PROGRAM (U)

Volume I

DDC
MAY 22 1968
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by

Measurements Automation Section
Information Processing Technology Division

Sponsored by

Advanced Research Projects Agency
Nuclear Test Detection Office
ARPA Order No. 183

DDC CONTROL NO. 62210

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Final Report

ELECTROMAGNETIC PULSE SIGNAL CLASSIFICATION AND IDENTIFICATION OF NEARBY SFERICS IN THE HIGH ALTITUDE NUCLEAR DETECTION STUDIES (HANDS) PROGRAM (U)

Volume I

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by

R. T. Moore
Don R. Boyle
Measurements Automation Section
Information Processing Technology Division

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PREFACE

This work is reported in two volumes. Volume I contains the description of the experimental plan which includes the rationale for the signal selection and classification criteria which were employed. Volume II contains the description of the experimental equipment and system configuration, the calibration procedures employed, the experimental results and conclusions.

We acknowledge the contributions of the many individuals which have made this project possible. The collaboration of A. Glenn Jean, and the entire HANDS staff of the ESSA Research Laboratories is especially appreciated. K. M. Gray, E. P. Ainsworth, W. B. Truitt, P. G. Stein, T. B. Hall and J. H. McGrath all contributed to the design, development, installation or operation of the experimental equipment. C. L. Albright and D. S. Grubb provided assistance in data reduction and J. R. Pino furnished essential administrative and secretarial support.

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ABSTRACT

Electromagnetic pulse signals from certain classes of nuclear events, in terms of burst and distance, have features which afford a means of recognition. Similar features are also observed in atmospherics, but these have a smaller normalized source function amplitude. An experiment was conducted to investigate the feasibility of measuring the distance to nearby sferics using azimuth and amplitude data observed at two sites separated by a few kilometers. Knowledge of the distance to the source and the observed amplitude would permit calculation of the normalized source function amplitude which might be used as a discriminant. Data were also collected on the frequency of simultaneous (within equipment and propagation delay) observation at both sites, of signals exceeding 10 V/m amplitude 10 V/m/μs rate of rise which persisted for one microsecond or less. Transients from lightning would not be expected to meet these criteria over propagation distances of more than a few kilometers.

The distance ranging experiment did not yield results which were within acceptable limits in accuracy based on the locations and dispersion of fixes plotted during a period of activity from a presumably isolated thunderstorm region whose position was established by weather radar. Results from the spaced transient detectors were favorable and this technique appears sufficiently promising to warrant further investigation under the HANDS program.

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I. Introduction

The High Altitude Nuclear Detection Studies (HANDS) project was established to investigate ground based techniques for detecting geophysical effects produced by nuclear explosions at high altitudes and in space. It has been charged with the responsibility of providing test facilities for evaluating possible bomb-detection equipments, and for the collection and analysis of background data obtained from them.

The principal HANDS facilities are located at Table Mountain, Colorado, about 13 miles north of Boulder, and consist of a variety of collocated sensors together with automatic data acquisition and data processing equipments including an on-line digital computer. Sensors selected for the HANDS facility include types which are responsive to optical, infrasonic, magnetic, ionospheric and electromagnetic disturbances. This report describes certain equipment and techniques which were developed for the investigation of electromagnetic pulse (EMP) disturbances.

Electromagnetic pulse techniques are considered to be one of the more important detection methods because of the size of the signals generated and their early arrival at a detection station. Atmospheric signals (sferics) compose most of the electromagnetic pulse background noise and present a serious recognition problem. Therefore, the design of observing equipments must attempt to provide ways of distinguishing a bomb from sferics. In the case of observations made from a single site, this is a formidable problem for which no satisfactory general solution is believed possible.

The effects of propagation over long distances tend to mask potentially distinctive features in waveform and spectral content. Even without these masking effects, the waveform of an electromagnetic pulse of nuclear origin varies somewhat with yield and considerably with detonation height. Thus, there is no "standard" shape of an electromagnetic pulse from nuclear detonations; instead, there is an evolution of wave shapes with height of burst, yield, distance and bomb design characteristics. The peak amplitude of the bomb-induced EMP tends to be somewhat larger than from a sferic as observed from a fixed distance. However, there are regions of overlap, and some means of estimating distance is necessary for this characteristic to be employed as a discriminant.

These considerations influenced the design of the experimental plan for electromagnetic pulse study in the HANDS project. The plan that evolved was based upon what appeared reasonable to attempt within the constraints imposed by the nominal single station facilities concept. It was based on the belief that electromagnetic pulse signals from certain classes (in terms of height, yield and distance) of nuclear events could be recognized by waveform features. The chief source of false alarms was expected to be from relatively nearby sferics, therefore, some means of identifying these nearby sferics would be required. Two approaches to the identification of nearby sferics were implemented through the use of a short base-line remote station and high-speed microwave data link.

One approach was based on establishing a position fix for nearby sferics and computing the normalized source function amplitude for comparison with a reference value. The second approach was based on coincidence comparison of signals exceeding amplitude and rate-of-rise criteria at both sites.

II. Experimental Plan

The original plan for the design of the HANDS EMP experiment has been reported by Jean and Hornback[1], and was guided by the following philosophy:

1. Assume that only unshielded detonations will occur.
2. Assume that the HANDS station is one station in a network of stations, arranged on a 2000 km grid and the area monitored is a circle of 2000 km radius centered at Boulder, Colorado.
3. Signal characteristic detectors and logic circuits are designed to monitor characteristics of bomb and atmospheric signals as follows:
    a. High-altitude or space burst within line-of-sight.
    b. Ground bursts at distances $\leq$ 500 km.
    c. Sferics (for the purpose of rejecting these signals).

The classes of signals of nuclear origin have been partitioned primarily on the basis of distinctive features which afford some opportunity of recognition based on observations at a single station. Signals from these classes of events are expected to have relatively large amplitude with rapid rate of rise and fairly short duration of the initial half-cycle. Their detection would be employed to alarm other nuclear detection sensors which might respond more slowly to bomb-induced effects and would also activate recording the output of equipment designed to record the azimuth, amplitude, waveform and other pertinent information on the EMP signal.

1. High-altitude or Space Nuclear Detonations within Line-of-sight

Experimental data indicate that electromagnetic pulses of large amplitude and wide spectra with energy peaks within the VLF region are received from detonations within line-of-sight of the receiving station. In what follows, no distinction is made between line-of-sight to the detonation and line-of-sight to the region from which the pulse is generated, although the two may be considerably different for burst heights well above the D-region. Electromagnetic pulses recorded at Hawaii from the three high-altitude detonations which were within line-Of-sight of the receiving station, all greatly exceeded 10 V/m peak amplitude. It is thought that a threshold trigger level of 1.0 V/m could be used to receive electromagnetic pulses from line-of-sight detonations of nominal yield at ranges well in excess of 2,000 km. Minimum signal amplitudes approaching this trigger level would be expected to occur from bursts occurring at a distance corresponding to the intersection of the null altitude with the minimum line-of-sight angle of elevation, or from bursts at ranges very greatly in excess of 2000 km.

Criteria for recognition of this class of signal include:

a. A rate of rise of the signal amplitude $\geq$ 20 V/m/µs.

b. Duration of the first half-cycle $\leq$ 30 µs.

c. Pulse amplitude $\geq$ 1.0 V/m.
Pulse amplitudes greater than tens of V/m would be indicative of a high altitude burst.

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2. Surface Nuclear Detonations at ≤ 500 km Range

The initial half-cycle of the electromagnetic pulse from a surface detonation is negative and the peak amplitude of the ground wave pulse from a 10 kt detonation is about 3 V/m at 500 km.

Criteria for recognition of this class of signal include:

a. Rate of rise of the initial half-cycle ≥ 1 V/m/µs.

b. Duration of the first half-cycle ≤ 30 µs.

c. Pulse amplitude ≥ 1.2 V/m.

d. Initial half-cycle polarity negative.

The estimates of signal features for the two classes of bomb signals described above are derived from Jean[1], Taylor[3,4], Wait[5], Korzas and Latter[6] and the Final Report-Project VELA Summer Study 1965 on EMP.

3. Atmospheric Signals vs Bomb Signals

The rate-of-rise criteria associated with the bomb signals described above are somewhat higher than the values expected from most atmospherics, although quantitative measurements of this parameter on significant sample sizes do not appear to be available. Some insight on sferic rate-of-rise characteristics can be gained from statistics on rise times reported by Millman[2], where the mean rise time of 30,000 sferics exceeding a 1.0 V/m amplitude threshold was 9.5 µs, and the mean rise time of 7000 sferics exceeding 2.0 V/m amplitude was 8.0 µs. From these data it appears that only a small fraction of atmospheric signals, primarily from nearby sources, would be expected to have a rate of rise as great as 1.0 V/m/µs.

The first half-cycle duration of bomb signals tends to be somewhat shorter than that of a large percentage of atmospherics, although significant overlap occurs. Millman[2] reports that the percentage of sferics having first half-cycle durations between 15 and 30 µs increases from 78 percent at propagation distances of less than 100 km to 91 percent for propagation distances between 400 and 800 km. The

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decrease in the percentage of signals having first half-cycle durations less than 15 μs is even more pronounced, dropping from 21 percent for propagation distances of less than 100 km to 6 percent at the 400 to 800 km range. Clearly, the nearby sferics are most likely to have features similar to the classes of bomb signals which have been selected and some means of identifying nearby sferics could function as a useful discriminant. Precursor detection has been suggested for this role, but was rejected in the HANDS project because of the lack of a clear distinction between the sferic precursors and staging spikes which may be associated with a nuclear burst, and also because of the difficulty of properly associating precursors with the main strokes of sferics.

Normalized source function amplitude appears to offer a potentially useful basis for the positive identification of a large fraction of nearby sferics. Millman[2] reports a median amplitude for sferics, normalized to 1 km, of 360 V/m. Taylor[3] has calculated a minimum normalized nuclear source function amplitude of approximately 900 V/m for a surface detonation of 1 kt yield. Based on these data, a discrimination level of 500 V/m was tentatively selected. Its implementation, however, required that the distance to the sferic source be determined, and this requires data from more than a single station.

III. Equipment Design Considerations

Normally, data from at least three stations is employed in radio position fixing; however, since the concern here is less with absolute location than with range, less redundant methods were adopted. These involve the use of a single, short base-line remote station with a line-of-sight high-speed data communication link to the Table Mountain facility. The peak amplitude and azimuth of signals exceeding a preset threshold at the remote station are relayed to the base station. These data, together with similar measurements on the same signal obtained at the base station, permit the calculation of range to sferics occurring within a radius of approximately 100 km. The experimental plan contemplated completing these calculations during the one millisecond delay interval required for signal amplitude normalization, and the system timing was established accordingly.

Referring to Figure 1, a pair of direction finding stations are located at the positions designated X and Y. The range to a signal source may be determined by plotting a fix using the measured azimuths at X and Y. The resulting position fix is most accurate for sources which are located along the bisector normal to the base line. No fix is possible for events occurring on the base line or its extensions beyond X or Y. The locus of positions which may be fixed by plotting azimuths and which have constant accuracy in terms of percentage error in range is shown by the dotted line.

If signal amplitudes are measured at X and Y, and assuming an inverse distance propagation law, then Figure 2 shows the loci of possible positions from which a constant difference in amplitude would be observed. These circles of constant amplitude difference can be employed to establish a fix on a signal source by forming the intersection with the azimuth obtained at the station observing the largest signal amplitude. Thus, by employing the appropriate combinations of azimuth data and amplitude data, it is possible to obtain fixes in any direction from observations from only two stations. The accuracy of fixes obtained in this way is limited and the design objective was to establish range within -25 percent and +40 percent at ranges of up to 100 km.

1. Site Selection

The site selected for the remote station is located 1.4 miles west of Campion, Colorado and 27.5 km on a true bearing of 026° from the HANDS facilities at Table Mountain. The criteria for its selection included a line-of-sight path for the microwave link to Table Mountain; terrain and geographical surroundings as similar as feasible to that at Table Mountain; distance between 25 and 35 km; and reasonable access to commercial power and telephone facilities.

2. Station Configuration

Each station is equipped with an AWRE azimuth digitizer which operates from crossed loops and a whip sense antenna. The uncertainty in indicated azimuth is reported to be on the order of ±2° because of instrumental factors. Uncertainties due to uncompensated siting errors or horizontally polarized components of signals from nearby sferics can increase this by a significant factor. An azimuth is digitized within 230 to 430 μs after generation of a master trigger that occurs after receipt of a signal which exceeds a preset amplitude threshold (normally 0.5 V/m). The variation in measurement time is a function of both waveform characteristics and azimuth of arrival. If the measurement has not been completed within 500 μs after triggering, it is taken as an indication of invalid data and an indicator bit is set in the azimuth data word. The azimuth data is expressed as a three digit BCD representation resolved to the nearest degree.

The north-south loops at both stations are oriented along the base line rather than along a true north-south direction. This arrangement provides the minimum difference in the times at which azimuth measurements are available at the two stations and simplifies triangulation.

Each station is also equipped with an analog-to-digital converter which is gated on by the master trigger for a period of 60 μs. The largest peak in signal amplitude which occurs during this interval is digitized. Since amplitude ratios are important and a large dynamic range is desired, a logarithmic operation is performed and the quantization is in terms of decibels. The resolution is 0.1 dB with an accuracy of ±0.2 dB and a dynamic range of 51.1 dB. The amplitude value in dB is expressed as a nine bit binary number and is available 31 μs after the end of the sampling aperture. Signals which exceed the uper limit of the dynamic range cause an overload bit to be set indicating that the amplitude data word is not valid.

Each station is also equipped with an AWRE Transient Detector. Signals which exceed a peak amplitude of 10 V/m and have a rate of rise of at least 10 V/m/μs which does not persist for more than one microsecond cause a flag bit to be set in the amplitude data word.

Amplitude and azimuth data words are transmitted from the remote station to Table Mountain by a microwave data communications system operating at a rate of 250 kilobits per second. The amplitude word is transmitted first. When it has been received at the base station, a priority interrupt is generated, and that word, together with the locally measured amplitude word, is input to the on-line SDS 930 computer. When the azimuth data has been received, another interrupt occurs and the process is repeated. Logical interlocks are incorporated to insure that only data which time coincidental within the aperture required to accommodate propagation and transmission needs is input to the computer.

3. Signal Processing Logic

Figure 3 is a scale drawing showing the two stations and the circles of equal signal amplitude ratio (in dB) and equal azimuth difference. Only one quadrant is shown because of symmetries about the base line and the perpendicular base-line bisector. The azimuth angles relative to station No. 1 are indicated in 0.1 radian increments.

It is helpful to consider what happens as a hypothetical signal source is moved over this area of interest. Assume this source produces signals at the low limit of interest, 500 V/m normalized to 1.0 km, and that the signal amplitude obeys an inverse distance law. Table I shows the received signal amplitude as a function of source distance.

TABLE I

Amp (dB)	Distance (km)	Amp (dB)	Distance (km)	Amp (dB)	Distance (km)
30	100	39	35.6	48	12.7
31	89.4	40	31.8	49	11.2
32	79.4	41	28.2	50	10.0
33	71.0	42	25.2	51	8.9
34	63.3	43	22.5		
35	56.5	44	20.0		
36	50.2	45	17.9		
37	44.9	46	15.9		
38	40.0	47	14.2		

0 dB = 0.158 V/m

The received signal is given in decibels so that changes in the critical normalized source function amplitude can be accommodated by translating the dB scale with respect to distance or by making a corresponding change in the zero dB reference level.

Using Figure 3 and Table I, it is possible to construct a family of curves showing received signal amplitude in dB as a function of azimuth angle for various azimuth differences and for various signal amplitude ratios expressed in dB. These curves are shown in Figure 4. The decision process can be accomplished by table look-up or by computation or by combinations of both.

As the first step, a number of determinations of conditions are necessary. These are shown in Table II and can be made from the amplitude and azimuth data words.

TABLE II. CONDITIONS

A. Base amplitude available.

B. Base amplitude ≥ 30 dB.

C. Base amplitude overloaded.

D. Remote amplitude available.

E. Remote amplitude ≥ 30 dB.

F. Remote amplitude overloaded.

G. Base amplitude $\geq$ remote amplitude.

H. $|$ Base amplitude - remote amplitude $| \geq 2$ dB.

I. $|$ Base amplitude - remote amplitude $| \geq 10$ dB.

J. Base azimuth available.

K. Remote azimuth available.

L. $|$ Base azimuth - remote azimuth $| \geq 0.2$ RADIANS.

Given the above determinations, several important decisions can be made. The first of these is whether or not additional processing will be useful. Obviously at least three of the four measurements must be available, i.e.,

$$(A \wedge D \wedge J \wedge K) \vee (D \wedge J \wedge K) \vee (A \wedge J \wedge K) \vee$$

$$(A \wedge D \wedge K) \vee (A \wedge D \wedge J) = 1 \; * \qquad (1)$$

There is no need for further processing if the signal is outside the ranging capability of the system and it may therefore be immediately classified as undetermined. To be within the ranging capability of the system, the amplitude ratio must be equal to or greater than 2.0 dB or the azimuth difference must be equal to or greater than 0.2 radians, i.e.,

$$H \vee L = 1 \qquad (2)$$

There are additional considerations when one of the measurements is missing. The remaining measurements must meet the condition for computability:

$$(A \wedge D \wedge H) \vee (J \wedge K \wedge L) = 1 \qquad (3)$$

There are two special cases, which can occur, that will meet the above criteria, yet not lead to a proper solution:

$$A \wedge D \wedge J \wedge \bar{K} \wedge H \wedge \bar{G} = 1 \qquad (4a)$$

$$A \wedge D \wedge \bar{J} \wedge K \wedge H \wedge G = 1 \qquad (4b)$$

This occurs when the amplitude ratio circle is around one station and the available azimuth is associated with the other station. When this occurs, the azimuth vector will generally intersect the amplitude circle in two places.

---

* In this equation and the ones which follow, the logical "and" operator is $\wedge$, and the logical "or" operator is $\vee$.

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Other special cases can be resolved with a minimum of computation. A signal can be immediately identified as a sferic (normalized source function amplitude < 500 V/m at 1.0 km) if equation (3) is satisfied and neither station observes an amplitude ≥ 30 dB. Another condition for immediate identification of a sferic is an amplitude ratio ≥ 10 dB. The reasoning for this conclusion is as follows: assume a 500 V/m normalized source on the base line extended. Its distance is such that the receiver driving the digital dB meter just saturates. The system has been set so that this occurs at a level of 47 dB. The amplitude ratio will then be a little over 9 dB, which is, therefore, the greatest amplitude ratio that can be achieved by this source. Only sources having smaller normalized amplitudes can achieve higher ratios. The conditions for positive sferic identification can then be expressed:

$$\left[(H \vee L) \wedge \bar{B} \wedge \bar{E}\right] \vee \left[I\right] = 1 \qquad (5)$$

Two special cases also can be used to immediately classify a signal as a bomb: if the signal is beyond the systems ranging ability and has an amplitude ≥ 30 dB, or if both digital dB meters indicate amplitude of 47 dB (saturation) i.e.,

$$\left[(\bar{H} \wedge \bar{L} \wedge (B \vee E)\right] \vee \left[C \wedge F\right] = 1 \qquad (6)$$

Further computation must be performed if equations (1) and (3) are satisfied and if neither equation (4), (5) nor (6) is satisfied. There are several ways of accomplishing the further computation as shown in Table III below:

TABLE III

C1. Use base azimuth and remote azimuth to compute distance from base station, and use base amplitude to compute source intensity.

C2. Use base azimuth and remote azimuth to compute distance from remote station, and use remote amplitude to compute source intensity.

C3. Determine distance from the base station to the intersection of the base station azimuth line with the amplitude ratio circle, which was determined from the remote and base amplitude; and use base amplitude to compute source intensity.

C4. Determine distance from the remote station to the intersection of the remote station azimuth line with the amplitude ratio circle, which was determined from the remote and base amplitude; and use remote amplitude to compute source intensity.

If one of the four measurements is missing or out of range, then the choice of a computational method is fixed since there would be only one method which would use the available data. When all four measurements are available, a choice must be made of the computational method which would probably produce the most reliable answer. The rule which will be used is: If the amplitudes differ by less than 2 dB ($H = 0$), then use computation C1; if the amplitudes differ by 2 dB or more and base amplitude is larger than remote amplitude ($H = 1$, $G = 1$), then use computation C3; if the amplitudes differ by 2 dB or more and remote amplitude is larger than base amplitude ($H = 1$, $G = 0$), then use computation C4. The following table summarizes all the conditions for which the various computation methods are used, including equations (1) through (6).

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TABLE IV

CONDITIONS	ACTION
$A \wedge B \wedge J \wedge K \wedge L \wedge \left[D \vee E \wedge \bar{H} \wedge \bar{I} \wedge (\bar{C} \vee F) \vee \bar{D}\right] = 1$	COMPUTE VIA METHOD C1
$\bar{A} \wedge D \wedge E \wedge J \wedge K \wedge L = 1$	COMPUTE VIA METHOD C2
$A \wedge B \wedge D \wedge E \wedge G \wedge H \wedge \bar{I} \wedge J \wedge (\bar{C} \vee \bar{F}) = 1$	COMPUTE VIA METHOD C3
$A \wedge B \wedge D \wedge E \wedge \bar{G} \wedge H \wedge \bar{I} \wedge K \wedge (\bar{C} \vee F) = 1$	COMPUTE VIA METHOD C4
$\left[(H \vee L) \wedge \bar{B} \wedge \bar{E}\right] \vee \left[I\right] = 1$	IDENTIFY AS A SFERIC
$\left[\bar{H} \wedge \bar{L} \wedge (B \vee E)\right] \vee \left[C \wedge F\right] = 1$	IDENTIFY AS A BOMB

The results of these computations then serve to generate one of three possible classifications for the observed signal:

a. Signal is identified as sferic.

b. Signal is identified as bomb.

c. Signal is undetermined (beyond ranging capabilities of system or essential data not available).

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This information may now be employed in combinatorial logic circuits with the information obtained from waveform feature measurements to inhibit the recording of signals which meet the acceptance criteria for signals from one of the classes of nuclear events but which have been identified as a sferic by the system.

As noted previously, the experimental plan contemplated that these computations would be made during the one second millisecond normalization delay interval. It was not possible to complete the necessary programming for the HANDS on-line computer (SDS 930) in time for use during the 1967 summer thunderstorm season. Rather than delay the experiment, separate magnetic tape recordings were made of amplitude and azimuth data and of waveforms selected by the feature extraction method. These were then correlated and processed using the National Bureau of Standards computer facilities at Gaithersburg, Maryland. The detailed description of this portion of the activity is reported in Volume II.

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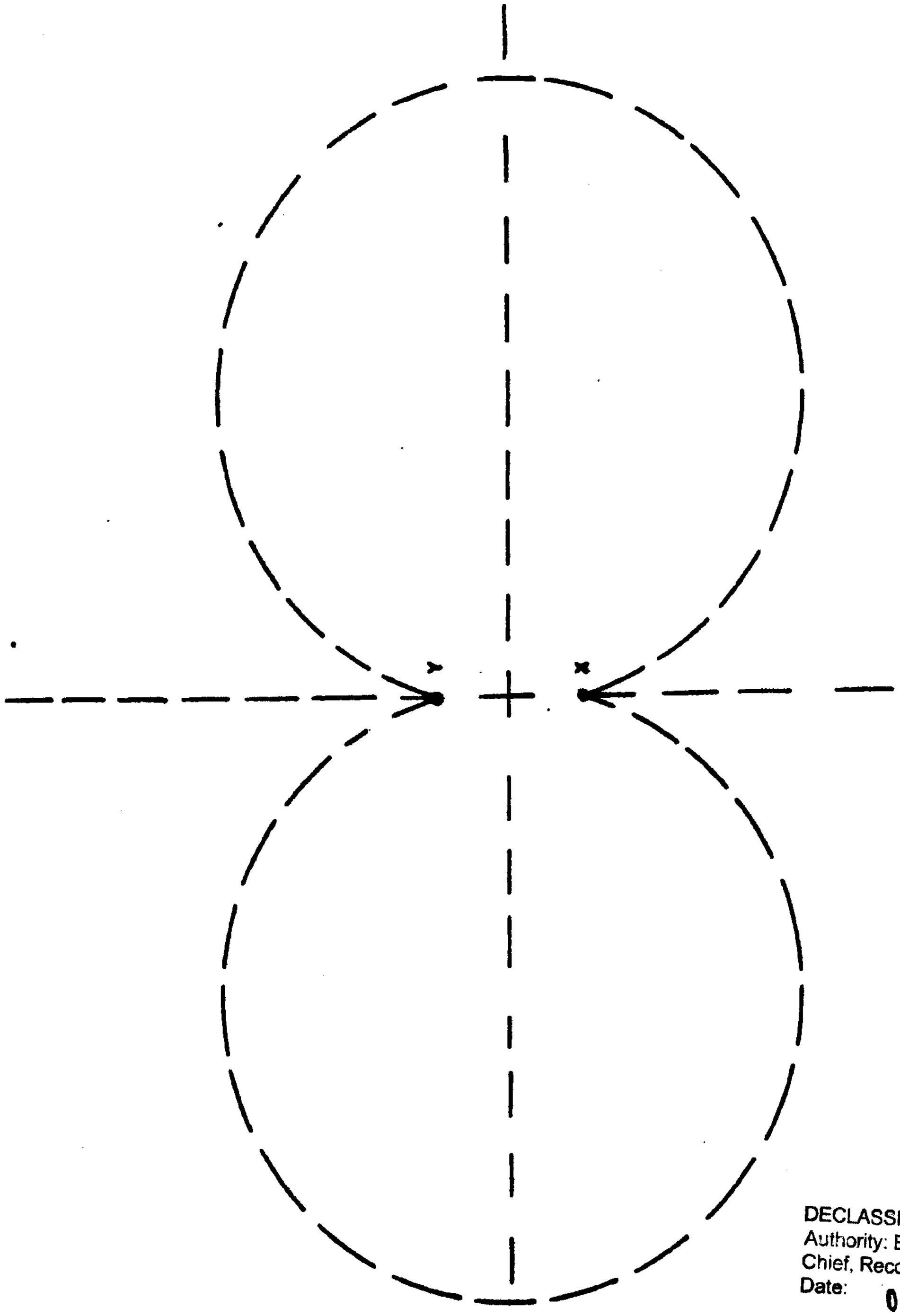

FIGURE I. LOCUS OF FIXES WITH EQUI-ACCURATE RANGE DETERMINATION BASED ON BEARING DATA

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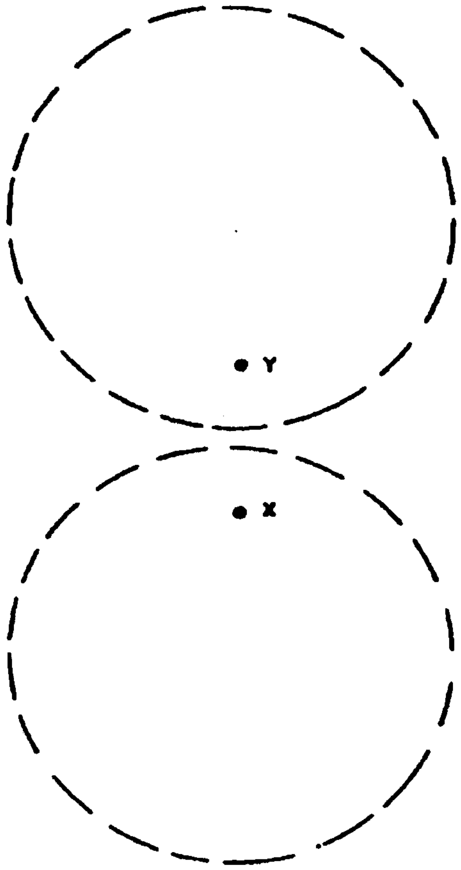

FIGURE 2. LOCI OF EQUI-ACCURACY RANGE CIRCLES BASED ON A 3dB DIFFERENCE IN AMPLITUDE DATA

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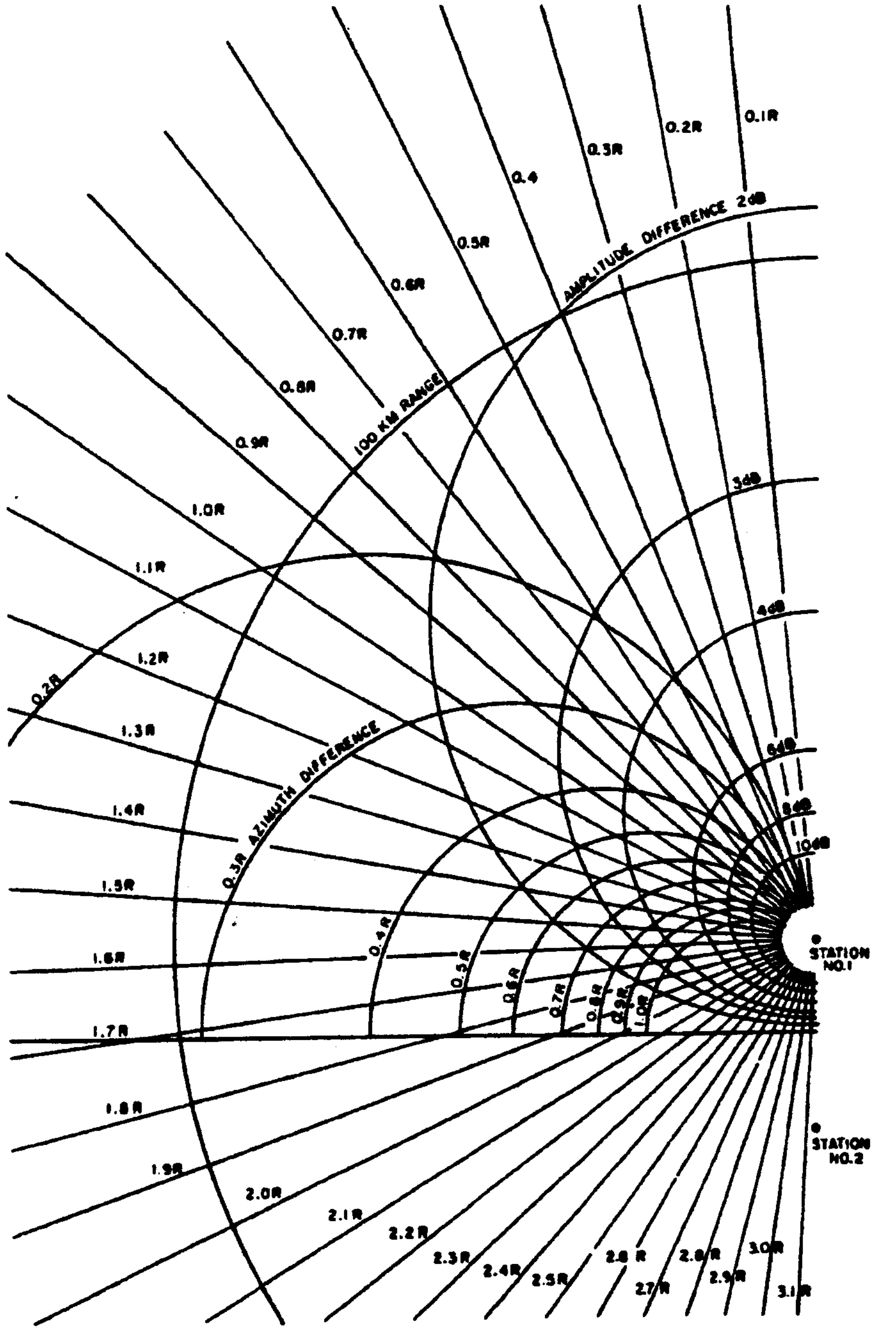

FIG. 3 PLOT SHOWING AZIMUTH DIFFERENCE AND AMPLITUDE RATIO CIRCLES

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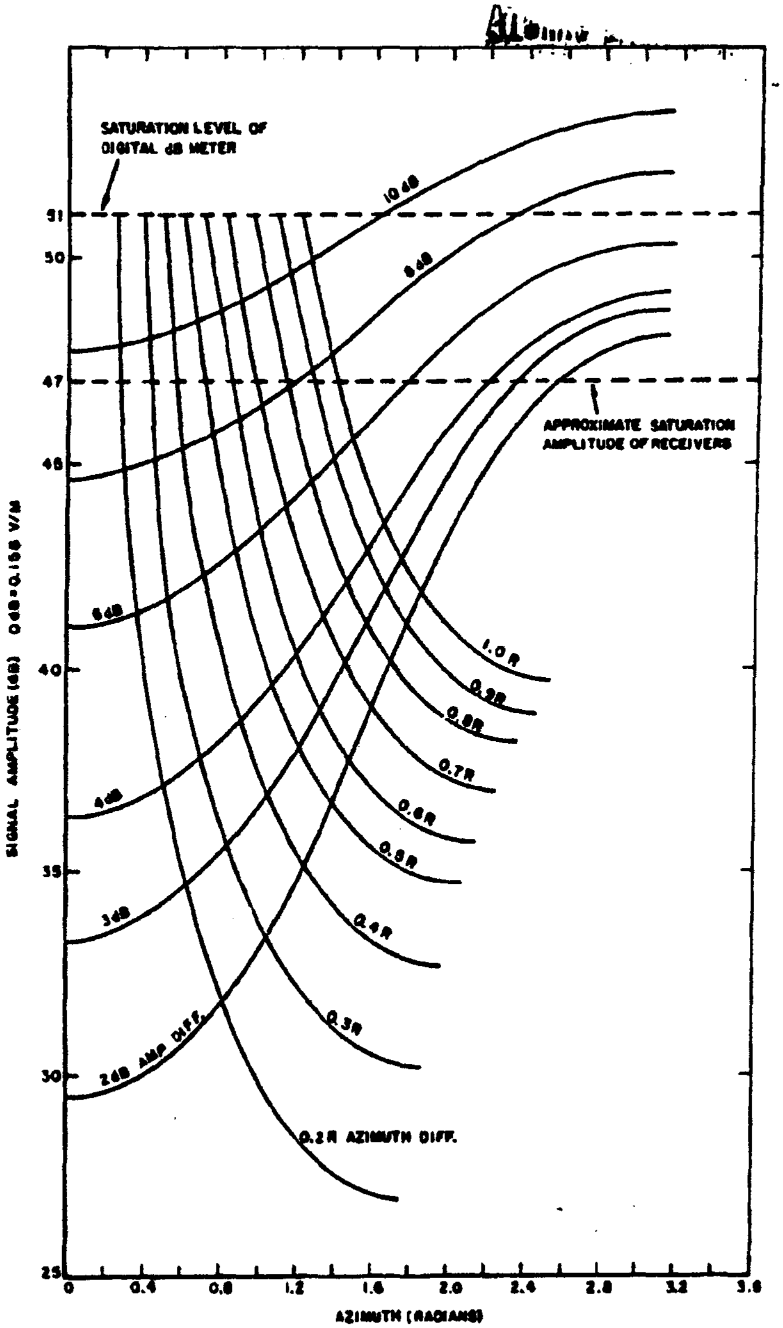

FIGURE 4. RECEIVED SIGNAL FROM A 500 V/M AT 1 km SOURCE AT STATION OBSERVING THE LARGER AMPLITUDE VALUE.

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