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THESIS

RADIO DIRECTION FINDING ON HIGH FREQUENCY
SHORT DURATION SIGNALS

by

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Results are presented using data collected with the Southwest Research Institute Coaxial Spaced Loop HFDF system. It is shown that for a limited sample of data from this system the standard deviation of the bearing estimate for a 200 ms signal varied from 15 to 59 degrees.

RADIO DIRECTION FINDING ON HIGH FREQUENCY SHORT DURATION SIGNALS

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I. INTRODUCTION

A. HISTORY

High frequency radio direction finding, abbreviated in this report as HFDF, has been a topic of interest since the first uses of radio. The science of HFDF has developed in spurts of ingenuity and need. The advances in electronic devices and the more accurate modeling of HF propagation have been important steps to developing accurate HFDF systems. However, it has been military necessity that has spurred the most important developments in this field. The greatest concentration of published literature on this subject resides in the technical reports published during and in the decade after World War Two.

The major studies of HFDF have dealt with the problems of polarization of skywave signals, the effects of multipath propagation, the statistics of HF propagation through the ionosphere and the development of HFDF antennas and arrays of antennas. An important distinction has developed from these studies. There are three types of HFDF antennas: (1) wide aperture, (2) medium aperture and (3) narrow aperture antennas. Whether an antenna array compares phase or amplitude, the primary measure of problems attendant to its accurate operation is the width of its aperture. The term aperture in this paper refers to the linear spatial extent of an antenna, not to an area. The unit of measurement is either meter or wavelength. If the aperture is on the order of one quarter or less of a wavelength, it can be considered narrow aperture, and it suffers the greatest number of difficulties to achieving accurate direction finding capability.

During World War Two the Allies experienced considerable success with the landbased medium and wide aperture systems and, not unexpectedly, limited success with narrow aperture, shipboard HFDF systems. One of the major targets of the shipboard HFDF systems was German submarines. As improvements were made to all types of HFDF systems, the submarine's transmissions became more and more vulnerable. In an effort to maintain communications and to thwart HFDF systems, the Germans shortened the duration of transmissions to lower the probability that the transmissions would be intercepted and subsequently located by HFDF. A highly effective means of shortening transmission time was to record the information on tape and then to transmit via the radio at a much faster playback speed. When this method was coupled with the practice of economizing on the amount of information sent, signal durations were shortened by more than an order of magnitude. A U-boat employing such measures was appreciably less susceptible to HFDF.

The problem of locating a short duration signal remains today. It is still a common problem, even when the target transmitter does not attempt to compress its signal. In a tactical situation it is typical that the communication net control station, usually co-located with the officer-in-tactical-command, will act as a broadcasting station, and the outstations will not transmit or will only transmit a brief signal. In the case of manual morse this signal may be an "r" for "roger your last transmission", or in the case of tactical voice communications the outstation will briefly key the microphone. In either case the transmission may not last longer than 200 to 400 milliseconds.

The rapid growth of digital communications has significantly increased the ease with which a burst signal can be generated and "reliably" received. Given a digital pulse of duration "t" and a total signal duration of "T", there is a simple expression for the amount of information in bits that can be transmitted.

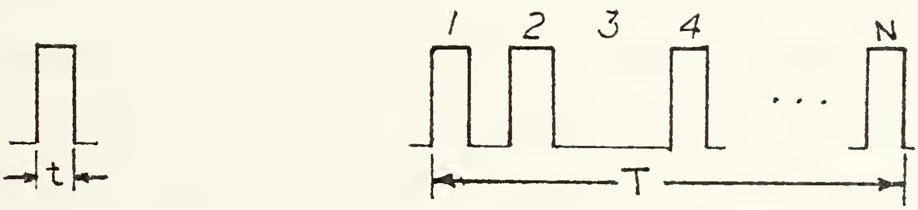


Figure 1

Partial short duration signal bit stream

If the number of bits is "N", then N=T/2t. 2t is approximately the reciprocal of the bandwidth; therefore, N=(T)(Bw), approximately. In the high frequency range a bandwidth of 10 kHz can be readily achieved. As an example, if BW=10 khz and T=500 ms, N equals 5000 bits. Five thousand bits is sufficient to provide considerable encoded tactical information. Even if the signal duration were limited to 200 ms and the first half of the signal dedicated to alerting the destination receiver, there would remain 1000 bits for information. At five bits per symbol and an average of five symbols per word, this would allow forty words to be communicated in the space of 200 ms. For a ship on a covert thirty day patrol sending a single daily status report via burst communications, the total communications transmission time would amount to six seconds (about two one millionths of the patrol period).

To date this author has not been able to find any past or current research on the capabilities of HFDF systems to exploit short duration signals. This is probably due to several reasons. The primary reason is that HFDF engineers are still absorbed in the more basic problem of improving HFDF against medium and long duration skywave signals. Especially in the case of narrow aperture HFDF antenna systems, there remains considerable need for improvement. In the case of wide aperture HFDF antenna systems, the problem of short duration signals seems to be tractable. However, there does not appear to exist a comprehensive study addressing this problem, and to conduct such a controlled study of skywave propagated signals would be expensive. Notwithstanding these difficulties, the short duration signal could easily become an acute tactical problem for the side that cannot exploit it, and the problem therefore deserves immediate attention.

B. PURPOSE OF THESIS

The general question of interest is how good are existing HFDF systems at determining lines of bearing on short duration signals. Any complete examination of an HFDF system requires one to investigate the characteristics of either wide or narrow aperture antennas. Additionally, one must examine the problems of site location, signal acquisition system, receiver demodulation, bearing sense circuits and the noise environment. Performance must also be determined for ground versus skywave and multipath versus single path. This would be an enormous task if all current HFDF systems were considered. The scope of this effort is much more restricted.

The purpose of this thesis is to investigate the mean and variance of bearing estimates for short duration skywave signals received with a narrow aperture HFDF system. Several statistical procedures are developed and compared with the intention of discriminating between reliable and unreliable data and calculating the best bearing estimate from the reliable data.

The problem of how to acquire a short duration signal or how to interface such an acquisition system to an HFDF system will not be addressed in this report.

II. THEORETICAL CONSIDERATIONS

A. HIGH FREQUENCY SKYWAVE CHANNEL

High frequency (HF) is the region from three to thiry megahertz. Its complexity is due to many natural phenomena which are interdependent, complex in themselves, some poorly understood, cosmic and microcosmic in extent and difficult to measure. The primary complexity for the HFDF engineer resides in the ionosphere. The ionosphere can be considered an inhomogeneous plasma that surrounds a sphere of finite, but variable, conductivity and separates the sphere from free space and numerous solar and galactic sources of disturbances. The ionosphere has been, and continues to be, a subject of considerable research. References 1 through 4 are a rich resource of information on the ionosphere and research reports are added monthly, but the scope of the problem is immense. To predict accurately ionospheric conditions, one must be equipped with more than the physics of the ionosphere. The physics provides the equations of the system, but the forcing functions and the boundary conditions must be sufficiently measured to forecast accurately.

The forcing functions are the solar flux, gravitational waves, weather related dynamics and the signal of interest. The ionosphere is usually modeled in terms of electron concentrations; therefore, phenomena which affect the concentration or the excitation of the electrons drive the system. The solar flux is primarily a diurnal phenomenon; its impact is strongest in the portion of the plasma illuminated by the sun. This flux is made up of electromagnetic energy and streams of particles. In the case of sun spots and solar flares, there are often increased emissions that tend to disturb the normal structure of the ionosphere. (Perhaps it would be more accurate to state that the disturbance is to our model of the ionosphere.) The solar disturbance evolves in three stages. The first is the impact of electromagnetic energy in the ultraviolet and x-ray ranges that causes an increased electron concentration in the lowest electron layer (D-layer). The second effect is the arrival of high energy protons and alpha particles that also increase the D-layer. The duration of the disruptions due to these two phases is limited to several hours. The third phase is the arrival of low energy protons and electrons which shower the earth in patterns molded by the Earth's magnetic field. In this phase, which may last as long as several days, the ionosphere experiences magnetic storms, an increase in the D-layer, sporadic conditions in the next higher E-layer and the spectacular aurorae.

Acousto-gravity waves constitute a forcing function of a different scope. Periodic variations in the dynamics of the

Earth-moon-sun gravitational system and isolated, anomalous gravitational activity on the Earth combined with HF acoustic waves (The Mt. St. Helen eruption was a recent source of such waves) exert forces that distort the general concentric spherical form of the electron plasma layers. The distortions are not only static. Traveling ionospheric disturbances are not uncommon, and their effect is to create a doppler shift on transmitted signals. If the ionospheric disturbance is tilted, the ray trace of a transmitted signal will be bent in azimuth.

The third mentioned forcing function is the weather. The dynamics of the weather affect the pressure, the temperature and the mixing of the atmosphere. These three factors in turn have a significant impact on the electron concentrations, particularly the concentrations at the lower altitudes. The weather is also a very important factor in high frequency ranges because it is a noise source. Much of the high frequency background noise is attributed to thunderstorm activity which is continually occurring at some point on the Earth. (It should be noted that most of the electromagnetic energy of a thunderstorm is in the VLF region.)

Manmade signals are one of the smallest forcing functions acting on the ionosphere, but they are naturally of great interest. The target signal injects itself into the ionosphere; it operates on the ionosphere and is operated on by the ionosphere. The study of this interaction has lead to a description of the change of transmitter antenna polarization to elliptical polarization, the phenomena of refracted high frequency waves, multipath interference and the concepts of maximum useable frequency (MUF), lowest useable frequency (LUF) and optimum working frequency (FOT).

The ionosphere is a system with largely fluctuating boundary conditions. The surface of the Earth is the only boundary that can be considered fixed with respect to daily, seasonal and eleven year solar cycles. Other boundary conditions are much more dynamic. Of these, the layering of electron concentrations is primary. The inner two layers, D and E, which are mostly the result of solar electromagnetic radiation have been mentioned. The outer layer, F, which often is subdivided into an F1 and F2 layer is relatively more stable. It remains when the portion of the ionosphere of interest rotates into the solar umbra and the D and E layers disperse. The D and E layers during daylight are responsible for the non-deviative attenuation of much of the HF spectrum of interest (3-12 MHz). The dispersion of the D and E layers permits the F layer to become a virtual reflector situated at altitudes typically from 200 to 400 km. (The actual mechanism of propagation through the F layer is refraction which can be modeled as reflection from a virtual height greater than the actual zenith of the bending ray.) F propagation opens up the evening airways to long distance communications and attendant long distance HFDF in the 3-12 MHz range. For the engineer this is a mixed blessing.

The HFDF engineer's interest in skywave propagation is in the difference between the direction of arrival of the target signal and the great circle bearing to the target and in the variance of the measurements of the angle of arrival. Aside from the equipment limitations and site location distortions and reflections, many of the errors and variances that need to be resolved to improve DF are due solely to the ionosphere.

In the evening, targets of interest in the 3-12 MHz band can be exploited, but there is a considerably greater chance of interference from other discrete sources or from general noise sources. Additionally, there is increased complexity when signals routinely arrive after two or three hops which correspond to maximum distances of 8000 and 12000 km, respectively. Over these distances the errors and variances due to intereference, fading, tilting and scattering increase to a point that even wide aperture antennas cannot produce useful fix information.

An important consideration for narrow aperture antennas is that the effective aperture of one-quarter wavelength at 20 MHz, a typical longhaul daytime frequency, becomes a one-sixteenth wavelength at 5 MHz, a nighttime frequency. The loss of effective aperture further exacerbates the problem of determing a bearing and its variance. The effective height of the antenna is also a function of frequency; therefore, one can expect the array pattern to change with the change in operating frequencies.

B. NARROW APERTURE OF ANTENNAS

The knowledge of the ionosphere has grown extensively in the past forty years. Investigators can now feel reasonably comfortable with the developed models and the improved sensors, especially the extra-terrestrially sensing satellites. General predictions are possible and a new favorite computer aid is the software that predicts propagation and displays ray tracings (see Ref. 13 and Appendix C). An HFDF engineer can review the general propagation scheme with an assurance that he understands sufficiently the problems presented by the ionosphere. But in the case of narrow aperture HFDF antennas one must guard against the feeling of confidence induced by a knowledge of the general situation. One is reminded of the situation where a blind man feeling the trunk of an elephant attempts a general description of the elephant. In the case of a 1.5-meter aperture antenna sampling a wavefront in the 60-meter band, the dimensional comparison with a hand and an elephant is accurate.

There are two commonly used types of narrow aperture antennas. One type relies on amplitude comparison to determine direction of arrival and the second type relies on phase comparison. An example of the former is the simple loop and of the latter is the Adcock. (Reference 5 points out that the phase and amplitude distinction is not clear cut in the case of the Adcock.) The case of the simple loop is illustrated below.

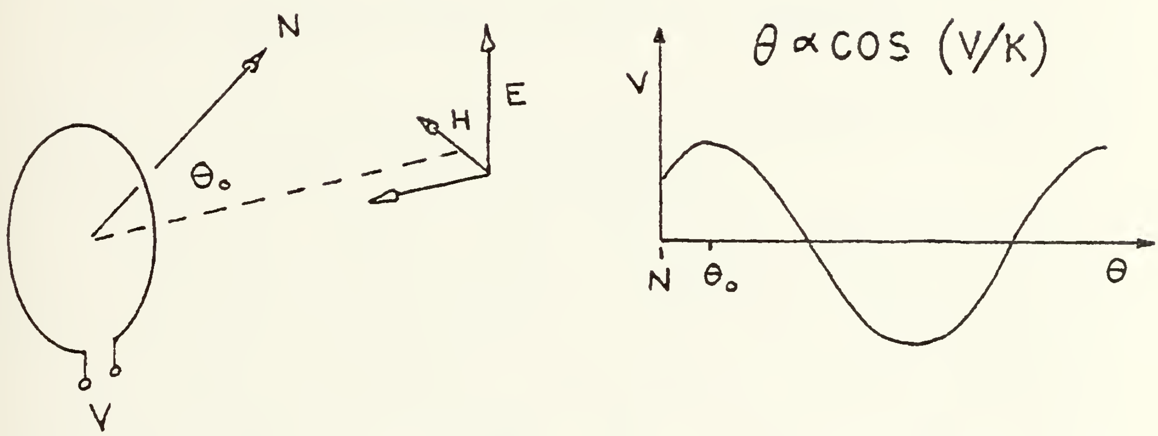
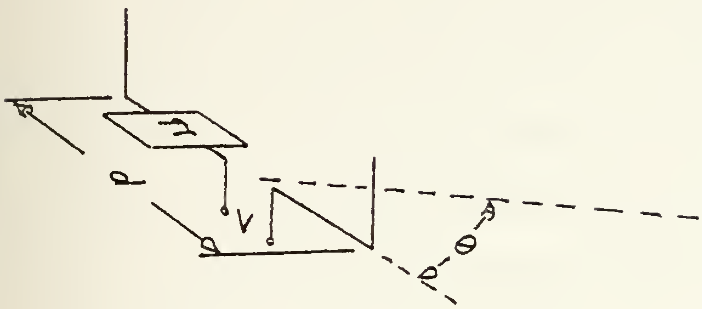


Figure 2

Simple loop sensing direction of arrival

The direction of arrival of the signal is determined by the relative orientation of the loop and the horizontal component of the magnetic field.

The case of the Adcock (actually one half of a U-Adcock) is illustrated as:



$$V \cong (2\pi d/\lambda)\ \mathrm{SIN}\ \theta$$

$$\theta \propto \mathrm{SIN}^{-1}(VK)$$

$$K = \lambda/2\pi d$$

Figure 3

Simple Adcock sensing direction of arrival

The direction of arrival of the signal is determined by the phase difference between the two elements.

The two examples above only serve to illustrate how direction of arrival information is determined. Real systems employ more elements to resolve ambiguities, improve accuracy and enhance resistance to noise. The point is that the fundamental process relies on an element sensing amplitude or phase. This fundamental process is in turn the fundamental difficulty for narrow aperture HFDF antennas.

In Ref. 6 Gething uses computer simulation to plot wave interference of multimode signals in terms of surfaces of constant phase (CP) and constant amplitude (CA). For the ideal case of a single specular component with no scattering, the surface of CP and CA is a plane whose normal is the direction of propagation. In the case of two rays, the interference patterns represented by the surfaces of CP and CA vary with the angular separation of the rays in elevation and azimuth. In all of the patterns presented in Ref. 6 in which the amplitudes of the two component rays differ by only ten percent, major distortions to the ideal planes of CA and CP occur. Approximately planar portions of the surfaces of CA and CP extending to several wavelengths in length are up to sixty degrees different from the true angle of arrival. There are also kinks in the phase fronts that vary the phase up to ninety degrees in less than the space of one wavelength. In the cases where more than two rays are present, the interference patterns become much more complex.

It is obvious that the spatial extent of wide aperture antennas is needed to resolve such interference patterns in a short period of time. Balser and Smith in Ref. 7 explained that when the outputs of two antennas were correlated, the antennas had to be spaced forty wavelengths in the case of single hop and ten wavelengths in the case of multihop to lower the correlation coefficient to 0.5 . For a narrow aperture antenna to detect phase or amplitude distortions of this magnitude, the time of observation must be relatively long. However, it is necessary to detect such distortions to permit an assessment of reliabilty to be assigned to bearings measured in distorted fields.

The description above of interference patterns was for two sources nearly equal in amplitude. The condition of comparable amplitudes is one that results in severe distortion. As the amplitude of one of the rays becomes substantially less than the other ray, the interference pattern approaches the ideal, undistorted planar pattern (implicit is the assumption that single mode scatter is also very weak). Assuming that at least one of the rays of a two ray interference pattern is fading, it can be expected that for short periods of time ideal planar CA and CP wavefronts can be observed. There is no ready means of identifying these moments; however, if the fading is random, the planar CA and CP wavefronts should be the statistical mean of the measured wavefronts. The rate of fading should therefore be a parameter to indicate the time duration required to statistically acquire a measurement of the true angle of arrival.

It is noted in Ref. 6 that for a single ray with Faraday rotation induced elliptical polarization the fade rates are measured in seconds per cycle. In Ref. 12 polarization fading with periods of 10 seconds and 20 db fade depths were reported as common. If two or more rays are present, fading is measured in cycles per second. This indicates that a narrow aperture HFDF system will require approximately a second to recognize the fading condition if strong multipath interference exists. The time required to average the interference pattern is related to the polarization fading of the dominate mode. The amplitude of a polarization faded signal is a stochastic process; therefore, there is no deterministic functional relationship between time and fading. A measure of the rapidity with which fading is fluctuating can be expressed in terms of a fading power spectrum. (Section 5.4.3 of Ref. 1 discusses the concept of fading power spectrum.) If there is a large portion of the "fading power" in the higher frequencies (100 to 1000 Hz), the fading is fast. If the "fading power" is primarily in the the 0.1 to 1.0 Hz region, the fading is slow. In the case of polarization fading it has already been noted that fading is typically in the seconds per cycle range. Therefore, an antenna which does not have sufficient spatial aperture to average interference patterns must rely on fading to permit time averaging. The time required for averaging is a function of the interference pattern and appears to be on the order of five to ten seconds.

A measurement experiment reported by Bain in Ref. 8 demonstrated how time averaging of bearings reduced the variance associated with the mean bearing. Using a U-Adcock with buried feeders, bearings on skywave signals were recorded at five bearings per second. An autocorrelation of the bearings was computed and the resulting curve was approximated by the exponential expression:

$$R(\tau) = \exp(-\tau/\tau_0)$$

where is a parameter associated with fitting an exponential curve to the measured bearings. The formula relating the variance of the mean bearing (σ_t^2) and the variance of a single observation $(\sigma)^2$ is:

$$\frac{\sigma_T^2}{\sigma^2} = \frac{\tau_0^2}{T}\left(e^{-T/\tau_0} + \frac{T}{\tau_0} - 1\right)$$

where T is the time interval over which the bearings were averaged. Bain reported that for $(\tau_0) = 0.56$ (corresponding to considerable bearing fluctuation), the variance was reduced by a factor of 10 in 12 seconds. The 12 second duration roughly corresponds in order of magnitude to the reciprocal of an average fade rate.

C. SUMMARY OF THEORETICAL CONSIDERATIONS

The narrow aperture HFDF antenna is physically limited to time averaging operation against skywave signals. In the case of ideal ionospheric propagation, the antenna system can perform within equipment and site limitations. If the site errors are known, the equipment and array calibrated and there is a good SNR, average bearing errors of 0.5 to 1 degree and variance of 5 degrees squared should be possible. If multipath propagation exists with fading up to 20 db, time averaging over at least ten seconds with sampling at about five per second should reduce most of the variance due to the complex interference patterns.

The difficulty of obtaining accurate HFDF against short duration signals using a narrow aperture array is considerable. In the case of multipath interference in which at least two rays are comparable in amplitude, the DF error on a short duration signal with only one sample bearing could be up to ninety degrees. This is the extreme of bearing error due to phase and amplitude front distortion. In a more hospitable multipath environment the system performance should be much better, but there is little experimental evidence by which one can assign typical bearing errors and variances. The analysis of the narrow aperture antenna system in the following sections provides performance data on an experimental, state of the art system.

III. SWRI HFDF ANTENNA SYSTEM

A. INTRODUCTION

The Electromagnetics Division of Southwest Research Institute (SWRI), located in San Antonio, Texas, has developed and tested a new design for a narrow aperture HFDF antenna system to operate against both ground wave and skywave signals. The significance of this new design is that it is a mast mountable narrow aperture antenna that is a fixed array. There are no moving parts; therefore, it is ideal for the shipboard environment. The elements of the array are simple loops and spaced loops. The latter will be shown to have polarization independent qualities and, therefore, to be ideal for exploiting skywaves. The array and the associated instrumentation of the system are high speed and computer controllable.

The primary reference for the analysis that follows is an in-house report prepared by the system architects [Ref. 9]. The system herein described has been patented. The author of this thesis has visited the San Antonio site and has operated the HFDF system with the assistance of the SWRI personnel.

B. THEORY

To understand the operation of the spaced loop array one must review the theory of the simple loop. The figure on the next page depicts a simple loop set in a coordinate system with an incoming signal ray (E field components labeled Ev and Eh). The angle phi (ϕ) is the azimuth measured in the XY plane of the incoming ray. The plane of the loop is aligned with the XZ plane. The incidence angle theta (θ) is measured in the plane defined by the Z axis and the signal ray. The signal is considered to have a vertical and horizontal electric field component (Ev and Eh). The expression for the output voltage (sinusoidal input, time variation suppressed) is:

$$V1 = -(Ev')\cos\phi + (Eh')(\cos\theta \sin\phi)\exp(j\phi h) \qquad (1)$$

Where:

- Ev': relative amplitude of the vertical component
- Eh': relative amplitude of the horizontal component
- ϕ: azimuth
- θ: angle of incidence
- ϕh: phase of horizontal component relative to the vertical component
- $V1$: simple loop output voltage

With respect to skywave signals, the significance of equation

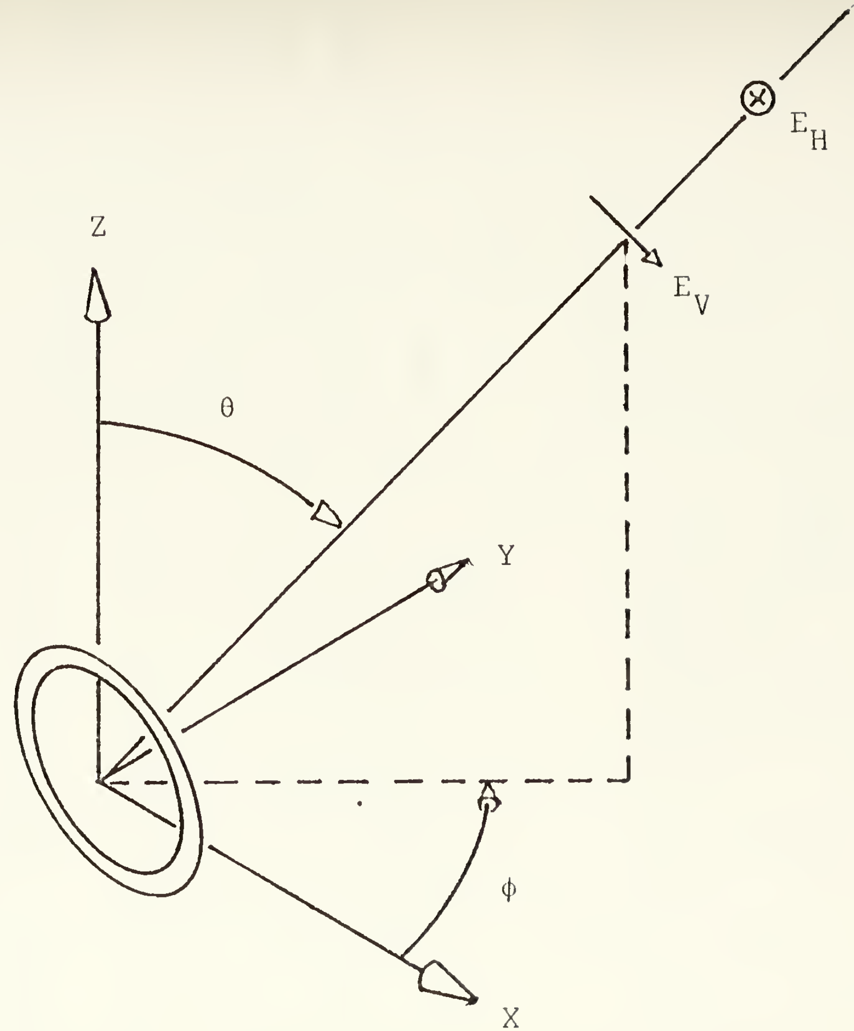


Figure 4

Simple Loop and Coordinate System

(1) is that it is polarization dependent. HFDF systems generally rely on isolating a null in the array pattern that can be related to the azimuth of the incoming signal. The null used should only be a function of the target's bearing. The simple loop works well with ground waves for which case theta is equal to 90 degrees. When theta is 90 degrees equation (1) reduces to a function of only one spatial variable, phi, which is the desired bearing. The output voltage in this case is:

$$V1 = -Ev' \cos \Phi$$

The simple loop does not function acceptably against skywaves. In the case of skywaves the loop voltage is a function of the two spatial variables, theta and phi, and the relative phase. The nulls created by these three variables are too numerous and the available measurements too sparse to resolve all the ambiguities.

A solution to the polarization dependence limitation of the simple loop is to combine two simple loops into a two element interferometer as illustrated in figure 2. The loops are connected in parallel with opposing phase. The output voltage of this array, known as coaxial spaced loops, can be determined by pattern multiplication [Ref. 10]. The pattern of the spaced loop array is equal to the product of the group pattern and the element pattern. The group pattern of the

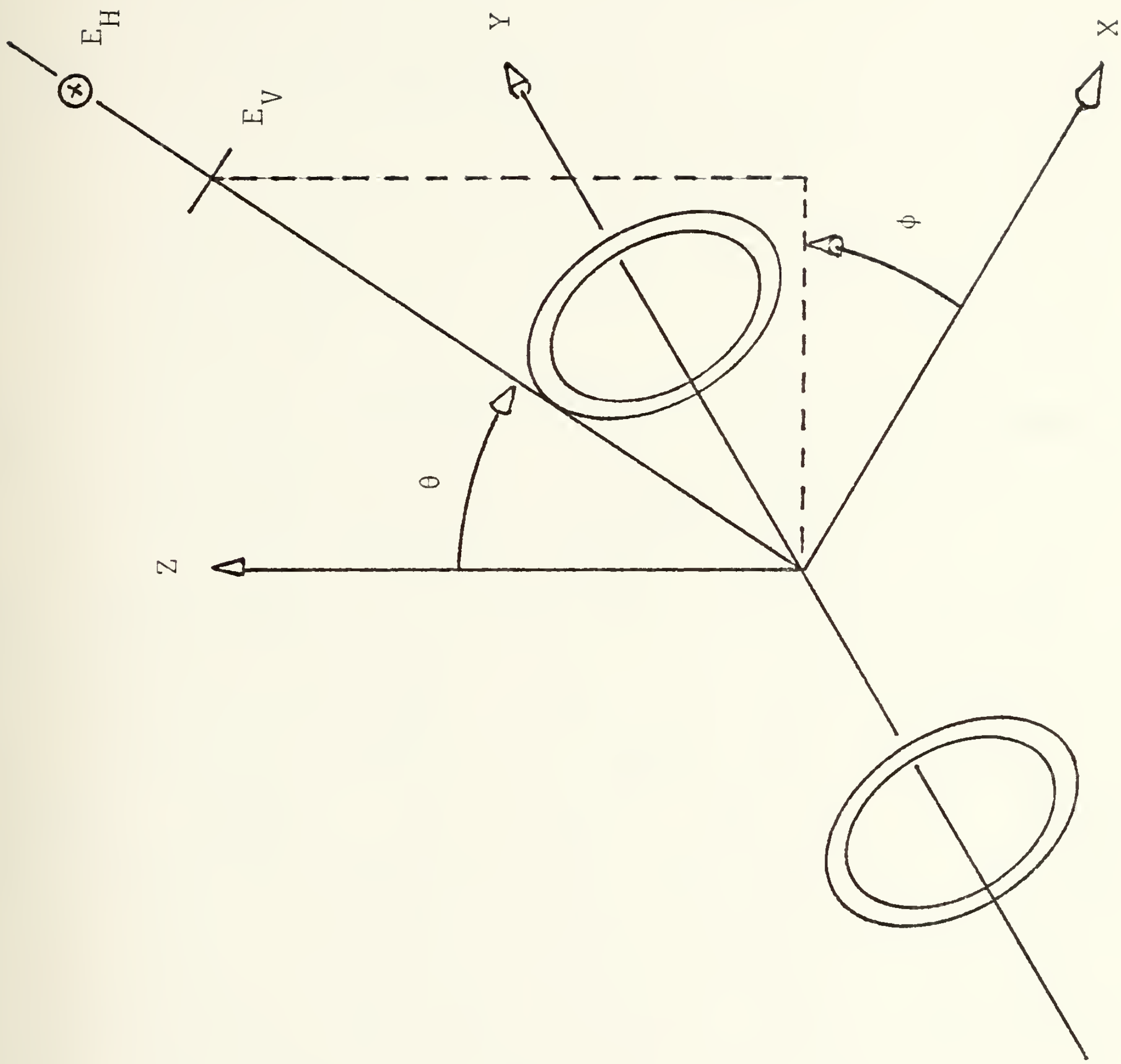


Figure 5

Coaxial Spaced Loops and Coordinate System array is:

$$Gr = j\,\beta\, d\, \mathrm{SIN}(\Theta)\mathrm{SIN}(\Phi)$$

d: separation of the two loops

β: $2\pi/\lambda$

λ: signal wavelength

Now let:

$$Ev = jEv' \;\; d/2$$

$$Eh = jEh' \;\; d/2$$

This permits the spaced loop output voltage to be written as:

$$Va = -Ev\ \mathrm{SIN}\theta \mathrm{SIN}\ 2\phi + Eh(\mathrm{SIN}\ 2\theta \mathrm{SIN}^2\phi)\exp(j\phi h) \quad (2)$$

The significance of equation (2) is the existence of polarization independent nulls. The output voltage equals zero whenever the azimuth angle equals 0 or 180 degrees. The incidence angle, the relative phase and the relative amplitudes of the electric field components do not affect these nulls. It is due to the interferometer structure that these nulls exist; they are therefore called interferometer nulls to distinguish them from the simple loop nulls. Figure 3, taken from reference 11, graphically displays the polarization independent nulls for different conditions of incidence and polarization.

Equation (2) is an expression for a fixed orientation of

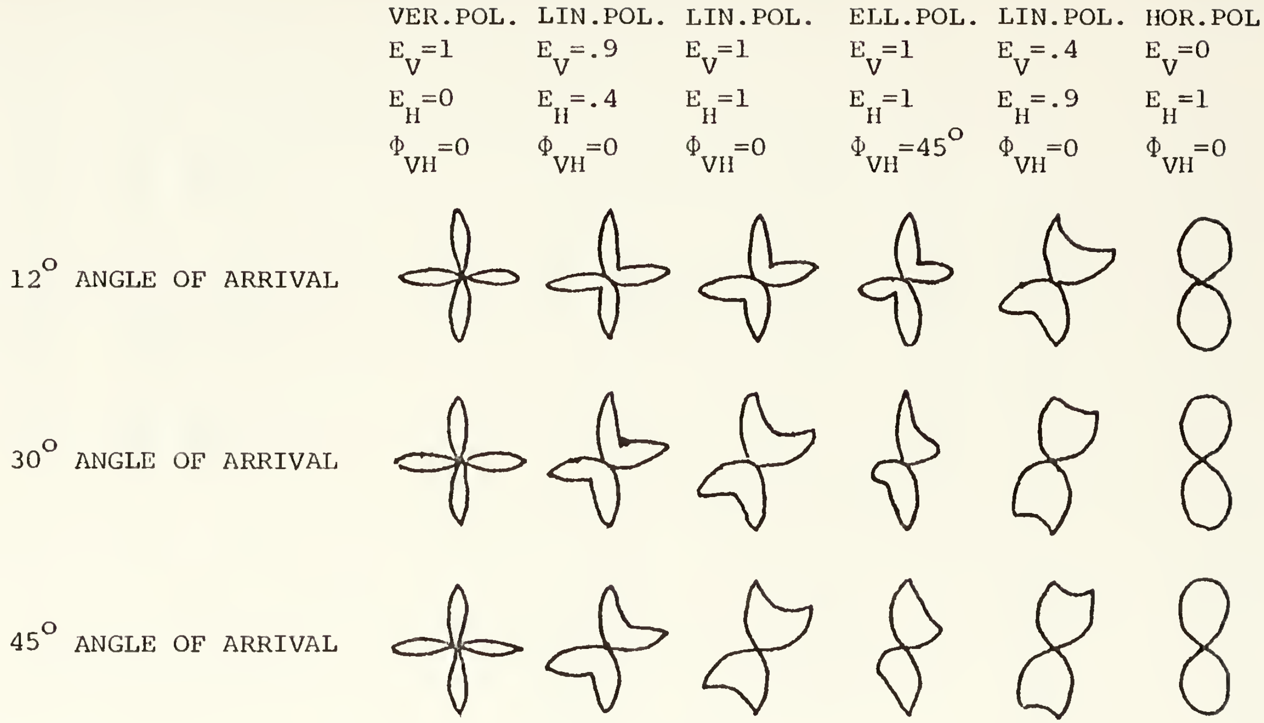


Figure 6

Coaxial Spaced Loop Patterns as a Function of Signal Polarization and Angle of Incidence the spaced loop array in the coordinate system. To make the orientation arbitrary the variable alpha is introduced into (2).

$$Va\alpha = -Ev\ SIN\ \ SIN2(\phi - \alpha) + Eh\ SIN2\theta\ SIN^{2}(\phi - \alpha) \qquad (3)$$

$(\phi - \alpha)$: relative azimuth angle

The alpha variable permits the expression of the output voltage of a spaced loop array oriented alpha degrees from the x-axis to be written as shown in (3). This will later allow equation (3) to express the output voltages of more than one pair of spaced loops set at different angles in the coordinate system.

By defining:

$$C = Ev\ SIN\,\theta$$

$$A0 = Eh\ SIN(2\theta)exp(j\phi h))/2$$

$$A2 = -C\ SIN\ 2\phi\ - A0\ COS\ 2\phi$$

$$B2 = -A0\ SIN\ 2\phi\ + C\ COS\ 2\phi$$

Equation (3) can be written as:

$$Va\alpha\ = A0 + A2\ COS\ 2\alpha\ + B2\ SIN\ 2\alpha \qquad (4)$$

This form permits a Fourier series interpretation of the spaced loop output voltage:

A0 = dc term of the output voltage

A2 and B2 are coefficients of the second harmonic

The significance of (4) is that for a fixed value of target azimuth and elevation, the spaced loop voltage as a function of relative azimuth is limited to a second harmonic of the relative azimuth. The application of the Nyquist sampling criterion reveals that the voltage pattern can be duplicated by four sample values. Therefore, a spinning spaced loop can be synthesized by a minimum of four samples taken equally spaced through 360 degrees of azimuth.

The solution for the bearing (the azimuth angle phi) is derived from equation (4) and the definitions given above for C, A0, A2 and B2. By algebraic manipulation it is determined that,

$$C = +/- (A2 + B2 - A0)^{1/2} \quad (5)$$

A0, A2 and B2 will be shown to be measureable quantities. C is determined from equation (5) above. Using the relationships,

$$\mathrm{SIN}\ 2\Phi = -[\ 1/(\ C\ \ + A0\ \ )]\ [\ (C)(A2) + (A0)(B2)\ ] \quad (6)$$

$$\mathrm{COS}\ 2\Phi = -[\ 1/(\ C\ \ + A0\ \ )]\ [\ (A0)(A2) - (C)(B2)\ ] \quad (7)$$

one can determine the azimuth, phi, by

$$\Phi = (0.5)\ \mathrm{ARCTAN}\ (\ \mathrm{SIN}\ 2\Phi\ /\ \mathrm{COS}\ 2\Phi\ ) + n \cdot 180 \quad n=0,1 \quad (8)$$

Inherent in equation (4) and made obvious in equation (8) are four null ambiguities. There are two nulls 180 degrees apart that can be attributed to the simple loops and two nulls 180 degrees apart that are the interferometer nulls. The SWRI analysis shows that by adding the simple loop phasors into the analysis, the simple loop nulls can be determined and then discarded. By comparing the spaced loop output to the simple loop output, the correct interferometer null which represents the desired bearing can be identified.

The engineers at SWRI used the ideas they developed above to design a fixed spaced loop array. The undesirable mechanical feature of the rotating spaced loop was eliminated by using four spaced loops fixed in an array to synthesize rotation as shown below.

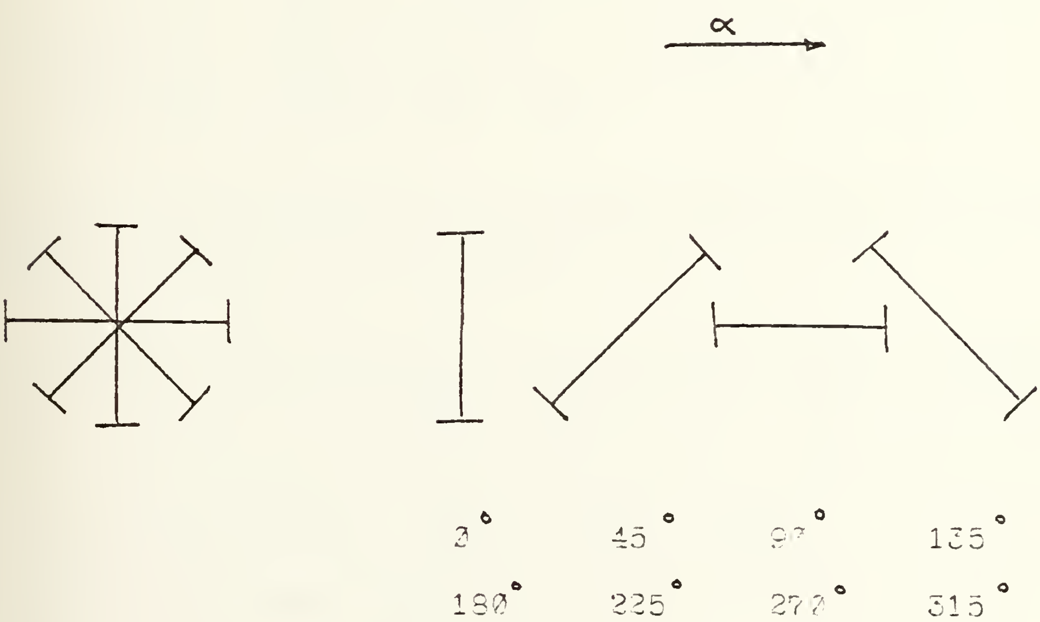


Figure 7

Spaced loop array geometry

The Nyquist criterion requires a minimum of four samples to synthesize equation (4). This could reliably be accomplished by three pairs of spaced loops, but to provide for additional reliability in the presence of noise, a four pair spaced loop array was constructed.

Assuming the orientation given in the diagram above, one can determine $A\emptyset$, $A2$ and $B2$ in terms of the individual spaced loops. Solving

$$Va\alpha = A\emptyset + A2 \cos 2\alpha + B2 \sin 2\alpha$$

in terms of alpha yields,

$$\alpha = \emptyset \qquad Va\emptyset = A\emptyset + A2$$

$$\alpha = 45 \qquad Va45 = A\emptyset + B2$$

$$\alpha = 9\emptyset \qquad Va9\emptyset = A\emptyset - A2$$

$$\alpha = 135 \qquad Va135 = A\emptyset - B2$$

where $Va\emptyset$, $Va45$, $Va9\emptyset$ and $Va135$ are the phasors of the spaced loops in the array shown above.

This provides four equations to solve for three unknowns. One solves for $A\emptyset$, $A2$ and $B2$ by the following equations,

$$A\emptyset = (\emptyset.25)\,(Va\emptyset + Va45 + Va9\emptyset + Va135)$$

$$A2 = (\emptyset.5)\,(Va\emptyset - Va9\emptyset)$$

$$B2 = (\emptyset.5)\,(Va45 - Va135)$$

After $A\emptyset$, $A2$ and $B2$ are determined from the phasor equations above, they are substituted into equations (6) and (7) which in turn are used to solve equation (8) for the four possible bearings.

Further algebraic and trigonometric analysis detailed in Reference [9] shows that the simple loop nulls can be determined by.

$$\alpha = \mathrm{ARCTAN}\ (VL0/-VL90) = \phi - \mathrm{ARCTAN}\ (C/A0)$$

where VL0 and VL90 are the phasors of the two simple loop pairs.

Once the simple loop nulls are known, the sign of C in equation (5) can be determined. This in turn leads to the unambiguous selection of the proper interferometer null.

$$\phi = \mathrm{ARCTAN}\ (V1/V2)$$

where,

$$V1 = [j/(-A0^2 - C^2)]\ [(C)(VL90) - (A0)(VL0)]$$

$$V2 = [j/(-A0^2 - C^2)]\ [(C)(VL0) + (A0)(VL90)]$$

It was noted above that four equations are available to solve for three unknown coefficients. The additional information permits two separate solutions for the A0 term.

$$[A0] = (0.5)\,(\,Va0 + Va90\,)$$

$$[A0]' = (0.5)\,(\,Va45 + Va135\,)$$

The difference between these two A0 terms should ideally be zero. If the difference is not zero there is an inconsistency within the system. This difference is called the A4 term because it corresponds exactly with the coefficient of the fourth harmonic of a Fourier series expansion of the spaced loop pattern in azimuth. The A4 term is therefore an important parameter in determining bearing quality.

C. SYSTEM DESIGN AND INSTRUMENTATION

The array of spaced loops and simple loops suitable for mast mounting shown in figure 8 was built by SwRI. There are four pairs of spaced loops in the lower bay. Each pair consists of 40 inch high by 20 inch wide simple loops separated by 60 inches. The output of these diametrically opposite loops are connected in parallel opposition. The simple loops in the upper bay are used to resolve ambiguities in the bearing algorithm. These diametrically opposite simple loops are connected in parallel assistance. The reference antenna is synthesized by quadrature addition of the simple loops.

A block diagram of the equipment suite is drawn in figure

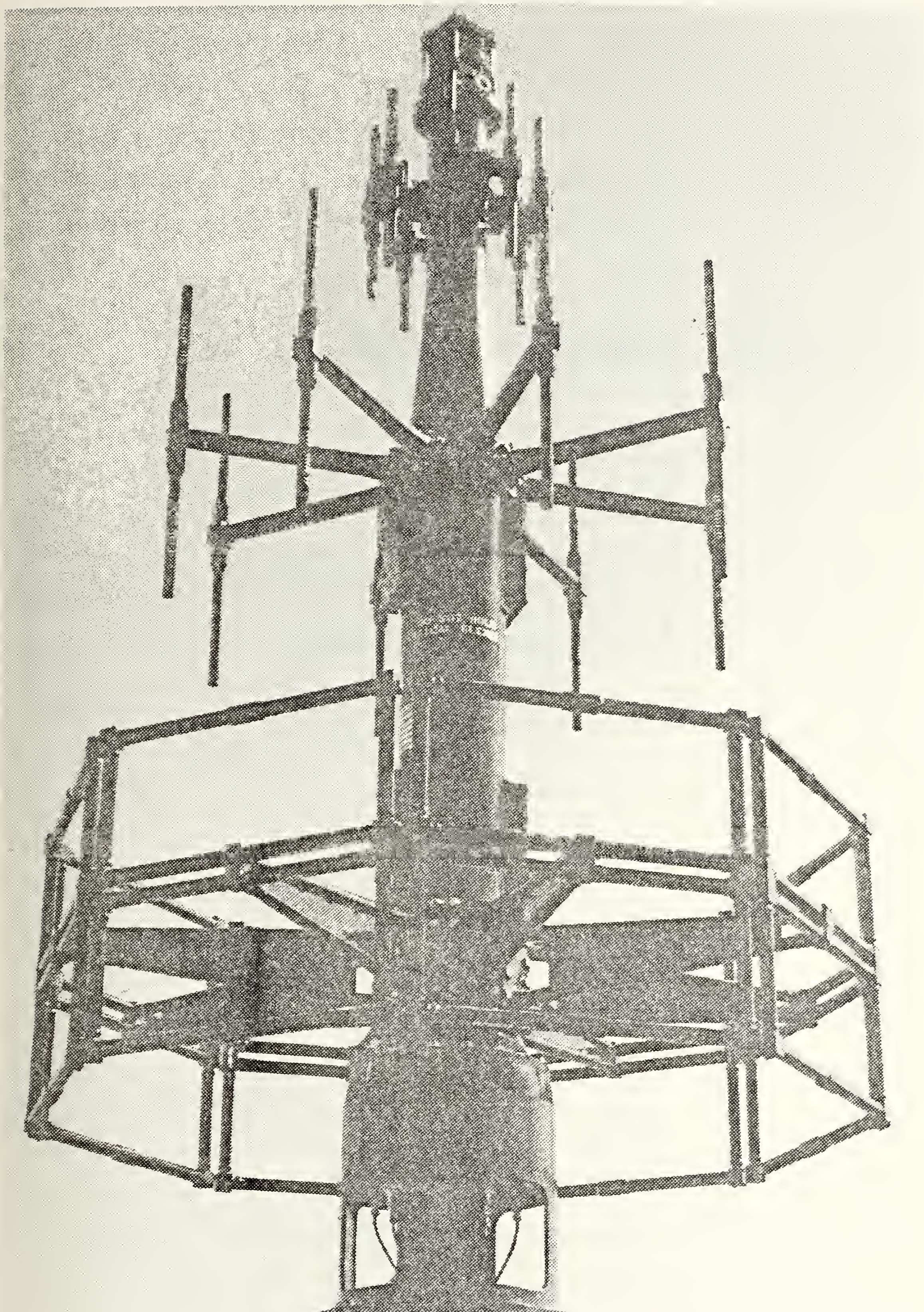


Figure 8
Coaxial Spaced Loop Mast-Mountable Array

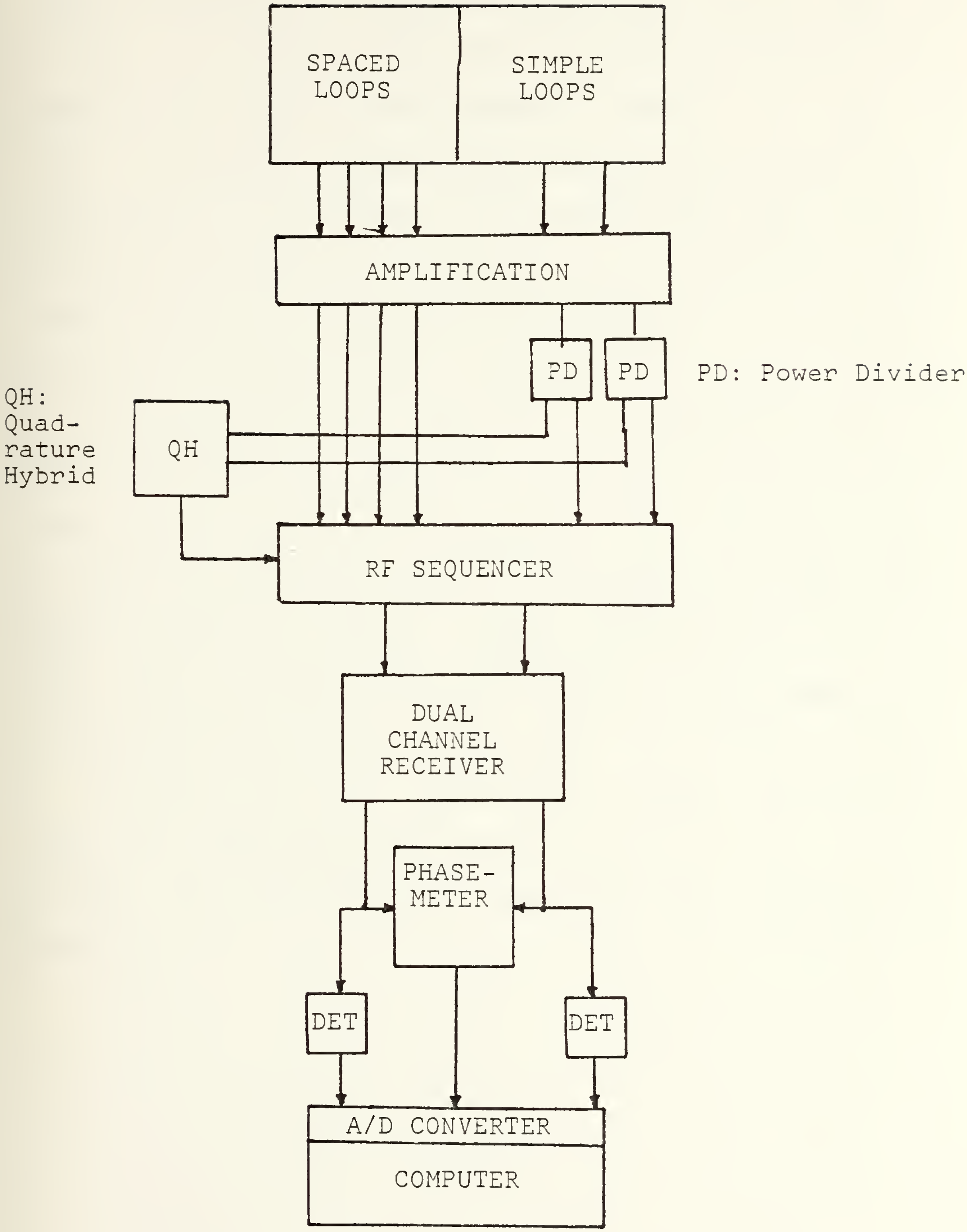


Figure 9
Block Diagram of SWRI Spaced Loop Antenna
System Instrumentation

9. The RF sequencer is a computer controlled switch that is necessary to provide high speed switching of the different elements of the array. A dual channel receiver is used to provide a receiver channel for the reference signal and a channel for the loop voltages. The predetected output of both channels of the receiver is monitored by a phasemeter that provides a digital measurement of the phase of the antenna elements with respect to the reference. The detectors are a pair of precision peak detectors. The detector output is sampled and digitized by the analog to digital converter. The digital data is routed to a minicomputer for processing. Each data frame is approximately 20 ms in duration. The data frame consists of the six complex numbers representing the six voltage phasors (Va0, Va45, Va90, Va135, VL0 and VL90). Not all of the data frames are acceptable. The voltage values must be within the linear range of the detector and receiver circuits. The acceptable data frames are the input to the algorithms that determine the bearings and resolve the ambiguities.

IV. DATA

A. DATA FILES

The SWRI equipment suite is arranged so that data measured from the spaced loop antenna instrumentation is stored on magnetic disk. This permits the DF operator to postprocess the data using statistical techniques to derive a more accurate bearing. Also available is the capability of mass storage on magnetic tape. It was on magnetic tape that SWRI provided the Naval Postgraduate School with nine files of data in 1979 and four files in 1980. The 1979 data consists of the following files. The test source was a transmitter placed close to the array to provide a ground wave in approximately the same direction as WWV.

File Number	Frequency (MHz)	Source	Time (CST)	Date
1	10	WWV	08:30	2/13/79
2	20	WWV	12:15	2/13/79
3	15	WWV	12:30	2/13/79
4	5	WWV	07:00	2/14/79
5	15	WWV	09:30	2/14/79
6	5.01	Test		
7	10.01	Test		
8	15.01	Test		
9	20.01	Test		

The 1980 files are as follows:

File Number	Frequency (MHz)	Source	Time (CST)	Date
10	5	WWV	22:40	2/6/80
11	10	WWV	07:40	2/5/80
12	15	WWV	09:00	2/5/80
13	8.666	KLC	08:15	2/7/80

It is known that file 10 is a low SNR data set. Files 11 and 12 are data sets with SNR's in excess of 20 dB.

B. WWV AND KLC

WWV is an ideal target because it is an amplitude modulated signal with no carrier suppression. For the majority of the hourly information duty cycle, the information modulated on the carrier is simple 440, 500 and 600 Hz tones; ticks; and occassional voice announcements. The WWV signal is stable to +/- two parts in (1[illegible]) , and it is available on 5, 10, 15 and 20 MHz for 24 hours a day. The WWV signal is transmitted from Boulder, Colorado, which is geographically fixed at 40.8 N and 105.1 W. The true bearing of the great circle arc passing through San Antonio, Texas, and Boulder is 336.7 degrees, and the length of the arc is 1387 km.

KLC is a manual morse ship-to-shore station transmitting from a platform in the Gulf of Mexico. This signal was chosen as a target because of the on-off keying (OOK) modulation and because its relatively short distance from San Antonio results in a skywave with a high angle of arrival at the SWPI antenna array. The OOK modulation is important because it is a favorite mode of tactical communications; it is brief and reliable. The true bearing from San Antonio to KLC is 089.9 degrees and the distance is 370 km.

C. DATA RECORDS

Each file consists of 10,000 records. Each record consists of the A0, phase, A4 and bearing terms calculated from frames of data (six voltage phasors) which were generated every 20 ms. The A0 in the data is a normalized version of the A0 explained in the previous section. In that section,

$$A0 = (0.5)\ Eh(\mathrm{SIN}\,2\theta)\exp(j\Phi n)$$

The data on the tape is A0 normalized by the factor EvSIN ,
which yields:

$$A0n = [\ Eh/Ev\ ]\ \mathrm{COS}\,\theta\ \exp(j\Phi h)$$

This is a complex number of which only the magnitude is used. All further references to A0 in the data and analysis section will be the magnitude of the normalized value:

$$A0 = [\ Eh/Ev\ ]\ \mathrm{COS}\,\theta$$

It should be noted here that the A0 term is a measure of the amount of horizontal polarization present. If Eh is greater than Ev, the ratio Eh/Ev will tend to make A0 a number greater than one. If the angle from the perpendicular, theta, is large, there is a greater effective array aperture in the plane of Ev, and A0 is smaller. If A0 is large, the horizontal component is dominant. If A0 is small, the vertical component dominates.

The second term of the record is the phase. It is the phase of the horizontal electric field relative to the vertical component of the field. It is a calculated value between -180 and +180 degrees. If this phase angle is a constant zero, the polarization is linear. If it is a nonzero constant, the polarization is elliptical. The phase value is typically noted to vary randomly within a limited range over short time durations. Over durations of several minutes, it will vary over the entire -180 to +180 degree range due to changes in Eh and Ev path lengths and multimode interference.

The third term in a record is the amplitude of the A4 term which was discussed in the previous section. It is a measure of the inconsistency within the spaced loop HFDF system. It is in large part due to noise, but it can also be to a limited degree a measure of circuit imbalance, measurement error, component failure, software failure and site error. Its value is that it is a measure of performance; however, it is not a system diagnostic tool.

The fourth member of the record is the calculated bearing. It is an integer value from 0 to 359 degrees. For the WWV signals this bearing is the system's estimate of the angle of arrival of the signal wavefront which should not vary far from the value 336.7 degrees. For KLC the true bearing is 289.9 degrees.

D. IONOSPHERIC DATA

No ionospheric sounding information was available for the time periods during which the data was recorded. However, propagation information was provided by the Naval Ocean System Center (NOSC). Using the known sun spot number for the data recording dates, they employed a computer propagation prediction program known as PROPHET to provide ray trace diagrams; MUF, LUF and power predictions; and 24 hour line of bearing variance curves. This data represents a good estimate of propagation conditons between Boulder and San Antonio for the times of interest. Examples of the program output provided by NOSC are reviewed in Appendix C. Using the NOSC data, propagation information for the WWV files is tabulated in TABLE I.

TABLE I

Summary of Ionospheric Data

File #	Freq MHz	Time GMT	Date	Variance degrees squared	MUF MHz	LUF MHz	Ionospheric Mode Prediction
1	10	14:30	2/13/79	1	17	2.5	probable multimode 1, 2, &3 hops
2	20	18:15	2/13/79	1	22	5	possible multimode 1 hop
3	15	18:30	2/13/79	1	22	5	highly probable multimode 1&2 hops
4	5	13:00	2/14/79	3	12	2	possible multimode terminator 1.2.3 hops
5	15	17:30	2/14/79	1	22	5	probable single mode
10	5	2:40	2/[illegible]/80	0.4	12	2	possible multimode 1.2&3 hops
11	10	13:40	2/5/80	3	17	2	probable multimode terminator 1.2 hops
12	15	17:00	2/5/80	1	23	5	single mode

V. ANALYSIS OF SWRI DATA

A. INTRODUCTION

The purpose of this analysis is to exam the capability of the SWRI spaced loop HFDF antenna system to determine the angle of arrival of a short duration signal. A short duration signal is considered to be from 100 to 1000 ms in duration. It is important to note that this is not a general analysis of the performance of the antenna system, the bearing and sense algorithms or the post-processing algorithms developed by SWRI. It is also important to recognize that system development is not complete, but is the subject of on-going research. The data provided to this investigator was provided from a system configuration not optimized for short duration signals or for some of the target frequencies recorded. Because the subject of this analysis is short duration skywave signals, the following analysis takes into consideration the need to make maximum use of the available data. Whereas SWRI algorithms stress a bearing selection process that eliminates a large percentage of the data records to enhance the reliability of the estimated bearing, this analysis recognizes that a signal of 200 ms duration is represented by only 10 data frames and that some compromise to reliability must be made. The term reliability in this report is used as a measure of confidence in the validity of the data. If one associates a standard deviation of 50 degrees with a data record and 20 degrees with a second data record, the latter would be considered more reliable.

The analysis first concentrated on examining the data primarily by filtering on the A4 term, the indicator of system inconsistency. If the A4 term is small, the bearing in that record should be considered more reliable than a bearing associated with a high A4 value. Using this approach a FORTRAN program called DFERR (DF ERRor) was developed to examine each file and report the average bearing error, standard deviation of bearing error and two other statistics of short duration signals with respect to the A4 term. A full discussion of the program is detailed in the next section. It was discovered that the A4 term is a useful parameter for determining bearing reliability in the majority of cases. However, when the A4 threshold is set to only allow the data record with A4 approaching close to zero (the theoretical ideal), there is not a large probability of determining a bearing on a short duration signal. In an attempt to improve on the sole use of the A4 term as a reliabilty indicator, a probabilistic likelihood ratio matrix based on all of the available signal parameters was employed in the analysis. The details of this approach are in the section titled LMAT (Likelihood MATrix).

A closer examineination was made of the problem of bearing ambiguity. The technique employed in this portion of the analysis is given in the section titled AMBIGUITY RESOLUTION. This analysis gives some useful insight into possible difficulties within the antenna system that may prove to be the most tractable.

B. DFERR

The purpose of this analysis was to determine how accurately a DF bearing could be calculated from the given data. The data consists of 200 seconds of WWV per file (one file of KLC). To study short duration signals it is only necessary to consider the 200 seconds of data to be a continuous concatenation of short duration signals. The 10,000 records in each file contain the data for the 20 ms sampling periods; therefore, integer multiples of records correspond to different signal durations. To examine system performance against a 200 ms signal, one need only examine a file 10 records at a time. A 200 second file may be thought of as containing 1000 signals of 200 ms duration. Similarly, for a signal duration of 1 second, 50 records may be used to synthesize the signal, and the file is made up of 200 signals.

A FORTRAN program named DFERR was written to examine the data files based on the above concept. The program was designed to examine signal durations from 20 ms to 200 seconds; however, it was used for this analysis in two ranges. 100 ms to 1000 ms in increments of 100 ms and 1 second to 10 seconds in increments of 1 second.

The general purpose of DFERR is to examine system performance as two parameters are varied. The first parameter is signal duration; the second is the A4 term. The A4 term, explained in section III, is the measure of inconsistency within the DF system. If the A4 term is large, the bearing value in a record is not considered reliable. If A4 is small, more confidence is placed in the bearing. The relative descriptors large and small have yet to be evaluated. In order to evaluate the pertinent range of A4 values, the A4 threshold (A4MAX) is varied between a small value, 0.1, and a large value, 1.0, in increments of 0.1.

If the value of A4 in a record is equal to or less than the value of A4MAX set in the program, the bearing is considered acceptable and used in further statistical processing. If the value of A4 is above the limit, the bearing of that record is discarded.

An explanation of further DFERR processing is best presented using an example. Suppose that the following records are being processed.

Record #	A0	Phase (deg)	A4	Bearing (deg)
...	.....	....	.....	...
350	0.821	-47	0.132	330
351	0.611	-60	0.015	340
352	0.432	-58	0.116	336
353	0.512	120	0.413	250
354	0.315	-80	0.178	233
355	1.011	-20	0.215	348
...	.....	....	.....	...

The value for the signal duration is 100 ms and the A4MAX value is 0.2; therefore, records 350 thru 354 are examined as representing a signal of 100 ms duration. Record 353 is immediately rejected because the value of A4 is greater than A4MAX. The remaining four records are called "A4 admissible" and are used to determine a bearing mean and standard deviation: (The mean and standard deviation formulas used in DFERR are derived in Appendix A.)

MEAN = 329 deg   STD = 44 deg

These statistics are used to form a window centered at 329 degrees extending 44 degrees on either side of the mean. The A4 admissible bearings must pass through this window for further consideration. Record number 354 is not "window admissible" and is discarded. The remaining three records, being both A4 and window admissible, are used to compute a second mean and standard deviation:

MEAN = 335 deg   STD = 4 deg

This mean is DFERR's best estimate of the bearing for this one 100 ms signal (records 350 through 354).

This reported bearing is compared with the true bearing, 337 deg, and the bearing error is computed as 335-337=-2 deg. Additionally, the valid signal counter is augmented by one. The number of valid signals will be used later to determine the probability of obtaining a bearing (POB).

If there are less than three A4 admissible records or less than two window admissible records in a given signal duration, the signal is considered invalid due to insufficient data and is counted in an invalid signal counter. To avoid the loss of reliable data in the case of a small standard deviation of the A4 admissible bearings, the screening window is not permitted to be narrower than 12 degrees.

The DFERR program processes ten separate signal durations at ten different A4MAX settings. Program output consists of four tables on separate pages. Each table is a ten by ten matrix; the rows correspond to the A4MAX vlaues and the columns correspond to the signal duration, see tables II through V. The first table (table II) is the average bearing error. This is the average of all the separate means reported. In the example above for 100 ms, the mean 335 would be one of a maximum possible 2000 values that would be averaged and then reported in the row A4MAX=0.2 and the column signal duration equals 100 ms.

The second table (table III) is the standard deviation of the bearing errors reported in the first table. For the 100 ms signal duration category the standard deviation would be of a maximum possible 2000 mean values (the actual sample size is equal to the number of valid signals). As the signal duration increases, the sample size decreases. For the 1000 ms column, the maximum possible number of signals is 200. If medium duration signals are examined with DFERR, one must be attentive to the sample size. For a 10 second duration signal category, the sample size has diminished to twenty. For 100 second signal durations, there are only two samples and the validity of a standard deviation is highly questionable.

The third table of output (table IV) is the average intra-signal standard deviation. This is the average of the standard deviations reported for individual signals. In the previous example, the STD=4 would be one of a maximum possible 2000 standard deviations to be averaged. If the average intra-signal standard deviation were equal to four, the interpretation would be that for all signals of 100 ms duration, after the unreliable bearings are discarded, the expected standard deviation of the remaining cluster of bearings is four degrees. The term intra-signal is used to distinguish it from the standard deviation of bearing errors.

The fourth table (table V) is the compilation of valid

1SOURCE: WWV 10 MHZ 8:30 2/79
0STANDARD DEVIATION MULITPLE USED TO DETERMINE BEARING WINDOW = 1

0AVERAGE BEARING ERROR AS A FUNCTION OF SYSTEM NOISE (A4 TERM) AND SIGNAL DURATION

	1.0	-6	-5	-6	-6	-5	-5	-6	-6	-7	-6
	0.9	-6	-5	-6	-6	-5	-5	-6	-6	-7	-6
M	0.8	-6	-5	-6	-6	-5	-5	-6	-6	-7	-6
A	0.7	-6	-4	-6	-6	-6	-5	-6	-6	-7	-6
X	0.6	-5	-5	-6	-6	-5	-6	-6	-5	-6	-6
	0.5	-5	-5	-5	-6	-5	-5	-5	-5	-6	-6
A	0.4	-4	-4	-4	-5	-4	-5	-5	-5	-5	-5
4	0.3	-4	-4	-4	-4	-3	-4	-4	-4	-5	-4
	0.2	-2	-4	-2	-3	-3	-2	-3	-3	-5	-2
	0.1	0	-1	0	0	0	-1	-1	-1	0	-2
		100	200	300	400	500	600	700	800	900	1000

Table II

DFERR Output Page 1, Average Bearing Error

OSTANDARD DEVIATION OF BEARING ERROR AS A FUNCTION OF SYSTEM NOISE AND SIGNAL DURATION

	1.0	33	30	26	24	24	22	19	20	15	19
	0.9	33	30	26	24	24	22	19	20	15	19
M	0.8	33	30	26	24	24	22	19	20	15	19
A	0.7	33	30	26	24	25	22	19	20	15	18
X	0.6	33	30	26	23	25	23	18	23	17	18
	0.5	31	29	27	24	25	23	20	23	16	17
A	0.4	29	28	26	24	23	21	20	21	17	17
4	0.3	29	27	26	25	23	19	20	21	18	17
	0.2	29	31	32	31	28	24	27	28	22	22
	0.1	20	22	25	25	28	23	24	22	23	22
		100	200	300	400	500	600	700	800	900	1000

SIGNAL DURATION (MILLISEC)

Table III

DFERR Output Page 2, Standard Deviation of Bearing Error

OAVERAGE INTRA-SIGNAL STANDARD DEVIATION

	1.0	6	8	9	10	11	12	13	12	13	13
	0.9	6	8	9	10	11	12	12	12	13	13
M	0.8	5	8	9	10	10	12	12	12	13	13
A	0.7	5	8	9	10	10	12	12	12	13	13
X	0.6	5	7	9	10	10	11	11	11	12	13
	0.5	5	7	8	9	9	11	11	11	11	12
A	0.4	5	6	8	8	9	10	10	11	11	12
4	0.3	4	6	7	7	8	9	9	10	10	10
	0.2	4	4	6	7	7	8	8	9	9	10
	0.1	2	3	3	5	3	5	5	7	6	7
		100	200	300	400	500	600	700	800	900	1000

SIGNAL DURATION (MILLISEC)

Table IV

DFERR Output Page 3, Intra-Signal Standard Deviation

ONUMBER OF VALID SIGNALS OF A GIVEN DURATION AS A FUNCTION OF SYSTEM NOISE AND SIGNAL

	1.0	2000	1000	666	500	400	333	285	250	222	200
	0.9	2000	1000	666	500	400	333	285	250	222	200
M	0.8	1997	1000	666	500	400	333	285	250	222	200
A	0.7	1995	1000	666	500	400	333	285	250	222	200
X	0.6	1990	1000	666	500	400	333	285	250	222	200
	0.5	1960	993	663	500	400	333	285	250	222	200
A	0.4	1897	974	656	497	399	332	285	250	222	200
4	0.3	1718	911	625	482	390	328	283	249	222	200
	0.2	1312	738	516	409	336	290	258	229	207	187
	0.1	717	474	363	291	247	217	191	171	163	147
		100	200	300	400	500	600	700	800	900	1000

SIGNAL DURATION (MILLISEC)

Table V

DFERR Output Page 4, Number of Valid Signals

signals for each of the A4MAX and signal duration categories. This is an important statistic needed to compute the probability of obtaining a bearing. In the case of the 100 ms signal duration, 2000 are possible. If A4MAX=0.2 and 1200 signals are valid, the POB for 100 ms is equal to the ratio of valid signals to possible signals. In this case, POB=0.6. In general, as either A4MAX or the signal duration increases, the number of valid signals approaches the number of possible signals. For A4MAX above 0.4 or the signal duration above one second, the POB is approximately one.

DFERR was used to process all of the files, including the OOK modulated KLC signal. The KLC file required a slightly modified version of DFERR because each record of data was searched for a flag that indicates that the signal is indeed present. Search was also made for flags that indicate that the system is saturated. KLC is considered a file of signals separated by noise. It is not a continuous signal like the WWV signal; in fact, the duty cycle is less than twenty-five percent.

The tabular output produced by DFERR can be considered a second level data base. To simplify follow-on discussions, the statistics in the DFERR output will be referred to as the "FOUR" statistics. Examination of the DFERR data base revealed that the FOUR statistics are a strong function of the A4 term. As the A4 term increases, corresponding to the acceptance of more inconsistent data, the standard deviation, intra-signal standard deviation and number of valid signals increases. Based on the large standard deviations recorded above A4=0.4 and the insignificant increase in PCB above A4=0.4, the range of interest was restricted to A4 values in the 0.1 to 0.4 region. Even with this restriction, the amount of data is too large to present in this report; however, it should be noted that the changes in the FOUR statistics are typically monotonic as A4 varies. The data presented herein is for A4MAX=0.2 and A4MAX=0.4. The best performance category, A4MAX=0.1, is not presented because of its low PCB and because it is not significantly different from A4MAX=0.2

The tabular data of DFERR does not permit easy visual perception of the characteristics of the FOUR statistics. A plot program was written to display the data. The figures at the end of this section are of the WWV 5.10 and 20 MHz files of 1979 (Fig. 10-24) and 1980 (Fig. 25-34). For each frequency there are five graphs. In each set of five, the first two and the last are the most important as they are concerned with the short duration signals. The second two graphs are for signal durations of one to ten seconds. They are included to illustrate how the FOUR statistics tend to reach steady state values. The fifth graph is the histogram of the bearing errors for A4MAX=0.2 and signal duration equal to 200 ms. Annotated in the upper right hand corner of all the computer drawn graphs are the average bearing (B), standard deviation (S) and average bearing error (E) for the entire file portrayed by the graph. These are the statistics for a signal duration of 200 seconds subject to the A4MAX constraint labelled on the graph. If one assumes that the true angle of arrival was fixed, that no multipath existed and that there was no slow term variance due to the ionosphere, the curves plotted should converge to the 200 second average bearing error. Both the standard deviation and the average intra-signal standard deviation should converge to the 200 second standard deviation. The POB should converge to one. However, the PROPHET program graphs show that in many cases there probably existed multimode conditions (actual amount of interference unknown) and that, in all cases, varying degrees of variance existed due to polarization fading and interference. Despite this difficulty, the 200 second statistics can be considered an approximate convergence point.

The first curve (X) of each graph is the average bearing error. This is the difference between the calculated bearing and the true geographic bearing to the signal transmitter (337 or 090). The most prominent feature of all the average bearing error curves is that they are not a strong function of signal duration. This could have been anticipated realizing that the average of the majority of small subsets of a large set will closely approximate the average of the large set. In this respect the average bearing error as a function of signal duration is not particularly useful. A much more significant view of the average bearing error is a histogram of the bearing errors from each valid signal. A histogram for A4MAX=0.2 and a signal duration equal to 200 ms is the fifth figure in each set of five (Fig. 14,19,24,29,34). These histograms show that the distribution of the bearing error for most of the files is only roughly approximate to a normal distribution. Major deviations from the normal curve are the accumulation of bearings in the 180 degree ambiguity region and the distributions where multimode propagation was highly probable. The major difficulty with the average bearing error data is the absence of calibration data. The amount of correctable bias error is unknown.

The standard deviation curve (*) is the most important information on the graphs. If a bearing is to be used with other bearings to compute a fix, the standard deviation is used to compute the fix area for a given probability that the target will be within the fix area. The standard deviation is also a measure of confidence in a single bearing. If the bearing distribution is normal and the standard deviation is 20 degrees, one can expect that the bearing calculated is within 20 degrees of the true bearing (assuming average bearing=true bearing) about 67 percent of the time. Because the distributions for the data files are only roughly normal. amplification of the significance of the standard deviations is pertinent. The following data are the approximate percentages (within five percent) of bearings falling within the standard deviation of each file for a 200 ms signal duration and A4MAX=0.2.

File #	STD	%
1 (Fig. 19)	31.1	90
2 (Fig. 24)	25.6	85
3	31.1	75
4 (Fig. 14)	15.5	85
5	37.4	90
10 (Fig.29)	59.6	75
11 (Fig. 34)	29.5	95
12 (Fig. 36)	16.2	88
13	19.3	83

This data indicates that the distributions are denser than the normal and that system performance is better than one, thinking in terms of a normal distribution, would believe. For example, in file 11 (Fig. 34) the standard deviation is about 30 degrees, but 95 percent of the data are within the standard deviation. The expression of standard deviation cannot be separated from its distribution and still retain meaning.

Observing the curves (Fig. 10-13, 15-18, 20-23, 25-28, 30-33) the reader will note that the standard deviation is in almost all cases a monotonically decreasing function of signal duration. An interesting comparison is the standard deviation at 100 ms (STD1) and at 10 seconds (STD2), again with A4MAX=0.2:

File #	STD1	STD2	STD1/STD2
1	29	5	5.8
2	25	11	2.3
3	31	13	2.4
4	18	5	3.6
5	42	10	4.2
10	57	18	3.2
11	30	4	7.5
12	16	9	1.8
13	17	6	2.8

These results are comparable to those reported by Bain [Ref.8] and consistent in order of magnitude to the time required to average the fluctuating surfaces of constant amplitude.

The third curve (.) is the average intra-signal standard deviation. It is typically a monotonically increasing function of signal duration from 100 ms to 10 seconds. The fact that the intra-signal standard deviation is the smallest at 100 ms indicates that the major factors affecting the variance are not rapidly fluctuating, i.e. the period is larger than 100 ms. The intra-signal standard deviation at 100 ms is small, four to eight degrees, except for file 14 (Fig. 25-28) which was recorded with a low SNR. In this case, a major source of variance was noise and its fluctuations were rapid. As the signal duration increases, the phenomena causing the majority of the variance have more effect within individual signals.

The fourth category of data on the graphs is the probability of obtaining a line of bearing. The derivation of this number has previously been explained. Its usefulness is a proper subject for operations research; it does not provide the engineer with any useful information about the process of HFDF on short duration signals. However, one does not need a specific operational context to know that high POB is good and low POB is bad.

One can summarize this section by stating: (1) A4 is an effective measure of reliability of the data, (2) the variance is high for short duration signals, (3) the average bearing error is not useful without calibration data and (4) variance improvement with time averaging corresponds in order of magnitude with that predicted by fading phenomena.

Figure 10

WWV 5 MHz 2/79 Short Signal Duration A4MAX=0.2

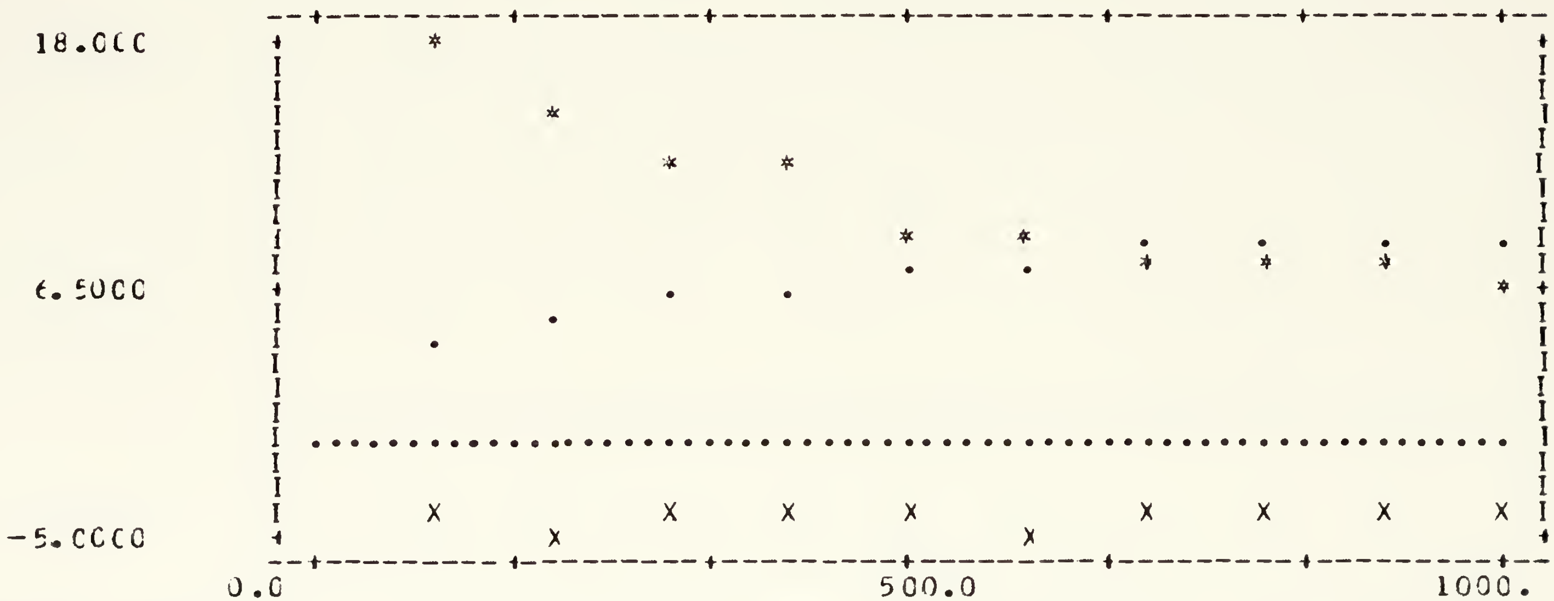
$\overline{B}$=335.5

σ_B=7.3

ε=-1.5

SOURCE: WWV 5M 7:00 2/79 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.919	0.989	0.995	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-4.	-5.	-4.	-4.	-4.	-5.	-4.	-4.	-4.	-4.
* :	18.	15.	12.	12.	9.	9.	8.	8.	8.	7.
. :	4.	5.	6.	7.	8.	8.	9.	9.	9.	9.

Figure 11

WWV 5 MHz 2/79 Short Signal Duration A4MAX=0.4

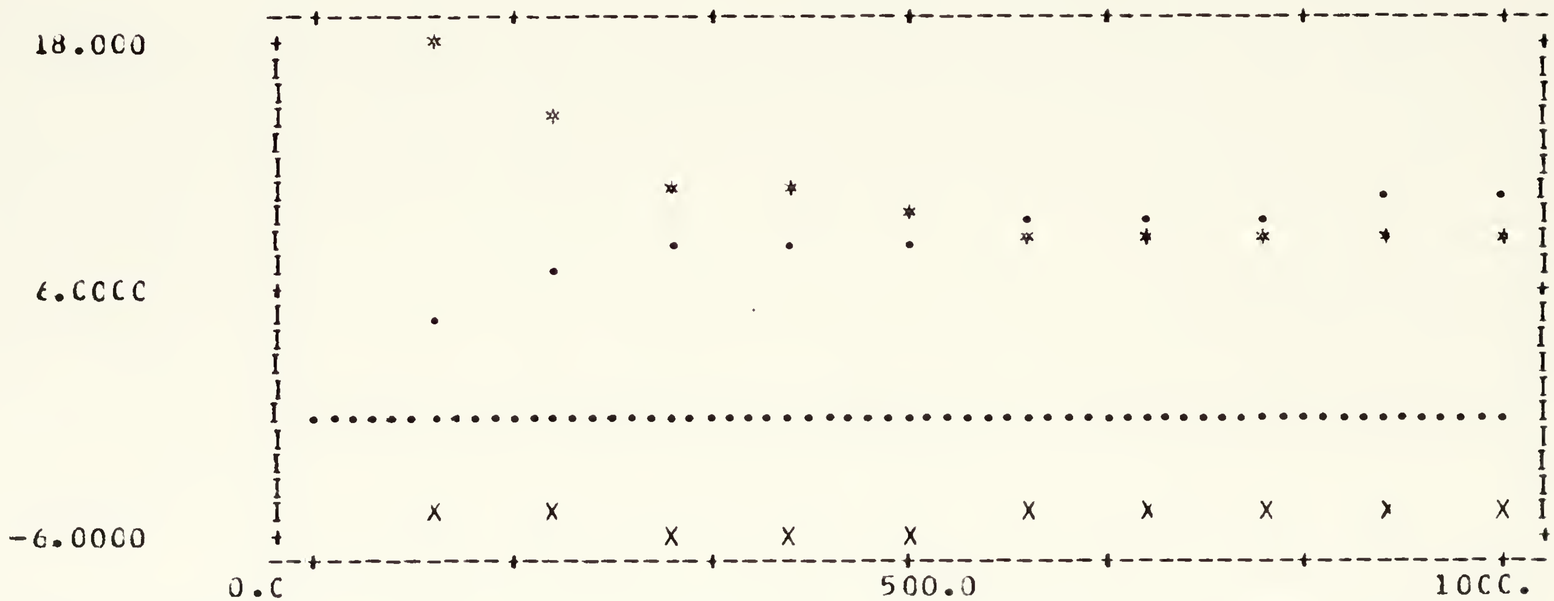
$\bar{B}$=334.8

σ_B=8.5

ε=-2.2

SOURCE: WWV 5M 7:CC 2/79 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1CC.	200.	300.	400.	500.	600.	700.	800.	9CC.	1C00.
PROBABILITY OF OBTAINING LOB :	C.996	1.000	1.000	1.000	1.CCO	1.000	1.000	1.000	1.CCC	1.000
X :	-5.	-5.	-6.	-6.	-6.	-5.	-5.	-5.	-5.	-5.
* :	18.	14.	11.	11.	10.	9.	9.	8.	8.	8.
. :	5.	7.	8.	8.	9.	10.	1C.	10.	11.	11.

Figure 12

WWV 5 MHz 2/79 Medium Signal Duration A4MAX=0.2

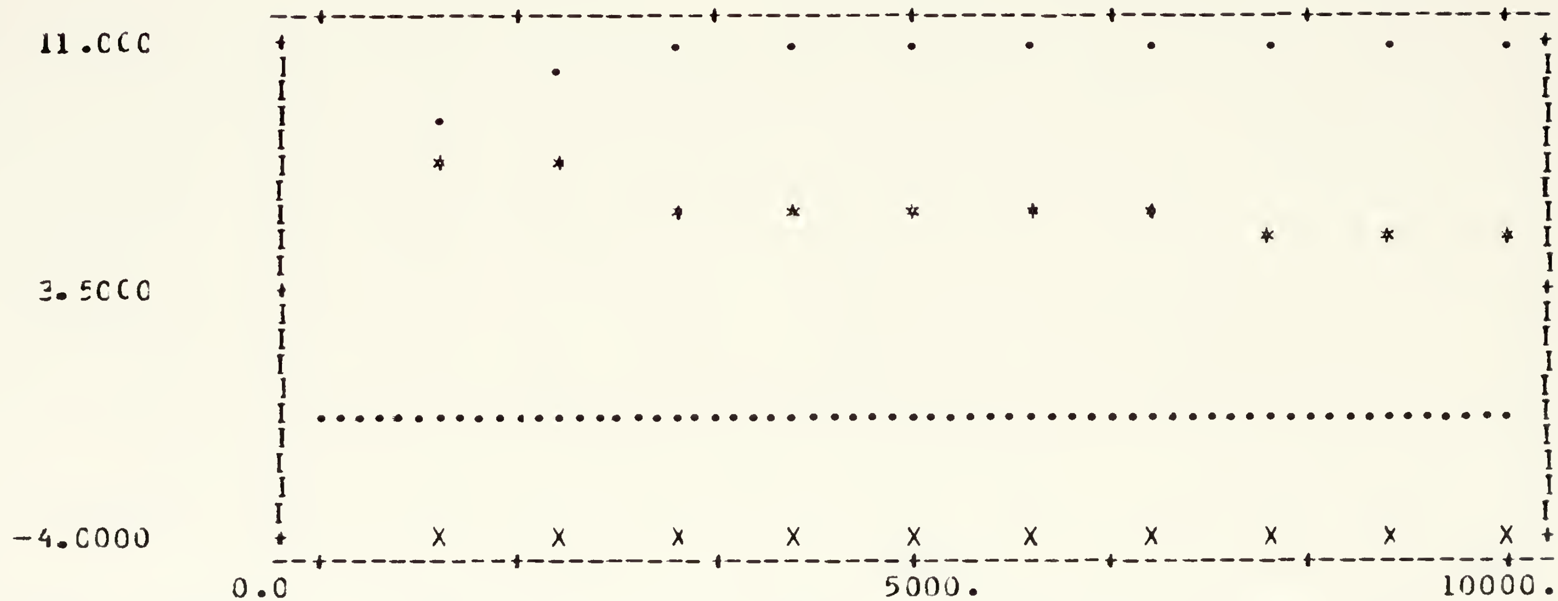
$\bar{B}$=335.5

σ_B=7.3

ε=1.5

SOURCE: WWV 5M 7:00 2/79 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF : OBTAINING LOB	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-4.	-4.	-4.	-4.	-4.	-4.	-4.	-4.	-4.	-4.
* :	7.	7.	6.	6.	6.	6.	6.	5.	5.	5.
. :	9.	10.	11.	11.	11.	11.	11.	11.	11.	11.

Figure 13

WWV 5 MHz 2/79 Medium Signal Duration A4MAX=0.4

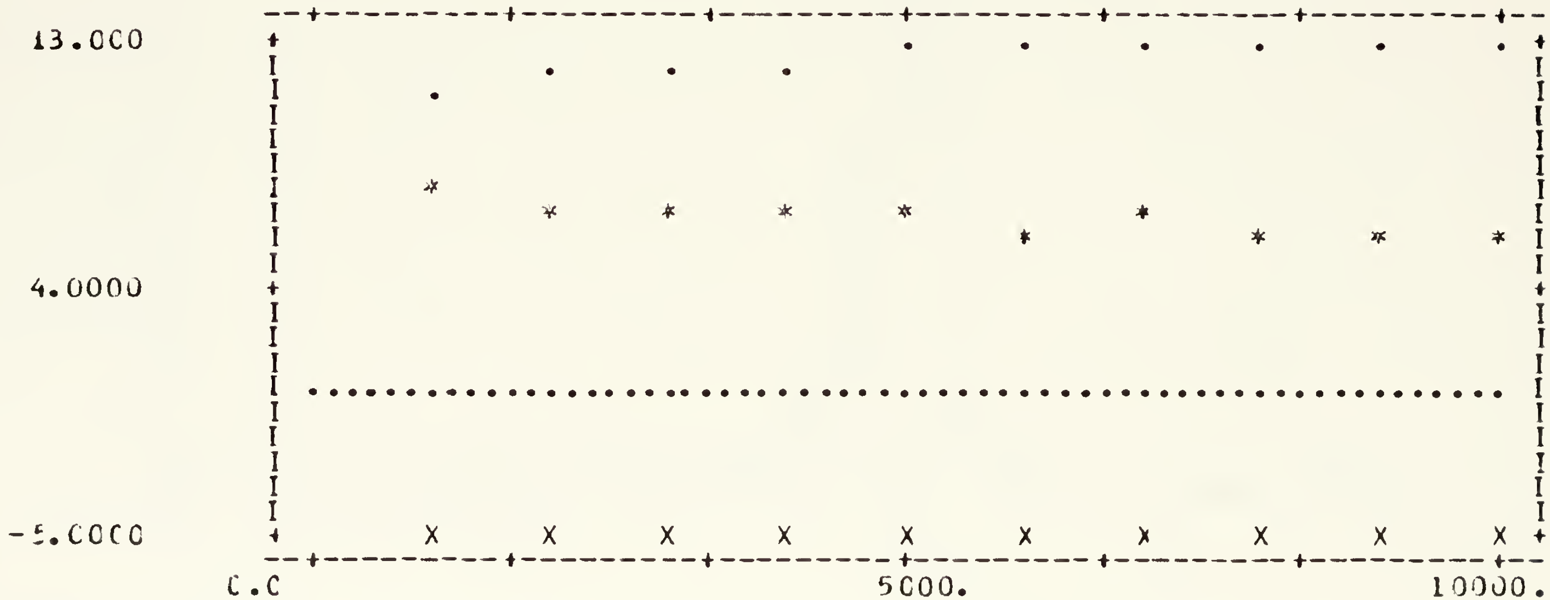
$\bar{B}=334.8$

$\sigma_B=8.5$

$\varepsilon=-2.2$

SOURCE: WWV 5M 7:00 2/79 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF OBTAINING LOB :	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-5.	-5.	-5.	-5.	-5.	-5.	-5.	-5.	-5.	-5.
* :	8.	7.	7.	7.	7.	6.	7.	6.	6.	6.
. :	11.	12.	12.	12.	13.	13.	13.	13.	13.	13.

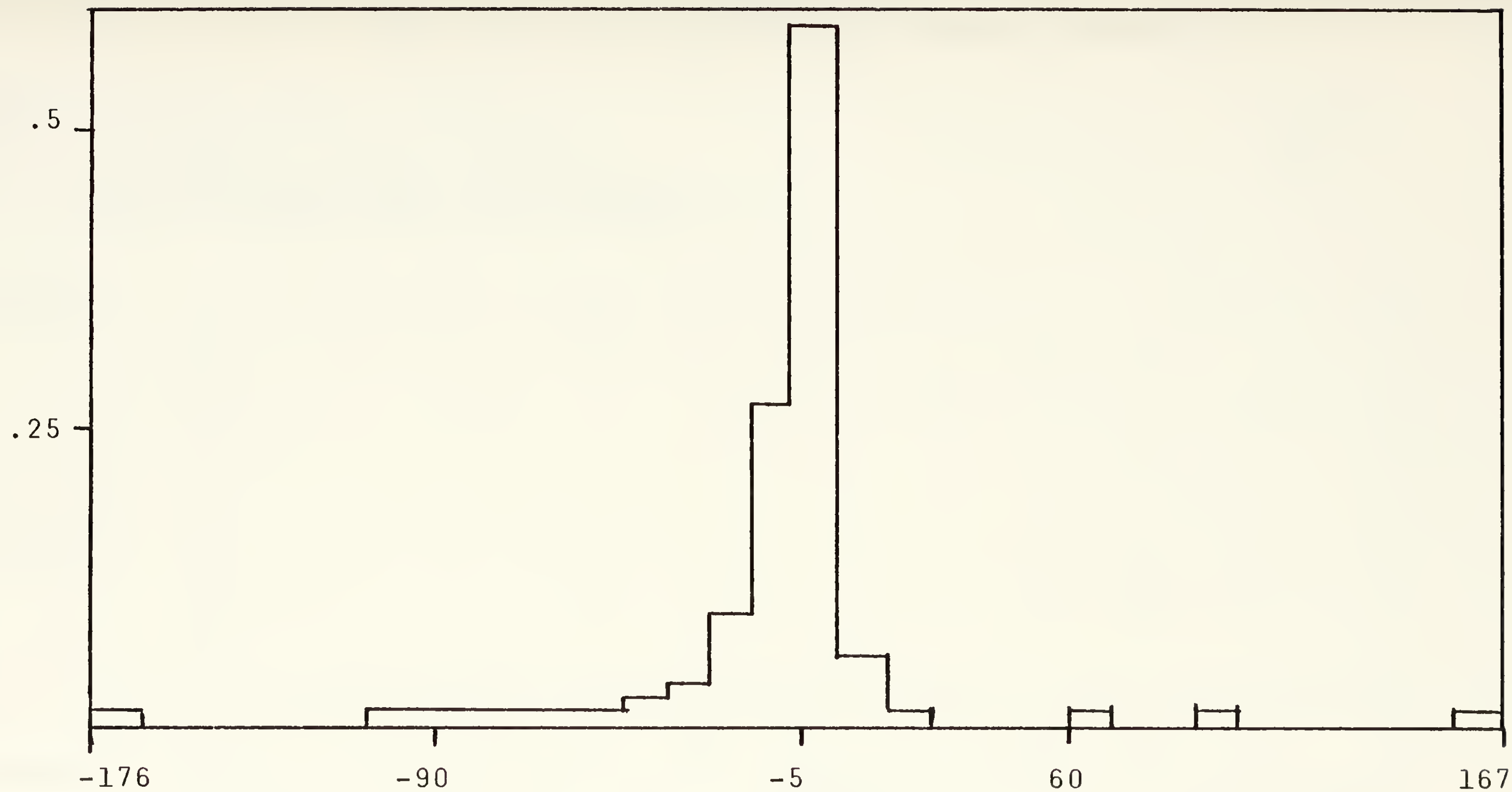


Figure 14
WWV 5 MHz 2/79 Bearing Error Histogram

Figure 15

WWV 10 MHz 2/79 Short Signal Duration A4MAX=0.2

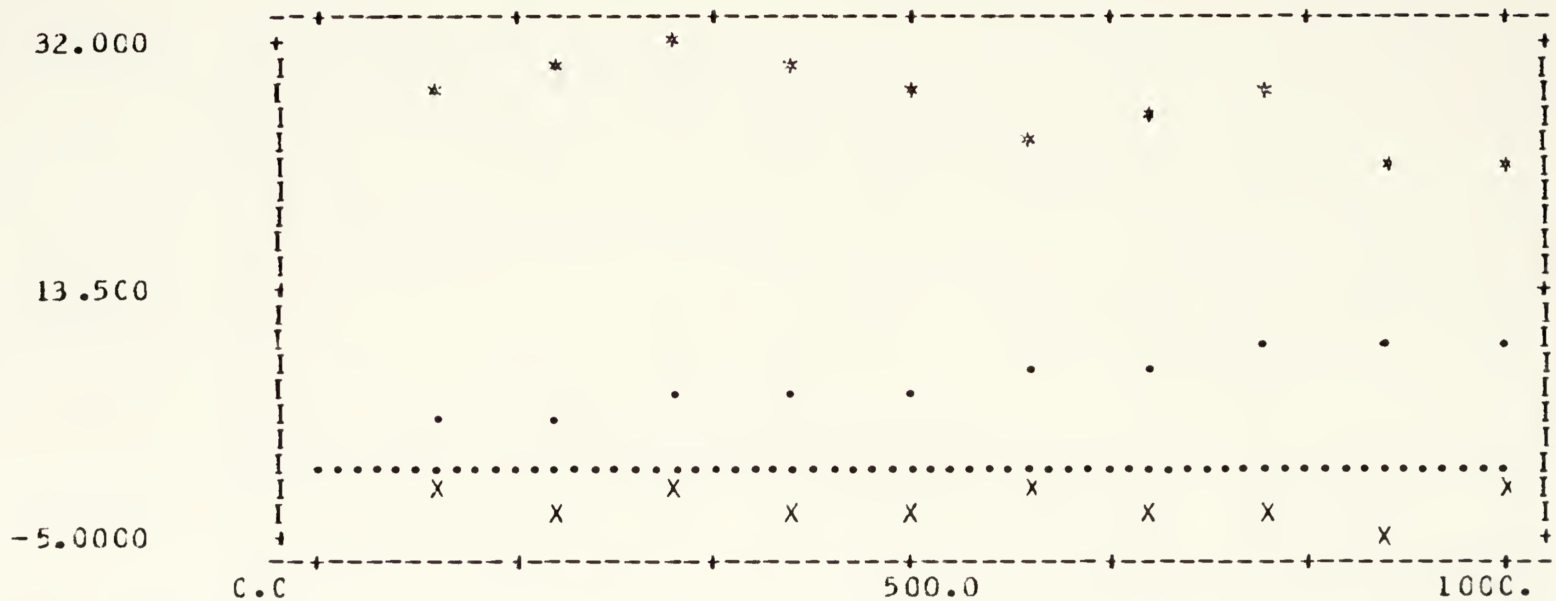
$\overline{B}$=334.6

σ_B=11.2

ε=-2.4

SCURCE: WWV 1CM 8:30 79 A4MAX=0.2

AVE BEARING ERRCR (CEGREES) : X
STC CF BEARING ERRCR (CEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.656	0.738	0.775	0.818	0.840	0.871	0.905	0.916	0.932	0.935
X :	-2.	-4.	-2.	-3.	-3.	-2.	-3.	-3.	-5.	-2.
* :	29.	31.	32.	31.	28.	24.	27.	28.	22.	22.
. :	4.	4.	6.	7.	7.	8.	8.	9.	9.	10.

Figure 16

WWV 10 MHz 2/79 Short Signal Duration A4MAX=0.4

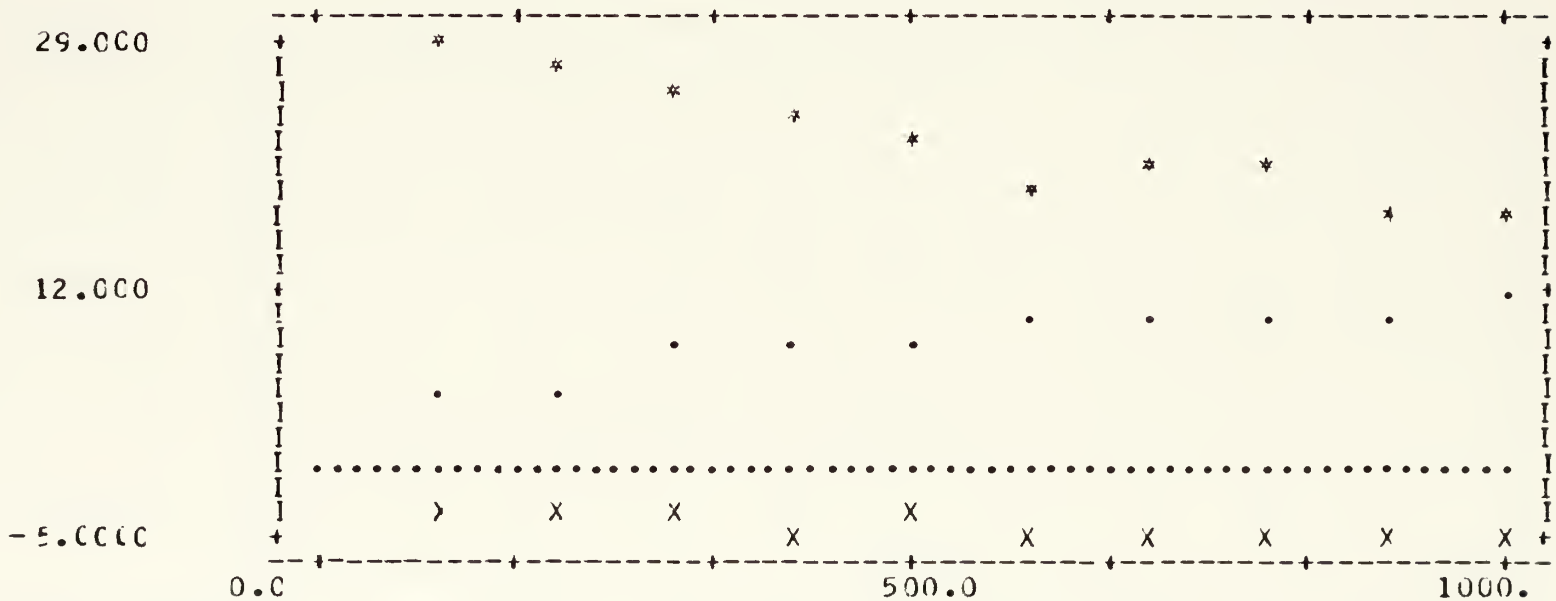
$\overline{B}$=332.8

σ_B=16.4

ε=-4.2

SOURCE: WWV 1CM 8:30 79 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.948	0.974	0.985	0.994	0.997	0.997	1.000	1.000	1.000	1.000
X :	-4.	-4.	-4.	-5.	-4.	-5.	-5.	-5.	-5.	-5.
* :	29.	28.	26.	24.	23.	19.	20.	21.	17.	17.
. :	5.	6.	8.	8.	9.	10.	10.	11.	11.	12.

Figure 17

WWV 10 MHz 2/79 Medium Signal Duration A4MAX=0.2

$\overline{B}=334.6$

$\sigma_B=11.2$

$\varepsilon=-2.4$

SOURCE: WWV 10M 8:30 2/79 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .

SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF : OBTAINING LOB	0.935	0.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-2.	-5.	-6.	-5.	-5.	-6.	-5.	-4.	-5.	-5.
* :	22.	12.	12.	10.	9.	9.	8.	7.	7.	5.
. :	10.	11.	13.	12.	14.	14.	15.	13.	15.	16.

Figure 18

WWV 10 MHz 2/79 Medium Signal Duration A4MAX=0.4

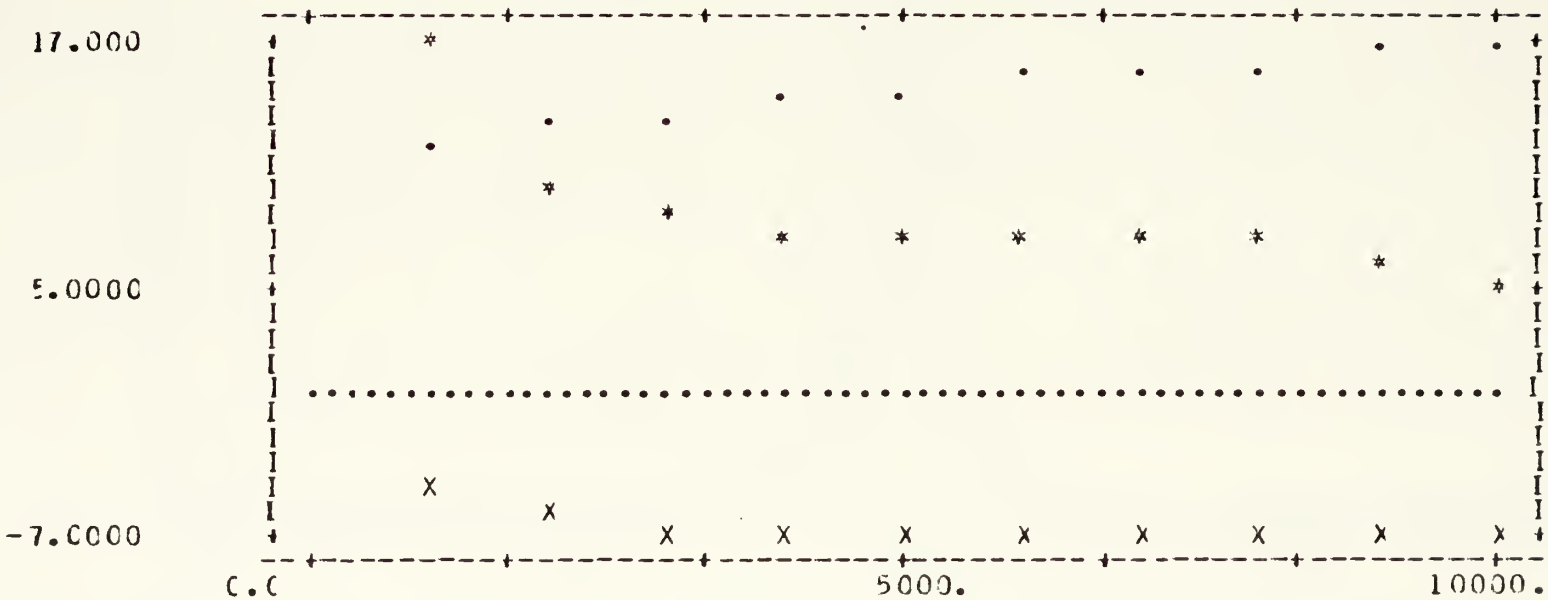
$\overline{B}=332.8$

$\sigma_B=12.8$

$\varepsilon=-4.2$

SOURCE: WWV 10M 8:30 2/79 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF : OBTAINING LOB	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-5.	-6.	-7.	-7.	-7.	-7.	-7.	-7.	-7.	-7.
* :	17.	10.	9.	8.	7.	7.	7.	7.	6.	5.
. :	12.	13.	14.	15.	15.	16.	16.	16.	17.	17.

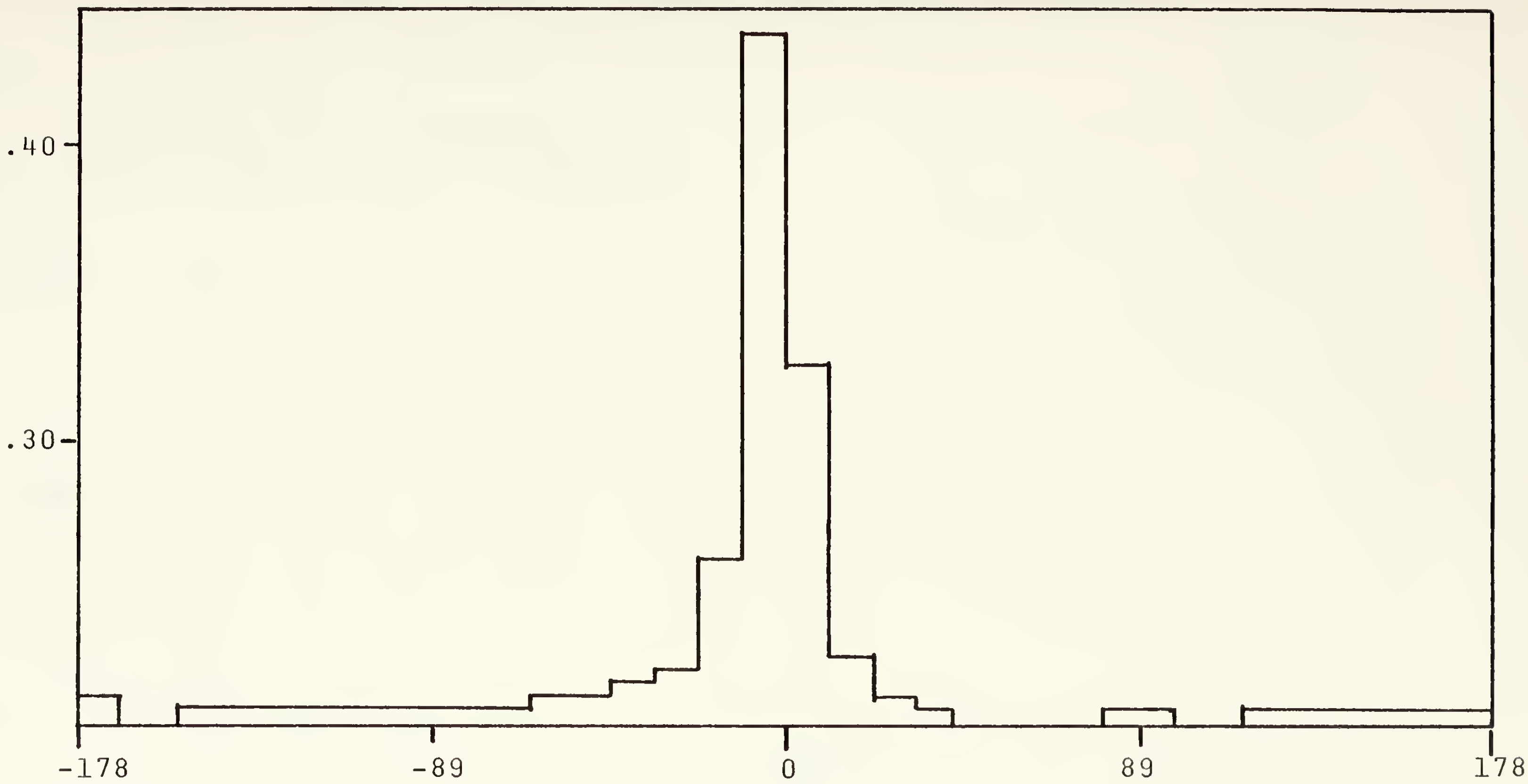


Figure 19
WWV 10 MHz 2/79 Bearing Error Histogram

Figure 20

WWV 20 MHz 2/79 Short Signal Duration A4MAX=0.2

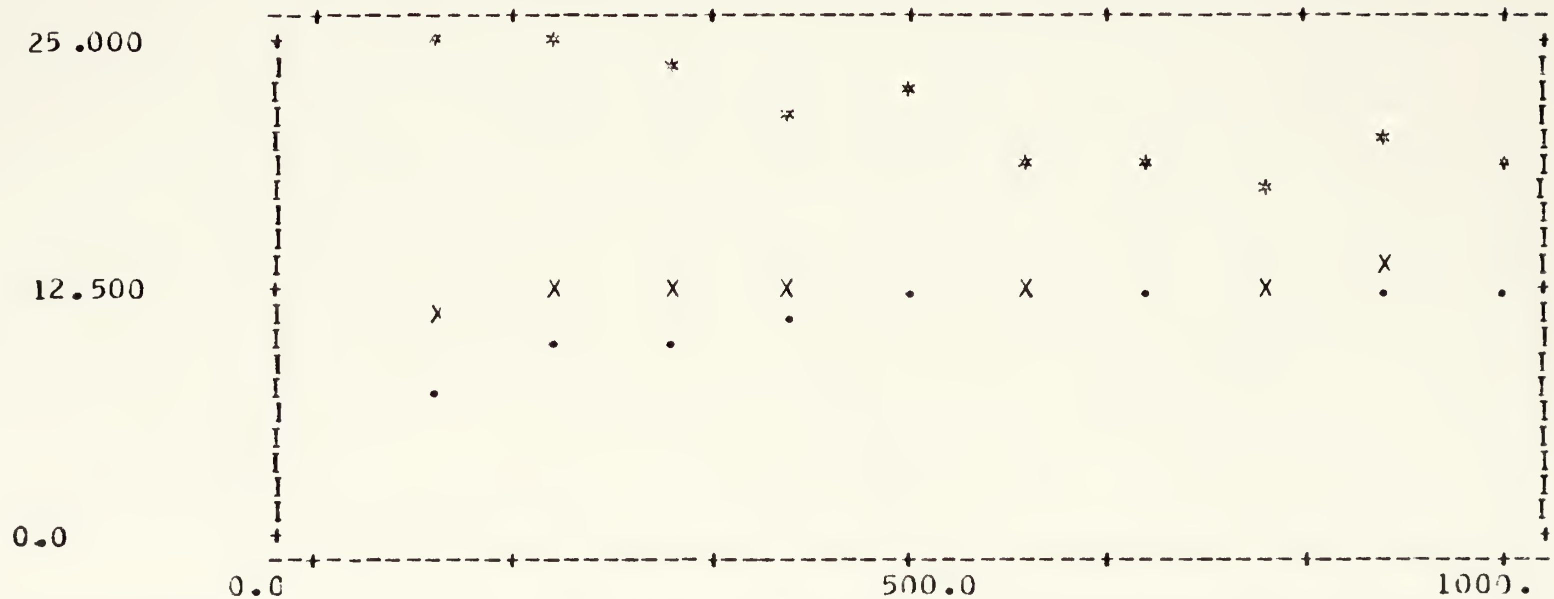
SOURCE: WWV 20M 12:15 79 A4MAX=0.2

$\overline{B}=346.4$

$\sigma_B=30.4$

$\varepsilon=9.6$

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.766	0.897	0.949	0.972	0.985	0.994	0.993	0.996	0.995	1.000
X :	11.	12.	13.	13.	13.	13.	13.	13.	14.	13.
* :	25.	25.	24.	21.	22.	19.	19.	18.	20.	19.
. :	8.	10.	10.	11.	12.	12.	12.	12.	13.	13.

Figure 21

WWV 20 MHz 2/79 Short Signal Duration A4MAX=0.4

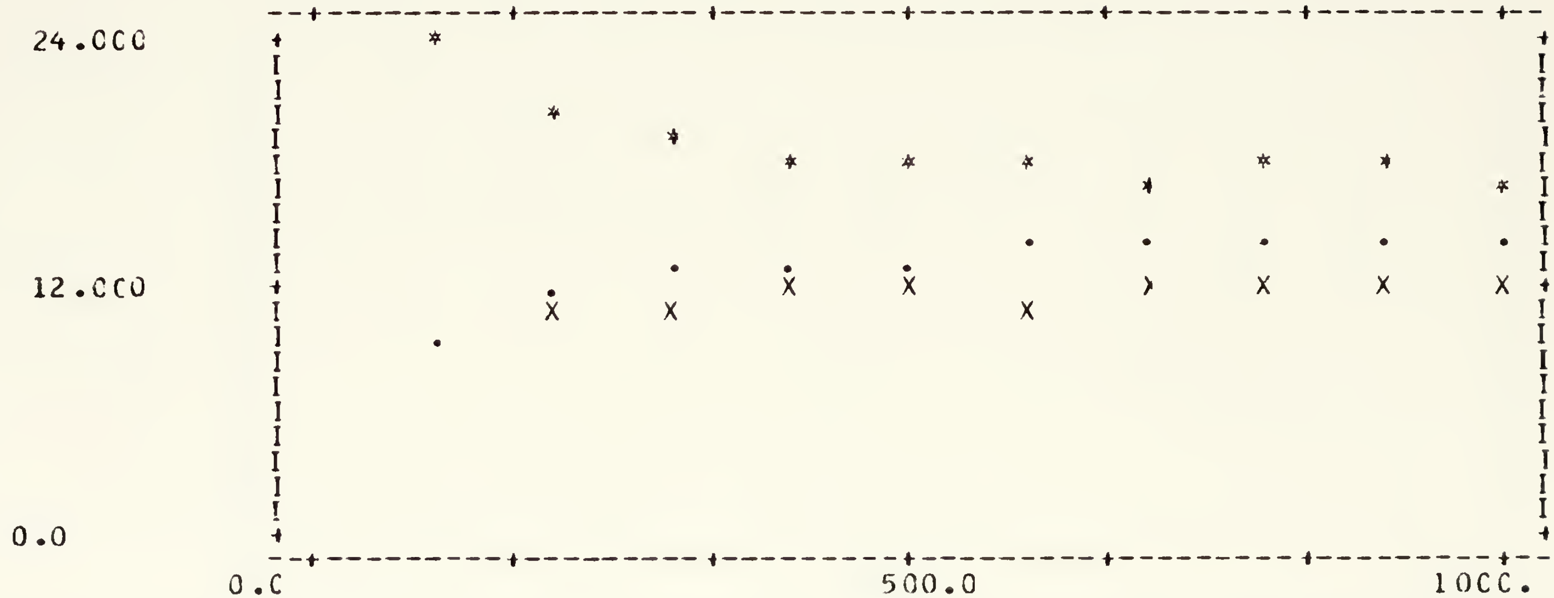
$\bar{B}$=343.9

σ_B=35.2

ε=6.9

SOURCE: WWV 20M 12:15 79 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF OBTAINING LOB :	0.988	0.999	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	10.	11.	11.	12.	12.	11.	12.	12.	12.	12.
* :	24.	21.	19.	18.	18.	18.	17.	18.	18.	17.
. :	10.	12.	13.	13.	13.	14.	15.	14.	14.	14.

Figure 22

WWV 20 MHz 2/79 Medium Signal Duration A4MAX=0.2

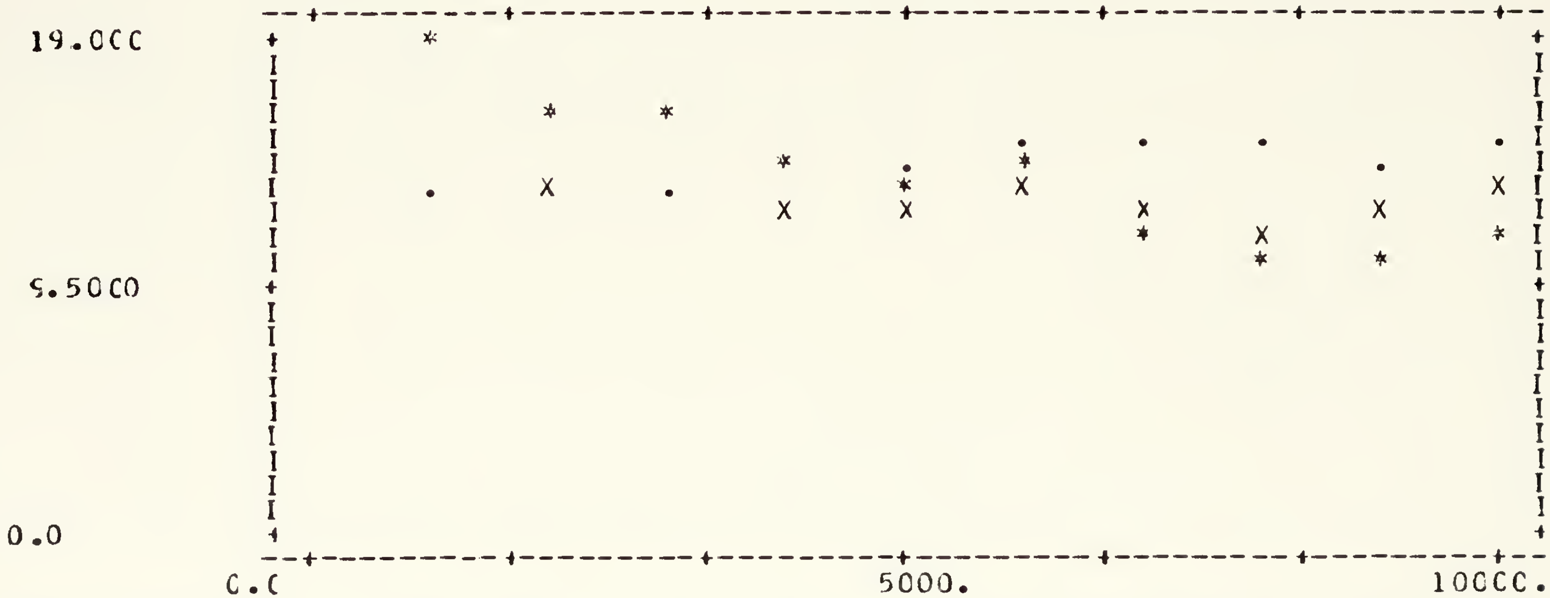
$\bar{B}=346.6$

$\sigma_B=30.4$

$\omega=9.6$

SOURCE: WWV 20M 12:15 2/79 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF : OBTAINING LOB	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	13.	13.	13.	12.	12.	13.	12.	11.	12.	13.
* :	19.	16.	16.	14.	13.	14.	11.	10.	10.	11.
. :	13.	13.	13.	14.	14.	15.	15.	15.	14.	15.

Figure 23

WWV 20 MHz 2/79 Medium Signal Duration A4MAX=0.4

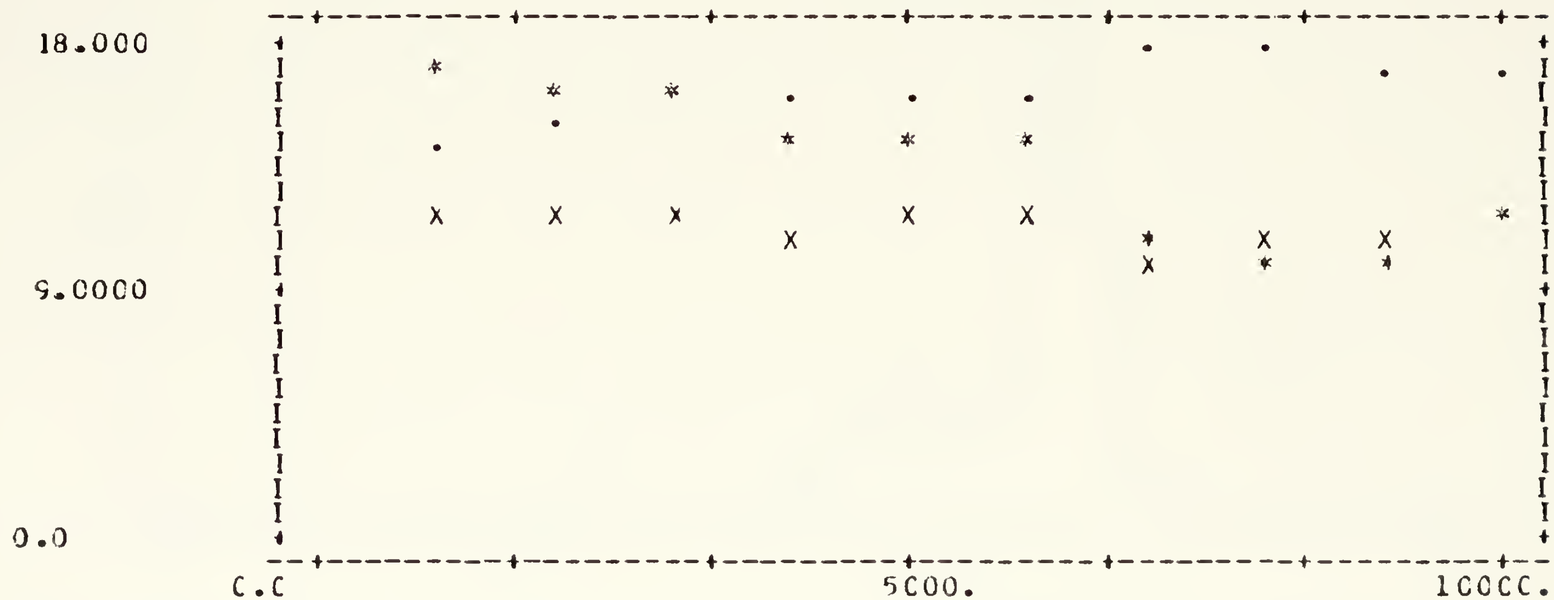
$\overline{B}$=346.6

σ_B=30.4

ω=9.6

SOURCE: WWV 20M 12:15 2/79 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF : OBTAINING LOB	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	12.	12.	12.	11.	12.	12.	10.	11.	11.	12.
* :	17.	16.	16.	14.	14.	14.	11.	10.	10.	12.
. :	14.	15.	16.	16.	16.	16.	18.	18.	17.	17.

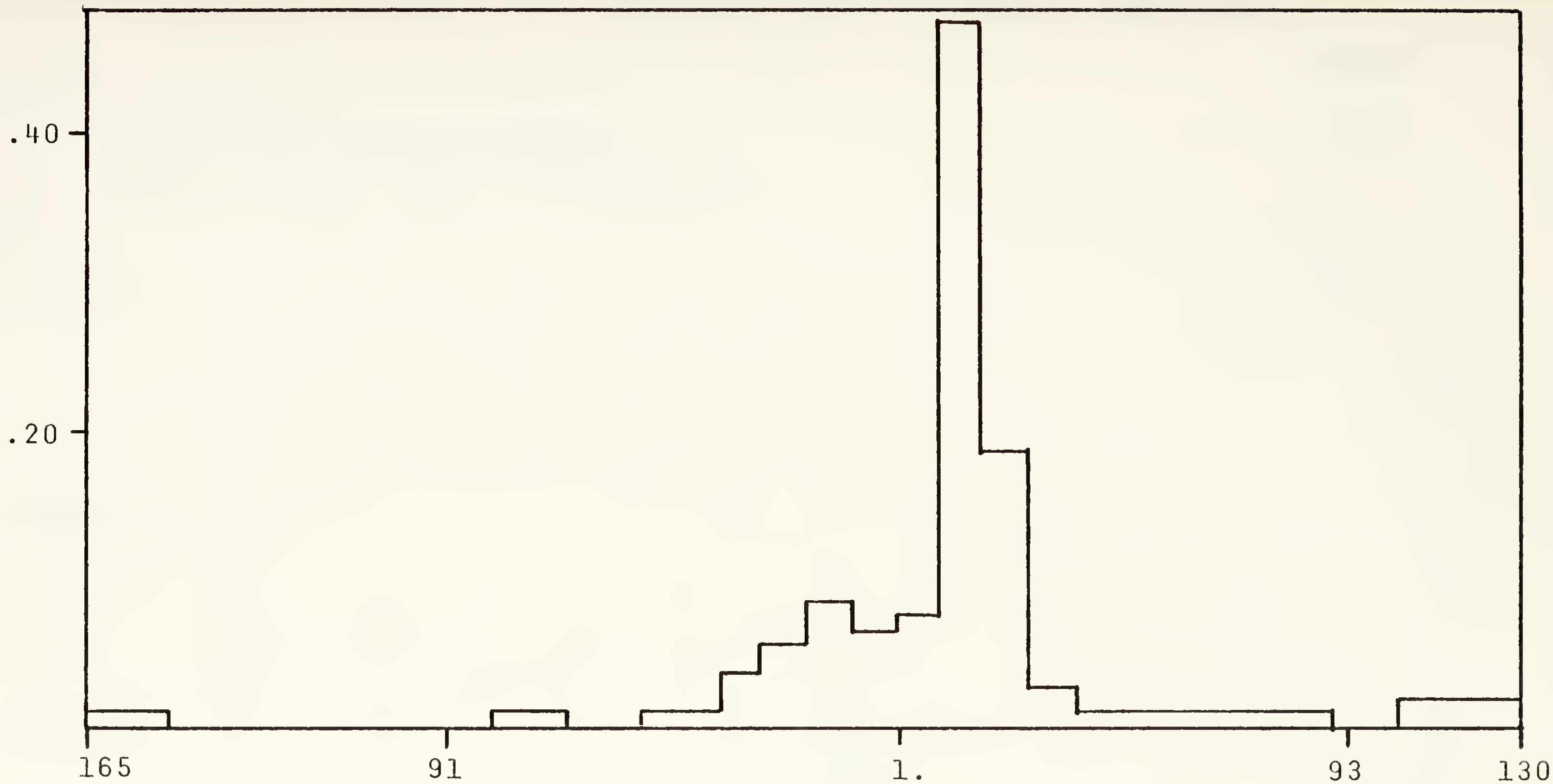


Figure 24

WWV 20 MHz 2/79 Bearing Error Histogram

Figure 25

WWV 5 MHz 2/80 Short Signal Duration A4MAX=0.2

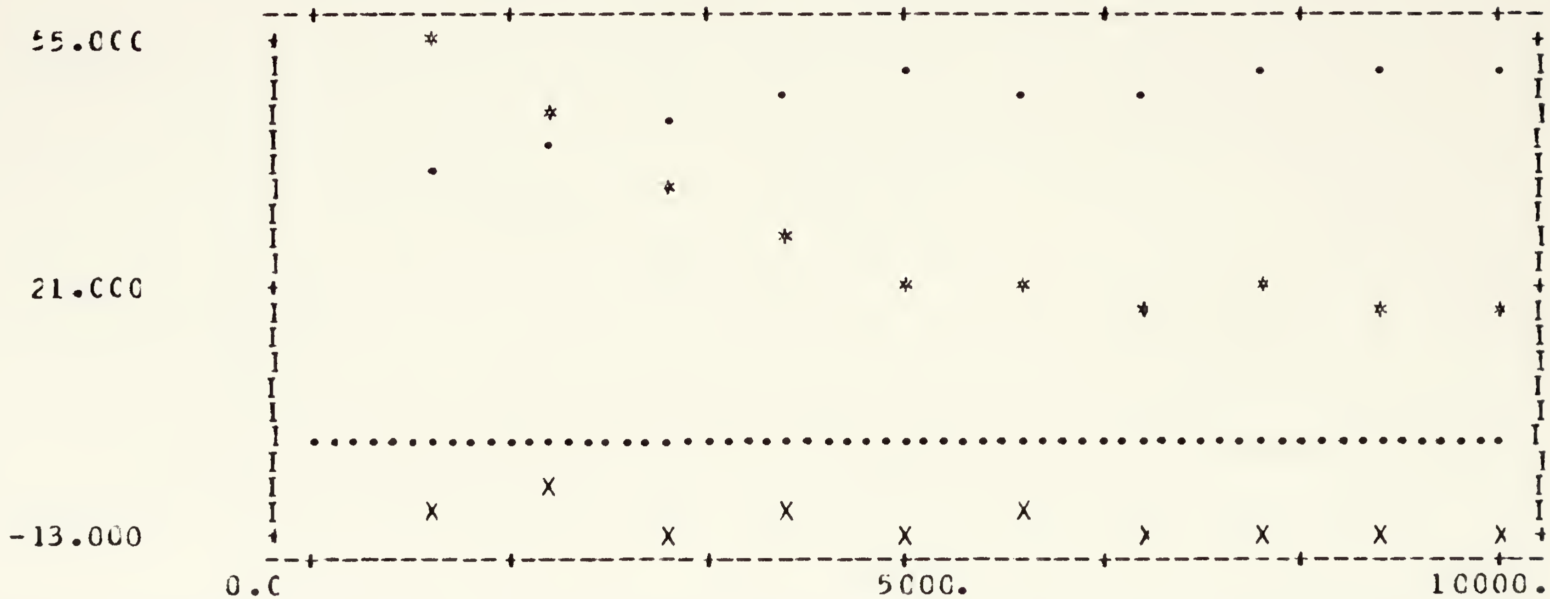
$\overline{B}$=290.4

σ_B=66.7

ε=-46.6

SOURCE: WWV 5M 20:40 2/80 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF OBTAINING LOB :	0.980	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-11.	-7.	-12.	-10.	-13.	-11.	-12.	-13.	-13.	-13.
* :	55.	44.	33.	29.	21.	20.	18.	22.	17.	18.
. :	38.	43.	46.	47.	51.	48.	49.	50.	50.	51.

Figure 26

WWV 5 MHz 2/80 Short Signal Duration A4MAX=0.4

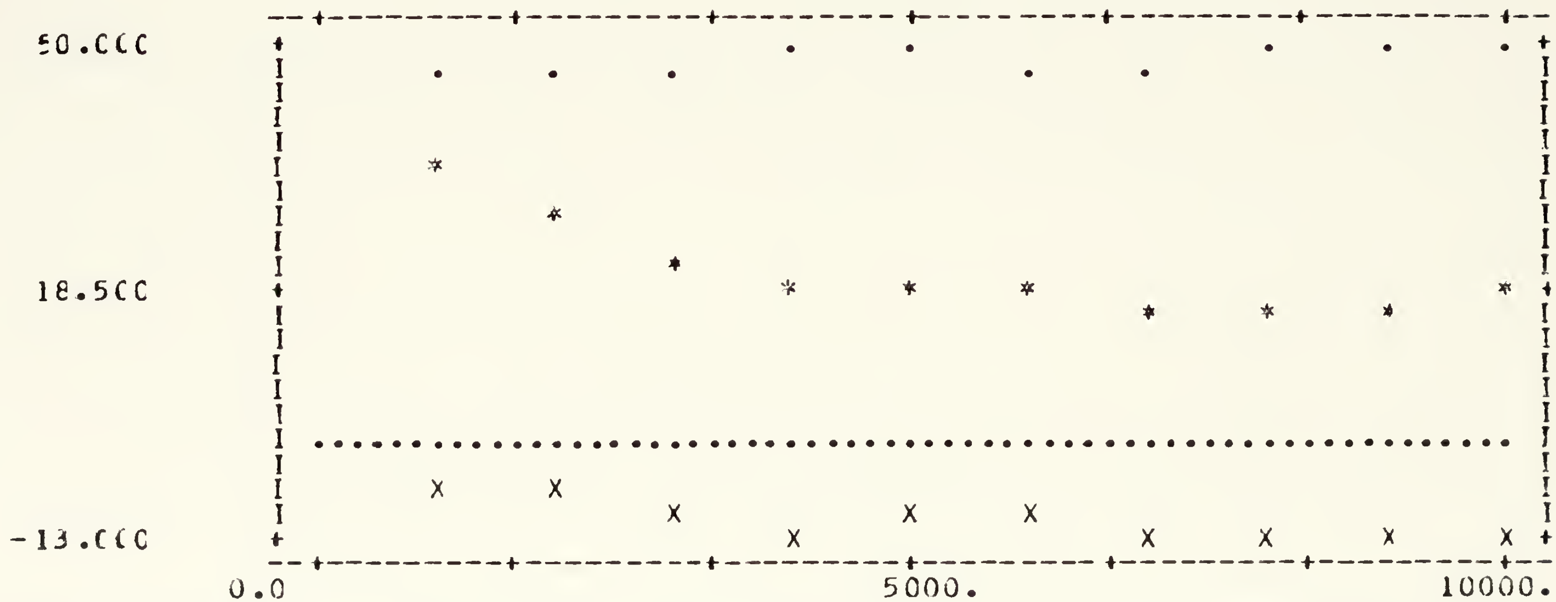
$\overline{B}=279.4$

$\sigma_B=70.9$

$\varepsilon=-57.6$

SOURCE: WWV 5M 20:40 2/80 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF OBTAINING LOB :	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-6.	-8.	-10.	-13.	-11.	-11.	-12.	-13.	-12.	-12.
* :	34.	27.	22.	19.	18.	19.	16.	16.	16.	17.
. :	47.	48.	48.	50.	50.	48.	47.	50.	49.	49.

Figure 27

WWV 5 MHz 2/80 Medium Signal Duration A4MAX=0.2

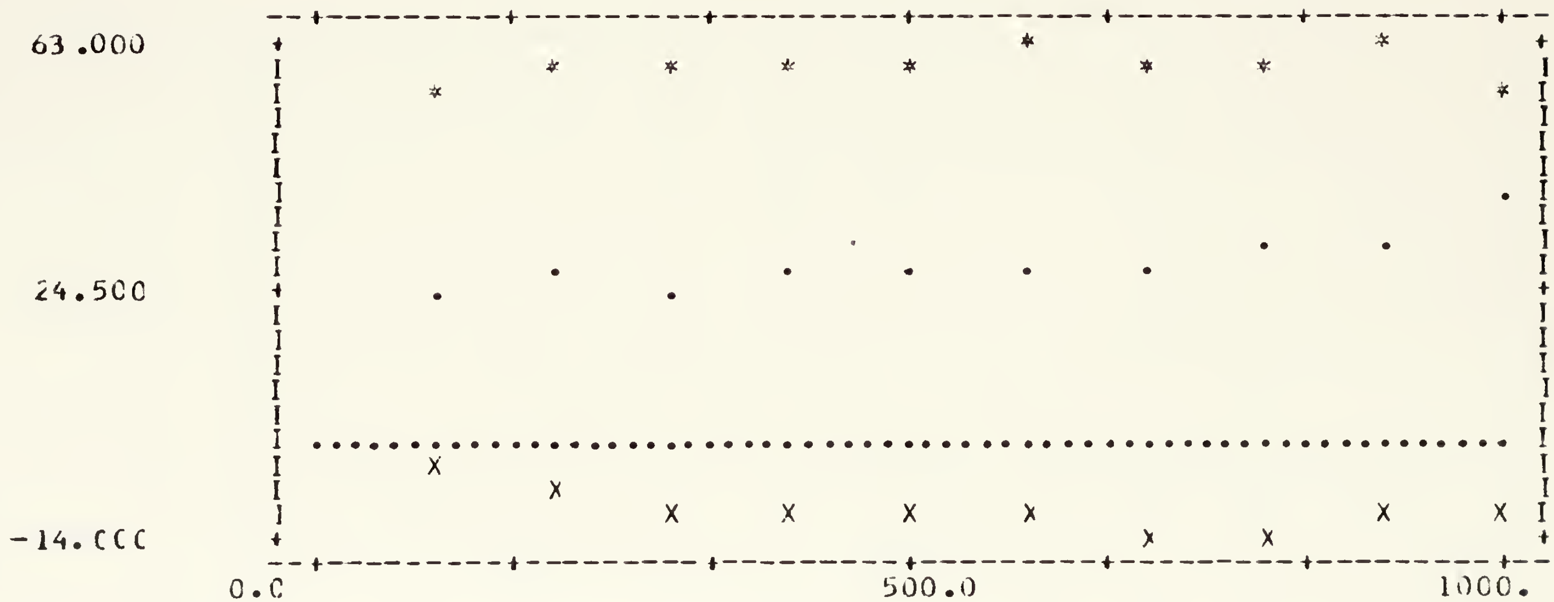
$\overline{B}=290.4$

$\sigma_B=66.7$

$\varepsilon=-46.6$

SOURCE: WWV 5M 20:40 2/80 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.113	0.328	0.520	0.652	0.767	0.835	0.898	0.912	0.946	0.980
X :	-4.	-6.	-10.	-9.	-9.	-10.	-14.	-14.	-11.	-11.
* :	57.	59.	58.	59.	59.	63.	61.	58.	62.	55.
. :	26.	29.	25.	27.	30.	28.	30.	31.	34.	38.

Figure 28

WWV 5 MHz 2/80 Medium Signal Duration A4MAX=0.4

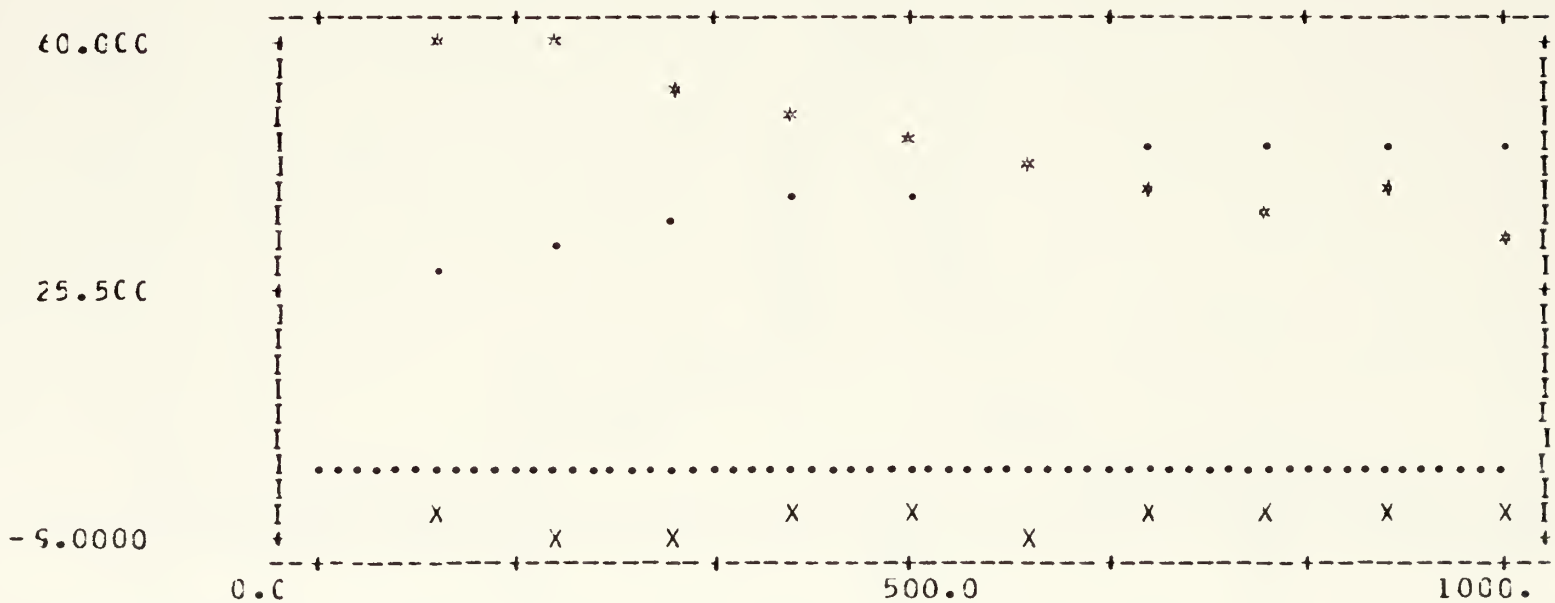
$\overline{B}=279.4$

$\sigma_B=70.9$

$\varepsilon=-57.6$

SOURCE: WWV 5M 20:40 2/80 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF OBTAINING LOB :	0.609	0.921	0.979	0.992	1.000	1.000	1.000	1.000	1.000	1.000
X :	-5.	-8.	-8.	-7.	-6.	-9.	-7.	-6.	-5.	-6.
* :	59.	60.	54.	51.	46.	44.	41.	37.	39.	34.
. :	28.	31.	36.	40.	41.	43.	45.	45.	46.	47.

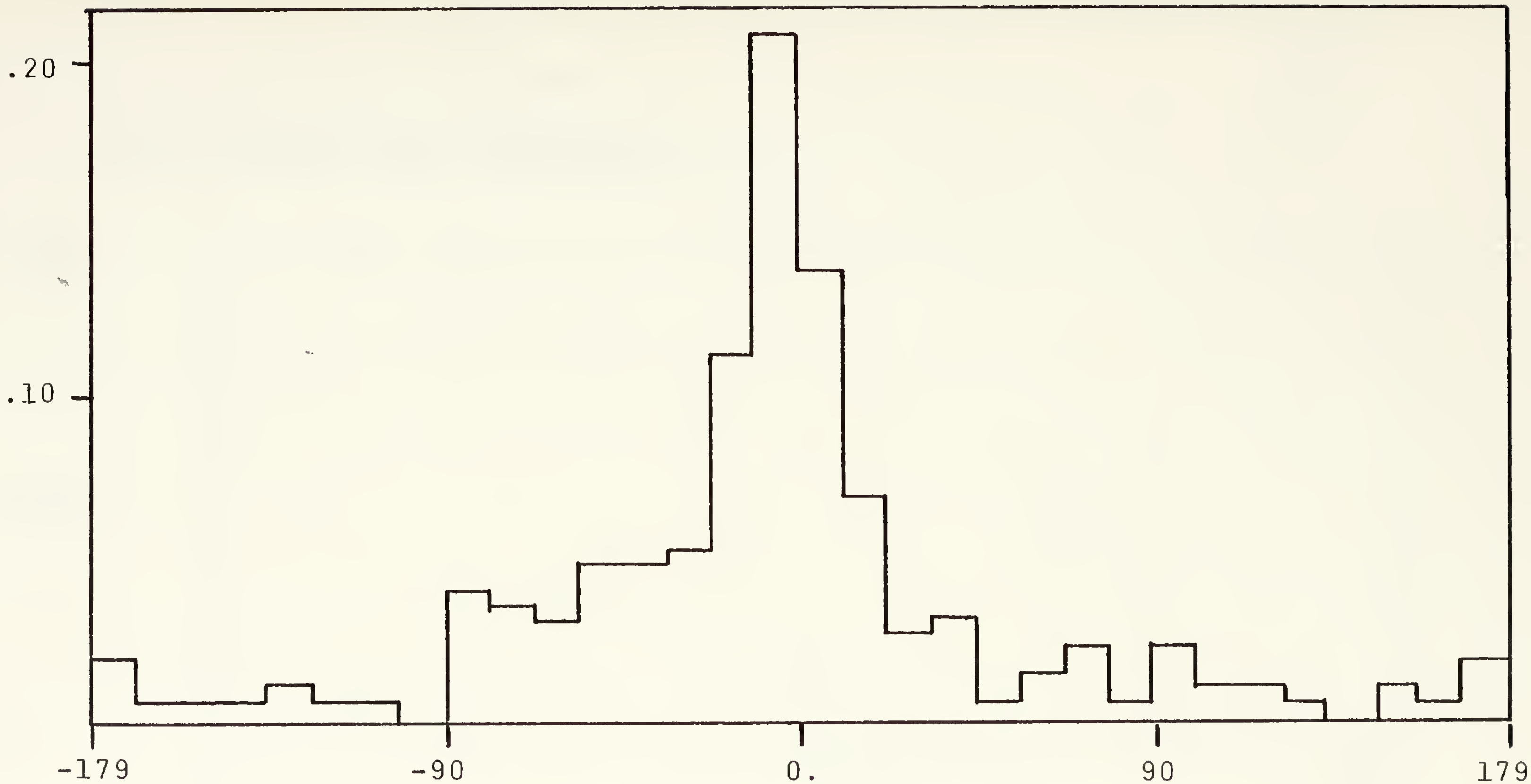


Figure 29

WWV 5 MHz 2/80 Bearing Error Histogram

Figure 30

WWV 10 MHz 2/80 Short Signal Duration A4MAX=0.2

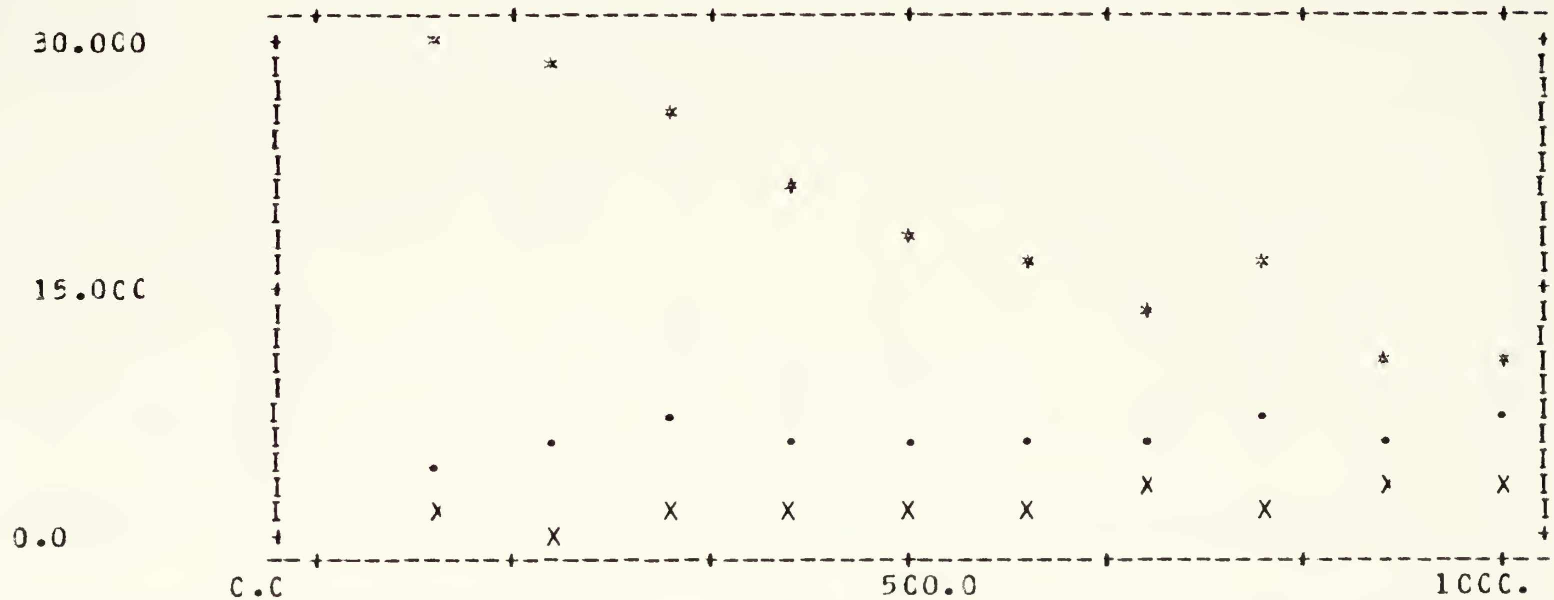
$\overline{B}=340.1$

$\sigma_B=7.9$

$\varepsilon=3.1$

SOURCE: WWV 10M 7:40 2/80 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.727	0.903	0.950	0.974	0.985	0.991	0.996	0.996	1.000	1.000
X :	1.	0.	2.	1.	1.	1.	3.	2.	3.	3.
* :	30.	29.	25.	21.	18.	17.	13.	16.	10.	11.
. :	5.	6.	7.	6.	6.	6.	6.	7.	6.	7.

Figure 31

WWV 10 MHz 2/80 Short Signal Duration A4MAX=0.4

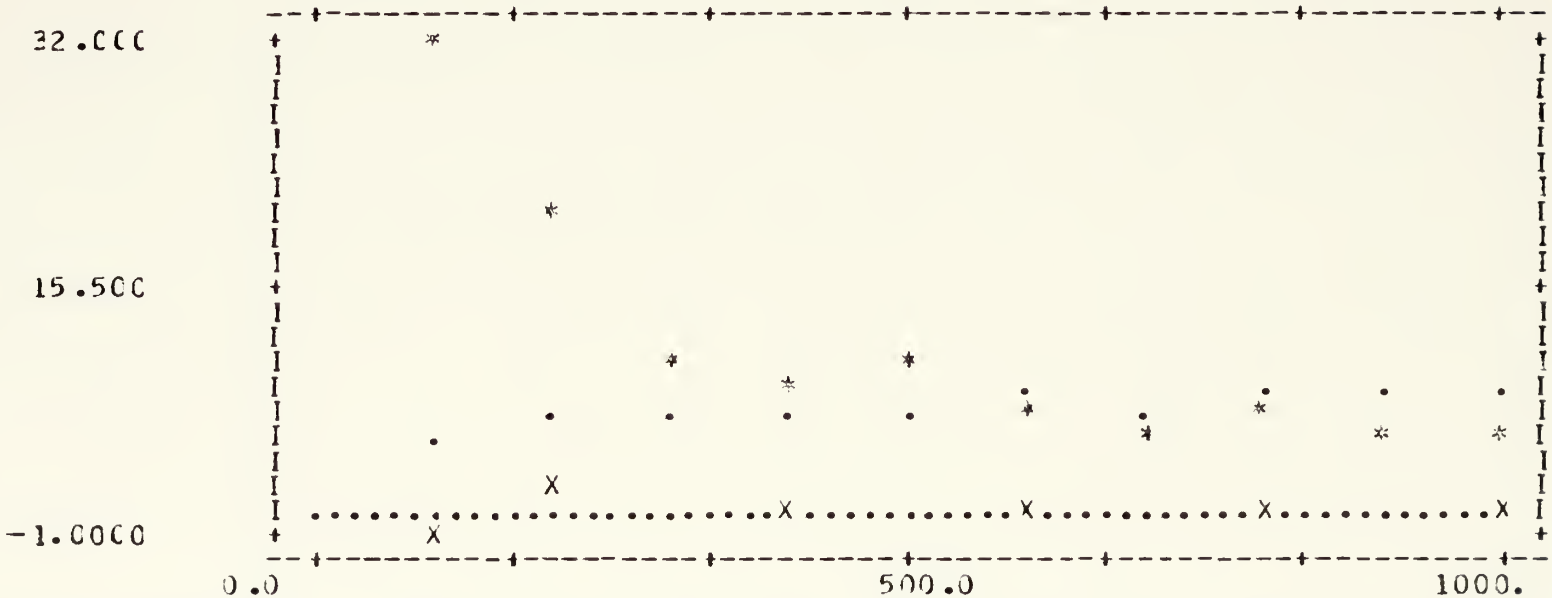
$\bar{B}$=339.4

σ_B=9.1

ε=2.4

SOURCE: WWV 10M 7:40 2/80 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF OBTAINING LOB :	0.990	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	-1.	2.	0.	0.	0.	1.	1.	1.	1.	1.
* :	32.	21.	11.	9.	10.	7.	5.	7.	5.	6.
. :	6.	8.	8.	8.	8.	9.	8.	9.	9.	9.

Figure 32

WWV 10 MHz 2/80 Medium Signal Duration A4MAX=0.2

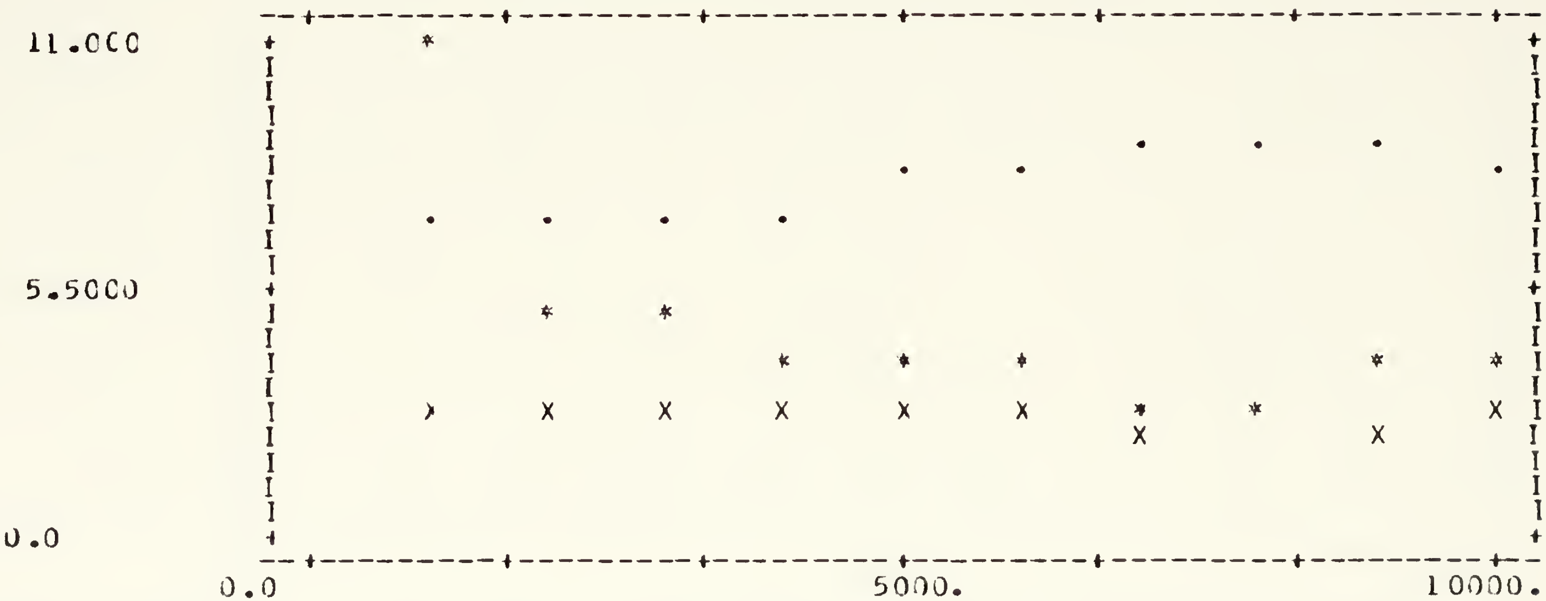
$\overline{B}=340.1$

$\sigma_B=7.9$

$\varepsilon=3.1$

SCURCE: WWV 10M 7:40 2/80 A4MAX=0.2

AVE BEARING ERRCR (DEGREES) : X
STD OF BEARING ERRCR (DEGREES) : *
AVE CF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATICN: (MILLISECCNDS)	1000.	2000.	30CC.	4000.	5000.	6000.	7000.	8000.	9CCC.	10CC0.
PRCBABILITY OF OBTAINING LCB :	1.000	1.000	1.0CC	1.000	1.000	1.000	1.000	1.00C	1.CC0	1.000
X :	3.	3.	3.	3.	3.	3.	2.	3.	2.	3.
* :	11.	5.	5.	4.	4.	4.	3.	3.	4.	4.
. :	7.	7.	7.	7.	8.	8.	9.	9.	9.	8.

Figure 33

WWV 10 MHz 2/80 Medium Signal Duration A4MAX=0.4

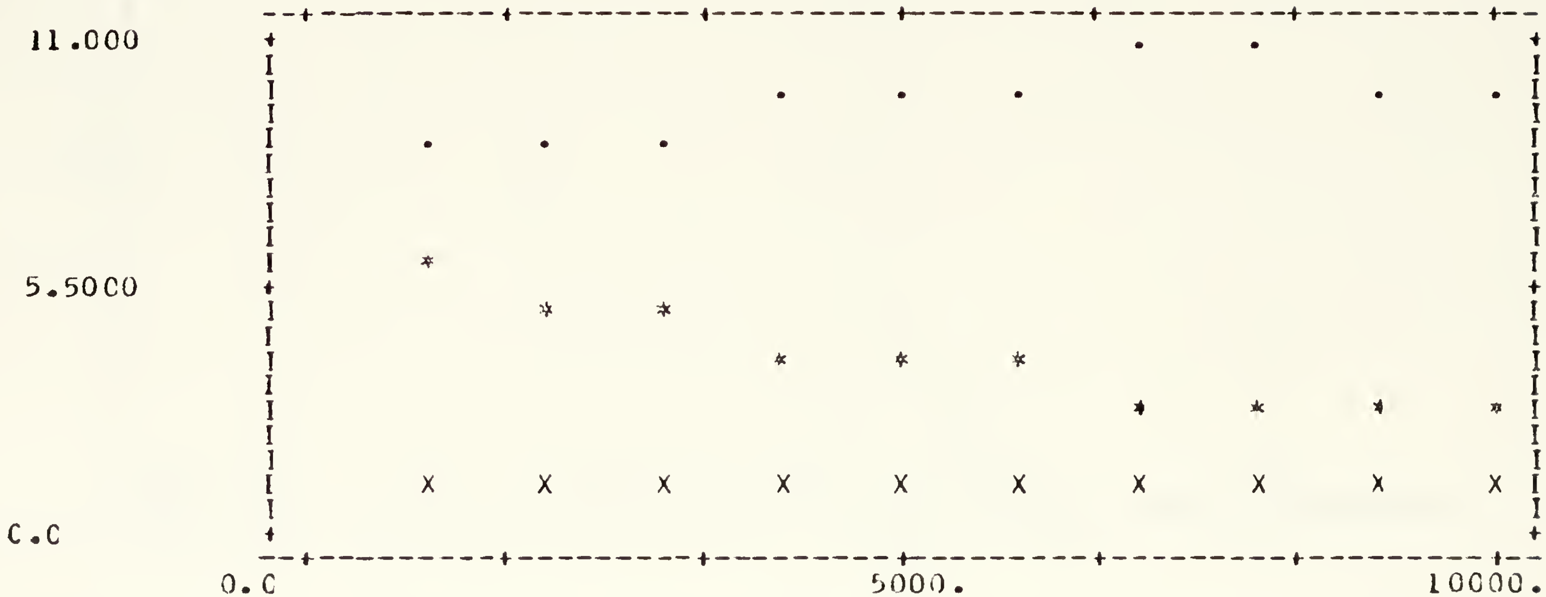
$\overline{B}=339.4$

$\sigma_B=9.1$

$\varepsilon=2.4$

SOURCE: WWV 10M 7:40 2/80 A4MAX=0.4

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF OBTAINING LOB :	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
X :	1.	1.	1.	1.	1.	1.	1.	1.	1.	1.
* :	6.	5.	5.	4.	4.	4.	3.	3.	3.	3.
. :	9.	9.	9.	10.	10.	10.	11.	11.	10.	10.

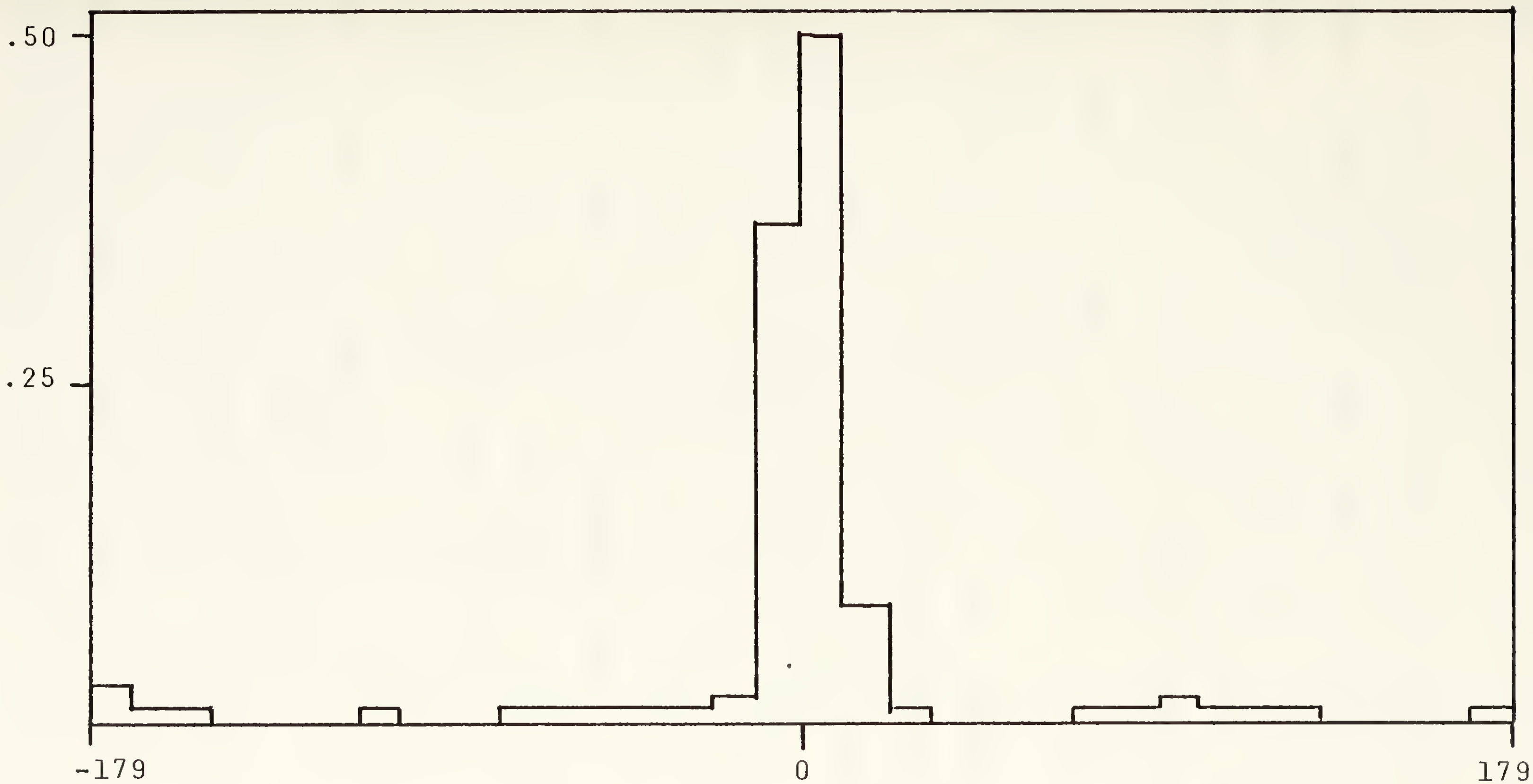


Figure 34

WWV 10 MHz 2/80 Bearing Error Histogram

C. LMAT

The previous section detailed the results of accepting data record bearings on the basis of the A4 term. The calculated variances are large and in some cases the corresponding POB is small. There is a strong need to lower the variances and increase the POB to approximately one. To do this requires a more complete use of the data; this includes the AØ and Phase terms.

The theoretical equations of the coaxial spaced loops prove the existence of polarization independent nulls in the ideal case. However, the construction of perfect loops and free space siting of these loops is clearly impossible. Recognizing that the spaced loop array does not perform ideally, one attempts to identify the sources of fixed error and correct them with a calibration data set. Other sources of error are random and are described in probabilistic terms. It is usually the case that more than one of the major errors is random. This results in joint probability density functions that are impossible to derive analytically and impossible to isolate in order to measure.

In an attempt to maximize the use of information available without a precise knowledge of either the fixed or random errors, it was decided to take a decision theory approach. An assessment of a bearing's reliability is what is most needed.

The decision to be made is binary; a bearing is reliable or unreliable. Once the bearing reliability is determined, the statistical procedure developed for DFERR can be used to determine a mean bearing. The decision to determine if a bearing is reliable will be based on the likelihood that it is reliable.

As an example, assume the following data records:

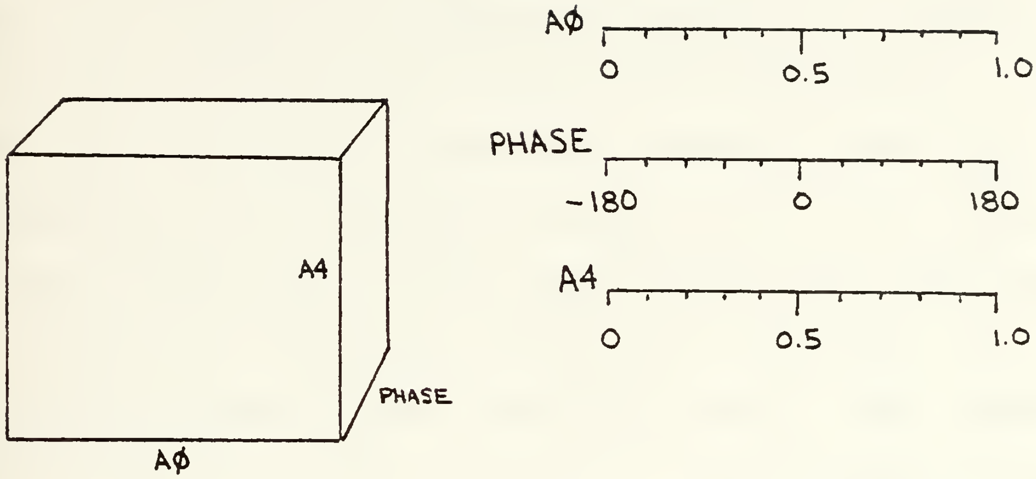
Record #	AØ	A4	Bearing
1	Ø.113	Ø.214	34Ø
2	Ø.612	Ø.2Ø8	358
3	Ø.514	Ø.421	288
4	Ø.815	Ø.113	3Ø5
.	...	...	...

The true bearing is known to be 337. Assume that a second data set is recorded on an unlocated target transmitter:

Record #	AØ	A4	Bearing
1	Ø.Ø56	Ø.298	1Ø5
2	Ø.822	Ø.173	Ø42
3	Ø.1Ø9	Ø.2Ø2	Ø93
4	Ø.666	Ø.432	Ø87

Which record is most reliable? It is known in data set one that the first record is the most reliable because its bearing is the most accurate. Using the maximum likelihood (ML) criterion, one would estimate that the record in data set two that most closely resembles record one of data set one is the most reliable. By ML criterion record three would be selected because its AØ and A4 parameters are the closest match to record one of the first data set. In this scheme there is no filtering on preset AØ or A4 limits. If the lowest level of AØ and A4 were the reliabilty criterion, record one of the second data set would have been selected as the best estimate. The advantage of the ML criterion is that it is a "use what works" technique. The deductive approach of analysis of the system and errors is discarded because it is too complicated. Instead, the inductive technique of observing and classifying provides the more attractive approach in this case.

To use the ML criterion with the SWRI data files one must expand upon the ideas presented in the example. Define two matrices, a bearing acceptable and a bearing unacceptable matrix. Each matrix is three dimensional; a dimension is allotted to AØ, one to Phase and the third to A4. This spans all the information in a data record. AØ is a measure of the horizontal field component; Phase is a measure of polarization; and, A4 is a measure of system inconsistency. These three measures are not sufficient to completely specify system performance; in fact, they are not sufficient to completely specify the horizontal field component, polarization or system inconsistency. They are what is available. Each dimension is divided into ten increments. The AØ and A4 dimension values are between Ø and 1.Ø in increments of Ø.1 . The Phase dimension is between -18Ø and +18Ø in increments of 36 degrees. The structure of both matrices can be sketched as:



The matrices are defined to be expressions of the conditional probability mass. They are created by using a file or files of data on a target of known position. Knowing the true bearing permits one to address either the bearing acceptable or bearing unacceptable matrix. Further explanation is best presented using an example. The following records are available from a data set with a true bearing known to be 337 deg:

Record #	AØ	Phase (deg)	A4	Bearing (deg)
1	Ø.911	-43	Ø.621	286
2	Ø.813	-64	Ø.518	273
3	Ø.517	12Ø	Ø.231	357
4	Ø.342	72	Ø.185	34Ø

All the elements of the bearing acceptable and unacceptable matrices are initialized at zero. The criterion for placement in one matrix or the other is the value of the bearing. A window about the true bearing is defined. If the window is defined as 10 degrees, a bearing is acceptable if it is within 5 degrees either side of the true bearing. Each record in a file is examined. Record number one is unacceptable because the bearing value is not in the 332-342 deg window. Therefore, its A0, Phase and A4 values are mapped into increments along the respective dimensions of the unacceptable matrix, thereby addressing one of the elements of the matrix. A one is added to the contents of this element. Each record in turn is examined .and a one is added either to an element in the bearing acceptable or the bearing unacceptable matrix. (Record number four is an example of a record that would apply to the bearing acceptable matrix.) After all records have been processed, each element in the bearing acceptable matrix is divided by the number of records that contributed to that matrix. Similarly, the elements of the bearing unacceptable matrix are divided by the number of records that contributed to it. This produces an expression of conditional probability. If a bearing is acceptable, the probability of it having a particular A0, Phase and A4 value is equal to the value in the acceptable matrix addressed by the given A0, Phase and A4 values. Likewise, if a bearing is unacceptable, the probabilities of its A0, Phase and A4 values can be read from the element addressed by those values.

The acceptable and unacceptable matrices are constructed from data on a located target. If one processes a file of data on an unknown target, the matrices are used as follows. Using the A2, Phase and A4 values to address both of the matrices, the element values of the matrices are compared. Suppose the value from the acceptable matrix is 0.211, and from the unacceptable matrix, it is 0.097. The ML criterion makes the decision for the matrix with the highest probability (maximum likelihood). 0.211 is the highest value; therefore, the decision is that the bearing is acceptable.

The requirement to address two matrices and compare the returned values can be eliminated by forming a single likelihood ratio matrix. This matrix is constructed by dividing each element of the bearing acceptable matrix by the corresponding element of the bearing unacceptable matrix. The decision can be made on a single element of the likelihood ratio matrix (also simply called likelihood matrix or denoted as [L]). In the example above, the ratio of the two values is 2.175. The decision is that a bearing is acceptable if the addressed element of the likelihood matrix is greater than or equal to one. If less than one, the bearing is unacceptable.

The above ideas can be set into mathematical notation as follows. Matrices are denoted with brackets. The elements of a matrix are indexed with i,j,k in the general case.

[A] : bearing acceptable matrix
[U] : bearing unacceptable matrix
[A (i,j,k)] = [A (AØ,Phase,A4)]
[U (i,j,k)] = [U (AØ,Phase,A4)]
Na = number of records tabulated in [A]
Nu = number of records tabulated in [U]
Na + Nu = (10000) X (number of files used)

The probability mass matrices are:

[Pa] = (1/Na)[A]
[Pu] = (1/Nu)[U]

The maximum likelihood (ML) criterion can be used to decide the acceptability of a bearing.

Let the record be $\{A0=\alpha_0, Phase=\beta_0, A4=\gamma_0, Bo\}$, then,

$$A_{\alpha_0 \beta_0 \gamma_0} \underset{D1}{\overset{D2}{\gtrless}} U_{\alpha_0 \beta_0 \gamma_0}$$

where, the decisions D1 and D2 are,

D2: Bearing is acceptable

D1: Bearing is unacceptable

If A > U, the decision is D2; if A < U, the decision is D1.

This comparison process can be simplified and at the same time be made more flexible by defining a likelihood ratio matrix [L]:

$$[L] = [Pa] \oplus [Pu]$$

where the symbol ($\oplus$) means to divide each element of the matrix [Pa] only by its i,j,k counterpart in [Pu]. (Define $x/0$ = infinity.)

The ML criterion can be rewritten as:

$$[L] \underset{D1}{\overset{D2}{\gtrless}} [1] \qquad [1] = 10x10x10 \text{ matrix of 1's}$$

or

$$L_{\alpha_0 \beta_0 \gamma_0} \underset{D1}{\overset{D2}{\gtrless}} 1$$

The above idea can be extended to the Minimum Probability of Error (MPE) and the Bayes Cost (BC) criteria straightforwardly:

$$[L] \underset{D1}{\overset{D2}{\gtrless}} \left[\frac{P\{B \text{ acceptable}\}}{P\{B \text{ unacceptable}\}} \right]$$

$$[L] \underset{D1}{\overset{D2}{\gtrless}} \left[\frac{(C_{21} - C_{11})}{(C_{12} - C_{22})} \quad \frac{P\{B \text{ acc}\}}{P\{B \text{ unacc}\}} \right]$$

C_{21} : cost of deciding acceptable when unacceptable
C_{11} : cost of deciding unacceptable when acceptable
C_{12} : cost of deciding unacceptable when unacceptable
C_{22} : cost of deciding acceptable when acceptable

The terms on the right side of the decision symbols are matrices. The ratio of P{Bacceptable} to P{Bunacceptable} must be determined separately for each element of the matrix.

The same will probably be true for the Bayesian costs. The MPE and BC criteria are more sophisticated and will probably yield better results, but data limitation prevented further investigation. Very large amounts of data would be needed to determine probability ratios for each element of a 10x10x10 matrix. It would also require a operational input for a realistic assessment of Bayesian costs.

Using the above concepts, the FORTRAN program LMAT was written to produce the likelihood ratio matrices [L] from individual files and from groups of files. Testing of the method centered on the 15 MHz files because they are the most numerous for a single frequency (three files). An L matrix was created from file 3 for two separate definitions of "bearing acceptable". The first, denoted L[3,90], considered the bearing acceptable window to be ninety degrees wide. The second, L[3,20], used a twenty degree window to construct the matrix.

Using the L matrices, several data files were processed employing the program LFILE (L matrix modified FILE). This program reads the A0, Phase and A4 term of each record and uses them to address the L matrix. If the element addressed is greater than one, the bearing in that record is considered acceptable, and the record is written into a new data file with a new A4 term equal to 0.01. Only the A4 term is changed. The new data file is subsequently processed by DFERR which will always treat an acceptable bearing (A4=0.01) as valid for statistical processing. If the L matrix element addressed is less that one, the bearing is unacceptable and assigned the A4 value 10.0 in the new data file. DFERR will reject any bearing with this large A4 value.

The file of interest is the 1980 15 MHz file. Figure 35 is the result of simple DFERR processing on this file; figure 36 is the histogram of the bearing error. Several examples of L matrix processing on this file are graphed in figures 37, 39 and 41. The explanation of these graphs is identical to the explanation given in the previous section. It will be noted ,however, that the graphs are labelled with the L matrix notation. The A4MAX term is not applicable. Each graph has an accompaning histogram of the bearing error. Figure 37 is the file processed by an L matrix made from the file itself. Figure 39 is the file processed by an L matrix created from a 1979 file at the same frequency. Figure 41 is the file processed by an L matrix created from four 1979 WWV files at different frequencies. Not unexpectedly, the best performance is by the L matrix formed from the file itself (Fig. 37). But it is interesting to note that the L matrix created from the single file of identical frequency (Fig. 39) performed better than the matrix made up from the four files (Fig. 41). This tends to confirm frequency sensitivity in the L matrix. It may prove valuable to add a frequency dimension, making the L matrix four dimensional.

A considerable amount of processing was devoted to determine an optimum window for the likelihood matrix. No one window width outperformed other widths in all categories. The central difficulty is that one thousand elements in the L matrix must be determined. Accuracy in terms of ML for each element is a limiting process; as the number of bearings used to determine each element approaches infinity, the true ML ratio is determined. To approximate the infinite sample ML ratio within 10 percent would require very roughly 100 records per element. But some elements are rarely addressed; therefore, large amounts of data are needed to fill the L matrix. The amount of data can be estimated in a very rough way. Using four files and a ninety degree window, it was observed that about 40 percent of the matrix elements are addressed zero or one times. If the requirement is that the probability of this happening should be less than 0.001, the expression (0.4) =(0.001) determines the number (n) of sets of four files required. In this case about thirty files would be required. This corresponds to 300,000 records or 100 minutes of data. This is an easily achieved number at the antenna system development site.

The most overall successful runs were made with a ninety degree window. In table VI are the results of processing the 1980 data files with a likelihood matrix constructed from the

1979 data. The first four 1979 files were used; the fifth, a second 15 MHz file. was not included to avoid a possible dominant 15 MHz bias. The data in table VI is the variance and POB from simple DFERR processing (A4MAX=0.2) and from L matrix processing (L(1-4,90)). For the 1980 5 MHz file the variance is high in either case. Starting at 300 ms signal duration, the L matrix processing has a lower variance, and as the signal duration increases. L matrix processing is better and better compared to DFERR processing. Perhaps much more significant is that the L processing has a much higher POB. With the 1980 10 MHz file. L matrix processing is superior at every signal duration. This is also true for the 15 MHz file. This is a significant result. L matrix processing is generally superior to the A4 filter process of DFERR. In some cases the variance is halved and the POB is more than doubled. However, performance against KLC is poorer as can be seen in the table. For the shortest signal durations. the L matrix variance is higher than DFERR processing. but the two approach each other past 500 ms. The POB is slightly higher for the L matrix process.

The results in table VI are very encouraging. A matrix created from 1979 data significantly outperformed DFERR processing on the 1980 data. The poorer results for KLC are not surprising. WWV bears 337 deg from San Antonio, and KLC bears 290 deg. The antenna array which is mounted atop a horizontally girded building suffers pattern distortion due to antenna element coupling with the building. The distortion to the pattern is dependent both on the azimuth and elevation angle at which the signal arrives. In fact, the KLC results are encouraging. The fact that L matrix processing and DFERR processing results are so close suggests that azimuthal dependence is not an overiding factor. It may be possible to achieve acceptable results using L matrices created from azimuth sector data. If a first guess is that a bearing is in the sector 210 to 270, post processing could use an L matrix specifically created for that 60 degree sector. In all six L matrices would be required to cover the full azimuth.

The optimism expressed above must be tempered by the fact that the technique and the results were derived with an inductive approach. A theoretical basis with which the L matrix success could have been predicted was not derived. L matrix success was observed, not predicted. Confidence that the technique is functional in the general case will require observation in situations where frequency, azimuth, SNR, vertical angle of arrival, polarization, shipboard siting and propagation modes are varied.

TABLE VI

Comparison of DFERR and L Matrix Processing

For all DFERR processing, A4MAX=0.2. For all L matrix processing, the L matrix is L(1-4.90).

Signal Duration in milliseconds:

	100	200	300	400	500	600	700	800	900	1000
				WWV 5 MHz 20:40 2/6/80						
STD										
DFERR	57	59	58	59	59	63	61	58	62	55
LMAT	62	62	54	49	46	40	40	36	36	35
POB										
DFERR	.11	.33	.52	.65	.77	.83	.94	.91	.95	.98
LMAT	.64	.93	.99	1	1	1	1	1	1	1
				WWV 10 MHz 7:10 2/5/80						
STD										
DFERR	30	29	25	21	18	17	13	16	10	11
LMAT	29	23	16	10	11	8	7	9	5	6
POB										
DFERR	.73	.90	.95	.97	.99	.99	1	1	1	1
LMAT	.90	.97	.99	1	1	1	1	1	1	1
				WWV 15 MHz 9:00 2/5/80						
STD										
DFERR	16	16	14	12	13	11	9	9	9	9
LMAT	13	13	13	10	9	10	9	10	10	9
POB										
DFERR	.83	.86	.87	.88	.89	.89	.90	.90	.91	
LMAT	.81	.86	.88	.90	.91	.91	.92	.93	.94	
				KLC 8.666 MHz 8:15 2/7/80						
STD										
DFERR	17	19	16	16	14	14	11	15	10	10
LMAT	23	20	22	20	18	17	12	11	14	8
POB										
DFERR	.22	.35	.40	.43	.46	.47	.48	.50	.50	.54
LMAT	.26	.38	.42	.46	.48	.48	.50	.52	.52	.56

Figure 35

WWV 15 MHz 2/80 Short Signal Duration A4MAX=0.2

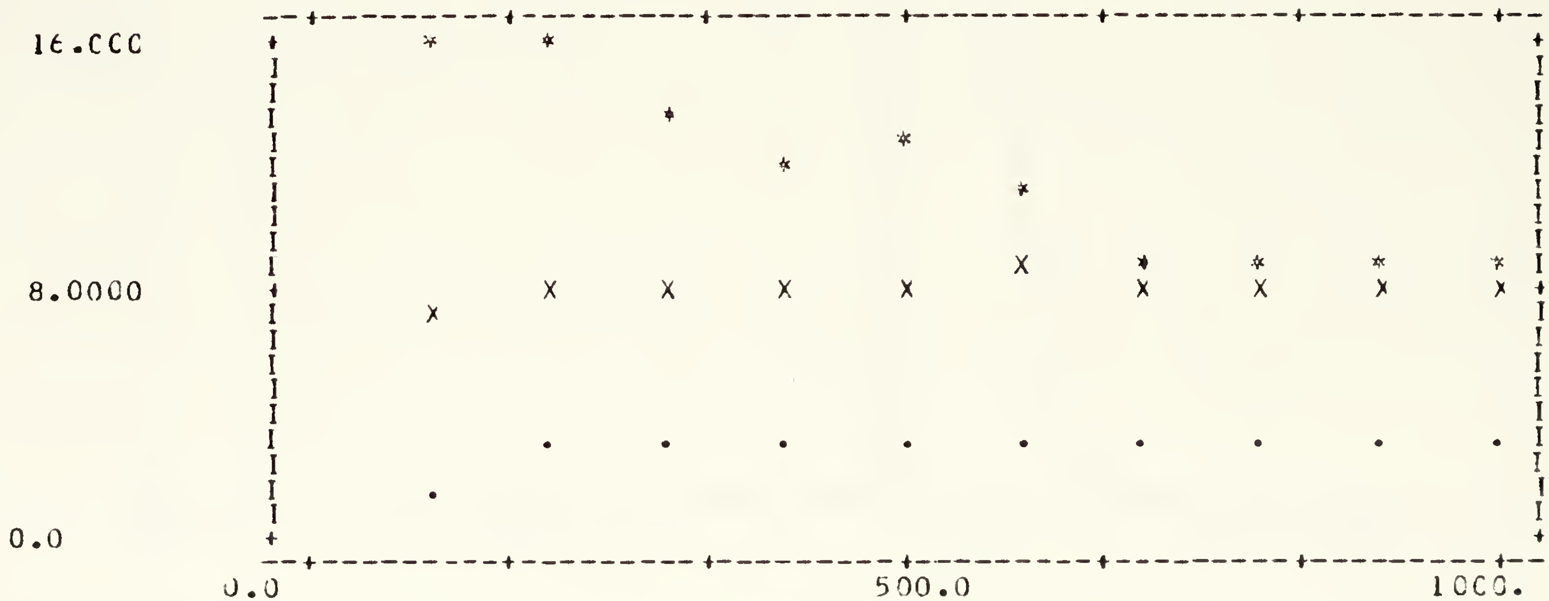
$\overline{B}=346.4$

$\sigma_B=10.7$

$\varepsilon=9.4$

SOURCE: WWV 15M 9:00 2/80 A4MAX=0.2

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.831	0.859	0.871	0.878	0.885	0.895	0.895	0.904	0.896	0.910
X :	7.	8.	8.	8.	8.	9.	8.	8.	8.	8.
* :	16.	16.	14.	12.	13.	11.	9.	9.	9.	9.
. :	2.	3.	3.	3.	3.	3.	3.	3.	3.	3.

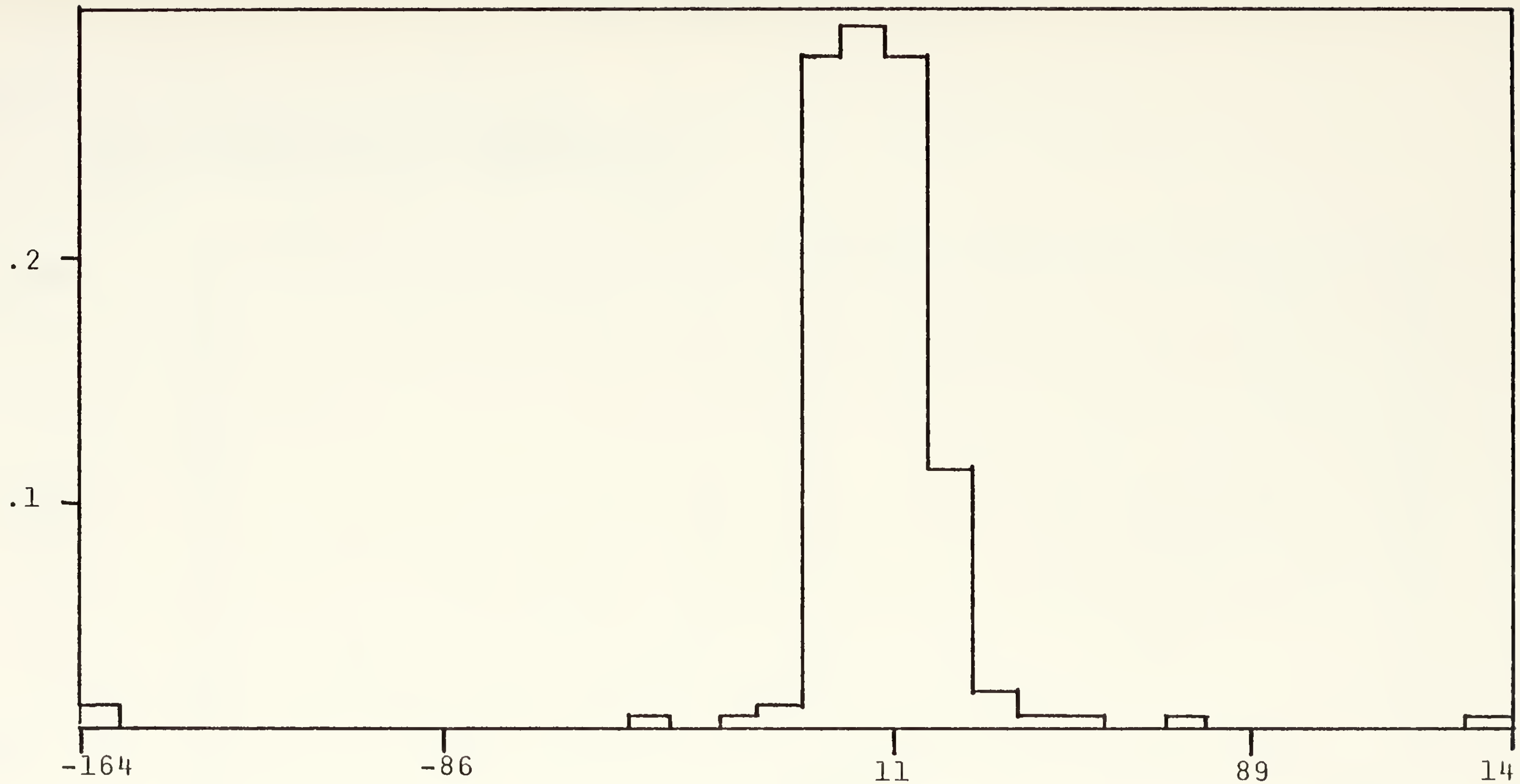


Figure 36

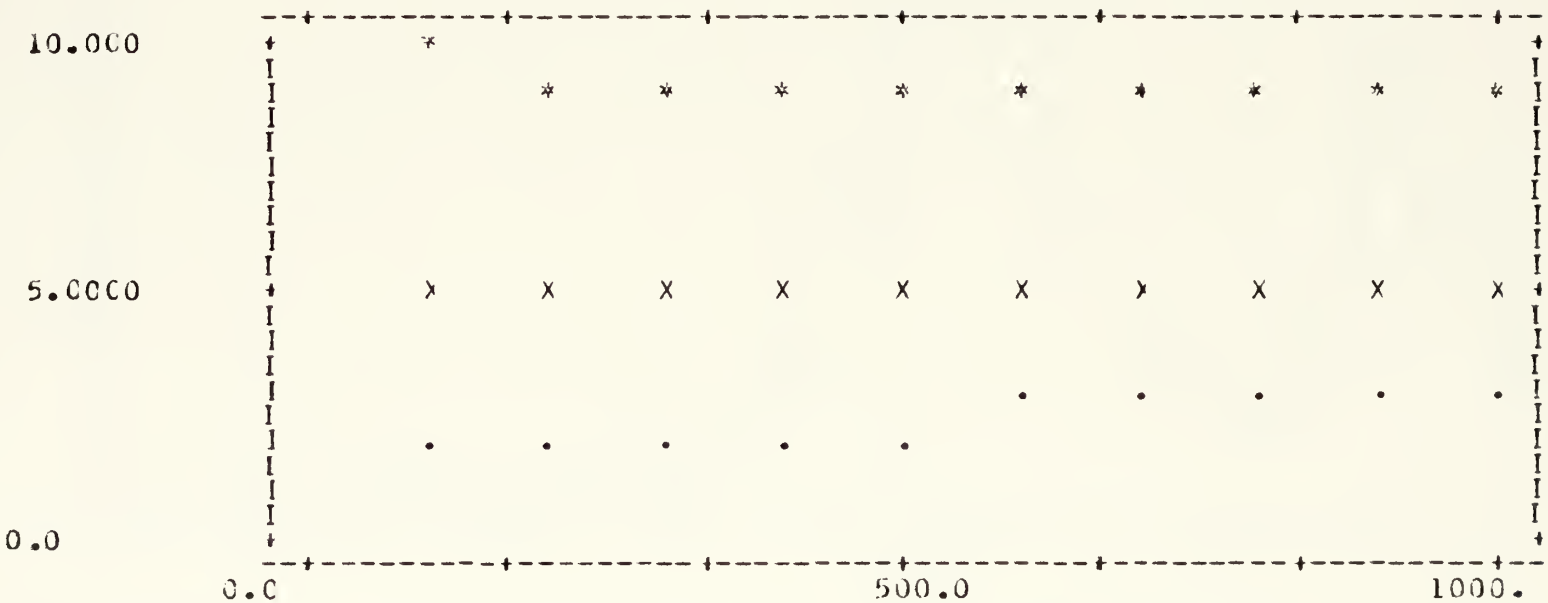
WWV 15 MHz 2/80 Bearing Error Histogram A4MAX=0.2

Figure 37

WWV 15 MHz 2/80 L(12,90)

SOURCE: WWV 15M S:CC 2/80 L(12,90)

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.914	0.923	0.923	0.924	0.925	0.925	0.926	0.924	0.928	0.930
X :	5.	5.	5.	5.	5.	5.	5.	5.	5.	5.
* :	10.	9.	9.	9.	9.	9.	9.	9.	9.	9.
. :	2.	2.	2.	2.	2.	3.	3.	3.	3.	3.

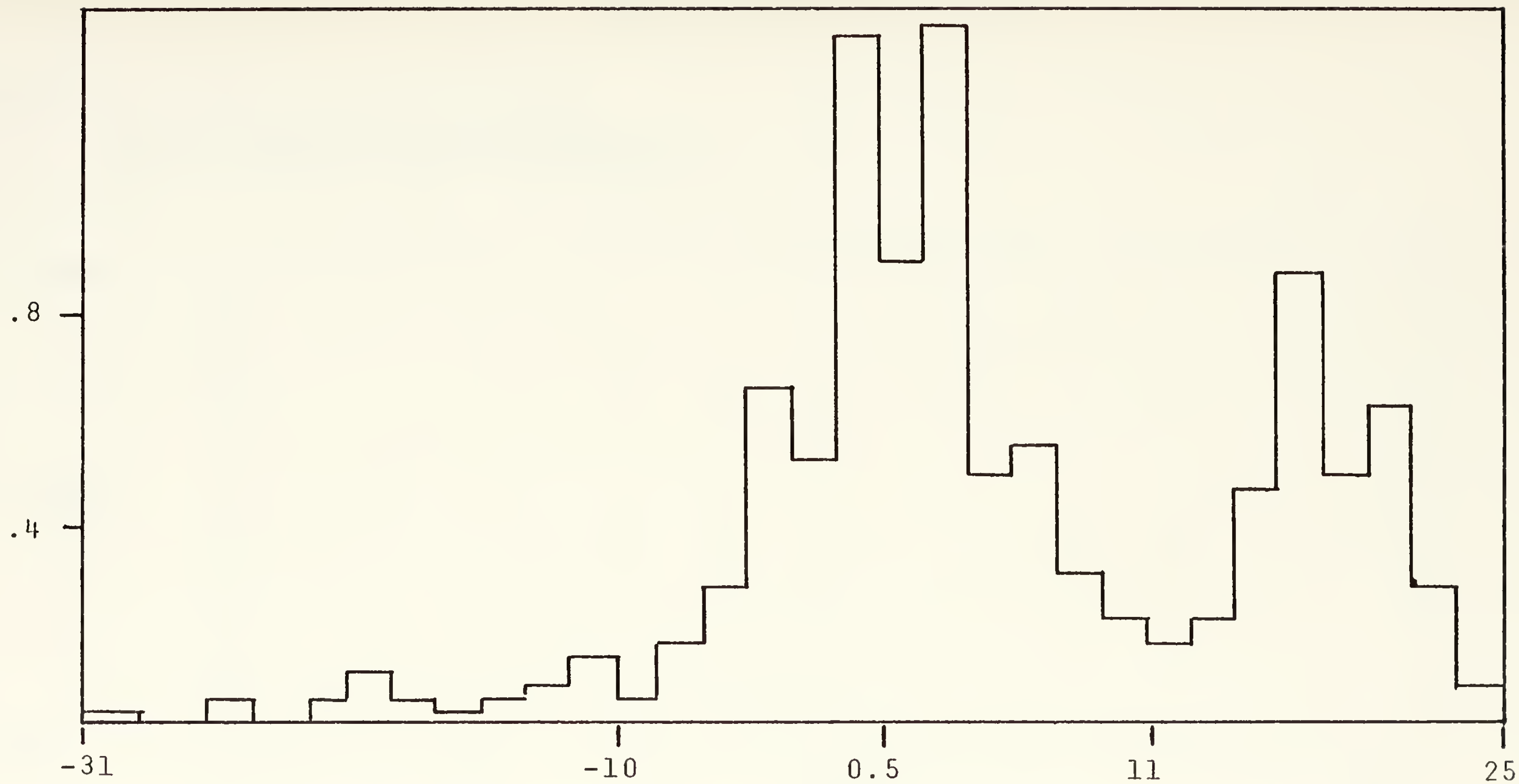


Figure 38

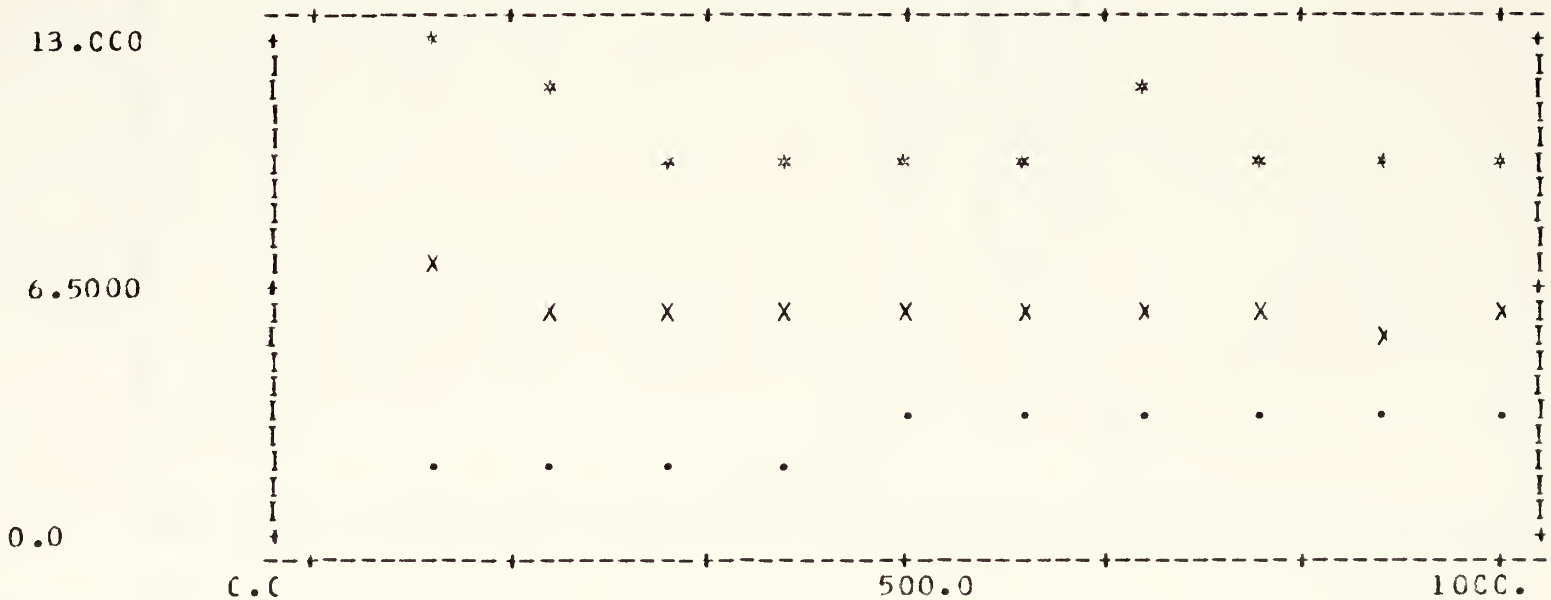
WWV 15 MHz 2/80 L(12,90) Bearing Error Histogram

Figure 39

WWV 15 MHz 2/80 L(3,90)

SOURCE: WWV 15M S:00 2/80 L(3,90)

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	100.	200.	300.	400.	500.	600.	700.	800.	900.	1000.
PROBABILITY OF : OBTAINING LOB	0.693	0.791	0.838	0.852	0.870	0.883	0.891	0.896	0.905	0.900
X :	7.	6.	6.	6.	6.	6.	6.	6.	5.	6.
* :	13.	12.	10.	10.	10.	10.	12.	10.	10.	10.
. :	2.	2.	2.	2.	3.	3.	3.	3.	3.	3.

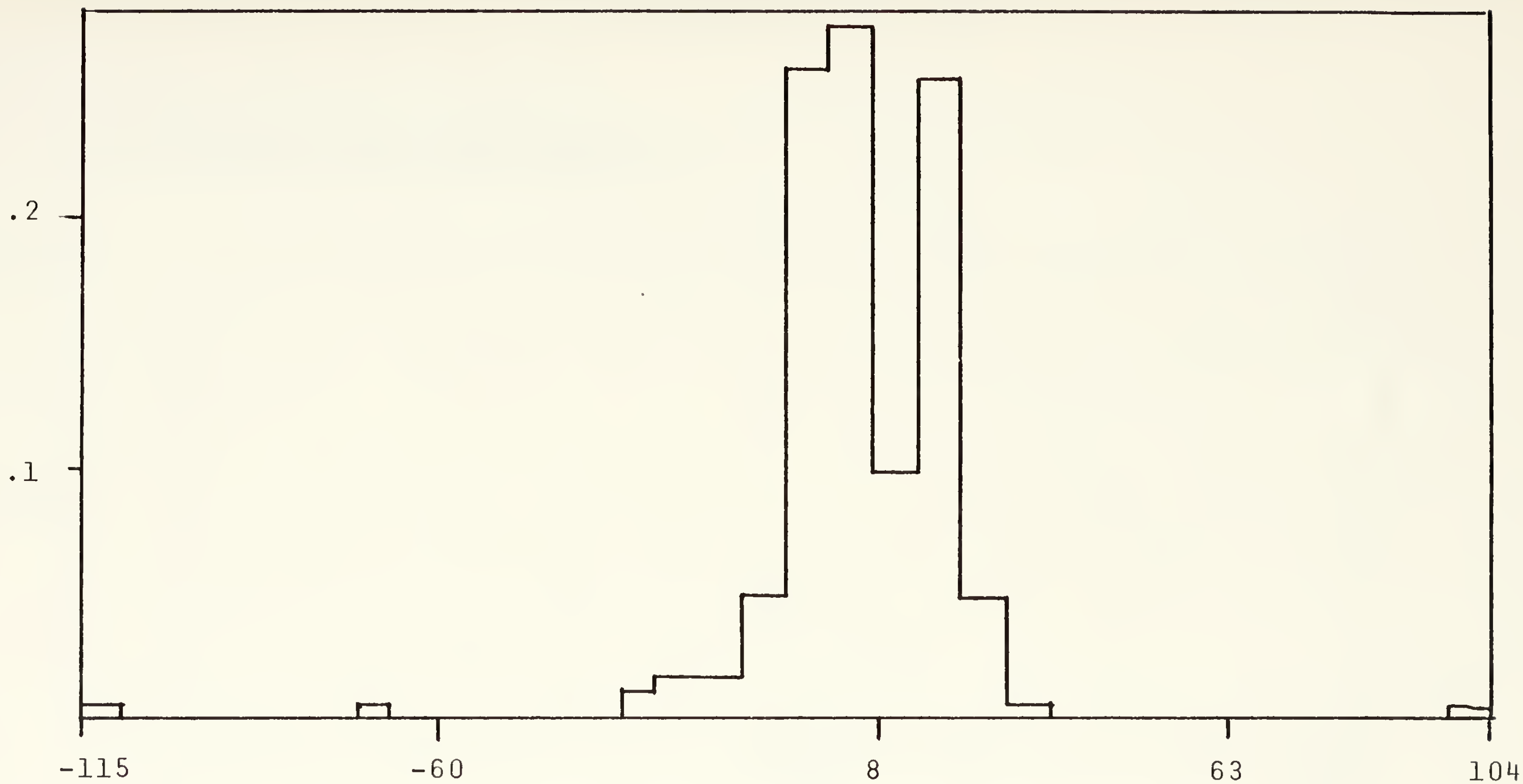


Figure 40

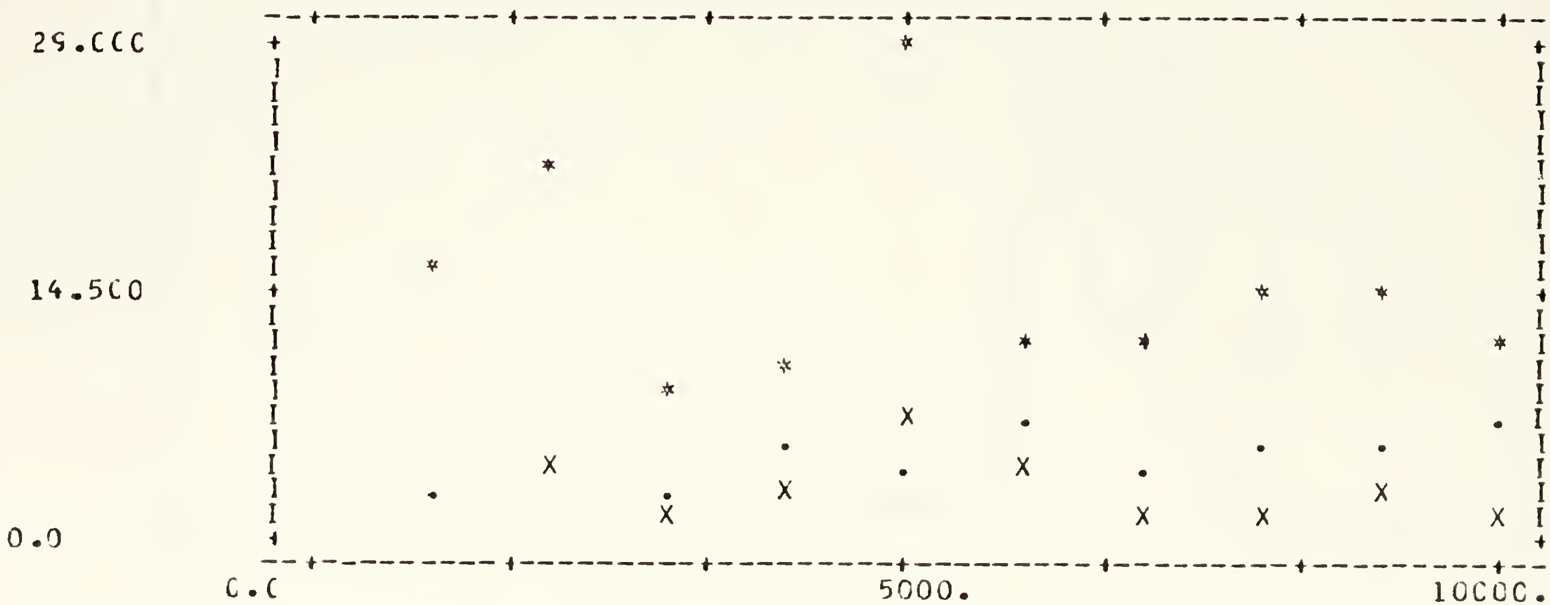
WWV 15 MHz 2/80 L(3,90) Bearing Error Histogram

Figure 41

WWV 15 MHz 2/80 L(1-4,90)

SOURCE: WWV 15M 9:00 2/80 L(1-4,90)

AVE BEARING ERROR (DEGREES) : X
STD OF BEARING ERROR (DEGREES) : *
AVE OF INTRA-SIGNAL STD (DEGREES) : .



SIGNAL DURATION: (MILLISECONDS)	1000.	2000.	3000.	4000.	5000.	6000.	7000.	8000.	9000.	10000.
PROBABILITY OF : OBTAINING LOB	0.605	0.670	0.682	0.700	0.750	0.758	0.786	0.800	0.818	0.800
X :	3.	5.	1.	3.	7.	4.	2.	2.	3.	2.
* :	16.	22.	9.	10.	29.	11.	11.	14.	14.	11.
. :	3.	4.	3.	6.	4.	7.	5.	6.	6.	7.

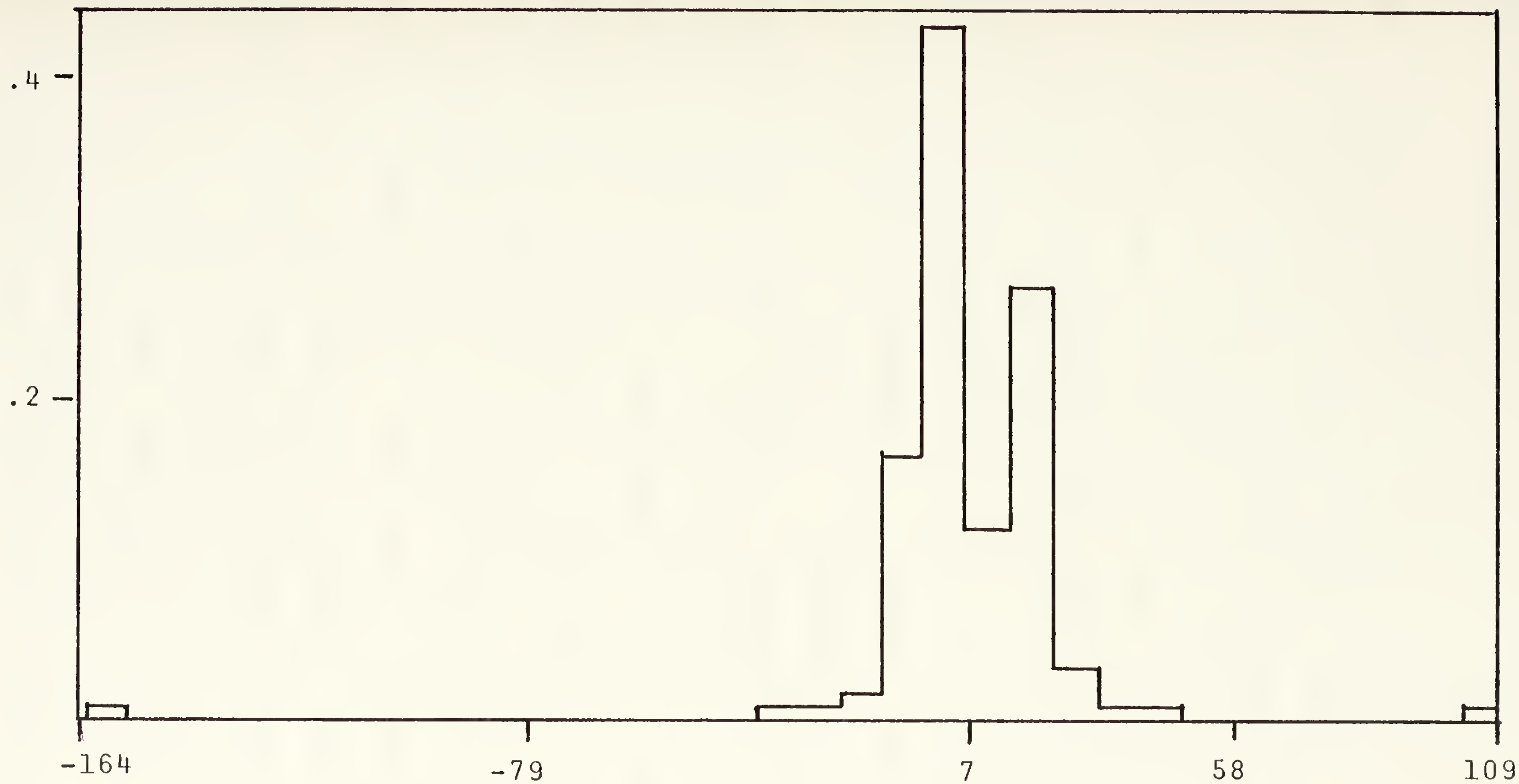


Figure 42

WWV 15 MHz 2/80 L(1-4,90) Bearing Error Histogram

D. AMBIGUITY RESOLUTION

The histograms of the average bearing error demonstrate one of the difficulties with the SWPI spaced loop antenna system in trying to DF short duration signals. It can be seen by looking at the histograms that there are bearing error numbers that cluster in relatively large values at points of 180 and 90 degree ambiguity. This corresponds to the antenna system deciding on the wrong null in the antenna array pattern. The severity with which this can affect the calculated variance is graphed in figure 43. This graph, plotted from an equation developed in appendix B, demonstrates that a small number of ambiguities have a very significant effect on the variance. The graph assumes 1000 bearings constitute the total sample. All the ambiguities are at 180 degrees. The abscissa is the number of 180 degree ambiguities. The ordinate is the ratio of the new variance to the old variance which is set at twenty degrees squared. If, for example, there are ten 180 degree ambiguities in the original sample and they are removed, the new standard deviation will be less than ten degrees squared. In the case of many small sets representing short duration signals, evaluated separately, the reduction in variance will be larger than that predicted in figure 43.

To examine the effect of removing the ambiguities from the

SWRI data files, a FORTRAN program AMBIG was written to set the A4 value to 10.0 for every record which is within a narrow window about the 90 and 180 degree ambiguities. Setting the A4 to such a large value permitted the use of the DFERR program which automatically rejects records with such a high A4 term. This test was run on several data files and the results are displayed in figures 44 and 45. It can be seen that sharp decreases in variance occur, serving to make the bearing estimate more reliable.

The resolution of ambiguities with narrow aperture systems is a difficult problem. The algorithms are especially sensitive to vertical angle of arrival, low SNR and multimode propagation. Time averaging, if the signal is sufficiently long, can overcome multimode propagation, but vertical angle of arrival is very dependent on array geometry, and SNR is often totally uncontrollable. The spaced loop array ambiguity problem may be due to equipment errors, but it is more likely that the physical limitation of the aperture is the primary difficulty. The aperture is insufficient to sense wavefront distortions or to sharply isolate pattern nulls. In the case of burst communications, time averaging is impossible. The narrow aperture array must be assisted by wide aperture elements to work against short duration signals. If a spaced loop array is mounted aboard a naval vessel, it may be possible to add a simple loop element at the bow and stern and two amidships. This simple cross shaped interferometer array would be medium aperture. By itself it would not provide reliable HFDF, but it could improve the reliability of the narrow aperture system by sensing wavefront distortions and providing deep, well defined nulls to resolve ambiguities.

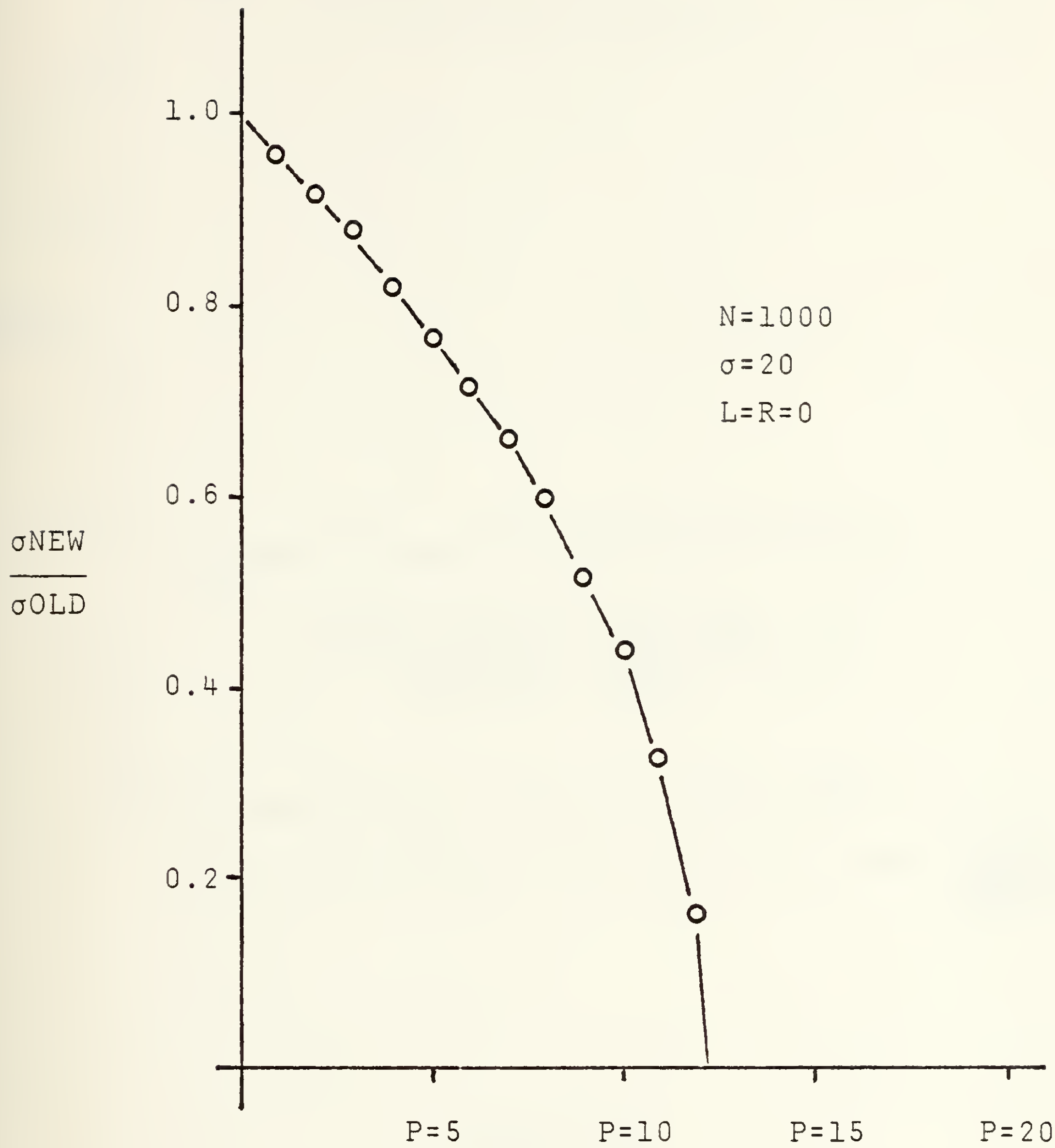


Figure 43

Ambiguity Suppression Curve

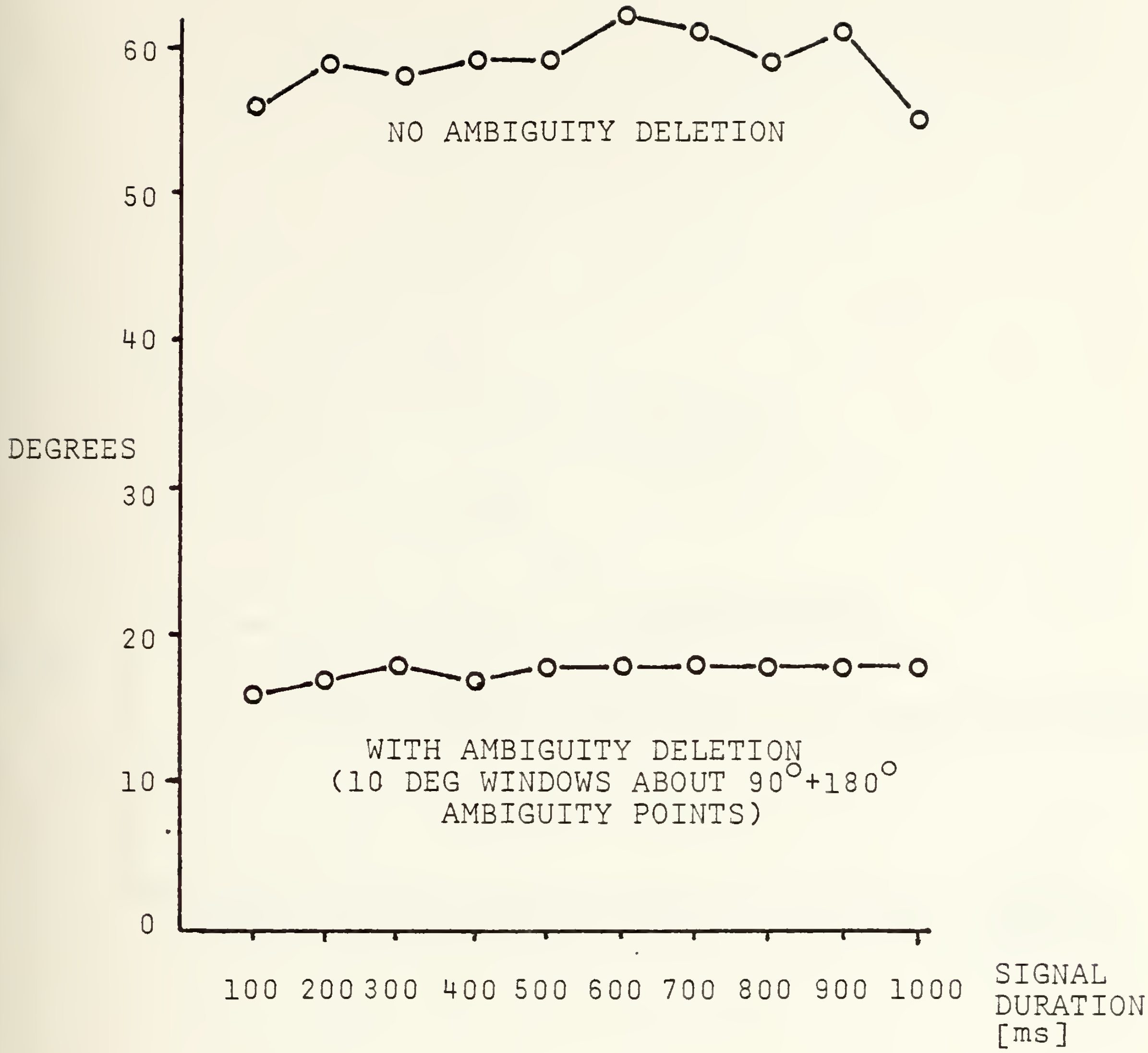


Figure 44

Ambiguity Suppression for WWV 5 MHz 2/80

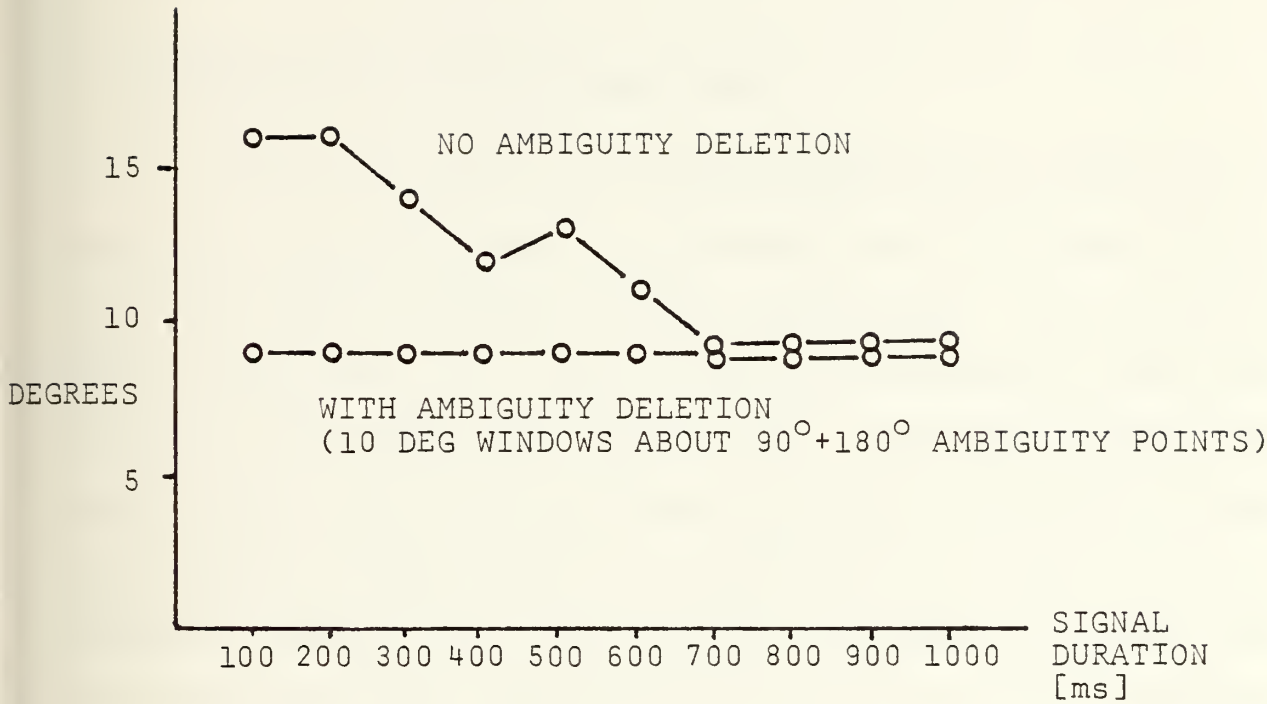


Figure 45

Ambiguity Suppression For WWV 15 MHz 2/80

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Performance and the Ionosphere.

The narrow aperture antenna is physically incapable of spatially sensing phase or amplitude wavefront distortions that have spatial periods of many wavelengths. This inherent disadvantage must be overcome by time averaging. Under the assumption that wavefront distortions fluctuate about the undistorted wavefront (the mean wavefront), the minimum time necessary to average out the distortions is equal to the longest period of the primary phenomena causing the distortion. The most severe distortions occur with multimode interference when two or more rays are comparable in amplitude. In this case the time required to average out the fluctuations is the fading period of the major spectral component of the fading power spectrum, roughly on the order of ten seconds for an HF signal. This means that a narrow aperture antenna cannot reliably determine the direction of arrival of a burst transmission in the presence of severe multimode interference. As the severity of distortion is reduced, the reliability of DF is improved. In the case of the SWRI spaced loop HFDF system, the range of standard deviation for the 200 ms signals studied here is from 15 degrees for signals sysnthesized from data in file 4 to 59 degrees for signals synthesized from data in file 10. The average standard deviation over the nine data files is 29.1 degrees. These data files are believed to include both multimode and single mode signals and signals with high and low SNR's.

2. Performance Specifications

The performance of a narrow aperture HFDF system against short duration signals is very dependent on ionospheric propagation. Therefore, the performance of the system cannot be specified separately from specifications on the state of the ionosphere. To state that a system must perform with a given standard deviation of bearing error during quiet ionospheric conditions with single mode propagation is much different from requiring the same standard deviation of bearing error during disturbed ionospheric conditions or with multimode propagation.

3. Fading and Bearing Reliability

There are several sources of fading in ionospheric propagation; however, fading can be considered a good measure of the distortion of local constant phase and constant amplitude wavefronts. If fading is severe, on the order of 20 db, one can be confident that significant distortion is occurring to the wavefront and that narrow aperture derived DF bearings on short duration signals will be generally unreliable.

4. Likelihood Ratio Matrix

The concept of using a likelihood matrix developed from given, reliable data to make a binary (acceptable or not acceptable) decision on a random data set has not been fully explored. However, the results from the limited processing are very encouraging. It should prove possible to develop appropriately sized and numbered L matrices capable of significantly outperforming algorithms based only on filtering by parameter limits.

5. Ambiguity Elimination

The filtering to eliminate 90 and 180 degree ambiguities demonstrated that a significant reduction in bearing variance can be accomplished if the source of the ambiguities can be corrected. It is doubtful, however, that the correction can be accomplished without the introduction of supportive medium aperture interferometer elements.

B. RECOMMENDATIONS

1. Use of All Ionospheric Data

HFDF with narrow aperture antennas on short duration signals must maximize the use of as much real time information as possible on the ionosphere. Evaluation of the vertical angle of arrival and polarization is needed to help determine if a ground wave or a skywave burst transmission is being received. The vertical angle of arrival will further permit an estimate of range. The range and vertical angle of arrival information should be used with a propagation prediction program to make an overall evaluation of the reliability of a calculated bearing based on predicted ionospheric induced bearing variance. To improve the propagation prediction program, real time measurements of ionospheric parameters are needed. This could be accomplished by updated inputs of geophysical data, shipboard ionospheric sounders, solar observations, data derived from satellite beacons and the use of geographically fixed transmitters as beacons. The provision of this information will probably not permit the calculation of a more accurate bearing, but it will help to determine the reliability of the bearing (the variance of the bearing).

2. Use of All Signal Parameter Data

Various receiver parameters, especially the AGC voltage, should be monitored to estimate the fading of a signal. A large variation of the AGC voltage could signify fading and somewhat reduce the confidence in the calculated bearing. A small variation in the AGC voltage would be inconclusive.

3. Detailed Performance Specifications

The specifications for the required performance of a narrow aperture antenna system must include the ionospheric conditions under which performance is to be measured. An example specification is that a system must have an average bearing error of five degrees and a standard deviation that encompasses at least 67 percent of the data when the signal is received in the 20 meter band via a predominantly one hop propagation path. The signal power of other propagation modes should be 30 db below the primary mode, and the SNR against background noise should be at least 12 db. To conduct such measurements aboard a ship may require that the ship be positioned close to a wide aperture array that would be able to resolve the local mode structure of a known target transmitter's signal.

4. Likelihood Ratio Matrix Technique

Though the results of using the probabalistic likelihood matrix were were not totally conclusive, it is recommended that this approach be further investigated. The strong appeal of the likelihood matrix approach is the maximum use of information in an imprecisely known and imprecisely knowable environment. Further investigation should include the following areas. Optimize the dimensions of the likelihood matrix, perhaps eliminating the phase dimension. Define the likelihood matrix in terms of the minimum probability of error criterion instead of the maximum likelihood criterion. Define the likelihood matrix in terms of Bayesian costs and compare the results with those of maximum likelihood and minimum probability of error. Determine the frequency, SNR and fading sensitivies of the likelihood matrix. Of greatest value and greatest difficulty would be a general theoretical development of the likelihood matrix in terms of the spaced loop system parameters. It may prove to be the case that the likelihood matrix could concisely store calibration data. This could be calibration in azimuth, elevation, polarization, frequency and SNR, all in a finite number of likelihood matrices. Using the measurements of frequency and SNR and the estimates of azimuth, elevation and polarization, a stored likelihood matrix would postprocess system data to refine the bearing estimate.

5. Ambiguity Diagnostic Algorithm

There is a need to develop a diagnostic algorithm that will use a known, fixed transmitter to tabulate ambiguity errors as a check of system sensitivity and of the phase sensing elements, particularily the phasemeter.

6. Medium Aperture Aid

The spaced loop array does not provide reliable data for various important tactical situations. The variance associated with a burst signal bearing is too large for most fix and targeting algorithms. To improve performance, the feasibility of adding a simple medium aperture interferometer should be investigated.

APPENDIX A

AVERAGE AND STANDARD DEVIATION CALULATIONS ON BEARINGS

The computer programs used in the analysis portion of this report computes average and standard deviation of bearings. These statistical calculations are straightforward, but not in the form generally recognized. In this report, bearings have been treated as integers in the set 0 to 359. When calculating averages of bearings that overlap the 0-359 boundary, it must be taken into account that 359 differs from 0 by only one degree. For this reason the following formulas were developed.

Assume that n bearings are available for averaging:

$B1, B2, \ldots, Bi, \ldots, Bn$

Normally the average would be calculated by:

$$B = (1/n) \sum Bi$$

Rewrite the bearings in terms of a reference bearing, B ref and a difference Δi.

$$Bi = B\,ref + \Delta i$$

Then,

$$B = (1/n) \sum (B\,ref + \Delta i) = B\,ref + (1/n) \sum \Delta i = B\,ref + \overline{\Delta}$$

Average bearing = Reference Bearing + Average Difference

It is most convenient to let B ref = 0; then,

$$\bar{B} = \bar{\Delta}$$

However, the greatest difference allowed in a closed set 0 to 359 is 180; therefore, max = 180, and the conditional definition is:

$$\Delta i = Bi \quad \text{if} \quad Bi < 180$$

$$\Delta i = Bi - 360 \quad \text{if} \quad Bi > 180$$

Now the average formula can be written:

$$B = (1/n)\sum \Delta i$$

subject to the conditional definition of , which is easily implemented in FORTRAN.

For the standard deviation, a typical formula is:

$$\sigma_B^2 = (1/n)\sum Bi^2 - (B)^2$$

Again let:

$$\Delta i = Bi \qquad 0 \leq Bi \leq 180$$

$$\Delta i = Bi - 360 \qquad 180 < Bi \leq 360$$

Then, in a like manner,

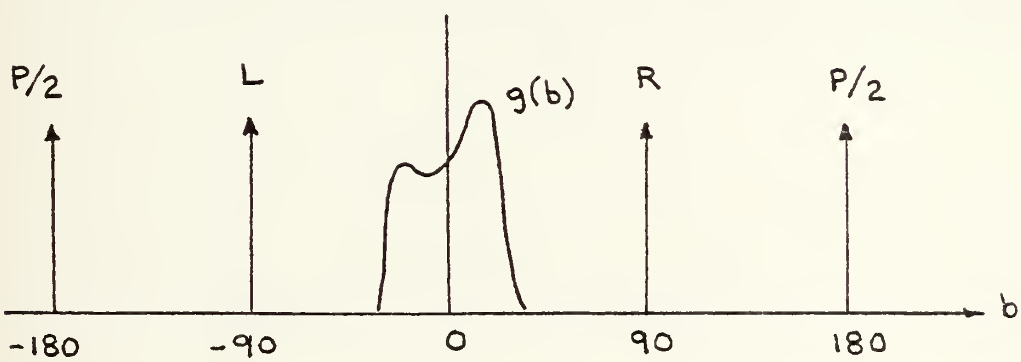
$$\sigma_B^2 = (1/n)\sum \Delta i - ((1/n)\sum \Delta i)^2$$

APPENDIX B

AMBIGUITY SUPPRESSION VARIANCE EQUATION

In the analysis portion of this report, the results of suppressing 90 and 180 degree ambiguities from a bearing data set were discussed. The equation used to describe the significance of ambiguity suppression is derived in this appendix.

Assume that a histogram of bearing errors closely approximates the probabiltiy density function p(b), where p(b) is sketched as:



The delta functions represent that portion of the histogram due to ambiguities. The function g(b) is general; the only restriction associated with it are that the origin of the b axis coincide with the mean of g(b) and that g(b) be wide compared with the distribution of the ambiguities.

One writes p(b) as:

$$p(b) = g(b) + (P/2)\delta(b+180) + L\delta(b+90) + R\delta(b-90) + (P/2)\delta(b-180) \quad (1)$$

Using $\int p(b)\,db = 1$

and $\int g(b)\,db + P + L + R = 1$

then $\int g(b)\,db = 1 - (P + L + R) \quad (2)$

The variance of $p(b)$ is:

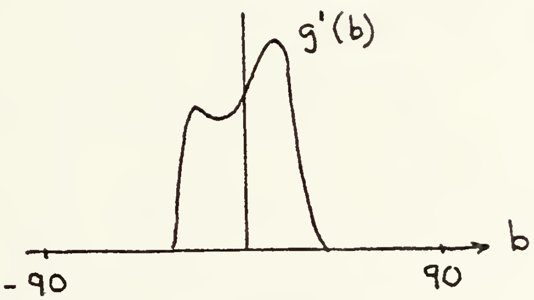
$$VAR[B] = \int b^2 p(b)\,db - \left[\int b\, p(b)\,db\right]^2$$

$$\int b\, p(b)\,db = \int b\, g(b)\,db + (P)(180)^2 + (L+R)(90)^2$$

$$\int b\, p(b)\,db = 0 + (L)(-90) + (R)(90) = (R-L)(90)$$

$$VAR[B] = \int b^2 g(b)\,db + (P)(180)^2 + (L+R)(90)^2 - (R-L)^2(90)^2 \quad (3)$$

If the ambiguities are eliminated, a new pdf $g'(b)$ results.



$g'(b)$ is a scaled version of $g(b)$; therefore.

$K\, g'(b) = g(b)$ where $K < 1$

$\int g'(b)\,db = 1 \implies \int g(b)\,db = K$

combining this with (2) yields:

$K = 1 - (P + L + R) \quad (4)$

The variance of the new pdf is:

$$VAR[B'] = \int b^2 g'(b)\, db - \left[\int b\, g'(b)\, db\right]^2$$

$$\int b^2 g'(b)\, db = (1/K) \int b^2 g(b)\, db$$

$$\int b\, g'(b)\, db = 0 \quad \text{(by assumption, centered at the origin}$$

$$VAR[B'] = (1/K) \int b^2 g(b)\, db \qquad (5)$$

Substitute (5) into (3) and solve for the new variance:

$$VAR[B] = K\ VAR[B'] + (P)(180) + (L+R)(90) - (R-L)(90)$$

$$VAR[B'] = \frac{VAR[B] + ((R-L)^2 - (L+R) - 4P)(90)^2}{1 - (P + L + R)} \qquad (6)$$

Equation (6) is the expression that approximates the new variance of a general distribution when the ambiguities are eliminated. There is one condition that must be observed. Because variance is always a positive quantity, the numerator of (6) must be a positive quantity. (The denominator is quaranteed to be positive.) Therefore,

$VAR[B] + ((R-L)^2 - (L+R) - 4P)(90)^2 > 0$ which can be re-expressed as,

$$\sigma_B^2 > 90\left[4P + (L+R) - (R-L)^2\right] \qquad (7)$$

APPENDIX C

PROPHET

The data used to compile the information of Table I was provided by Mr. Bob Rose of Naval Ocean Systems Center (NOSC). The diagrams included in this appendix are some examples of the graphical output available from the ionospheric prediction program PROPHET.

Figures 46 and 49 are ray trace plots of the signal path from WWV at Boulder, Colorado, to San Antonio Texas. The necessary inputs to the program are the date, time and geophysical data. The date and time were selected to correspond with the SWRI spaced loop antenna data. The sunspot number and x-ray flux were determined from published geophysical data. The 10.7 cm flux is a number that can be determined from the sunspot number. PROPHET also requires the transmitter's location, power and gain which in the case of WWV was determined from published sources. The traces represent the signal at launch angles from 0 to 50 degrees in 5 degree increments; the traces are framed in a spatial coordinate system, altitude versus range. The receiver's location is denoted by an asterisk at the correct distance along the range axis. This distance is the great circle arc connecting the transmitter and receiver.

Refraction causes the traces to bend back to the Earth unless the launch angle is sufficiently high to permit the ray to escape the Earth. This is the case for the 50 degree launch ray in figure 46. Multimode occurs when ray traces cross each other and return to the surface at approximately the same position. In figure 49 there is a potential multimode condition at the receiver. The severity of multimode interference depends on the strengths of the multihop traces after reflection at the surface of the Earth and D layer absorption.

Figures 47 and 50 are relative power diagrams in a frequency versus 24 hour coordinate system. The curves are relative power contours. The top cuve represents the MUF, and its relative power value is -30 db. The bottom contour is the LUF, and it too has a relative power value of -30 db. As one works inward from the outer two contours, each succeeding contour is a +10 db higher than its outside neighbor. The inside contours may reach values of +10 and +20 db. The actual power received is dependent upon the transmitter power and the propagation conditions.

Plots of ionospheric induced variance are shown in figures 48 and 51. The values of variance are especially useful for direction finding work in that they are a measure of error induced by the ionosphere independent of any HFDF system. The values are calculated from empirically derived formulas. The first order effect is frequency dependent, and the second order effect is based on the Ross curve of variance as a function of range. Reference 13 is the NOSC documentation on the development of the empirical formulas. Figures 48 and 51 show that variance is typically between 1 and 2 degrees squared with occassional sharp peaks reaching 3 degrees squared for about one hour duration. The major peak at 1330Z is due to sunrise effects (terminator).

Additional information on the capabilities of PROPHET can be obtained from NOSC.

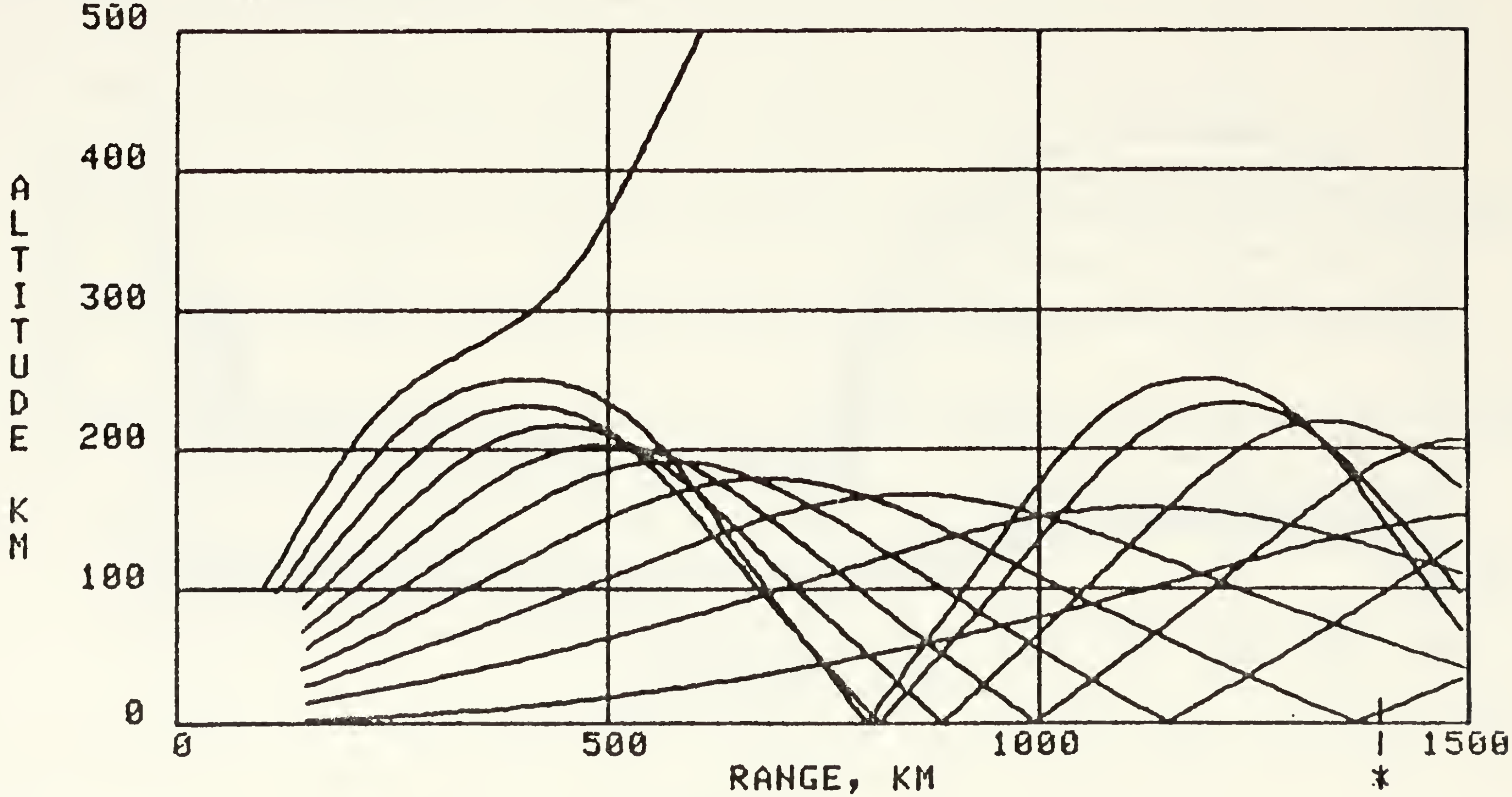
5 FEB 1980 1500Z
SUNSPOT NUMBER = 181
10.7 CM FLUX = 225
X-RAY FLUX = 1.000E-004

LAUNCH ANGLES:
MIN = 0.0 DEG
MAX = 50.0 DEG
INC = 5.0 DEG

TPM/NOSC

TRANSMITTER: BOULDER
40.8N, 105.1W
POWER = 10000 WATTS
ANTENNA GAIN = 0 dB
FREQUENCY = 15000.0 kHz

RECEIVER: SA
29.5N, 98.6W
RANGE = 1387 KM
BEARING = 152.9 DEGREES



:>

Figure 46

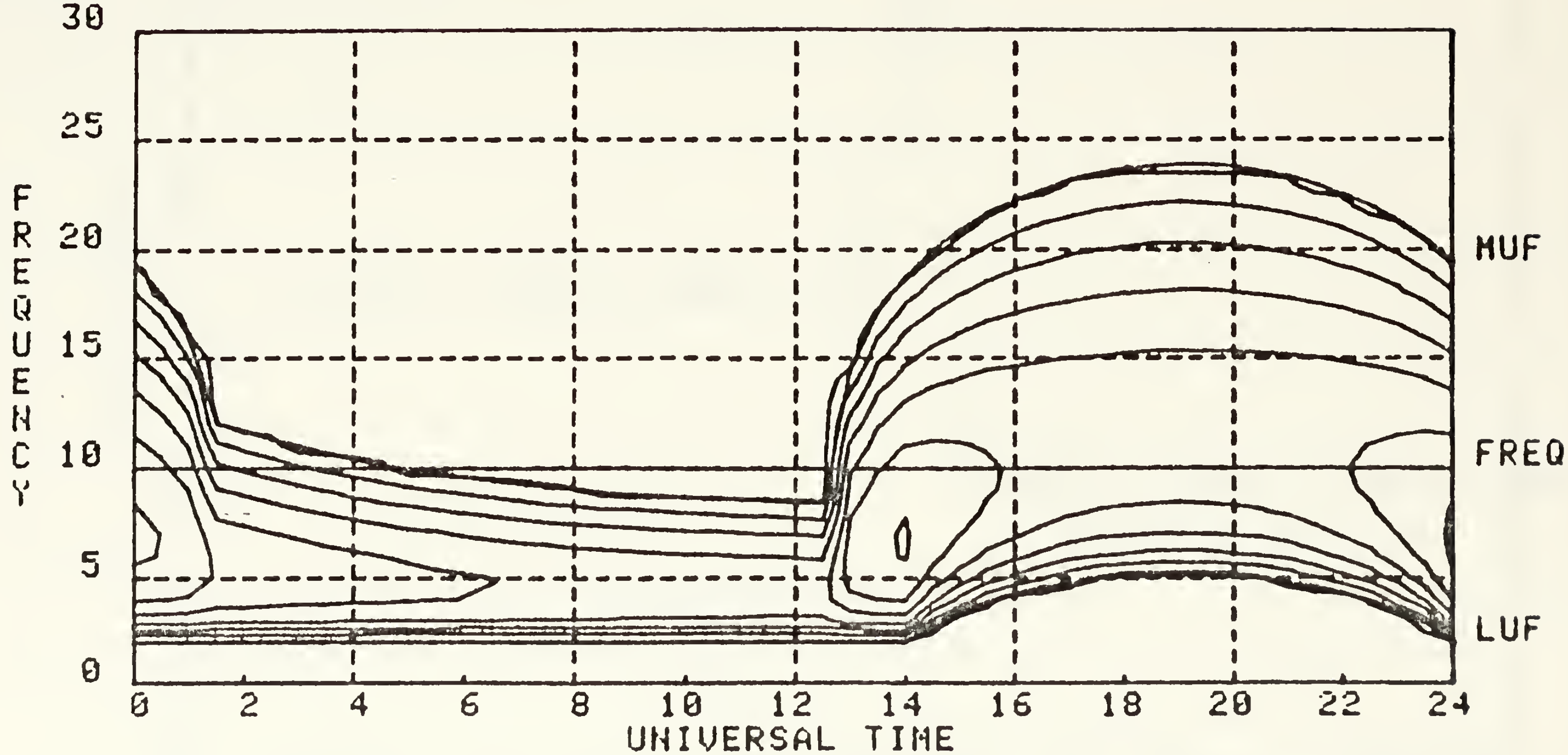
WWV 15 MHz 2/5/80 Ray Trace

TPM/NOSC

SUNSPOT NUMBER = 181
10.7 CM FLUX = 225
X-RAY FLUX = 1.000E-004

TRANSMITTER: BOULDER
40.8N, 105.1W
POWER = 10000 WATTS
ANTENNA GAIN = 0 dB
FREQUENCY = 10000.0 kHz

RECEIVER: SA
29.5N, 98.6W
RANGE = 1387 KM
BEARING = 336.6 DEGREES



:>

Figure 47

WWV 10 MHz 2/5/80 Relative Power Diagram

5 FEB 1980 [redacted] FRQ = 15000 KHZ
X-RAY FLUX = 1.00E-004 SUNSPOT # = 181
TGT: TARGET LAT = 40.80; LON = 105.10
PWR = 10000 WATTS; ANT GAIN = 0 DB

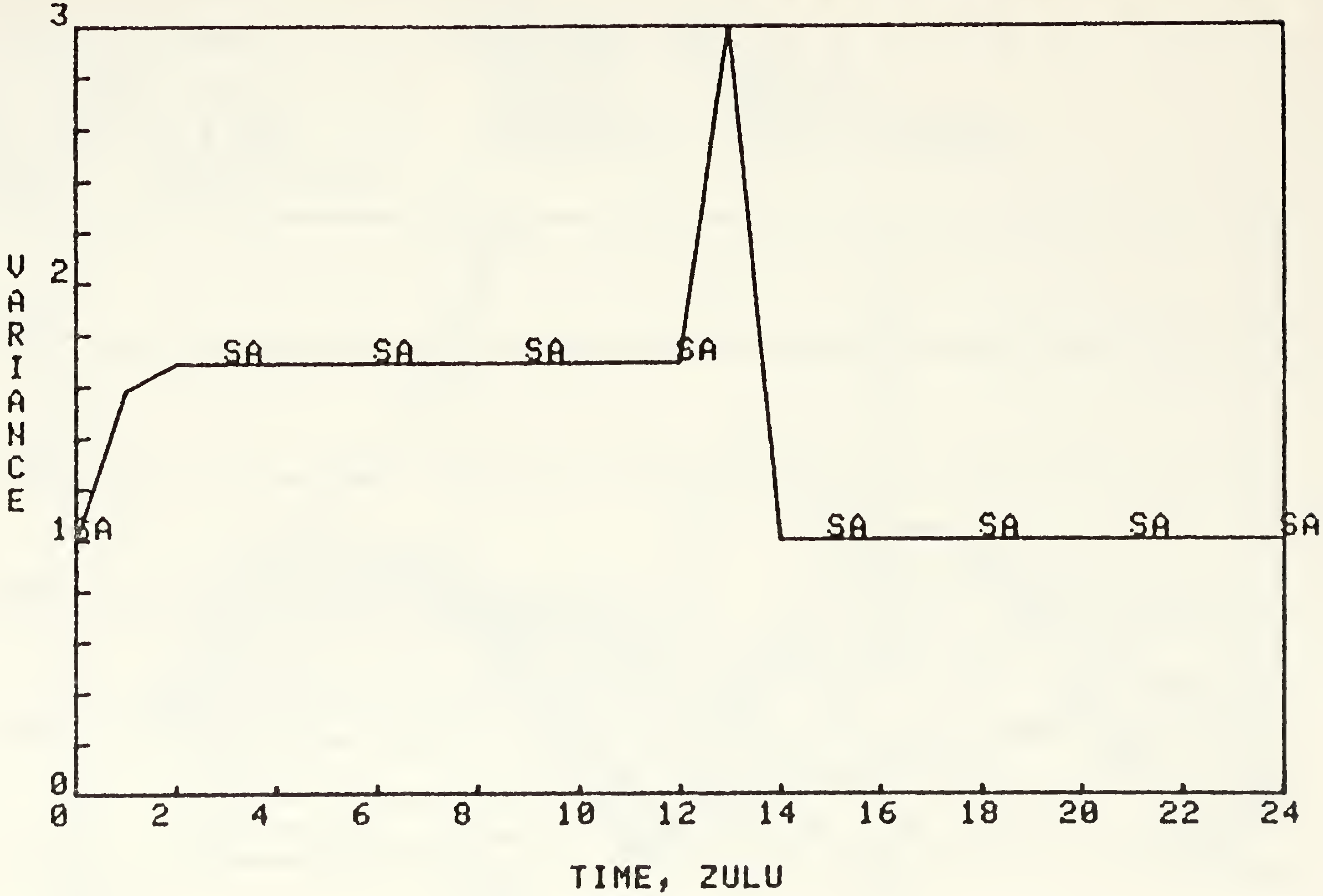


Figure 48

WWV 15 MHz 2/5/80 24 Hour Variance Diagram

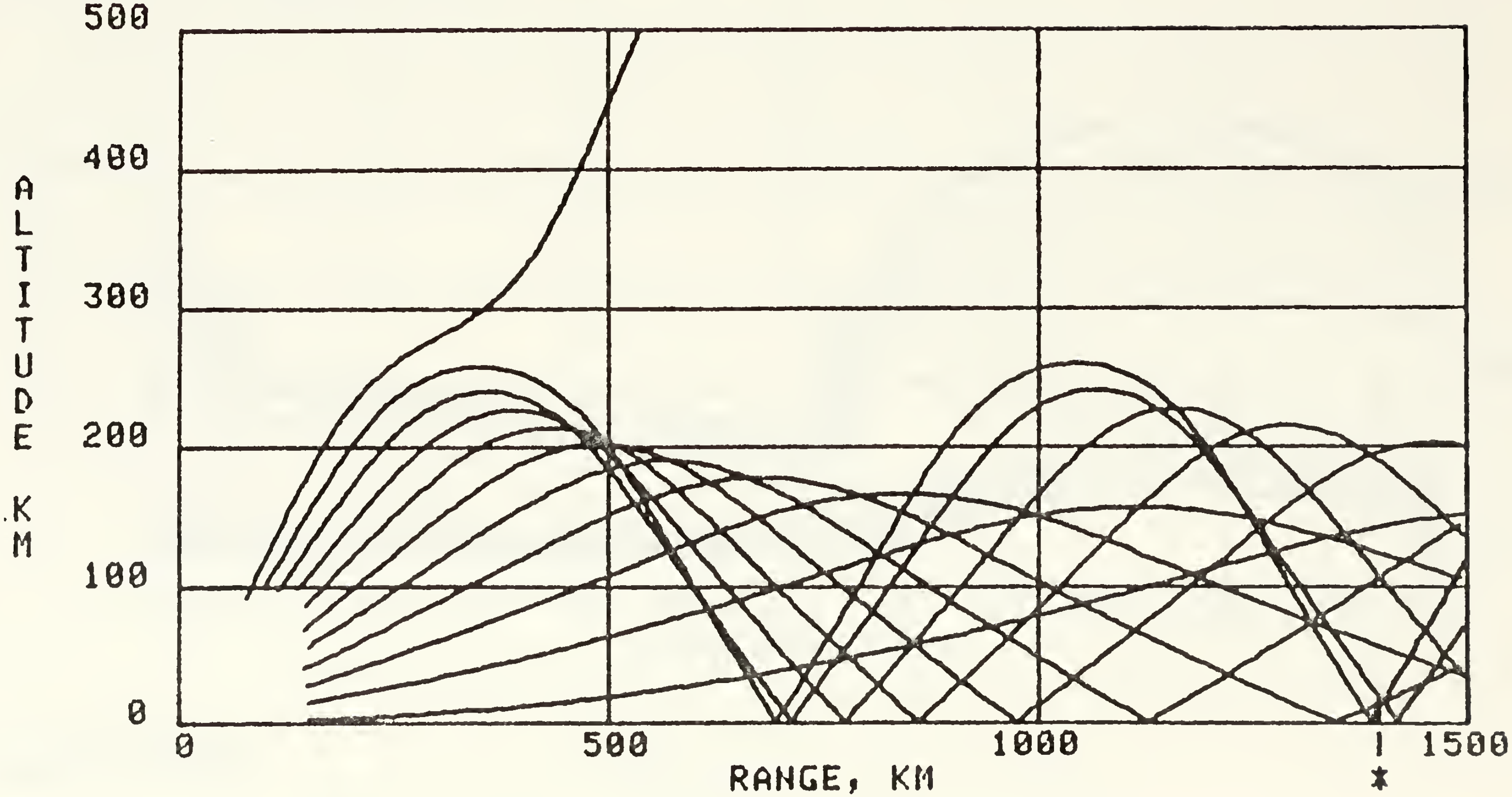
13 FEB 1979 1830Z
SUNSPOT NUMBER = 151
10.7 CM FLUX = 194
X-RAY FLUX = 1.000E-004

LAUNCH ANGLES:
MIN = 0.0 DEG
MAX = 50.0 DEG
INC = 5.0 DEG

TPM/NOSC

TRANSMITTER: BOULDER
40.8N, 105.1W
POWER = 10000 WATTS
ANTENNA GAIN = 0 dB
FREQUENCY = 15000.0 kHz

RECEIVER: SA
29.5N, 98.6W
RANGE = 1387 KM
BEARING = 152.9 DEGREES



:>

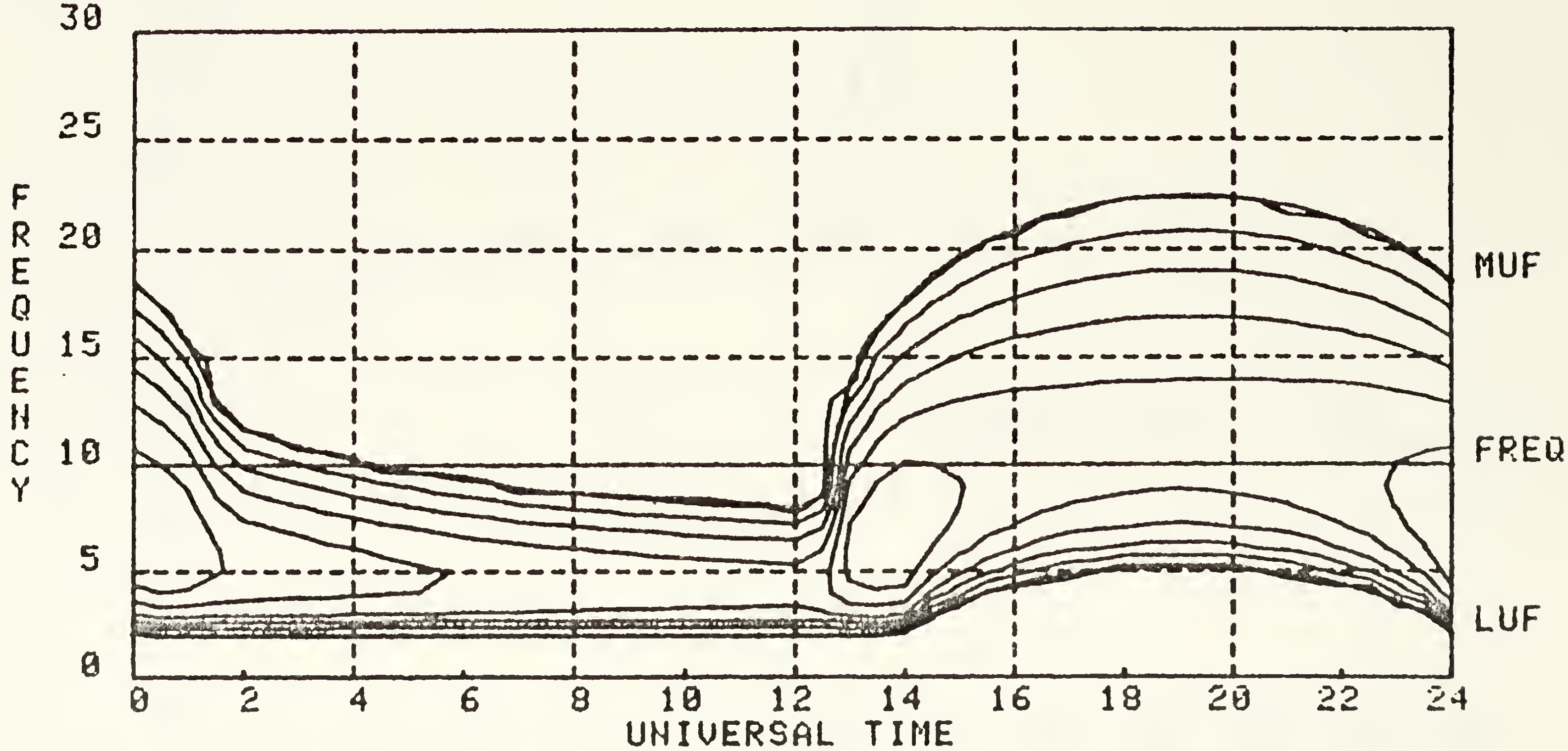
Figure 49
WWV 15 MHz 2/13/79 Ray Trace

13 FEB 1979 [redacted]
SUNSPOT NUMBER = 151
10.7 CM FLUX = 194
X-RAY FLUX = 1.000E-004

TPM/NOSC

TRANSMITTER: BOULDER
40.0N, 105.1W
POWER = 10000 WATTS
ANTENNA GAIN = 0 dB
FREQUENCY = 10000.0 kHz

RECEIVER: SA
29.5N, 98.6W
RANGE = 1387 KM
BEARING = 336.6 DEGREES



:>00000000000

Figure 50
WWV 10 MHz 2/13/79 Relative Power Diagram

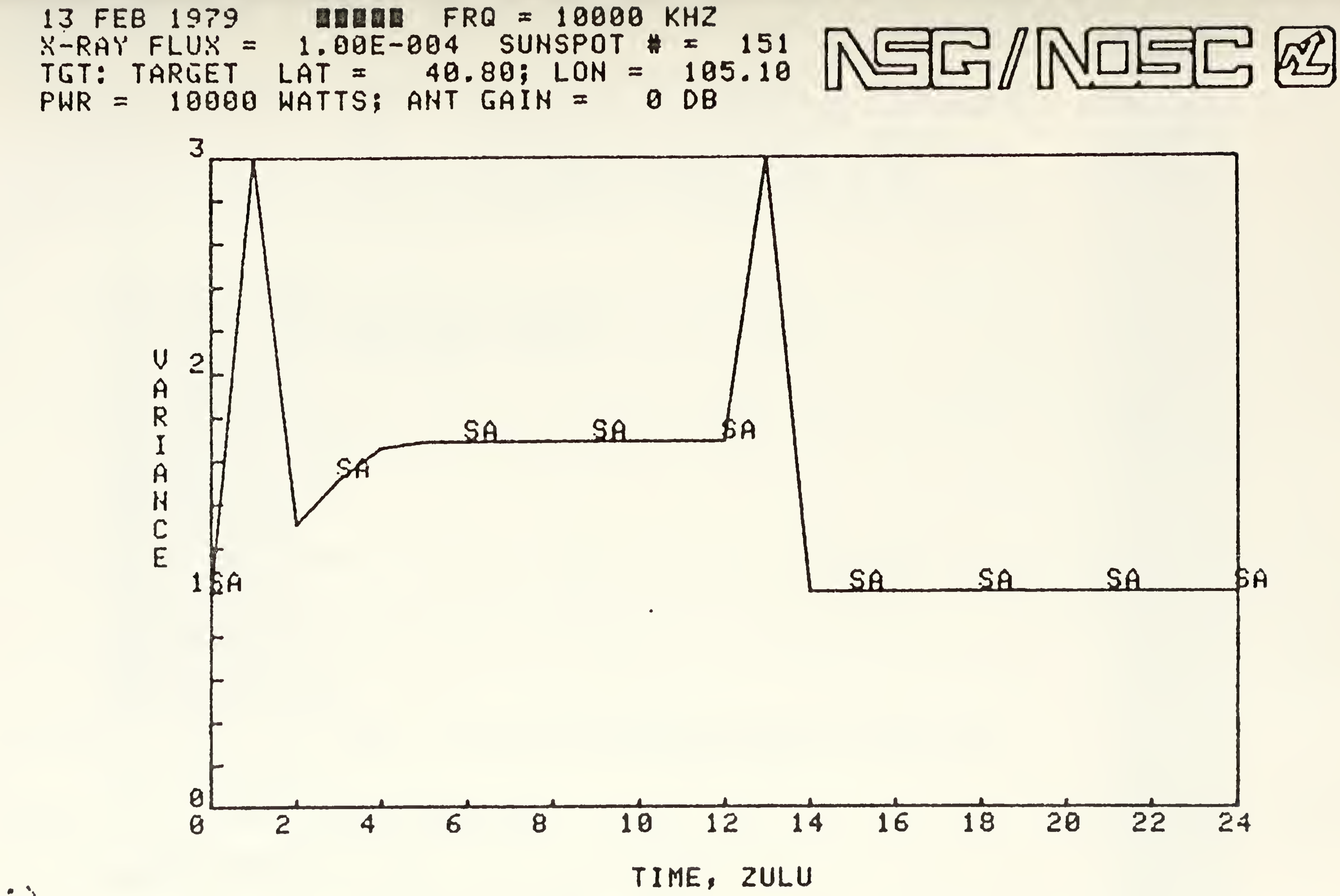


Figure 51

WWV 10 MHz 2/13/79 24 Hour Variance Diagram

```
DFERR

C THIS IS A PROGRAM TO CALCULATE DF ERROR STATISTICS OF THE SWRI
C SPACED LOOP ANTENNA SYSTEM. A GIVEN SET OF BEARINGS IS ANALYZED TO
C FIND THE MEAN AND STANDARD DEVIATION. THESE STATISTICS ARE USED TO
C RE-EVALUATE THE DATA SET BY TRIMMING OFF BEARINGS WITH LARGE
C DEVIATIONS FROM THE MEAN. A NEW MEAN IS CALCULATED AND COMPARED
C TO THE TRUE BEARING TO FIND THE ERROR. STATISTICS ARE THEN
C COMPUTED FOR GIVEN SIGNAL DURATION ACROSS THE ENTIRE DATA SET
C AND FOR SELECTED VALUES OF A4 WHICH IS A MEASURE OF SYSTEM NOISE.
C
C
      LOGICAL*1 SOURCE(30)/30*' '/
      INTEGER*2 NBRG2
      DATA CLR/'LR'/,CSR/'SR'/,CSA/'SA'/
      DIMENSION NBVEC(5000),A4VEC(5000),NDATA(10,10,4)
C     FOR CP/CMS, MUST REFORMAT DSRN 01
      CALL DSDSET(1,1600,2,16)
      WRITE(10,600)
      WRITE(10,601)
      READ(5,500) SOURCE
      WRITE(10,602)
      READ(5,501) NREC
      WRITE(10,603)
      READ(5,502) MINS
      MINS=MINS/20
      WRITE(10,604)
      READ(5,501) MAXS
      MAXS=MAXS/20
      WRITE(10,605)
      READ(5,502) NINC
      NINC=NINC/20
      WRITE(10,606)
      READ(5,503) NTBRG
      WRITE(10,607)
      READ(5,504) NSTD
C
C CALCULATE ROTATION SHIFT TO SIMPLIFY DETERMINATION OF BRG ERROR
C
      NSHIFT=360-NTBRG
C
C SET UP LOOP FOR A4MAX INCREMENTING
C
      DO 100 I1=1,10
      A4MAX=0.1*FLOAT(11-I1)
C
C SET UP LOOP FOR SIGNAL DURATION DECLARATION
C
```

```
      DO 101 J1=MINS,MAXS,NINC
      NC1=0
      NC2=0
      M2=0
      M3=0
      M4=0
      M10=0
      M12=0
C
C SET UP LOOP TO READ THRU ENTIRE FILE
C
      M5=NREC/J1
      DO 102 K1=1,M5
C
C SET UP LOOP TO READ NUMBER OF RECS CORRESPONDING TO SIG DURATION
C
      DO 103 L1=1,J1
      READ(1,505,END=201,ERR=103) A4,SS,NBRG2
      NBRG=NBRG2
C IF SS=','SR',OR 'SA'LF', THE REFERENCE SIGNAL IS LOW AND THE RECORD
C SHOULD BE DISCARDED. THIS IS DONE BY SETTING THE A4 TERM = 10.0
      IF(SS.EQ.CLR.OR.SS.EQ.CSR.OR.SS.EQ.CSA) A4=10.0
C     COUNT TOTAL NUMBER OF RECORDS READ WITH NC2
      NC2=NC2+1
      A4VEC(L1)=A4
103   NBVEC(L1)=NBRG
C
C NBVEC NOW CONTAINS BRGS FOR GIVEN SIG DURATION. A4VEC CONTAINS
C A4 VALUES ASSOCIATED WITH THESE BEARINGS. NOW CALL 'TRIM'.
C
      CALL TRIM(NBVEC,A4VEC,J1,NSTD,A4MAX,MSTD,MEAN,INSUF)
C
C IF INSUFFICIENT DATA TO DETERMINE STATS, MUST BE NOTED IN "INSUF".
C
      IF(INSUF.EQ.1) GO TO 200
C
C DETERMINE ERRORS BETWEEN TRUE AND MEAN BEARING
C
      M1=MEAN+NSHIFT
      IF(MEAN.GT.180) MEAN=MEAN-360
      IF(M1.GE.360) M1=M1-360
      IF(M1.GE.180) M1=M1-360
C
C TOTAL THE ERRORS IN M2 AND ERRORS SQUARED IN M3
C TOTAL MEAN IN M12 AND MEAN SQUARED IN M10
C
      M2=M2+M1
      M3=M3+M1*M1
```

```
      M10=M10+MSTD
C
C COUNT NUMBER OF SIGNALS FOR WHICH STATS ARE OBTAINED
C
      NC1=NC1+1
      GO TO 102
200   M4=M4+INSUF
102   CONTINUE
C
C READ TO END OF DATA FILE IF NECESSARY INORDER TO REWIND FOR NEXT RUN
C
      IF(NC2.GE.NREC) GO TO 206
      M8=NREC-NC2
      DO 104 K2=1,M8
104   READ(1,505,END=206) A4,SS,NBRG2
      NBRG=NBRG2
206   REWIND 1
C
C FIND AVE BEARING ERR AND STD OF BEARING ERR
C
      IF(NC1.EQ.0) GO TO 202
      GO TO 203
C
C IF NO SIGNALS FOR WHICH STATS OBTAINED, THIS SHOULD BE FLAGGED IN
C THE OUTPUT WITH 99999.
C
202   M6=99999
      M7=M6
      NC1=M6
      M4=M6
      M13=M6
      M14=M6
      GO TO 204
C
C CALCULATE MEAN BEARING ERROR (M6) AND STD OF BEARING ERROR (M7).
C CALCULATE MEAN BRG (M14) AND STD OF BRGS ABOUT MEAN (M13)
C
203   M6=M2/NC1
      X1=FLOAT(M2)/FLOAT(NC1)
      X2=FLOAT(M3)/FLOAT(NC1)
      M7=INT(SQRT(X2-X1*X1))
      M14=M10/NC1
      M11=J1/MINS
C
C STORE VALUE TO BE PRINTED IN THE ARRAY 'NDATA'.
C
204   NDATA(I1,M11,1)=M6
      NDATA(I1,M11,2)=M7
```

```
      NDATA(I1,M11,3)=NC1
      NDATA(I1,M11,4)=M14
101   CONTINUE
100   CONTINUE
      GO TO 205
201   WRITE(6,609)
205   CONTINUE
      DO 106 I1=1,3
      WRITE(6,614) SOURCE,NSTD
      DO 105 I2=1,4
      IF(I2.EQ.1) WRITE(6,610)
      IF(I2.EQ.2) WRITE(6,611)
      IF(I2.EQ.3) WRITE(6,612)
      IF(I2.EQ.4) WRITE(6,613)
105   CALL PRINT(NDATA,I2,MINS,NINC)
106   CONTINUE
      STOP
C
C
500   FORMAT(30A1)
501   FORMAT(I5)
502   FORMAT(I4)
503   FORMAT(I3)
504   FORMAT(I1)
505   FORMAT(8X,A4,A2,A2)
C
C
600   FORMAT('0THIS PROGRAM FINDS AVE BEARING ERROR AS A FUNCTION',/,
     A'0 OF SIGNAL DURATION AND SYSTEM NOISE (A4 TERM)')
601   FORMAT('0ENTER SOURCE AND TIME(30A1)')
602   FORMAT('0ENTER NUMBER OF RECORDS(I5)')
603   FORMAT('0ENTER MIN SIGNAL DURATION,XPLE OF 20 MSEC(I4)')
604   FORMAT('0ENTER MAX SIGNAL DURATION,XPLE OF 20 MSEC(I5)')
605   FORMAT('0ENTER SIGNAL INCREMENT,XPLE OF 20 MSEC(I4)')
606   FORMAT('0ENTER TRUE BEARING (I3)')
607   FORMAT('0ENTER STD XPLE FOR TRIMMING (I1)')
608   FORMAT(10I7)
609   FORMAT('0END OF DATA FILE ENCOUNTERED.')
610   FORMAT('0AVERAGE BEARING ERROR AS A FUNCTION OF SYSTEM ',
     A'NOISE (A4 TERM) AND SIGNAL DURATION',//)
611   FORMAT('0STANDARD DEVIATION OF BEARING ERROR AS A FUNCTION ',
     A'OF SYSTEM NOISE AND SIGNAL DURATION',//)
612   FORMAT('0NUMBER OF VALID SIGNALS OF A GIVEN DURATION ',
     A'AS A FUNCTION OF SYSTEM NOISE AND SIGNAL DURATION',//)
613   FORMAT('0AVE STANDARD DEVIATION OF BRGS ABOUT AVE BRG',//)
614   FORMAT('1SOURCE: ',30A1,/,'0STANDARD DEVIATION MULITPLE ',
     A'USED TO DETERMINE BEARING WINDOW = ',I1,//)
      END
```

```
C
C
C   SUBROUTINE TRIM
C
C  THIS SUBROUTINE CALCULATES MEAN AND STD OF 'N' ELEMENTS
C  (0-360 BEARINGS) OF VECTOR NVEC AFTER FILTERING OUT NVEC TERMS
C  ASSOCIATED WITH A4 VALUES IN XVEC THAT ARE TOO LARGE. FILTERED
C  ELEMENTS ARE STORED IN IVEC. USING MEAN AND AN INTEGER MULTIPLE
C  OF STD, ELEMENTS OF IVEC ARE FILTERED. VALUES WITHIN LIMITS OF
C  MEAN ARE USED TO COMPUTE A NEW MEAN (MEAN). THERE MUST BE AT LEAST 3
C  VALUES IN NVEC AND AT LEAST 2 VALUES AFTER FILTERING, IF NOT, THE
C  VALUE OF 'INSUF' IS SET TO 1
C
      SUBROUTINE TRIM(NVEC,XVEC,N,NSTD,XMAX,MSTD,MEAN,INSUF)
      DIMENSION NVEC(N),XVEC(N),IVEC(5000)
      DATA IVEC/5000*0/
C
C  INITIALIZE COUNTERS AND SUMMERS
C
      NC1=0
      M1=0
      M2=0
      INSUF=0
      MEAN=0
      M=0
      M11=0
C
C  IF LESS THAN 3 BEARINGS IN NVEC, RETURN TO MAIN PROGRAM WITH
C  INSUF=1.
C
      IF(N.LE.2) GO TO 200
C
C  FILL IVEC WITH ELEMENTS OF NVEC THAT PASS A4MAX FILTERING
C  COUNT NUMBER OF VALID NVEC ELEMENTS WITH NC1
C  M1 AND M2 SUM TERMS FOR FINDING MEAN AND STANDARD DEVIATION
C
      DO 100 I1=1,N
      IF(XVEC(I1).GT.XMAX) GO TO 100
C
C  COUNT NUMBER OF BRGS THAT PASS XMAX FILTERING WITH NC1
C
      NC1=NC1+1
      IF(NVEC(I1).GT.180) NVEC(I1)=NVEC(I1)-360
      IVEC(NC1)=NVEC(I1)
      M1=NVEC(I1)+M1
      M2=NVEC(I1)*NVEC(I1)+M2
100   CONTINUE
C
```

```
C IF LESS THAN 2 BRGS IN IVEC, STATS WILL BE MEANINGLESS, RETURN TO
C MAIN PROGRAM WITH INSUF=1.
C
      IF(NC1.LE.1) GO TO 200
C
C CALCULATE MEAN (M5) AND STD (M3) OF XMAX FILTERED ELEMENTS.
C FLOATING POINT IS USED IN SOME OPERATIONS FOR BETTER ACCURACY.
C
      X1=FLOAT(M1)/FLOAT(NC1)
      X2=FLOAT(M2)/FLOAT(NC1)
      M5=INT(X1)
      IF(M5.LT.0) M5=M5+360
      M3=INT(SQRT(X2-X1*X1))
      IF(M3.LT.6) M3=6
C
C APPLY STD MULTIPLIER NSTD, CALCULATE ACCEPTABLE WINDOW (M6&M7)
C ABOUT THE MEAN (M5) AND ZEROIZE COUNTER M AND SUMMER M9.
C
      M4=NSTD*M3
      M6=M5+M4
      M7=M5-M4
      NWIN=M6-M7
      M=0
      M9=0
      M10=0
C
C FIND BEARINGS WITHIN WINDOW ABOUT THE MEAN
C
      DO 101 I2=1,NC1
      M8=IVEC(I2)+360
      IF((IVEC(I2).LT.M7.OR.IVEC(I2).GT.M6).AND.M8.GT.M6) GO TO 101
      M=M+1
      IF(IVEC(I2).LT.M7) IVEC(I2)=IVEC(I2)+360
      M9=M9+IVEC(I2)
      M10=M10+IVEC(I2)*IVEC(I2)
101   CONTINUE
C
C COMPUTE MEAN OF BEARINGS
C
      IF(M.EQ.0) GO TO 200
      X4=FLOAT(M9)/FLOAT(M)
      X5=FLOAT(M10)/FLOAT(M)
      MSTD=INT(SQRT(X5-X4*X4))
      MEAN=INT(X4)
      GO TO 201
C
C IF NUMBER OF VALID ELEMENTS NOT SUFFICIENT, SET INSUF=1
C
```

```
200   INSUF=1
201   RETURN
      END
C
C
C THIS SUBROUTINE IS USED TO PRINT THE DATA CALCULATED IN THE
C MAIN PROGRAM
C
      SUBROUTINE PRINT(NDATA,N,MINS,NINC)
      LOGICAL*1 TITLE(10)
      DATA TITLE/' ',' ','M','A','X',' ','A','4',' ',' '/
      DIMENSION A4LBL(10),NDATA(10,10,4),NSDLBL(10)
      DO 100 I1=1,10
      A4LBL(I1)=FLOAT(11-I1)*0.1
100   NSDLBL(I1)=MINS*20+((I1-1)*NINC*20)
      WRITE(5,600) (TITLE(I),A4LBL(I),(NDATA(I,J,N),J=1,10),I=1,10)
600   FORMAT(5X,A1,5X,F3.1,2X,10I6,/)
      WRITE(5,601) NSDLBL
601   FORMAT(//,16X,10I6)
      WRITE(5,602)
602   FORMAT(//,25X,'SIGNAL DURATION (MILLISEC)'///)
      RETURN
      END
```

```
LMAT

C THIS PROGRAM READS A FILE OF SWRI SPACED-LOOP DATA AND CONSTRUCTS
C A THREE DIMENSIONAL CONDITIONAL PROBABILTY LIKELIHOOD RATIO
C MATRIX (L)
C
      LOGICAL*1 SOURCE(30)/30*' '/
      INTEGER*2 NB2
      DIMENSION A(10,10,10),U(10,10,10),XL(10,10,10)
C
C SET UP FOR CP/CMS READ OF DATA FILE
C
      CALL DSDSET(1,1600,2,16)
C
C INITIALIZE THE ACCEPTABLE (A), THE UNACCEPTABLE (U) AND THE
C LIKELIHOOD RATIO (XL) MATRICES WITH ALL ZEROS.
C
      DATA A/1000*0./,U/1000*0./,XL/1000*0./
C
C SET IN PARAMETERS:
C
      DATA CLR/'LR'/,CSR/'SR'/,CSA/'SA'/
      WRITE(10,601)
601   FORMAT('OENTER SOURCE (30A1)')
      READ(5,501) SOURCE
501   FORMAT(30A1)
      WRITE(8,602) SOURCE
602   FORMAT(30A1)
C NUMBER OF RECORDS AND NUMBER OF FILES
      NREC=10000
      NFILE=4
C SET UP TWO ACCEPTABLE BEARING WINDOWS TO ACCOUNT FOR 360 TO 000
C CROSSOVER INHERENT IN BEARING PROBLEMS. E.G. IF YOU WANT A 20 DEG
C WINDOW AROUND B=350, SET UP TWO WINDOWS 330-360 AND 000-010. IF
C THE WINDOW DOES NOT SPAN THE CROSSOVER, SET WINDOW 2 = WINDOW 1.
C
C LOWER BOUND OF ACCEPTABLE BEARING WINDOWS 1 AND 2
      NBMIN1=000
      NBMIN2=292
C UPPER BOUND OF ACCEPTABLE BEARING WINDOWS 1 AND 2
      NBMAX1=022
      NBMAX2=360
C INITIALIZE ACCEPTABLE AND UNACCEPTABLE BEARING COUNTERS
      NA=0
      NU=0
C INITIALIZE CONSTANTS NEEDED FOR THE SUBROUTINE THAT MAPS
C A0, PHASE, AND A4 INTO APPROPRIATE MATRIX ADDRESS.
      A0MIN=0.
```

```
      AOMAX=1.
      NAODIM=10
      PMIN=-180.
      PMAX=180.
      NPDIM=10
      A4MIN=0.
      A4MAX=1.
      NA4DIM=10
C
C USE A DO LOOP TO READ THRU THE ENTIRE FILE AND PLACE
C APPROPRIATE ENTRIES INTO THE A AND U MATRICES.
C
      DO 108 I8=1,NFILE
      DO 109 I1=1,NREC
      READ(1,500, END=109) AO,NP,A4,SS,NB2
      NB=NB2
500   FORMAT(3A4,A2,A2)
      IF(SS.EQ.CLR) GO TO 109
      IF(SS.EQ.CSR) GO TO 109
      IF(SS.EQ.CSA) GO TO 109
      P=FLOAT(NP)
C
C CALL SUBROUTINE MAPF TO DETERMINE MATRIX ELEMENT ADDRESS (I,J,K).
C AO DETERMINES I, PHASE DETERMINES J, AND A4 DETERMINES K.
C
      CALL MAPF(AO,AOMIN,AOMAX,NAODIM,I)
      CALL MAPF(P,PMIN,PMAX,NPDIM,J)
      CALL MAPF(A4,A4MIN.A4MAX,NA4DIM,K)
C
C DECIDE IF A 1 SHOULD BE ADDED TO A OR U.
C
      IF(NB.GE.NBMIN1.AND.NB.LE.NBMAX1) GO TO 200
      IF(NB.GE.NBMIN2.AND.NB.LE.NBMAX2) GO TO 200
C
C THIS PATH, AUGMENT UNACCEPTABLE COUNTER AND MATRIX.
C
      NU=NU+1
      U(I,J,K)=U(I,J,K)+1.
      GO TO 109
C
C THIS PATH, AUGMENT ACCEPTABLE COUNTER AND MATRIX.
C
200   NA=NA+1
      A(I,J,K)=A(I,J,K)+1.
109   CONTINUE
108   CONTINUE
C
C CONSTRUCT LIKELIHOOD RATIO MATRIX
```

```
C
      DO 101 I2=1,NADDIM
      DO 102 J2=1,NPDIM
      DO 103 K2=1,NA4DIM
C AVOID DIVISION BY ZERO
      IF(U(I2,J2,K2).EQ.0.) GO TO 201
      IF(A(I2,J2,K2).EQ.0.) GO TO 103
C
C CONSTRUCT XL FROM THE RATIO OF THE PROBABILTY MASS MATRIX ELEMENTS
C OF A AND U.
C
      XL(I2,J2,K2)=(A(I2,J2,K2)/FLOAT(NA))/(U(I2,J2,K2)/FLOAT(NU))
      GO TO 103
C
C IF THE U MATRIX ELEMENT IS ZERO,SET XL MATRIX ELEMENT TO 9999.99
C
201   XL(I2,J2,K2)=9999.99
103   CONTINUE
102   CONTINUE
101   CONTINUE
C
C WRITE XL MATRIX INTO A STORAGE FILE
C
      WRITE(8,600) XL
600   FORMAT(F12.3)
      STOP
      END
C
C
C
C               SUBROUTINE MAPF
C
      SUBROUTINE MAPF(VAR,VARMIN,VARMAX,M1,M2)
C     THIS SUBROUTINE MAPS A VARIABLE (VAR) WHICH LIES ON OR BETWEEN
C     A MINIMUM VALUE (VARMIN) AND A MAXIMUM VALUE (VARMAX) TO AN
C     ADDRESS (M2) OF AN ARRAY OF LENGTH (M1).
C
      IF(VAR.LT.VARMIN) VAR=VARMIN
      IF(VAR.GT.VARMAX) VAR=VARMAX
      M2=INT(FLOAT(M1)*(VAR-VARMIN)/(VARMAX-VARMIN))+1
      IF(M2.GT.M1) M2=M1
      RETURN
      END
```

```
LFILE

C THIS PROGRAM USES A LIKELIHOOD RATIO MATRIX (XL) TO CREATE AND
C OUTPUT FILE THAT IS THE SAME AS THE INPUT FILE EXCEPT FOR THE
C A4TERM.
C
      INTEGER*2 NB2
      LOGICAL*1 SOURCE(30)/30*' '/
      DATA CLR/'LR'/,CSR/'SR'/,CSA/'SA'/
      DIMENSION XL(10,10,10)
      CALL DSDSET (1,1600,2,15)
      CALL DSDSET (2,1600,2,16)
      READ(8,502) SOURCE
502   FORMAT(30A1)
      READ(8,500) XL
500   FORMAT(F12.3)
      NREC=10000
C
C REQUIRED MAPPING CONSTANTS
C
      AOMIN=0.
      AOMAX=1.
      NAODIM=10
      PMIN=-180.
      PMAX=180.
      NPDIM=10
      A4MIN=0.
      A4MAX=1.
      NA4DIM=10
C
C READ THRU THE INPUT FILE AND USE MAPF TO FIND ADDRESS OF XL.
C IF XL IS LT 1 OR IF RCD TAGGED LR, THE BEARING IS MADE
C UNACCEPTABLE BY SETTING A4=10.0 . IF GREATER THAN 1, THE BEARING
C IS ACCEPTABLE AND A4 IS SET EQUAL TO 0.01 .
C
      DO 100 I1=1,NREC
      READ(1,501) AO,NP,A4,SS,NB2
      NB=NB2
501   FORMAT(3A4,A2,A2)
      P=FLOAT(NP)
C
C FIND THE APPROPRIATE I,J,K ADDRESS
C
      CALL MAPF(AO,AOMIN,AOMAX,NAODIM,I)
      CALL MAPF(P,PMIN,PMAX,NPDIM,J)
      CALL MAPF(A4,A4MIN,A4MAX,NA4DIM,K)
C
C COMPARE THE XL MATRIX ELEMENT WITH 1.
```

```
C
      IF(XL(I,J,K).LT.1.0) GO TO 200
      IF(SS.EQ.CLR) GO TO 200
C
C THIS PATH, BEARING ACCEPTABLE, SET A4=0.01 .
C
      A4=0.01
      GO TO 201
C
C THIS PATH, BEARING UNACCEPTABLE, SET A4=10.0 .
C
200   A4=10.0
C
C WRITE THE NEW RECORD
C
201   WRITE(2,600) A0,NP,A4,NB
600   FORMAT(4A4)
100   CONTINUE
      STOP
      END
C
C
C SUBROUTINE MAPF
C
      SUBROUTINE MAPF(VAR,VARMIN,VARMAX,M1,M2)
      IF(VAR.LT.VARMIN) VAR=VARMIN
      IF(VAR.GT.VARMAX) VAR=VARMAX
      M2=INT(FLOAT(M1)*(VAR-VARMIN)/(VARMAX-VARMIN))+1
      IF(M2.GT.M1) M2=M1
      RETURN
      END
```

```
PLOT3

C THIS PROGRAM PLOTS THE RESULTS OF ANALYSIS OF SWRI OF SYSTEM DATA.
C
C
      LOGICAL*1 SOURCE(30)/30*' '/
      DIMENSION A(10),S(10),C(10),V(10),P(10),RANGE(4),X(6),
     AD1(10),D2(10),SC1(10),SC2(10)
      DATA D1 /100.,200.,300.,400.,500.,600.,700.,800.,900.,1000./,
     A     D2 /1000.,2000.,3000.,4000.,5000.,6000.,7000.,
     B8000.,9000.,10000./,
     C     SC1 /2000.,1000.,666.,500.,400.,333.,285.,250.,222.,
     D200./,
     E     SC2 /200.,100.,66.,50.,40.,33.,28.,25.,22.,20./
C
C IF MORE THAN ONE DATA FILE IS TO BE PLOTTED, SET NFILE=1
C
      NFILE=1
204   CONTINUE
C
C NUMBER OF PLOTS TO BE MADE
C
203   READ(10,502,END=202,ERR=203) NPLOT
502   FORMAT(I2)
C
C FOR SHORT (1) OR LONG (10) SIGNAL DURATIONS
C
      N1=1
C
C FIX THE SCALE PARAMETERS
C
      RANGE(1)=1000*FLOAT(N1)
      RANGE(2)=0.
C
C
      DO 100 I1=1,NPLOT
      READ(10,500) SOURCE
500   FORMAT(30A1)
      READ(10,501) A,S,C,V
501   FORMAT(10F7.0)
      IF(N1.EQ.10) GO TO 200
C
C DETERMINE THE SCALING PARAMETERS FOR THE Y AXIS OF THE PLOT
C
      CALL MINMAX(A,X(1),X(4),10)
      CALL MINMAX(S,X(2),X(5),10)
      CALL MINMAX(V,X(3),X(6),10)
      CALL MINMAX(X,RANGE(4),RANGE(3),6)
```

```
      IF(RANGE(4).GT.0.) RANGE(4)=0.
      DO 101 I2=1,10
      P(I2)=C(I2)/SC1(I2)
101   CONTINUE
      GO TO 201
200   DO 102 I3=1,10
102   P(I3)=C(I3)/SC2(I3)
201   CONTINUE
      WRITE(6,600) SOURCE
600   FORMAT('1',33(/),1X,'SOURCE: ',30A1,/)
      WRITE(6,601)
601   FORMAT(9X,'AVE BEARING ERROR (DEGREES) : X',/,
     A9X,'STD OF BEARING ERROR (DEGREES) : *',/,
     B9X,'AVE OF INTRA-SIGNAL STD (DEGREES) : .',//)
      CALL UTPLTT(D1,S,10,RANGE,1,1)
      CALL UTPLTT(D1,V,10,RANGE,1,2)
      CALL UTPLTT(D1,A,10,RANGE,1,3)
      WRITE(6,603) D1,P
603   FORMAT(//,1X,'SIGNAL DURATION:',3X,10F6.0,/,2X,'(MILLISECONDS)',
     A/,1X,'PROBABILITY OF :',2X,10F6.3,/,2X,'OBTAINING LOB')
      WRITE(6,604) A,S,V
604   FORMAT(/,13X,'X :',3X,10F6.0,/,13X,'* :',3X,10F6.0,/,
     A13X,'. :',3X,10F6.0)
      REWIND 5
100   CONTINUE
      IF(NFILE.EQ.1) GO TO 203
202   CONTINUE
      STOP
      END
C
C THIS SUBROUTINE FINDS THE MIN (AMIN) AND MAX (AMAX) VALUES
C OF AN ARRAY OF LENGTH N.
C
      SUBROUTINE MINMAX(ARRAY, AMIN,AMAX,N)
      DIMENSION ARRAY(N)
      AMAX=ARRAY(1)
      AMIN=ARRAY(1)
      DO 100 I1=2,N
      IF(ARRAY(I1).GT.AMAX) AMAX=ARRAY(I1)
      IF(ARRAY(I1).LT.AMIN) AMIN=ARRAY(I1)
100   CONTINUE
      RETURN
      END
AMBIGUITY

C THIS PROGRAM EDITS A SWRI FILE TO MAKE THE A4 TERM = 10.0 FOR ALL
C RECORDS THAT ARE WITHIN A DEFINED WINDOW ABOUT THE 90 AND 180 DEGREE
C AMBIGUITIES ASSOCIATED WITH THE TRUE BEARING.
```

```
C
C
      INTEGER*2 NBRG2
C
C NEED DSDSET FOR CP/CMS
C
      CALL DSDSET(1,1600,2,16)
      CALL DSDSET(2,1600,2,16)
C
C SET NTBRG WITH THE VALUE OF THE TRUE BEARING.
C
      NTBRG=337
      NREC=10000
C
C SET THE WIDTH OF THE AMBIGUITY WINDOW. PROGRAM ACCOUNTS FOR
C FOLD AROUND AT 360 DEGREES.
C
      NWIDTH=10
      NA180=NTBRG-180
      IF(NA180.LT.0) NA180=NA180-360
      NAP90=NTBRG+90
      IF(NAP90.GT.359) NAP90=NAP90-360
      NAM90=NTBRG-90
      IF(NAM90.LT.0) NAM90=360+NAM90
C
C USE WINDOW SUBROUTINE TO DETERMINE WINDOW LIMITS ABOUT THE
C 90 AND 180 DEGREE AMBIGUITIES.
C
      CALL WINDOW(NA180,NWIDTH,N1,N2)
      CALL WINDOW(NAP90,NWIDTH,N3,N4)
      CALL WINDOW(NAM90,NWIDTH,N5,N6)
C
C LOOP THRU ALL OF THE RECORDS OF THE FILE.
C
      DO 100 I1=1,NREC
      READ(1,500) A0,NP,A4,SS,NBRG2
500   FORMAT(3A4,2A2)
      NB=NBRG2
C
C IF BRG IN A RECORD IS INSIDE AMBIGUITY WINDOW, SET A4 VALUE TO
C 10.0 AND WRITE WHOLE RECORD TO FILE DSRN 02.
C
      IF((NB.GE.N1.OR.NB.GE.N3.OR.NB.GE.N5).AND.
     A(NB.LE.N2.OR.NB.LE.N4.OR.NB.LE.N6)) A4=10.0
      WRITE(2,600) A0,NP,A4,SS,NBRG2
600   FORMAT(3A4,2A2)
100   CONTINUE
      STOP
```

```
      END
C
C THIS SUBROUTINE DETERMINES THE MIN BEARING AND THE MAX BEARING
C THAT DEFINES A WINDOW OF WIDTH NWIDTH CENTERED AT NBRG.
C
      SUBROUTINE WINDOW(NBRG,NWIDTH,MIN,MAX)
      N1=NWIDTH/2
      MIN=NBRG-N1
      IF(MIN.LT.0) MIN=MIN+360
      MAX=NBRG+N1
      IF(MAX.GT.360) MAX=MAX-360
      RETURN
      END
```

```
BRGCNT

C THIS PROGRAM SUMS THE NUMBER OF BEARINGS BY INTEGER BEARING VALUE
C OF A DATA FILE OF 10,000 RECORDS. ONE CONSTRAINT CAN BE APPLIED
C TO THE DATA SET. THE A4 TERM OF SWRI DATA SETS CAN BE SPECIFIED TO
C HAVE A MAXIMUM TOLERABLE VALUE.
C
C BRGMAX IS A 360 ELEMENT LINEAR ARRAY IN WHICH EACH BLOCK
C CORRESPONDS TO A NUMBER OF DGREES. THE CONTENTS OF AN ELEMENT
C ARE THE NUMBER OF RECORDS WITH THAT BEARING.
C
      DIMENSION BRGMX(360)
      INTEGER*2 NBRG2
      DATA BRGMX/360*0.0/
C USE DSDSET FOR CP/CMS
      CALL DSDSET(1,1600,2,16)
      CALL DSDSET(2,1600,2,16)
      CALL DSDSET(3,1600,2,16)
      CALL DSDSET(4,1600,2,16)
      WRITE(6,600)
200   WRITE(6,601)
      READ(5,500)NFILE
      WRITE(6,608)
      READ(5,504) NREC
      WRITE(6,602)
      READ(5,501)A4MAX
      NDEL=0
C
C READ THRU THE FILE. IF A4 NOT TOO LARGE, AUGMENT APPROPRIATE
C ELEMNET IN BRGMX
C
      DO 101 I1=1,NREC
      READ(NFILE,502,ERR=100,END=100)A4,NBRG2
      NBRG=NBRG2
      IF(A4.GT.A4MAX)GO TO 100
      IF(NBRG.EQ.0)NBRG=NBRG+360
      BRGMX(NBRG)=BRGMX(NBRG)+1
      GO TO 101
100   NDEL=NDEL+1
101   CONTINUE
C
C WRITE OUTPUT TO FILE 6
C
      WRITE(6,605)NFILE
      WRITE(6,606)A4MAX
      WRITE(6,603)(I,BRGMX(I),I=1,360)
      WRITE(6,604)NDEL
      NVAL=NREC-NDEL
```

```
C
C QUERY FOR ANOTHER RUN. REWIND IF NECESSARY
C
      WRITE(6,607)
      REWIND NFILE
      READ(5,503)M1
      IF(M1.EQ.1) GO TO 200
      STOP
500   FORMAT(I1)
501   FORMAT(F5.3)
502   FORMAT(8X,A4,2X,A2)
503   FORMAT(I1)
504   FORMAT(I6)
600   FORMAT('0PROGRAM SUMS INDIVIDUAL INTEGER BRGS OF A DATA SET')
601   FORMAT('0ENTER FILE NUMBER (I1)')
602   FORMAT('0ENTER MAX A4 VALUE (F5.3)')
603   FORMAT(10(1X,I3,1X,F5.1,2X)/)
604   FORMAT('0NUMBER OF DELETES = ',I5)
605   FORMAT('0FILE NUMBER ',I1)
606   FORMAT('0A4 MAX = ',F5.3)
607   FORMAT('0TYPE A 1 FOR ANOTHER RUN, TYPE A DIFFERENT INT TO END')
608   FORMAT('0ENTER NUMBER OF RECORDS (I6)')
      END
```

BRGH2

```
C THIS PROGRAM DISPLAYS A HISTOGRAM OF FILTERED BEARINGS IN FILE DSRN 1.
C FILTERING IS DONE ON THE A4 TERM. MAXIMUM LEVEL IS SET IN A4MAX.
C A4 ADMISSIBLE BRGS ARE USED TO DETERMINE MEAN AND STD. A WINDOW
C IS CREATED ABOUT THIS MEAN. WIDTH OF WINDOW IS STD TIMES AN INTEGER
C ENTERED BY THE USER
C
      LOGICAL*1 SOURCE(30)/30*' '/
      INTEGER*2 NBRG2
      DIMENSION BRGMAT(10000),STAT(5),SCALE(2),IOPT(5),DATMAT(10000)
      DATA IOPT/1,0,0,0,1/
C
C USE DSDSET FOR CP/CMS
C
      CALL DSDSET(1,1600,2,16)
      WRITE(10,600)
      WRITE(10,603)
      READ(5,502) SOURCE
201   WRITE(10,607)
      READ(5,500) A4MAX
      WRITE(10,610)
      READ(5,500) X2
      NVAL=0
C
C READ 10000 RECORDS AND FILTER ON A4. FILL BRGMAT WITH
C A4 ADMISSIBLE BEARING VALUES.
C
      DO 100 I1=1,10000
      READ(1,501,END=200) A4,NBRG2
      NBRG=NBRG2
      IF(A4.GT.A4MAX) GO TO 100
      NVAL=NVAL+1
      BRGMAT(NVAL)=NBRG
100   CONTINUE
200   CONTINUE
C
C FIND MEAN AND STD OF BRGMAT AND SET PARAMETERS OF WINDOW.
C
      CALL BEIUGR(BRGMAT,NVAL,IOPT,STAT,IER)
      X1=FLOAT(IFIX(STAT(1)))
      X3=FLOAT(IFIX(X2*SQRT(STAT(5))))
      X4=X1+X3
      X5=X1-X3
      M1=0
C
C FILTER BRGMAT THRU WINDOW. PUT WINDOW ADMISSIBLE VALUES IN DATAMAT.
C
```

```
      DO 101 I2=1,N/AL
      X6=BRGMAT(I2)+360.
      IF((BRGMAT(I2).LT.X5.OR.BRGMAT(I2).GT.X4).AND.X6.GT.X4) GO TO 101
      M1=M1+1
      IF(BRGMAT(I2).LT.X5) BRGMAT(I2)=BRGMAT(I2)+360
      DATMAT(M1)=BRGMAT(I2)
101   CONTINUE
      WRITE(5,605) SOURCE
      WRITE(6,608) A4MAX
C
C CREATE AND OUTPUT HISTOGRAM. SET UP FOR ANOTHER RUN.
C
      CALL HISTF(DATMAT,M1,0)
      REWIND 1
      WRITE(10,609)
      READ(5,505) M2
      IF(M2.EQ.1) GO TO 201
      STOP
500   FORMAT(F5.3)
501   FORMAT(8X,A4,2X,A2)
502   FORMAT(30A1)
504   FORMAT(F5.1)
505   FORMAT(I1)
600   FORMAT('0THIS PROGRAM DISPLAYS A HISTOGRAM OF BEARINGS IN FILE',
     A' DSRN 01')
603   FORMAT('0ENTER RADIOWAVE SOURCE (30A1)')
605   FORMAT('1RADIOWAVE SOURCE: ',30A1)
607   FORMAT('0ENTER MAXIMUM A4 VALUE (F5.3)')
608   FORMAT(//,'0A4MAX: ',F5.3)
609   FORMAT('0ENTER A 1 FOR ANOTHER RUN,IF NOT, DIFFERENT INTEGER')
610   FORMAT('0ENTER PERMISSIBLE NUMBER OF STD (F5.3)')
      END
```

BRGHIS

```
C THIS PROGRAM DISPLAYS A HISTOGRAM OF THE BEARINGS IN FILE DSRN 1.
C FILTERING IS DONE ON EACH RECORD ON THE A4 TERM.
C SCALING OF THE HISTOGRAM CAN BE SET BY THE USER.
C
      LOGICAL*1 SOURCE(30)/30*' '/
      DIMENSION BRGMAT(10000),SCALE(2)
C USE DSDSET FOR CP/CMS
      CALL DSDSET(1,1600,2,16)
      WRITE(10,600)
      WRITE(10,603)
      READ(5,502) SOURCE
      WRITE(10,607)
      READ(5,500) A4MAX
      WRITE(10,601)
      READ(5,504) SCALE(1)
      WRITE(10,602)
      READ(5,504) SCALE(2)
      NVAL=0
C
C READ RECORDS, FILTER OUT HIGH A4 VALUES. PUT A4 ADMISSIBLE
C VALUES IN LINEAR ARRAY BRGMAT.
C
      DO 100 I1=1,10000
      READ(1,501,END=200) A4,NBRG
      IF(A4.GT.A4MAX) GO TO 100
      NVAL=NVAL+1
      BRGMAT(NVAL)=NBRG
100   CONTINUE
200   CONTINUE
      WRITE(6,605) SOURCE
C
C DETERMINE HISTOGRAM SCALE AND THEN CREATE IT WITH HISTF.
C
      CALL FIX(SCALE)
      CALL HISTF(BRGMAT,NVAL,0)
      STOP
500   FORMAT(F5.3)
501   FORMAT(8X,2A4)
502   FORMAT(30A1)
504   FORMAT(F5.1)
600   FORMAT('0THIS PROGRAM DISPLAYS A HISTOGRAM OF BEARINGS IN FILE',
     A' DSRN 01')
601   FORMAT('0ENTER MINIMUM VALUE OF SCALE (F5.1)')
602   FORMAT('0ENTER MAXIMUM VALUE OF SCALE (F5.1)')
603   FORMAT('0ENTER RADIOWAVE SOURCE (30A1)')
605   FORMAT(/////,'0RADIOWAVE SOURCE: ',30A1)
```

```
607   FORMAT('0ENTER MAXIMUM A4 VALUE (F5.3)')                    BRG02070
      END                                                         BRG02080
```

```
TIME1

C THIS PROGRAM PLOTS THE A0,A4,BEARING AND PHASE MEASUREMENTS FROM
C THE SWRI SPACED LOOP ANTENNA VERSUS TIME.
C
C
      LOGICAL*1 SOURCE(20),BRGARY(45),PHSARY(45),A0ARY(20),A4ARY(20),
     ACB,CP,CA0,CA4,CS,CINVAL
      INTEGER*2 NBRG2
      DATA BRGARY/45*' '/,PHSARY/45*' '/,A0ARY/20*' '/,A4ARY/20*' '/,
     ACB/'B'/,CP/'P'/,CA0/'0'/,CA4/'4'/,CS/' '/,CLR/'LR'/,CSR/'SR'/,
     BCSA/'SA'/,CINVAL/'?'/
      CALL DSDSET(1,1500,2,16)
C
C FOLLOWING DECLARATIONS REPRESENT THE RANGE OF VALUES EXPECTED FOR
C THE BEARING,PHASE,A0 AND A4 TERMS.
C
      A0MIN=0.0
      A0MAX=2.0
      A4MIN=0.0
      A4MAX=1.0
      NPMIN=-180
      NPMAX=180
      NBMIN=0
      NBMAX=360
      WRITE(10,600)
      WRITE(10,603)
      READ(5,501) SOURCE
206   WRITE(10,604)
      READ(5,502) NOUT
C
C SET ARRAY PARAMETERS M1,M2 AND M3 FOR EITHER PRT OR CON OUTPUT
C
      M1=45
      M2=20
      M3=20
      IF(NOUT.EQ.1) GO TO 208
      M1=24
      M2=15
      M3=10
C
C DETERMINE NUMBER OF RECORDS TO BE PLOTTED IN TERMS OF TIME.
C ONE SECOND EQUALS FIFTY RECORDS.
C
208   WRITE(10.601)
      READ(5,500) NSTART
      WRITE(10,602)
      READ(5,500) NSTOP
```

```
      NADV=0
      IF(NSTART.EQ.0) GO TO 200
      NADV=NSTART*50
C
C READ FILE TO START POINT.
C
      DO 100 I1=1,NADV
100   READ(1,503,END=205,ERR=204)
200   NHALT=NSTOP*50
C
C DETERMINE NUMBER OF RECORDS TO BE READ.
C
      NRUN=NHALT-NADV
      IF(NRUN.LE.0) GO TO 206
C
C PRINT THE OUTPUT LABEL.
C
      CALL LABEL(NOUT,SOURCE)
C
C READ THRU THE REQUESTED RECORDS.
C
      DO 101 I2=1,NRUN
      READ(1,503,END=101,ERR=204) A0,NPHS,A4,SS,NBRG2
      NBRG=NBRG2
C
C USE MAPF AND MAPI TO MAP DATA RECORD VALUES TO OUTPUT ARRAYS
C A0ARY, PHSARY, A4ARY AND BRGARY. MAPF IS FOR FLOATING POINT AND
C MAPI IS FOR INTEGER MAPPING.
C
      CALL MAPF(A0,A0MIN,A0MAX,M2,MA1)
      A0ARY(MA1)=CA0
      CALL MAPI(NPHS,NPMIN,NPMAX,M1,MA2)
      PHSARY(MA2)=CP
      CALL MAPF(A4,A4MIN,A4MAX,M3,MA3)
      A4ARY(MA3)=CA4
      CALL MAPI(NBRG,NBMIN,NBMAX,M1,MA4)
      BRGARY(MA4)=CB
      IF(SS.EQ.CLR.OR.SS.EQ.CSR.OR.SS.EQ.CSA) GO TO 209
      GO TO 210
C
C IF LR, SR OR SA FLAGS ARE READ IN A RECORD, WRITE THE SYMBOL
C ? TO THE FIRST ELEMENT OF OUTPUT ARRAYS.
C
209   A0ARY(1)= CINVAL
      PHSARY(1)= CINVAL
      A4ARY(1)= CINVAL
      BRGARY(1)= CINVAL
210   IF(NOUT.EQ.1) GO TO 202
```

```
C
C THIS PATH, WRITE TO CRT.
C
      WRITE(8,605)((BRGARY(I),I=1,24),(PHSARY(I),I=1,24),
     A(A0ARY(I),I=1,15),(A4ARY(I),I=1,10))
      GO TO 203
C
C THIS PATH, WRITE TO PRINTER.
C
202   WRITE(8,606) BRGARY,PHSARY,A0ARY,A4ARY
203   A0ARY(MA1)=CS
      PHSARY(MA2)=CS
      A4ARY(MA3)=CS
      BRGARY(MA4)=CS
101   CONTINUE
C
C QUERY FOR ANOTHER RUN.
C
207   WRITE(10,607)
      READ(5,502) NRERUN
      IF(NRERUN.NE.1) GO TO 204
      NCLOSE=10000-NHALT
C
C IF ANOTHER RUN, READ TO END OF FILE AND REWIND.
C
      DO 102 I3=1,NCLOSE
102   READ(1,503,END=205)
205   REWIND 1
      GO TO 206
204   STOP
600   FORMAT('0THIS PROGRAM GRAPHS SWRI DATA VERSUS TIME')
601   FORMAT('0FILE CONSISTS OF 10000 RECORDS REPRESENTING 200 SECS.',
     A/,'0ENTER START TIME IN SECONDS (I3):')
602   FORMAT('0ENTER STOP TIME IN SECONDS (I3) (200 MAX):')
603   FORMAT('0ENTER SOURCE,FREQ AND TIME:')
604   FORMAT('0OUTPUT TO PRINTER ENTER 1, TO CONSOLE, ENTER 2:')
605   FORMAT(1X,24A1,'**',24A1,'**',15A1,'**',10A1)
606   FORMAT(1X,45A1,'*',45A1,'*',20A1,20A1)
607   FORMAT('0ENTER 1 FOR ANOTHER RUN,IF NOT, ENTER OTHER INTEGER:')
500   FORMAT(I3)
501   FORMAT(20A1)
502   FORMAT(I1)
503   FORMAT(3A4,2A2)
      END
C
C THIS SUBROUTINE WRITES A LABEL TO A CRT OR A PRINTER.
C
      SUBROUTINE LABEL(NOUT,SOURCE)
```

```
      LOGICAL*1 SOURCE(20)
      WRITE(8,600)
      WRITE(8,601) SOURCE
      IF(NOUT.EQ.1) GO TO 200
      WRITE(8,602)
      WRITE(8,603)
      RETURN
200   WRITE(8,604)
      WRITE(8,605)
      RETURN
600   FORMAT('1',20X,'SWRI SPACED LOOP ANTENNA PARAMETERS',/,
     A21X,'A0,PHASE,A4 AND BEARING VERSUS TIME',////)
601   FORMAT(21X,'RADIOWAVE SOURCE: ',20A1,//)
602   FORMAT(11X,'BEARING',19X,'PHASE',18X,'A0',11X,'A4',/,
     A'00',20X,'360',2X,'-180',7X,'00',7X,'+180',2X,'0',
     B13X,'2',2X,'0',8X,'1')
603   FORMAT(1X,79('*'),/,1X,79('*'))
604   FORMAT(18X,'BEARING',41X,'PHASE',33X,'A0',19X,'A4',/,
     A'00',41X,'360',1X,'-180',37X,'+180','0',18X,'2',
     B1X,'0',18X,'1')
605   FORMAT(1X,132('*'))
      END
C
C THIS SUBROUTINE MAPS A VARIABLE (VAR) WHICH LIES ON OR BETWEEN
C A MINIMUM VALUE (VARMIN) AND A MAXIMUM VALUE (VARMAX) TO AN
C ELEMENT (M2) OF AN ARRAY OF LENGTH (M1).
C
      SUBROUTINE MAPF(VAR,VARMIN,VARMAX,M1,M2)
      IF(VAR.GT.VARMAX) VAR=VARMAX
      M2=INT(FLOAT(M1)*(VAR-VARMIN)/(VARMAX-VARMIN))+1
      IF(M2.GT.M1) M2=M1
      RETURN
      END
C
C THIS SUBROUTINE IS AN INTEGER VERSION OF THE ABOVE ROUTINE MAPF.
C
      SUBROUTINE MAPI(N,NMIN,NMAX,M1,M2)
      IF(N.GT.NMAX) N=NMAX
      M2=INT(FLOAT(M1)*FLOAT(N-NMIN)/FLOAT(NMAX-NMIN))+1
      IF(M2.GT.M1) M2=M1
      RETURN
      END
```

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