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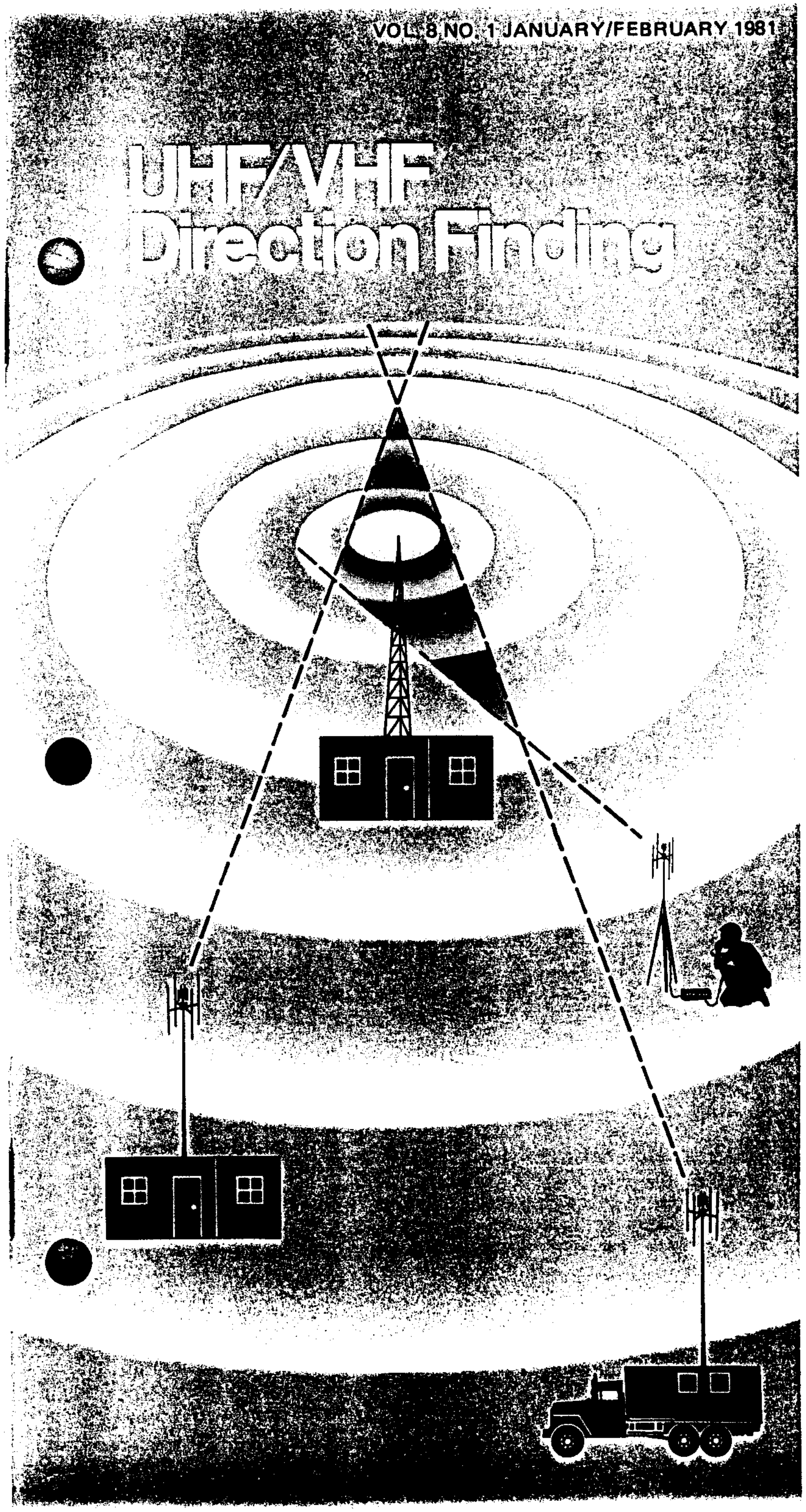
UHF/VHF Direction Finding



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VHF/UHF Direction Finding

This article investigates the tactical communications environment in relationship to engineering constraints pertinent to the design of effective direction-finding (DF) equipment. The pseudodoppler FM DF design approach is discussed along with performance results in operational test conditions.

Exploitation of the tactical communications spectrum is ever increasing in importance. Signal intelligence and associated electronic support measures provide a key dimension in completing the picture of an attacking force and its disposition. Information derived from these sources can give the number, type, strength and location of enemy units. When combined with DF information, weapon dispositions can be determined. Knowing the position of a station in a communications net can be crucial. For jamming operations, signal intercept is a normal prerequisite, although precise location data is not essential for communications targets. However, general emitter location is necessary to orient jammer directional antennas.

Operational Environment

Aspects of the operational environment within which intercept and DF are conducted and within which the DF system must perform may be grouped in categories which generate and describe requirements and constraints. These categories are electrical, doctrinal and performance. In general, the frequency band of interest encompasses 1.5 to 500 MHz (MF, HF, VHF, UHF). During conflict, when performance is most urgent, spectral power density in the band will be high. Furthermore, the target communication signals will be of short duration and present only a fleeting opportunity to intercept or accomplish DF.

A second category consists of the doctrinal approach to deployment of intercept capability. Employment of DF resources depends on the organizational infrastructure of the tactical units. Intercept equipment operators may be deployed with intermediate headquarters or with maneuver elements. The latter approach requires mobile or man-portable equipment. How the DF capability complements operations in various phases of conflict will have an impact on performance requirements. How the planned deployment relates to the distinct maneuver stages will determine such performance requirements as range and signal-handling capacity. The maneuver stages are: Wait in Reserve, Movement to Contact, Meeting Engagement, Engagement, and Withdrawal.

The third category is the set of objective performance parameters expressed in operational terms. These result from measures of responsiveness to the doctrinal approach taken and the signal environment. The parameters include speed of intercept and DF, accuracy, physical and electrical survivability, and electrical versatility. In the most general tactical environment, equipment should be designed to meet the following specifications:

Intercept/DF Time . . . . < 2 sec
Line of Bearing
  Accuracy . . . . < 5 degrees
Camouflage . . . . Low silhouette
Mobility . . . . Man portable

Electrical Environment

The physical environment of interest includes virtually all types of terrain, topographical features, man-made obstructions and weather. Variance of the physical features and phenomena between potential scenarios is wide, and each situation will affect radiowave propagation to a unique degree. However, within the variance range, propagation characteristics can be classified and bounded quantitatively.

A target-transmitted signal is described by its frequency, strength, modulation waveform and polarity. Propagation geometry conforms to the transmitter antenna radiation pattern.

The signal expressed as a propagation electric field, E, is:

$$E(f,t,\phi) = E(t)\sin\left(\omega t - \frac{2\pi d}{\lambda} + \phi\right)$$

Where,

$\omega = 2\pi f$, radian frequency
$\lambda = (3\times10^8\ \text{m/sec})/f$, wavelength in meters
f = frequency in Hertz
d = the distance from the transmitter in meters
$E(t)$ = the modulation waveform
E = the electric field vector
$\frac{2\pi d}{\lambda} + \phi$ = true phase referenced to the transmitter.

The expression gives the electric field vector, E, at any distance, d, with respect to its value at the transmit antenna. Existing perpendicular to the electric field is the magnetic field, represented by the vector, H. Interaction of the two fields, as in the cross product of H x E (H cross E), causes propagation perpendicular to their mutual vector plane (the electromagnetic wavefront of the signal). Figure 1 depicts a propagation radial, d, for a vertically polarized signal.

Propagation geometry in three-dimensional space conforms to the transmitting antenna radiation pattern. The received target signal is described by its frequency, strength, modulation waveform and polarity. These signal parameters yield the essential characteristics required for signal-intelligence intercept. However, for direction finding, one other target signal characteristic is paramount: the propagating wavefront. Thus, direction finding equates to the determination of angle of arrival for an rf wavefront. It is on this basis that all direction-finding systems have the same task. The extent to which a direction finder can detect a radio wavefront, and the accuracy with which it can measure the angle of arrival determine its operational capability.

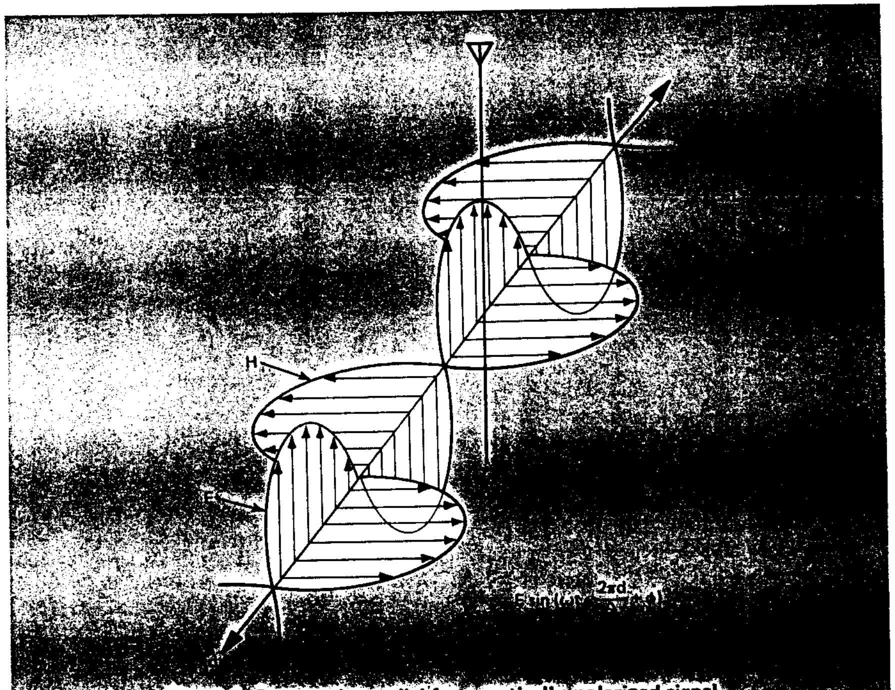


Figure 1. Propagation radial for a vertically polarized signal.

By virtue of the signal receiving process, a directional finder must also be a radio receiver. Therefore, DF systems are subject to the limitations and problems of radio communications in general. The desired received signal (the target), will be degraded by natural and system noise, interfering signals and system processing distortion. Direction finding is also affected by wavefront distortion, i.e., the difference from true line of sight between the target transmitting and receiving DF antennas and the wavefront angle of arrival. Minimizing these adverse effects is a function of system sensitivity, dynamic range and linearity.

Because the phenomena and equipment design problems are frequency-band related, the scope of this examination will be constrained to direction finding against target signals within the following category:

Frequency	20-500 MHz (HF, VHF, UHF)
Modulation	FM, short duration
Polarization	Vertical
Radiation Pattern	Omnidirectional
Radiated Power	30+dBm
Location	Out to 30 Km

Signal Propagation

It can be shown from free space and plane earth theories that:

$$P_r = \left(\frac{E\lambda}{2\pi}\right)^2 \frac{G_r}{120} \quad (1)$$

$$P_t = \frac{E_o^2 d^2}{30\ Gt} \quad (2)$$

$$\frac{E}{E_o} = 2 \sin\left(\frac{2\pi h_t h_r}{d}\right); \quad (3)$$

$$\Delta > 0.5 \text{ radian}$$

$$\left|\frac{E}{E_o}\right| = \left|\frac{4\pi h_t' h_r'}{\lambda d}\right|; \ \Delta < 0.5 \text{ radian} \quad (3a)$$

Where,

G_r = Power-gain ratio of receiving antenna
E_o = Free-space electric field
P_t = Transmitted power
h_t & h_r = Antenna height in meters (transmitting and receiving, respectively)
d = Distance, in meters, between antennas
λ = Wavelength
$\Delta = 4\pi h_t h_r/\lambda d$; for d>5 (h_t+h_r) (Δ represents the phase difference in radians between direct and reflected rays of the received signal.)

An equation showing the ratio of received power to transmitted power is:

$$\frac{P_r}{P_t} = \left(\frac{E}{E_o}\right)^2 \left(\frac{\lambda}{4\pi d^2}\right)^2 G_r G_t \quad (4)$$

$$= \left(2 \sin \frac{2\pi h_t h_r}{\lambda d}\right)^2 \left(\frac{\lambda}{4\pi d}\right)^2 \quad (4a)$$

$$\text{x } G_r G_t; \Delta > 0.5$$

$$= \left(\frac{h_t' h_r'}{d^2}\right)^2 G_r G_t; \Delta < 0.5 \quad (4b)$$

Note that equation 4b is independent of frequency.

The equations just presented assume a flat plane earth. An equation developed by Egli [2] for irregular terrain with average hill height of 15 meters is:

$$\frac{P_r}{P_t} = \left(\frac{h_t h_r}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 G_r G_t \quad (5)$$

Schmid [3] takes this even further for specified receiving antenna heights:

$$\frac{P_r}{P_t} = \left(\frac{h_t h_r}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 G_r G_t; \quad (6)$$

for $h_r \geqslant 9$ meters

$$= \left(\frac{h_t\ [9.15(h_r/9.15)1/2]}{d^2}\right)^2$$

$$\left(\frac{40}{f}\right)^2 G_r G_t;$$

$$2 \text{ m} \leqslant h_r \leqslant 9 \text{ meters}$$

For $h_r < 2$ meters use equation 5 and minimum effective antenna height.

In short-range operation, the surface wave is of major importance. Thus, due to the conductiveness of the earth, there is a phenomenon known as the *effective antenna height*, where, depending on the type of soil, an antenna will behave in the same manner as an antenna of much greater height (see Figure 2).

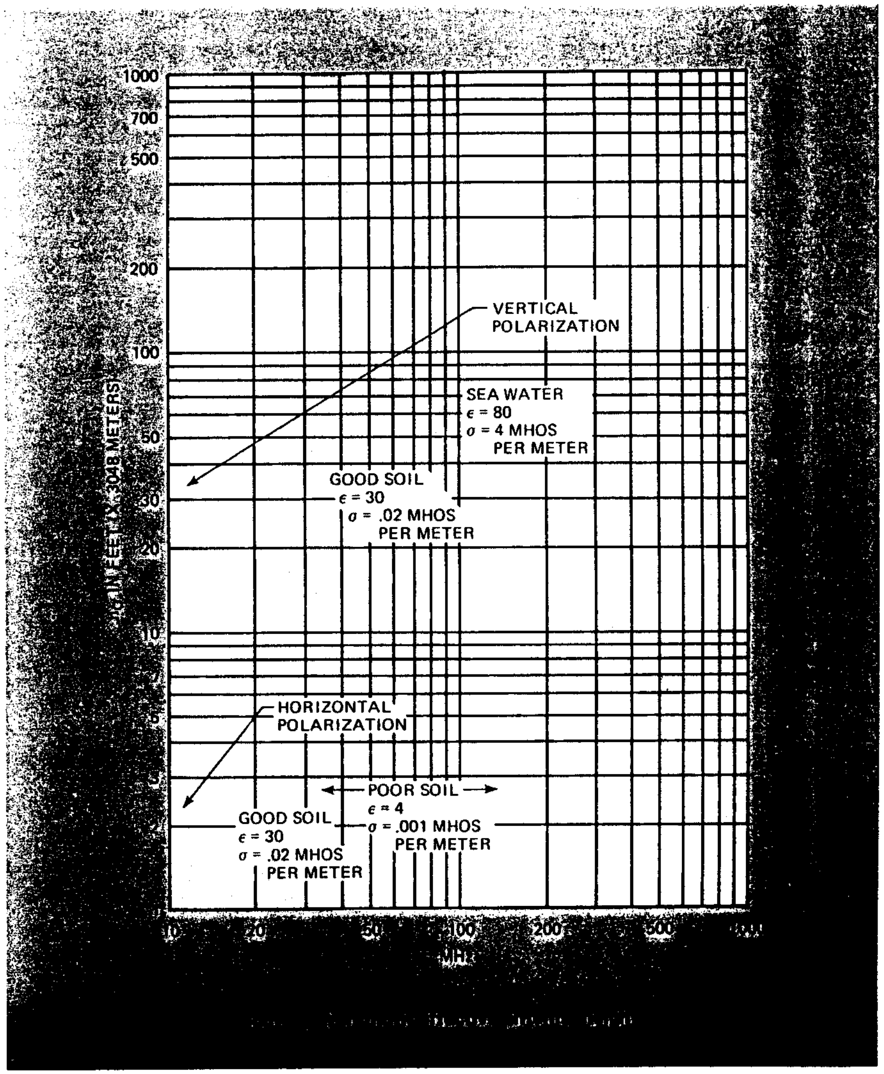
Final Propagation Formulas

The empirical formula for RF-wave propagation has been developed to:

$$\frac{P_r}{P_t} = \left(\frac{h_t h_r}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 G_r G_t \quad (7)$$

where,

h = antenna height in meters; h > λ. (Physical or electrical height, whichever is greater)
d = distance between antennas in meters; d < 64.4 Km
G = power-gain ratio (1.64 for halfwave dipole)
f = frequency in MHz, good for 40 MHz ⩽ f ⩽ 400 MHz, but will show little error up to 1000 MHz.



Average terrain level of 15 meters (50 ft.)

When represented as a dB loss, the empirical formula becomes:

$$L = 40 \log_{10} d + 20 \log_{10} f - 20 \log_{10} h_t h_r - 32 - 10 \log_{10} G_r G_t \quad (8)$$

Expressed in English units; h in feet, d in miles (d < 40 miles)

$$\frac{P_r}{P_t} = 0.129 \left(\frac{h_t h_r}{d^2}\right)^2 \left(\frac{40}{f}\right)^2 \times G_r G_t \times 10^{-14} \quad (9)$$

dB loss is

$$L = 117 + 40 \log_{10} d + 20 \log_{10} f - 20 \log_{10} h_t h_r - 10 \log_{10} G_r G_t \quad (10)$$

Also, the equations extend down to 20 MHz with at least a 0.3 dB/MHz improvement.

Received power values versus propagation distance are plotted in Figures 3a, 3b, and 3c for various transmitter power levels using vertical halfwave dipoles and the effective antenna height.

In either metric or English units, to allow for hill heights other than 50 feet (15 m), add the terrain correction factor found in Figure 4 to the dB loss obtained in equations (8) or (10).

Finally, other special conditions affect radio propagation. Atmospheric noise decreases with increasing frequency. Trees in full foliage cause highest attenuation at frequencies near 450 MHz.

The propagation formulas take into account that E-field intensity will be reduced by attenuation, absorption and shadowing, and also that electrical phase delay can occur due to reflection. The wavefront will be composed of direct and reflected waves. However, since air is a linear medium, these components will exist separately and do not combine except in a receiver non-linear stage. For a properly designed DF system, wavefront distortion in the vertical plane is of no

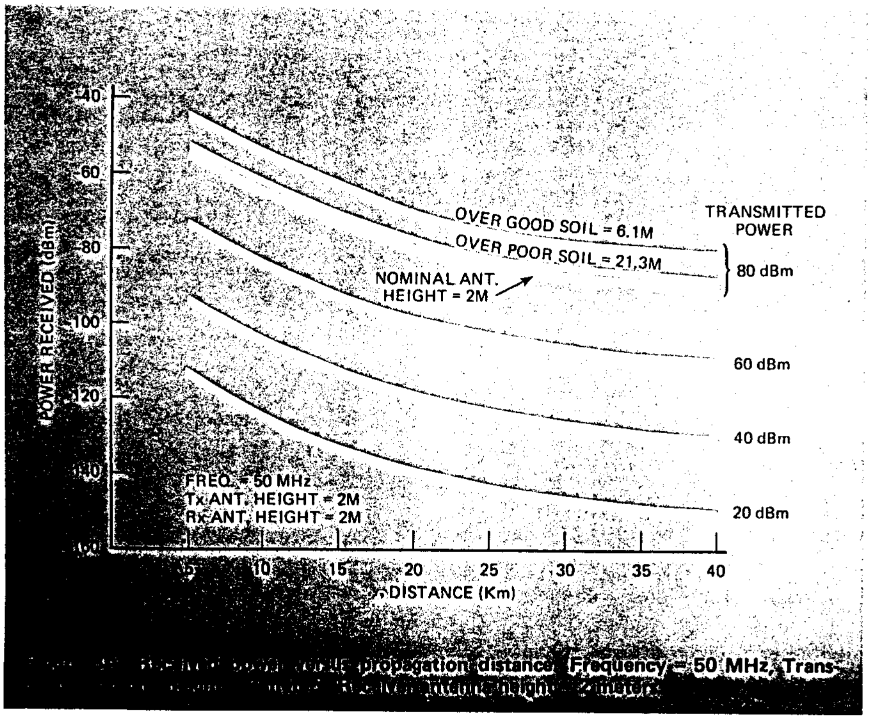


Figure 3A. Received power versus propagation distance. Frequency = 50 MHz, Transmitter antenna height = 2 meters, Receiver antenna height = 2 meters.

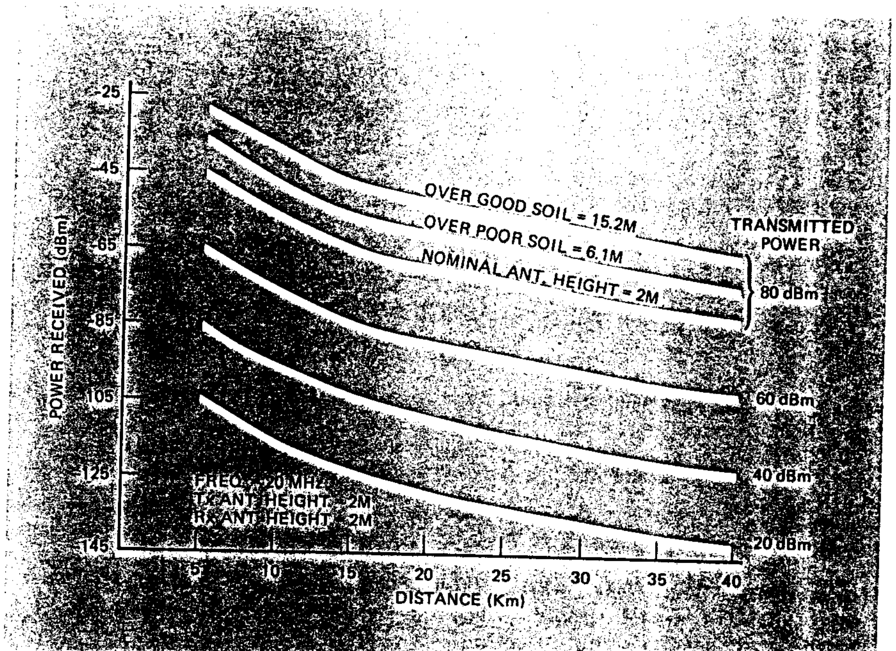


Figure 3B. Received power versus propagation distance. Frequency = 20 MHz, Transmitter antenna height = 2 meters, Receiver antenna height = 2 meters.

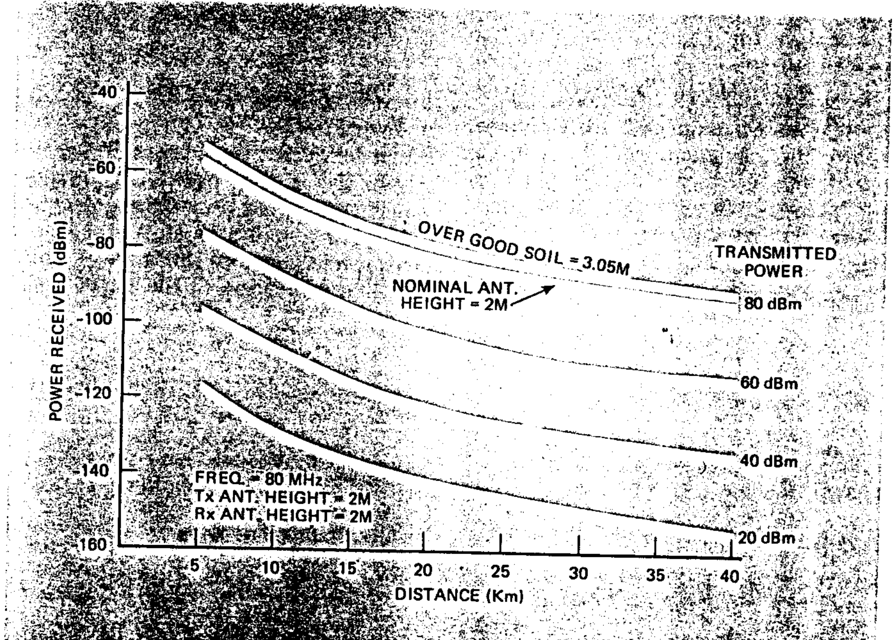


Figure 3C. Received power versus propagation distance. Frequency = 80 MHz, Transmitter antenna height = 2 meters, Receiver antenna height = 2 meters.

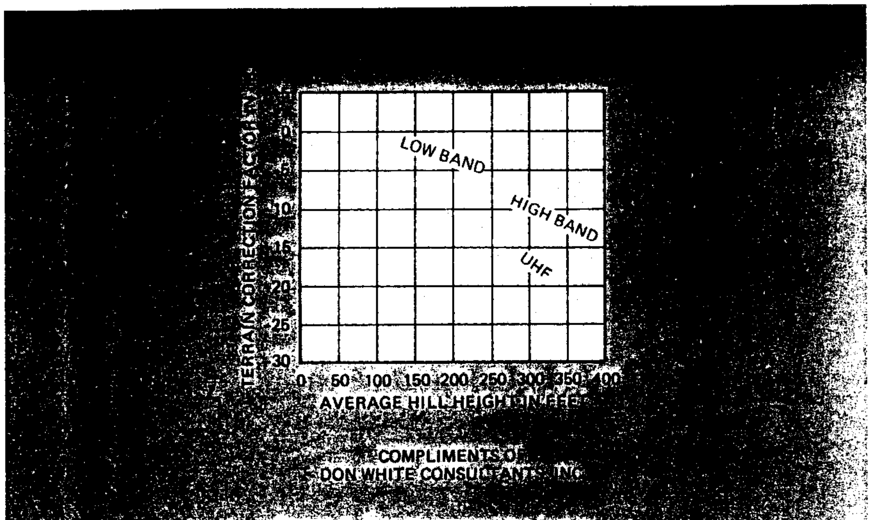


Figure 4. Terrain correction factor.

consequence. Only the horizontal plane angle of arrival should affect the line of bearing. The direction-finding geometry is shown in Figure 5.

The wavefront is vertically polarized and travels in the direction of the normal vector which, when related to North, is 180° + θ. The DF problem is to determine the angle of arrival, or, precisely, θ.

Doppler FM DF Technique

A rotating dipole DF antenna is shown in Figure 6.

The received signal, $E_r(t)$, varies periodically in frequency according to its angular velocity, α. That is,

$$E_r(t) = GE \sin\left(\omega t + \Delta\,\omega t - \frac{2\pi d}{\lambda} + \phi\right)$$

Where,

G = antenna gain
l = radius arm
α = angular velocity

$$\Delta\omega t = f(\alpha, t, \theta) = \frac{l}{\lambda} \cos(\theta - \alpha t)$$

A maximum frequency shift occurs when the angular position equals the angle of arrival, or when $\alpha = \theta$. (Another maximum shift to higher frequencies occurs 180° later.) Thus, the line of bearing to the target signal can be determined from the output of an FM discriminator processing $E_r(t)$. In this system, electromechanical interface is required. Accuracy and resolution are dependent on knowing the position αt, FM deviation and detector threshold, and the magnitude of α relative to FM modulation components on the target signal.

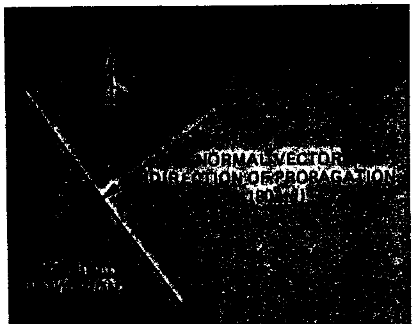


Figure 5. Horizontal plane view radio [illegible]

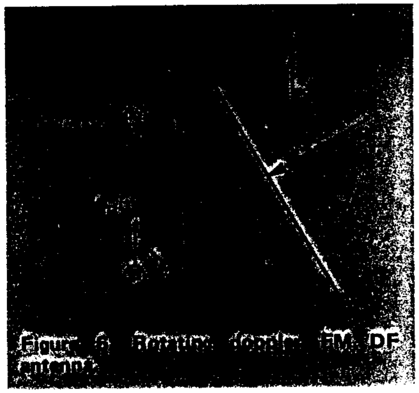


Figure 6. Rotating doppler FM DF antenna.

Pseudodoppler FM Technique

An approach which eliminates the mechanical disadvantages mentioned above is a quadrature-mounted, four-element DF antenna array (see Figure 7). The array remains stationary, but the elements are switched on and off in sequence to achieve an apparent electrical rotation. The received signal (S_i) is represented by any one of the following values: S_1, S_2, S_3, and S_4.

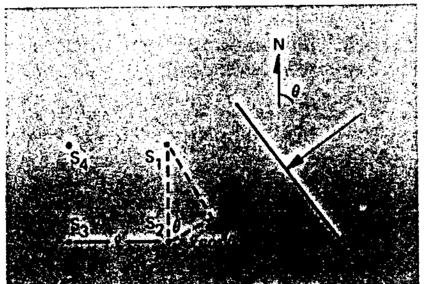


Figure 7. Pseudodoppler FM DF antenna array.

$$S_1 = A \sin\left(\omega t - \left(\frac{2\pi d}{\lambda} + \phi\right)\right)$$

$$S_2 = A \sin\left(\omega t - \left(\frac{2\pi d}{\lambda} + \phi + \frac{2\pi \ell}{\lambda} \sin\theta\right)\right)$$

$$S_3 = A \sin\left(\omega t - \left(\frac{2\pi d}{\lambda} + \phi + \frac{2\pi \ell}{\lambda} \cos\theta - \frac{2\pi \ell}{\lambda} \sin\theta\right)\right)$$

$$S_4 = A \sin\left(\omega t - \left(\frac{2\pi d}{\lambda} + \phi + \frac{2\pi \ell}{\lambda} \cos\theta\right)\right)$$

Where, ℓ is the spacing between elements on the same side and A is the information on the received signal.

The radio frequency does not shift between elements, although a shift is apparent to a phase detector mixing the signals of two elements. Thus, the technique is labeled pseudodoppler. Not revolving the antenna simplifies knowing its instantaneous orientation relative to North.

If the signal pairs are compared sequentially, the real rf phase compared to the value at the transmitter vanishes and the instantaneous phase component differences result as follows:

$$S_1 - S_2 = A \sin\left(\omega t + \frac{2\pi \ell}{\lambda} \sin\theta\right)$$

$$S_2 - S_3 = A \sin\left(\omega t + \frac{2\pi \ell}{\lambda} \cos\theta\right)$$

$$S_3 - S_4 = A \sin\left(\omega t - \frac{2\pi \ell}{\lambda} \sin\theta\right)$$

$$S_4 - S_1 = A \sin\left(\omega t - \frac{2\pi \ell}{\lambda} \cos\theta\right)$$

These are four constants with unique values for any value of θ, and may be used to derive θ. These relationships establish the design parameters for this approach. The antenna gain must provide system sensitivity compatible with field intensity, E. The element spacing (ℓ) determines resolution and is selected to avoid ambiguous periods of the target signal wavelength. In general, the design constraint

$$\frac{\lambda}{18} < \ell < \frac{5\lambda}{12}$$

is observed.

The four phase values follow the general characteristics shown in Figure 8.

Three signals are enough to derive an unambiguous value for θ. However, four signals will enhance resolution and accuracy.

If the sampled signals are processed through a linear system to a digital network, averaging reduces the un-

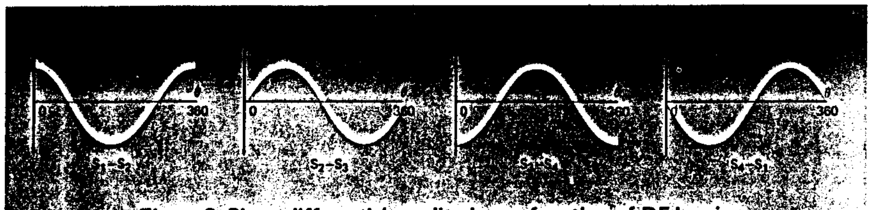


Figure 8. Phase differential amplitude as a function of DF bearing.

desirable effects of noise, interference and reflected wavefronts resulting from horizontal multipathing of the wave. The basis of the pseudodoppler FM design used in the WJ-8975 Manpack DF Processor is depicted in Figure 9.

This approach uses a common local oscillator with the radio receiver. Thus, the DF processor is frequency independent. The sampled waveform passes through the time analog section to a commutative filter that integrates successive phase shift samples between the same element pair. The system is linear. Its accuracy depends on rejection of unwanted energy in the passband and FM discriminator linearity. Processing after the discriminator narrows the effective bandwidth and nulls random noise and modulation components by averaging through the integrator. The digital network permits repeat sampling and gives control flexibility.

Performance Test Results

To evaluate the accuracy of the pseudodoppler FM technique, the WJ-8975 DF Processor and WJ-9880 DF Antenna were tested in typical tactical environments. System accuracy tests were conducted at sites with rolling terrain in proximity to trees.

The expected error characteristic shown in Figure 10 is the theoretical performance of the four-element array, and results from parasitic reradiation among the elements. The WJ-9880 has resistively loaded elements to control this error characteristic and also to achieve broadband frequency response.

Actual results for frequencies from 20 to 175 MHz are shown in Figures 11 through 14.

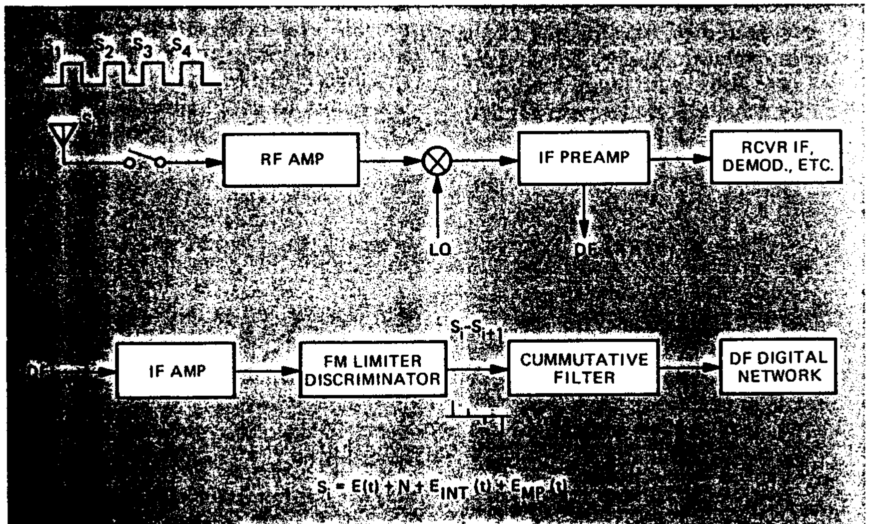


Figure 9. Pseudodoppler FM DF processor.

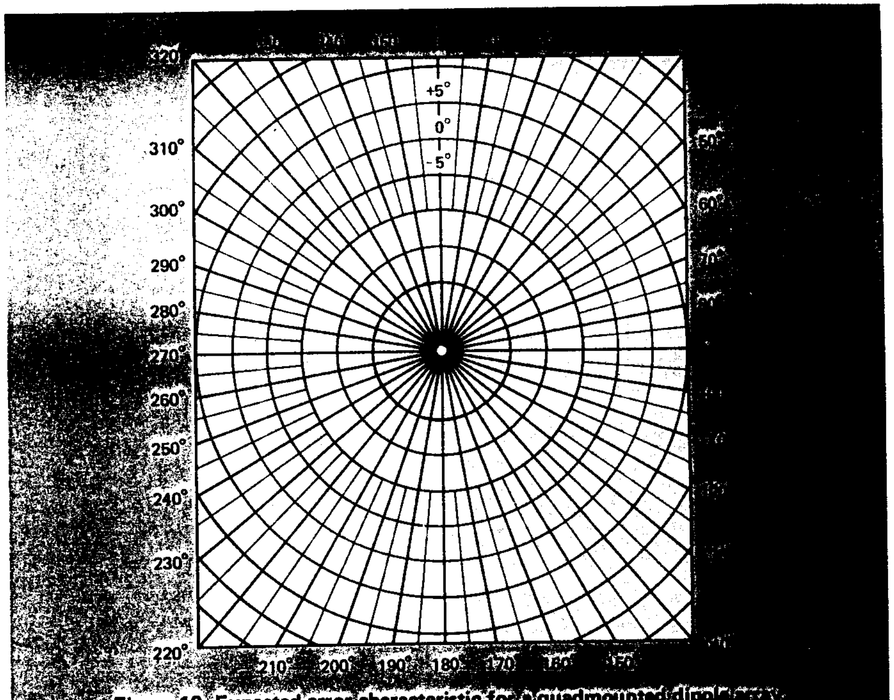


Figure 10. Expected error characteristic for a quadmounted dipole array.

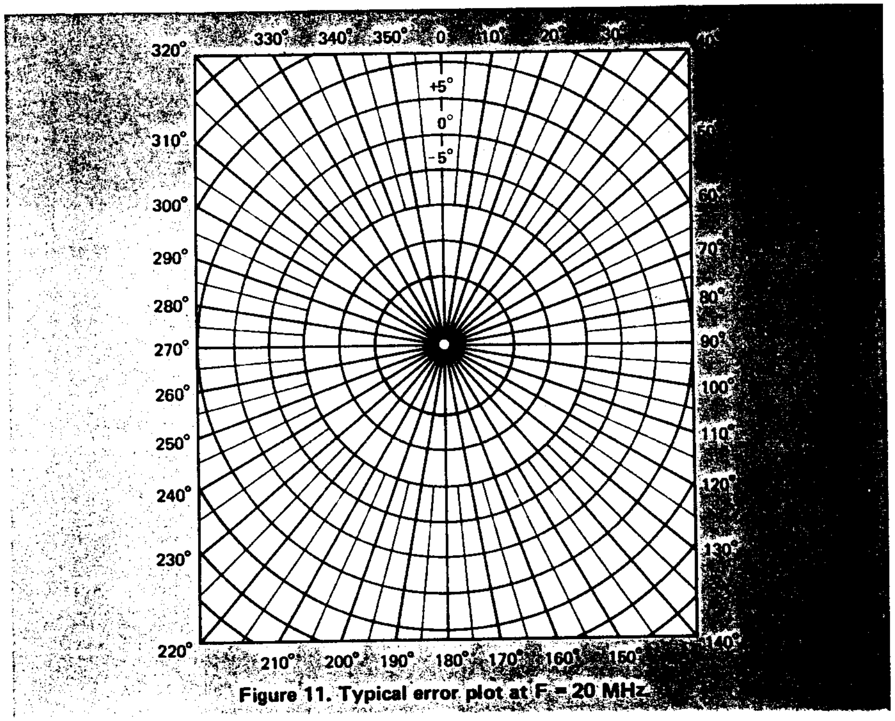


Figure 11. Typical error plot at F = 20 MHz.

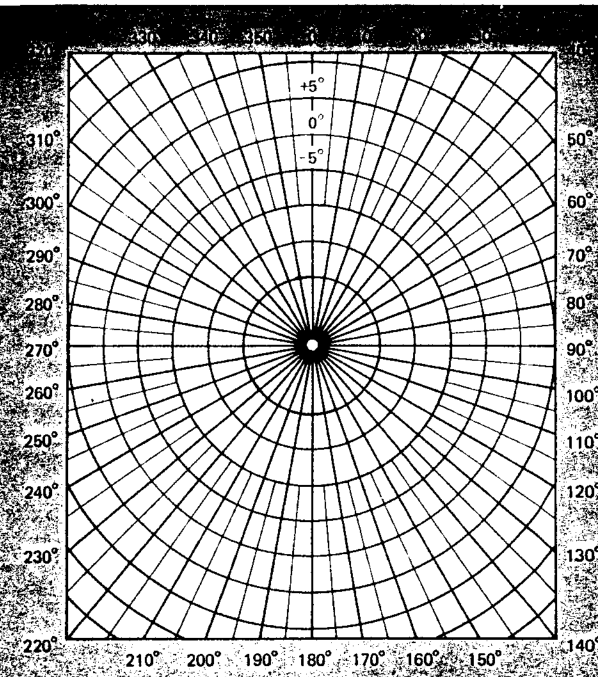


Figure 12. Typical error plot at F = 40 MHz.

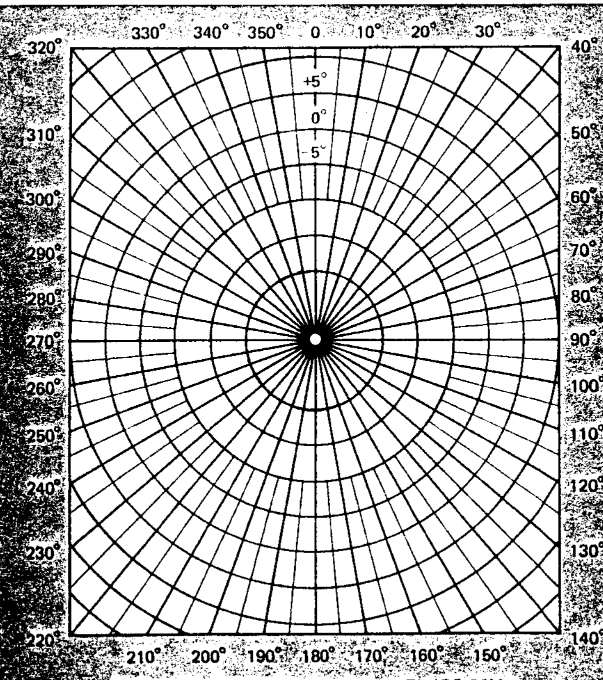


Figure 13. Typical error plot at F = 80 MHz.

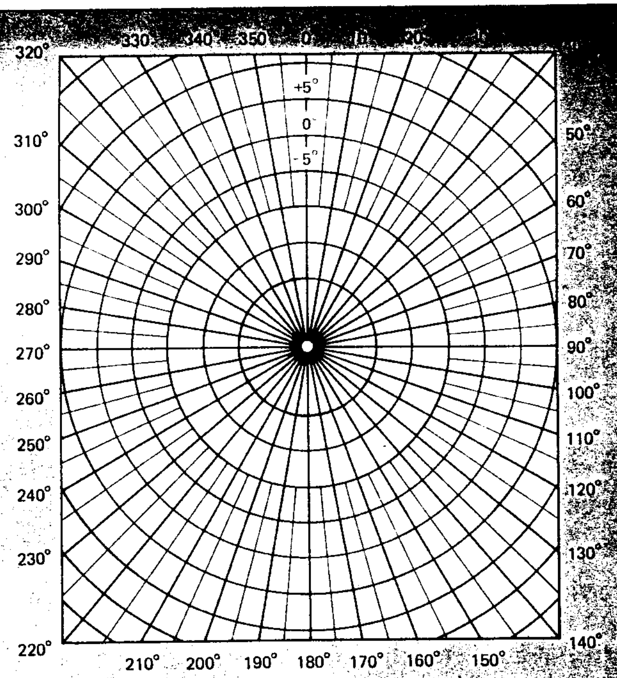


Figure 14. Typical error plot at F = 170 MHz.

The responses show a high degree of symmetry and worst-case error deviations at the frequency-band end points.

Summary

This paper is an introductory discussion of the theory of communications as it applies to direction finding. Also presented is one possible solution to resolving the angle of arrival of a wavefront — the pseudodoppler technique. By reviewing the DF error plots, Figures 11 through 14, the W-J method for pseudodoppler direction finding is a viable application of this solution.

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