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**ANTENNA CONCEPTS AND TECHNOLOGY FOR NAVY HIGH
FREQUENCY SHORE SITES**

by

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ABSTRACT

This research has investigated some new and existing technologies that might be employed to improve the performance of high frequency (HF) Navy shore sites. The focus is primarily on the antenna. Conventional HF antennas like wires and loops have low gain and nearly isotropic radiation patterns. An array of these simple elements can overcome these limitations and provide increased gain, improved signal-to-noise ratio on receive, low sidelobes, and scanned directive beams. Digital beamforming with electronically scanned phased arrays is of special interest. This analysis reveals that several shore site configurations are possible. For a particular case, the best selection will depend on the circumstances of the site geography, available land area, local electromagnetic issues (i.e., interference, radiation restrictions, etc.) and the desired coverage. A detailed tradeoff study is recommended for each site.

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LIST OF ACROYNMS

ALE	automatic link establishment
AREPS	Advanced Refractive Effects Prediction System
AM	amplitude modulation (standard broadcast)
ADC	analog to digital converter
AZ	azimuth
BW	bandwidth
COTS	commercial off-the-shelf
DAC	digital to analog converter
DDS	direct digital synthesis
EL	elevation
F/B	front-to-back (ratio)
HPBW	half power beamwidth
HF	high frequency
IP	internet protocol
I/Q	in-phase/quadrature
ISM	instrumentation, scientific and measurement (frequency band)
LAN	local area network
LNA	low noise amplifier
LO	local oscillator
LOS	line of sight
LPDA	log periodic dipole array
LPMA	log periodic monopole array
LPI	low probability of intercept
MKS	meter-kilogram-second
NVIS	near vertical incidence skywave
PA	power amplifier
SATCOM	satellite communications
SNR	signal-to-noise ratio
SDR	software defined radio
T/R	transmit/receive
UHF	ultra-high frequency

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I. INTRODUCTION

A. BACKGROUND

The high frequency (HF) band in the range of 3 MHz to 30 MHz has been used for decades for long-range communications (comms). Long ranges are made possible by some unique propagation mechanisms that occur at these frequencies, primarily ground waves and ionospheric reflections [1–3]. Since the advent of satellite communication (SATCOM) systems in the 1960s, HF systems have gradually decreased in importance. Recently, concerns over the security and vulnerability of satellite systems have renewed the interest in HF comms as a backup network in the event of SATCOM performance degradation or failure.

For two-way communication, the important considerations are the transmitters, receivers, antennas, and propagation channel, i.e., the physical environment between the two communicating nodes. The propagation mechanisms at HF frequencies are generally divided into three categories as illustrated in Figure 1: the space wave (line of sight plus surface reflection), ground wave (a wave guided by the interface between the ground and air) and sky wave (propagation via the ionosphere). Several of these may be present simultaneously, and they can change with time [1].

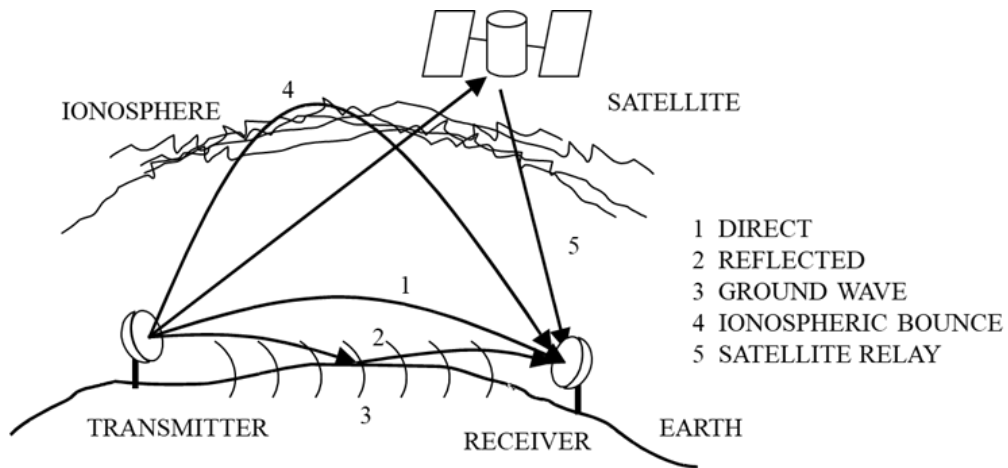


Figure 1. Illustration of HF propagation mechanisms.

The communication links of interest in this study are those for longer distances (hundreds to thousands of km) that are achieved via skywave paths. For long distance paths with ground-based antennas, vertical polarization is desired, and the launch angle of the antenna beam is near

the horizon. An example of a skywave path is shown as item 4 in Figure 1. The AREPS software tool can be used to calculate the ray paths for various ionosphere conditions [4].

For long distances, the systems require high transmitter powers and very sensitive receivers that can detect weak signals. In this study, we limited the system to half duplex operation (i.e., not transmitting and receiving simultaneously). This simplifies the transmit/receive isolation problem because the receiver can be switched out while transmitting and vice versa if necessary.

B. ANTENNA AND SHORE SITE CONFIGURATIONS

The antenna performance affects both the transmitted and received signal strengths, so maximizing the antenna gain is also desirable. However, the gain is just one of the many tradeoffs in the antenna selection. Electrically large antennas are characterized by $L / \lambda \gg 1$ where L is the maximum dimension of the antenna and λ is the wavelength. At HF frequencies, the wavelengths range from 100 m at the low end to 10 m at the high end. Therefore, even electrically small antennas are physically large. The maximum allowable size, and thus gain, is often limited by the available space. Some existing HF radar systems have antennas that are several kilometers long [5].

Electrically large antennas also have the advantages of greater gain, a narrow beam and potentially low sidelobes [6]. These characteristics increase covertness and yield a low probability of intercept (LPI) by an adversary's intercept receiver. Even if an intercept receiver can detect the presence of signal, it may be too weak to process and recover the signal's information, or to determine the location of the transmitter.

An important characteristic of the system is its operating bandwidth. HF systems tend to have a narrow instantaneous bandwidth; that is, the bandwidth necessary to transmit a waveform pulse of specific width with sufficient fidelity. Another measure is the tunable bandwidth, which can be much larger. An analogy is an individual AM radio station's bandwidth (instantaneous) versus the entire AM band (tunable). Ideally, a shore site should be able to operate over a large enough frequency range to cover all the remote HF systems of interest. A single antenna that covers the entire band is one option. Another option is to use multiple antennas that operate over a set of contiguous narrow bands.

The transmitter power level is another consideration. If hundreds of kilowatts are transmitted, the antenna and other radio frequency (RF) components must be able to handle the power. On the other hand, the receiving components must be very sensitive to handle the low power levels received while adding minimal noise. These requirements can impose stringent demands on devices and antennas that both transmit and receive. It might be more efficient to have separate transmitting and receiving antennas to optimize their individual performances. The two antennas would likely be located at the same site, although they could be more widely separated. We refer to this geometry as the bistatic case, analogous to radar terminology. Similarly, a single antenna for transmitting and receiving is referred to as the monostatic case. The two possible geometries with antenna patterns shown are depicted in an overhead view (plane of the ground or azimuth plane) in Figure 2. Most current systems use low-gain antennas with high-power transmitters that make the systems detectable.

C. ANTENNA PARAMETERS

We adhere to the IEEE definitions of directivity, gain, and realized gain. Somewhat arbitrarily, we consider the term low gain to refer to antennas that have a nearly isotropic pattern and peak gain value (G_0) in the range of ~ 0 dB or less, while high gain refers to a more directive antenna with gain values greater than about 5-10 dB. Other important antenna parameters are the input impedance (Z_{in}), bandwidth (BW or Δf), and half power beamwidth (HPBW or θ_B). In this report the MKS system of units is used unless otherwise stated.

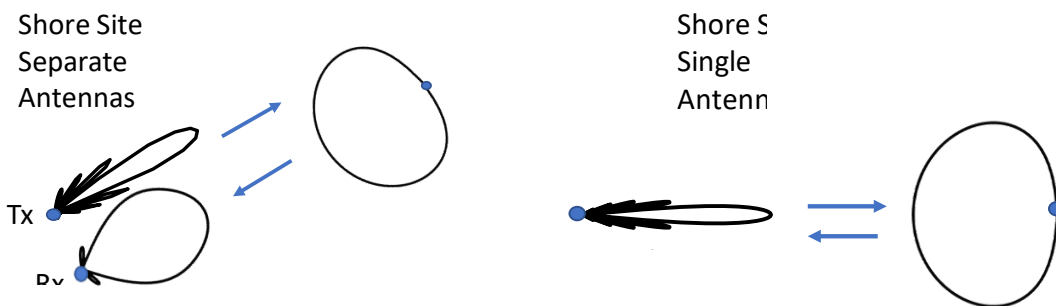


Figure 2. Two approaches to the system configuration: two antennas collocated at a site or separated sites (bistatic case, left) and one antenna for both transmitting and receiving (monostatic case, left).

A typical ground-based aperture antenna and one possible coordinate system definition are shown in Figure 3. A vertically polarized aperture is shown, with broadside being along the y axis in this case. Azimuth, elevation, horizontal and vertical are referenced to the ground. The x -

y plane is azimuth or horizontal (the ground). The y - z plane is vertical or elevation. The elevation angle is measured from the ground ($EL = 90^\circ - \theta$). Azimuth angle AZ is generally measured from broadside for antennas with a well-defined aperture with positive azimuth in a clockwise direction. The E and H planes are referenced to the antenna polarization. For the case shown, the E -plane is y - z , and the H -plane is x - y . These relationships may change if the antenna orientation changes with respect to the global (ground) cartesian coordinate system.

HF antenna technology is considered “mature” although new designs are being proposed as new materials and fabrication techniques come online. Surveys of “small antennas” appear in the literature (see for instance [7, 8]). Perhaps the most fundamental antennas are variants of wires: dipoles and monopoles. Other simple antennas include cones, bicones, folded dipoles, V-dipoles, meanderlines, loops, and helices. Of course, collections of these antennas can be used to form arrays. Fundamentally, the overall physical size of the antenna system is driven by the need to cover the lowest frequencies in the HF band where the wavelength is longest.

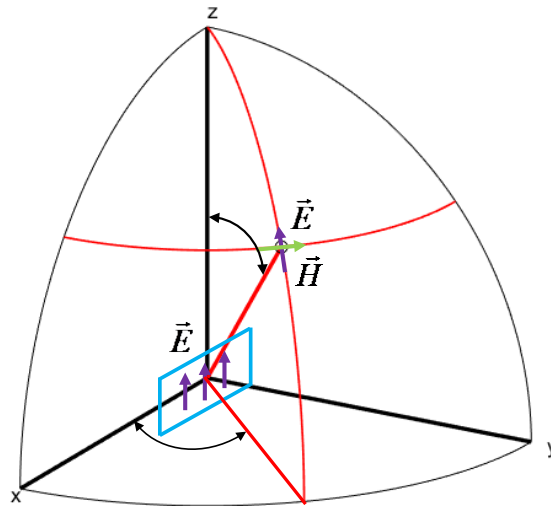


Figure 3. Typical vertically polarized antenna and ground-based coordinate system.

D. ANTENNA TECHNOLOGY

A particular case of interest in this study is where one node is a shore site and the other a ship-based or some other “mobile” user at long distance. Therefore, near vertical incidence skywave (NVIS) is not a priority. The mobile antenna is limited to the electrically and physically small regime, which implies a low gain and a broad beam as in Figure 2. There are more options available for the shore-based site. A practical limit for a shore site might be about

the size of an airfield. An advanced antenna at one end of the link can relax the demands of the hardware at the other end.

Commercial off-the-shelf (COTS) digital hardware is now available in the ISM (industrial, scientific and medical) bands, including HF and many of the surrounding frequencies. Other COTS system components (i.e., receiver and transmitter blocks) are briefly examined to see how new antennas might be exploited to improve system performance. Sophisticated transceivers are available that perform multiple functions, such as communications, data transfer, and possibly signal interception and emitter location. To date, most of these systems use simple antennas such as dipoles.

Improved shore site antenna gain and SNR would allow shipboard HF systems to transmit lower power, thus reducing the probability of a threat receiver intercepting the ship's transmission and locating the ship using the transmitted signal. Figure 4 shows a block diagram of a shore site system using a conventional passive array for both transmitting and receiving (the dashed block is a "transceiver"). A phased array is shown, but any other type of passive antenna can be used, for example a single dipole. The array might be comprised of N dipoles or monopoles. A passive array can incorporate adjustable phase shifters to scan the beam, but they have losses which reduce the array's gain. The losses are compensated for somewhat by adding the amplifiers to boost the input and output signal levels, but amplifiers introduce noise.

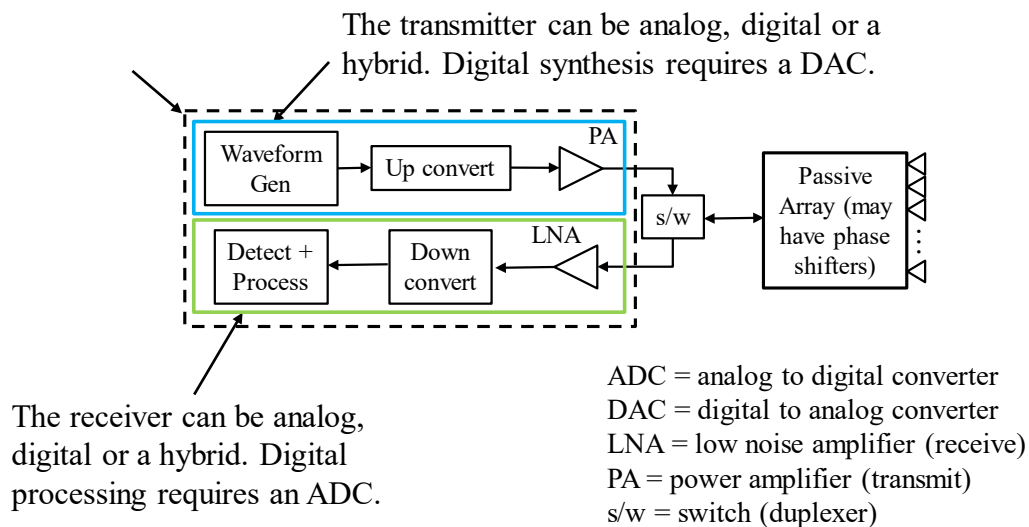


Figure 4. Block diagram of a system with a passive antenna.

In Figure 5 the block diagram of a shore site with an active antenna is shown. Active devices (e.g., low noise amplifiers, LNAs) are integrated into the antenna. The best receive SNR

is achieved when the LNAs are located directly behind the array element [9]. In order to perform coherent processing on the data, the array elements must be synchronized in time and frequency. For the passive system in Figure 4, the waveform generation, up and down conversion, and detection and processing are done in the transceiver block. For an active antenna, the up and down conversion process is moved from the transceiver into the array. The distribution of these functions makes it difficult to simply substitute an active array for a passive array when using existing transceivers.

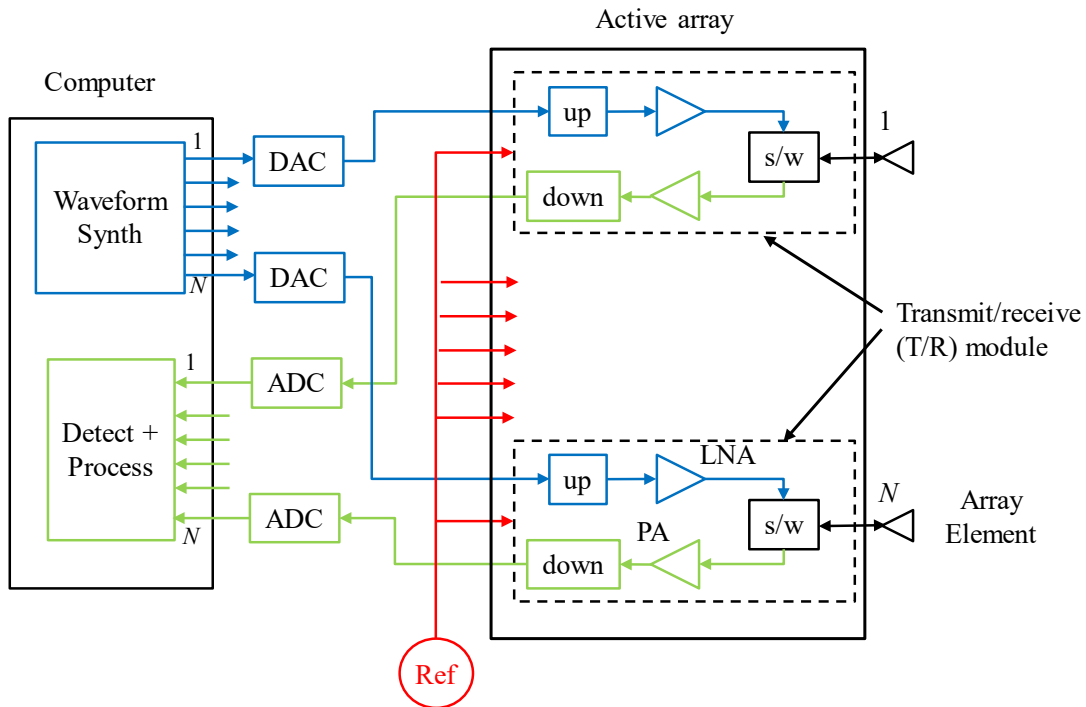


Figure 5. Block diagram of a generic shore site system using a digital array.

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II. ANTENNAS

A. INTRODUCTION

In this chapter, some traditional HF antenna architectures are presented, and their suitability for the shore site application is examined. As mentioned previously, the interest is in linear vertical polarization for long-range skywave links. Also, it is desirable to minimize the structural characteristics, which favors wire structures over solids or large meshes. For this reason, reflector antennas are not considered because of the large reflector areas that would be required for useful efficiencies at HF frequencies.

B. DIPOLES AND MONOPOLES

An efficient resonant center fed dipole is approximately a half wavelength, which is usually not practical in the HF band (half wavelengths range from about 5 to 50 m). Furthermore, the effect of the ground is important, and it significantly affects the antenna pattern and impedance. The presence of good ground can be exploited to reduce the overall antenna height by creating a monopole. The ground parameters are usually not reliable and stable, so ground wires or radials need to be added.

Figure 6 shows a simple 1-30 MHz monopole designed for mobile platforms, along with its specifications [10]. The efficiency is unacceptably low at the bottom of the band. Efficiency can be improved using variable tuning circuits, but even the tuned bandwidth will only be about 5% or less about the tuned frequency. There is a settling time for tuning, which limits the response time when changing frequency. To cover a wide band, a series of tuned dipoles can be used.

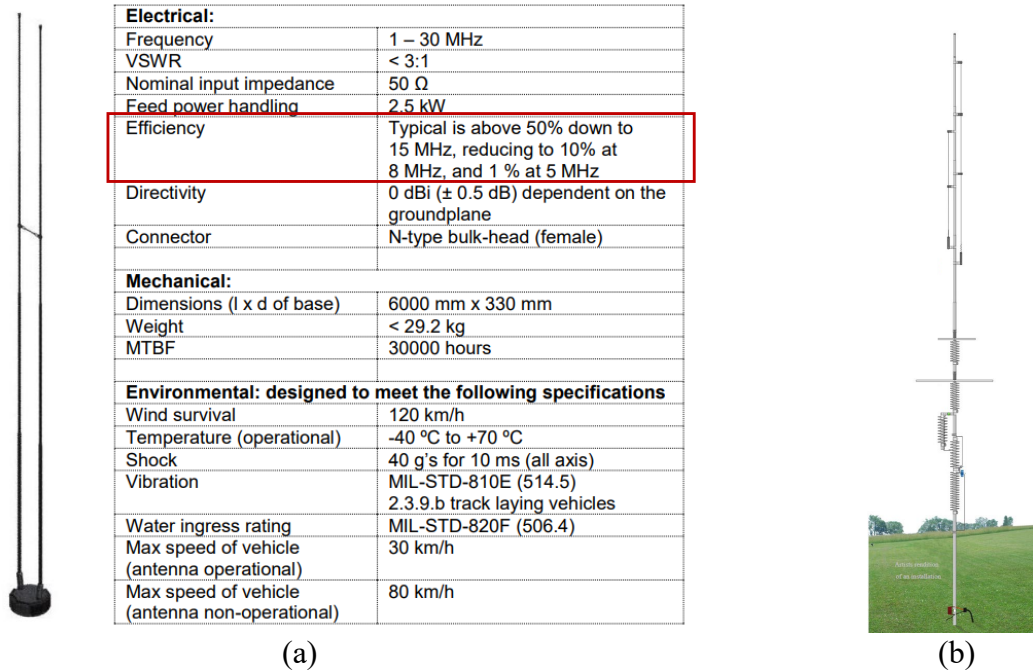


Figure 6. (a) Alaris Antennas wideband HF monopole with specifications [10] (b) nine-band Butternut tunable monopole [11].

C. ARRAYS

In principle, an array can be constructed using multiple monopole or dipole elements. In order to cover a wide band with dipoles, a series of narrowband dipoles or arrays of dipoles with contiguous bands can be used. If partial band arrays are used, they can occupy separate areas or be interlaced. Covering the band with two separate dipole “curtain arrays” is illustrated in Figure 7 [12]. The curtains function as ground planes to prevent radiation in the rear hemisphere and give a unidirectional pattern with a low backlobe.

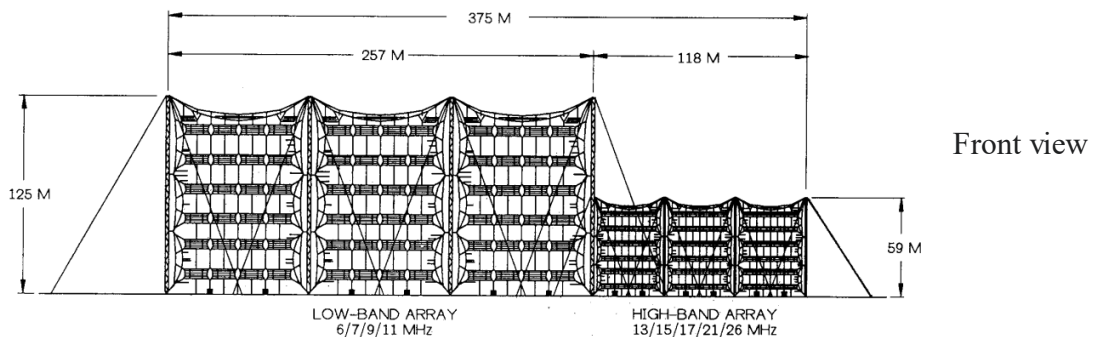


Figure 7. HF dipole curtain arrays that together cover 6-26 MHz [12].

The interlaced concept is illustrated in Figure 8, which shows short dipoles integrated into an array of longer dipoles. Only the long wires are used at low frequencies. Both the long

and short wires are used at higher frequencies. The long wires incorporate switched circuits that can form open, short, or matched conditions. The highest operational frequency is determined by the segment length, which would be about $\lambda_H/4$.

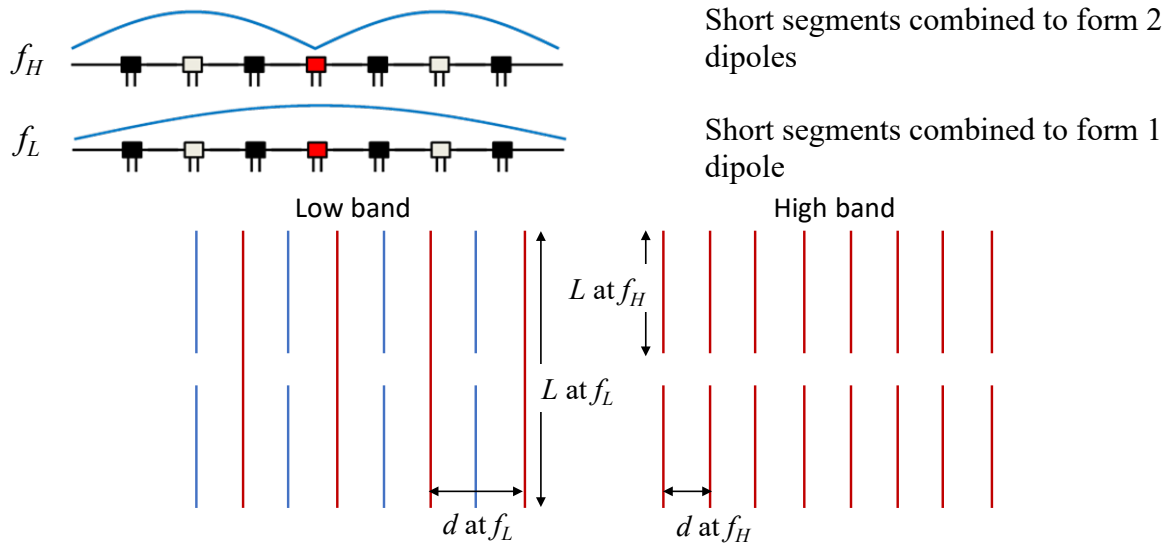


Figure 8. Current distributions at a high and low frequency for an eight-segment case (top); excited elements are red (blue elements not used) at the low and high frequencies (bottom).

To reduce the back radiation from a dipole array, a ground plane screen or reflector element must be added. An example of a dipole with a reflector element is shown in Figure 9. Typically, to maximize the pattern in the forward direction, the reflector should be about $\lambda/4$ from the element. A single fixed spacing does not perform well because of the wide operating bandwidth. Multiple reflector elements can be used to achieve a wide operating band as shown in Figure 9. Another option is to use a second fed dipole with an excitation phase versus frequency that together provide a unidirectional element pattern (Figure 10). This approach is equivalent to using two parallel excited planar arrays.

Additional considerations for arrays are the effects of mutual coupling and the possibility of grating lobes. For an array with wideband elements, the array elements are likely to be closely spaced at the low end of the band, and mutual coupling will be strong. At the high end of the band, the elements will be far apart in terms of wavelength, so mutual coupling is weak but grating lobes may occur. These effects can be modeled precisely using full wave solvers such as FEKO [13].

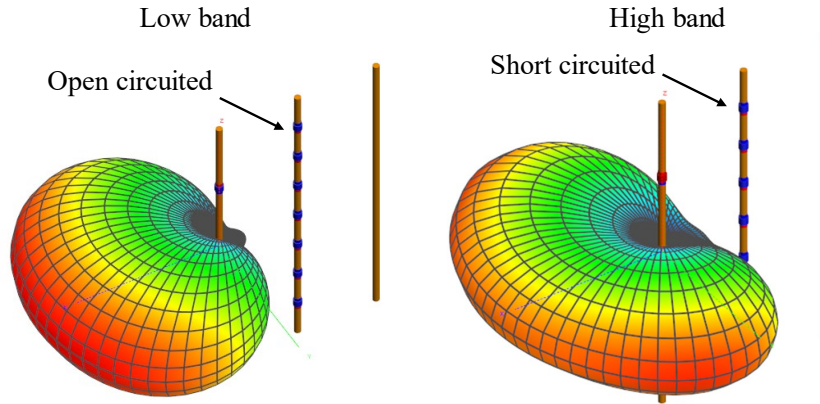


Figure 9. Dipole with a reflector element that gives a unidirectional pattern. The high and low band frequencies are an octave apart.

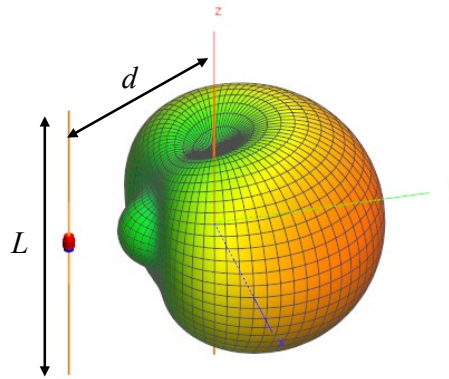


Figure 10. Two-fed dipoles excited to form a unidirectional beam, which can be used as an element in a planar array.

D. YAGI-UDA ANTENNAS

The HPBW can be reduced and the gain increased by adding reflector and director elements to a fed dipole to form a Yagi array antenna (Figure 11) [6]. The beam is in the endfire direction (+ x axis, along the boom). Figure 12 gives a comparison between measured and simulated azimuth and elevation patterns of a COTS UHF Yagi [14], verifying the accuracy of the simulated results when the array is properly modeled. Simulations are done using the FEKO solver.

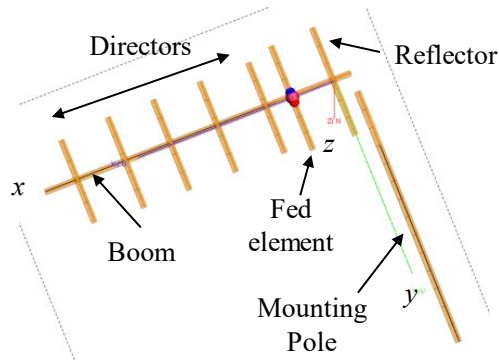


Figure 11. Yagi antenna with 5 directors (modeled in the software FEKO [14]).

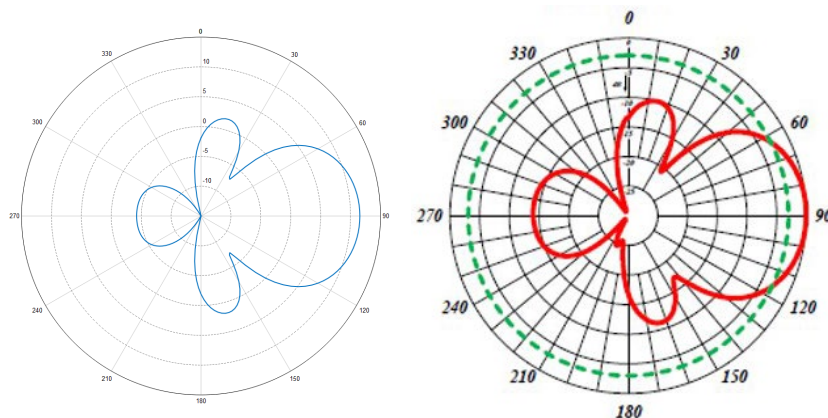


Figure 12. Comparison of FEKO simulated pattern (left) and measured pattern (right) for a COTS Yagi array at 450 MHz elevation plane (vertical, E-plane) [13].

Various ground conditions can be included. Frequency scaling can be used to resize the array and move the operating band to the lower HF frequencies. There is a limit to the number of directors that can be added before the gain limit is obtained ($\sim 10\text{--}12$ [6]). The bandwidth is still relatively narrow.

Figure 13 shows the pattern of an array of Yagis fed in phase to give a broadside beam. The Yagi pattern in Figure 13 (a) can be scanned by rotating the entire boom. If the antenna location does not have sufficient volume to rotate the entire array, an alternate technique is to rotate the individual elements about their boom mounts. An example of 45° scan from broadside (from 90° to 135°) is shown in Figure 13 (b).

E. LOG PERIODIC DIPOLE ARRAY (LPDA)

1. ENDFIRE MODE

A collection of dipoles of various lengths that are tuned to cover a wideband with nonuniform (logarithmic) spacing is a log periodic dipole array (LPDA). The design process for

LPDAs is well known, and the design formulas are available in numerous references, for example [6]. The shortest dipole is approximately a half wavelength at the high frequency, and the longest dipole approximately a half wavelength at the lowest frequency. To illustrate LPDA properties, we use a FEKO design (Figure 14) with $N=12$ elements that operates from 10 to 35 MHz (boom length, 12.22 m, longest dipole 4.44 m, shortest 2 m). In principle, frequency scaling can be used to move the operating band lower.

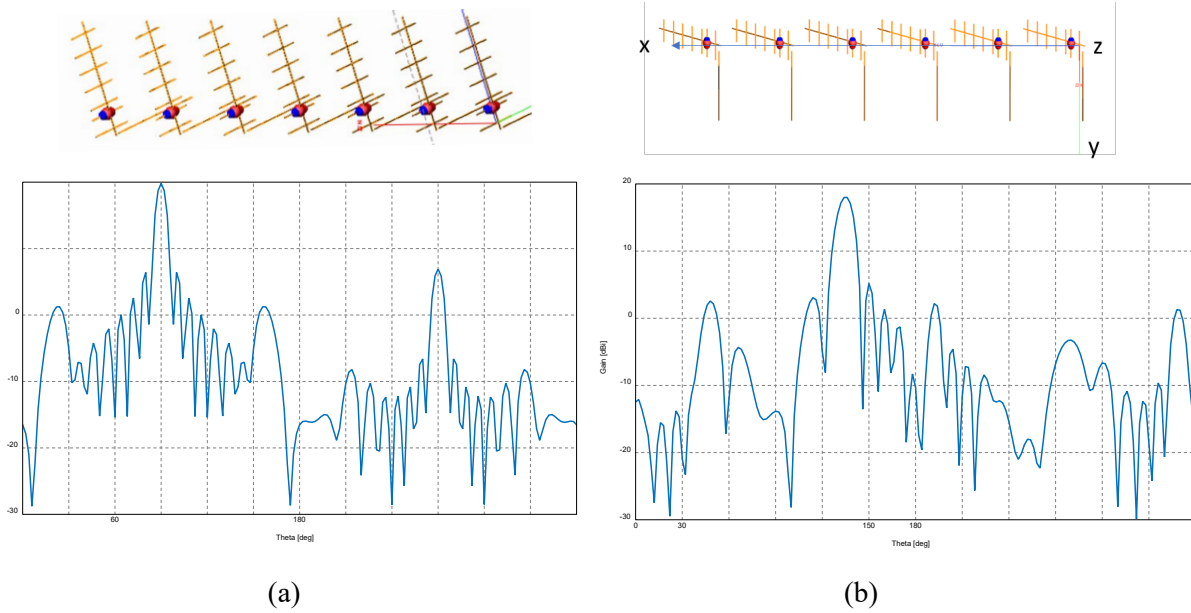


Figure 13. (a) An array of Yagi antennas for a broadside beam. (b) Scanning the beam by rotating the individual Yagis and adding a linear phase shift.

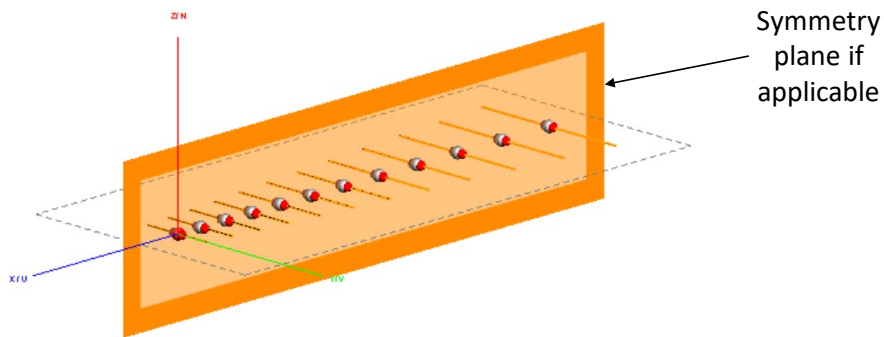


Figure 14. LPDA modelled in FEKO.

Figure 15 presents the pattern of the LPDA operating in the conventional endfire mode. The array is fed from the long-dipole end with a series transmission line network. For a given frequency, the active region of the array is centered around the dipole that has a resonance near that frequency.

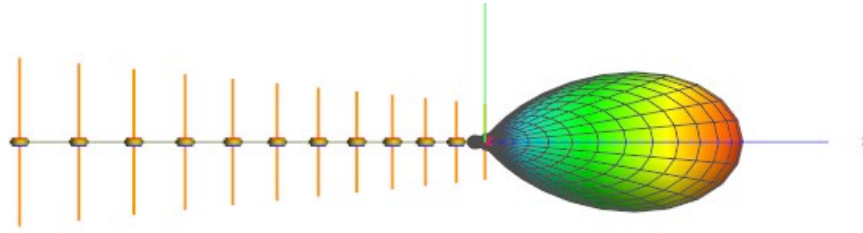


Figure 15. Top view of the FEKO LPDA with pattern at 35 MHz.

As with the Yagi, the LPDA beam can be scanned by mechanical rotation of the entire boom. Similar to the Yagi, rotation of the elements around the boom mounting points can be used for scanning in a confined space if the entire array cannot be rotated. For example, Figures 16 and 17 show that rotating the elements 45 degrees gives a beam scan of approximately 26 degrees. This method may not be feasible because the scanning loss results in approximately the same as the gain at 26 degrees when the elements are not rotated.

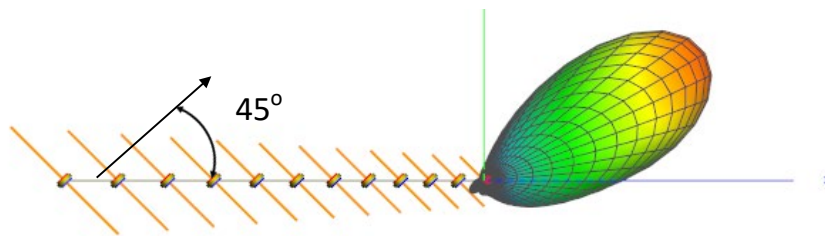


Figure 16. Top view of the FEKO LPDA with rotated elements to scan the beam (35 MHz).

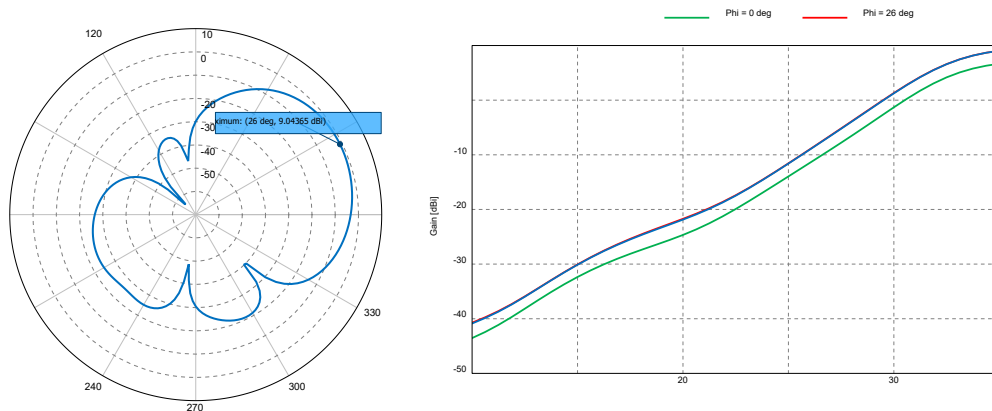


Figure 17. Pattern (left) and gain (right) of a 12 element LPDA array with 45 deg element rotation gives an approximate scan angle of 26 deg. Scan loss at 26 deg is 0.8 dB.

An improvement in gain can be obtained using V-dipoles in place of straight dipoles in the LPDA. The arms of the V-dipole are bent slightly to give a more directive pattern inside of the V and a reduced backlobe. Scanning can be done by rotating the boom or the individual

elements. Figure 18 shows an array of rotated V-dipoles to scan 20 degrees. This array was designed to cover 4 to 5.5 MHz.

LPDAs can be arrayed and placed over a ground plane as shown in Figure 19. Azimuth beam scanning can be done by phase shifting the fixed array, rotating the entire array around the center vertical axis, or rotating the individual LPDAs around their individual vertical axes. An array presents an opportunity to lower the sidelobes by applying an amplitude taper as demonstrated in Figure 20. There is also the opportunity of future antenna expansion by adding more elements.

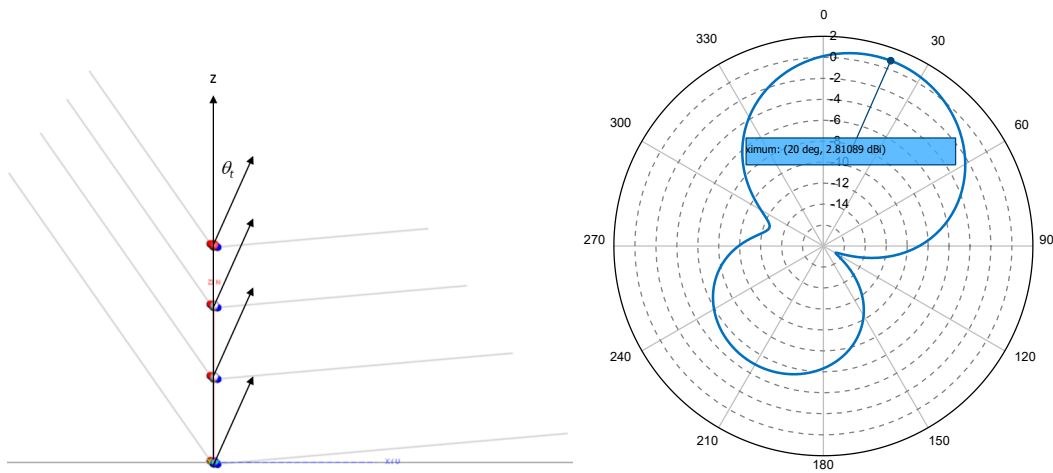


Figure 18. V-dipole LPDA with rotated elements (left), and the scanned azimuth pattern at 5.25 MHz (right).

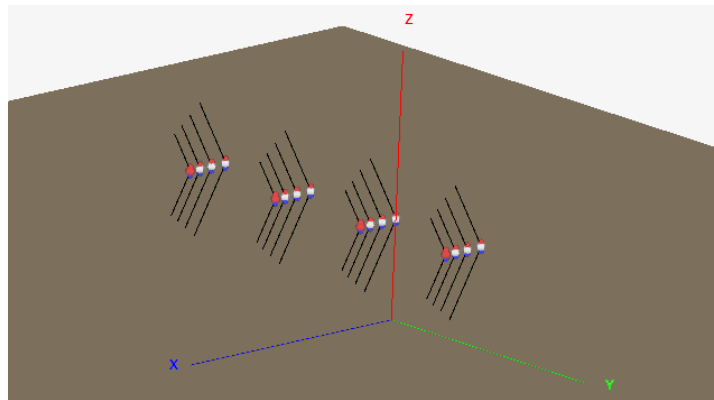


Figure 19. A V-dipole LPDA array over a ground plane (height 30 m and spacing 35 m).

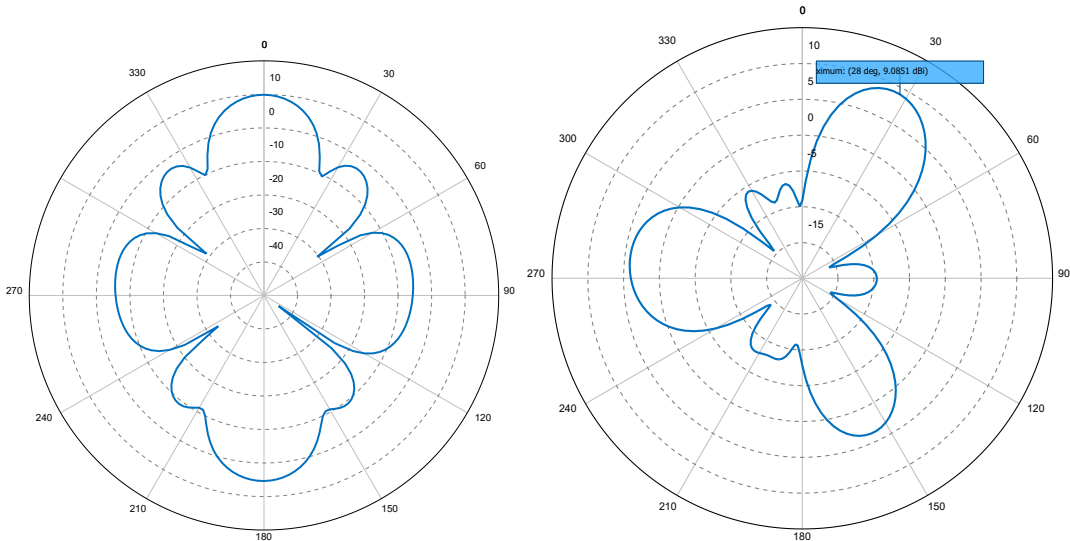


Figure 20. Azimuth patterns for a 4-element LPDA array of V dipoles over a ground at 5.15 MHz. Uniform amplitude array broadside pattern (left), beam scanned to 30 deg with a 20 dB Chebyshev sidelobe taper applied (right).

A method of scanning with multiple LPDAs is illustrated in Figure 21. The arrays are located along an arc and adjacent arrays combined to form an endfire beam. The beam is scanned by switching the arrays.

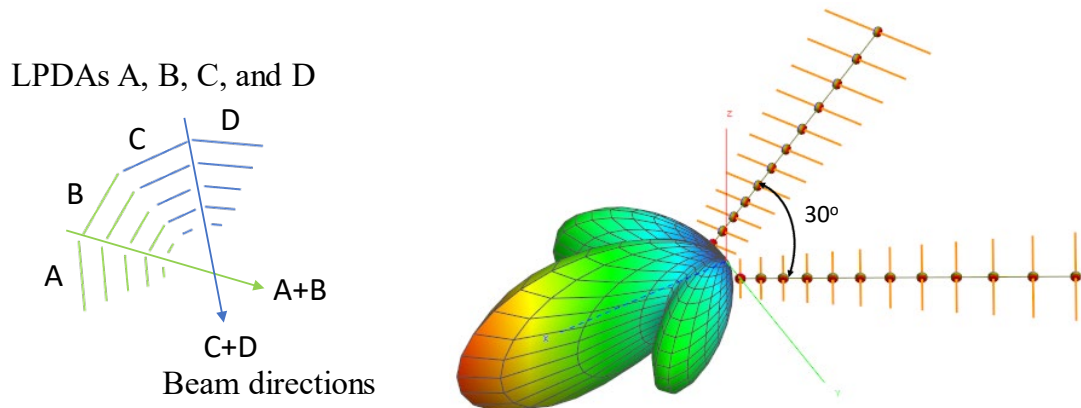


Figure 21. Azimuth scanning using switched multiple LPDAs (left). FEKO simulation showing the combined beam (right).

2. WIDEBAND LPDA EXAMPLES

LPDAs that cover the entire HF band have been reported [15–17]. Figure 22 shows a conventional commercial design [16]. The elements are basically V-dipoles with additional tethers and guy wires added to maintain shape. Figure 23 shows a miniaturized design. It is the smallest reported antenna with some significant gain covering the entire HF band. Antenna patterns at several frequencies are given in Figure 24.

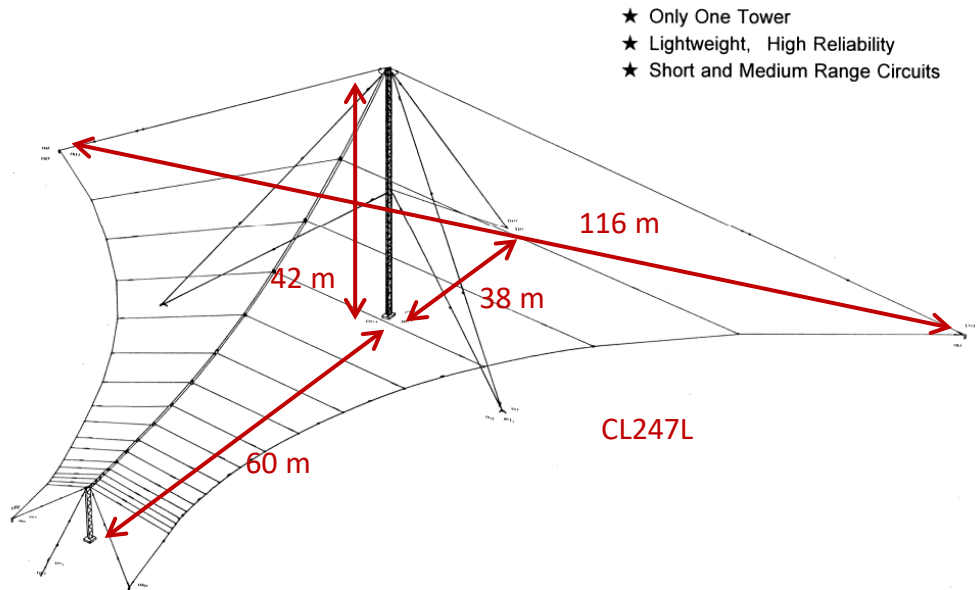


Figure 22. Typical HF LPDA commercial design with dimensions shown (3-30 MHz, 10 dBi gain, VSWR 2:1, front-to-back ratio (F/B) =10 dB, azimuth HPBW=60-80 deg) [16].

Item	Our Proposal	TCI 530	Duoconical Monopole	Invert-V LPDA
Dimension	29 m × 24 m	72 m × 32 m	20 m × 6 m	30 m × 19.8 m
Impedance Bandwidth	2-30 MHz	2-30 MHz	7.5-25 MHz	6-30 MHz
Gain	5-7 dBi (over 4 MHz)	4-7 dBi	0.2 dBi	2-8 dBi
VSWR	≤2.5	≤2.5	≤3.0	≤2.5

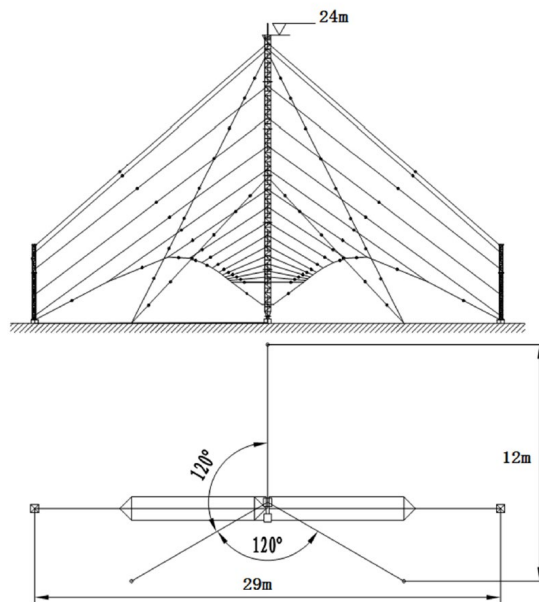


Figure 23. This miniaturized LPDA is the smallest reported design [16].

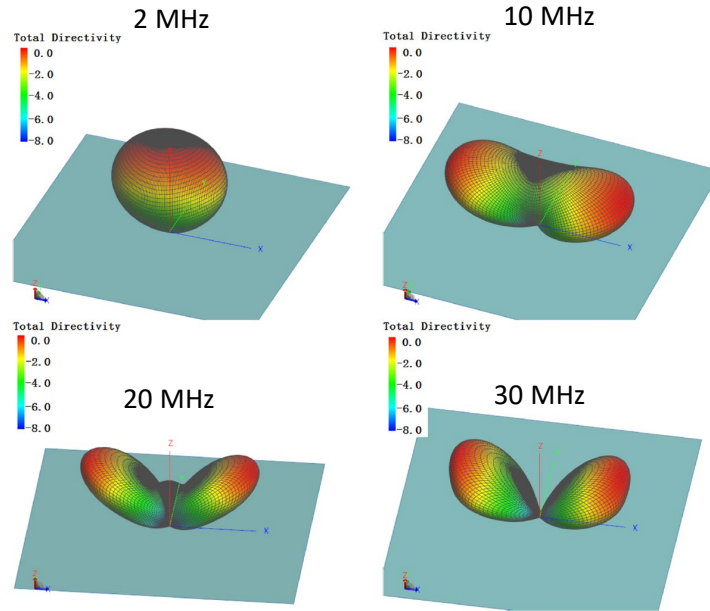


Figure 24. Patterns of the miniaturized LPDA at several frequencies.

For vertical polarization, a log periodic monopole array (LPMA) can be formed using the ground (Figure 25) [17]. A series of terminated horizontal transmission lines (inset) provides short and open circuits that change with frequency. This behavior controls the excited area of the array versus frequency. The array shown operates from 4–15 MHz with a VSWR < 2. Several LPMAs can be used in an array that would be able to scan in azimuth. However, the LPMAs that cover the entire HF band are so large that the spacing between them would be too far apart at the high end of the band to prevent grating lobes from forming.

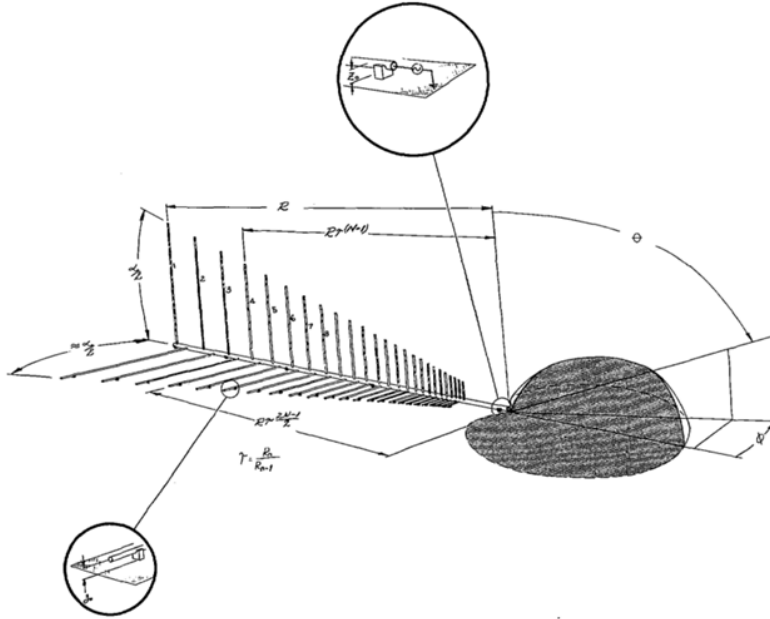


Figure 25. Log periodic monopole array (from [17]).

3. BROADSIDE MODE

LPDAs are typically operated in an endfire mode, as described in the previous section. The spacing between short dipoles at the high-frequency end of the array is about $\lambda_H/4$ while the spacing between the long dipoles at the low-frequency end of the array is about $\lambda_L/4$. The close spacing must be used to prevent a large backlobe (i.e., grating lobe) in the reverse direction.

LPDAs can also be used in a broadside mode, as depicted in Figure 26. In this mode, the dipoles can be spaced farther apart, from about $\lambda_H/2$ at the high end to $\lambda_L/2$ at the low end. In the figure, there are 48 elements to cover 3-30 MHz. The dipole with resonance closest to the operating frequency is the central dipole of the excited array. For a given frequency of operation, only a few of the dipoles close to the central dipole will radiate efficiently. In the figure the 12 black elements centered at the half wave dipole with resonance closest to 5 MHz are excited. Total length is 212 m. As dipoles at greater distances from the central dipole are added to the active array, its pattern properties deteriorate.

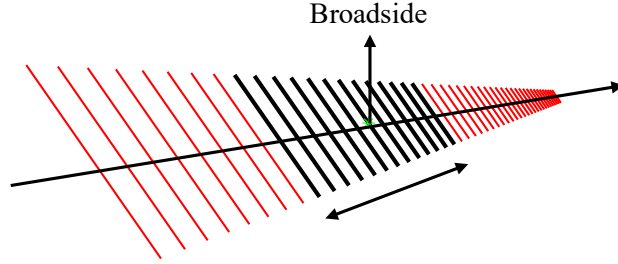


Figure 26. Example LPDA with 48 elements to cover 3-30 MHz.

The behavior of the array with isotropic elements is illustrated in Figure 27. Typical normalized power patterns for high and low frequencies are shown when all elements are excited. Notice there is no well-defined main beam because there are no first nulls. The high shoulder (first ripple) is much higher than the uniform array level of -13.2 dB. This behavior is expected because the variation in spacing is adding phase errors to the element contributions.

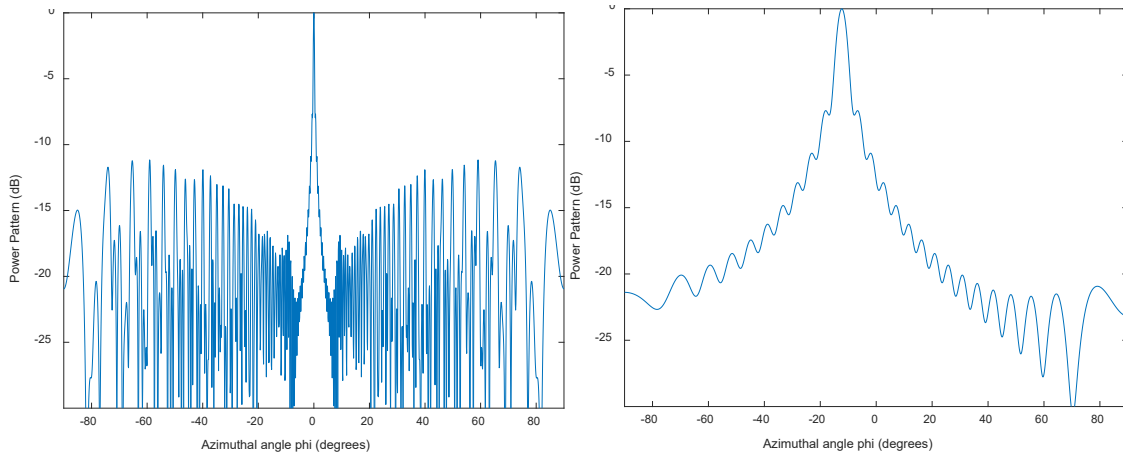


Figure 27. All elements isotropic 30 MHz, broadside scan (left), 3.2 MHz scanned to -12.3 deg (right).

In Figure 28 the calculation is repeated for dipole elements. The long-dipole formula for the normalized electric field is used [6]

$$E_{\theta_{\text{norm}}} = \left[\frac{\cos\left(\frac{k\ell}{2} \cos \theta\right) - \cos\left(\frac{k\ell}{2}\right)}{\sin \theta} \right], \quad (1)$$

where $k = 2\pi / \lambda$ and ℓ is the dipole length. This assumes that the long dipoles at the low end will radiate efficiently at high frequencies. If this were true, there would be many cycles of current on the long dipoles that when superimposed in the array, summation would result in complicated constructive and destructive effects. The result is a large rapid variation of pattern

behavior with frequency and angle as seen in Figure 28(a), a property that is undesirable because it leads to fading. Furthermore, efficiently matching the dipoles over the entire band is not possible, as seen in previous sections.

The pattern features can be improved by limiting the number of active elements. In Figure 29, 12 dipole elements are used at 30 MHz. The envelope is approaching a uniform array pattern shape, but there is still undesirable ripple in the pattern.

Finally, in Figure 30 the pattern is shown when only 12 elements are excited for an operating frequency of 5 MHz (black elements in Figure 26). The result is close to that of a uniform array. The patterns can be phase scanned as shown. A sidelobe taper could also be applied. Note that two widely spaced frequencies could be used simultaneously if they do not require overlapping regions of the LPDA. The beamwidths are approximately constant with frequency.

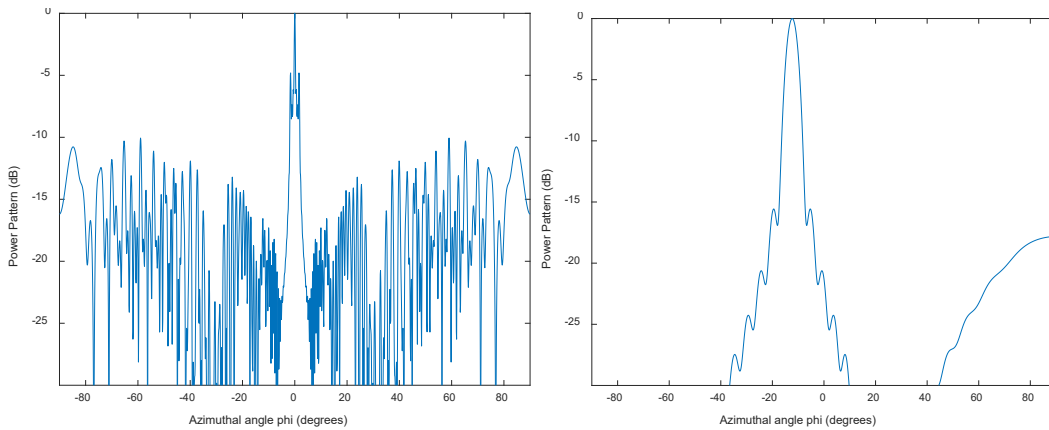


Figure 28. Dipole elements, 30 MHz, broadside scan (left), 3.2 MHz scanned to -12.3 deg (right).

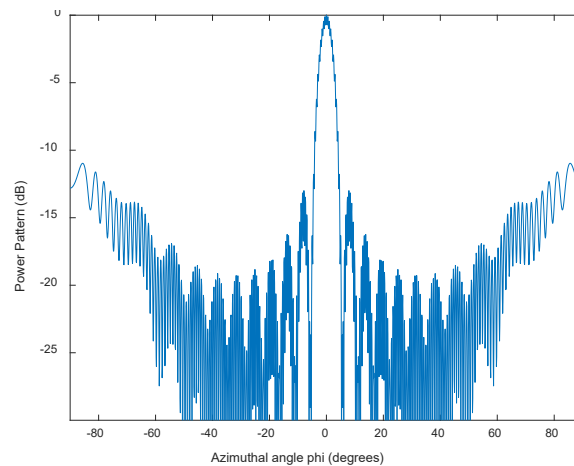


Figure 29. 12 dipole elements, broadside, 30 MHz.

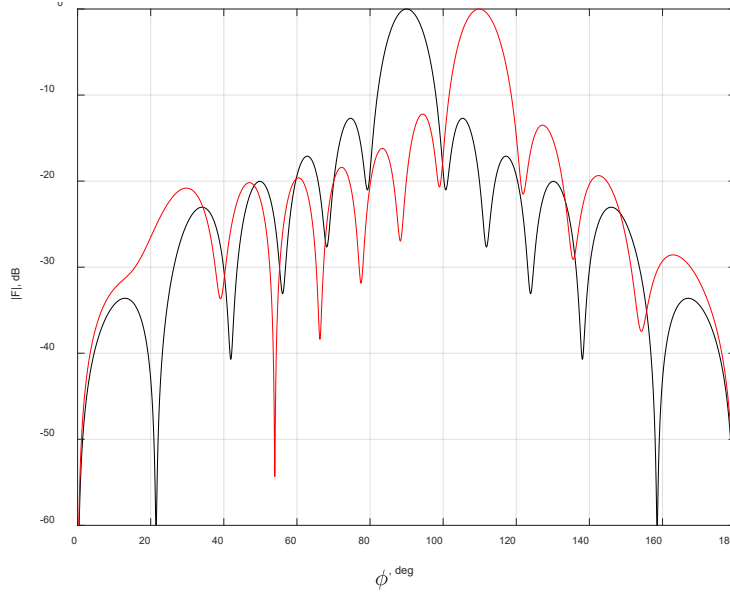


Figure 30. Patterns using 12 active dipoles of a 48-element LPDA over a ground plane operating in the broadside mode at 5 MHz. Broadside beam and scanned 20° . The gain is approximately 15.7 dB.

To assess the directivity, we compare a broadside LPDA with an active length L with a uniformly spaced array of the same length and same number of elements. The uniform array gives the maximum directivity for the length L . It is assumed that Eq. (1) applies and that all dipoles are matched at all frequencies (not possible of course).

In the top block of Table 1, the directivity is shown for LPDAs with isotropic (D_{iso}), dipoles (D_{dip}), and dipoles with a ground plane (D_{gp}) at 10 MHz. The LPDA has 48 elements and a total length of 667 m (same one used for Figures 27-29). For the ground plane case, a properly spaced reflecting element is located at each dipole to approximate a ground plane (see the next section). N_{act} is the number of active elements used, centered at the dipole that is resonant at 10 MHz, and L is the length of the active part of the array. In the bottom block of Table 1, the corresponding directivities are shown for an array the same length L as the active part of the LPDA but with the same number of elements that are uniformly spaced. This uniform array would give the maximum directivity for the length L . A uniform array provides a useful reference, since its pattern properties are ideal if the separation between the elements is approximately one-half of the narrowband operational wavelength (d/λ bottom table).

Table 1. Comparison of directivities of uniform spaced and LPDA arrays at 10 MHz.

Broadside LPDA					
N_{act}	L (m)	D_{iso} (dB)	D_{dip} (dB)	D_{isogp} (dB)	D_{dipgp} (dB)
48	667.0	13.9	16.6	20.1	18.4
32	595.0	13.9	16.5	20.6	21.3
24	450.5	13.8	16.5	20.0	18.4
12	212.4	11.6	14.7	17.3	15.8
6	104.6	9.0	12.2	14.4	13.1
Broadside Uniform Spacing					
N_{act}	d (m), d/λ	D_{iso} (dB)	D_{dip} (dB)	D_{isogp} (dB)	D_{dipgp} (dB)
48	14.2, 0.47	16.4	19.9	22.4	23.9
32	19.2, 0.64	16.0	19.4	21.8	23.4
24	19.6, 0.65	14.7	18.2	20.7	22.2
12	19.3, 0.64	11.4	14.8	17.7	19.0
6	20.9, 0.7	9.2	12.4	15.1	15.5

The following observations are made:

1. As expected, the ground plane cases have a directivity 2.5 to 3 dB higher than those without because the backlobe is eliminated or reduced.
2. For the LPDA, there is only a single configuration of the array element locations intended to cover the wide overall span of frequencies from 2 MHz to 30 MHz, although only the elements near the resonant element for a given selected wavelength are active. There is a maximum number of active elements that can be used efficiently. For the case in Table 3, when $N_{act} < 12$ the LPDA and uniform cases are approximately the same. When $N_{act} > 12$ the LPDA directivities can be much less than the uniform cases for isotropic and dipoles.
3. This behavior of the LPDA is similar to Carrel's observations for endfire operation [18]: the array consists of transmission, active, and unexcited regions. For this particular case, when more than 12 elements are used, the phase errors introduced by the additional elements degrade the pattern. The optimum number active elements depends on the design: how fast the spacing between elements changes.
4. Small changes in spacing for a small number of elements can cause a sizeable change in D for the uniform case. A significant amount of the sidelobe solid angle can move in or out of the visible region with small spacing changes.

To summarize, when the excited region is limited to dipoles close to the central dipole, the performance of the broadside LPDA is nearly the same as a uniform array of the same length.

4. FEKO SIMULATIONS

The FEKO endfire model can be used to illustrate some of the properties of the broadside operating mode. This requires using the model at a higher frequency where the localized spacing between dipoles is near a half wavelength. Table 2 lists the spacing in wavelengths indicating that the FEKO model can be used in the broadside mode for frequencies between 60 MHz and 80 MHz. Also, the dipole lengths are adjusted to be resonant over this band using this scaling. Figure 31(a) shows the resulting broadside pattern of the array at 60 MHz.

Table 2. Maximum and minimum spacings of the FEKO model versus frequency.

f , MHz	λ m	d_L/λ	d_H/λ	
10	30	0.148	0.067	Endfire
35	8.57	0.518	0.23	
60	5	0.88	0.4	Broadside
80	3.75	1.18	0.533	

The backlobe can be suppressed using a “curtain” or reflector elements. The pattern in Figure 31(b) is obtained when a reflector array is used. The distance between the reflector element and its dipole should be approximately a quarter of a wavelength at the dipole’s resonant frequency. The result is a rotated LPDA of shorted elements shown in the figure. The patterns are not displayed in dB. The typical front to back (F/B) ratio is about 5-10 dB.

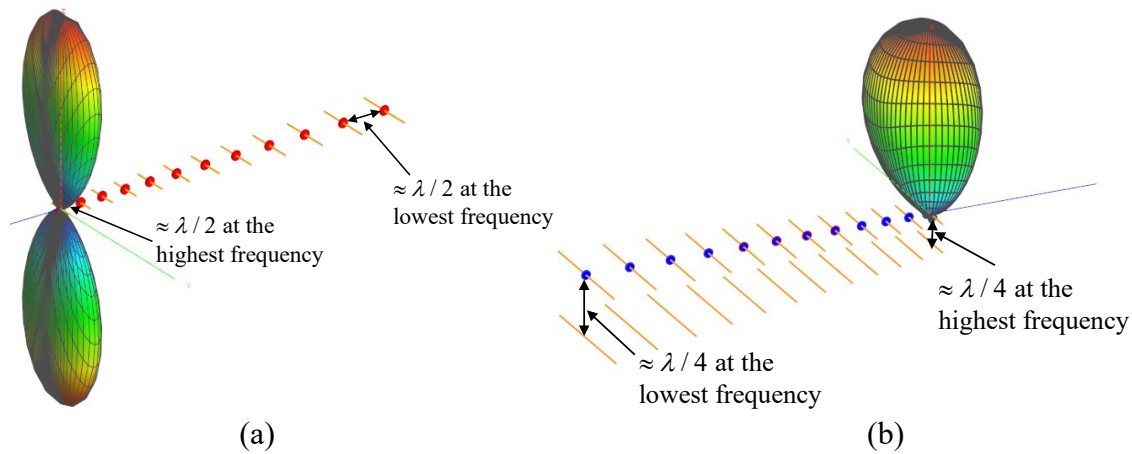


Figure 31. FEKO design at 60 MHz. (a) Ports 5-8 excited, $Z_{load} = 50$ Ohms for ports 1-4 and 9-12. (b) FEKO design at 60 MHz with reflectors added to reduce the back lobe.

III. COMMUNICATION SYSTEM AND ANTENNA INTEGRATION

A. MATCHED RECEIVER SIGNAL-TO-NOISE RATIO (SNR)

The successful detection and processing of a signal is directly related to the received SNR at the shore site, which depends on the system parameters as well as the transmitter-receiver distance, r , and the propagation environment. For a receiver matched system [19]

$$SNR_{\text{match}} = \frac{\lambda^2 G |\vec{E}_i|^2}{8\pi\eta_0 k_B B \left[\frac{G}{4\pi} \iint_{4\pi} T_B(\theta, \phi) U(\theta, \phi) d\Omega + (1 - \xi) T_0 \right]} \quad (2)$$

where $|\vec{E}_i| = \sqrt{\frac{30P_t G_t}{r}}$ = incident plane wave electric field intensity [1]
 P_t = mobile user transmitter power
 G_t = mobile user antenna gain
 $T_B(\theta, \phi)$ = background brightness temperature
 $U(\theta, \phi)$ = normalized radiation intensity (power pattern) of the antenna
 $G_r = \xi D$ = receiving (shore site) antenna gain
 ξ = antenna radiation efficiency
 D = antenna directivity
 λ = wavelength
 $P_n = k_B T_s B$ = system noise power
 $k_B = 1.38 \times 10^{-23}$ = Boltzman's constant
 B = bandwidth
 $T_s = T_A + T_e$ = system noise temperature
 T_A = antenna noise temperature
 $T_e = (F_e - 1)T_0$ = effective noise temperature of the receiver channel
 F_e = effective noise figure of the receiver channel
 T_0 = antenna physical temperature (generally standard temperature 290 K)

A matched receiver is the most common approach. Note that for the matched case, there is no mismatch loss, and the gain is equal to the realized gain. Although it minimizes the mismatch loss with the receiver, there are some disadvantages. A good match between the antenna and receiver can only be achieved over a narrow band as evident from the previous antenna simulations. Also, a matched system delivers maximum noise to the receiver.

B. MISMATCHED RECEIVER SIGNAL-TO-NOISE RATIO (SNR)

It is possible that a small receiving antenna with low radiation resistance and high reactance can provide higher SNR when connected directly to a high impedance receiver [19].

This has an advantage in that no LNA is required. The open circuit voltage is twice the voltage provided when matched. Furthermore, a high-impedance receiver has virtually unlimited bandwidth and contributes almost no noise.

For the open-circuited receiver the SNR is [19]

$$SNR_{\text{open}} = \frac{|V_s^{oc}|^2}{|V_n^{oc}|^2} = \frac{\lambda^2 |\vec{E}_i|^2}{2\eta_0 k_B B \iint_{4\pi} T_B(\theta, \phi) U(\theta, \phi) d\Omega} \quad (3)$$

V_s^{oc} = signal voltage at antenna terminals = $|\vec{E}_i| \ell_e(\theta, \phi) = |\vec{E}_i| |\ell_e| U(\theta, \phi)$
 $\ell_e(\theta, \phi)$ = effective length (height) of the antenna

$$V_n^{oc} = \text{noise voltage at antenna terminals} = \frac{2\eta_0}{\lambda^2} k_B B \iint_{4\pi} T_B(\theta, \phi) |\ell_e(\theta, \phi)|^2 d\Omega.$$

Taking the ratio for the two cases in Eqs. (2) and (3) gives

$$\frac{SNR_{\text{open}}}{SNR_{\text{match}}} = \frac{\iint_{4\pi} T_B(\theta, \phi) U(\theta, \phi) d\Omega + (1-\xi)T_0}{\iint_{4\pi} T_B(\theta, \phi) U(\theta, \phi) d\Omega} = 1 + \frac{(1-\xi)T_0}{\xi T'_A} \quad (4)$$

where T'_A is for a lossless antenna with directivity D : $T'_A = \frac{D}{4\pi} \left[\iint_{4\pi} T_B(\theta, \phi) U(\theta, \phi) d\Omega \right]$. Plots

for several T_B are shown Figure 32. If the antenna is looking at a blackbody background with constant temperature $T_B = T_0$,

$$\frac{SNR_{\text{open}}}{SNR_{\text{match}}} = 1 + \frac{(1-\xi)T_0}{\xi T'_A} = \frac{1}{\xi}. \quad (5)$$

This open circuit approach has been taken by DX Engineering with their Hi-Z antennas [20]. The element amplifier provides the output signal to a standard 75 Ohm transmission line over the entire HF band.

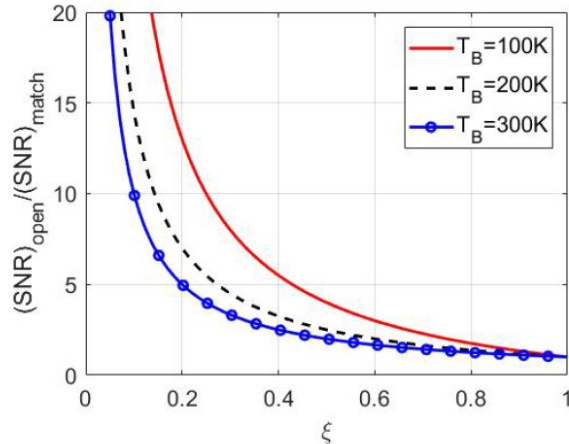


Figure 32. Comparison of SNRs for open and matched cases (from [19]).

C. SYSTEM COMPONENTS

1. INTRODUCTION

Several manufacturers have high performance electronic warfare HF transmitting and receiving systems on the market. Major vendors include *Rhode & Schwarz*, *Leonardo*, and *BAE Systems*. Other potential software defined radio (SDR) products are available, such as the *Flex Radio* commercial line of products. Current state of the art systems are digital based with solid state components. Digital allows for flexibility and multifunctionality. An overview of receivers is given in [21].

The direct substitution of a new antenna with an existing system is not always possible, in particular, when the original antenna is analog and passive, and the new antenna is active and/or digital. All commercial systems encountered employ passive antennas. (Although some switching might occur in the antenna, we still classify the antenna as passive.)

2. RHODE AND SCHWARZ

Rhode and Schwarz (R&S) offers a line of transmitters, receivers and transceivers [22]. Numerous capabilities are integrated into the boxes such as transmit/receive switch control; up and down conversion, if any; I/Q processing for receiver functions; frequency band scanning/selection; and direction finding and emitter identification. Generally, functions performed by the closed box R&S 4100 transceiver cannot be altered or accessed.

A conceptual block diagram showing how a scanning passive array might be used with a R&S transceiver is shown in Figure 33. It is assumed that the antenna has reciprocal phase

shifters [23]. Further extensive consultations with R&S engineers will be necessary to assess the potential for employing active digital arrays.

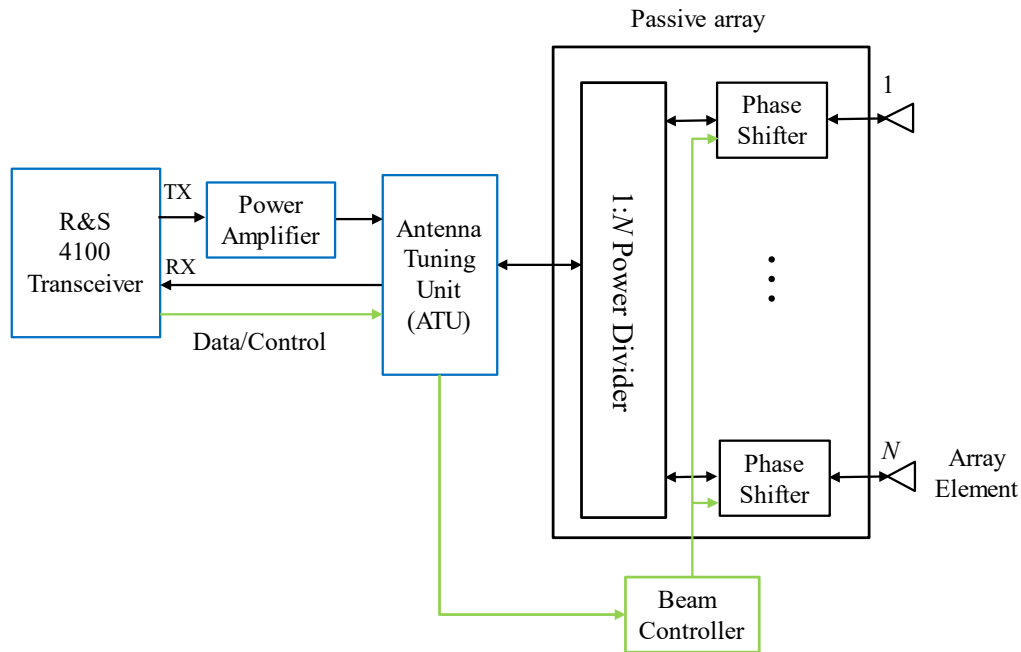


Figure 33. Functional block diagram of a new antenna with an R&S 4100 transceiver.

3. RECEIVERS

Several manufacturers offer HF receiver hardware: Eclipse (BAE Systems) RXR6332, R&S EK4100 VLF-HF receiver, and Leonardo DRS receivers. All have similar performance and capabilities. Multiple receiver channels can be combined coherently; therefore, they can function as a digital beamformer. The output is baseband I/Q, allowing for additional processing to be performed. Standardized control and data networking are used.

4. FLEX RADIO

Another possible COTS transceiver would be based upon FlexRadio's ML-9600W wideband Software Defined Radio (SDR) [26]. It supports the required band of 2 MHz to 30 MHz with 78 kHz of transmission bandwidth and 1.8 MHz of receiver bandwidth. The standard unit supports power levels up to 100 Watts, and the additional use of FlexRadio's Power Amplifier enables support for power levels up to 10 kW. FlexRadio's SDRs also support the use of a broad span of waveforms that are optimum for propagation at the HF frequencies of interest. In addition, the SDR units provide Automatic Link Establishment (ALE) support and Internet Protocol (IP) datagram processing to support communications with users at various locations. However, most of this advanced functionality appears to operate automatically with little ability

for the user modifications to support custom applications. Overall, it appears that a number of commercial transceivers including FlexRadio, Rhode and Schwarz, Harrier, Leonardo, and others, could be candidates for a given selected or designed antenna system.

5. WIRELESSLY NETWORKED ARRAY

Wireless beamforming has the potential to fundamentally change the deployment of antennas for radar, communication, and electronic warfare applications [27]. As illustrated in Figure 34, the wired connections between the T/R modules and beamforming computer can be replaced with a wireless network. This provides all the advantages of conventional wireless networks: the ability to reconfigure and add elements (growth), adaptability to the operational environment, and upgrades to the system performance via software.

As described in [27], the realization of a wirelessly beamformed phased array has several technological challenges. One is distribution of timing and phase references. The wireless local area network (WLAN) performance is crucial (i.e., degradation due to obstructions, weather, etc.) Another is the rapid transfer of large amounts of data between the elements and the digital beamformer, and data processing speeds fast enough to permit real-time operation. The position of the elements must be known to be within a fraction of a wavelength in order to compensate for phase errors and dispersion. However, at HF frequencies where the wavelength is large, controlling these errors to a fraction of a wavelength is achievable. Many of the techniques have been demonstrated on a small scale in the laboratory, including wireless LO distribution [28], transmit waveform generation via direct digital synthesis (DDS), up conversion [29], and development of a T/R module at 2.4 GHz using off-the-shelf components [30].

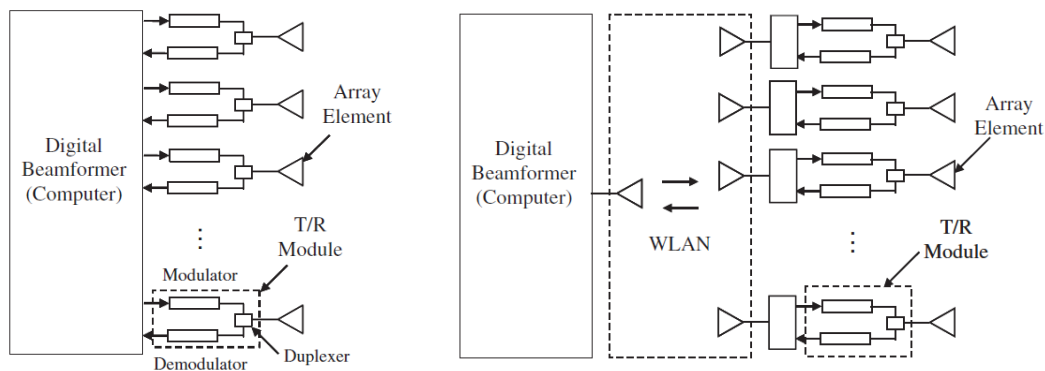


Figure 34. Conventional wired digital array (left) and a wirelessly networked array (right) [27].

IV. SUMMARY AND CONCLUSIONS

This research has investigated some new and existing technologies that might be employed to improve the performance of high frequency Navy shore sites. The focus is primarily on the antenna. Conventional HF antennas like wires and loops have low gain and nearly isotropic radiation patterns. An array of these simple elements can overcome these limitations and provide increased gain, improved SNR on receive, low sidelobes, and scanned directive beams. Digital beamforming with electronically scanned phased arrays is of special interest. This approach is similar to the active electronically scanned array technology used at higher radar frequencies (e.g., the SPY radar).

A major challenge for a conventional wideband array approach is finding a wideband element that would be small enough to allow a close enough spacing to avoid grating lobes at the high end of the band. There have been designs reported to be efficient and electrically very small, but the performance has had mixed reviews and the claims have been disputed [31-32].

Clearly, a number of shore site configurations are possible. For a particular case, the best selection will depend on the circumstances of the site geography, available land area, local electromagnetic issues (i.e., interference, radiation restrictions, etc.) and the desired coverage. A detailed tradeoff study is recommended for each site.

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