HF WIRE ANTENNA ARRAYS

NUMERICAL SIMULATIONS
&
DESIGN GUIDELINESS

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SUMMARY

The concept of the Integrated Maritime Surveillance (IMS) system is pictured in Fig.1.

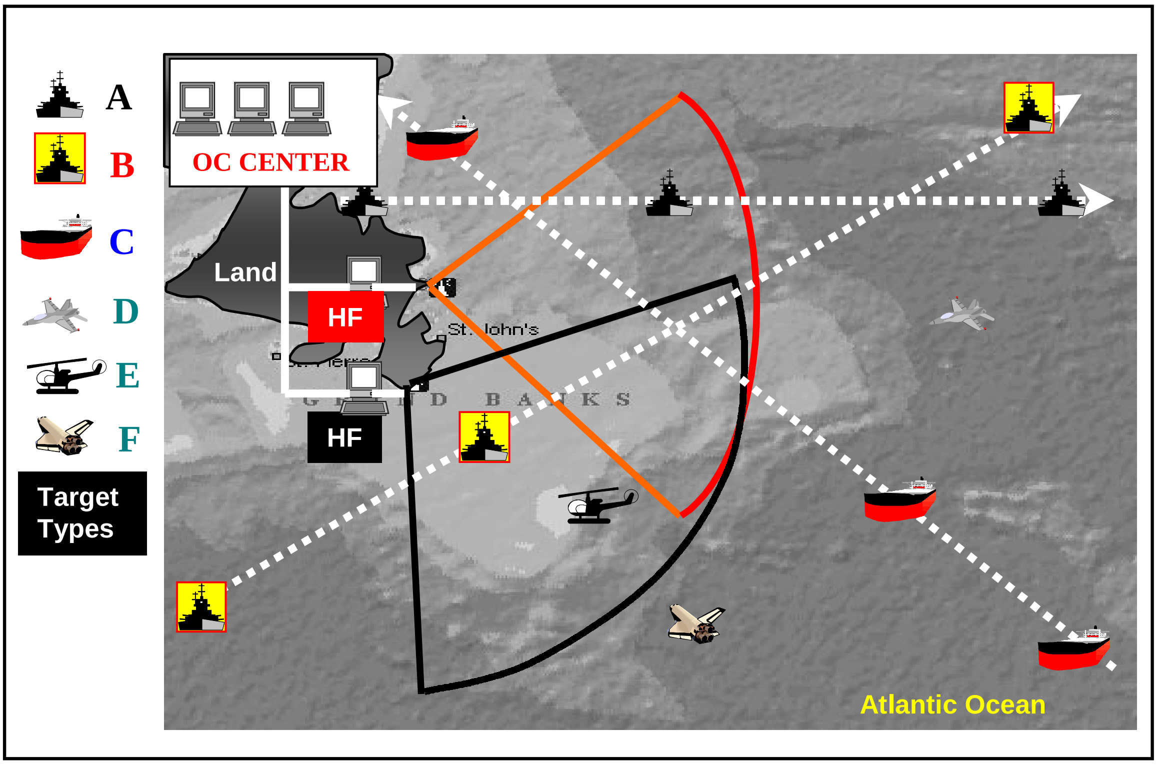


Fig.1: Two SWHFR and the Integrated Maritime surveillance System

Although it shows the East Coast of Canada, this picture may belong to any country adjacent to sea or ocean with substantial coastal region. In this picture, there are isolated or grouped, moving and/or anchored surface targets (ships and boats) and low-flying aircraft. The targets may be military or commercial, friend or foe, small or large. According to United Nations Convention on the Law of the Sea (UNCLOS) of 1992 the participating country has extensive rights of exploitation within an Exclusive Economic

Zone (EEZ) which extends up to 200 nautical miles (nm) from shore. Beside the economic benefits, a participating country carries responsibilities such as prevention of smuggling, terrorism and piracy, the effective management and protection off-shore fisheries, search and rescue, vessel traffic services, pollutant control and meteorological and oceanographic data collection.

The questions behind the IMS idea are simple. How could this picture be reflected on a computer monitor in an Operation Control Centre (OCC)? What would the reliability of the picture be and how close would the OCC picture be to the real one? Do all the targets in EEZ appear in this picture? Are there any virtual targets? Are all the targets classified and identified? Although answers for all these questions are extremely complex, the key issue in developing the IMS system is simple; a better understanding of the physics behind this concept. In order to bring the IMS system to reality, electromagnetic wave - ocean wave interaction, surface and sky wave propagation characteristics, target reflectivity, undesired interference sources must all be very well understood.

What are the alternatives to monitor EEZ? Traditional land-based microwave (MW) radars are limited with the line-of-sight, which means a maximum range of 50-60km even with the elevated radar platforms. The EEZ can be covered by a MW radar in a patrol aircraft, but requires three to five aircraft (well above 20,000ft) with many hours on station. Satellites have neither the spatial nor the temporal resolution to provide this surveillance in real-time. Sky wave high frequency (HF) radars can be used for this purpose, but they need huge installations, are extremely expensive and detection of surface targets is still limited.

The optimal solution is IMS. IMS uses HFSWR as the primary sensors. The requirements of the IMS system based on HFSWR radars are two-fold. First; to detect, track, classify and identify targets on and above the ocean surface out to 500km. Second; to remotely sense and map surface currents, winds, sea state and ice. No single sensor can achieve all these objectives. Effective surveillance requires the integration of data from a number of complementary sensors. Main sensors are two HFSWR. The radar data as well as direct identification knowledge (from Automatic Dependent Surveillance, ADS, systems) are fused in OCC to obtain real time picture of activities within the EEZ. For this aim, every indirect information (e.g., from patrol vessels, communications, mandatory reporting procedures, etc.) is also fused in OCC.

HFSWR removes the line-of-sight limitation of the traditional MW radars. They use vertically polarised HF surface waves and, because of relatively low attenuation over highly conductive ocean surface, these waves follow the curvature of the earth through shadow regions. With today's technology and signal processing techniques a HFSWR can provide a 24-hour full coverage in regions up to 500 km in range and 120° in azimuth. HFSWR are used not only in detecting and tracking targets but also in supplying meteorological and oceanographic data.

HFSWR radar uses the lower end of HF band (typically 3MHz-6MHz) which brings its own characteristic problems. These problems include understanding:

- the propagation characteristics of surface wave over spherical earth with rough surfaces including possible mixed-paths,
- difficulty in finding useful unoccupied frequency in an already over crowded spectrum,
- land and sea clutter effects,
- environmental noise, which is typically 40-60 dB higher than thermal noise,
- undesired interferences from both ionospheric self-reflections and other HF spectrum users,
- Radar Cross Section (RCS) behaviours of radar targets in resonance region where the radar wavelength and the target dimensions are in the same order,

- the problems of large transmit and receive antenna arrays located over lossy ground.

The first step in finding solutions to almost all of these problems is designing suitable antenna systems. Good antenna system design will

- improve directivity, gain and surface wave coupling to reach longer ranges,
- enlarge azimuth coverage,
- increase front-to-back ratio to minimise interference originates sources behind the array and back-located site interferences,
- provide deeper over-head null to reduce self-generated ionospheric interferences, etc.

The design parameters of a HFSWR antenna system are

- Operating frequency bandwidth
- Maximum Directivity and Gain
- Maximum Front-to-back ratio
- Maximising over-head null
- Vertical and horizontal radiation patterns.

HFSWR antenna systems are located on earth's lossy ground, where the bore-sight points the centre of azimuth coverage. The electrical parameters of the ground play a critical role in antenna performance. Typical parameters for *Good Land* and *Poor land* are ε_{rg}=15.0, σ_g=0.01 S/m and ε_{rg}=4.0, σ_g=0.003 S/m, respectively. On the other hand, ocean parameters are ε_{rg}=80.0, σ_g=5.0 S/m. At HF frequencies the smooth ocean surface acts almost as a perfectly electrical conductor (PEC). A vertical monopole with length l over a PEC surface acts as a dipole with an equivalent length of $2l$ in free-space. Therefore, a quarter-wavelength monopole over PEC acts as a half-wavelength dipole in free-space.

The angle between the horizontal plane and the vertical radiation maximum is called the *take-of-angle* (TOA). Vertical monopoles over PEC surface have a 0° TOA. As the surface loss increases TOA also increases.

A vertical monopole element has a *donut* radiation characteristic. That is, isotropic in azimuth plane with horizontal maximum and vertical minimum radiation. However, when placed over lossy ground the horizontal maximum tilts up to between 25° to 40° and the antenna gain reduces by 10dB to 15dB, depending on the ground parameters.

To compensate ground losses and to lower TOA (so, more EM energy may couple over ocean surface) *ground screens* under the antennas are used. The aim of ground screen is two-fold. First, it stabilises the input impedance of each monopole over the entire frequency band, which results compensation in antenna gain. Second, it increases the surface impedance, so that vertical element has a better image and lower TOA to allow more surface wave coupling. Depending on the crucial needs a variety of ground screens may be designed. Some general rules may be listed regarding to ground screen design:

- If the *gain* is crucial, then stabilising the elements' input impedances is essential. It may be done either by locating circular or rectangular PEC patches under each vertical monopole element or using by radial wires.
- If *lowering the TOA* is crucial, then using horizontal wires that are perpendicular to antenna bore-sight seems to be the most proper solution. In this case, horizontal wires should extend at least quarter-wavelength at each side, half-wavelength at the back and a wavelength in the front.
- If the *over-head nulling* is the most important requirement, keeping the antenna array and ground screen depth (i.e., the size of the array along bore-sight) and avoiding complex wiring in the ground screen layout are necessary. The more complex the wire connections the higher the diffractions and the lesser over-head nulling property.

The general design guidelines for HFSWR antenna systems may be outlined as:

- Use structures as simple as possible (to avoid electromagnetic complexity)
- Use vertical monopoles (*for better over-head nulling*)
- Locate the array as close to shore as possible (*to reduce mixed-path loss and diffraction*)
- Level the ground as much as possible (*to reduce diffraction effects*)
- Keep channel depth as short as possible (*to reduce ionospheric clutter*)
- Use simple ground screen layouts (*to reduce ionospheric clutter*)

I Introduction

The Integrated Maritime Surveillance (IMS) system basically relies on the information obtained from two HF surface wave radars (HFSWR) to 24-hour continuously monitor large ocean areas. Therefore, the information supplied from HFSWR to IMS is the key issue for system reliability and performance. The main sub-systems in the HFSWR are

- The transmitter and receiver sub-systems
- The signal processing unit
- The HF spectrum monitoring unit
- The operation control centre (OCC).

Since the HFSWR operation is based on electromagnetic (EM) reflectivity of surface and air targets in the coverage area, EM surface wave producing by the transmit antenna system and target-reflected EM wave capturing by the receiver antenna system are very important. The transmit and receiver antennas are systems, which satisfy the physical requirement essential for the reliability in SHFSWR.

Both transmit and receive antennas of HFSWR are compound of vertical monopoles located over earth's lossy ground under which certain ground screen layouts are used. The mission of the transmit antenna system are

- to couple as much EM energy as possible over the sea surface,
- to give as much gain as possible over the desired frequency band,
- to give as much front-to-back ratio as possible over the desired frequency band,
- to cover azimuth range up to 120°,
- to have as deep over-head null as possible, in order to get rid of ionospheric self-interference effects.

Similarly, the receive antenna system missions are

- to cover azimuth range up to 120°,
- to give as much front-to-back ratio as possible over the desired frequency band,
- to have as deep over-head null as possible, in order to get rid of ionospheric self-interference effects,
- to allow electronic beam steering abilities as close to theoretical behaviours as possible.

In this report, HFSWR antenna systems are overviewed. First, Cape Bonavista and Cape Race transmit and receive arrays are investigated. The channel elements of both sites are analysed over lossy ground without and with ground screens. A doublet, a triplet and a quadlet are used as channel elements for both Cape Bonavista and Cape Race receive arrays and their performances are numerically simulated. Different radiators are used as channel elements, such as monopoles, fat monopoles and inverted cones. Then, a seven, a sixteen and a twenty-four channel arrays are analysed and electronic beam forming capabilities are investigated. Finally, the conclusions are outlined together with major design guidelines.

Two well-known numerical techniques are used for these simulations. They are the Finite-Difference Time-Domain (FDTD) and Method of Moments (MoM) techniques. FDTD is a time domain technique where broad band frequency behaviours can be obtained via a single simulation. MoM is a frequency domain technique where complex structures over lossy ground with different ground screen layouts can easily be investigated. While in-house written FDTD code is used for FDTD simulations, commercially available NEC2 package is used for MoM simulations.

II Time and Frequency Domain Numerical Techniques

Broad class of complex EM problems can be handled via a few time and/or frequency domain techniques. In this section, FDTD and MoM techniques will be outlined.

2.1 Finite-Difference Time-Domain Method

This method is based on the discretization of Maxwell' s two curl equations directly in time and spatial domains and divide the volume of interest into unit cells as shown in Fig.2.1. This unit cell is called Yee cell [1] where electric and magnetic field components are located at different places. For the numerical implementation of FDTD method, the observations listed below are made:

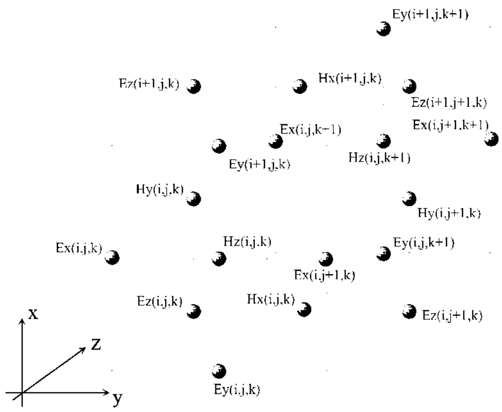


Fig.2.1: Yee cell for the FDTD method

- There are three electric and three magnetic field components in each Yee cell which is distinguished by (i, j, k) label. The discretization steps are Δt and Δx, Δy, Δz for time and position, respectively which gives the co-ordinate (i, j, k) and the time n as

$$(i, j, k) = (i\times\Delta x, j\times\Delta y, k\times\Delta z), \qquad t = n\times\Delta t \qquad (2.1)$$

(for clarity, the time index n is suppressed and unless otherwise is stated the field components are given for time n, i.e., $E_x=E_x^n$).

- Although field components in each cell are labelled with the same (i, j, k) numbers (such as E_x (i, j, k) or H_z (i, j, k)), their locations are different.

- Besides the location difference between field components in a cell, there is also a time difference between electric and magnetic field components. That is, the electric field components are calculated at time steps $t=\Delta t/2$, $3\Delta t/2$, $5\Delta t/2$, …..
- Both magnetic and electric field components in any cell may be moved to origin by just cell averaging. This is accomplished by using two magnetic field components as;

$$H_x(i,j,k) = \frac{1}{2} \times \left[H_x(i,j,k) + H_x(i+1,j,k)\right] \tag{2.2}$$

but four electric field components as;

$$E_z(i,j,k) = \frac{1}{4} \times \left[E_z(i,j,k) + E_z(i+1,j,k) + E_z(i,j+1,k) + E_z(i+1,j+1,k)\right]\ . \tag{2.3}$$

- As can be seen from the iterative FDTD equations [1], any object may be simulated by the medium parameters ε, μ, σ. Two of them, ε and σ appear in electric field components and the third, μ appears in magnetic field components. Three different ε and σ values may be assigned for three electric field components, so those different objects may be located within the Yee cell. Similarly, different μ values may be given for H_x , H_y and H_z for the same purpose. For example, an infinitely thin wire antenna (with length $\ell=4\Delta z$) located along z-axis may be simulated by taking;

$$E_z(i,j,k) = E_z(i,j,k+1) = E_z(i,j,k+2) = E_z(i,j,k+3) = 0 \tag{2.4}$$

during FDTD iterations. Similarly, an infinitely thin PEC plate may be located at the bottom of (i, j, k) cell along xy-plane by just taking

$$E_x(i,j,k) = E_x(i,j+1,k) = 0$$
$$E_y(i,j,k) = E_y(i+1,j,k) = 0 \tag{2.5}$$

- Although electric and magnetic field components are updated during the time simulation, the voltage and currents in (i, j, k) cell may be obtained from Gauss and Ampere laws directly. For example, V_z and I_z can be obtained as

$$V_z(i,j,k) = -E_z(i,j,k)\times\Delta z$$
$$I_z(i,j,k) = [H_x(i,j-1,k) - H_x(i,j,k)]\times\Delta x + [H_y(i,j,k) - H_y(i-1,j,k)]\times\Delta y \tag{2.6}$$

- Both sinusoidal and pulse type source simulations can be handled in FDTD. For example, a voltage source $V_z(t)$ at (i, j, k) cell may be injected via

$$E_z^{\,n}(i,j,k) = E_z^{\,n}(i,j,k) + V_z(n\times\Delta t)/\Delta z \tag{2.7}$$

where,

$$V_z(n\times\Delta t) = A_o\times\mathrm{Sin}(2\pi f_o n\Delta t) \tag{2.8}$$

for sinusoidal source with amplitude and frequency values A_o and f_o, respectively,

$$V_z(n\times\Delta t) = A_o\times\exp(-(n-M)^2/L^2) \tag{2.9}$$

for a Gaussian source with M and L (integers) representing the time shift and pulse width, respectively.

2.2 Method of Moment

One of the most powerful techniques in frequency domain is the MoM. The primary formulation of MoM is an integral equation [2] obtained through the use of Green's functions. The technique is based on solving complex integral equations by reducing them to a system of linear equations and on applying *method of weighted residuals*. Actually the terms *method of moments* and *method of weighted residuals* are synonymous. It is Harrington [2], who popularised the term *method of moments* in electrical engineering society. His pioneering efforts first demonstrated the power and flexibility of this numerical technique for solving problems in electromagnetics.

All *weighted residuals* techniques begin by establishing a set of trial solutions with one or more variable parameters. The *residuals* are a measure of the difference between the trial solution and the true solution. The variable parameters are determined in a manner that guarantees a *best fit* of the trial functions based on a minimisation of the residuals.

The equation solved by MoM technique is generally a form of the *electrical field integral equation* (EFIE) or the *magnetic field integral equation* (MFIE). Both of these equations can be derived from Maxwell's equations by considering the problem of a field scattered by a perfect conductor (or a lossless dielectric). These equations are of the form

$$\text{EFIE:} \qquad \mathbf{E}=fe(\mathbf{J}) \tag{2.10}$$

$$\text{MFIE:} \qquad \mathbf{H}=fm(\mathbf{J}) \tag{2.11}$$

where the terms on the left-hand side of these equations are incident field quantities and **J** is the induced current.

The form of integral equation used determines which type of the problems a MoM technique is best suited. For example, one form of EFIE may be particularly well suited for modelling thin-wire structures, while another form is better-suited analysing metal plates. Although it can also be applied in time-domain the majority of these equations are in frequency-domain.

The first step in the MoM solution process is to expand **J** as a finite sum of basis (or expansion) functions,

$$\mathbf{J} = \sum_{i=1}^{M} J_i \, \mathbf{b}_i \qquad (2.12)$$

where $\mathbf{b}_i$ is the i^{th} basis function and J_i is an unknown coefficient. Next, a set of M linearly independent weighting (or testing) functions, w_j, are defined. An inner product of each weighting function is formed with both sides of the equation being solved. In the case of the MFIE, this result s in a set of M independent equations of the form,

$$\langle w_j, \mathbf{H} \rangle = \langle w_j, fm(\mathbf{J}) \rangle \qquad j=1,2, \;..\; ,M \qquad (2.13)$$

By expanding **J** using eq. (2.12) a set of M equations in M unknowns are obtained as

$$\langle w_j, \mathbf{H} \rangle = \sum_{i=1}^{M} \langle w_j, fm(\mathbf{J_i}, \mathbf{b_i}) \rangle \qquad j=1,2, \;..\; ,M \qquad (2.14)$$

This can be written in matrix form as,

$$[\mathbf{H}] = [Z]\;[\mathbf{J}] \qquad (2.15)$$

where: $Z_{ij} = \langle w_j, f_m(b_i) \rangle$

$\mathbf{J_i} = J_i$

$\mathbf{H_j} = \langle w_j, \mathbf{H_{inc}} \rangle$.

The vector **H** contains the known incident field quantities and the terms of the Z-matrix are the functions of the geometry. The unknown coefficients of the induced currents are the terms of the **J** vector. These values are obtained by solving the system of equations. Other parameters such as the scattered electric and magnetic fields can be calculated directly from the induced currents.

Depending on the form of the integral equation used, MoM can be applied to configurations of

- conductors only,
- homogeneous dielectrics only, or
- very-specific conductor-dielectric

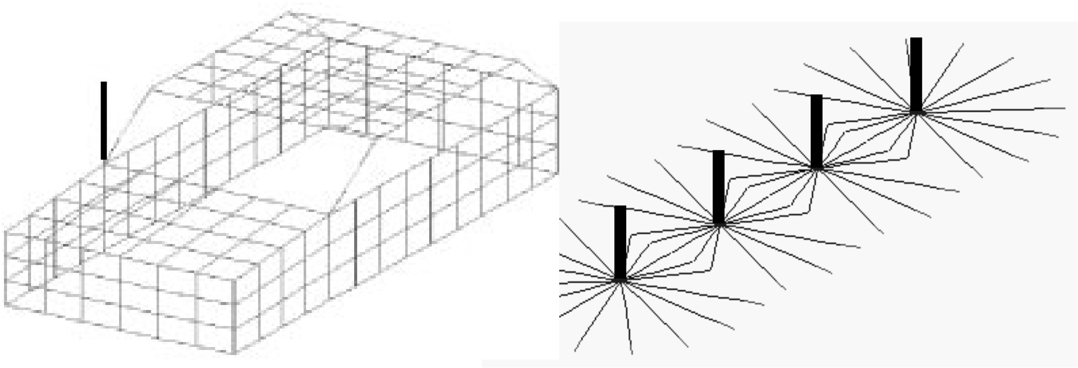
geometries. MoM techniques applied to integral equations are not very effective when applied to arbitrary configurations with complex geometries or inhomogeneous dielectrics.

Nevertheless, MoM techniques do an excellent job of analysing a wide variety of important three-dimensional radiation and scattering problems. General purpose MoM codes are particularly efficient of modelling wire antennas or wires attached to large conductive surfaces.

Any metallic object is assumed to be a superposition of small segments on which the current distributions are of interest. Depending on the number of segments, a matrix representation is used and the current distributions are calculated by matrix inversion (see eq.(2.15). Once the current distributions are calculated, any desired parameter, such as near and far fields, S parameters, impedance, etc., can be calculated. In Fig.2.2, two examples that can be handled via MoM are given.

In Fig.2.2a, a vertical wire antenna over the body of a car is shown. In Fig2.2b, a monopole quadlet (four vertical wires) with a ground screen is plotted. These two examples are too complex to handle via analytical solutions. Structures such as shown in this figure can easily be modelled via MoM. The limitations of MoM are

- the number of segments
- and diffraction effects.



(a) (b)

Fig.2.2: The segmentation of (a) a wire antenna over a car, (b) four vertical monopoles with 16 ground screen radials under each

Since MoM is based on the calculation of currents on small segments and since it is formulated as a matrix system, the memory and computation time requirements drastically increase as the number of segment increases. Number of segment depends on the size of the structure and the frequency. Segmentation with one over ten wavelength (i.e., $\lambda/10$) is usually a good choice for most of the EM problems.

Attention should be paid when interpreting MoM results in problems where diffraction effects are important. In MoM, diffraction effects are not taken into account, so edge and/or tip treatments in problem geometries must be handled via some other methods.

NEC2 Package

The NEC2 package [3] uses MoM technique that is based on numerical solution of integral equations for the currents induced on metallic structures by sources or by an incident field. Antenna and or radar cross-section (RCS) modelling is possible as long as a structure is modelled as a collection of thin wires. The package is especially handy in modelling wire antennas having lengths up to several wavelengths.

The major capabilities and their range of validity may be outlined as follows:

- Wire antennas over PEC or lossy ground can be modelled via NEC.
- Radial ground screen option (see Fig.2.3) can only be used for broadcasting antennas (i.e., for a standalone vertical wire antenna over lossy ground).
- Radial and/or rectangular mesh type ground screens for arrays can only be modelled by the user as a combination of separate wires (see Fig.2.2b). Attention should be paid when horizontal wires are located close to ground. Horizontal wires may be as close as $10^{-6}\lambda$ to ground.
- Diffraction effects are not taken into account in NEC, so any difference more than 30-40dB in radiation patterns (or gains) has no practical meaning.
- An option is added into NEC (See Fig.2.4) to model two mediums (e.g., poor land and sea) and/or cliffs with a surface impedance approximation.

References

[1] **K. S. Yee**, “Numerical solution of initial boundary value problems involving Maxwell’s equations,” IEEE Trans. AP, V-14, no. 3, pp. 302-307, May 1966

[2] R**. F. Harrington**, “Field Computation by Moment Methods”, The Macmillan Co., New York 1968

[3] **G. J. Burke & A. J. Poggio**, "Numerical Electromagnetic Code - Method of Moments, Part I: Program Description, Theory", Technical Document, 116, Naval Electronics System Command (ELEX 3041), July 1977

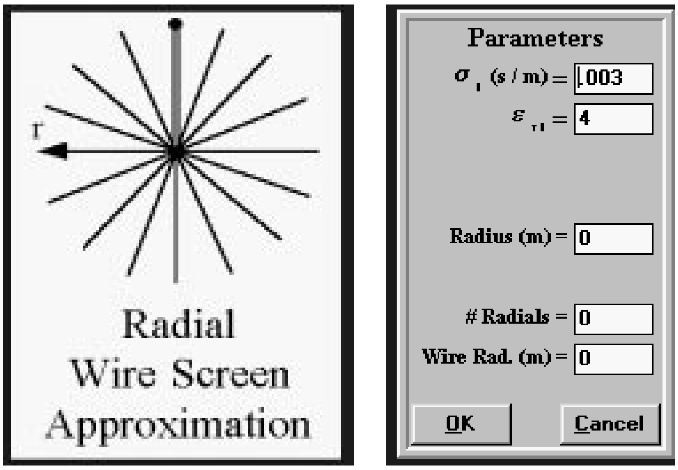


Fig. 2.3: Ground screen with radial wires in NEC (NEC calculates approximate equivalent surface impedance for the ground and screen)

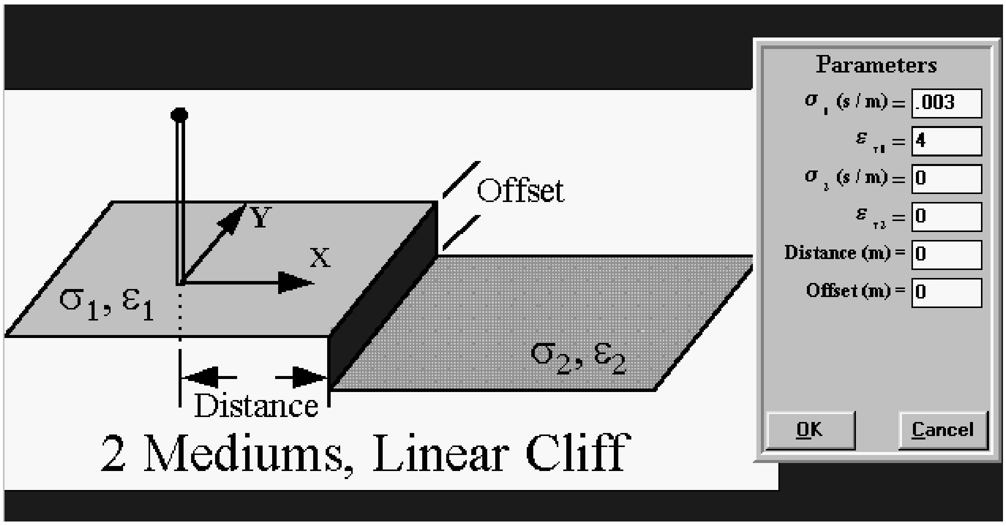


Fig. 2.4: Linear cliff modelling and two mediums with parameter specifications in NEC. By using this module, land-sea coupling, beam shooting over a hill towards the sea can be modelled up to a certain extend. The two medium parameters, distance from the antenna to cliff and the cliff's height above sea level are supplied from the table on the right. The antenna must be on the upper medium.

III Receive Array Channel Elements

Different structures are analysed as the channel elements of the receive array. They are channels with monopoles and fat monopoles. Channels with monopoles are used in Cape Bonavista and with fat monopoles in Cape Race.

Three different structures are used as channels. They are quadlet, triplet and doublet. In quadlet, four elements are spaced approximately quarter-wavelength apart and are phased to form an end-fire channel. Similarly, three and two elements are used in triplets and doublets, respectively.

The mission of these channel elements is

- To form a maximum radiation along the channel axis with as much azimuth coverage as possible (typically 120°),
- To give as high gain as possible (at least 2-3dB)
- To give as much front-to-back ratio as possible (at least 12-15 dB),
- To give as deep over-head null as possible (at least 25-30dB)

in the whole frequency band of operation.

In this section these channel elements are investigated. Their gain, vertical and horizontal radiation characteristics are calculated at different frequencies. A 16-radial ground screen layout is used for all calculations. NEC2 package is used for this purpose. Fortran codes are written to prepare input files for NEC modelling.

Also, CODAR antenna systems are simulated via NEC package. The beam-forming performance of a four-element crossed monopole and a five-element, two-tower systems are presented.

3.1 Quadlet, Triplet and Doublet with Monopoles

First, channel design with monopoles is taken into account. Short monopoles are used in quadlet, triplet and doublet. The top view of the channel elements (quadlet, triplet and doublet) with the ground screen layout are shown in Fig.3.1. Their 3D view is pictured in Fig.s 3.2 to 3.4.

Each vertical monopole has a ground screen of 16 radials. Radials of different elements in a channel are connected to each other when intersected. The channels are optimised for the frequency band of 3MHz-5.5MHz. The parameters of the channels are listed in Table 3.1. The numerical simulations, performed via NEC2 package for the channel elements, are carried out with these parameters.

Table 3.1

Antenna parameters used in NEC simulations

Antenna height	9.22	[m]
Element spacing	19.0	[m]
Element wire radius	0.15	[m]
Number of radials	16	
Radial wire lengths	19.0	[m]
Radial wire radius	0.001	[m]
Incremental increase in cable length	19.0	[m]
Phase velocity in electrical cable	0.84×c	[m/s]

Feeding voltage drops are used to account for the cable losses. For this, elements are fed with 5V decrements, i.e.,

100V, 95V, 90V and 85V	for the quadlet
100V, 95V and 90V	for the triplet
100V and 95V	for the doublet.

This approximately corresponds to 0.5dB/100ft cable loss (typical cable loss for RG-213u is given as 0.55dB/100ft at 10MHz).

Ground is assumed to be “POOR” (i.e., ε_r=4.0, σ=0.003 S/m).

Parameters for the sea are assumed to be ε_r=80.0, σ=5.0 S/m for the *cliff option* calculation in NEC, where EM shooting towards sea surface is simulated.

Vertical and horizontal radiation patterns are obtained at three different operating frequencies, 3.5MHz, 4.5MHz and 5.5MHz. Vertical radiation pattern is obtained at xz-plane (φ=0°, -90°<θ<90°). Horizontal radiation pattern is plotted 5° above xy-plane (θ=85°, 0°<φ<360°).

In Fig.s 3.5 to 3.18, vertical and horizontal radiation patterns of the quadlet, triplet and doublet are given, where power gain profiles -normalised to 0dB- are plotted and exact gains, relative to isotropic radiator, are mentioned in the figure insets.

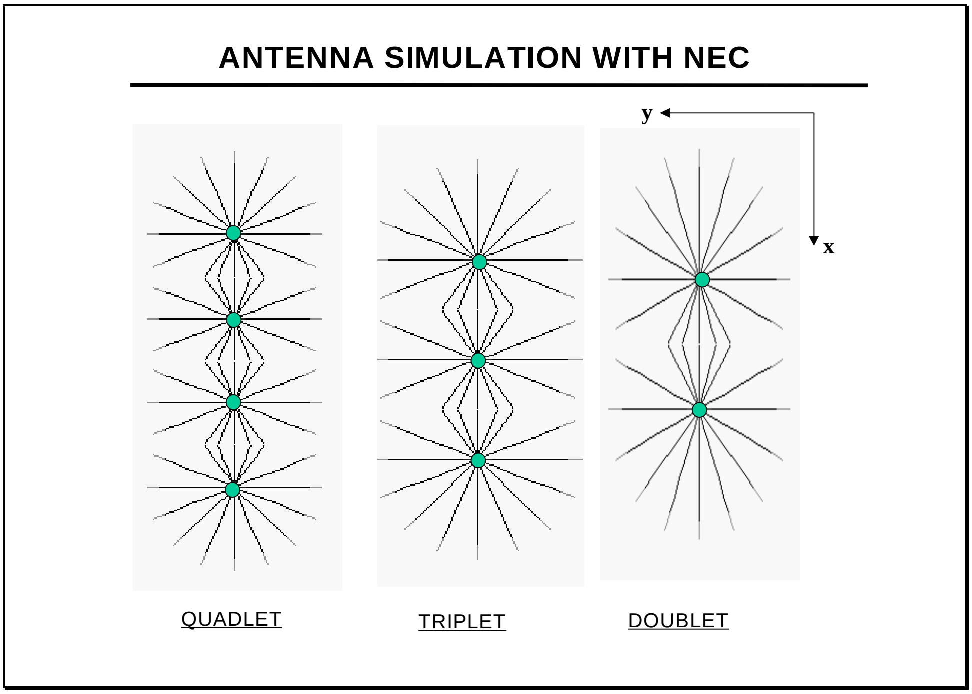

ANTENNA SIMULATION WITH NEC
y
x
QUADLET
TRIPLET
DOUBLET

Fig.3.1:

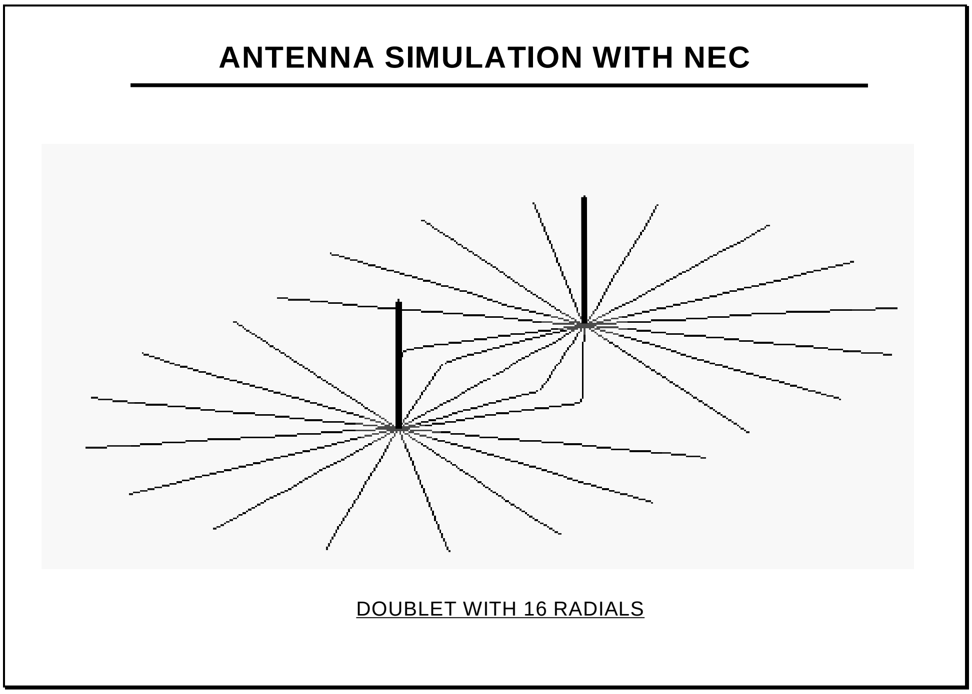

ANTENNA SIMULATION WITH NEC
DOUBLET WITH 16 RADIALS

Fig.3.2:

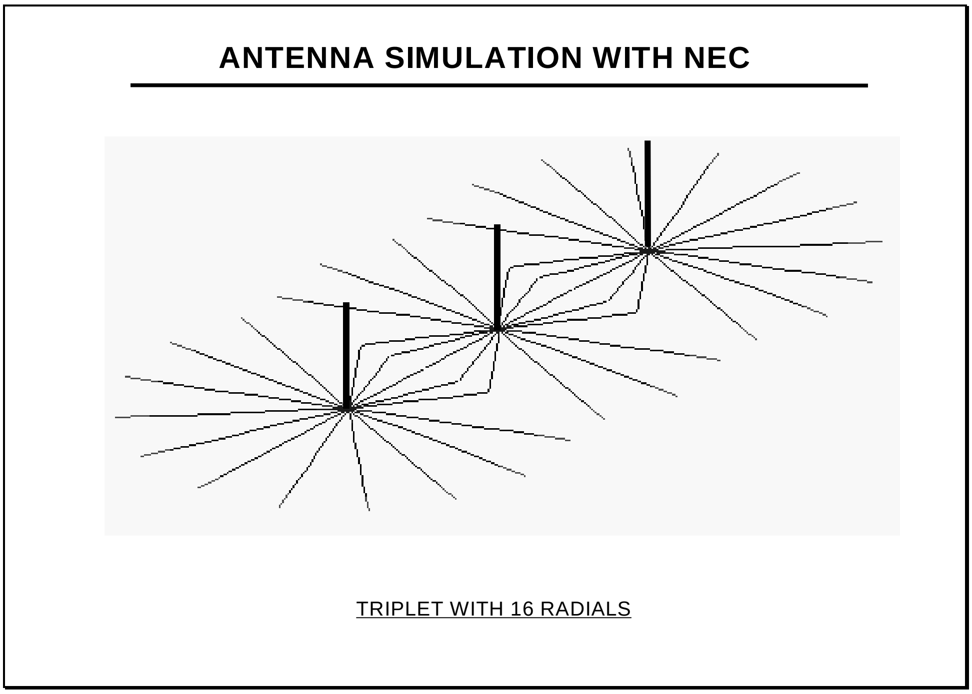

ANTENNA SIMULATION WITH NEC
TRIPLET WITH 16 RADIALS

Fig.3.3:

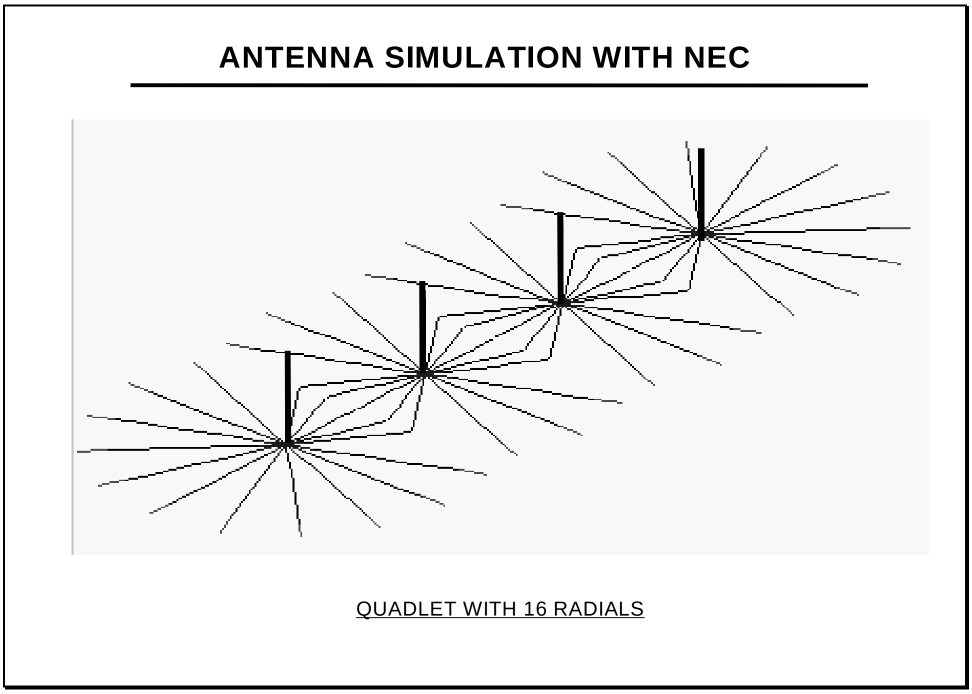

ANTENNA SIMULATION WITH NEC
QUADLET WITH 16 RADIALS

Fig.3.4:

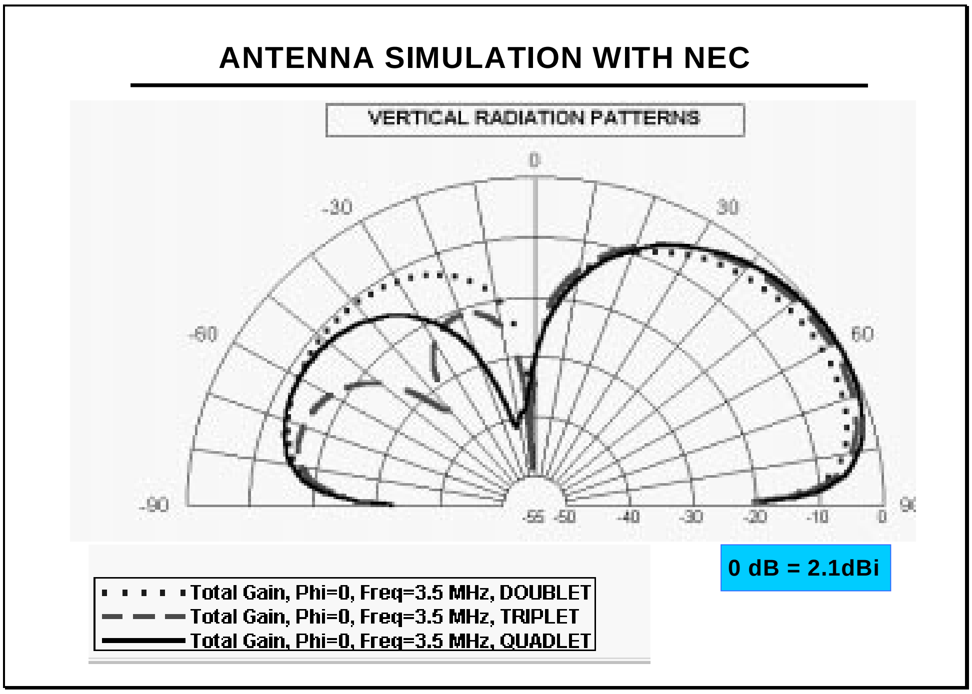

ANTENNA SIMULATION WITH NEC
VERTICAL RADIATION PATTERNS
0
-30
30
-60
60
-90
90
-55 -50 -40 -30 -20 -10 0
0 dB = 2.1dBi
Total Gain, Phi=0, Freq=3.5 MHz, DOUBLET
Total Gain, Phi=0, Freq=3.5 MHz, TRIPLET
Total Gain, Phi=0, Freq=3.5 MHz, QUADLET

Fig.3.5:

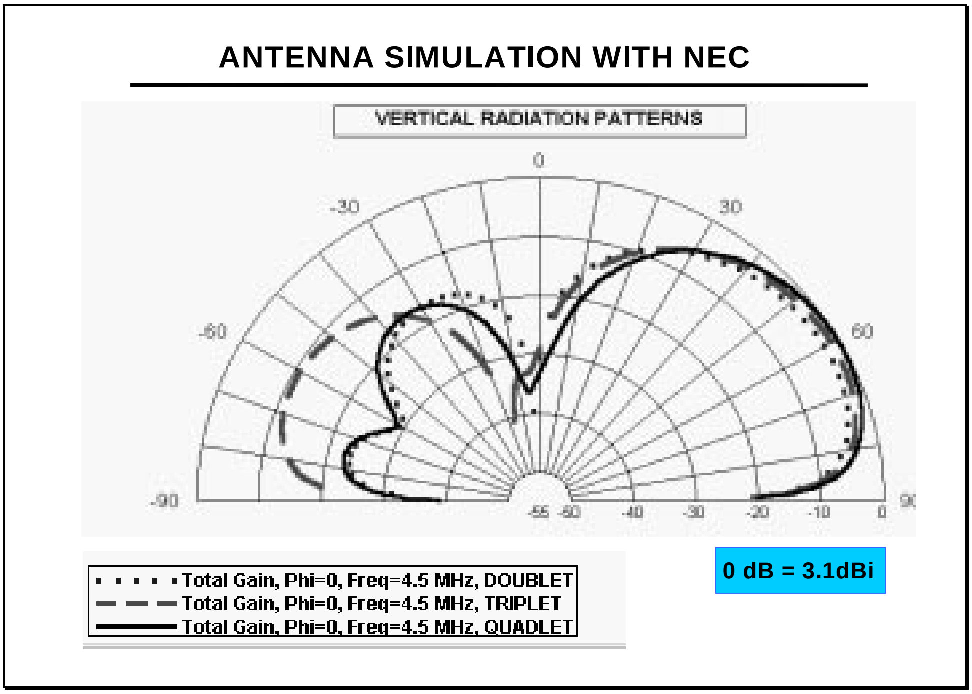

ANTENNA SIMULATION WITH NEC
VERTICAL RADIATION PATTERNS
0
-30
30
-60
60
-90
90
-55 -50 -40 -30 -20 -10 0
0 dB = 3.1dBi
Total Gain, Phi=0, Freq=4.5 MHz, DOUBLET
Total Gain, Phi=0, Freq=4.5 MHz, TRIPLET
Total Gain, Phi=0, Freq=4.5 MHz, QUADLET

Fig.3.6:

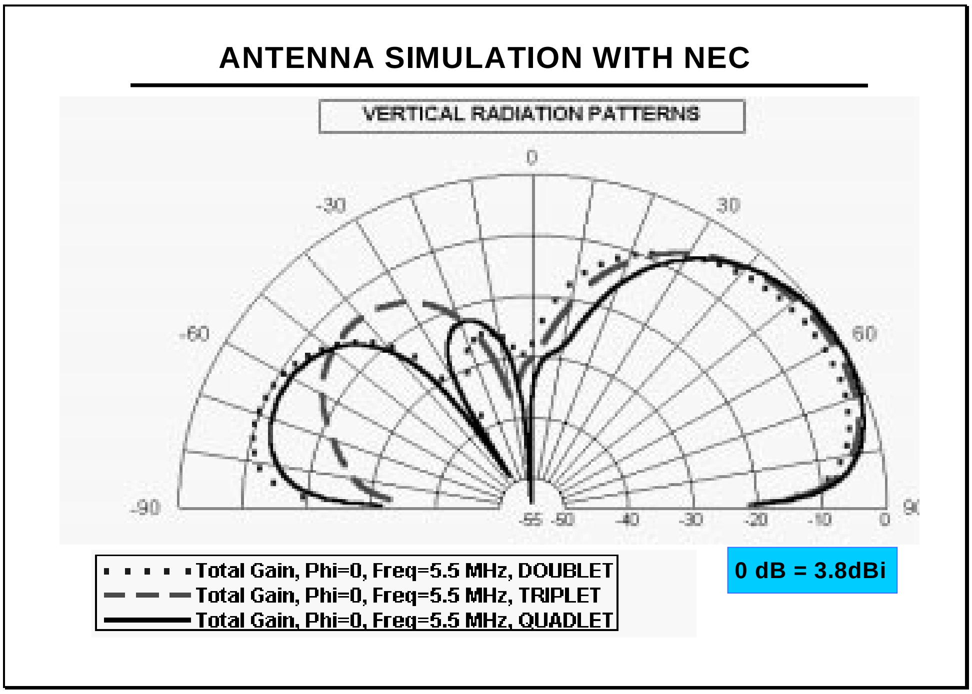

ANTENNA SIMULATION WITH NEC
VERTICAL RADIATION PATTERNS
0
-30
30
-60
60
-90
90
-55 -50 -40 -30 -20 -10 0
Total Gain, Phi=0, Freq=5.5 MHz, DOUBLET
Total Gain, Phi=0, Freq=5.5 MHz, TRIPLET
Total Gain, Phi=0, Freq=5.5 MHz, QUADLET
0 dB = 3.8dBi

Fig.3.7:

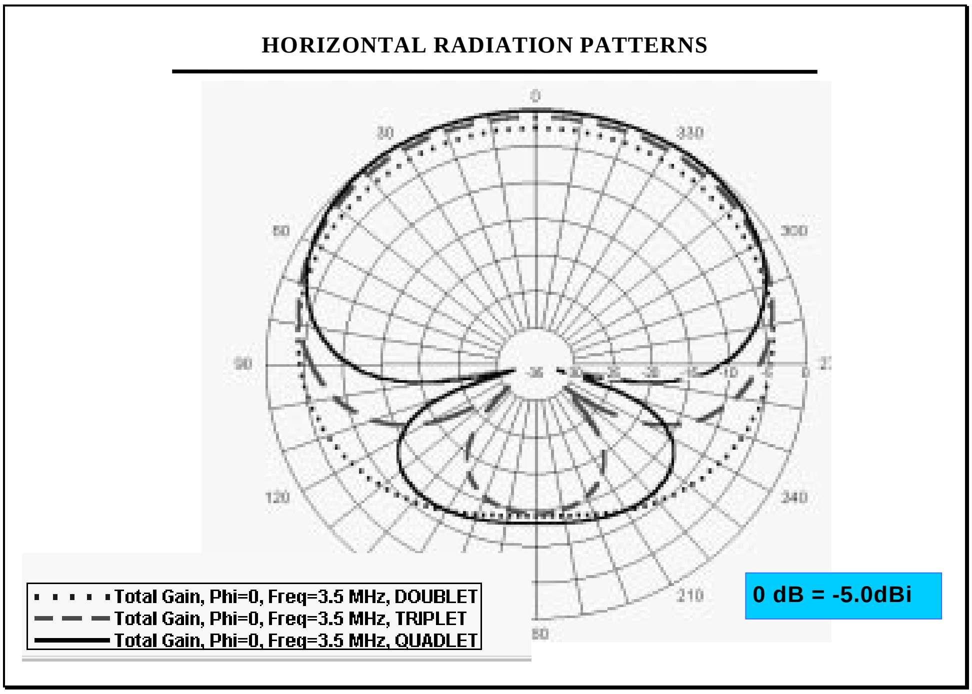

HORIZONTAL RADIATION PATTERNS
0
30
330
60
300
90
120
240
210
Total Gain, Phi=0, Freq=3.5 MHz, DOUBLET
Total Gain, Phi=0, Freq=3.5 MHz, TRIPLET
Total Gain, Phi=0, Freq=3.5 MHz, QUADLET
0 dB = -5.0dBi

Fig.3.8:

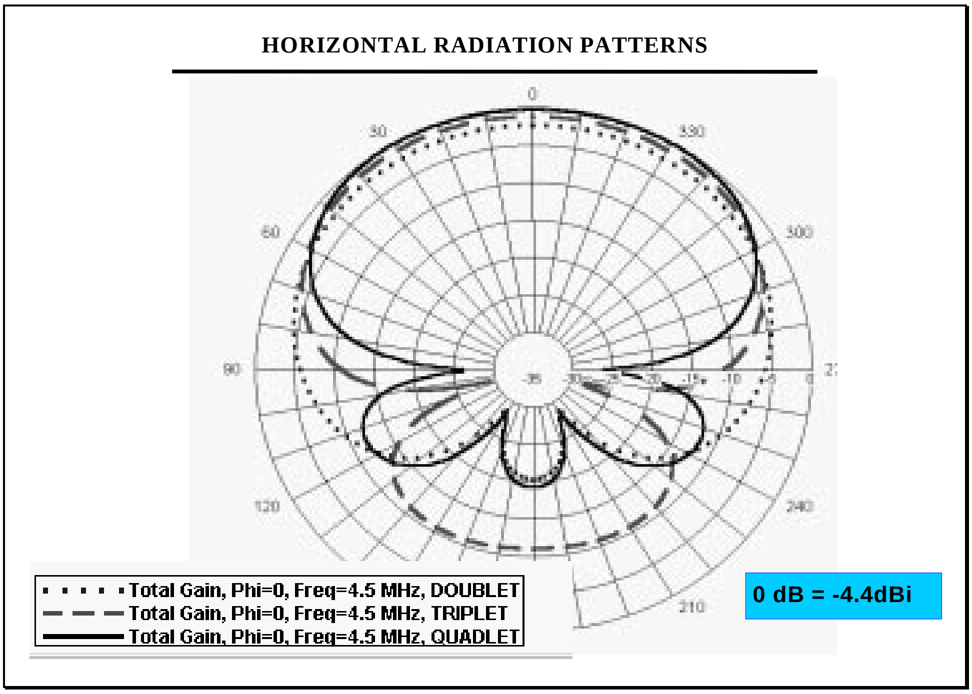


Fig.3.9:

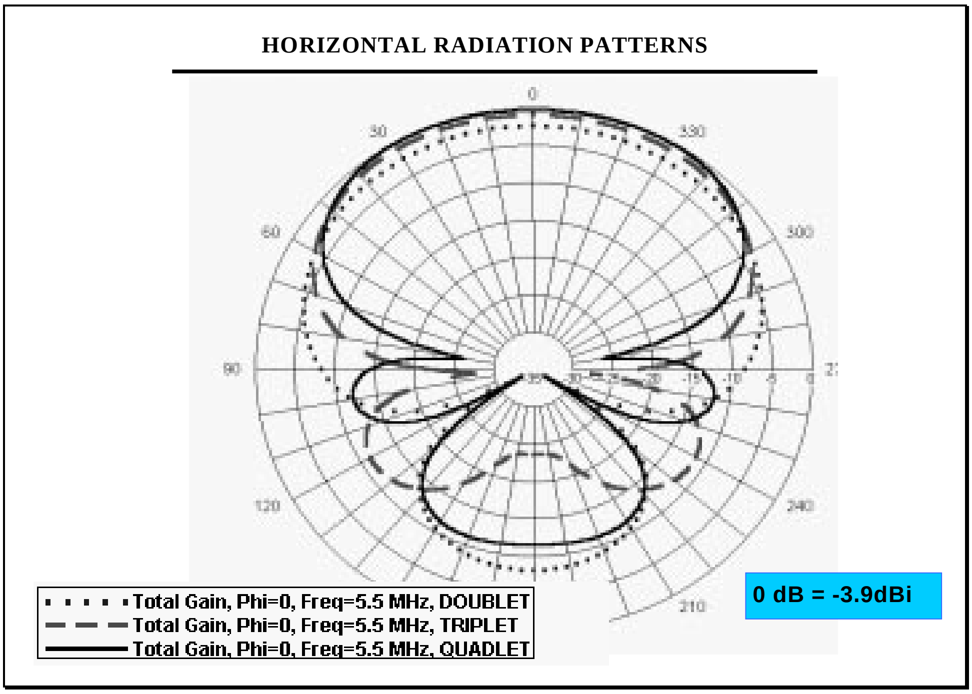


Fig.3.10:

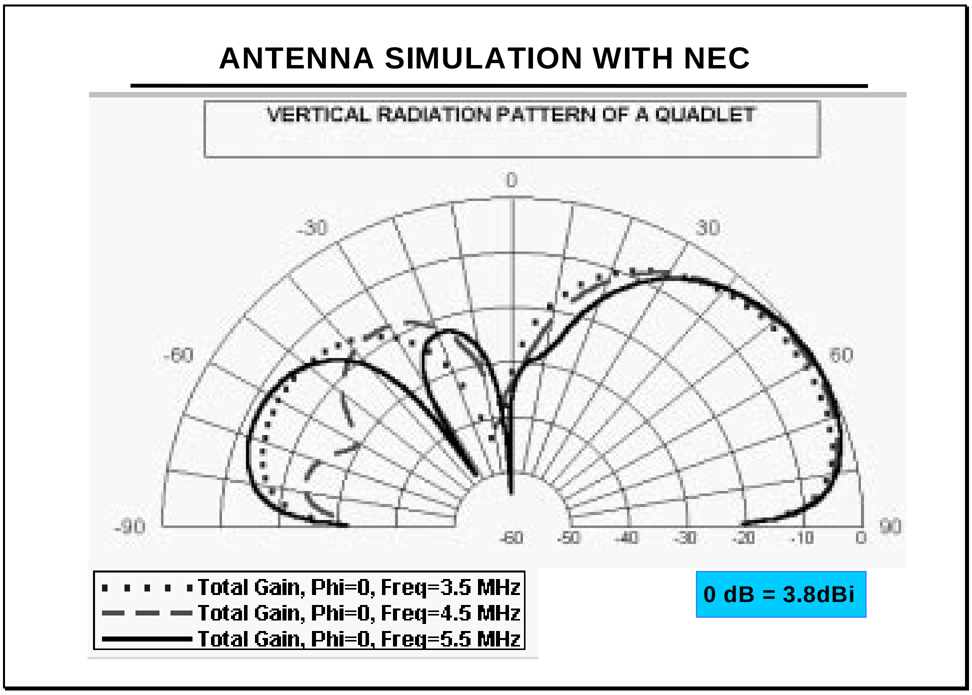


Fig.3.11:

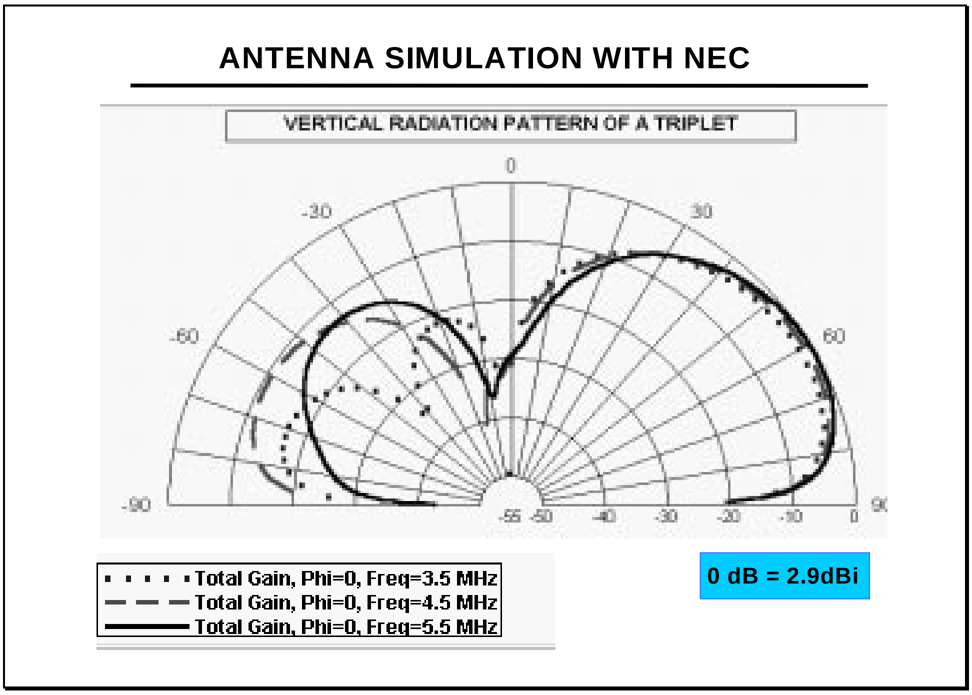


Fig.3.12:

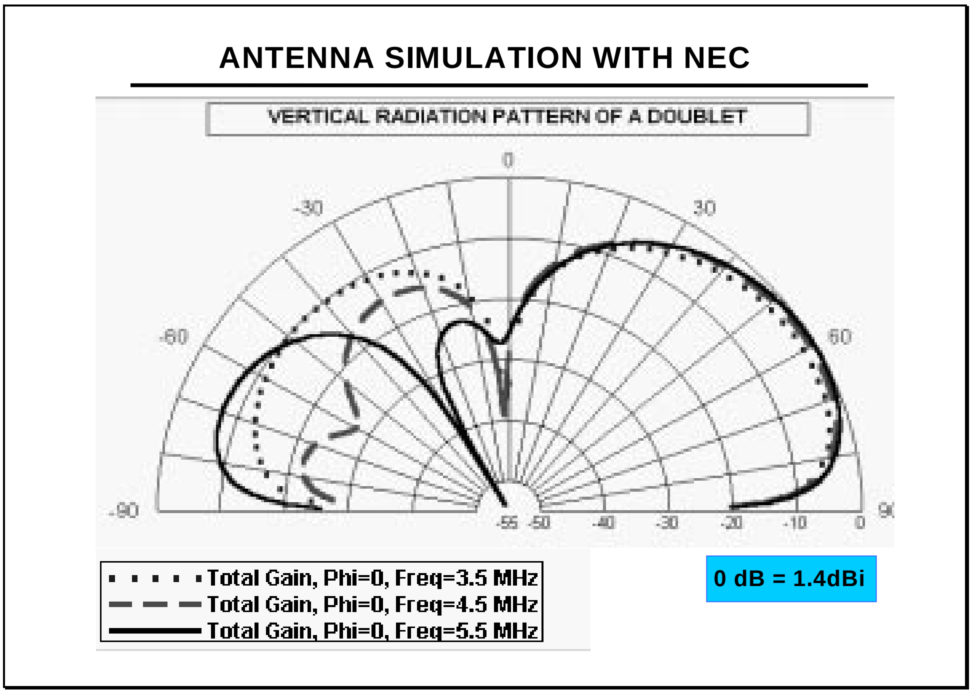


Fig.3.13:

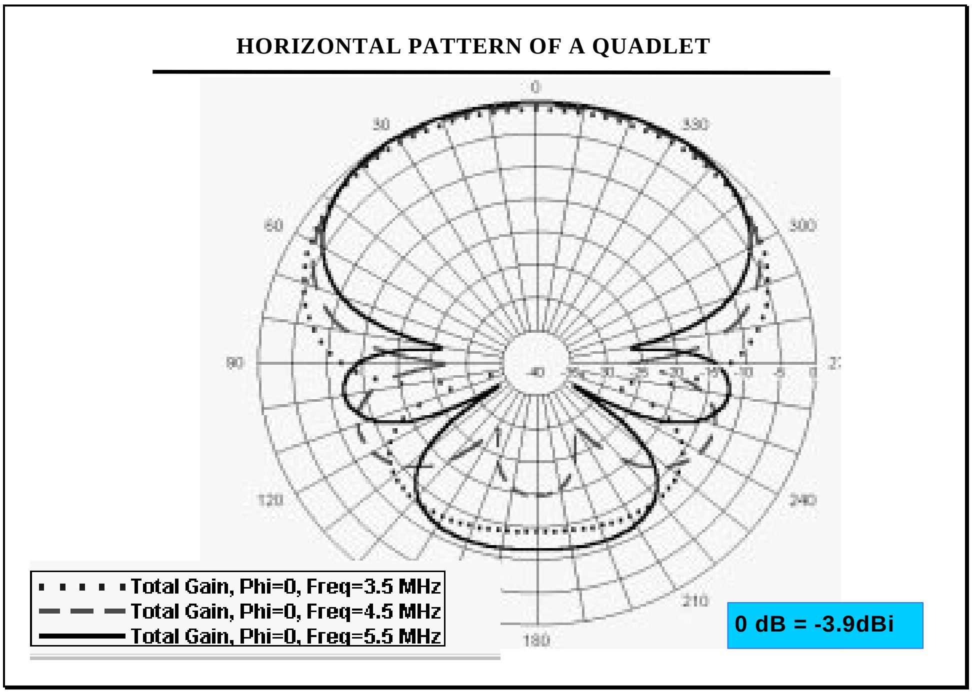


Fig.3.14:

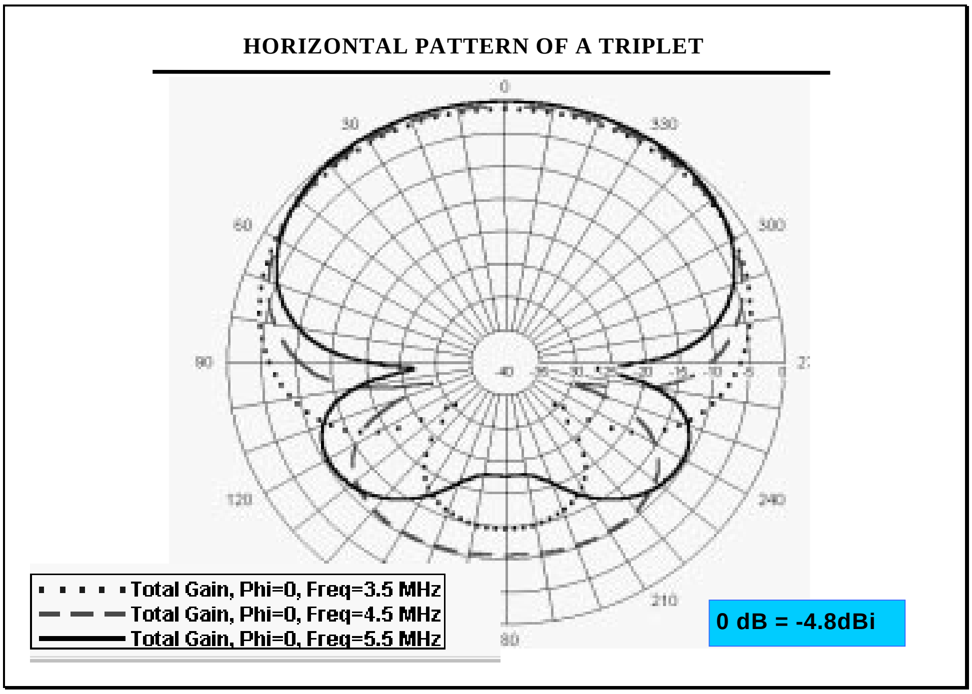


Fig.3.15:

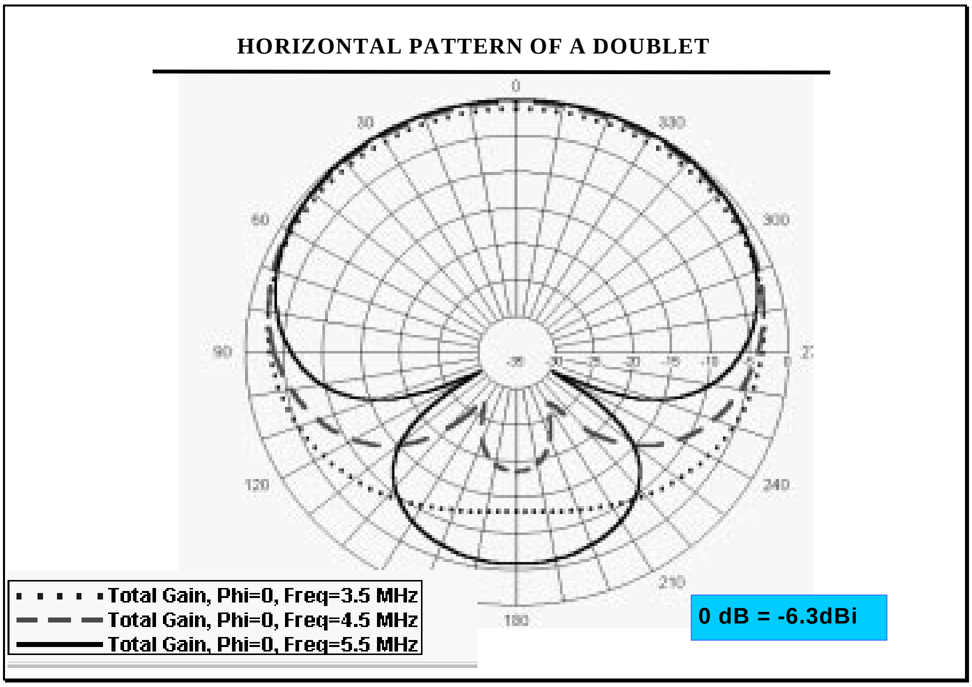


Fig.3.16:

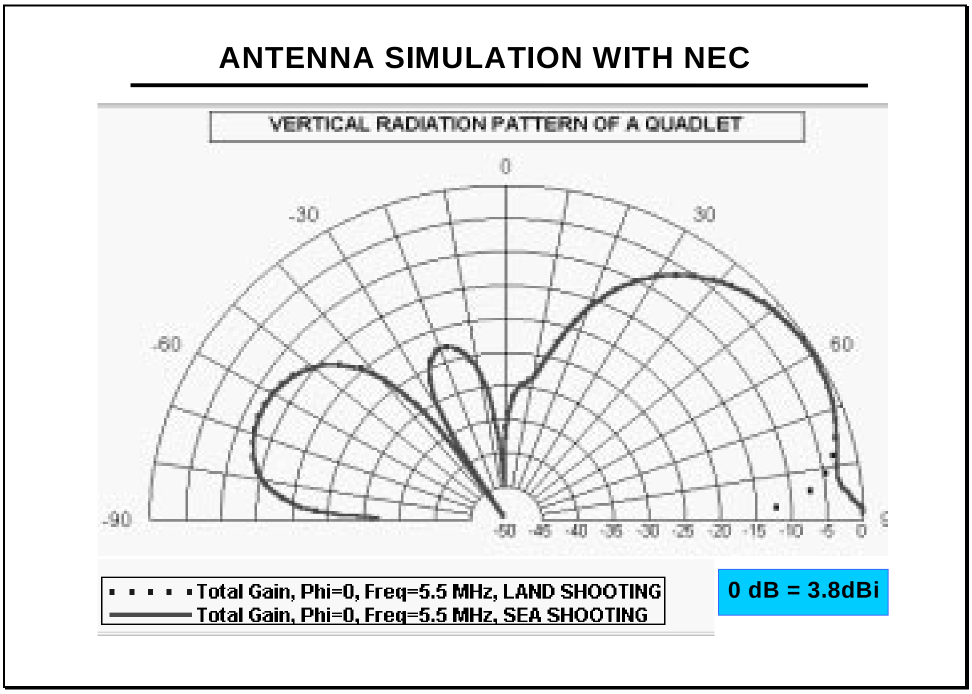


Fig.3.17:

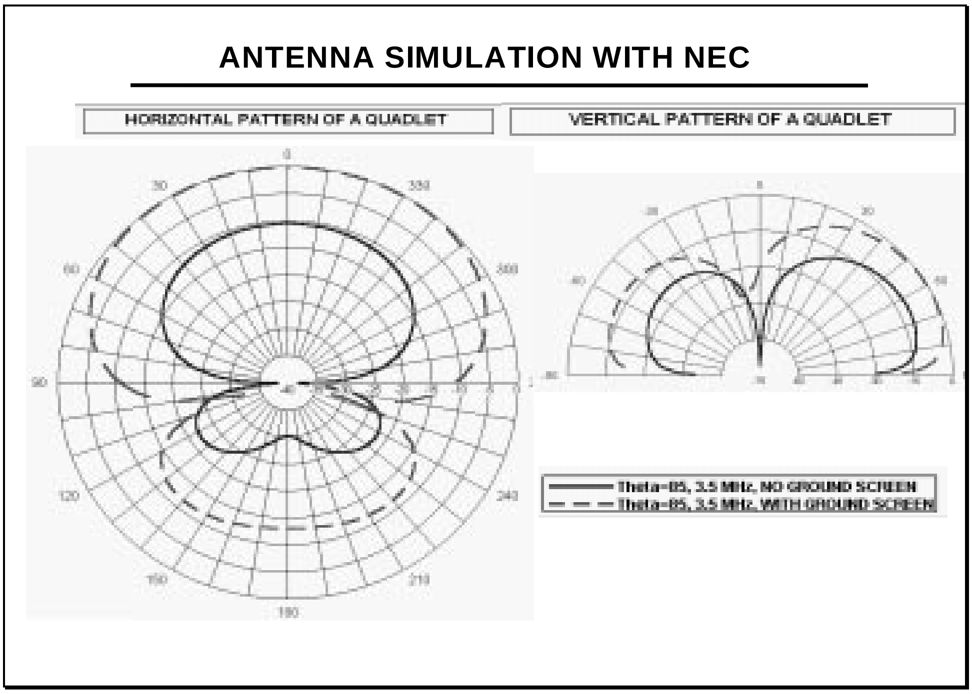


Fig.3.18:

3.2 Quadlet, Triplet and Doublet with Fat Monopoles

The same channel analysis is repeated for the fat monopoles and is included in this sub-section. In Fig.s 3-19 to 3.21, these channel elements are pictured. The parameters used for fat monopole channels are listed in Table 3.3.

Table 3.3

Antenna parameters used for fat monopoles in NEC simulations

Total antenna height	6.1	[m]
Semi-antenna height	4.6	[m]
Monopole fatness	4.2	[m]
Element spacing	19.0	[m]
Element wire radius	0.15	[m]
Number of radials	16	
Radial wire lengths	19.0	[m]
Radial wire radius	0.001	[m]
Incremental increase in cable length	19.0	[m]
Phase velocity in electrical cable	0.84×c	[m/s]

Feeding voltage drops are used to account for the cable losses. For this, elements are fed with 5V decrements, i.e.,

100V, 95V, 90V and 85V	for the quadlet
100V, 95V and 90V	for the triplet
100V and 95V	for the doublet.

This approximately corresponds to 0.5dB/100ft cable loss (typical cable loss for RG-213u is given as 0.55dB/100ft at 10MHz).

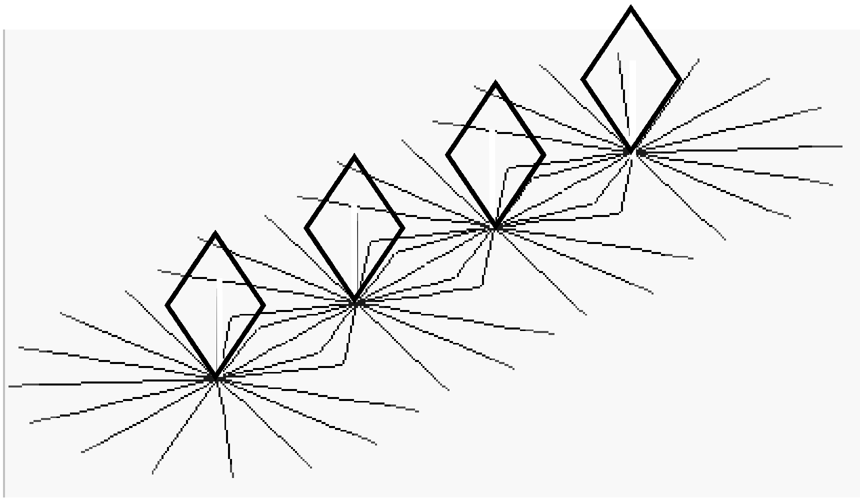
Ground is assumed to be "POOR" (i.e., ε_r=4.0, σ=0.003 S/m).

Parameters for the sea are assumed to be ε_r=80.0, σ=5.0 S/m for the *cliff option* calculation in NEC, where EM shooting towards sea surface is simulated.

Vertical and horizontal radiation patterns are obtained at three different operating frequencies, 3.5MHz, 4.5MHz and 5.5MHz. Vertical radiation pattern is obtained at xz-plane ($\varphi=0°$, $-90° < \theta < 90°$). Horizontal radiation pattern is plotted 5° above xy-plane ($\theta=85°$, $0° < \varphi < 360°$).

Again, vertical and horizontal radiation patterns of the quadlet, triplet and doublet are given in Fig.s 3.22 to 3.33. There in the figures, power gain profiles -normalised to 0dB- are plotted and exact gains, relative to isotropic radiator, are mentioned in the figure insets.

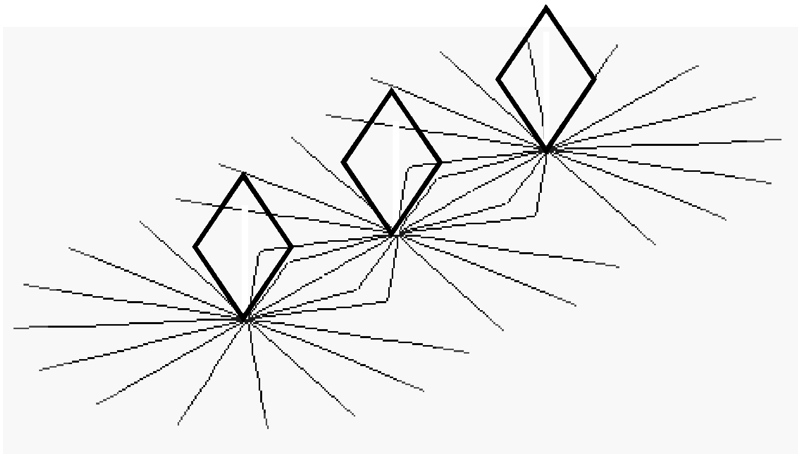
ANTENNA SIMULATION WITH NEC



FAT QUADLET WITH 16 RADIALS

Fig. 3.19

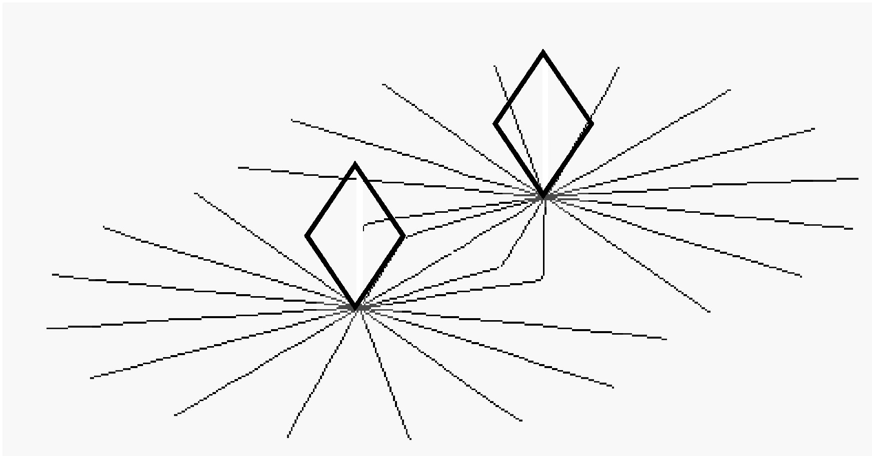
ANTENNA SIMULATION WITH NEC



FAT TRIPLET WITH 16 RADIALS

Fig. 3.20

ANTENNA SIMULATION WITH NEC



FAT DOUBLET WITH 16 RADIALS

Fig. 3.21

Channels with Fat Monopoles

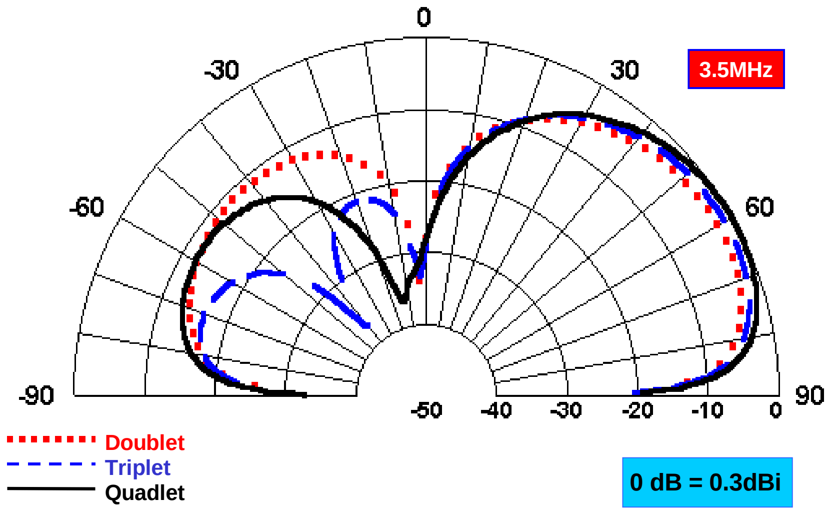


Fig.3.22

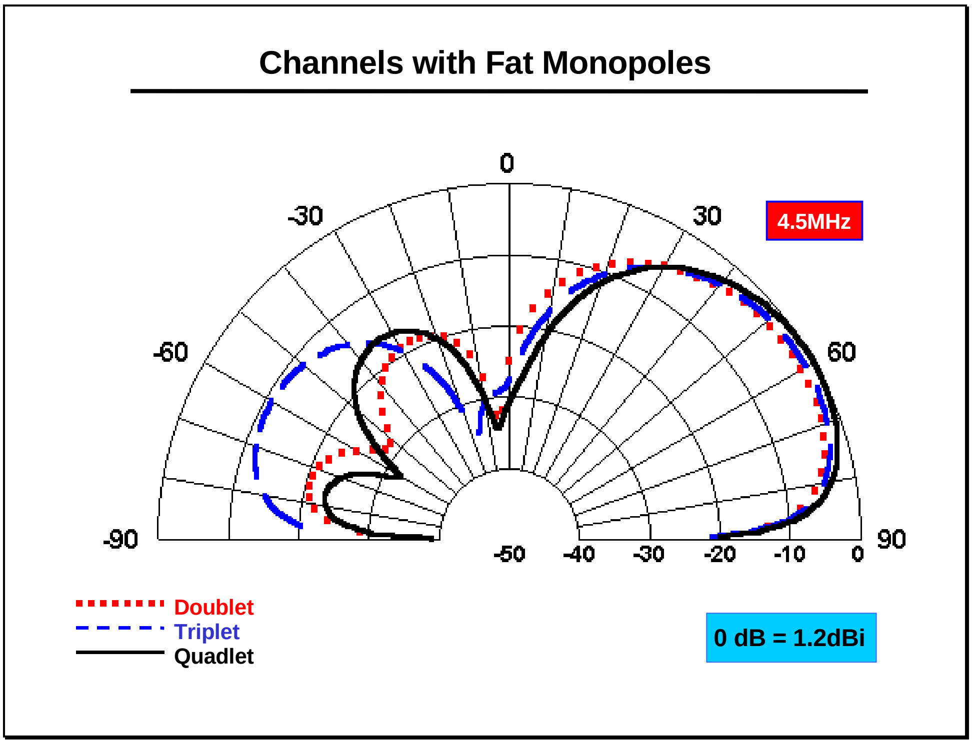


Fig. 3.23

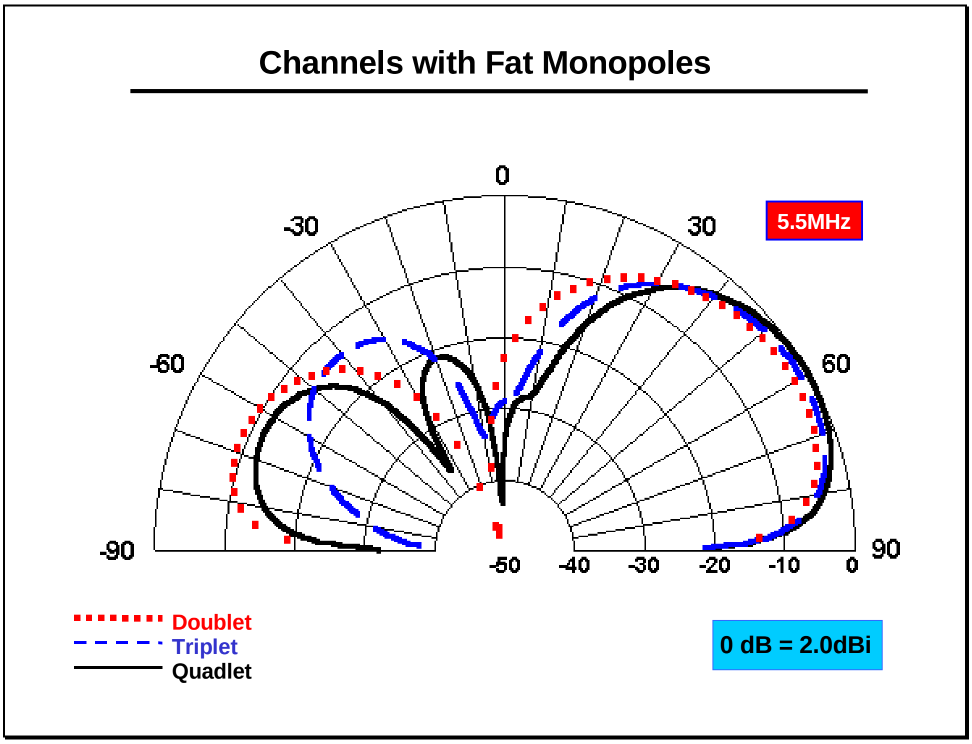


Fig. 3.24

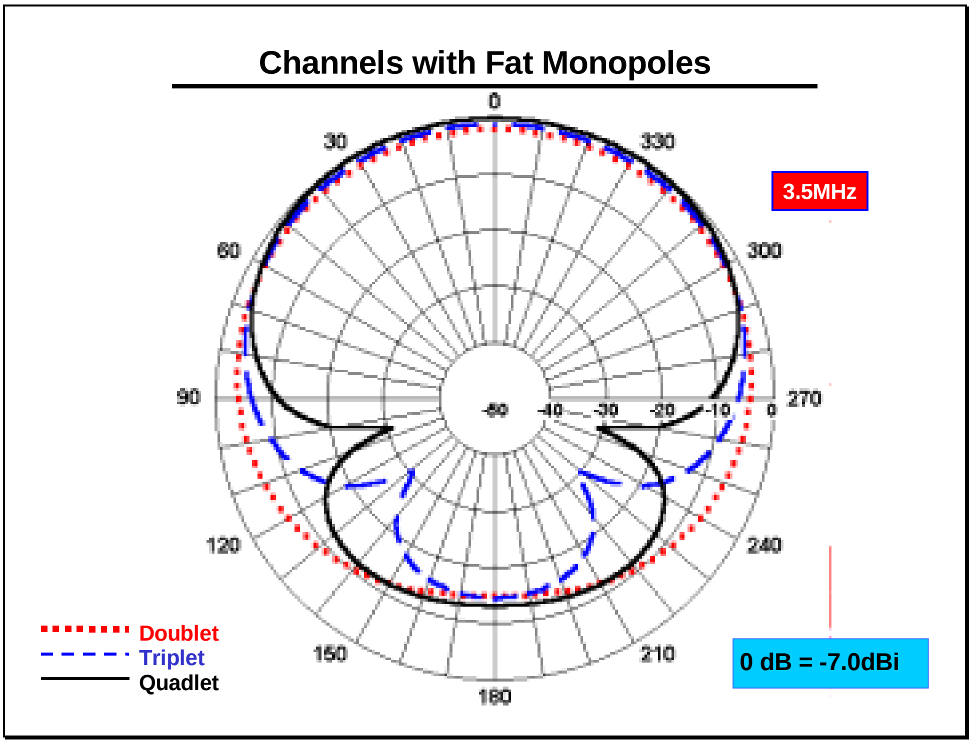


Fig. 3.25

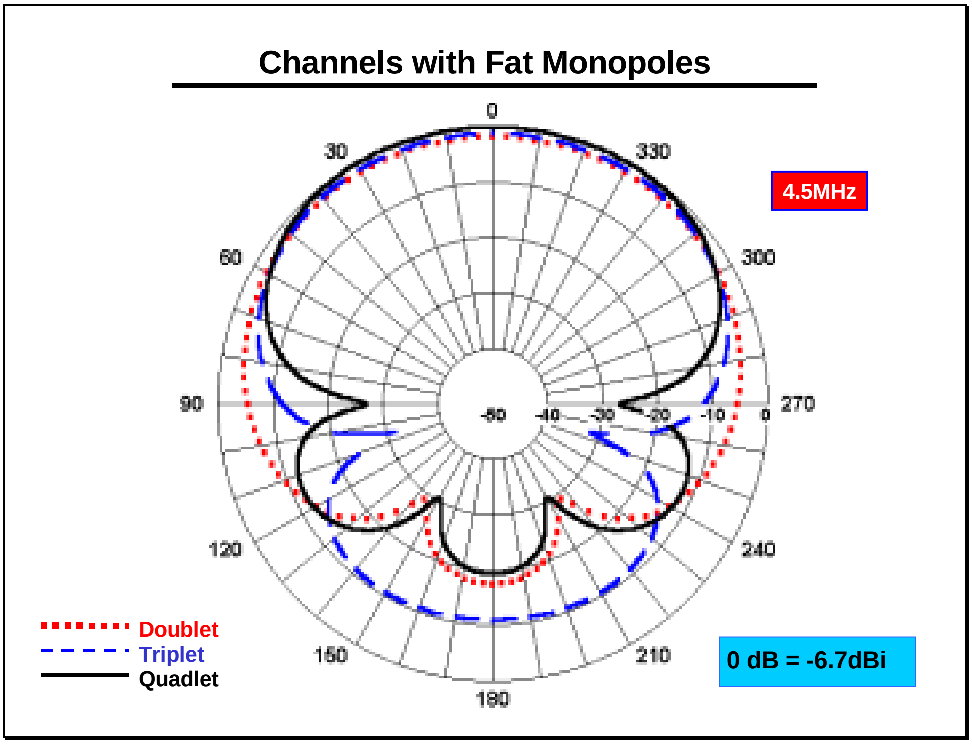


Fig. 3.26

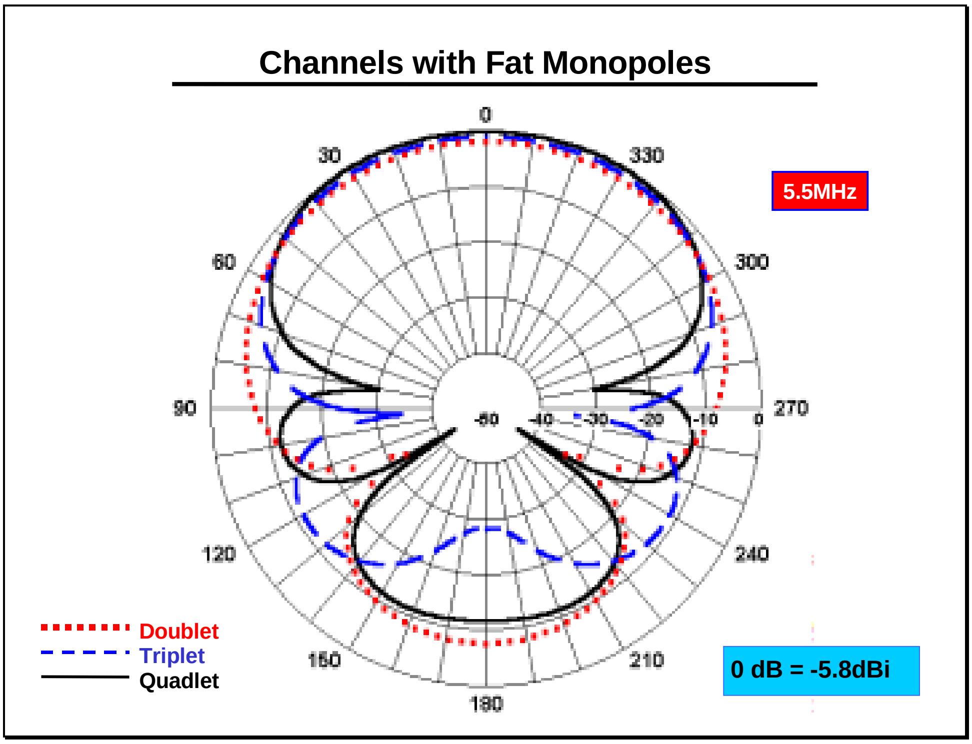


Fig. 3.27

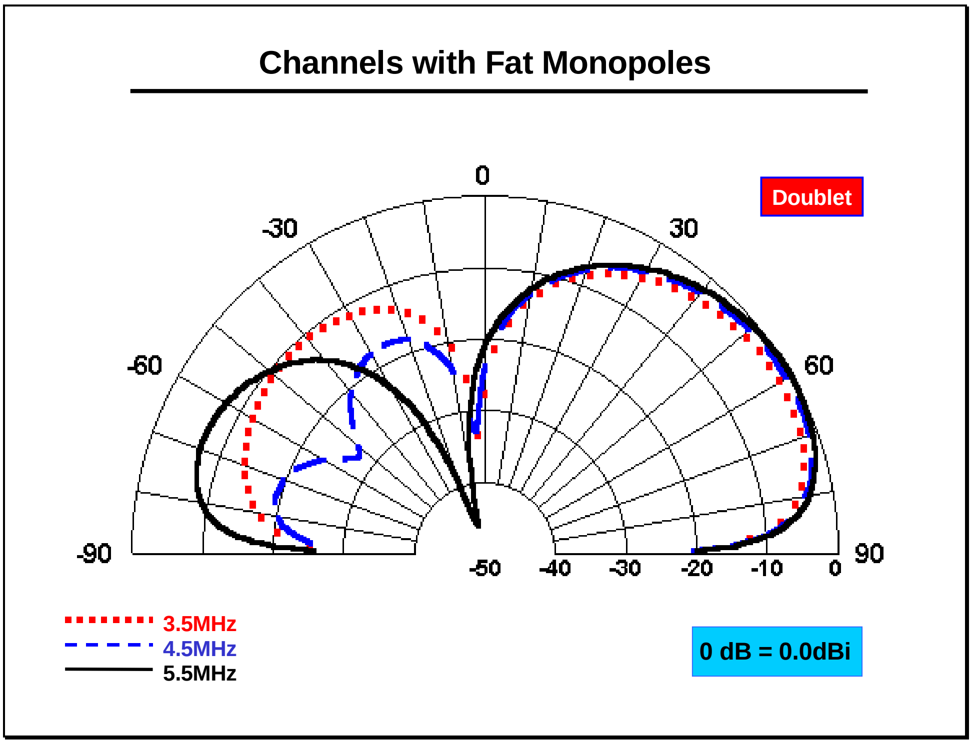


Fig. 3.28

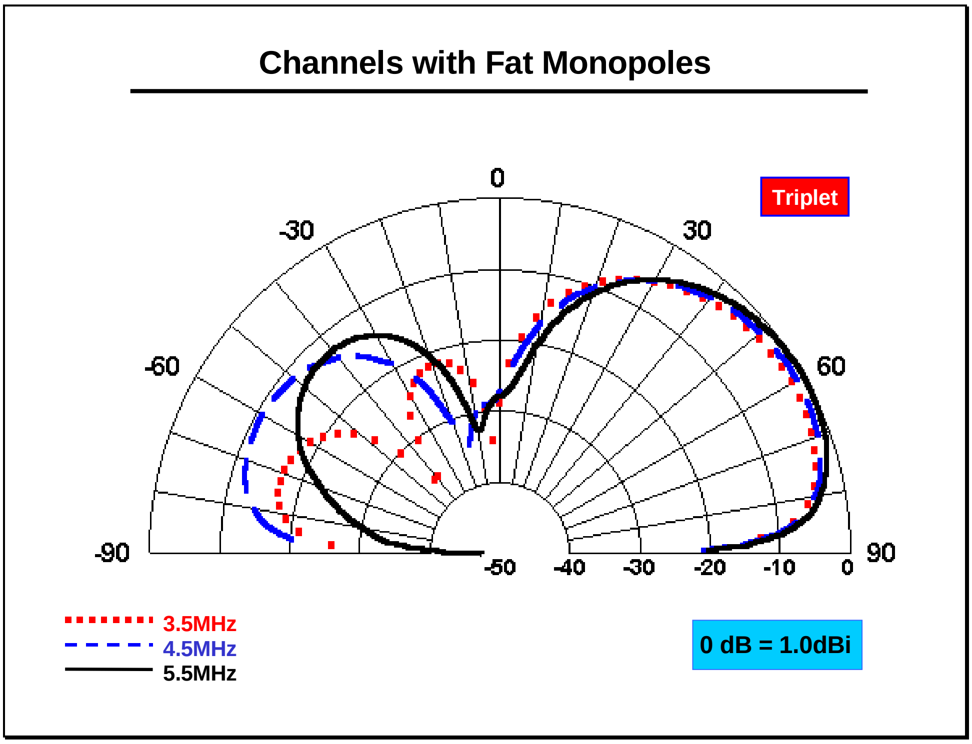


Fig. 3.29

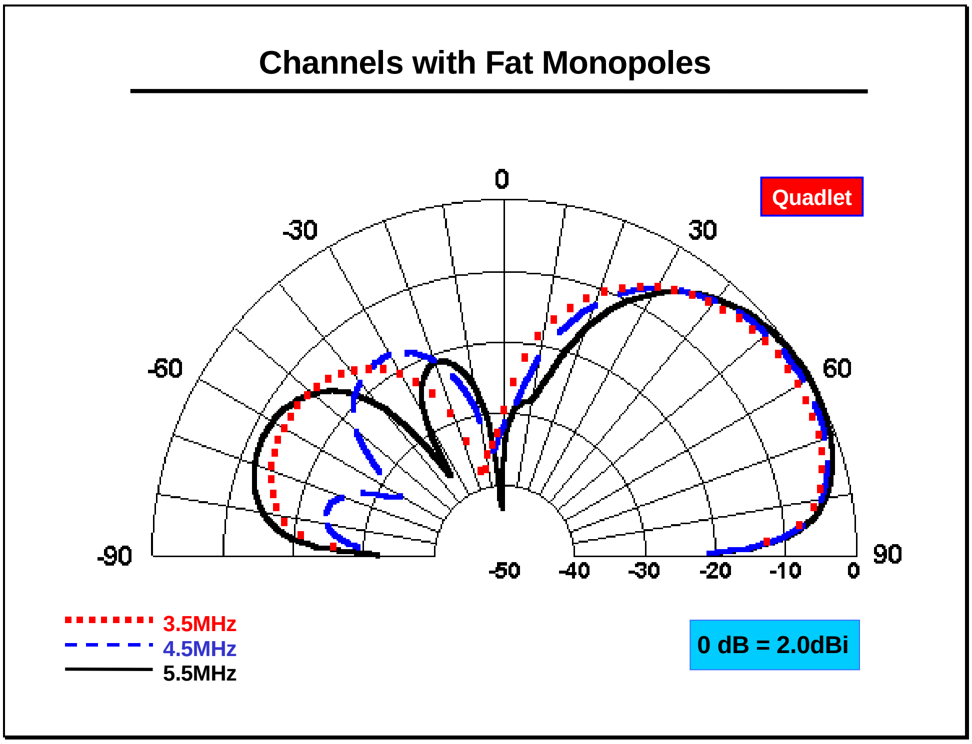


Fig. 3.30

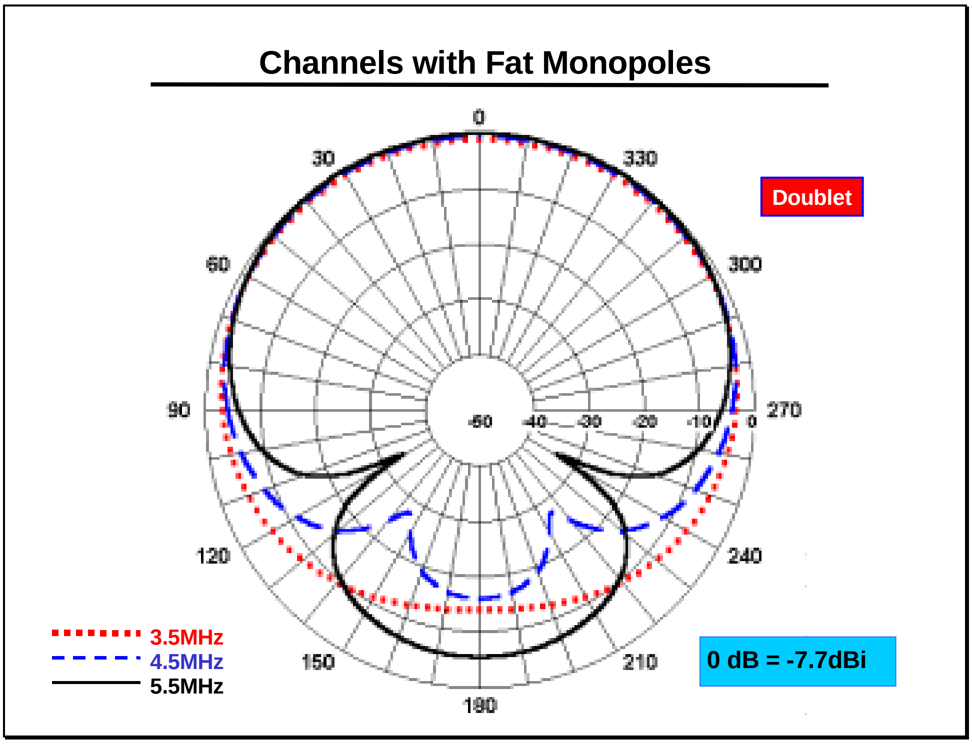


Fig. 3.31

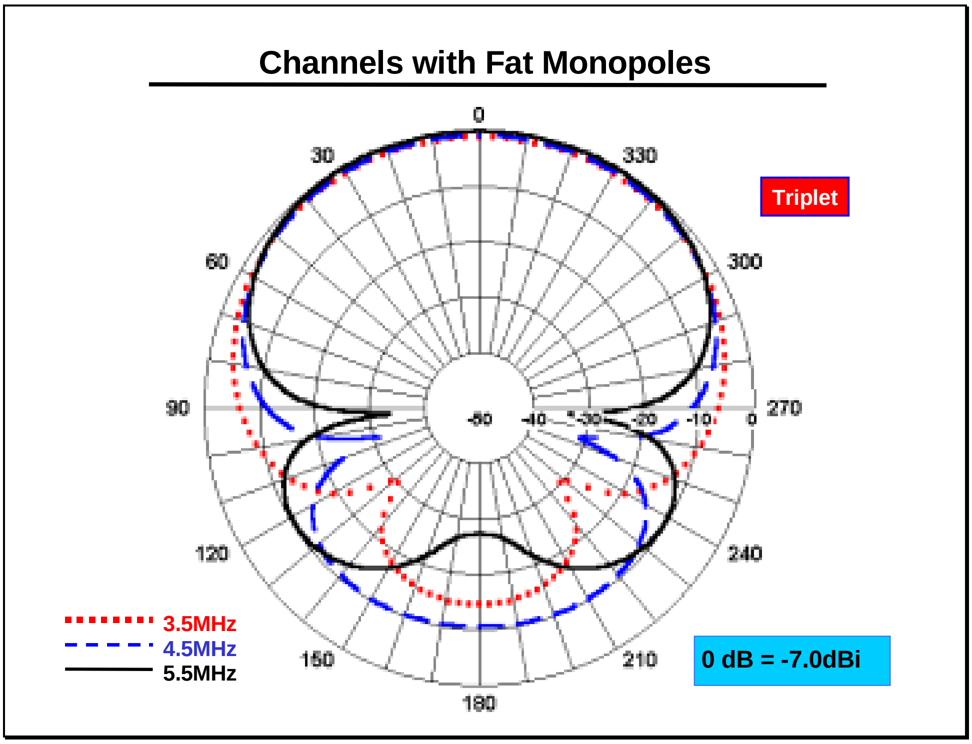


Fig. 3.32

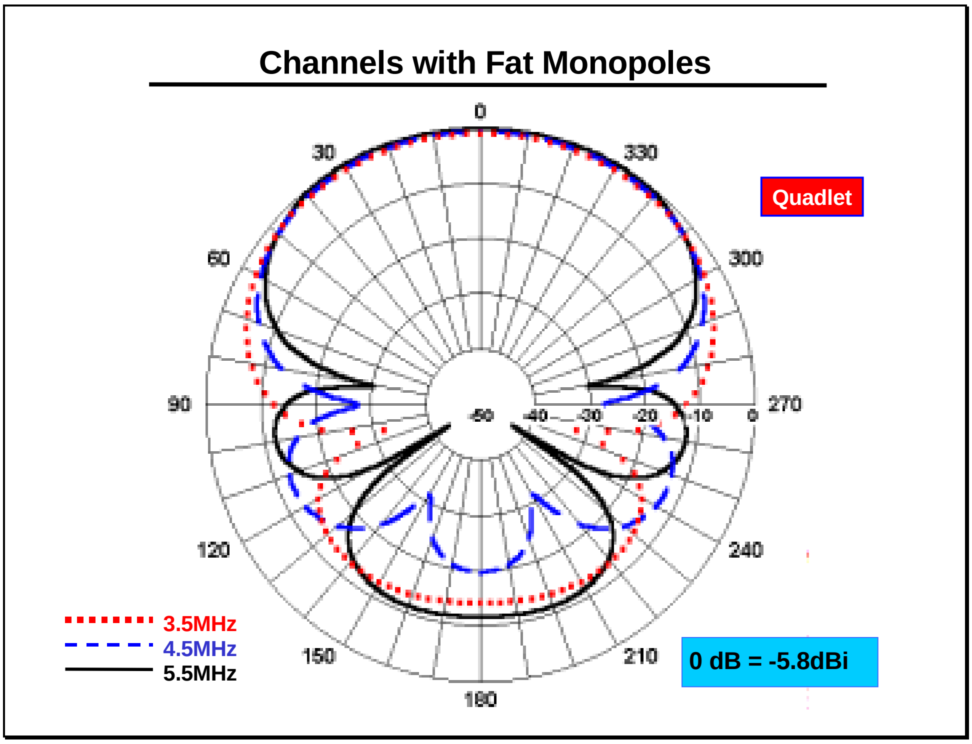

Channels with Fat Monopoles
0
30
330
60
300
90
270
120
240
150
210
180
-50
-40
-30
-20
-10
0
Quadlet
3.5MHz
4.5MHz
5.5MHz
0 dB = -5.8dBi

Fig. 3.33

3.3 Crossed Monopoles

CODAR system [1] has been used in remote sensing of ocean currents. The system operates at 25.4MHz and uses four quarter-wavelength vertical whips (as a unique array), where they are symmetrically laid out on a circle with a radius of slightly less than quarter-wavelength.

CODAR receive array is used both in beam forming and direction finding. The elements of the array are fed in a way to maximise horizontal radiation in a desired direction. Since there are four elements symmetrically laid out on a circle, the beam-width of the array is nearly 90°. A special software package is used in conjunction with the array.

By phasing four-whips, 360° in azimuth may be steered. Examples related to azimuth beam steering are given in Fig.s 3.34 to 3.36. The location of the array and whip numbers, the phases of element feeding voltages are also mentioned in the figures.

It should be noted that, this array is effective when used in conjunction with the special software package mentioned above. Otherwise, it is impossible to get azimuth information with a beam-width of 90°. The package is used for the estimation of the angle of arrival of a possible target signal by calculating the energy of beams formed for a full circle of look-directions. Then, target signals arriving at certain angles appear as peaks in beam energy versus angle plots.

Recently, a different design -based on CODAR array- has been introduced as an alternative to linear arrays used in HFSWR. There, five 2m whips are grouped as pentagon. The pentagon is elevated 20m on a pole, and two such poles are spaced 30m apart (half-wavelength at 5MHz), so that ground screen is not essential.

This system is simulated via NEC package and the results are pictured in Fig.3.37. Here, horizontal radiation patterns obtained by phasing each element in a way to maximise in a desired direction is plotted.

Again, it should be noted that these antenna systems need to be used with powerful direction estimation softwares

References

[1] **D. E. Barrick & M. W. Evans**, “Implementation of Coastal Current-Mapping HF Radar System” Progress Report No 1, NOAA Technical Memorandum, ERL-373-WPL-47, 1976

Fig.3.34

Fig.3.35

Fig.3.36

Fig.3.37

IV Receive Arrays

In a HFSWR based IMS system, the azimuth information is obtained by electronic beam steering ability of the receive antenna system. Therefore, receive antenna system is designed as an array of number of channels, which is adequate for the required beam-width. Roughly speaking, the beam-width is inversely proportional with the antenna length. The more narrower the beams the longer the arrays (i.e., higher number of channels). For example, an array of nearly 1km length is required in order to obtain a 5° beam-width at 3MHz frequency. If the channel spacing is quarter-wavelength (i.e., 25m at 3MHz), then number of channels will be at least twenty.

In this section, arrays with different number of channels are investigated. First, seven-channel arrays of both monopoles and fat monopoles are taken into account.

4.1 A seven-channel Array

In order to simulate array performances via NEC package effectively, number of wires and segments is important. MoM technique is based on numerical solution of a set of equations in a matrix form. The order of the matrix system is proportional with the number of segments. As the number of segments increases linearly, the computation time required for the matrix inversion increases exponentially. With a P-II based PC having 128MB RAM memory segments up to 2000 can be handled in a reasonable time. After 2000 segments it takes hours, even days to obtain NEC simulation results. In multi-channel receive array modelling via NEC, the number of segments mostly depends on the ground screen.

In order to get the array behaviour, while using reasonable amount of segments a seven-channel array is taken into account. Since a monopole quadlet and fat monopole doublet are used as the channel elements in Cape Bonavista and in Cape Race, respectively, simulations are also carried out with these channel elements. A sixteen-element radial ground system is used in both simulations. Radials of different vertical radiators are cut and connected when intersected. The top view of the array, where quadlets are used as channel elements, is pictured in Fig.4.1.

Numerical values such as antenna heights, wire and radial radii, inter-channel separations are taken as mentioned in Sec.III.

Inter-array distances are taken as 31m and 33m for monopole and fat monopole arrays, respectively.

Calculations are performed at two different frequencies, 3.5MHz and 4.5MHz.

The ground is assumed to be POOR.

In Fig.s 4.2 to 4.4 vertical as well as horizontal radiation characteristics –normalised to 0dB- are plotted and the gains with respect to isotropic radiator are mentioned in the figure insets.

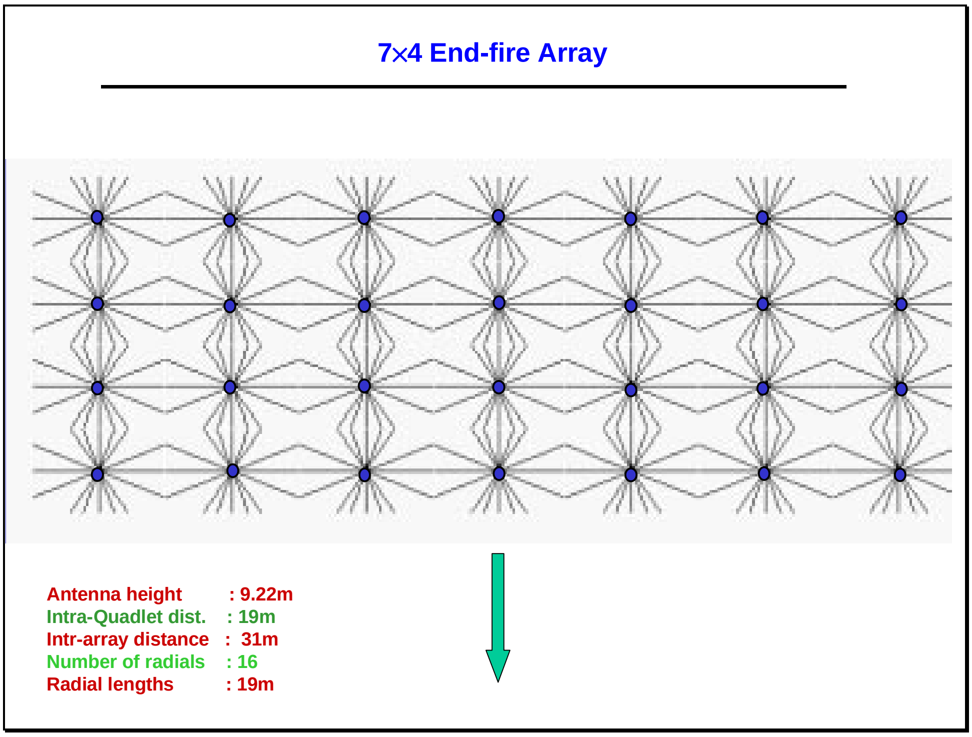

7×4 End-fire Array
Antenna height : 9.22m
Intra-Quadlet dist. : 19m
Intr-array distance : 31m
Number of radials : 16
Radial lengths : 19m

Fig.4.1:

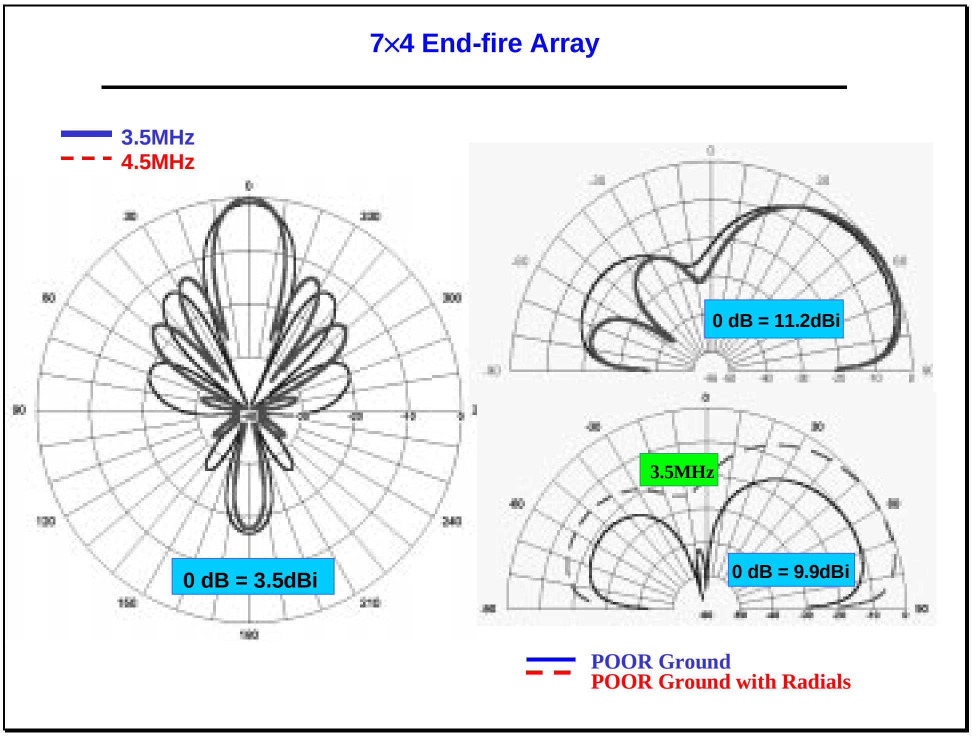

7×4 End-fire Array
3.5MHz
4.5MHz
0 dB = 3.5dBi
0 dB = 11.2dBi
3.5MHz
0 dB = 9.9dBi
POOR Ground
POOR Ground with Radials

Fig.4.2:

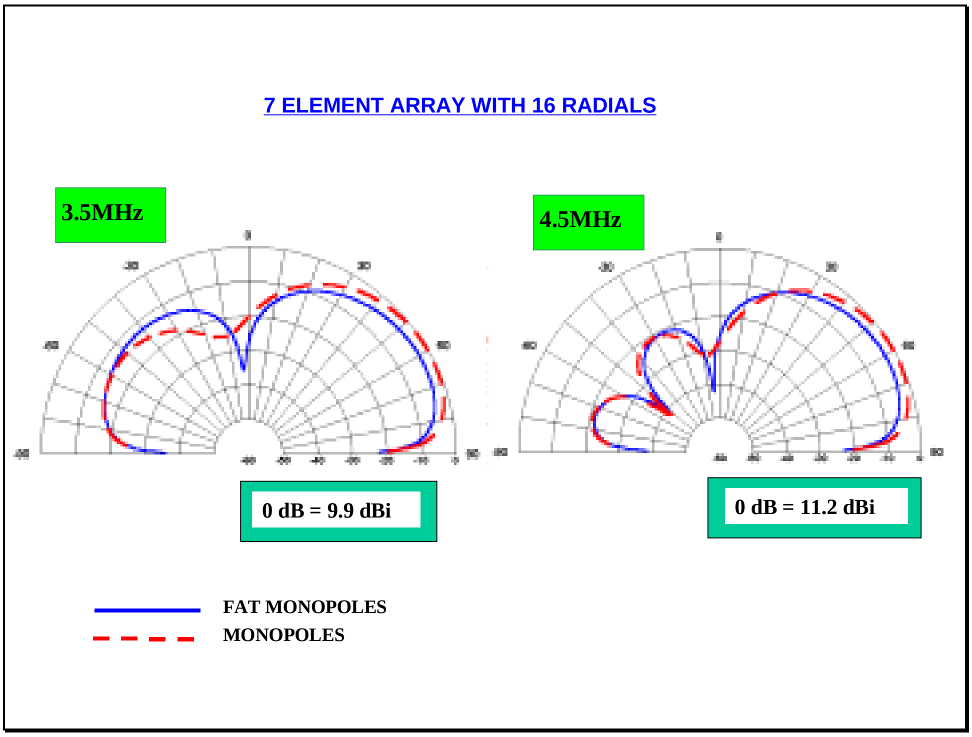

7 ELEMENT ARRAY WITH 16 RADIALS
3.5MHz
4.5MHz
0 dB = 9.9 dBi
0 dB = 11.2 dBi
FAT MONOPOLES
MONOPOLES

Fig.4.3:

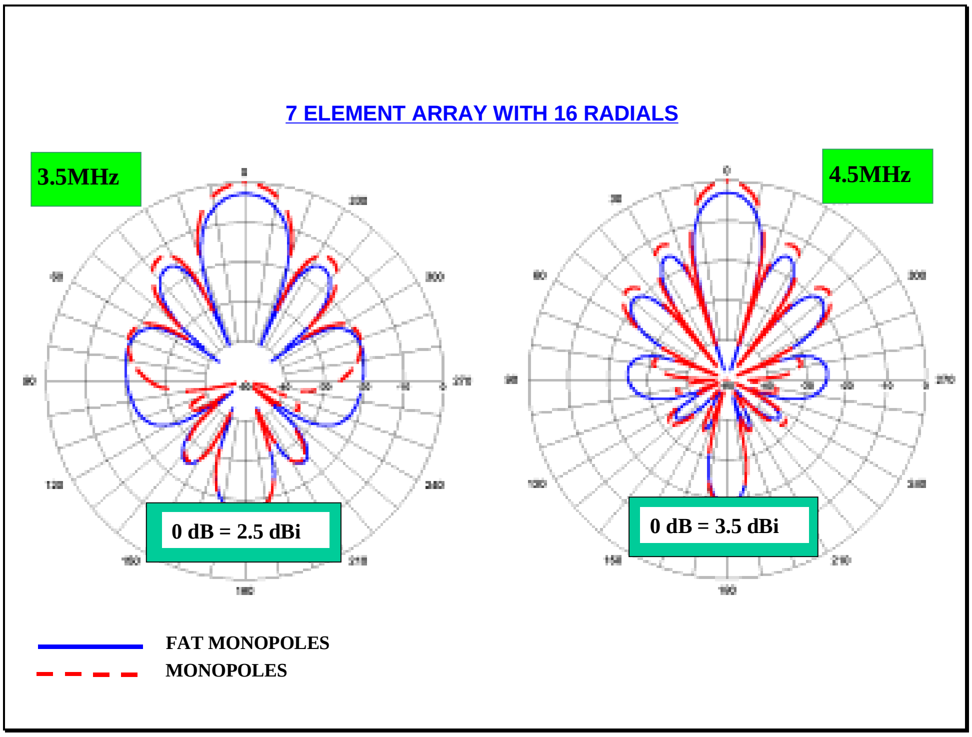

7 ELEMENT ARRAY WITH 16 RADIALS
3.5MHz
4.5MHz
0 dB = 2.5 dBi
0 dB = 3.5 dBi
FAT MONOPOLES
MONOPOLES

Fig.4.4:

4.2 A sixteen-channel Array

Simulations with seven-channel array show that horizontal radiation characteristics are not much affected by the ground screen. But, array gain –with and without ground screen- differs nearly 10dB.

HFSWR receive arrays will most probably be made up sixteen or twenty-four channels depending on the requirements. Therefore, a sixteen-channel array is taken into account in this section.

Again, the numerical values such as antenna heights, wire radius, inter-channel separations are taken as mentioned in Sec.III.

Inter-array distances are taken as 31m and 33m for monopole and fat monopole arrays, respectively.

Calculations are performed at 3.5MHz.

The ground is assumed to be POOR.

Suitable phasing the channels in the arrays simulates electronic beam steering characteristics. The 3dB beam-width is approximately 8°.

In Fig.s 4.5 and 4.6 vertical as well as horizontal radiation characteristics –normalised to 0dB- are plotted and the gains with respect to isotropic radiator are mentioned in the figure insets.

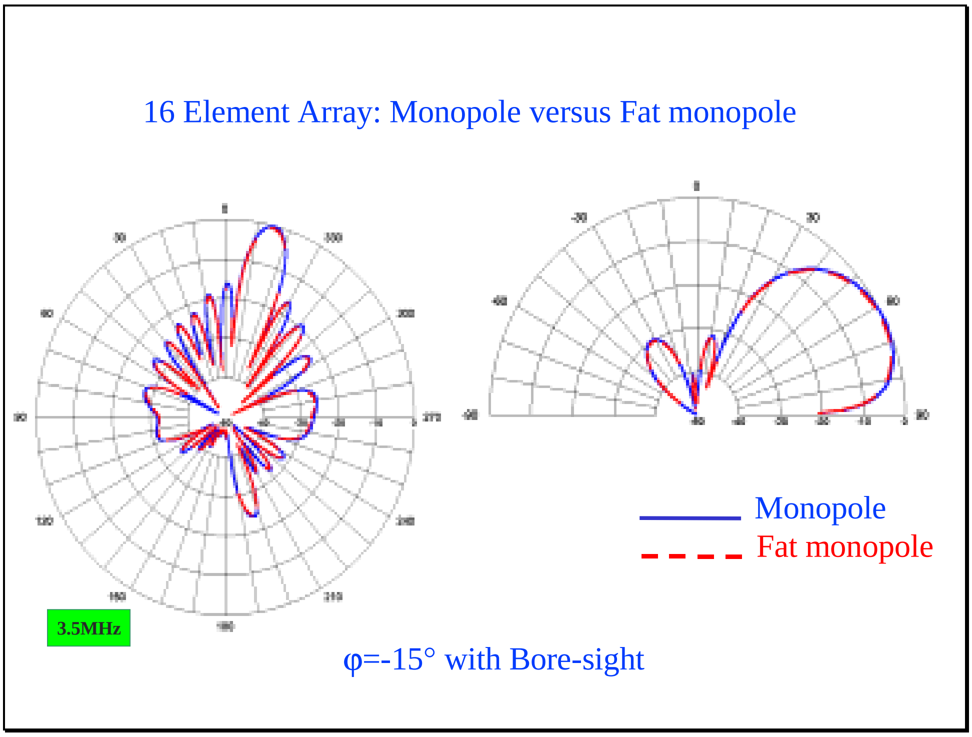

16 Element Array: Monopole versus Fat monopole
Monopole
Fat monopole
3.5MHz
φ=-15° with Bore-sight

Fig.4.5:

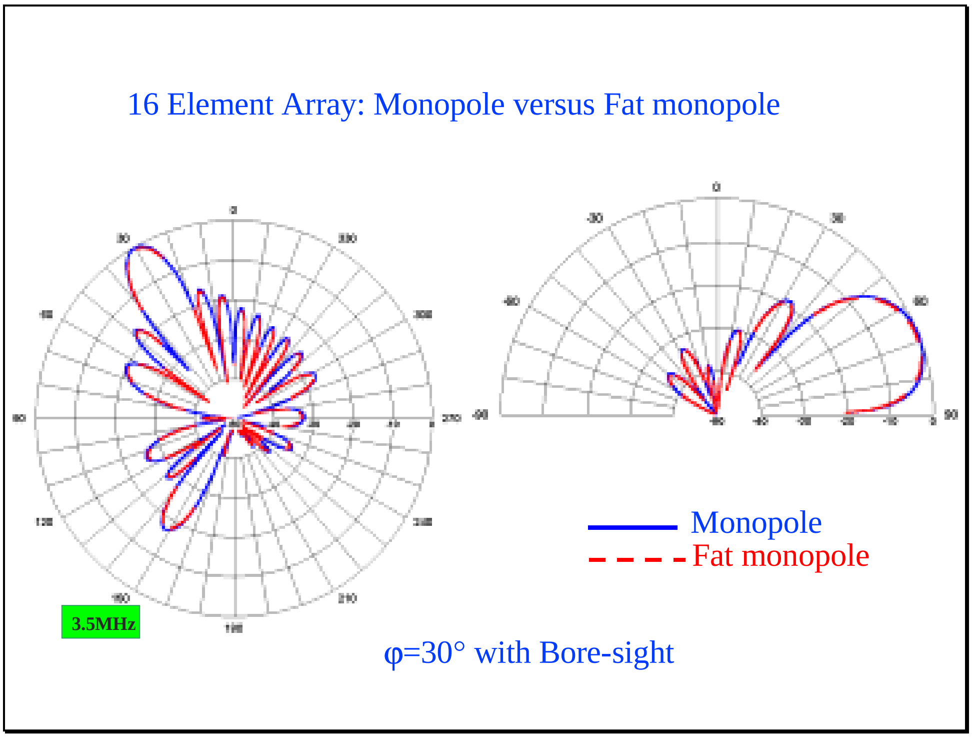

16 Element Array: Monopole versus Fat monopole
Monopole
Fat monopole
3.5MHz
φ=30° with Bore-sight

Fig.4.6:

4.3 A twenty-four channel Array

Finally, arrays at Cape Bonavista and Cape Race are simulated via NEC package. Because of the segment limitations arrays are assumed to be located over POOR ground without ground screen. Therefore, only horizontal beam forming is pictured in Fig.s 4.7 to 4.9.

Cable lengths from channels to the receiver are used as in Table 4.1.

Table 4.1:

Electrical cable lengths for 24 channels

CH #	Cable [m]	CH #	Cable [m]	CH #	Cable [m]	CH #	Cable [m]
1	405.25	7	237.55	13	67.93	19	232.67
2	376.82	8	209.84	14	96.36	20	260.14
3	350.28	9	179.56	15	123.66	21	288.66
4	323.20	10	153.34	16	148.81	22	315.90
5	294.53	11	124.74	17	180.89	23	343.12
6	262.77	12	95.97	18	209.17	24	375.21

In an array of a large number of channels, it is of interest to know what happens if one or more channels are turned off either intentionally or accidentally. Also, to reduce the cost it is important to know how many and which channels can be omitted without appreciably affecting the performance characteristics. Therefore, channel blanking is also simulated in NEC calculations and the results are pictured in Fig.4.9. The channels are numbered from 1 to 24 and the array is located along y-axis, where x-axis points the array bore-sight. If top of this page is the array bore-sight, then the number of channels increases from right to left. In Fig. 4.9, at top of each plot, the blanked channels are mentioned.

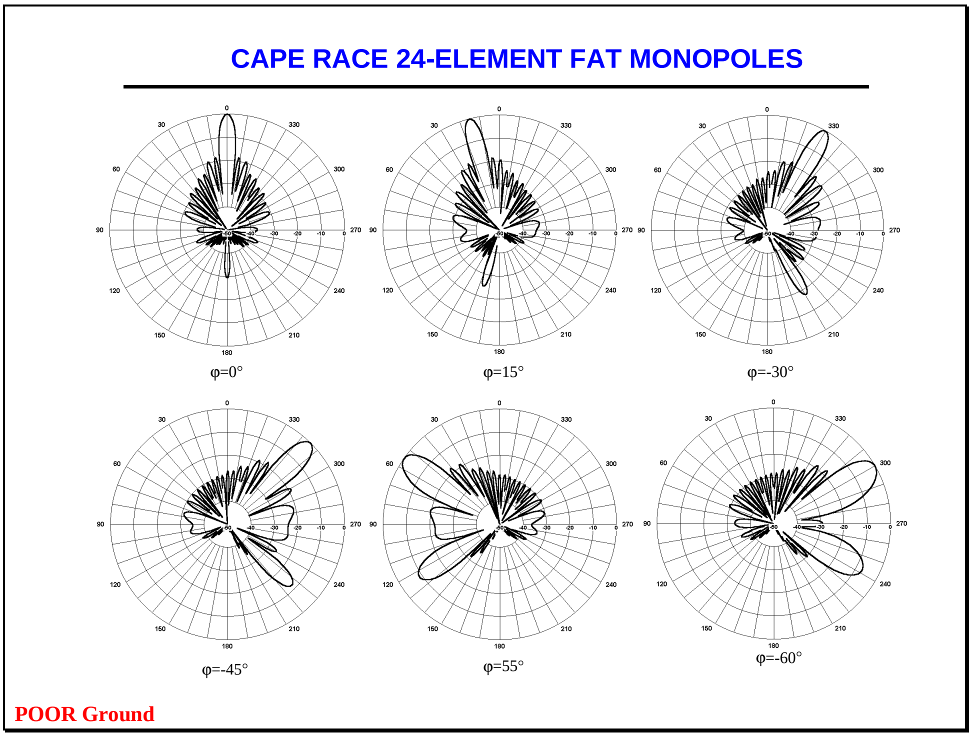

CAPE RACE 24-ELEMENT FAT MONOPOLES
φ=0°
φ=15°
φ=-30°
φ=-45°
φ=55°
φ=-60°
POOR Ground

Fig.4.7:

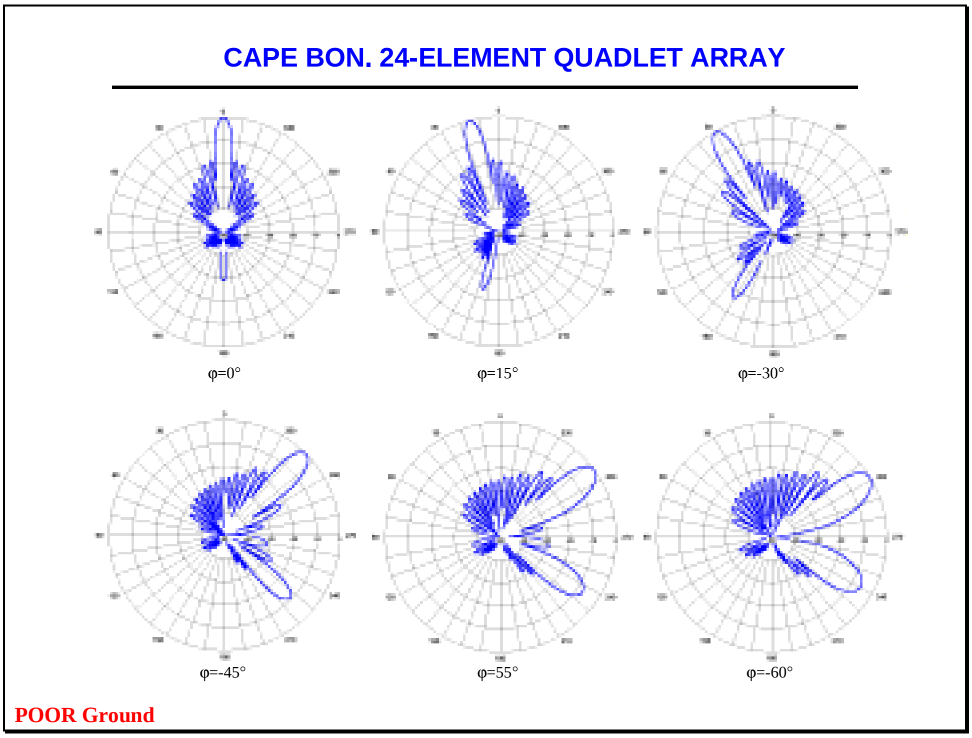

CAPE BON. 24-ELEMENT QUADLET ARRAY
φ=0°
φ=15°
φ=-30°
φ=-45°
φ=55°
φ=-60°
POOR Ground

Fig.4.8:

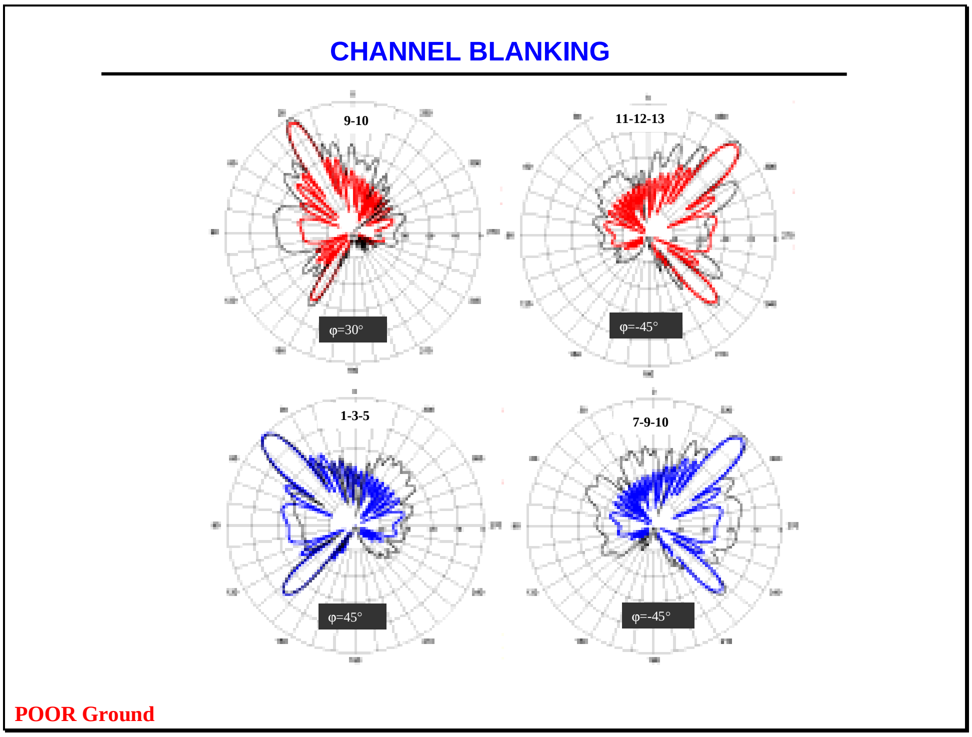

CHANNEL BLANKING
9-10
φ=30°
11-12-13
φ=-45°
1-3-5
φ=45°
7-9-10
φ=-45°
POOR Ground

Fig.4.9:

V Ground Screen Design

A PEC surface has ideal 0Ω surface impedance. A quarter-wavelength vertical radiator over PEC surface acts as a half-wavelength element in free-space. Therefore, its vertical radiation pattern has a maximum towards horizontal. This is the design goal for an HFSWR antenna element.

A lossy ground with ground parameters σ_g and ε_g has surface impedance, which can be calculated via

$$Z_s = \eta_0 \left[\frac{i\omega\varepsilon_0}{\sigma_g + i\omega\varepsilon_g} \right]^{1/2} \left[1 + \frac{i\omega\varepsilon_0}{\sigma_g + i\omega\varepsilon_g} \right]^{1/2} \qquad \eta_0 = 377\Omega \qquad (5.1)$$

where $\omega=2\pi f$ is the radian frequency and η_0 is the free space impedance. The surface impedance of the POOR ground (i.e., the ground with σ_g=0.003 S/m and ε_g =4.0) is around 150Ω at 2MHz, increases exponentially with the frequency and reaches to 300Ω at 10MHz. But, the surface impedance of the ocean (i.e., when σ_g=5.0 S/m and ε_g =80.0) is in between 5Ω-10Ω in the same frequency region. Therefore, ocean surface may easily be assumed as a PEC surface at HFSWR operating frequencies.

The difference between erecting the antennas over POOR ground or PEC surface may result in a reduction of gain by up to 15dB.

Beside this loss, there is also an extra near field propagation path loss because of the POOR ground. Table 5.1 lists vertical electrical field strength and path loss at 1km away from a 1kW vertical radiator.

It is clear from Table 5.1 that, at 1km distance; propagation loss over POOR ground may be 10-15dB higher than the propagation loss over ocean surface.

Table 5.1:

Field strength and path loss values of a vertical radiator

with 1kW transmitter power at 1km distance

d=1km	ε_g *=15.0*	*f=3MHz*
Conductivity [S/m]	**Field Strength [dBµV/m]**	**Path Loss [dB]**
0.0001	95.2	56.3
0.001	96.6	55.0
0.01	106.4	45.1
0.1	109.3	42.2
1.0	109.5	42.0
5.0	109.5	42.0

Therefore, together with the reduction in antenna gain, there may be a total of 30dB extra loss just because the antenna elements are erected over POOR ground.

In order to overcome this problem, the surface impedance of the *Antenna Park* must be reduced to an acceptable level. This is accomplished by one of two ways:

- The antenna park may be selected at the edge of the shore so that ocean water flows under the antenna elements, or
- Using *ground screen* may reduce the surface impedance of the Antenna Park.

The first choice depends on available antenna site. If not available, then, ground screen shall be used to reduce surface impedance of the Antenna Park.

Using ground screen

- will stabilise radiator's input impedance, hence increase the antenna gain
- will lower the antenna TOA, hence more energy shall be coupled to ocean surface.

In practice, three different types of ground screens are available. They are radials, horizontal wires and rectangular meshes, or combinations of the three basic types.

It is simple to evaluate the effects of ground screen via approximate analytical approaches. The impedance of a horizontal wire screen can be given as

$$Z_{scr} \approx \frac{i\mu\omega d}{2\pi} \ln\left[\frac{d}{2\pi a}\right] \tag{5.2}$$

where a is the wire length and d is the wire separation. The same equation may also be used for a mesh type screen if the mesh sizes are equal (i.e., square mesh) and equal to d.

Using the ground screen with impedance Z_{scr} over lossy ground with surface impedance Z_s will cause an equivalent surface impedance, which can be given as

$$Z_{eq} = \frac{Z_{scr} \times Z_s}{Z_{scr} + Z_s} \tag{5.3}$$

the parallel equivalent of the two impedances.

In this section, different ground screen layouts are taken into account as pictured in Fig.s 5.1 to 5.4. Their effects on radiation patterns and antenna gains are modelled via NEC package and are plotted in Fig.s 5.5 to 5.8.

The NEC simulations are performed at 3.5MHz, 4.5MHz and 5.5MHz operating frequencies.

The quadlet with monopoles mentioned in Sec.III are used with the same parameters.

Sixteen elements with 1m length are used as short radials. Quarter-wavelength horizontal wires are used on each side of the antenna. The ground screen extends quarter-wavelength behind and half-wavelength in front of the channel.

These results show the effect of ground screen for a single channel element. In HFSWR arrays of multi-channel the effects may be more complicated.

Some general rules may be listed regarding to ground screen design:

- If the *gain* is crucial, then stabilising the elements input impedances is essential. It may be done either by locating circular or rectangular PEC patches under each vertical monopole element or using by radial wires.
- If lowering the *TOA* is crucial, then using horizontal wires that are perpendicular to antenna bore-sight seems to be the most proper solution. In this case, horizontal wires should extend at least quarter-wavelength at each side, half-wavelength at the back and a wavelength in the front.
- If the *over-head nulling* is the most important requirement, keeping the antenna array and ground screen depth (i.e., the size of the array along bore-sight) and avoiding complex wiring in the ground screen layout are necessary. The more complex wire connections the higher the diffractions and the lesser over-head nulling property.

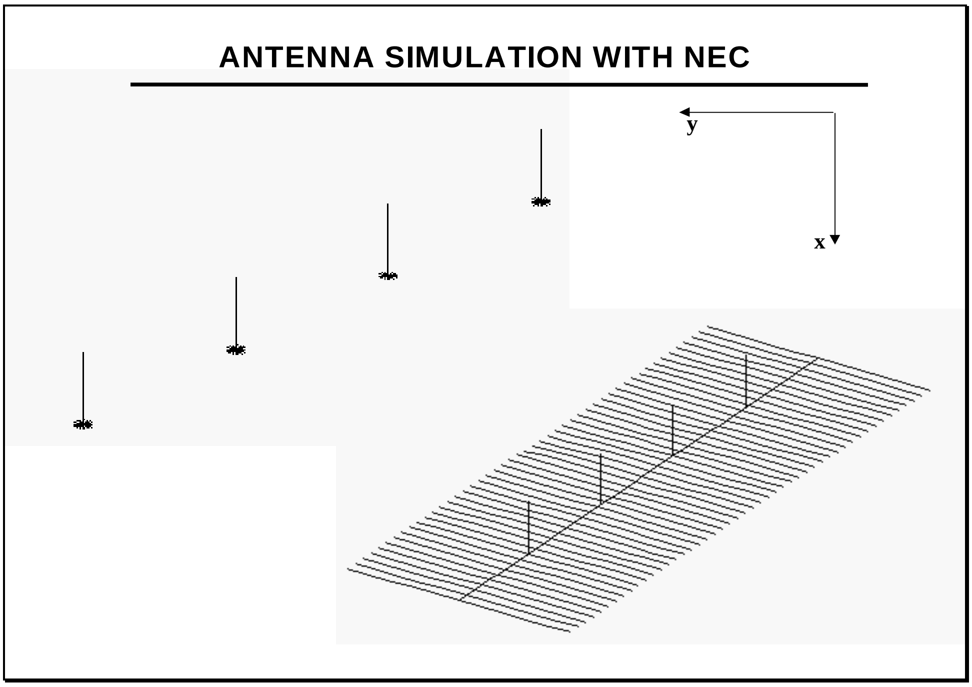

ANTENNA SIMULATION WITH NEC
y
x

Fig.5.1:

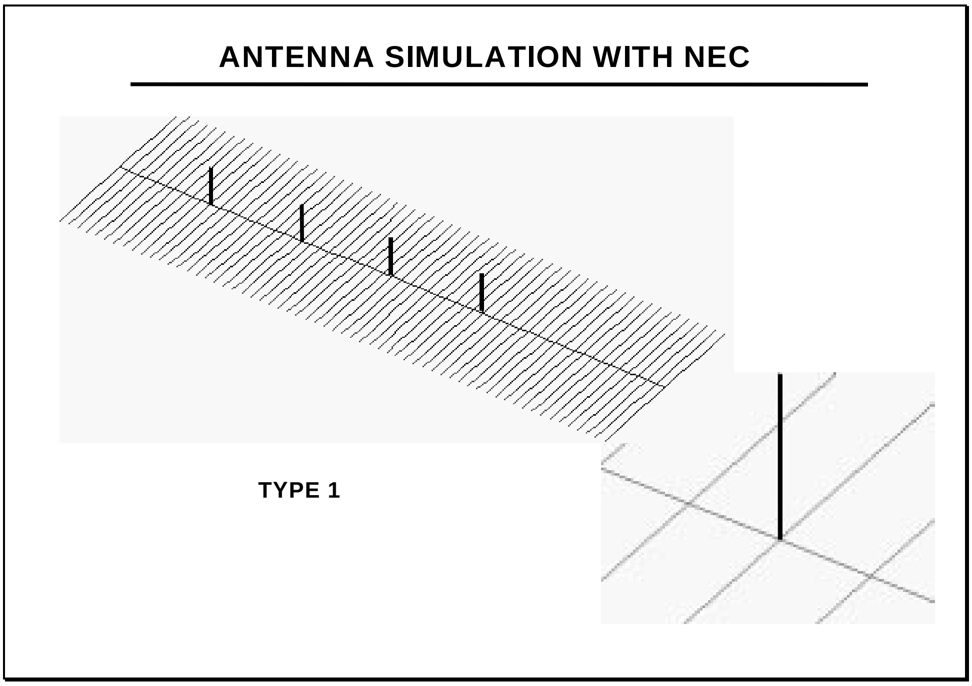

ANTENNA SIMULATION WITH NEC
TYPE 1

Fig.5.2:

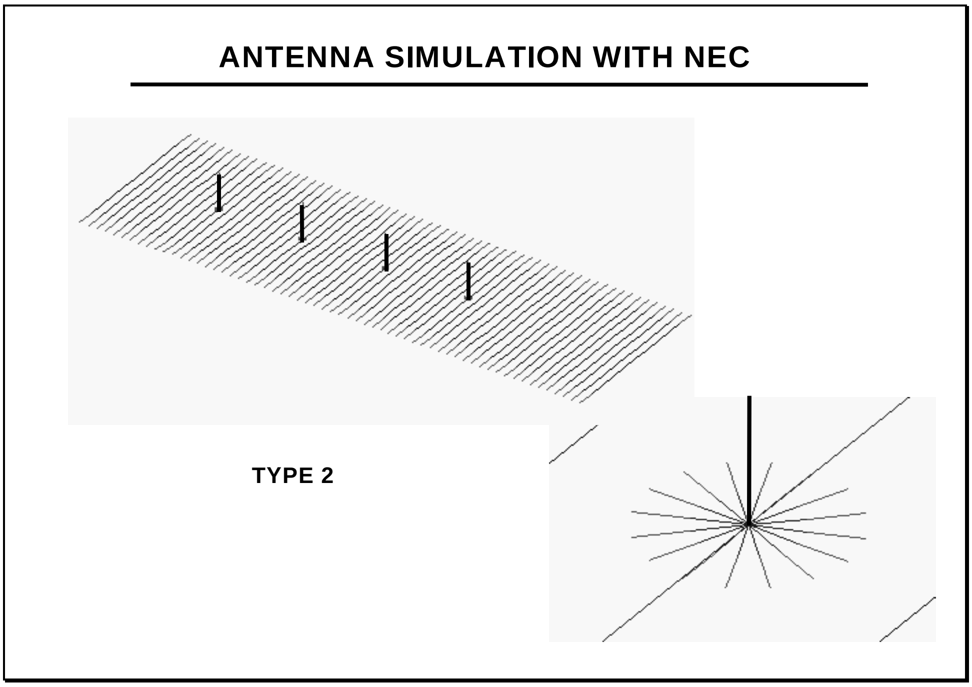

ANTENNA SIMULATION WITH NEC
TYPE 2

Fig.5.3:

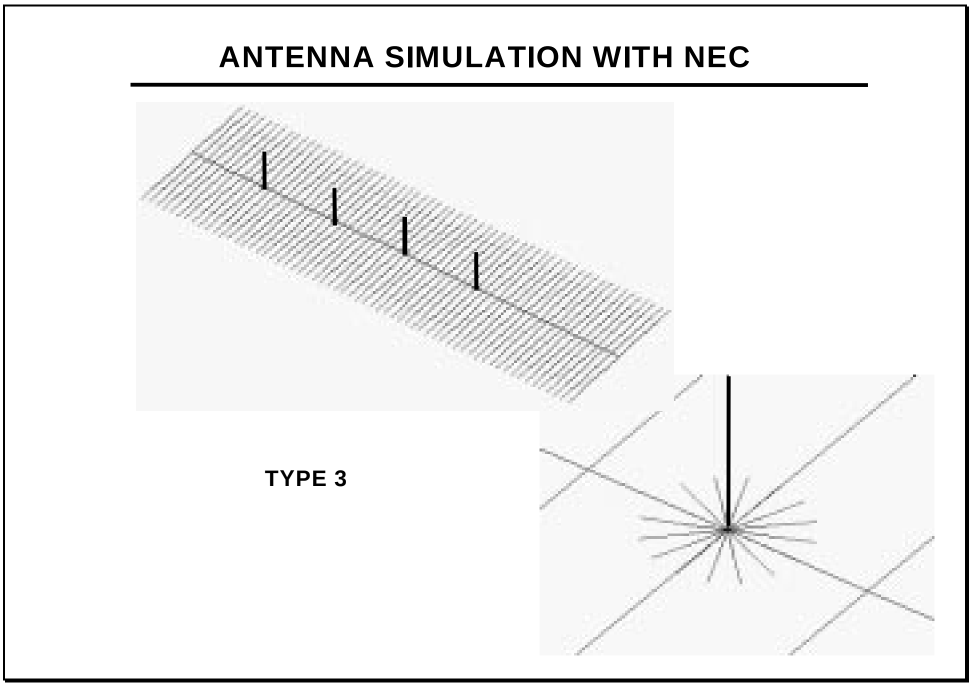

ANTENNA SIMULATION WITH NEC
TYPE 3

Fig.5.4:

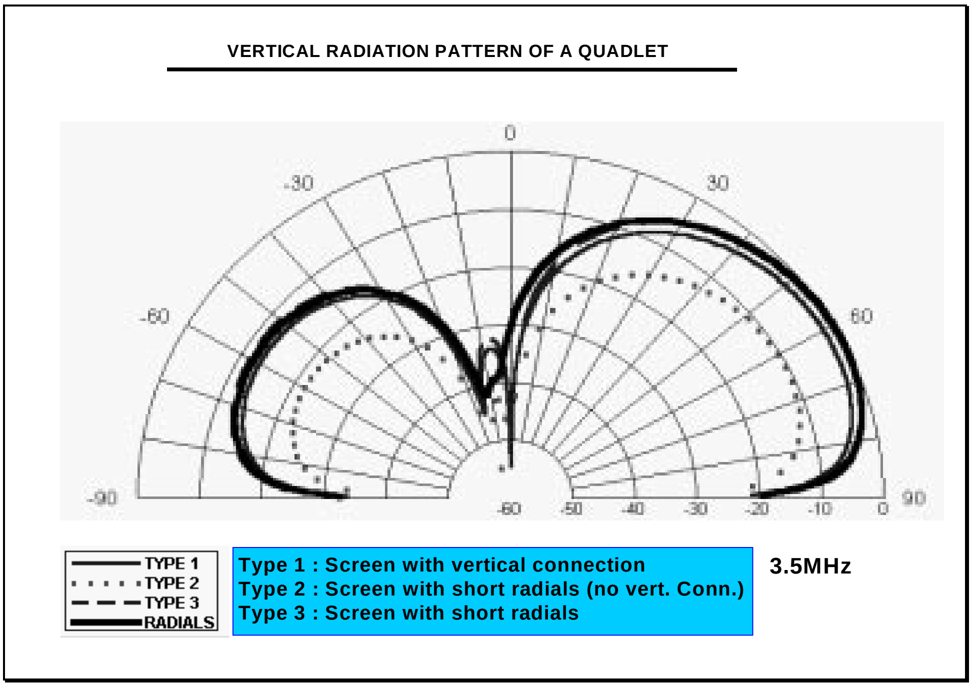

VERTICAL RADIATION PATTERN OF A QUADLET
0
-30
30
-60
60
-90
90
-60 -50 -40 -30 -20 -10 0
TYPE 1
TYPE 2
TYPE 3
RADIALS
Type 1 : Screen with vertical connection
Type 2 : Screen with short radials (no vert. Conn.)
Type 3 : Screen with short radials
3.5MHz

Fig.5.5:

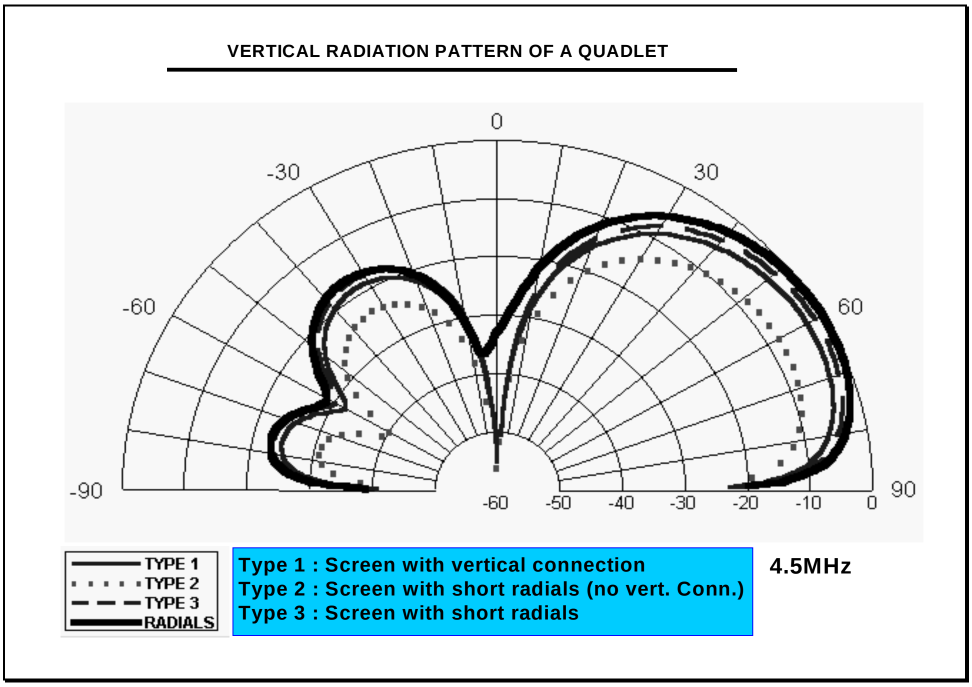

VERTICAL RADIATION PATTERN OF A QUADLET
0
-30
30
-60
60
-90
90
-60 -50 -40 -30 -20 -10 0
TYPE 1
TYPE 2
TYPE 3
RADIALS
Type 1 : Screen with vertical connection
Type 2 : Screen with short radials (no vert. Conn.)
Type 3 : Screen with short radials
4.5MHz

Fig.5.6:

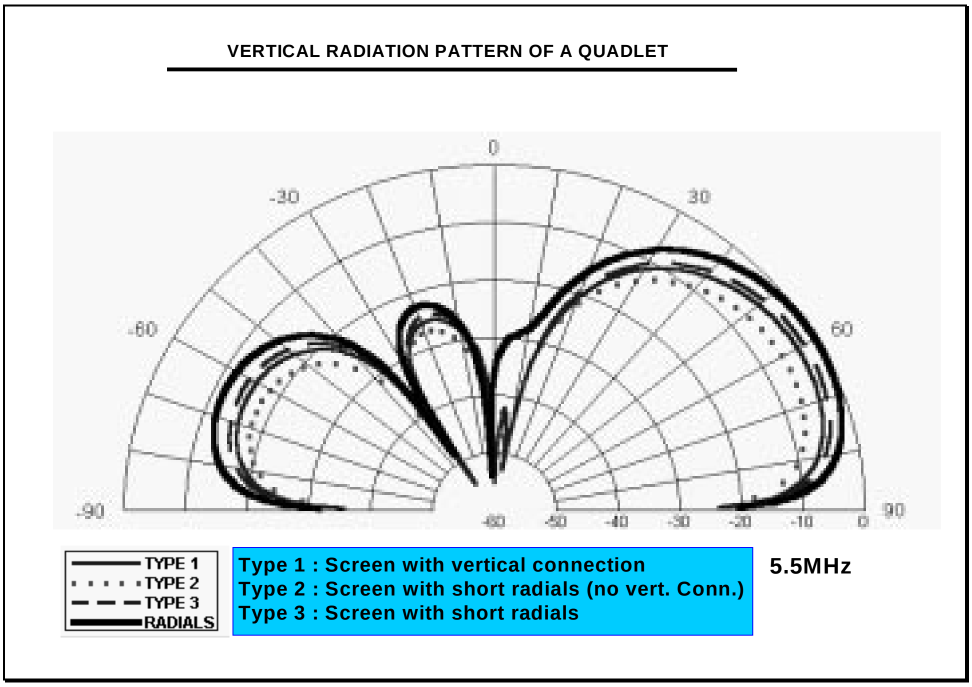

VERTICAL RADIATION PATTERN OF A QUADLET
0
-30
30
-60
60
-90
90
-60
-50
-40
-30
-20
-10
0
TYPE 1
TYPE 2
TYPE 3
RADIALS
Type 1 : Screen with vertical connection
Type 2 : Screen with short radials (no vert. Conn.)
Type 3 : Screen with short radials
5.5MHz

Fig.5.7:

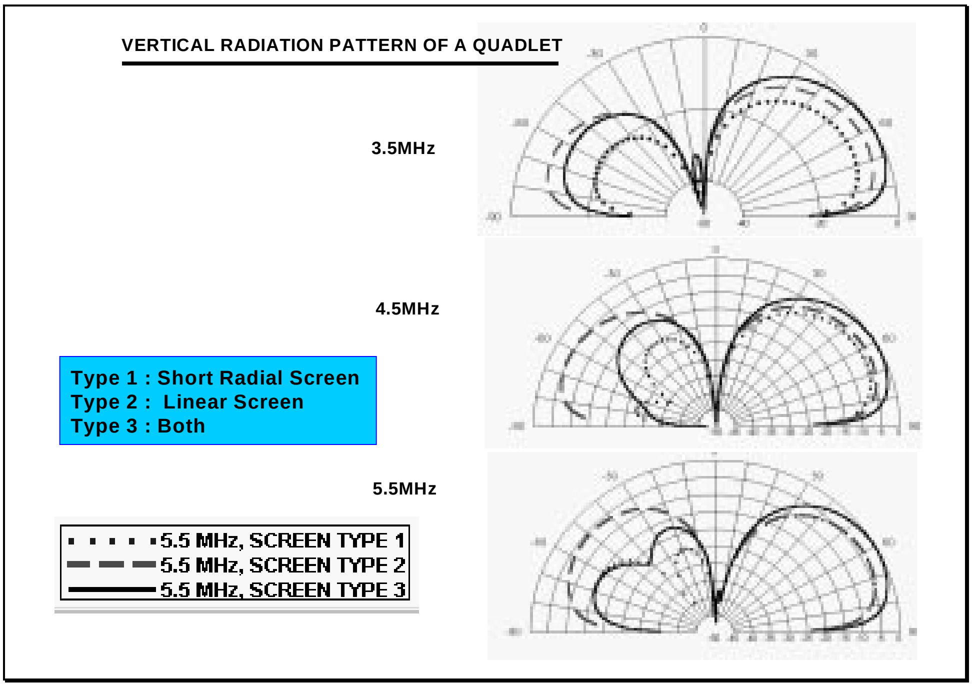

VERTICAL RADIATION PATTERN OF A QUADLET
3.5MHz
4.5MHz
5.5MHz
Type 1 : Short Radial Screen
Type 2 : Linear Screen
Type 3 : Both
5.5 MHz, SCREEN TYPE 1
5.5 MHz, SCREEN TYPE 2
5.5 MHz, SCREEN TYPE 3

Fig.5.8:

VI Conclusions and Design Guidelines

In this report, HFSWR antenna arrays are investigated. Two powerful numerical techniques are used to analyse

- Radiator elements such as monopoles and fat monopoles,
- Channel elements such as doublet, triplet and quadlets,
- Arrays with different number of channels,
- Ground screen designs.

General Design Guidelines

The design parameters of a HFSWR antenna system are

- Operating frequency bandwidth
- Maximum Directivity and Gain
- Maximum Front-to-back ratio
- Maximising over-head null
- Vertical and horizontal radiation patterns.

Good antenna system design will

- improve directivity, gain and surface wave coupling to reach longer ranges,
- enlarge azimuth coverage,
- increase front-to-back ratio to minimise interference originates sources behind the array and back-located site interferences,
- provide deeper over-head null to reduce self-generated ionospheric interferences, etc.

Antenna Site Requirements –Ideal:

Transmitter Site

The transmitter system requires a coastal shore site approximately 200m × 200m square reasonable levelled (better than %1 grade) and not more than 10m above sea level.

The distance between the transmitter site and coastal line should be homogeneous and not more than 100m.

The site characteristics must be suitable for the erection of transmitter antennas and possible support tower, which may be up to 50m tall.

Receiver Site

The receiving system requires a coastal shore site approximately 1000m × 100m levelled and not more than 10m above the mean sea level.

The long axis of this area must be parallel to the seashore and a line perpendicular to this axis will define the receiving antenna array bore-sight. Land-sea transitions on each side of the bore-sight should be similar and not include deep cavities and/or sharp edges.

The receiving antenna array must be separated from the transmitting antenna by at least 50m to avoid cross coupling. The transmit and receiving antenna systems must horizontally null each other to increase cross-coupling strength.

The site characteristics must be suitable for the erection of primary receiving array, the most probably a 16 channel doublets, nominally separated by 33m and not more than 15m tall, and the deployment of the receive equipment shelter.

It is essential that the receiving site be electrically quiet with respect to man-made noise.

The ground parameters of the antenna sites must be measured before installation. The difference between the parameters (especially the conductivity, σ) of any two points in the sites should not exceed two orders of magnitude (i.e., if σ_1 at point one is 0.001 S/m, then σ_2 at point two should be at most 0.1 S/m).

Land-Sea Transition

The coastal location of the antenna is as important as the ground losses and screen design. That is, the distance between the array and the ocean on each side and in the front also plays a critical role in the array performance. Table 1 lists the near-field path loss values of a 1kW vertical short radiator placed over *POOR* and *GOOD* grounds, respectively. It is clear that a 100m over POOR ground causes 3-5dB more path loss. Similarly, it is between 2dB to 4dB over GOOD ground.

Table 5.1:

Near-field Path loss values of a 1kW vertical radiator over POOR and GOOD grounds

POOR Ground [ε_r=4, σ=.001S/m]		**GOOD Ground [ε_r=4, σ=.01S/m]**	
Dist [m]	Loss[dB]	Dist [m]	Loss[dB]
100	29	100	24
200	37	200	31
300	43	300	35
400	47	400	37
500	51	500	40
600	54	600	42
800	59	800	45
1000	63	1000	48

Therefore, the location of the antenna array with respect to coastal line must be as symmetrical as possible. Also the distance to coastal line must be as short as possible.

The Antenna Channel

Typical channel for both transmit and receive array is pictured in Fig.1.

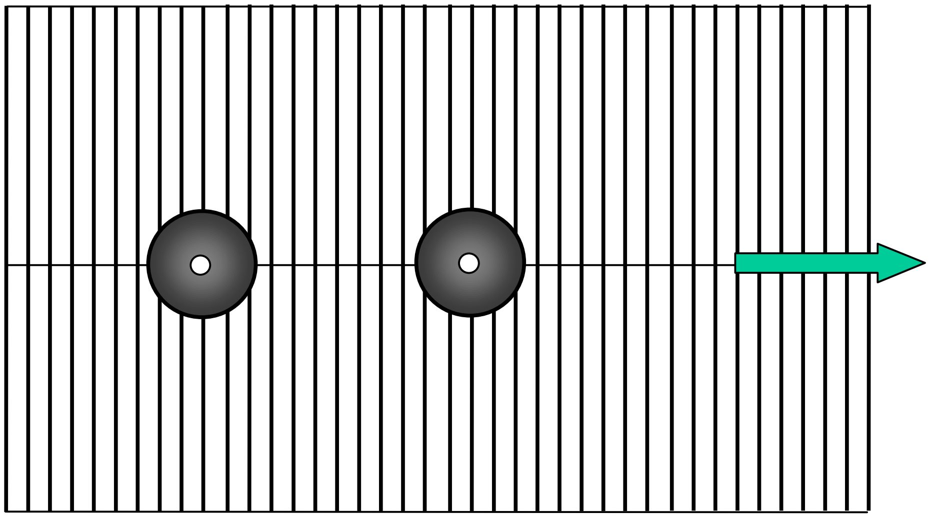


Figure 1: The top view of the HFSWR antenna channel

Transmit Array

- Transmit array has two vertical monopoles separated quarter-wavelength at the nominal operating frequency.
- Under each vertical radiator there are 32 short radials (approximately 2m in length)
- The ground screen of the array is compound of horizontal wires, perpendicular to array bore-sight.
- Ground screen should extend at least quarter-wavelength ($\lambda_{min}/2$) on each side.
- Ground screen should extend at least quarter-wavelength ($\lambda_{min}/2$) at the back.
- Ground screen should extend at least half-wavelength (λ_{min}) in the front (if not directly located at the coastal line).

Receive Array

- Receive array has nominally 16 channels, where each channel has two vertical monopoles separated quarter-wavelength at the nominal operating frequency.
- The separation between the channels is approximately half-wavelength at the nominal operating frequency.
- Under each vertical radiator there are 32 short radials (approximately 2m in length)
- The ground screen of the array is compound of horizontal wires, perpendicular to array bore-sight.
- Ground screen should extend at least quarter-wavelength ($\lambda_{min}/4$) on each side.
- Ground screen should extend at least quarter-wavelength ($\lambda_{min}/4$) at the back.
- Ground screen should extend at least half-wavelength ($\lambda_{min}/2$) in the front.

HFSWR RADAR ANTENNA ARRAYS

General Design Guidelines

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- Operating frequency bandwidth
- Maximum Directivity and Gain
- Maximum Front-to-back ratio
- Maximising over-head null
- Vertical and horizontal radiation patterns.

Good antenna system design will

- improve directivity, gain and surface wave coupling to reach longer ranges,
- enlarge azimuth coverage,
- increase front-to-back ratio to minimise interference originates sources behind the array and back-located site interferences,
- provide deeper over-head null to reduce self-generated ionospheric interferences, etc.

HFSWR antenna systems are located on earth's lossy ground, where the bore-sight points the centre of azimuth coverage. The electrical parameters of the ground play a critical role in antenna performance. Typical parameters for *Good Land* and *Poor land* are ε_{rg}=15.0, σ_g=0.01 S/m and ε_{rg}=4.0, σ_g=0.003 S/m, respectively. On the other hand, ocean parameters are ε_{rg}=80.0, σ_g=5.0 S/m. At HF frequencies the smooth ocean surface acts almost as a perfectly electrical conductor (PEC). A vertical monopole with length l over a

PEC surface acts as a dipole with an equivalent length of *2l* in free-space. Therefore, a quarter-wavelength monopole over PEC acts as a half-wavelength dipole in free-space.

The angle between the horizontal plane and the vertical radiation maximum is called the *take-of-angle* (TOA). Vertical monopoles over PEC surface have a 0° TOA. As the surface loss increases TOA also increases.

A vertical monopole element has a *donut* radiation characteristic. That is, isotropic in azimuth plane with horizontal maximum and vertical minimum radiation. However, when placed over lossy ground the horizontal maximum tilts up to between 25° to 40° and the antenna gain reduces by 10dB to 15dB, depending on the ground parameters.

Ground Screen Design

A PEC surface has ideal 0Ω surface impedance. A quarter-wavelength vertical radiator over PEC surface acts as a half-wavelength element in free-space. Therefore its vertical radiation pattern has a maximum towards horizontal. This is the design goal for an HFSWR antenna element.

A lossy ground with the ground parameters σ_g and ε_g has surface impedance, which can be calculated via

$$Z_s = \eta_0 \left[\frac{i\omega\varepsilon_0}{\sigma_g + i\omega\varepsilon_g} \right]^{1/2} \left[1 + \frac{i\omega\varepsilon_0}{\sigma_g + i\omega\varepsilon_g} \right]^{1/2} \qquad \eta_0 = 377\Omega \qquad (1)$$

where $\omega=2\pi f$ is the radian frequency and η_0 is the free space impedance. The surface impedance of the POOR ground (i.e., the ground with σ_g=0.003 S/m and ε_g =4.0) is around 150Ω at 2MHz, increases exponentially with the frequency and reaches to 300Ω at 10MHz. But, the surface impedance of the ocean (i.e., when σ_g=5.0 S/m and ε_g =80.0) is in between 5Ω-10Ω in the same frequency region. Therefore, ocean surface may easily be assumed as a PEC surface at HFSWR operating frequencies.

The difference between erecting the antennas over POOR ground or over the PEC surface may result in a reduction of gain by up to 15dB.

Beside this loss, there is also an extra near field propagation path loss because of the POOR ground. Table 1 lists vertical electrical field strength and path loss at 1km away from a 1kW vertical radiator.

Table 1:

Field strength and path loss values of a vertical radiator
with 1kW transmitter power at 1km distance

d=1km	$\varepsilon_g = 15.0$	*f=3MHz*
Conductivity [S/m]	**Field Strength [dBμV/m]**	**Path Loss [dB]**
0.0001	95.2	56.3
0.001	96.6	55.0
0.01	106.4	45.1
0.1	109.3	42.2
1.0	109.5	42.0
5.0	109.5	42.0

It is clear from Table 1 that, at 1km distance; propagation loss over POOR ground may be 10-15dB higher than the propagation loss over ocean surface.

Therefore, together with the reduction in antenna gain, there may be a total of 30dB extra loss just because the antenna elements are erected over POOR ground.

In order to overcome this problem, the surface impedance of the *Antenna Park* must be reduced to an acceptable level. This is accomplished by one of two ways:

- The antenna park may be selected at the edge of the shore so that ocean water flows under the antenna elements, or
- Using a *ground screen* to reduce the surface impedance of the Antenna Park.

The first choice depends on available antenna site. If not available, then ground screen shall be used to reduce surface impedance of the *Antenna Park.*

Using ground screen

- will stabilise radiator's input impedance, hence increase the antenna gain
- will lower the antenna TOA, hence more energy shall be coupled to ocean surface.

In practice, three different types of ground screens are available. They are radials, horizontal wires and rectangular meshes, or combinations of the three basic types.

It is simple to evaluate the effects of ground screen via approximate analytical approaches. The impedance of a horizontal wire screen is given by:

$$Z_{scr} \approx \frac{i\mu\omega d}{2\pi} \ln\left[\frac{d}{2\pi a}\right] \qquad (2)$$

where "a" is the wire length and "d" is the wire separation. The same equation may also be used for a mesh type screen if the mesh sizes are equal (i.e., square mesh) and equal to "d".

Using the ground screen with impedance Z_{scr} over lossy ground with surface impedance Z_s will cause an equivalent surface impedance, which is given by:

$$Z_{eq} = \frac{Z_{scr} \times Z_s}{Z_{scr} + Z_s} \tag{3}$$

the parallel equivalent of the two impedances.

Land-Sea Transition

The coastal location of the antenna is as important as the ground losses and screen design. That is, the distance between the array and the ocean on each side and in the front also plays a critical role in the array performance. Table 2 lists the near-field path loss values of a 1kW vertical short radiator placed over *POOR* and *GOOD* grounds, respectively. It is clear that a 100m over POOR ground causes 3-5dB more path loss. Similarly, it is between 2dB to 4dB over GOOD ground.

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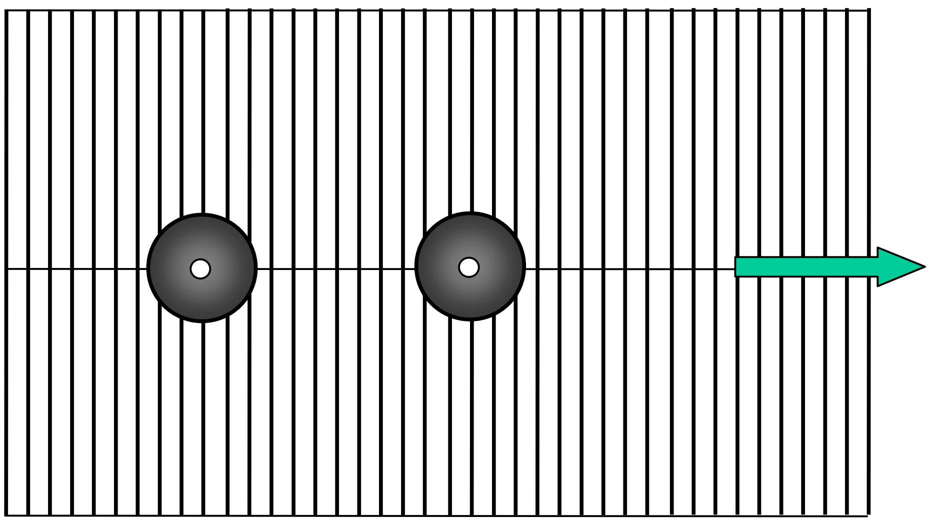

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- The separation between the channels is approximately half-wavelength at the nominal operating frequency.
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- The ground screen of the array is compound of horizontal wires, perpendicular to array bore-sight.
- Ground screen should extend at least quarter-wavelength ($\lambda_{min}/4$) on each side.
- Ground screen should extend at least quarter-wavelength ($\lambda_{min}/4$) at the back.
- Ground screen should extend at least half-wavelength ($\lambda_{min}/2$) in the front.