Sensor and Simulation Notes

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Ship Platform for HF/VHF Arrays

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Abstract

In order to transmit and receive electromagnetic waves as a surface wave over the ocean and scan the beam in azimuth as a radar one can design arrays of antennas on a ship. The frequencies of interest for such surface waves and for some targets of interest near the ocean surface lie in the HF and VHF bands. Such arrays can be mounted on the deck, hull, and/or gunwale, with various relative advantages and disadvantages for each. Considerations include the directional characteristics of the array elements to minimize interference from sources and scatterers on the ship, efficiency in transmission and/or reception, and interaction with the ocean environment.

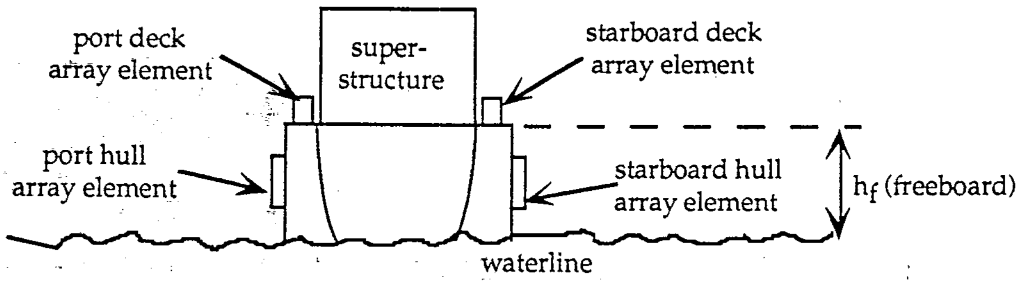
1. Introduction

A ship such as a surface naval vessel is an important antenna platform for both communications and radar. There can be many antenna on the exterior (above the water line) operating on numerous frequencies with a potential for various mutual interferences. Adding new antennas exacerbates this problem. Some antennas, such as for microwave radars, operate at sufficiently high frequencies that one can think of ray paths (as in optics) and associated lines of sight to understand their performance and minimize the interaction with the ship structure and other antennas. Other antennas, such as VLF (very low frequency) communication antennas operate at wavelengths larger than the ship, in which case the ship structure is, in general, a fundamental part of the antenna. This paper considers an intermediate case, HF (high frequency, 3-30 MHz) where wavelengths are of the order of various ship dimensions, complicating the problem considerably. A recent paper [7] considers the comparable situation for an aircraft.

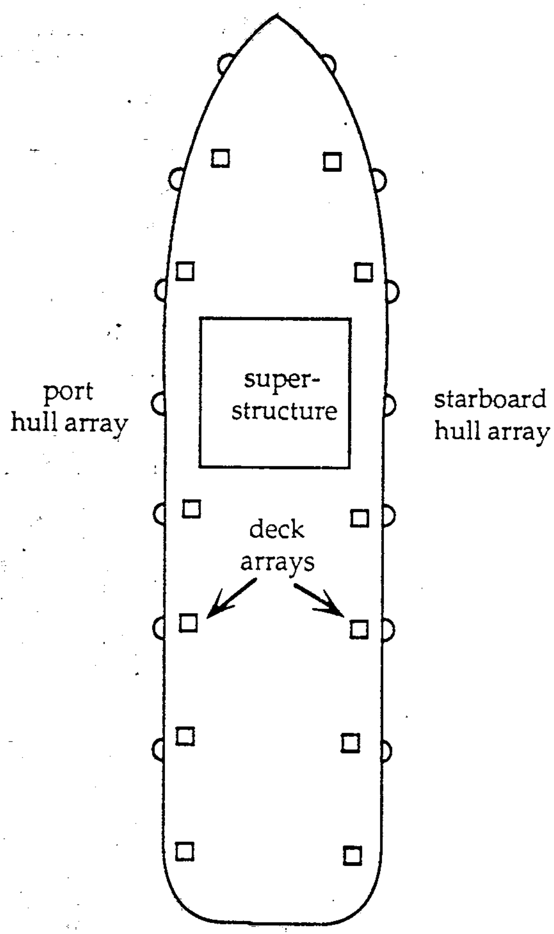
Specifically consider a surface-wave radar (vertical polarization) operating at such frequencies and mounted on a ship. Consider the general geometry of a typical naval vessel as in fig. 1.1. The propagation of such a surface wave has been considered in some detail in [8,9]. the distance out to which a wave can effectively propagate is strongly affected by the sea state (wind speed). The water waves, sea-water conductivity (about 4 S/m), and sea-water relative dielectric constant (about 81) combine to give an effective surface impedance which guides the electromagnetic wave along the surface. As one goes out to distances of the order of 100 km the effect of the sea state is quite significant. As one might expect, the electromagnetic wave has less loss at the lower HF band than at the upper HF band and lower VHF band [9].

In order to transmit and/or receive such a surface wave there are various places one might mount antennas on a metal ship surface as indicated in fig. 1.1. Since one will, in general, wish to steer the radar beam so as to locate the target in range and azimuth, one can have one or more arrays of antennas mounted on the ship. While one can use arrays for both transmit and receive, one can also use an array for one function and a more azimuthally omnidirectional antenna for the other function, and still obtain target bearing. Such arrays can be extended along either or both sides of the ship to steer the beam fore and aft on the desired side. Note that as a surface-wave radar, it is targets near the sea surface (ships, low-flying aircraft and missiles, periscopes, etc.) that are of interest.

Consider where the array elements can be located. Assuming a typical ship with an approximate vertical symmetry plane, then port and starboard arrays can be placed symmetrically with respect to this plane. Figure 1.1 illustrates possible locations on the hull and on the deck. One could also consider locations where the hull meets the deck, i.e., the gunwale. Mounting antennas outside the hull involves



A. Stern view



B. Top view

Fig. 1.1. Deck and Hull Antenna Arrays

various considerations. One may wish the elements to be near the water line (say within a quarter wavelength, or about 7.5 m at 10 MHz or 2.5 m at 30 MHz). However, antenna efficiency is not the only factor since one must allow for the spray and splash from the sea under various conditions. Mounting antennas on the deck has other problems, including closer proximity to other electromagnetic radiators. The antenna design is also influenced by the various frequencies one may wish to use. This could take the form of operating one frequency at a time, or some spectrum of frequencies simultaneously, or even some kind of pulse, the two-sided Laplace (or Fourier) transform of which has some special spectrum for use in target identification.

2. Electrically Small Deck Elements

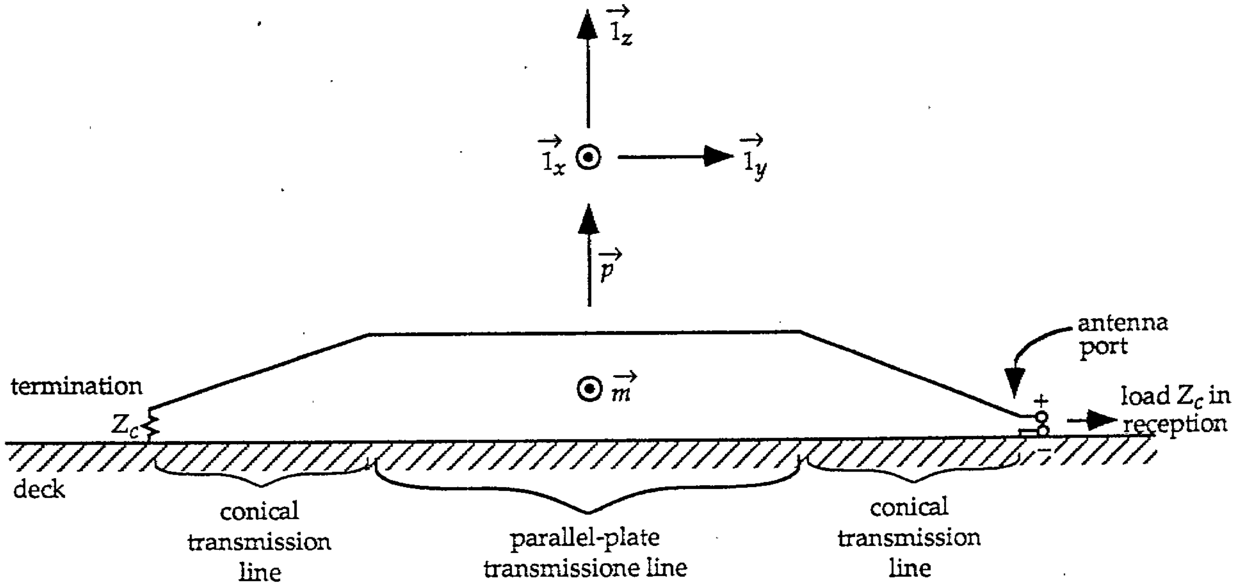
Electrically small antennas are characterized primarily by their electric- and/or magnetic-dipole characteristics [10]. Assuming a flat metal deck, the deck can be regarded as a symmetry plane and used as a local reference for the transmit and/or receive signals at the antenna. The presence of the image plane makes such antennas better described as equivalent electric and magnetic dipoles. The electric type consists of a conductor (perhaps impedance loaded) which is isolated from the image plane except through the signal port (terminal pair) which may be a coaxial cable (with shield locally electrically attached to the connecting deck). It responds in reception to the local vertical incident electric field, not only from the target scattering but also from scattering from other parts of the ship. Such electric fields may also be radiated from other antennas on the ship. The magnetic type consists of a half loop (including the image in the ground plane) connected to the ground plane at two positions to allow a low-frequency closed current path (with due care concerning the signal-port location). It responds in reception to the local horizontal incident magnetic field from the target, other scattering, and other sources.

An interesting antenna for this application combines electric- and magnetic-dipole characteristics in a way which balances the equivalent dipole moments in transmission as

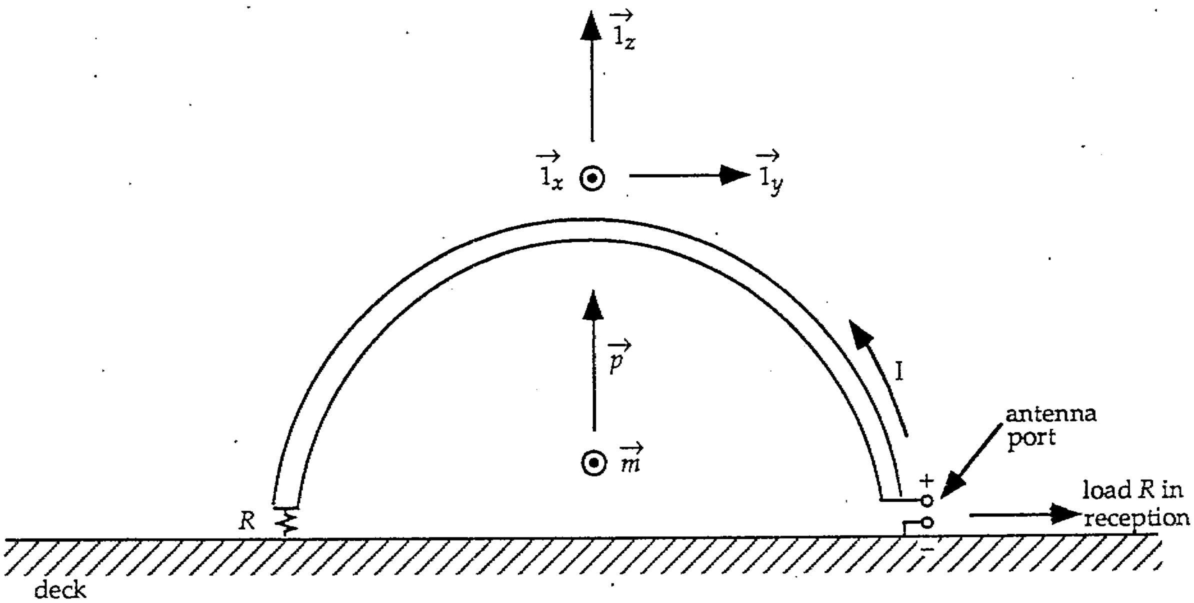
$$\begin{aligned} \vec{p} &= p\,\vec{1}_z = \text{equivalent electric dipole moment} \\ \vec{m} &= m\,\vec{1}_x = \text{equivalent magnetic dipole moment} \\ p &= \frac{m}{c} \\ c &= \left[\mu_0 \varepsilon_0\right]^{-\frac{1}{2}} \equiv \text{speed of light} \\ \vec{p} \times \vec{m} &= pm\,\vec{1}_y \end{aligned} \tag{2.1}$$

where (x,y,z) are the usual Cartesian coordinates with z = 0 taken as the ground plane (deck) as in fig. 2.1. In this case transmission is in the $\vec{1}_y$ direction with a cardiod pattern, such as an antenna being referred to as a $\vec{p} \times \vec{m}$ antenna or as MEDIUS [1-5, 10]. Here the array elements have been taken as on the starboard side, those on the port side having the opposite direction for $\vec{p} \times \vec{m}$.

There are various ways to realize such a $\vec{p} \times \vec{m}$ antenna in a single antenna with a single port, such as those illustrated in fig. 2.1. In the first example (fig. 2.1A), a parallel-plate transmission line of characteristic impedance Z_c and propagation speed c has conical transmission lines (tapers) also of impedance Z_c at both ends, one being terminated in a resistive termination of value Z_c. When operated in reception the signal port is also loaded with impedance Z_c (as in a coaxial cable, including any



A. Terminated transmission line (characteristic impedance Z_c).



B. Terminated loop.

Figure 2.1. Combined Equivalent Electric- and Magnetic-Dipole Antenna (Illustrated in Transmission)

matching network). This conceptually simple device is referred to as a Balanced Transmission-Line Wave (BTW) sensor [4]. One could also construct the mechanically simpler loaded loop as in fig 2.1B. This is connected to the deck at one end with a resistance R, and at the other end to the signal port which is also loaded with R when in reception. Detailed calculations and/or experiments can determine the value of R for balancing $\vec{p}$ and $\vec{m}$. Note that the half loop need not be circular, but can be rectangular, triangular, or some other convenient shape.

In reception such a $\vec{p} \times \vec{m}$ antenna is maximally sensitive to EM waves arriving in the $-\vec{1}_y$ direction, and minimally sensitive to those arriving in the $+\vec{1}_y$ direction. So if scattering objects (e.g., the superstructure) and other interfering EM sources are located in the $-\vec{1}_y$ from the antenna (i.e., "behind" the antenna) their effects are reduced compared to the desired target-scattered signal coming in the $-\vec{1}_y$ direction. The ship deck in the $\vec{1}_y$ direction from the antenna is in general not uncluttered (e.g., the gunwale) which can scatter unwanted waves into the antenna, but hopefully such effects can be small in a relative sense.

One disadvantage of $\vec{p} \times \vec{m}$ antennas in transmission is their relative inefficiency (relative to single electric or magnetic dipoles) due to the power absorbed in the resistive load. In reception, however, this is not so significant if one is using the antenna to drive a resistive load anyway (such as a coaxial cable terminated in its characteristic impedance). Thus one might also consider a $\vec{p} \times \vec{m}$ array for reception, but something else for transmission.

3. Hull Elements

On the outside surface of the conducting (metal) hull there are various types of antennas that one might use. As discussed in [6] and illustrated in fig. 3.1, for transmitting and receiving EM waves propagating perpendicular to a conducting surface a magnetic dipole is preferable to an electric dipole. This is seen in transmission by noting that the magnetic dipole moment parallel to the surface is increased by the image to give twice the effective magnetic dipole moment. On the other hand, the electric dipole moment parallel to the surface is canceled by the oppositely directed image to give a zero effective electric dipole moment. In reception an EM wave propagating perpendicular to the surface has a reflection which doubles the tangential magnetic field but cancels the tangential electric field. Thus a magnetic dipole antenna is more effective in this location. This can be a simple semicircular loop as in fig. 3.1, or more elaborate loop structures.

There are some environmental concerns for such hull array elements. Being located on the outside of the hull, above the waterline and below the gunwale, one needs to allow for the presence of sea spray and splash. One can protect these antenna elements by some kind of dielectric potting or covering. Note that this has a less significant effect on electrically small magnetic-dipole antennas (loops) than on the electric counterpart, thereby giving another reason to prefer the magnetic type.

One can extend the concept of an electrically small magnetic dipole to a larger antenna by extending it as a shorted transmission line as indicated in fig. 3.2. If the length ℓ is electrically small (in the dielectric potting material) then this can be thought of as merely one realization of a loop, albeit a practical one in that it keeps the protrusion of the array element from the hull surface to a minimum. Then appropriately shaping the dielectric cover, one can minimize the interaction of the structure with sea spray and splash (and high waves).

In order to increase the current in the antenna element (and hence magnetic moment) in transmission with a given loop area

$$A = \ell b \tag{3.1}$$

one can increase the width w (or 2a) of the flat metal strip comprising the loop conductor. In reception this decreases the source impedance of the antenna relative to the load it is driving, say a coaxial cable terminated in its characteristic impedance. The cable shield should be well bonded to the hull at the antenna port (as well as other parts of the hull if it passes up over the gunwale instead of immediately penetrating the hull).

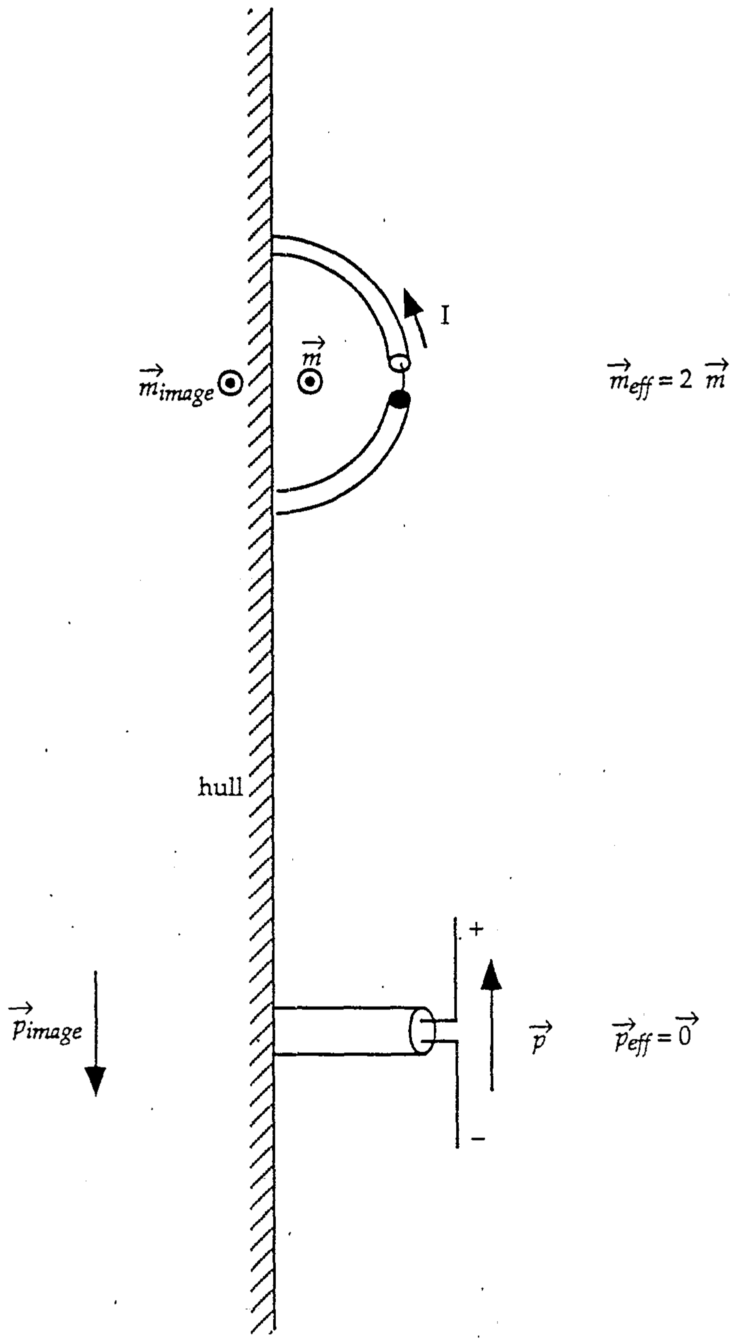


Figure 3.1. Effects of Images Behind Conducting Surface on Low-Frequency Antenna Performance

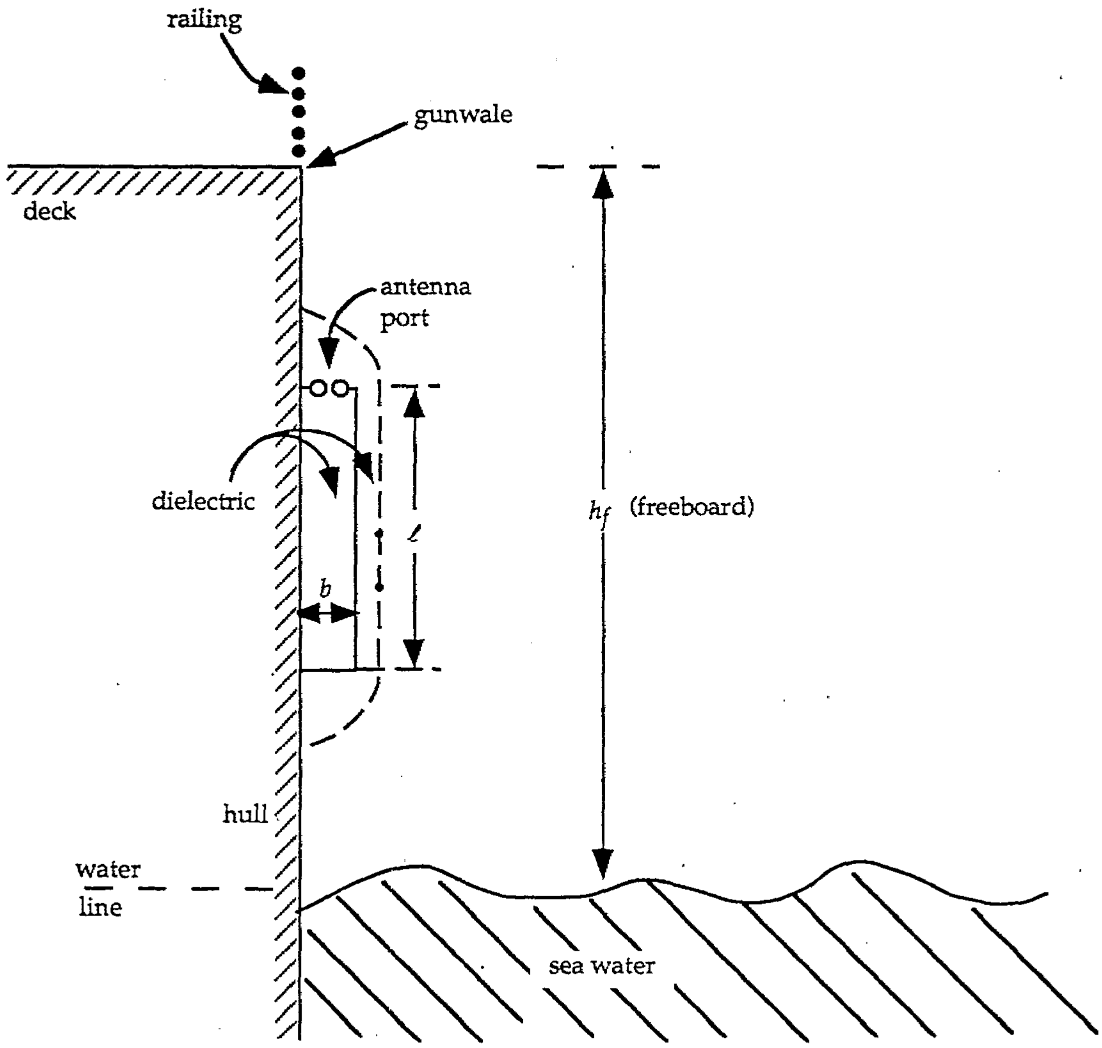


Figure 3.2. Shorted Transmission-Line Antenna on Hull

With the loop extended as a transmission line one can also operate it in a resonant manner to gain greater efficiency. If ℓ is a quarter wavelength (in the dielectric) there is a current maximum at the bottom with now a high input impedance at the top (the antenna port). Adjusting the frequency in relation to ℓ one can optimize the antenna impedance (including the influence of radiation resistance). Of course one is limited in length by $\ell < h_f$ where h_f is the freeboard or height of the hull above the waterline as in fig. 3.2.

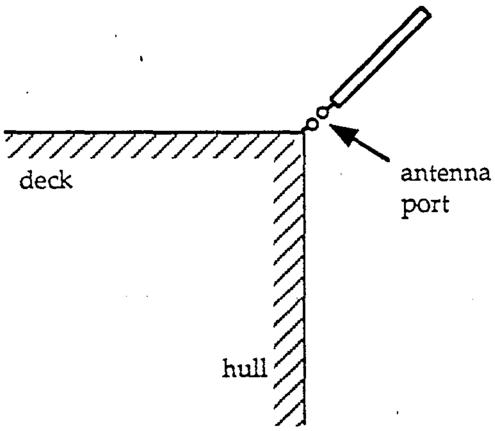
4. Gunwale Elements

Besides the deck and hull as locations for the array elements, one might consider their intersection at the gunwale (figs. 1.1 and 3.2) as another possible location. Of course, the geometry near the gunwale can be more complicated than a simple right-angle bend in a metal sheet. There may be a conducting railing which would considerably complicate the electromagnetic properties. Note that the presence of the gunwale complicates the performance of both deck and hull elements due to the electromagnetic scattering of the various electromagnetic waves there.

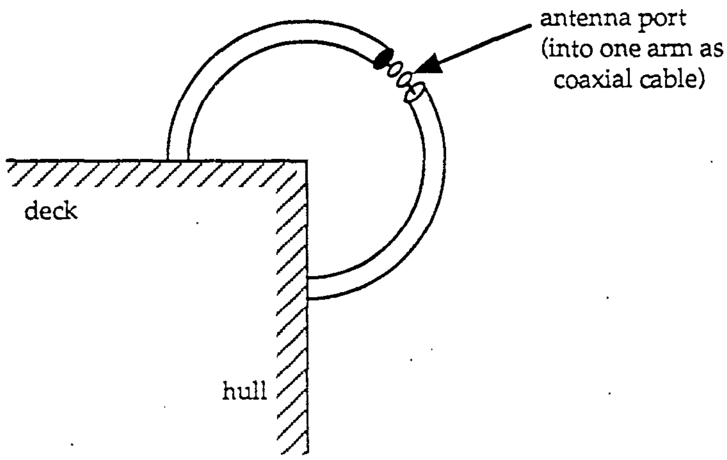
If one considers a simple gunwale as a right angle bend in a metal sheet, then one might consider electrically small antenna elements as illustrated in fig. 4.1. An electric type antenna is indicated in fig. 4.1A. Note the orientation to take advantage of the singularity in the electric field at the gunwale resulting from some electromagnetic wave incident on the gunwale. This introduces an additional frequency dependence in the antenna response (to an incoming plane wave) due to the scattering at the gunwale, giving additional sensitivity to the lower frequencies. There is also a phase shift in the scattered field relative to the incident field associated with the edge diffraction.

One can also consider a magnetic antenna (loop) on the gunwale as indicated in fig. 4.1B. Here the loop (or 3/4 loop) is oriented to be sensitive to the incident magnetic field parallel to the gunwale. By positioning the antenna port at the appropriate location in the loop the sensitivity to the local electric field (as a receiver) can be minimized. The signal from the port travels to the hull or deck via a coaxial cable, the shield of which also serves as one of the loop arms.

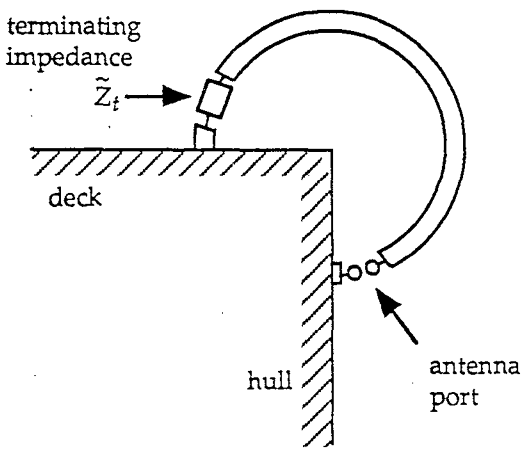
Analogous to the antennas in fig. 3.1 one can also design an antenna as in fig. 4.1C which combines the electric and magnetic sensitivities so as to preferentially transmit to and receive from the direction away from the ship (to the right in the illustration). Equivalently this means that the antenna will be insensitive (relatively) to sources and scatterers on the ship (to the left in the illustration). Noting in reception that the local incident electric and magnetic fields (due to some source or scatterer out above the sea surface) will not be simply related as in a plane wave, but will have an enhanced ratio of electric to magnetic field (as well as a phase shift between the two), one can place a terminating impedance $\tilde{Z}_t(s)$ somewhere to the left in the loop and take the signal where the loop meets the hull. Note the dependence of the terminating impedance on the complex frequency s so that $\tilde{Z}_t(s)$ can be complex and allow for the phase difference between the electric and magnetic fields. Detailed calculations and/or measurements can establish the complex value and location of $\tilde{Z}_t(s)$ for optimal performance. In addition, one may wish to place a matching network at the antenna port to present some desirable complex impedance to the antenna (and perhaps even move the antenna port to other locations on the loop).



A. Electric antenna



B. Magnetic antenna



C. Combined electric and magnetic antenna

Figure 4.1. Combined Electric and Magnetic Antenna at Gunwale.

5. Concluding Remarks

There are then various ways to mount HF/VHF arrays on a ship for use in a surface-wave radar. They can be used for transmission, reception, or both. They can be mounted on various parts of the ship with various relative advantages and disadvantages. These concern both the electromagnetic performance and interaction with the sea environment.

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