# The Influence of Different Realization of Ground Plane on a Characteristic of HFSWR Transmitter Monopole Array

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***Abstract*—Mutual coupling of antennas in systems that use multiple antennas is a phenomenon that can be detrimental to a system's functionality. Mutual coupling of antennas in an existing High Frequency Surface Wave Radar (HFSWR) transmitter is analyzed in this paper. Earlier measurements of VSWR had indicated that significant coupling may be present. After various simulations, its presence was confirmed, and it was shown that the simulated radiation pattern has differences compared to the theoretical. In this paper, simulations were performed to analyze the effects of different realization of ground planes on antenna coupling and its effect on radiation pattern while keeping the deployment area and antenna foundations intact. The nature of the coupling was analyzed along with different realizations of ground planes. Simulation results are presented and discussed in details, showing that coupling through the free space is dominant in nature of this effect.**

***Index Terms*—Ground Realization, HFSWR, Monopole, Mutual Coupling.**

## I. Introduction

Economies are becoming heavily reliant on overseas shipping making maritime traffic denser than ever. Without going further into the significance of maritime areas, the Exclusive Economic Zone (EEZ) is where it practically all takes place. The EEZ is a strip of sovereign water going 200 nautical miles (around 370 km) from the coastline to the open sea [1]. To control such a large area, an efficient surveillance system is needed, which is no easy feat. Microwave radars and electro-optical systems can only bypass the curvature of the earth using mobile platforms, this solution does not have a satisfactory uptime, nor operational cost.

In contrast to that, high frequency surface wave radar (HFSWR) is a system that satisfies mentioned needs. HFSWR is a radar that works in the High Frequency (HF) band ranging from 3 MHz to 30 MHz [2-3]. These frequencies allow propagation of electromagnetic (EM) surface waves closely coupled to some surface, in this case seawater. Initially, they were used for oceanographic observations such as the height and direction of waves, speed and direction of currents, as well as tsunami detection [2-4]. Such waves follow the curvature of the earth, allowing for detection well beyond the horizon, going as far as 370 km, which is a requirement for complete EEZ observation [5-6].

The analysis presented in this paper is inspired by experience gained from currently operating system in the Gulf of Guinea [6-9], which represents the backbone of a complex multi-layer system for maritime surveillance [10]. It is a frequency-modulated continuous-wave (FMCW) radar occupying a 100 kHz bandwidth with central frequency at 6.9 MHz. The system is comprised of 2 separate sites, transmitter (Tx) and the Receiver (Rx). The receiver is an antenna array consisting of 16 monopole antennas. The transmitter is made of 4 quarter-wave monopole antennas, as illustrated in Fig 1. Further details regarding this radar can be found in [6-8].

Certain measurements of this radar have raised suspicion of significant mutual coupling between transmitter antennas. Different realizations of ground plane and its influence on the coupling of antennas will be discussed.

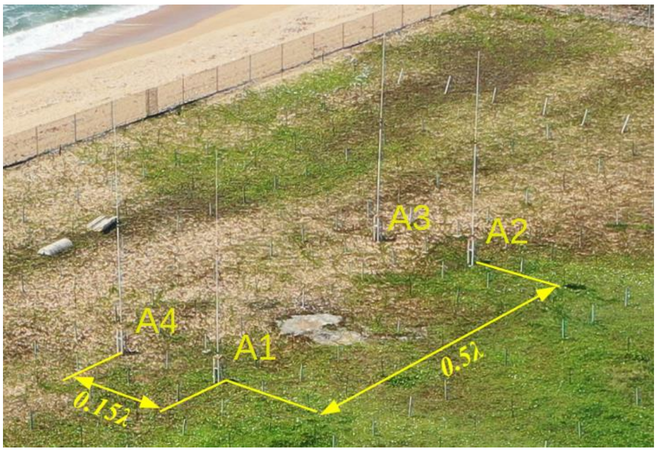


Fig. 1. Transmitter site located in the Gulf of Guinea.

Section II contains a brief introduction to the problem of mutual coupling of antennas, and all relevant data for used numerical models will be presented. Section III will present several numerical models of the ground plane and its effects on antenna array performance. Conclusions are presented in Section IV.

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## II. MUTUAL COUPLING

Mutual coupling between array elements can be separated as a free-space coupling (radiation coupling) and/or coupling through currents flowing on the ground plane shared by these elements (conductive coupling) [11-13]. Regardless of its nature, the mutual coupling of array elements generally affects radiation pattern and the input impedance of array.

As can be seen from Fig. 1, the transmitting array consists of 4 antennas arranged to be corners of a rectangle. The side facing the shoreline is 0.5λ, while the side perpendicular to it is 0.15λ, where λ is the free space wavelength at 6.9 MHz. The 0.15 λ separation is of particular importance since it is believed that it is the main reason for mutual coupling.

VSWR measurement was performed for individual antennas and the splitter that feeds them. VSWR measured for each antenna was below 1.5 at 6.9 MHz, as shown in Fig. 2 for one of the antennas. For this measurement, one antenna is excited while all others are closed with loads. In the second measurement, all transmitting antennas are fed by a 1:4 splitter, and then VSWR at the input of splitter is measured. As can be seen from Fig. 2, in this case, the VSWR was 3 and practically flat in a 200 kHz span around 6.9 MHz. The splitter is declared to have VSWR less than 1.1. Because of this, it was suspected that antennas are (significantly) mutually coupled.

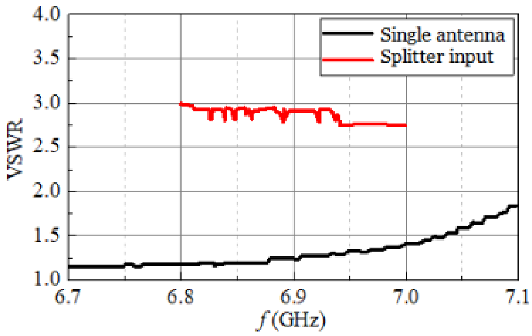


Fig. 2. VSWR measured for one antenna (black) and the input of a 1:4 splitters connected to 4 antennas.

This prompted further analysis, and simulations were performed using the software package WIPL-D Pro [14]. All WIPL-D Pro simulations were performed at 6.9 MHz. To demonstrate the mutual coupling, the initial model was made with vertical monopoles arranged exactly the same as those for the transmitter of HFSWR in the Gulf of Guinea. However, to simplify the model, the ground for the monopoles is made as an infinitely large perfect electric conductor (PEC) plane. The excitation of the front row of antennas (3 and 4), closer to the sea, is delayed for 126° to simulate longer feed cables compared to those that excite the back row of antennas at the site in the Gulf of Guinea. This was done in order to get a null in radiation pattern away from the sea (direction of 270°), while having a sufficiently wide main lobe. Common antenna array theory was used for this calculation [15-16]. The theoretical model was also derived from these calculations. It implies monopoles with infinite PEC ground plane without mutual coupling. Fig. 3. shows the overlay of the theoretical radiation pattern versus the WIPL-D Pro results. Both of the given radiation patterns are obtained when all 4 antennas are active while being normalized to 0 dB, meaning that they are not absolute values.

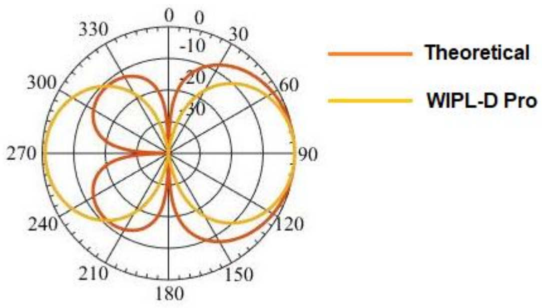


Fig. 3. Overlay of theoretical radiation pattern (red) versus WIPL-D Pro results (yellow) when all 4 antennas are active.

The sideways null in results has a purpose of preventing the signal leakage from transmitter directly to the receiver, and it is fairly equal in both models. However, the null away from the sea has drastic differences. Using the WIPL-D Pro software, it is shown that there is a significant lobe in the direction of 270°. It seems reasonable to assume that 0.15λ spaced monopoles are strongly coupled, which changes radiation pattern relative to theoretical.

In models with multiple excitations, WIPL-D Pro allows analysis when only one excitation is active at a time while the others are terminated with a short circuit. This short circuit is not consistent with the measurement set up and the real system. To remedy this, all non-excited antennas are terminated with a concentrated load of 50 Ω. This is shown in Fig. 4, where only one antenna has an active excitation. The displayed radiation pattern is shown for the horizontal cut. From this result, we see that other (non-excited) antennas affect radiation pattern, since the monopole antenna has an omnidirectional radiation pattern. It is important to note that WIPL-D presents the radiation pattern from the center of the coordinate system, regardless where the excitation is.

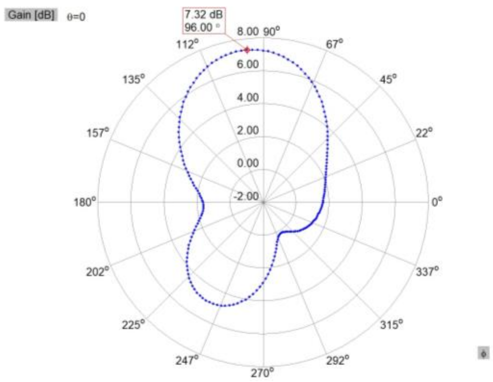


Fig. 4. Radiation pattern in the horizontal cut of a singly excited antenna in the transmitting array in the vicinity of all others antennas.

Looking at the *s*-parameters, in this case, off-diagonal elements of *s*-matrix, it can be seen that monopoles have significant coupling (especially $s_{41}$), as shown in Table I. Antenna numeration (A1-A4) is counter-clockwise starting from the left antenna farther from the sea, meaning 1-2-3-4 counter-clockwise from that antenna, as shown in Fig. 1. Keep in mind that this analysis is reciprocal and that the array has a plane of symmetry.

TABLE I
*S*-PARAMETER MAGNITUDES BETWEEN EACH ANTENNA FOR INFINITE PEC GROUND

| | |
|---|---|
| $\lvert \underline{s}_{41} \rvert$ | -6.9350 [dB] |
| $\lvert \underline{s}_{42} \rvert$ | -20.7820 [dB] |
| $\lvert \underline{s}_{43} \rvert$ | -17.5511 [dB] |

In these kinds of implementations, ideally, parameters from Table I should be zero to ensure the desired performance. Also note that *s*-parameters of 0.5λ spaced antennas ($s_{42}$ and $s_{43}$) are more than 10 dB lower in amplitude, meaning that the coupling effect is of lesser intensity. This clearly signifies that mutual coupling in this model is a consequence of antennas being too close to each other. At first glance, a simple solution would be to simply separate antennas further and calculate the necessary phase shift. However, a larger site is not an option. For HFSWR in the Gulf of Guinea, it is very difficult to find and then obtain, suitable land, especially due to the rising costs of coastal land. It is also worth mentioning that sometimes increasing antenna separation can increase coupling [13].

In this paper, analysis will be made on effects of different ground planes on the mutual coupling of antennas without changing the size of the transmitter allocated area, or drastically changing the array configuration. The area allocated for a transmitter in the Gulf of Guinea is approximately 92 m x 76.5 m, with the wider side being parallel to the sea. In Fig 5. the WIPL-D Pro model with a finite PEC ground can be seen. It should be noted that the allocated area is in fact the area for the ground plane for the transmitter array.

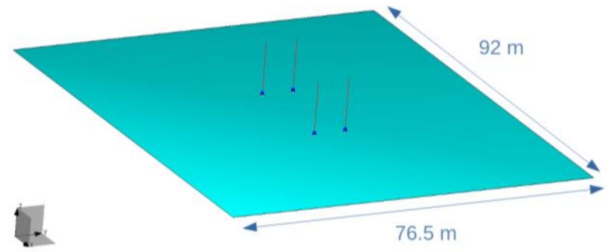


Fig. 5. Finite PEC ground model cut into 4 plates.

## III. SIMULATION WITH DIFFERENT GROUND PLANES

Since the initial request is to keep the same antenna separation, there is very little that can be done against free-space coupling. This leaves the possibility to reduce mutual coupling via manipulations of currents flowing through the ground plane. Previous WIPL-D Pro model has an infinite PEC plane as ground, which obviously cannot be constructed in practice, but represents a good starting point. The first modification will consist of a finite PEC plane with dimensions equal to space allocated for the transmitter site, as mentioned in the previous chapter. The magnitudes of *s*-parameters in dB of such a configuration are presented in Table II.

TABLE II
*S*-PARAMETER MAGNITUDES BETWEEN EACH ANTENNA FOR FINITE PEC GROUND

| | |
|---|---|
| $\lvert \underline{s}_{41} \rvert$ | -7.3780 [dB] |
| $\lvert \underline{s}_{42} \rvert$ | -22.1203 [dB] |
| $\lvert \underline{s}_{43} \rvert$ | -17.3683 [dB] |

Compared to the results from Table I, it can be seen that coupling is now slightly reduced, but practically it remains the same. The next step is to look at current distributions for finite PEC ground model. Please note that all further figures regarding current distribution display current density amplitude.

The current distribution of a finite PEC ground model when only excitation 4 is active is shown in Fig. 6. It can be seen that there is a considerable current at antenna 1 feed point, while much less at feed points 2 and 3. The unit of current density displayed is mA/m.

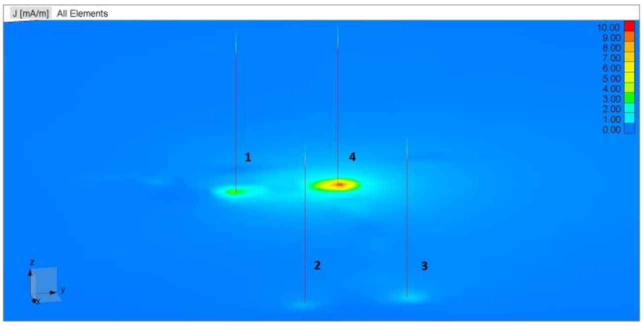


Fig. 6. Current distribution for finite PEC ground model when only generator 4 is active.

From this analysis, it is difficult to discern the exact ratio of contribution of current and free-space coupling. Antennas 4 and 1 have significant currents in the sector of a ground plane between them. The next step in order to try to reduce coupling is to galvanically separate all the antennas. The idea is to separate the current finite PEC into 4 equal plates, as shown in Fig. 7. The width of all slits is 2 m, which was chosen as to have an adequate graphical presentation.

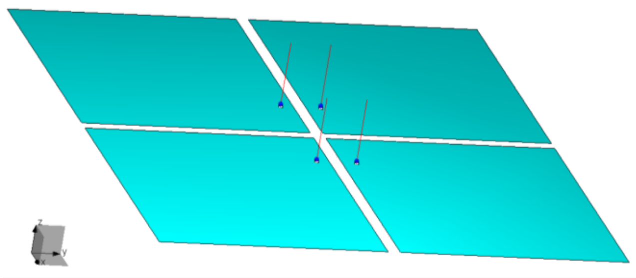

Fig. 7. Finite PEC ground model cut into 4 plates.

Next, we will determine how *s*-parameters depend on the width of the slit. A sweep was done with slit width ranging from 0.5 m to 3 m in increments of 0.5 m. The results are shown in Fig 8. The abscissa of Fig. 8 is a separation width value, and the ordinate is the linear magnitude of *s*-parameters. Four curves displayed represent magnitudes of $\lvert \underline{s}_{41} \rvert$, $\lvert \underline{s}_{42} \rvert$, $\lvert \underline{s}_{43} \rvert$ and $\lvert \underline{s}_{44} \rvert$ shown in blue, red, purple and green respectively in [dB].

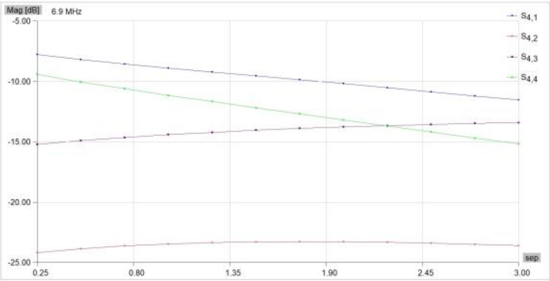


Fig. 8. *S*-parameter magnitude in respect to the slit width.

From Fig. 8 it can be seen that the coupling of the nearest antennas ($s_{41}$) is reduced as slit width increases. The coupling of the diagonal antenna ($s_{42}$) remains practically unchanged. Interestingly enough, coupling for 0.5λ separated antennas ($s_{43}$) slightly increases with slit width increase. The next step is to see the current distribution. Results for slit width equal to 2 m are presented in Fig. 9. Again, only generator 4 is active.

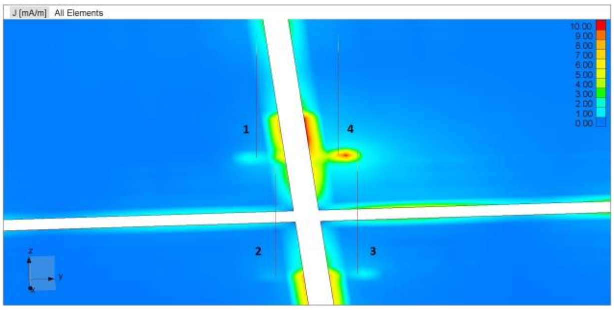


Fig. 9. Current distribution for finite PEC ground model with slit when only generator 4 is active.

Fig. 9 shows interesting results. There are significant currents on all four plates' edges, implying a strong radiation coupling since there is no galvanic contact between these plates. The horizontal cut of the radiation pattern when all four generators are turned on is shown in Fig. 10.

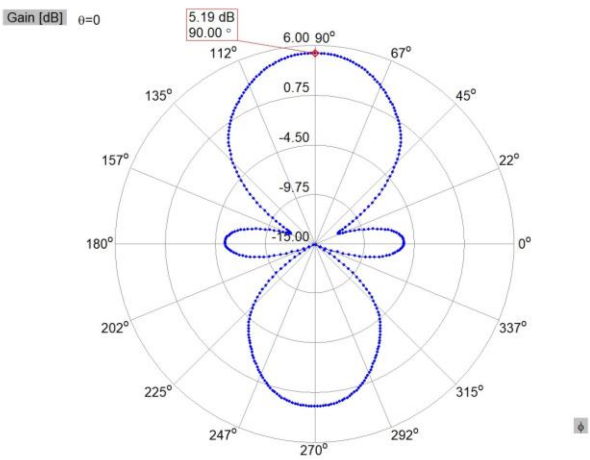


Fig. 10. Radiation pattern in the horizontal cut of finite PEC ground model with slit with all 4 active generators.

From the Fig. 10, we can see that there is significant radiation directly above the antennas, going up to 3 dBi. The back-lobe intensity is about 3 dB lower than the frontal main lobe which is 5.19 dBi. This solution proves to be energy-inefficient because a significant portion of the energy is radiated upwards, providing no benefit for HFSWR analyzed in this paper. In fact, this occurrence can degrade radar operation as it allows for significant ionospheric reflections which for this type of system are interference. Based on this, one should be very careful when attempting this kind of antenna decoupling.

Final analyzed realization of ground for the monopoles will be in the form of radials. Radials are wires going from the feed point of the antenna and act as a ground plane for it. They are galvanically connected to the "cold" conductor of the transmission line, in this case, coaxial cable. Their purpose is to increase the radiation efficiency of an antenna by preventing losses in the earth, which is far from a perfect conductor. Increasing the number of radials and their length acts as a better ground. The transmitter of HFSWR in the Gulf of Guinea has 36 radials per monopole, with 35 m of length. This length is greater than the distance between each transmitting antenna, especially for distances of antenna pairs 1-4 and 2-3. Because wires in the WIPL-D Pro model must not have unspecified intersections to ensure an appropriate model, radials should be carefully modeled. The radials placed on the real site are not symmetrically placed around the monopole itself. A reason for this is to fit all wires and to enable movement of personnel on-site. It should be noted that all of them are galvanically isolated with rubber. Therefore, the transmitter is modeled as close as possible to the deployed antenna array. Antennas 1 and 3 are rotated 5° around their monopoles, while antennas 2 and 4 have no rotation. Furthermore, all antenna feed points are slightly elevated, all to prevent wire intersection, and this model is presented in Fig. 11.

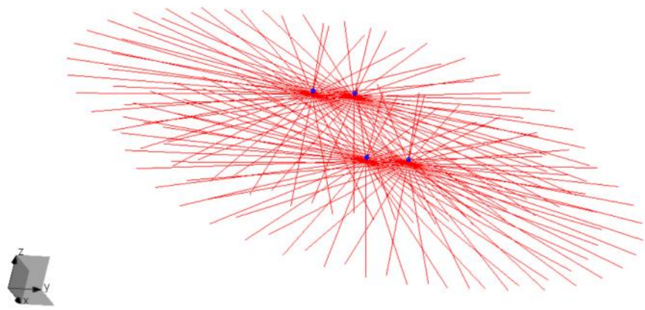

Fig. 11. Model of transmitting antennas with radials.

Similar to previous cases, *s*-parameter magnitudes in dB are shown in Table III.

TABLE III
*S*-PARAMETER MAGNITUDES BETWEEN ANTENNAS IN RADIAL GROUND MODEL

| | |
|---|---|
| $\|s_{41}\|$ | -6.7407 [dB] |
| $\|s_{42}\|$ | -24.2707 [dB] |
| $\|s_{43}\|$ | -19.2778 [dB] |

From these results, it can be seen that antenna coupling is on a similar order with previous cases. The radiation pattern of the array with radials is shown in Fig. 12.

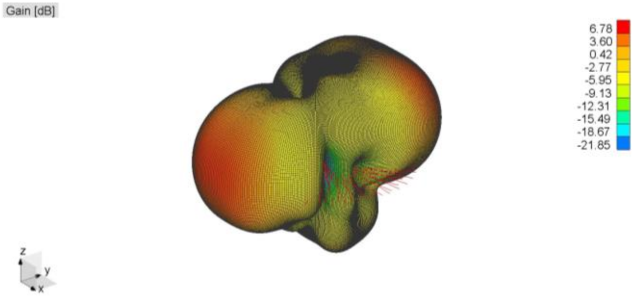


Fig. 12. Radiation pattern for array with radials when all generators are active.

It can be seen that the main lobe is tilted upward. This is typical for a monopole with radials and has nothing to do with coupling [17]. More importantly, the back-lobe is still very pronounced as it was expected (similar to results in Fig. 3), indicating significant antenna mutual coupling, more clearly seen in Fig. 13.

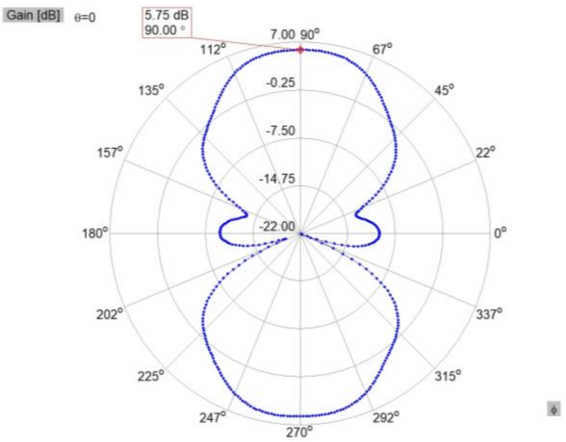


Fig. 13. Radiation pattern in the horizontal cur for array with radials in the horizontal cut when all generators are active.

## IV. Conclusion

In this paper, the effects of different realizations of the ground plane on mutual coupling of antennas on the transmitting array of a deployed HFWR were analyzed. The simulated radiation pattern has differences compared to the theoretical, mainly in the 270° direction. Different realizations of ground planes provided similar *s*-parameters. Considering the restrictions of keeping the antenna array configuration and the maximum allocated area the same, this analysis indicates that a different approach should be taken to affect mutual coupling. This opens the course of future work in the form of obtaining more information about free space coupling of the transmitter array antennas and methods that can affect it.

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