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HF Broadband Antenna Design for Shipboard Communications: Simulation and Measurements

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ABSTRACT:

The objective pursued in this work is to highlight the convenience of using electromagnetic simulation software as an alternative to the traditional scale model measurement when dealing with the design of HF antennas on real complex platforms.

The experience was developed during the building process of a real vessel. A low and a medium band antennas (fan-wire type) were designed ad-hoc for this project. The HF broadband antennas' study covered from the preliminary design stages to the final verification measurements completed onboard the ship. The experiment has demonstrated that more accurate results can be obtained when using an adequate electromagnetic simulation code, which, besides, brings important advantages in flexibility and usability. These advantages, inherent to the use of virtual models, hinge on the ability of the simulation tools to properly handle any modification of the vessel's structure that might arise during the platform construction.

Index terms/Keywords: Antenna measurements; Wire antennas; HF antennas; Fan-wire antennas; Scale model measurements; Impedance matching.

1. INTRODUCTION

Communications in the high frequency (HF) band are one of the main concerns in modern ships and vessels. Although the use of HF was expected to decay with the advent of satellite communications (SATCOMs) [1] providing enhanced data rates and usability, nowadays it is still of great relevance due to various reasons. Mainly, HF systems are long-range and very robust communication systems, independent of any relay mechanism (such as a satellite), which is of strategic importance in the naval environment. They may even become the only communication system available under some circumstances (very high latitude mobiles could be an example), with the consequent safety implications.

Typical naval HF antennas include single pole whips, twin pole whips, long wires and fans [2], [3]. Whips (monopoles) are usually used in narrowband (NB) and they are the most common antennas for shipboards. However, in the current context, the number of HF communication circuits required to satisfy the increasing operational requirements in modern naval units prevents the exclusive use of narrowband tuned whip antennas. Instead, HF broadband (BB) antennas such as the twin pole whips, long wires and fans need to be used in order to accommodate several communication circuits sharing the same antenna, thus reducing the number of antennas placed on the usually limited space available for this purpose on the deck. Typically, two or three BB antennas cover all the HF frequency range [1], [3]. Several transceivers are connected throughout a diplexer (two ports) or triplexer (three ports) to the antennas by means of the proper combining and matching networks. Diplexers/triplexers are band-pass filters connecting the common port with the other ports ensuring high isolation between the latter. Signals of different frequency bands can coexist on the common port without interfering between them.

Otherwise, the aforementioned demand of operational requirements in modern ships and vessels implies the coexistence of a wide number of sensors and radiating systems in a very limited physical space. Therefore, electromagnetic interference (EMI) amongst the different systems becomes a major issue. In such a complex electromagnetic environment, a proper strategy to carry out a reliable electromagnetic compatibility (EMC) study becomes crucial. Thus, nowadays it is unquestionable that EMI/EMC considerations must be taken into account from the very early topside design stages. This dense electromagnetic environment forces the topside designer to address different interrelated aspects simultaneously. Namely, the optimization of antenna patterns, input impedances, coverage and blockage, issues concerning the hazard of electromagnetic radiation (EMR) to personnel (HERP) [4], ordnance (HERO) [5], and/or fuel (HERF) [4], or minimization of EMI, among others things.

The above exposition of the current context makes it clear that it is mandatory to find an alternative to the expensive and time-consuming build-and-test procedures used in the past. Scale brass models [6] and electromagnetic simulations can be useful ways to incorporate the electromagnetic constraints into the vessel design process already at the preliminary stages, improving the efficiency of the whole process in terms of time, cost and also in the final systems' performance. In this paper, we show the main advantages and drawbacks of both alternatives based on the results of a real experience, since from 2006 we had the extraordinary opportunity of participating in the electromagnetic design of a modern ship from the initial building stages to the final harbor acceptance trials (HAT) and sea acceptance trials (SAT). The conclusions of this paper are the outcome of the work developed during six years, from the preliminary design of the HF BB fan-type antennas to their implementation on the real platform and subsequent measurements. The work is focused on the study of the fan antennas because of their challenging design. The use of fan antennas is standardized for low HF ranges [1] and destined to cover a very large bandwidth. Additionally, their radiation patterns, and especially the input impedance, are strongly influenced by the elements of the superstructure whose size is comparable to the wavelength. Therefore, this study is a good example of how helpful the electromagnetic simulation tools used in this work can be in the optimization and characterization of the antennas' performance. The experiment allowed us to compare the capacities of the traditional scale model measurements versus the electromagnetic simulation when exploring the design of HF antennas for real complex platforms. Their accuracy was contrasted with measurements carried out onboard the real platform.

2. SCALE MODELS VS. EM SIMULATIONS

In the past decades, scale brass model measurement has been the most extended methodology to assist in the onboard antennas design and in the selection of their optimal placement. The capacity of the computers available at that time was still far away from the massive computational resources required for the EM simulation of this kind of problems. For this reason, since the eighties different countries like the United States of America (USA) [6], the Netherlands [7], India [8], Germany [9], or China [10] have evaluated different sorts of naval platforms with scale models.

The scale model of a ship is a detailed brass model linearly downscaled from the original dimensions of the vessel. The scaling factor is determined by the manageable size of the model and the frequency capabilities of the measuring equipment. Also the frequency must be suitably scaled in order to maintain the size of the brass model in terms of the wavelength [3]. The place where the measurements of the model are carried out must complain restrictive characteristics of isolation and absorption at the proper frequency band, such as an anechoic or semi-anechoic chamber.

Despite the widespread use of scale brass models during the design process, there are undeniable disadvantages [7]. One of them arises from the fact that they are handmade, using bend or twisted metal plates that have been welded together. A single model on the scale of 1/50 takes about four months to be finished, and it has a very high economic cost. Another of the drawbacks is that the ideal design of the vessel is used to create the scale model but, unfortunately, this initial design experiments a lot of modifications during its construction process. Any change entails modifying or rebuilding the scale model, which inevitably leads to a slow and expensive process. Hence, certain changes are oftentimes omitted such that the final installed versions of the antennas and other topside elements significantly differ from those used to create the scale model.

As previously mentioned, EM numerical simulations involve dense and complex shipboard environments, becoming extremely demanding in terms of computational resources (both memory and CPU time). In recent years, there have been increasing endeavors to achieve rigorous solutions for extremely large electrodynamic problems. The development of fast and efficient algorithms has gone hand-in-hand with the constant breakthroughs in computer science and technology. Modern high performance computing (HPC) systems provide the scientific community with unprecedented computational resources (meaning large amounts of memory and parallel processors). In this context, parallelized implementations of the fast multipole method (FMM) [11] and its multilevel version, the multilevel fast multipole algorithm (MLFMA) [12], [13] have been extensively applied to expedite the iterative resolution of the large and dense matrix systems resulting from the application of the integral-equation formulations and the method of moments (MoM) [14], showing their ability to solve large problems that were unattainable in the past decades [15], [16].

Thus, in this new scenario the EM simulation has become a necessary complement or even an essential alternative to scale models. Nowadays, it is possible to simulate a real complex electromagnetic environment involving the whole set of radar, communication, and electronic warfare systems placed in the topside of a modern ship. This allows the integrated topside design (ITD) engineer to handle important electromagnetic issues (EMC, EMI, EMR) in the early stages, prior to the physical placement of the systems onboard. Moreover, the assessment of the influence of any design modification using simulations on a virtual model instead of the scale model results in evident cost and time savings.

3. EXPERIMENT SETUP

3.1. The ship

The vessel we have used in this experiment is a platform of the Spanish Navy with over 240 meters in length. It is a landing helicopter dock (LHD) class vessel, a new model of warship smaller than an aircraft carrier that can also work as a transport and landing ship. Nowadays many countries are building such a class of ships: USA (WASP class [17]), Australia (CANBERRA CLASS), France (MISTRAL CLASS [18]), and other countries (Japan, China [19] and Algeria [20]).

Figure 1 shows the model discretized with the proper format to carry out the simulations. It is based on the CAD drawing of the vessel provided by Navantia, which is the company responsible for the construction of the platform. The position of the low and medium BB fan antennas under study is indicated in this figure. It can be appreciated that all the transmitting antennas (blue wires in Figure 1) were considered in the model employed for the numerical simulations.

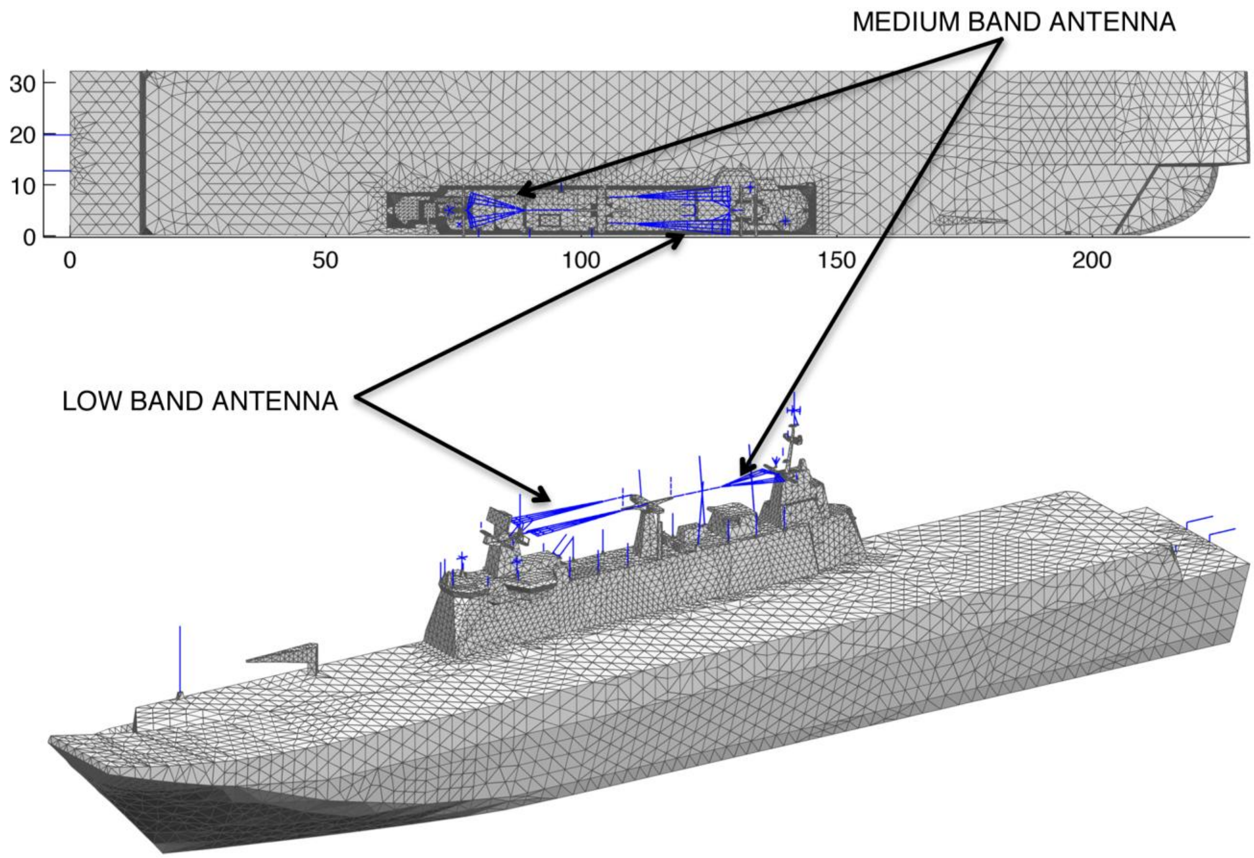

Figure 1. Model of the LHD vessel of the Spanish Navy used in the simulations for validating the antenna designs. The position of the low and medium BB antennas, on which this work is focused, is marked.

3.2. The EM simulation code

The EM tool we have used for the simulations is the M^3 solver, previously named HEMCUVE (hybrid electromagnetic code of the Universities of Vigo and Extremadura) [21]. It is a general-purpose software package for the electromagnetic design and analysis of complex three-dimensional (3-D) electromagnetic engineering problems. This software is the culmination of more than 15 years of research, and its modular and robust development has enabled the inclusion of the most recent advances in computational electromagnetics (CEM). It provides a unified environment to solve a wide range of electromagnetic problems, from radiofrequency to optical frequencies [22]. Typical applications include antenna placement EMC/EMI/EMR analysis and design, radar cross section (RCS) and radar imaging analysis and control of modern vessels, aircraft, satellites, cars and any other kind of complex platform. M^3 also incorporates an impedance matching unit optimizer [23] that can be fed with simulated data or with impedances measured at the antenna terminal. The electromagnetic kernel of the code is based on the well-known surface integral equation-method of moment (SIE-MoM) formulation, which is a full wave solution of Maxwell's equations in the frequency domain for piecewise homogeneous problems. Its accuracy and versatility have made it the most usual reference solution for scattering and radiation problems in CEM. Indeed M^3 solved some of the largest problems in CEM up to date (the last one with more than 1 billion unknowns [24]) using supercomputers at CESGA and CenitS Spanish supercomputing centres. Due to the consecution of these challenges the software was awarded with the Partnership for Advanced Computing in Europe (PRACE) Award 2009, and the Intel Itanium Solutions Alliance Innovation Award 2009, in the category of Computationally Intensive Applications. Otherwise, the efficiency, versatility and reliability of M^3 have also been demonstrated in many published works ([22] , [24]- [27]).

The software package was used to obtain different output calculations required to carry out diverse essential tasks in the framework of the project:

- Voltage Standing Wave Ratio (VSWR) [28] [29] calculations. The VSWR is a measure that numerically quantifies how well the antenna is impedance-matched to the transmission line it is connected to. It is a real and positive number and its minimum value is 1, which implies that no power is reflected from the antenna (ideal case). The design criterion for the BB fan antennas is based on the fulfillment of VSWR lower than 3.
- Mutual coupling calculations. These results are indispensable for the EMI/EMC analysis and can be interpreted as a first validation of the antennas' design and their emplacements, which were initially restricted to a reduced set of possibilities.
- Electric and magnetic field levels. These computations are required to study and guarantee the fulfilment of the regulations on hazard of EMR, HERP, HERO and HERF, depending on the case (see Figure 2).
- Matching units' design. The goal of the antennas' initial design stage is to find a radiating structure, which, together with a viable matching network, meets the design requirement of VSWR < 3. In order to yield feasible matching unit designs, with an implementation complexity as low as possible, appropriate limitations to the values of the circuit elements are imposed according to the commercial availability of component

- values. Importantly, only reactive elements and transformers are used. Resistive elements are discarded due to their impact on the system efficiency. It must be noted that the above requirement, together with the imposition of VSWR < 3, poses a very demanding design criterion.

  Subsequently, once the antenna is installed on the real platform, the matching network design is adjusted by feeding the M^3 matching unit module with real data. The measured input impedance is used in place of the simulation data to take into account the final real condition of the vessel.

  The two-step procedure described above, by jointly designing the antenna and its unit through intensive simulation, and finally adjusting the design of the matching network on the basis of the actual measurements, ensures the achievement of optimized (and more simple) antennas and matching units in compliance with the specifications.

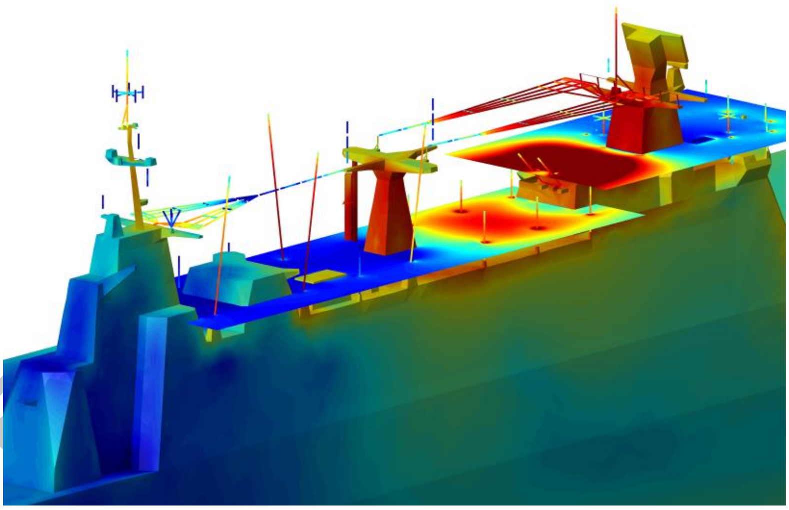

Figure 2. Electric field level on cut planes representing personnel transit zones and surface current distribution corresponding to the low band antenna.

Remarkably, the experience in using M^3, extracted from this project and further works, indicates us that the deviations observed between the M^3 predictions and the onboard measurements are usually closely-related with superstructure changes not included in the simulations, external metallic elements (harbor measurements) or onboard elements that are not part of the vessel such as scaffoldings or containers.

3.3. The antennas

We were responsible for the BB HF antennas onboard the ship of Figure 1: one BB double whip and two BB fans. A commercial twin whip antenna covering the upper band (15 to 30 MHz) was optimized in length, feeding and emplacement, while the two fans covering the low (2 to 5.5 MHz) and the medium (5.5 to 15 MHz) bands were designed ad-hoc for this vessel using M^3. The large wavelength involved in the HF band results in strong electromagnetic couplings between fan antennas and structural elements such as masts, intake/uptake stacks and cranes. This is a critical issue that demands specific designs of fan antennas for each platform. The location and final design of the BB fan antennas for this vessel can be seen in Figures 1 to 4.

Fan-type antennas are the most frequently used type of BB HF antennas. They are primarily suitable for low HF ranges, in particular for the low sub-band (2 to 6 MHz) and the medium sub-band (4 to 12 MHz). The interactions with the superstructure may lead to strongly mismatched impedances and to a deterioration of the antenna performance. Owing to this reason and due to the previously mentioned space constraints and the high number of systems operating simultaneously in a military vessel, the integration of HF fan antennas becomes a challenge.

3.4. Scale model measurements

The first step was the selection of the optimal scale factor for the scale model. Taking into account that the vessel length is over 240 meters, a scaling factor of 1/50 was chosen so as to obtain an accurate model of the superstructure. The part under waterline is not modeled since the sea is the ground plane [6]. All in all, the resulting model was 4.8 meters long, suitable to be measured into an anechoic or semi-anechoic (the absorbent of the floor can be removed) chamber. The Radioelectric Measurements Laboratory (LMR) of the University of Vigo, with a semianechoic chamber of dimensions 9 meters (width) x 7 meters (long) x 7 meters (high), was used [30]. According to the scaling factor of 1/50, the corresponding scaled frequency range for an extended HF band (2-30 MHz) is 0.1-1.5 GHz [31]. The absorbers of the anechoic camera can work in this frequency range.

As shown in Figure 3, the designs of the low and medium band fan antennas (obtained after the M^3 optimization) were added to the scale model in order to make the measurements in the semi-anechoic chamber. All the transmitter HF antennas in the model were isolated and connected with 50 ohms coaxial cables. The antennas that were not under test were loaded with 50 ohms. The whole model was placed on the floor of the semi-anechoic chamber to guarantee the ground plane representing the surface of the sea. The measurements were focused on the antenna impedance, which is the main factor that determines the performance of the antenna and consequently its real bandwidth. The coaxial cable of each HF antenna must be previously calibrated, such that the input-impedance of the antenna without the transmission line is known.

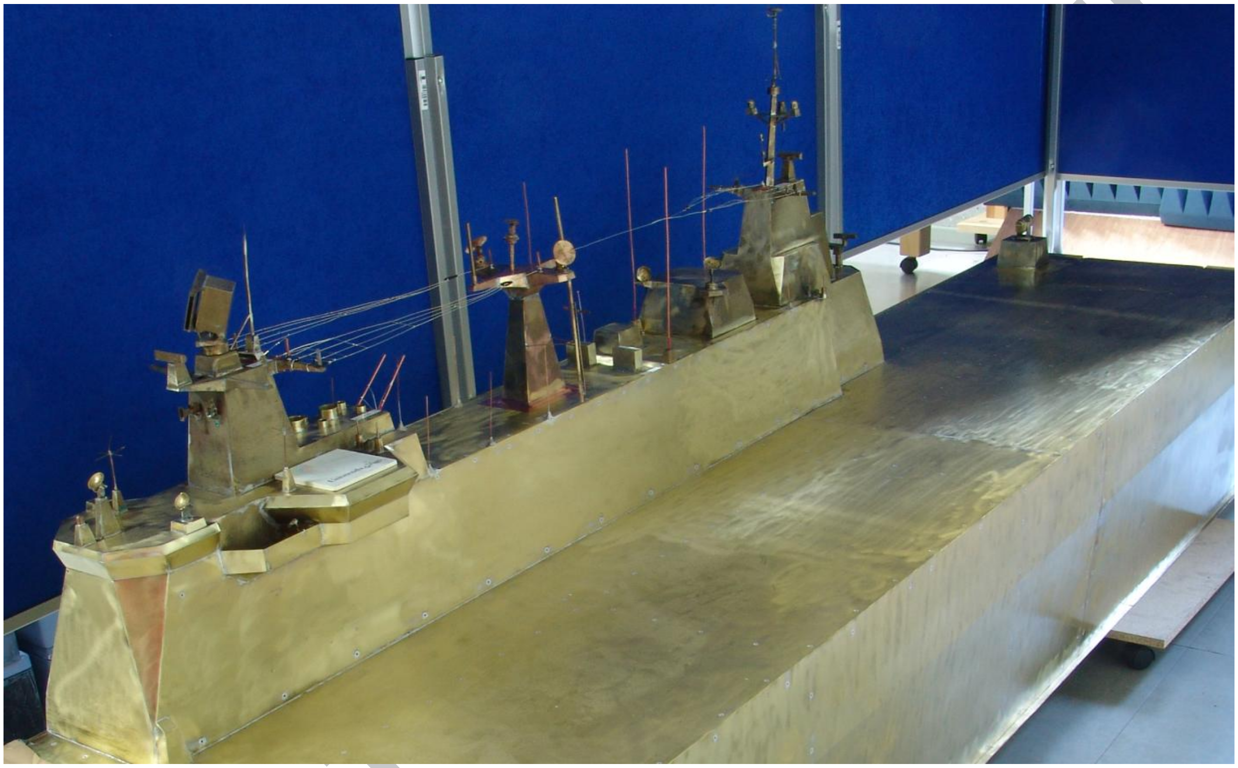

Figure 3. Scale model used in this work with the low and medium band antennas' design implemented.

A calibrated network analyzer PNA E8361A by Agilent Technologic covering the range of 10 MHz to 67 GHz was used. The HF antenna cables come out through a hole in one of the sides of the hull. This ensures a good electric connection between the woven of the coaxial cable and the model superstructure, which is the ground plane for all the antennas. The connector join was mechanically made to have a suitable mechanical resistance. All the 50 ohms HF lines are coiled inside the superstructure. The only line coming out through the whole is the one needed to proceed with the measurement, which is managed by an external computer connected to the network analyzer via a local area network (LAN). All of these details are very important to ensure the adequate conditions for the measurements.

3.5. Onboard measurements

After the EM software validation and the scale model measurements, the low and medium band antennas were built and installed in the real platform. This work was done by Rohde & Schwarz and Navantia according to the final designs achieved by M^3. The result of the antennas' assembly can be observed in Figure 4. The two fan antennas were measured onboard with a network analyzer Agilent HP 8753E. Each transmission line between the triplexer output and the feedline of both antennas was characterized to eliminate the cable influence of the registered data. The measurements were carried out with the ship sailing, given that this reflects the real operational situation, with high transmission power and far away from buildings, cranes, civil population, etc.

(a)

(b)

Figure 4. Real platform: (a) Low (right side of the image) and medium (left side of the image) band fan antennas after their installation. (b) Low band antenna (inset: detail of the feeding point).

4. RESULTS

The measurements carried out onboard the real platform are compared in this section with the results obtained by the M^3 simulations and with those obtained after measuring the scale model in semi-anechoic chamber. For each antenna, the VSWR versus frequency is plotted, in addition to the S_{11} complex parameter in a Smith chart.

The results of VSWR and S_{11} corresponding to the low band antenna are depicted in Figures 5 and 6, respectively. Observing these figures, it can be appreciated that the measurements from the scale model differ slightly from the other two results corresponding to the measurements on the real platform and those derived from the simulations with M^3, especially for the higher frequencies of the sub-band (from 4.5 MHz to 5.5 MHz). However, there is a better agreement between the solution predicted by M^3 and the real antenna behavior described by the onboard measurements, which, obviously, can be taken as the reference result in this comparative study.

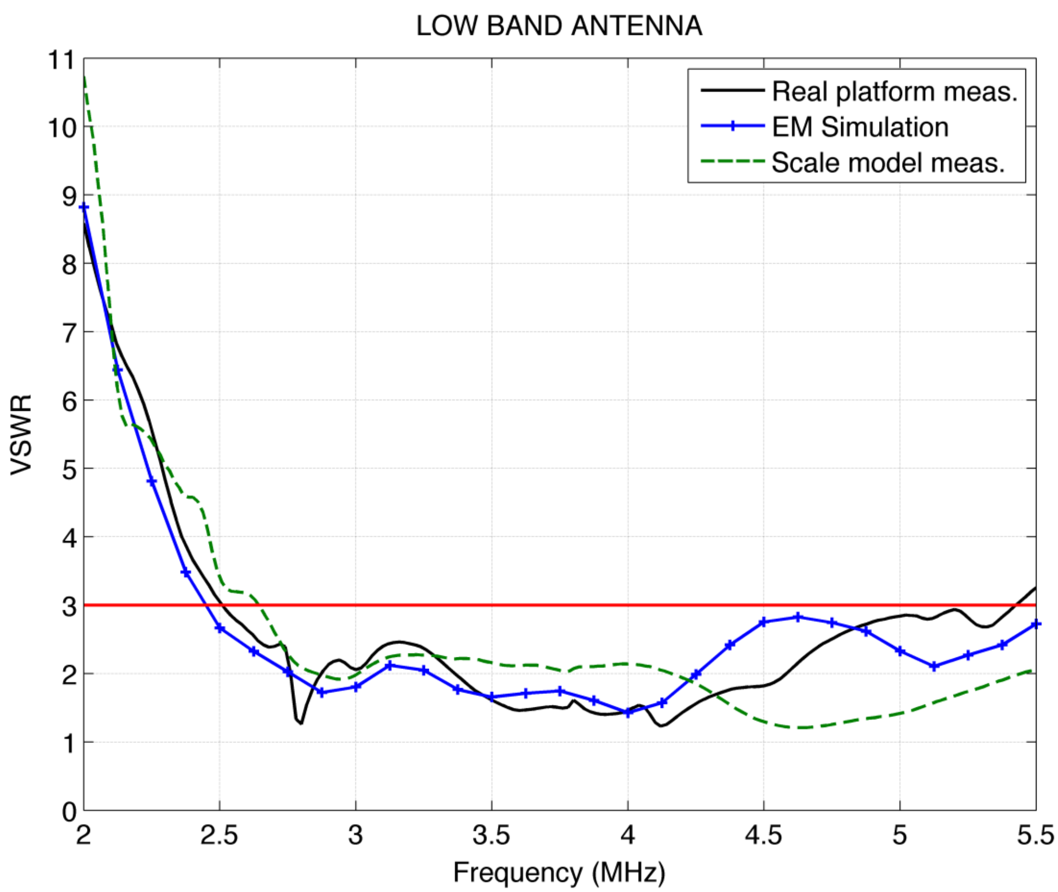

Figure 5. VSWR of low band antenna: real platform measurement (black solid line), EM simulation (blue line with marker +) and scale model measurement (green dashed line).

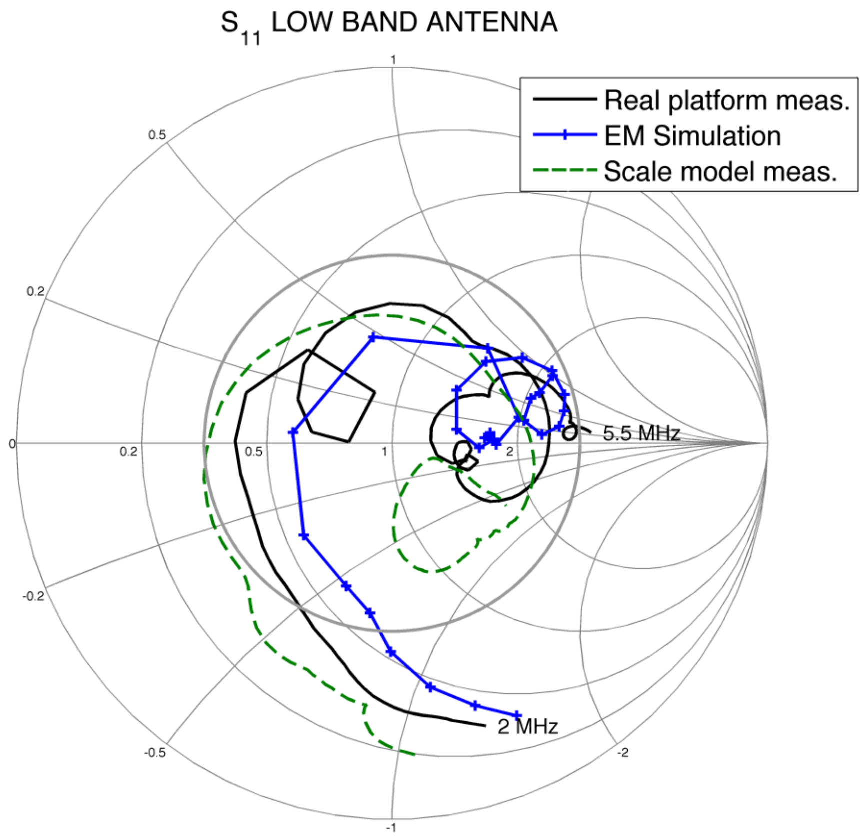

Figure 6. S_{11} of low band antenna: real platform measurement (black solid line), EM simulation (blue line with marker +) and scale model measurement (green dashed line).

For the medium band antenna, the VSWR and the S_{11} parameter are shown in Figures 7 and 8, respectively. The results indicate that both the simulation predictions and the scale model measurements differ slightly more from the real antenna measurements for this band than for the low band. The discrepancies are mainly given by the influence of some superstructure modifications subsequent to the last simulations. The mentioned influence of the superstructure elements in the antenna frequency range became clearly apparent after the large number of tests done (with both scale model measurements and numerical simulations) to assess the impact of small changes in the BB antenna behavior in the course of the project development. The antenna mechanical tension is especially important, as well as the elements surrounding the antenna and its feeder, such as the HF whips which have physical lengths comparable to the wavelength of the antenna's operation range. In spite of the perceptible differences, the Smith chart S_{11} representation of Figure 8 clearly shows that the M^3 result fits the real measurements curve satisfactorily and more accurately than the scale model measurements.

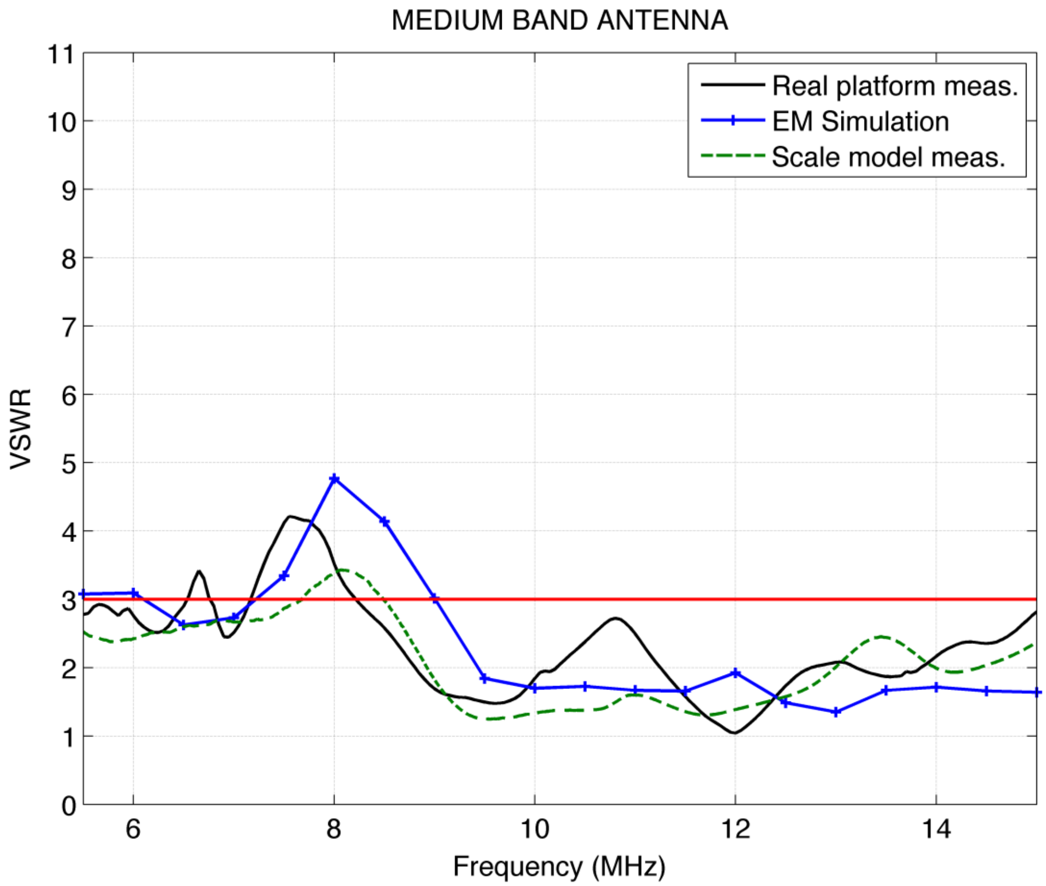

Figure 7. VSWR Medium Band Antenna: real platform measurement (black solid line), EM simulation (blue line with marker +) and scale model measurement (green dashed line).

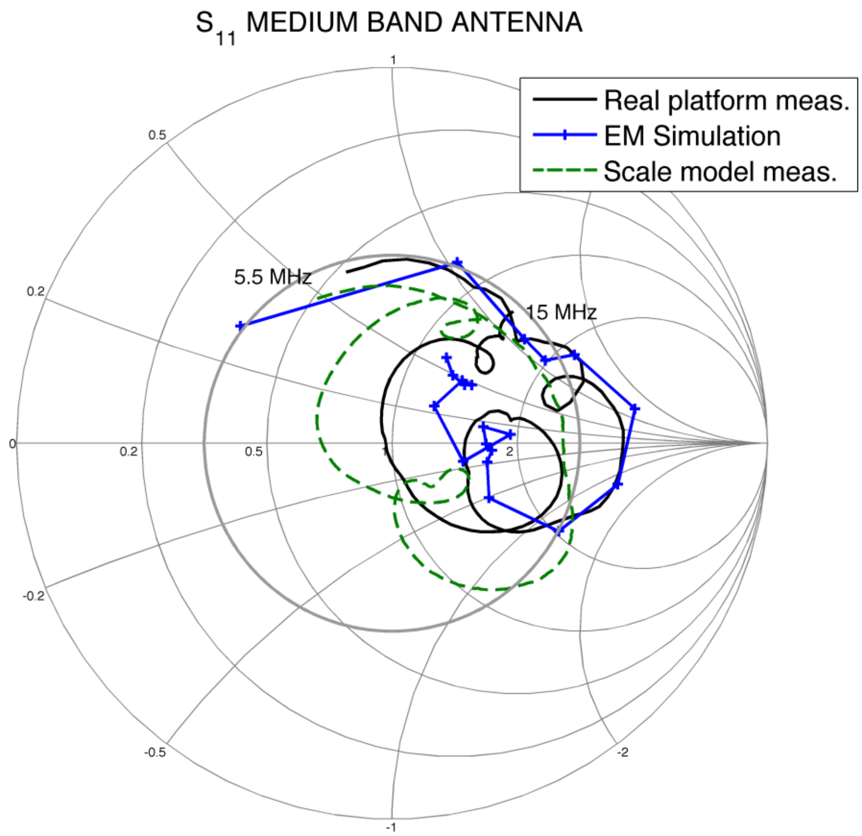

Figure 8. S_{11} of medium band antenna: real platform measurement (black solid line), EM simulation (blue line with marker +) and scale model measurement (green dashed line).

Once the antennas were installed and measured on the vessel, these real measurements were used to feed the M^3 matching unit optimization module. The optimized designs of the matching units provided by the M^3 code were implemented and mounted onboard for each antenna and new measurements were carried out. Figures 9 and 10 show the comparison between the measurements completed before and after the installation of the matching units for the low and medium band antennas, respectively. Figures clearly illustrate that both matching units provide full compliance with the VSWR specifications.

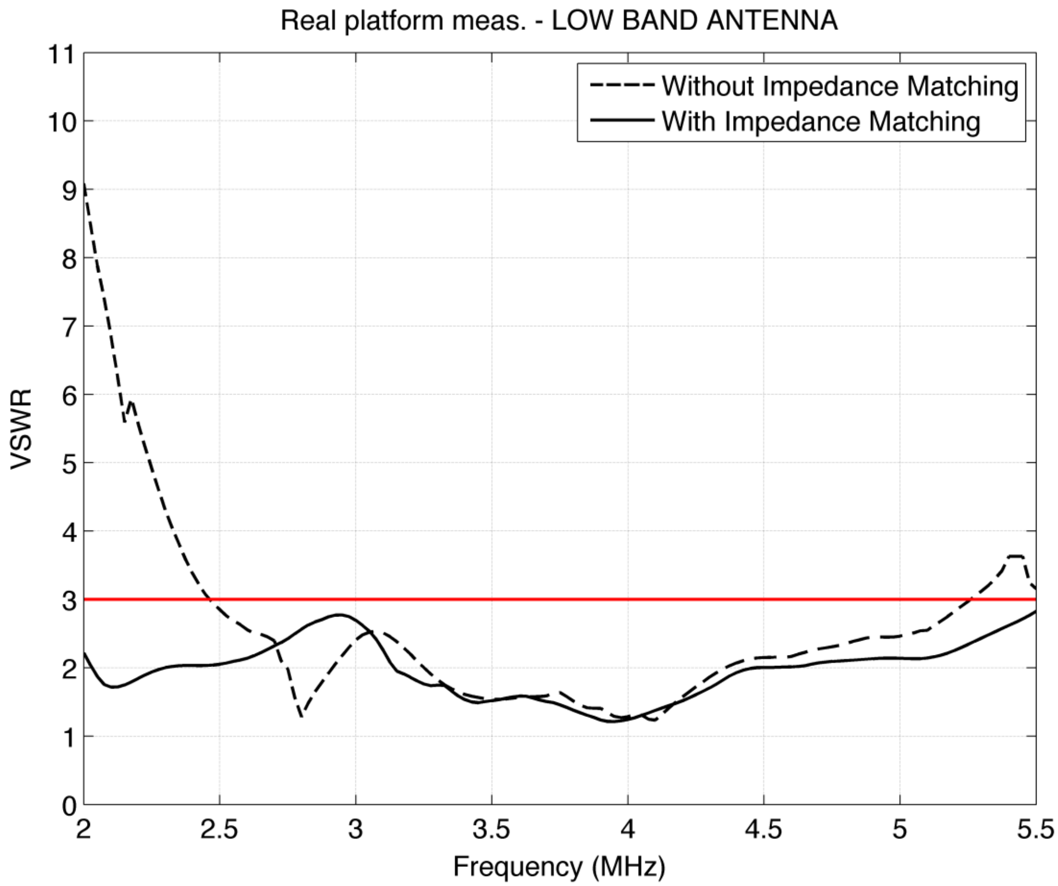

Figure 9. VSWR of the low band antenna with (solid line) and without (dashed line) impedance matching.

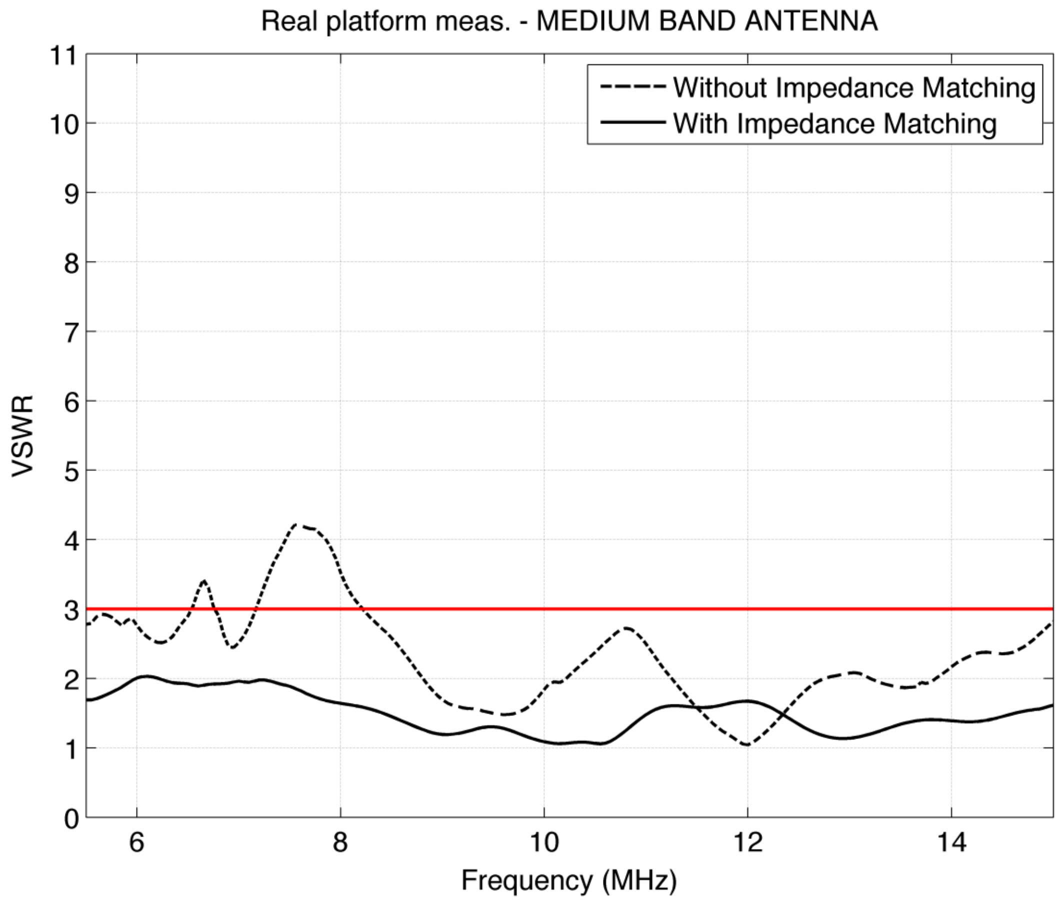

Figure 10. VSWR of the medium band antenna with (solid line) and without (dashed line) impedance matching.

5. CONCLUSIONS.

A complete HF-BB-antenna design experience has been described in this paper. The work was developed during the construction of a Spanish Navy vessel. The design of the BB fan antennas and their matching units was done using the M^3 software package developed by part of the authors linked to the Universities of Vigo and Extremadura. The preliminary designs given by M^3 were implemented on a scale model, which was measured in a semi-anechoic chamber. The measured data was compared with the results obtained with the M^3 simulations. In order to provide a definitive validation, measurements were successfully performed onboard after the fabrication and installation of the final designs.

Results have shown that the use of a simulation code for the design of HF broadband antennas is easier, faster, cheaper, more versatile and more accurate than the use of scale models. The ability of the code to take into account structural or design modifications that arise throughout the development of the global project is a key issue. Thus, the results indicate that building a scale model is actually unnecessary whenever a simulation code with the demonstrated accuracy, reliability and efficiency of M^3 is available.

The successful experience allowed us to participate in later programs developed by Navantia for building Offshore Patrol Vessels (BAM), AOR logistic ships (BAC) and the F-105 frigate for the Spanish Navy. In these projects, the design process was carried out in its entirety without resorting to the scale model, by solely running the M^3 software package, the advantages of which became readily apparent both time-wise and money-wise.

6. ACKNOWLEDGE

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Highlights

Validation of software for high frequency and low and medium band antenna design.
Electromagnetic simulation as an option to scale models for antenna design.
Simulation tools properly handle any modification of the platform’s structure.
Suitable electromagnetic simulations result cheap, fast, versatile and accurate.
Simulations aid to include electromagnetic constraints from very early design stages.