The Impact of Vertical Structures on Ship Radar Cross Section in the High Frequency Range

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Abstract **–** The monostatic and bistatic Radar Cross Section (RCS) of various complex ship targets are numerically simulated in the High Frequency range of 3-20 MHz. The process by which these complex ship models are built and simulated using the FEKO code is described. Validation of the simulated RCS against full-scale measurements is described. Details are added to the ship model and the changes in the bistatic RCS are explored. Bistatic data from the simulations are used to assess the performance of a pair of surface-wave radar stations operated in a bistatic mode. The results of these findings will be of importance to future RCS simulation work using numerical modelling.

I. INTRODUCTION

High Frequency Surface Wave Radar (HFSWR) operates in the High Frequency (HF) band between 3 and 30 MHz. Capitalizing on the conducting properties of the ocean, the radar's vertically-polarized surface wave propagates well beyond the visible horizon, by following the curvature of the earth. HFSWR is increasingly seen as an attractive, cost-effective means in providing near-real time monitoring for Beyond-the-Line-Of-Sight (BLOS) surveillance applications over large areas of sea surface [1].

Bistatic HFSWR potentially offers better coverage than a monostatic system as the ionospheric clutter may appear farther away in the bistatic configuration [2]. The reduction of any Electromagnetic Interference (EMI) to other HF users is an important factor in the densely-populated HF frequency band. There is the potential to reduce the EMI susceptibility when utilizing the spectrally-efficient Frequency Modulated Continuous Wave (FMCW) method of transmission. This mode of transmission can only be supported through a sufficient separation between the transmitter and receiver, which represents a bistatic configuration. The performance of bistatic HFSWR for coastal surveillance is currently being investigated. As part of this investigation, it is desired to estimate the Radar Cross Sections (RCS) of certain Targets of Interest (TOI). This paper describes some of the ship models that were built for simulation in the 3-20 MHz range, and describes the behavior of the bistatic RCS as topside detail is added.

Very little has been published in the open literature with regard to ship RCS. As a rough approximation, the monostatic, free-space RCS of vessels is often given by the empirical formula [3],

$$\sigma = 52 f^{1/2} D^{3/2} \tag{1}$$

where σ is the RCS in square meters, D is the full-load displacement of the vessel in kilotons and f is the radar frequency in Megahertz. This relationship was based on measurements of various ships at low grazing angles in the X, S and L bands, of bow and both port and starboard quarter aspects, to produce the median RCS of those aspects. It was later used as a rough approximation for the HF range [4], where the ratio of the target dimensions to the wavelength signifies that the RCS values fall in the Rayleigh or resonance (Mie) regions [5]. As was proven in [6], the rough estimate of equation (1) does not account for vertical resonators such as ship masts, cranes and antennas, which can significantly impact RCS values. These structures are especially important in HFSWR scattering and they often are aligned with the vertically-polarized electric field vector used in HFSWR.

The monostatic RCS of ship targets in the HF band has already been researched and observed, in [5, 6], through the use of numerical techniques, which is an effective means of exploring the behavior of scattering from complex targets such as ships. The work in [5] highlighted the potential impact on monostatic RCS of vertical wires on a complex target, when they are of resonant lengths at the operating frequency. It showed that components up to the third order of resonance can have a significant influence on the monostatic RCS. The present work reports the bistatic RCS of similar complex targets illuminated by an HFSWR.

This research uses models that have been built with CAD FEKO [7], which computes ship RCS using the Method Of Moments (MOM) [8]. The *Bonn Express* (~36000 ton) of Fig. 1 and the *Teleost* (~2400 ton) of Fig.

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2 were used as sample complex targets. As described in the following, models of these ships with increasing levels of detail were built and analyzed with the FEKO program. Monostatic RCS predictions from the models were validated by comparing with the measured RCS of these ships, available from an actual HFSWR. The models were then used to explore the behavior of the bistatic RCS, and the influence of vertical, conductive components of the vessel such as antennas, crane wires, and masts on the RCS.

Fig. 1. The Cargo Vessel *Bonn Express.*

Fig. 2. The CCGS *Teleost.*

II. MODELING PROCEDURE

When modeling Rayleigh-region targets, such as a ship much smaller in size than the wavelength in the HF band, a simple representation can be applied and few details are required. Indeed, equation (1) uses no detail at all except for the ship's displacement. However, as size of the ship approaches the resonance region, details such as vertical, conductive components can have a strong influence on the RCS returns and should be included in the model. This work uses detailed wire-grid models of the ship targets and solves them with the FEKO program.

All the models were composed of Perfect Electric Conductor (PEC) material and designed using reference information, which included actual ship's drawings, when available, to accurately represent the target's geometry. Meshing was applied such that edges and segment lengths were approximately $\lambda/10$ long at the highest tested frequency. For instance testing was conducted such that the 3-20 MHz range was separated into three sub-ranges, 3-10 MHz, 10-15 MHz and 15-20 MHz. Therefore meshing was set in accordance with 10, 15 and 20 MHz respectively. The number of unknowns that FEKO used for meshing is much larger at 20MHz than at 15 or 10 MHz, so a substantial saving in simulation time is achieved by using sub-ranges. The wire radius was set to be approximately equal to the segment length divided by 2π [5]. Models were attached to an infinite PEC ground plane to simulate a flat, conductive ocean surface. This feature was used as a method of accounting for the scattering influences from the targets image and any potential coupling. Vertically polarized, low grazing angle, incident plane waves were utilized to find the 360^o XY-plane scattering returns at 2^o intervals. All the simulations described were conducted at 1 MHz intervals from 3 to 20 MHz. The solutions used MOM with Combined Field Integral Equations (CFIE), instead of Electric Field Integral Equations (EFIE), to avoid potential internal body resonance impacts on the collected data [9].

Simulation models to be solved with the FEKO program were built for the freighter *Bonn Express*, shown in Fig. 1, and the Canadian Coast Guard Ship (CCGS) *Teleost* in Fig. 2. These targets were of primary interest because a set of measured RCS data was available from an actual Surface Wave Radar [6]. This set of measured data was used to validate the models.

Various different models were built for each ship that included increasing amounts of topside detail. The RCS from the simulations was then compared to the measured RCS, as described below. The agreement showed that the simulation models predicted monostatic RCS values that corresponded well to the measured data and so validated the models. The same simulation models were then used to study the bistatic RCS of these ships.

The *Teleost* was used to explore the monostatic-to-bistatic RCS returns relations, as detailed ships drawing were available to allow a realistic simulation model to be built. Figures 3(a), (b), and (c) show the basic, intermediate, and most detailed models used to represent the *Teleost* in this work.

III. VALIDATION RESULTS

All three of the *Teleost* models predicted monostatic RCS values that compared extremely well to the measured, full-scale RCS. There was generally a difference of no more than a single decibel when compared individually at each tested aspect and a difference of about 0.7 dB on average [10]. When the results were summarized, the detailed model of Figure 3c had only a slight advantage over the simpler models. For instance the measured RCS for stern incidence was 40.5 dBsm. The basic, intermediate and detailed models resulted in 41.76 dBsm, 40.70 and 40.49 dBsm respectively.

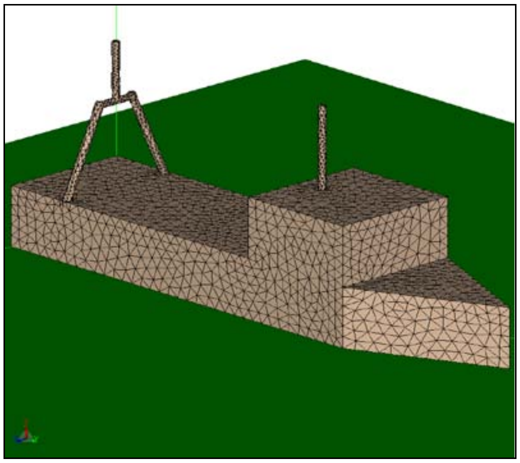

Fig. 3(a). The Basic *Teleost* Model.

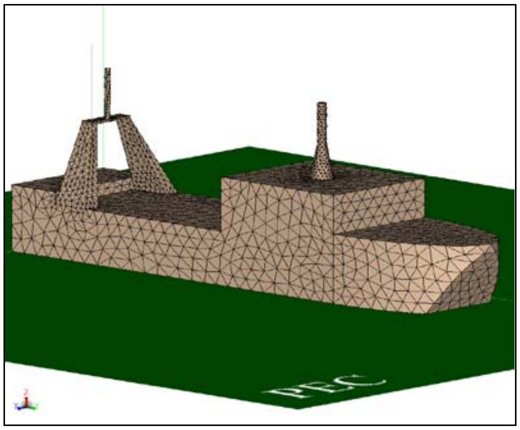

Fig. 3(b). The Intermediate *Teleost* Model.

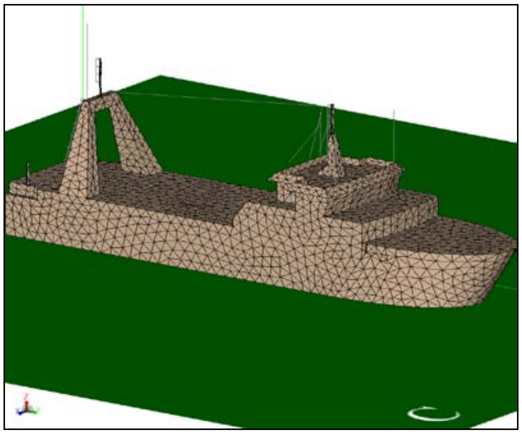

Fig. 3(c). The Detailed *Teleost* Model.

Figure 4 shows one of the *Bonn Express* models, which was comparable in the level of detail to the basic *Teleost* model. The simulated monostatic RCS of the *Bonn Express* models did not compare as well to the measurements as found in the *Teleost* models, but the results were still considered to be acceptable. The different models varied showing an average difference of 1-2 dB, with an even higher variation found when comparing individual aspects. As more detail was added to the models, the more significant was the variance in the RCS returns. Indeed the best *Bonn Express* results came from the simplest model used with the addition of forward and after masts, as seen in Fig. 4. It was found that without the addition of these masts there was an average difference of 11.65 dB when compared to the measured data and a maximum difference of 19.28 dB when compared around a testing aspect of 130-135^{o}. When the model was modified to include the masts the values improved dramatically to an average difference of 3.53 dB and a maximum difference of 5.41 dB. The presence of vertical scattering points on the ship models could be observed using POST FEKO, by looking for high concentration of currents formed on current on edges and vertical masts. The relatively good agreement of all these results to those of experimental data gave us the confidence that the models provided a sound basis to explore bistatic RCS behaviour.

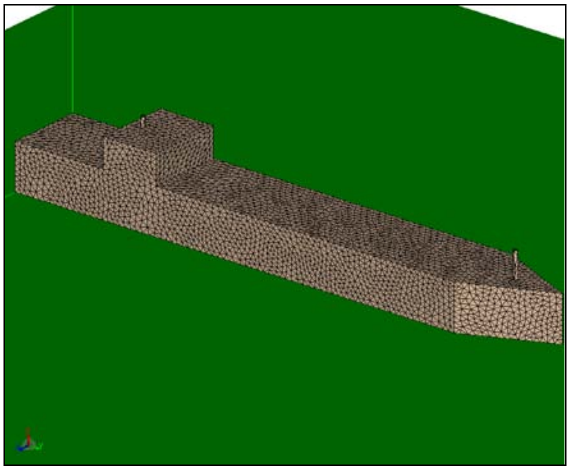

Fig. 4. Bonn Express with added masts.

Since no measured bistatic RCS values were available, to test the validity of the ship models constructed for analysis with the FEKO code, similar models were built to be solved with the NEC program [11]. Like FEKO, NEC uses a moment-method solution to find the currents on the wires of the ship model, but the details of the formulation are very different, and so an agreement of the simulations with NEC and FEKO is a good measure of validity. The bistatic RCS was compared for incidence on the stern and on the bow, and for broadside incidence of the plane wave, and in each case the bistatic RCS was calculated at 30° intervals. NEC and FEKO were in good agreement for the bistatic calculation, with a maximum deviation of 0.22 dB in the values and an average difference of 0.19 dB. This was better than the agreement between the methods for the monostatic case. The simulation models were then used to study the bistatic RCS using the FEKO code.

IV. BISTATIC RCS

This section examines the bistatic RCS of the *Teleost* models of various complexity. All three of the *Teleost* models gave similar monostatic RCS values for each of the different tested aspects. The basic *Teleost* model, Fig. 3(a), being symmetrical, produced the same RCS results for both the starboard and port broadside aspects. Very few actual ships share this design feature. The intermediate and detailed *Teleost* models of Fig. 3(b) and 3(c) respectively are unsymmetrical, giving rise to different monostatic RCS from the port and starboard sides, which is similar to the behaviour of the measured RCS values. The intermediate and detailed *Teleost* models provided the unique scattering detail for these complex targets that could be used to establish the target's orientation by matching the returns to the experimental RCS data.

The bistatic returns from the three *Teleost* models differ in the location and size of maxima and nulls as the bistatic angle varies. This was noted to occur at every frequency throughout the 3 - 20 MHz test range. For example, Fig. 5 shows the bistatic RCS of all three *Teleost* models for starboard broadside incidence at 18 MHz. Nulls at 90 degrees and 240 degrees differ by as much as 20 dB. Some peaks, such as those noted at 75 and 290 degrees, show deviations as large as 8 dB, which is not as much difference as in the nulls. Slight changes of a couple of degrees in the angle of the peaks and nulls were noted as well. At other frequencies, generally the monostatic returns were comparable for the three models for bow, stern and broadside incidence, whereas the bistatic returns showed strong variations in the size of nulls and peaks and small changes in the angles of these features.

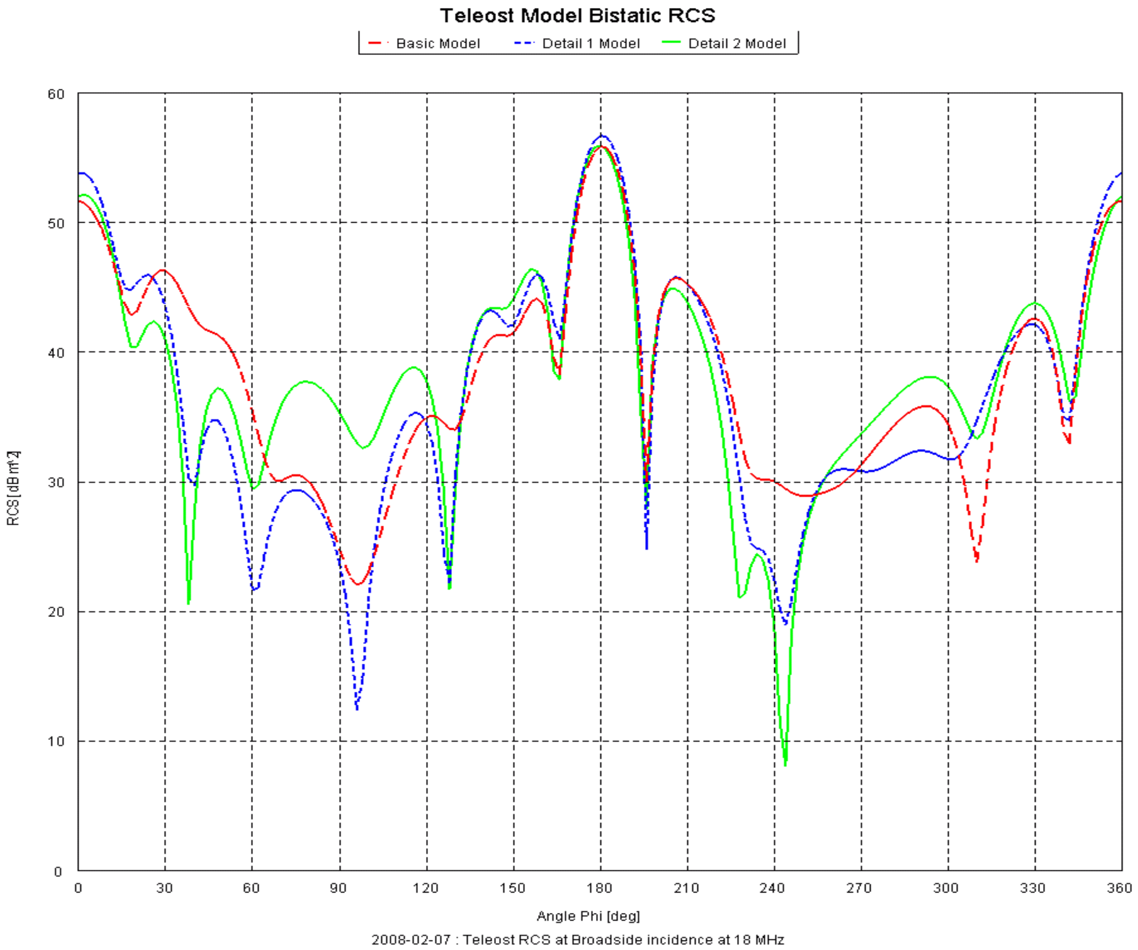

Fig. 5. Teleost models bistatic results.

The nature of the bistatic RCS fluctuations suggests that multiple receivers in for this type of HFSWR would be optimal. This arrangement would provide consistent coverage, as the different receivers would monitor different bistatic angles to offset when any one antenna was experiencing a null. This configuration has potential for classification and even identification purposes as well.

V. CURRENTS ON THE SHIP MODELS

Some features of the RCS of a ship model can be directly related to the currents flowing on the surfaces of the ship, and on the masts and other topside features. The FEKO code can be used to examine the surface currents, shown for the *Bonn Express* model at 18 MHz for bow incidence in Fig. 6. The 236m *Bonn Express* is 14 wavelengths long at 18 MHz, and when the vessel is many wavelengths long, currents tend to concentrate on vertical edges. The masts on the bow of the ship and on the top of the deckhouse also carried strong RF currents, which was typical of all the ship targets tested. As an observation of this trait Fig. 7 shows the current on the *Teleost's* mast, located on top of the deckhouse, illuminated at starboard broadside incidence at 3 MHz.

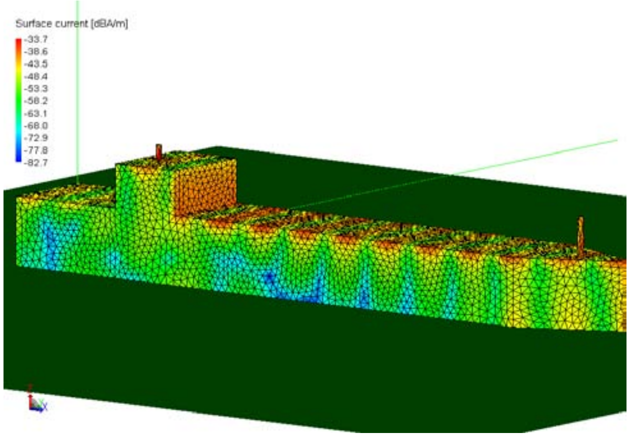

Fig. 6. Bonn Express with vertical scatters along the vertical edges, masts and sides.

Each of these concentrations forms a vertical scattering point on the ship. Interference of the fields scattered from the various edges and masts is what influences the nulls and peaks of the bistatic RCS pattern. Vertical edges are longer in terms of the wavelength with increasing frequency and gain in importance. The bistatic angles of the nulls in the scattering pattern changes with frequency and angle of incidence of the plane wave and characterize the ship. These unique RCS signatures from a sample of different aspects suggest a strong potential for applications such as vessel classification or even identification.

In many situations, such as that in Fig. 6, the plane wave induces large currents on the ship, which are seen across the horizontal portion of the deck and edges. It is important to note that these horizontal "deck" currents do not radiate a vertical component and are quickly attenuated by the ocean. They do not contribute to the peaks-and-nulls in the bistatic RCS that would be observed by receivers in the horizontal plane.

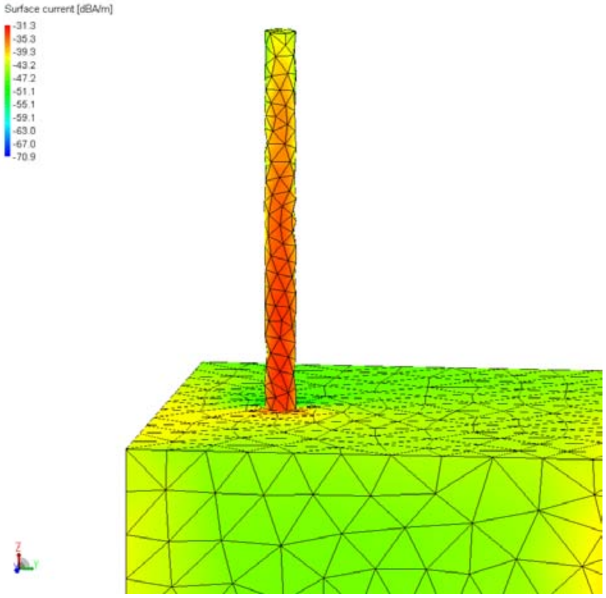

Fig. 7. Current concentration along modeled masts and vertical edges of the *Teleost* basic model.

V. CONCLUSION

The close agreement of the simulation results to the available measured data for monostatic RCS suggest that the MOM numerical technique implemented in the FEKO code is quite accurate for the computation of the RCS of ships in an HFSWR environment.

The scattering results found through this work were consistent with that in [5, 6]; however, it was also observed that the inclusion of potential resonators, such as masts, antennas and thin metal structures with a vertical component, were even more important factors in the overall bistatic RCS than that of the monostatic case. This is understandable, particularly when the mast or other structure approaches a resonant length. Such features had a greater impact on the number, position, intensity and sharpness of nulls in the bistatic RCS patterns than for monostatic RCS patterns, even for non-resonant wavelengths. These findings suggest that bistatic HFSWR configurations could be used to better accomplish such goals as target classification and potentially identification.

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