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PERSPECTIVES OF HF HALF LOOP ANTENNAS FOR STEALTH COMBAT SHIPS

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Abstract—Based on technical analysis and budget link experimentation, the main purpose here is to show improvement of HF half loop antennas in terms of signal-to-noise ratio (SNR) and stealthy for a combat ship. A special designed HF antenna brings a high quality communication over 1000 NM. A suitable integration of a HF half loop antenna at ship corners contributes to the ship stealthy. This paper shows the antenna performance and the benefit of the completely body integrated HF half loop antenna regarding whip antennas. The corresponding SNR is 15 to 20 dB better than for a conventional antenna.

1. INTRODUCTION

High frequency (HF) loop antenna is the perfect solution to guarantee communications on the battlefield for harsh environment conditions when satellite communications are not available. During navy maneuvers, HF communication systems aboard a ship shall allow radio links from off-shore to other ships and overseas ground stations.

With the advent of network centric capabilities (integrated combat management, navigation, communication, platform management and video surveillance systems) and the sophistication of the on-board electronic and radiating devices, modern ships are increasingly exposed to damages and risks of mission failure induced by the electromagnetic (EM) phenomena. To increase the future platform capabilities, the latter were largely studied by the scientific community. Indeed many solutions are available by radio engineering such as compact and broadband antenna, integrated RF architecture, material development and software helps.

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The aim of this article is to show the different reliability, flexibility, stealthy and radio-frequency (RF) enhancements of a novel HF antenna design which can satisfy the modern combat systems requirements.

To carry out this task, loop antenna is used to provide more reliability and flexibility whereas its integration in the ship structure offers further stealthy and RF enhancements.

When the High Frequency band is of interests for antenna integration aboard, that standard techniques are faced to radio-systems as well as ship dimensions due to the high power emissions and some generated intermodulation.

Here below are proposed a review of the general E.M. constraints meet when a HF antenna system is integrated on ship. The innovative solution named "HF deck corner loop antenna" developed together by CMN (Constructions Mécaniques de Normandie) shipyard and Cobham Antennas industries will be described. Cobham Antennas has the antenna solution since ten years ago whereas CMN process to antenna integration in the Ship's body. This joint project between Cobham and CMN has been launched after consulting the worldwide military users and radio manufacturers in order to provide a further NVIS [1] and ground wave capabilities without missing the stealth requirement unlike whip, fan wire, discone-cage and towel bar antennas.

2. ANTENNA ARCHITECTURE

Figure 1 shows a typical ship with conventional HF antennas. So, our goal is to efficiently integrate HF antennas on the ship body.

By using the ship structure and taking advantage from the theory of images, half loop antenna can replace a loop one. In this case, the

Figure 1. Typical Patrol Vessel (78 m of length) and theirs HF antennas in red.

half loop antenna is the best performing and most convenient small space antenna available to combat ships today in the HF band starting from 2 MHz to 30 MHz.

Hereafter, an explanation of a COTS half loop antenna which has been developed by Cobham in order to fulfill ground HF communication army's requirement.

2.1. HF Tactical Half Loop Antenna

The Cobham antenna part number 3190-99 is a NVIS half loop antenna designed for tactical and on-the-move with a 150 W power capability.

The antenna is only 90 cm in diameter and integrates a semi-automatic tuning unit with a built-in RFU. All tuning and control voltages are coupled to the antenna through the coaxial feed-line. Fig. 2 shows a schematic of the half-loop antenna.

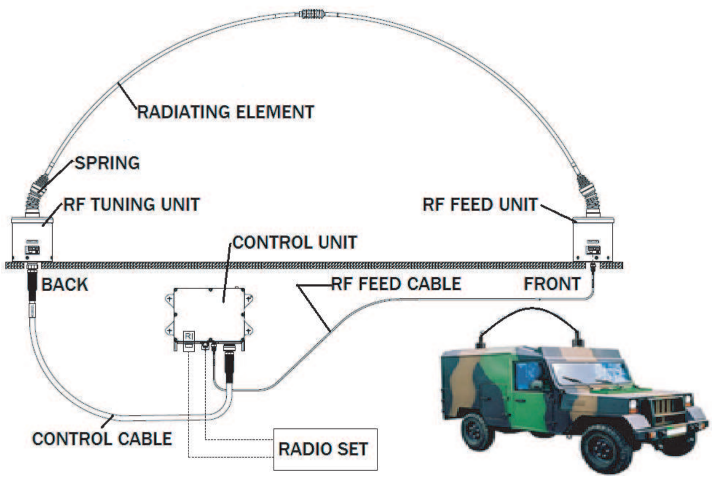

Figure 2. Half-loop antenna schematic mounted on army's vehicle.

2.1.1. Description

The PN-3190-99 HF NVIS antenna, introduced above, was designed for land mobile applications. It is qualified and certified in this context for military environment according to MIL standards.

This half loop antenna is frequency reconfigurable thanks to a set of capacitors used in series. Then, a high selectivity allows the rejection of the unwanted channels such a selective filter. Added to that, there is no external coupler and so no additional power losses.

The capacitors which are necessary to tune the antenna reactance are scaled from 3300 pf to 60 pf at 2 MHz and 12 MHz respectively, with 1.5 pf accuracy at the highest frequency. A logarithmic series of 12 switchable capacitors in parallel are guaranteed with 5% precision to recover each frequency bands of 3.5 kHz [2].

The antenna efficiency was measured over whole operating bandwidth with 57 frequency points referring to a whip antenna.

Its radiation pattern, shown Fig. 3, over a metallic ground plane is quasi hemispheric with horizontal polarization in the broadside direction and vertical polarization at endfires. The typical gain of the 3190-99 antenna is -12 dBi and $+2$ dBi at 2 MHz and 24 MHz respectively.

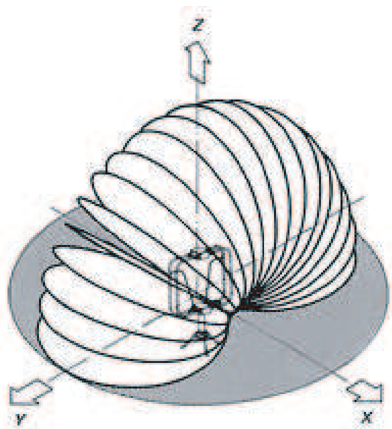

Figure 3. Theoretical half-loop antenna radiation pattern.

The PN-3190-99 half loop antennas comply with Automatic Link Establishment (ALE), Fixed Frequency (FF) and Frequency Hopping (FH), using powerful microprocessors, fast vacuum relays and a linear power amplifier. Basically used in the 2 to 30 MHz frequency range, the antenna is automatically tuned at the requested frequency by the radio set where the tuning time is compatible with the ALE, FF and FH standards [3].

Many tests have been made for the French army in 2001 and 2012 (critical year due to a low sunspot number) and all Signal to Noise Ratios (SNR) have confirmed a good behavior on 0–2000 km range.

The main purpose here is to apply the above proven antenna in a ship context.

Indeed, limitations of the communications facility on-board a combat ship are mainly related to the couplings between radios, antenna geometry and their positions.

Operator in the trade will seek to establish communications over long distances by fitting additional antennas to get a polarization and space diversity. However, there will always be forced to accept the increase in antennas size on board and increase inter-system coupling. Moreover, this approach will reduce the performance of camouflage, so radar stealth.

Many technical analysis and operational requests lead to an integration of the HF antennas at ship corners in order to make their systems more compact and stealthy. So, we will show how it is possible to improve the communication availability and physical integration in the ship body.

2.1.2. Corner HF Half Loop Antenna

Starting from the well-known loop antenna, it was thought best to use the ship body as reflecting plane to reduce its size to half and then to integrate the half loop antenna in a cavity so as to steer the radiated field and surface currents.

The corner HF half loop is made up of 4 elements which are the tuning unit, the feed unit, the radiation element and the control unit. The radiating element is shown Fig. 4.

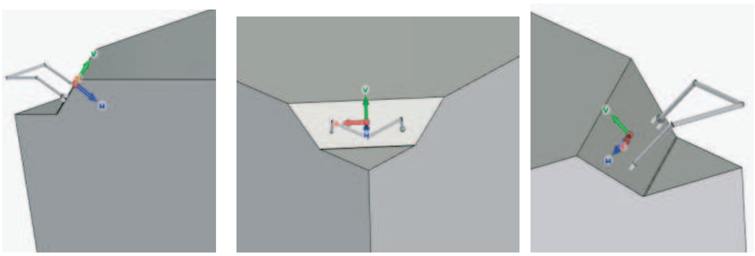

Figure 4. Different views of the half-loop antenna at the ship corner.

A simplified structure has been simulated thanks to CST Microwave Studio in order to show the electrical performance of such antenna. This structure is made up of one 5 m half loop antenna and fitted in an etched corner of a metallic cube.

2.1.3. Antenna Specifications

Note that for a 90% of reliability, 10 dB of SNR, 1 μv of sensitivity and 1000 km of range, each channel shall have 3 kHz of bandwidth at least.

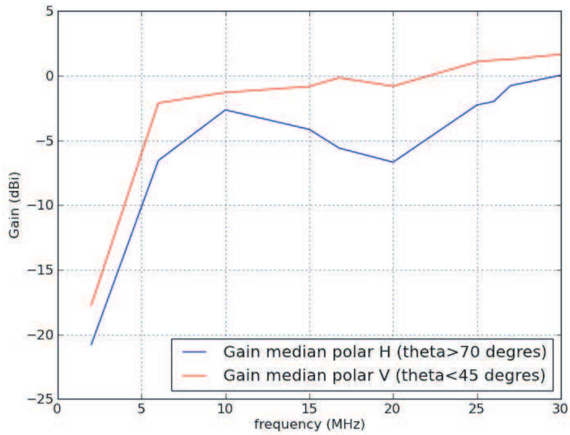

Figure 5. Simulated gain vs frequency of one integrated 5 m half-loop.

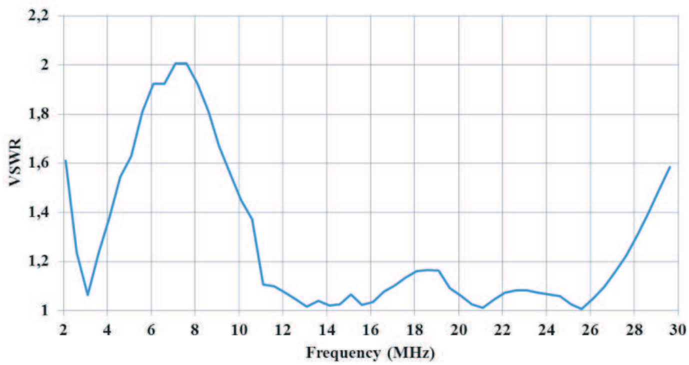

Figure 6. VSWR values versus the corresponding frequency of one integrated 5 m half-loop.

Supplied by 125 W power generator and considering 5 m length of radiating element in 1 m^3 volume, the new antenna gave the below performances. Fig. 5 shows the simulated median gain over the HF frequency band.

Figure 6 shows the VSWR performance of one corner antenna. Remember that the antenna integrates a semi-automatic tuning unit. So, the taking VSWR values correspond to the tuned frequency. For example, when the antenna is tuned at 4 MHz, the corresponding VSWR is 1.35.

In addition, the antenna bandwidth taken at -6 dB of reflection coefficient increases with the frequency as Fig. 7 shows. Starting from 6 MHz of operating frequency, the antenna bandwidth will be higher than 24 kHz.

First, it should be noticed that the gain level remains low at lower frequencies because of low antenna efficiency nearby 2 MHz. The vertical polarization is obtained by ground waves up to 45° elevation angle while the horizontal polarization is obtained by NVIS propagation between 70° and 90° elevation angle.

Next, the gain with a vertical polarization remains around 0 dBi from 6 MHz and around 3 dB higher than the gain with a horizontal one. Remember that the efficiency is an important parameter for such

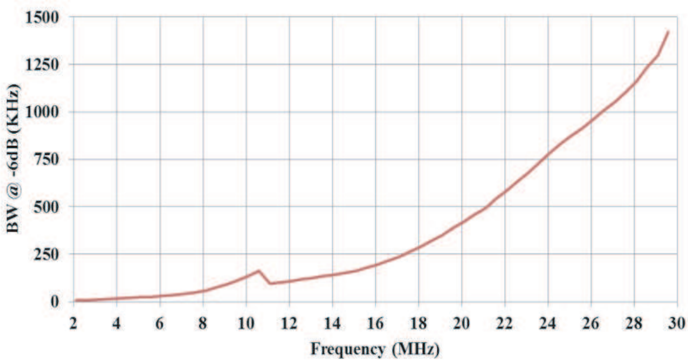

Figure 7. Bandwidth at -6 dB of one integrated 5 m half-loop.

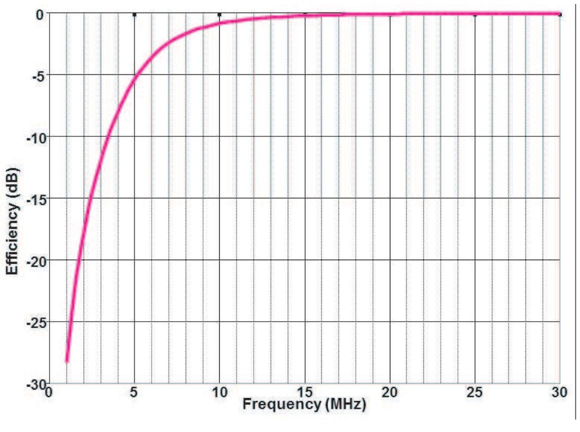

Figure 8. Simulated radiation efficiency of the half loop antenna.

antenna system. Fig. 8 shows the efficiency of a 5 m half loop antenna integrated in a ship corner with its tuning unit.

The antenna efficiency depends on radiation and loss resistances, then on antenna dimensions and frequency. It starts from −17 dB at 2 MHz until 0 dB at 30 MHz.

The radiation pattern, shown Fig. 9, point out some ripples in the roll ship axis. These ripples are well-known lobes of an antenna above an infinite ground plane (6.5 m of height) as sea water is.

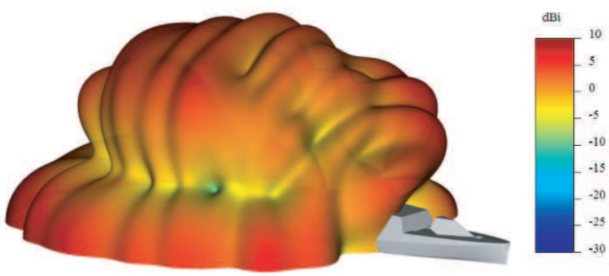

Figure 9. Simulated 3D radiation pattern at 30 MHz.

What should now be regarded as being for information only is that the 5 m half loop antenna, integrated in a ship corner, presents a higher gain than an 8 m whip antenna. The difference is about 1.5 dB at 15 MHz.

This last difference is due to a good radiation surface and efficiency of the half loop antenna comparing to the whip one even if the whip antenna is bigger. Moreover, the half-loop antenna has intrinsically, during the transmission and reception modes, a SNR which is 12 dB higher than that of a whip antenna and this is for a distance greater than 34 km and vice versa.

3. NAVAL INTEGRATION

3.1. Radio-electrical Simulated Results

The corner half loop antenna is now integrated in each rear corner of the ship body. This system will be treated as an array of two antennas. Note that the distance between the two antennas is about 8 m and then the antenna integration is consistent with the MIL-STD 461E for battlefield validation. The whole structure is simulated and the results are obtained thanks to ship EDF$^{\mathrm{TM}}$ software.

Figures 10 and 11 show the meshed ship structure with an illustration for the electric near-field.

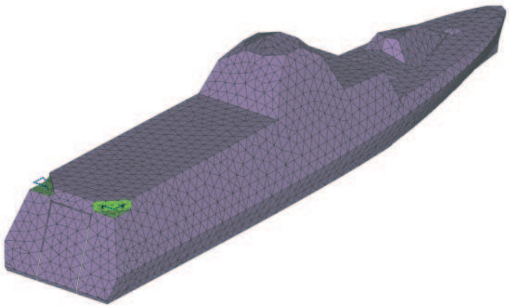

Figure 10. The meshed ship model with two corner HF antennas.

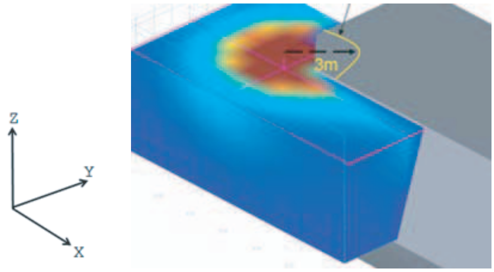

Figure 11. The electric near-field at 30 MHz with the 3 m radius restricted area.

As for the results, the radiation patterns in azimuth and elevation cut-planes are shown Fig. 12 and Fig. 13 respectively.

Radiation patterns remain almost omnidirectional, even if 4 dB of ripples is predicted at the highest frequency. Fig. 14 shows the overall antenna gain from two half-loop antennas integrated on ship over the frequency band. Also, Fig. 15 shows the 3D radiation patterns of the two integrated corner antennas at two spaced frequency.

Indeed, gain increases with the frequency and depends on the elevation angle (vertical/horizontal polarization or NVIS/ground-wave modes) and it is about 2 dBi at the highest frequency.

It is clearly observed that a 3 dB is added to the gain which indicates that the two antennas system has been physically considered as a two half-loop array with two modes:

- NVIS mode (for a distance greater than 34 km) with a gain of about 0 dB.
- Ground-wave mode with 2 dBi of gain average which corresponds to the case of a conventional dipole.

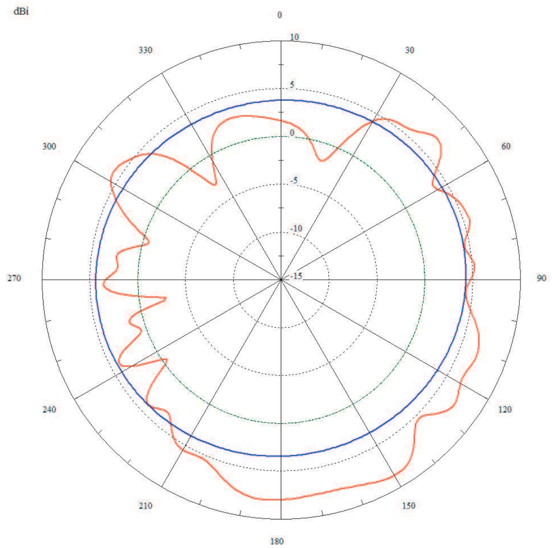

Figure 12. Azimuth directivity patterns (XY-plane) at $f = 2\,\text{MHz}$ (blue) and $30\,\text{MHz}$ (red) respectively.

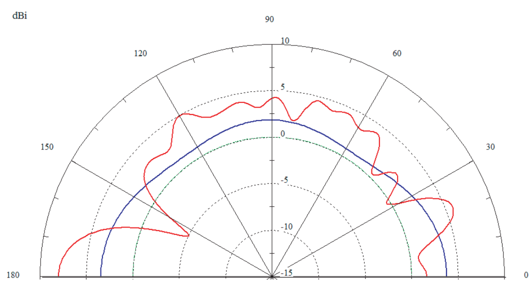

Figure 13. Elevation directivity patterns (XZ-plane) at $f = 2\,\text{MHz}$ (blue) and $30\,\text{MHz}$ (red) respectively.

These are due to a low coupling obviously acquired by cross polarization and to a far-field zone relative positioning between antennas at the ship corners.

3.2. Signal-to-noise Ratio

As for the SNR, shown Fig. 16, it is 12 dB higher than that of a whip antenna for the same transmission antenna gain and power and for 1000 km of distance. Although, the half-loop antennas allow out-band

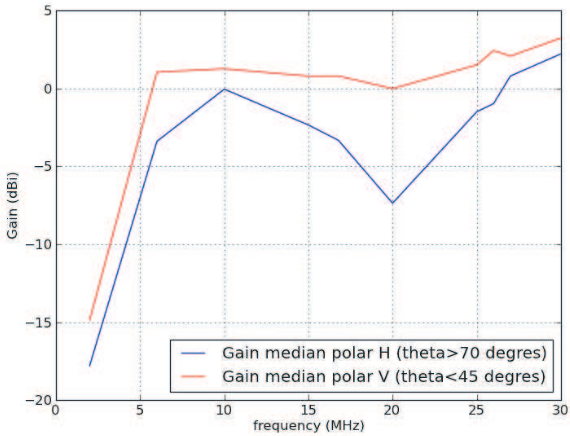

Figure 14. Median gain versus frequency of two integrated 5 m half-loops.

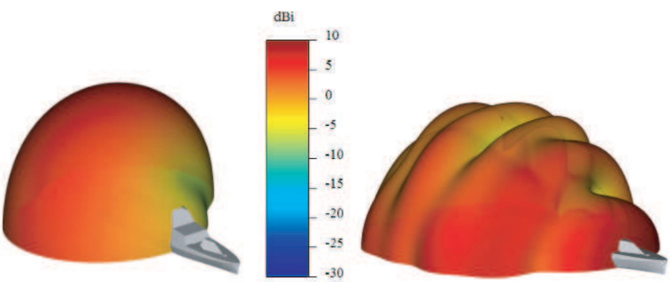

Figure 15. 3D Far field radiation pattern of the 2 integrated corner antennas at 4.0 MHz and 15.0 MHz.

noise reduction and jamming minimization following the high Q-factor ($Q = 450$ at 2 MHz).

Obviously, the above described half loop antenna provides a SNR that is 10 to 20 dB greater than a receiver dipole in a harsh environment. The antenna gain or efficiency is not the most important criterion for a good SNR. In the lower HF band, impact of external man-made, season and solar cycle on the reception quality is minimized thanks to a half loop antenna.

3.3. Electromagnetic Susceptibility

The coupling between two antennas is about −30 dB because of the orthogonal polarization. It should be stressed here that the coupling

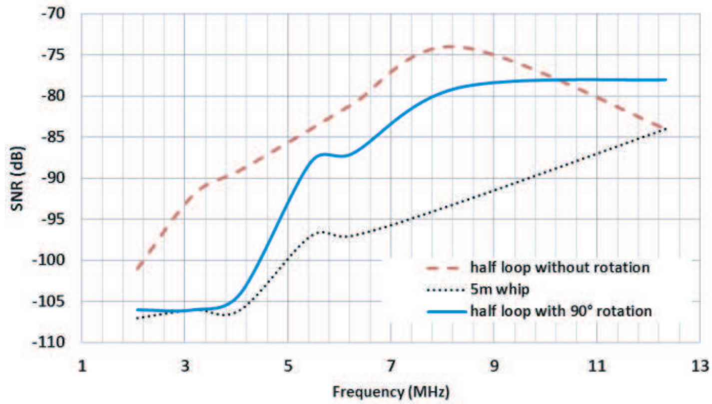

Figure 16. SNR according to the frequency.

level between two whip antennas at the same distance is about -8 dB. Thus, the half-loop antennas offer a good level of mutual coupling and then a reduced Bit Error Rate (BER) as well as coverage, EMC and EMI improvements.

Now, we will give some required specifications on-board a ship in terms of obstruction, EM hazards and stealthy.

3.4. Obstruction

Existing shipboard High Frequency (HF) transmit antennas cause major problems for proper mechanical integration on ship. Some problems are caused by the large dimensions of the antennas which obstruct the on-board sensors and/or weapons systems. The conventional fan wire antennas are representatives of this class of problems, with theirs large extensions above the ship.

As instance the HF deck corner loop antenna could be advantageously located into aft corner of the ship structure, which corresponds to the helicopter platform on the large patrol craft and beyond. Covered by a radome, the antenna is flush-mounted and none masking is perceptible by other radars or radio equipment.

3.5. Electromagnetic Hazards

Other problems are due to the Hazards of Electromagnetic Radiations [4, 5] on Personal (HERP), Equipment (HERE), Ordnance (HERO) and Fuel (HERF). Often located at the middle part of ship, which means at the top of the wheelhouse or around the main mast, the antennas radiations limit respectively the free movement of the crew, interfere or even saturate the equipment, activate some electrically initiated explosive components or set on fire the fuels.

Comparatively, the HF deck corner half-loop antenna as located on the edges of ships corresponds to the farthest position of conventional antennas and therefore generates a minimum coupling. Especially the HF radiations which interact by the fundamental or harmonic frequencies with camera video, GPS receiver are limited.

Again, spacing from major ships structures that act as parasite radiators are very small and these results in major coupling problems. The active coupling between the numerous communications antennas that must be placed in this small area is very high. This leads to particularly difficult problems in the receiving-system design because of the very large voltages that exist on receiving antennas as a result of the nearby transmitting antennas. In the case of two identical antennas such as HF deck corner loop located on the each aft deck corner (Fig. 10), the crossed polarizations propose a minimum in-band self-coupling (-28 dB @ 9.4 MHz) compared to the standard whips (-8 dB @ 9.4 MHz) in the same configuration.

By this way, the near-field was computed for 150 W power and a maximal gain as equal to 200 V/m at 3 distances.

3.6. Stealth Strategy

In parallel, the stealth topic appears as an important new feature required by Navy for the future platform. This feature, named Radar Cross Section (RCS), means mainly the reduction of the projected area combined to the suppression of the dihedral and trihedral effects. So, straight angles and parallel line have to be avoided during the ship design. Then, the scattered power is decreased. Other solutions tried recently to be developed as the structural HF antenna [6–8].

The below simplified equation shows that the RCS is function of scattered power.

$$\mathrm{RCS} = \lim_{r\to\infty} 4\pi r^2 \cdot \frac{P_s}{P_i}$$

where:

- P_s: power intercepted and scattered by the target, Watts.
- P_i: Incident power, Watts.
- $4\pi r^2$: equivalent sphere of the target.
- The derivation of the expression assumes that a target extracts power from an incident wave and then radiates that power uniformly in all directions.

A baseline application is two whips antennas integrated aboard ship as shown Fig. 17. It can be analyzed in free space condition to estimate the RCS figures versus azimuth and elevation angles, at 10 GHz. Fig. 18 shows the RCS of the basic ship with 2 HF whips.

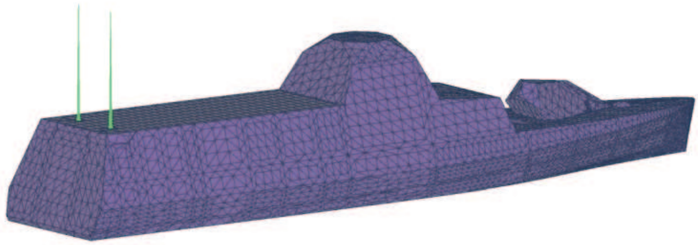

Figure 17. The meshed ship model with two corner HF antennas.

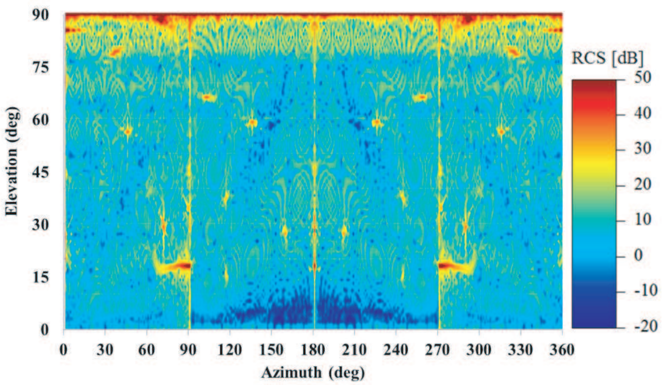

Figure 18. RCS map of two whip antennas aboard (10 GHz, *HH* polarization).

The HF deck corner loop antenna benefits to the best RCS out-of-band behavior (i.e., radar band) due to the high band rejection filter (Fig. 19). The latter configuration permits a 3 dB reducing of the radar signature in any direction and 90% of space comparing to the RCS map of a populated stealth ship.

4. LINK BUDGET ANALYSIS AND SEA VALIDATION

A particular attention is given to the communication range due to the high dependence on the medium.

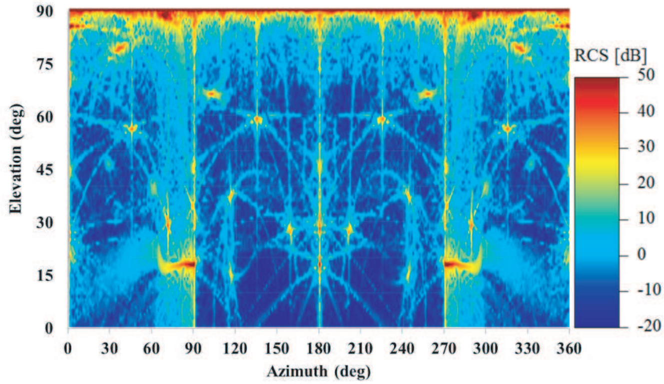

Figure 19. RCS map of corner HF antennas aboard (10 GHz, *HH* polarization).

The half-loop antenna presents a toroidal radiation pattern and brings:

- 0–30/60 km communication (range depends on ground conductivity) by ground wave with a vertical polarization.
- 30–500 km transmission in NVIS mode with horizontal polarization.
- 500–2000 km communication with a low take-off angle skywave.

Link budget equation can be written as follows:

$$P_r = P_t + G_t + G_r + 20\log\left(\frac{\lambda}{4\pi d}\right) + L$$

where:

- P_r = Received Power (dBm).
- P_t = Transmitter Power (dBm).
- G_t = Transmitter Antenna Gain (dBi).
- G_r = Receiver Antenna Gain (dBi).
- λ = wavelength (m).
- d = distance between transmitter and receiver (m).
- L = miscellaneous losses.

It should be noticed that losses (L) origin depends on the system and the environmental area especially that the link is established by NVIS propagation. Losses can arise from multiple origins such as: cable, connectors, fading, polarization misalignment, Modulation, absorption in atmosphere, flat-earth propagation, multipath [9] and obstruction losses.

4.1. Comparison to Other Market Products

Figure 20 shows a comparison between the different HF antennas gain. We observe that the half-loop antenna gain is higher than any whip antenna gain starting from 8 MHz.

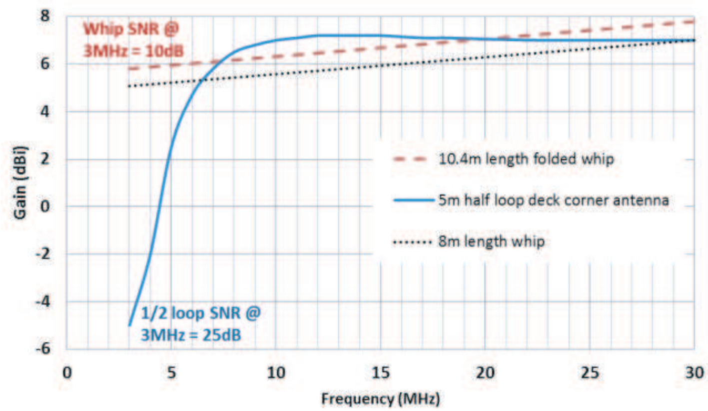

Figure 20. Antennas gain according to the frequency.

As for the lower frequency band, the half-loop antenna gain is lower than the whip one but we keep in mind that the half-loop antenna SNR is 15 dB higher. Thus, 4 dB of advantage in term of link budget.

Moreover, half loop antenna has one distinct advantage over conventional antennas due to its radiation pattern. The maximum gain occurs at both low and high angles. In fact, it radiates equally well at all elevation angles and offers a limited occupation volume and an enhanced stealthy.

Although, corner half-loop antenna presents a real design for on-the-move communication in a harsh environment. The radiating element ensures a good mechanical flexibility in case of shocks and can be easily replaced during a military or assistance operation.

4.2. Experimental Results

Simulations and link budget measurements prove that the deck corner half loop antenna is very suitable (> 45 dB/Hz) for communication on long range without any skip zone as Fig. 20 shows. Moreover, corner deck half-loop antenna is sea proven. Indeed, it is validated by measurements in the Middle East region between a combat ship and mobile vehicle and pointed the communication availability up to 2000 km specially at 10/500/1000/2000 km critical distances throughout most 2010 days and nights.

These experimental tests have been done in 2010 and 2012 where the sunspot number was low (i.e., 30) and corresponding to a difficult propagation as shown Fig. 21.

Results of this communication test campaign are satisfactory and show a high Quality of Service (QoS) when the adequate operating frequency is chosen according to the NTIA/ITS recommendations shown Fig. 22.

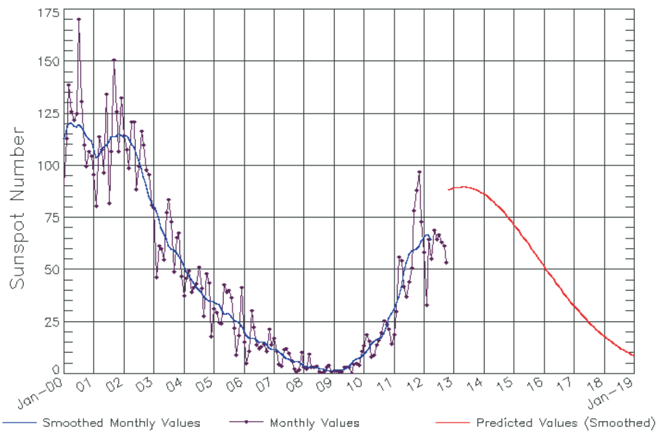

Figure 21. ISES solar cycle sunspot number progression.

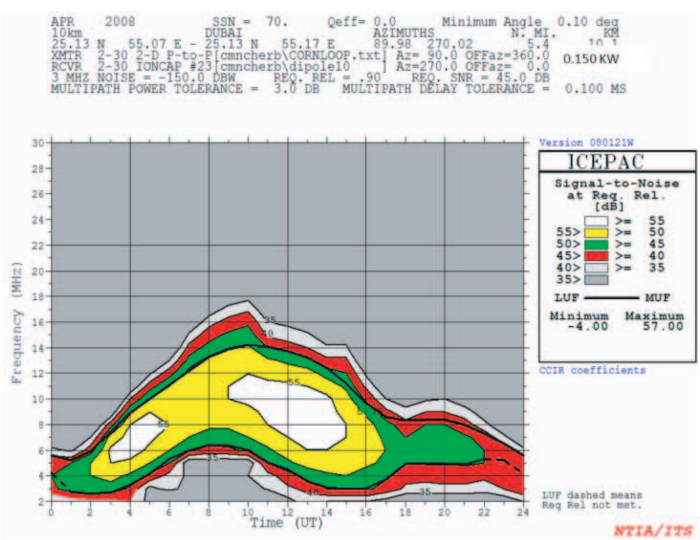

Figure 22. Example of HF link budget.

5. CONCLUSION

A valid HF half loop antenna has been detailed in this paper. This antenna enhances the QoS of a HF communication by giving a suitable SNR in a 0–2000 km range without any skip zone. This antenna has been integrated in ship corners and tested in the Middle East region between 2010 and 2012. The deck corner half loop antenna gives high stealthy and lower susceptibility and then gives back an advantage during the military maneuvers. It should be noticed that this integrated half loop antenna matches most of HF radio receiver sets.

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