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THE HIGH FREQUENCY SURFACE WAVE RADAR SOLUTION FOR VESSEL TRACKING BEYOND THE HORIZON

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Abstract. *With maximum range of about 200 nautical miles (approx. 370 km) High Frequency Surface Wave Radars (HFSWR) provide unique capability for vessel detection far beyond the horizon without utilization of any moving platforms. Such uniqueness requires design principles unlike those usually used in microwave radar. In this paper the key concepts of HFSWR based on Frequency Modulated Continuous (FMCW) principles are presented. The paper further describes operating principles with focus on signal processing techniques used to extract desired data. The signal processing describes range and Doppler processing but focus is given to the Digital Beamforming (DBF) and Constant False Alarm Rate (CFAR) models. In order to better present the design process, data obtained from the HFSWR sites operating in the Gulf of Guinea are used.*

Key words: *High Frequency Surface Wave, radar, maritime surveillance, Digital Beamforming, Constant False Alarm Ratio, Frequency Modulated Continuous Wave.*

1. INTRODUCTION

In recent years organized crime in maritime regions has flourished, threatening both secure flow of goods from Exclusive Economic Zones (EEZ) [1] and lives of participants in the marine operations. Henceforth, all marine nations are forced to fully control whole EEZ, not only territorial waters. Moreover, in some areas of the world, the situation is so serious that UN [2] and/or EU intervention [3] has been required, since nations which have jurisdiction over those waters have limited resources. Since EEZs are huge bodies of water which can cover hundreds of thousands of square kilometers, complete monitoring is much easier said than done. So, the first question is how to monitor the whole EEZ?

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To the best of our knowledge, there are only two ways to achieve complete EEZ monitoring, especially if your primary targets are non-cooperative vessels. First approach utilizes optical and microwave sensors on platforms such as satellites and airplanes, thus avoiding sensor's limitations, but introducing platform's limitations. The most limiting factor is interrupted data availability, since no airplane is able to stay in the air constantly during whole year and all-weather conditions, while satellites are orbiting around Earth and will be over the zone of interest for a limited time. Other approach uses network of HFSWRs [4] to ensure constant surveillance well beyond horizon. Since the price of HFSWR network is significantly less than the combined cost of aforementioned sensors and data are available constantly during whole year, it is clear why these radars are slowly becoming the sensors of choice for maritime surveillance at over-the-horizon (OTH) distances.

The paper examines the most important questions that have been encountered in the design of Vlatacom's High Frequency Over The Horizon Radar (vHF – OTHR). Please note that this paper relies on [5] and while in [5] main focus is on signal processing, this paper provides an overview of vHF OTHR. A general overview of HFSWR principles can be found in [4,6-9]

Our solution relies on FMCW and main reason for that choice are:

1. Peak power requirement. Since we wanted to minimize needed transmit peak power we opted for FMCW hence it requires significantly less peak power than pulsed waveforms.

2. Secondly, our targets are staying within the radar resolution cell for few minutes, so we wanted to fully use available integration time.

For a difference, solution presented in [10] is based on a pulsed waveform which requires at least an order of magnitude greater peak power in order to achieve same radar range. On the other hand solution presented in [10] is requiring less land area in order to deploy the system, since RXs can be blanked during transition.

The rest of the paper is organized as follows: tactical situation and environmental challenges are presented in Section 2. Section 3, is dedicated to general vHF – OTHR design. Section 4, focuses on signal processing and conclusions presented in Section 5.

2. Tactical Situation and Environmental Challenges

Usually demands which end users put in front of HFSWR designers may be formulated in the following manner:

- Cover areas of the sea beyond the range of shore–based microwave radars. Ideally cover complete EEZ and neighboring areas.
- Provide reliable detection and stable tracking at OTH distances regardless of environmental conditions. Simultaneously minimize number of false tracks.

In order to completely understand such demands designers must be proficient with situation in maritime arena and fully understand what types of vessel are present in the open sea. Vessels which are the most interesting are vessels used for transportation of goods, such as various types of cargo vessels and tankers. All those vessels have following common characteristics:

- Most of the vessels are very large and their length is often more than 100 meters, while their displacement is usually more than 50000 Dead-Weight Tonnages (DWTs). Although, those vessels are mandated to carry and use AIS devices by international regulations, it is not always the case in the Gulf of Guinea.
- The top speed of the vessels seldom exceeds 25 knots, while usual cruising speed is ranging from 10 to 20 knots, or even less. Please note, vessels may be stationary as well, like fishing vessels for example.
- Most of the time these vessels are traveling along strait line and when they make turns they are doing slowly in a wide arcs. Although in some cases some (smaller) vessels can perform sharp manoeuvers.

It is clear that tracking this type of vessels is not very demanding and their influences on HFSWR coverage are presented in [11]. On the other hand, track initiation process may be a very demanding task, especially at the long ranges. However, since tracking is not the focus of this paper, readers are suggested to rely on works [12, 13]. Unfortunately, this is the only favorable circumstance; all other factors present quite demanding challenges. Those challenges can be divided into natural and man–made challenges.

2.1. Natural challenges

The very first natural challenge is direct consequence of operating band, since natural noise levels in HF band depend on geographical location, most notably geographic latitude [14]. This leads to the situations where the very same HFSWR will achieve different range performances at different locations. An example of noise influence can be found in appendix A of [15].

Next roughness of sea is a factor which must be carefully considered during HFSWR design, since additional propagation losses result from the roughness of the sea surface. There are two scales which describe roughness of the sea surface – Douglas and Beaufort scale. Beaufort scale is usually used by mariners, while Douglas scale represents World Meteorological Organization (WMO) standard. In this paper we decided to rely on Douglas scale. By this scale sea state is expressed with digits from 0 to 9. A higher number on the scale corresponds to a higher wave height, which leads to higher losses in the propagation. Analysis of sea states from 0 to 6 shows that increase of wave height is proportional to increase in the propagation loss. Detailed analyze of this phenomenon could be found in [16]. It is also important to note that losses are increasing with increase of the operational frequency.

Many shore lines are quite low and it may not be feasible to mount an HFSWR on an embankment of cliff which though not impacting the performance of an HFSWR does represent another challenge in installing and maintaining HFSWR. If there is no other option other than to install at the shore line (and in some regions there is no other option) wave erosion can present danger to the HFSWR installation and in some cases inflict significant damage to the installation site and thus HFSWR itself. Although this is more civil engineering problem than design issue it must be carefully considered prior to the HFSWR deployment.

2.2. Manmade challenges

The first challenge is a man–made noise sources which are constantly changing, especially in the developing countries. In developed countries all changes are regulated by governmental bodies. On the other hand in developing countries (especially in Africa) those changes are not strictly regulated. Moreover, due to the fast development of those countries, international recommendations are not quite up to date regarding the man–made noise data. Furthermore, in those countries very often there is no strong regulative body which controls bandwidth occupancy and users. This leads to situations where completely unexpected noise source appears in the HFSWR operating band (see Fig. 1).

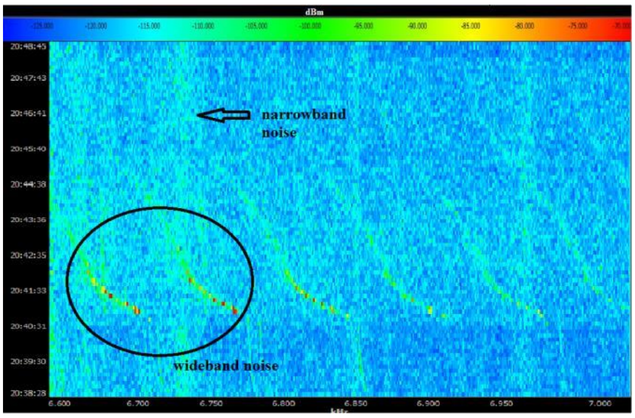

Fig. 1 Unexpected noise sources

As it can be seen from Fig. 1, a strong unexpected noise source (red and yellow dots in the spectrogram) appeared and lasted for a few minutes across whole band. This should not be confused with regular radio devices operating in the same band as HFSWR (light blue vertical lines in the spectrogram).

Although this usually happens in developing countries, it doesn't mean that there are no noise sources in HF band in developed countries. On the contrary, in highly developed countries HF band can be fully occupied and find a suitable operating band can be quite challenging. In extreme cases HFSWR are forced to operate at very low power levels (less than 40 dBm Equivalent Isotropically Radiated Power - EIRP) in order to avoid need for designated band. Obviously, this naturally significantly limits range performance. On the other hand, there are some signal processing techniques which can be applied in order to mitigate the influence of noise [17, 18].

Next problems are mostly present in developing countries. Those problems are:

- Connectivity problems and
- Power supply problems.

2.2.1. Connectivity problems

One sensor, no matter how large area it can cover, is often not enough to provide constant surveillance of EEZ. So, a network of HFSWRs is needed. In order to form the network a connection to the command and control (C2) centers is a must. However, in developing countries it can be a major problem, especially in remote areas.

From our point of view, connection between remote sites and C2 centers in developing countries can be established in one of following ways:

- Mobile telephony,
- Microwave links and
- Satellite links.

Mobile telephony represents an optimal solution, if it is available. Since no additional infrastructure is needed, deployment costs are literately negligible. Since HFSWR doesn't require high data rates (approximately 256 Kb/s is quite enough) and total data-transfer is around 5 GB on a monthly basis any today mobile network will be suitable. Moreover, in many countries some mobile telephony operators are state controlled, or even state owned, so data security should be at the very good level. Even then, encryption of output data is recommended. Unfortunately, mobile telephony is not always available, especially in scarcely inhabited areas, so the other means of connection are needed.

Microwave links as a mean of connectivity between HFSWR sites and C2s is definitely the most reliable and the safest one. On the other hand, cost of deployment is very high, which limits its usefulness.

As the last mean, there is a satellite link. Although it may look appealing, it is crucial to understand its flaws. The first of all is security issue, since whole network is dependent on the third party (link provider). Second issue is an availability of data. HFSWR as a sensor is only slightly affected by a meteorological - factors and virtually unaffected by rain and clouds, while usual satellite links are very susceptible to the weather conditions. So, choosing satellite link as a mean of data transfer is not recommended, unfortunately sometimes it is the only viable solution, due to lack of mobile network or lack of funds to develop a MW link network.

2.2.2. Power supply problems

All electrical devices require a power supply to perform their functions and HFSWRs are not exceptions. This simple requirement can be a real problem in developing countries, since electrical power network is not always available and if it is available quality of provided electrical energy is questionable. It is clear that other means of power supply are needed. Usually, diesel generators or solar panels are only viable options. Regardless how electrical energy is provided, Uninterrupted Power Supply (UPS) units are a must. Moreover, it is highly advisable to back-up both generators and UPS systems, in order to provide uninterrupted HFSWR operation.

3. General HFSWR Design

3.1. Usual site deployment

Like all the other radars, the HFSWR consists of transmitter and receiver with their antenna arrays. Beside those crucial elements the vHF-OTHR site includes a Central Site Location (CSL). Although this area is not mandatory, in some cases it is a must. In those cases the CSL provides power supply, connectivity to the C2 and sometimes even physical security (armed guards) to the HFSWR. A typical site layout is shown in Fig. 2.

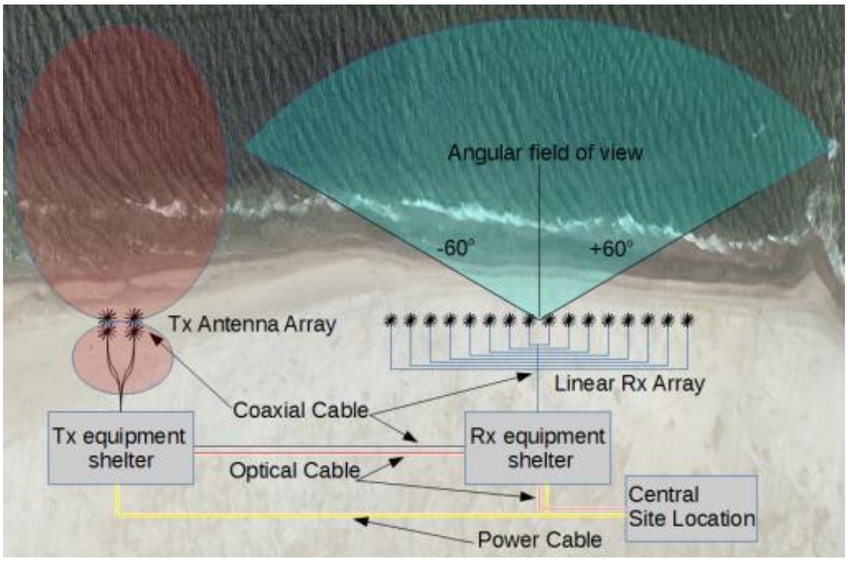

Fig. 2 vHF-OTHR site deployment

Selected site geometry and working frequency define coverage area as well as area required for site deployment. As an example, for a system centered at 4.6 MHz, which yields maximum range of approximately 200 nautical miles (370 km) will be discussed. Site geometry for the antenna arrays is presented in Fig. 3.

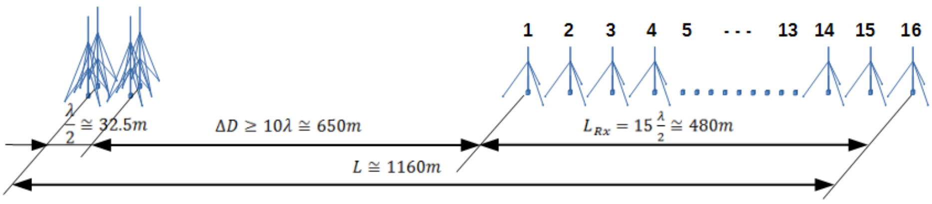

Fig. 3 HFSWR array layout for system centered at 4.6 MHz

According to Fig. 3. minimal length of the Rx antenna array is 7.5 wavelengths, which for the operating frequency of 4.6 MHz is nearly 500 meters. In order to prevent self-interference RX and TX arrays needs to be separated at least 10 wavelengths, or 650 meters for system operating at 4.6 MHz. Next, transmit array length is at least half of wavelength, or 32 meters in a case of 4.6 MHz system. Furthermore, in order to boost antenna efficiency radials are needed. Taking into account that radial length is 25 meters, required area is increased for another 50 meters (25 meters prior to receive antenna 1 in Fig. 3. and after transmit antenna). Finally, in order to secure the site fencing is needed so occupied area rises again. To summarize in order to deploy the 4.6 MHz site land area nearly 1.5 km long and 100 meters wide is required. This area needs to be as close as possible to the sea; practically the best location is at the shoreline (see Fig. 4).

Fig. 4 Deployed vHF-OTHR site

For applications where 200 nm coverage range is not a requirement the occupied area can be reduced as a higher frequency can be used. For example, for a system centered at 12 MHz requires only an area 300 meters long, but maximal range is reduced to 60 nautical miles.

3.2. System's block diagram

Brief description of the vHF-OTHR block diagram with most important parameters which influence its performance is presented here and shown in the Fig. 5. More detailed description of the individual components is presented in the following sections or even in the standalone articles.

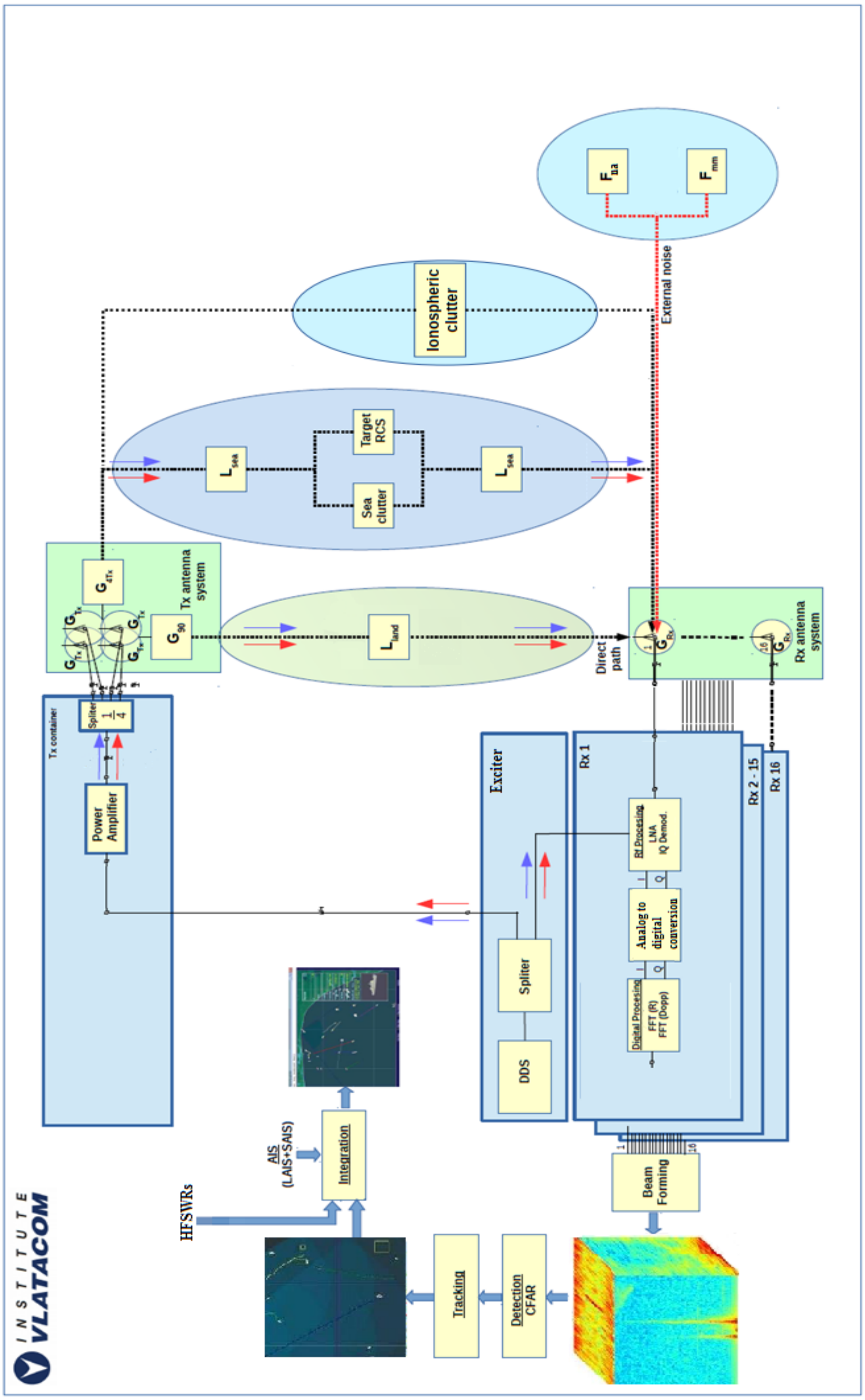

Fig. 5 vHF-OTHR System’s block diagram

It is important to note that this radar is Frequency Modulated Continuous Wave (FMCW) principles, similarly to the ones presented in [19]. As in all other radar systems the exciter generates waveforms needed for system operation. Here, Direct Digital Synthesizer (DDS) is used to generate linearly frequency modulated signal, also known as chirp. This signal is split into 17 channels, one for the transmitter and 16 for receiver channels. The transmitter signal is amplified to the desired level using a power amplifier and fed to the transmit antenna array. Although the majority of the signal is transmitted towards the open sea, some portion is also radiated directly towards the receiving array which consequently interferes with signal reflected from the open sea. It is important to note that losses during propagation over any type of soil (L_{land}) are much greater that losses over the sea surface (L_{sea}). Therfore the echo returned from the sea is dominant at the receiver input. The echo itself consists of two predominant components, signal reflected from vessels (defined by each target radar cross section – RCS) and signal reflected from the ocean waves, also known as sea clutter. Besides direct and reflected signal components at the receiver inputs external noise originating from the natural (F_{na}) and manmade sources (F_{mm}) is also present. In some cases the third component ionospheric clutter may appear at the receiver inputs. This ionospheric clutter is the result of unwanted sky-wave propagation of the transmitted signal that is reflected back to the radar via the ionosphere.

Each Rx antenna receives signal completely independently of the others and feeds it to the separate receiver (see Fig. 6).

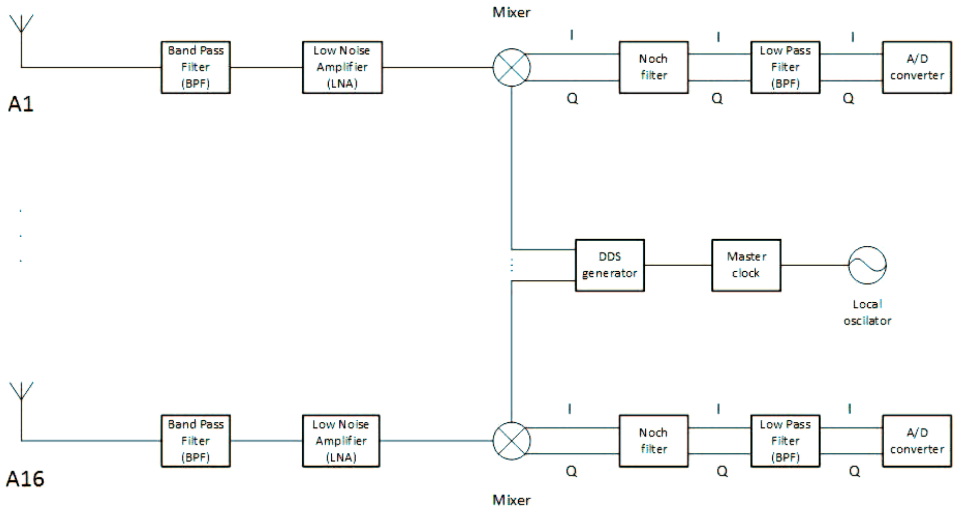

Fig. 6 Receivers block diagram

From each of the 16 antennas (A1 - A16), signal is firstly filtered in order to suppress out- of -band components, then it is amplified to the level needed for the further processing. Next it is mixed with the signal from the exciter that translates it to the baseband I and Q signals. After, the signal passes through a notch filter and a low pass filter. The notch filter suppresses signals around 0 Hz (DC), in order to reduce the impact of transmitter leakage. It is important to note that this filter comes after the received signal is already translated to frequency domain thus it does not influence the stationary targets located away from the HFSWR, but only close targets and most importantly leakage from the transmitter. The low pass filter with a cut off frequency of 1 kHz is used to clean channel from higher harmonics which are mainly produced by the mixer. At the final stage, the signal is converted to digital with a 16 bit A/D (analog-to-digital) converter, after which it is sent to the digital signal processing.. Digital signal processing steps are presented in section 4, while tracking and integration processes are presented in [13] and [15] respectively.

At the end, in order to completely cover nation EEZ multiple HFSWRs may be needed so the HFSWR network must be formed [20].

3.3. Antenna arrays

Receiver antenna array consists of the 16 monopole antennas [21] with each antenna feeding its own independent receiver. Beamforming is done digitally and presented in section 4.3.

The transmit array radiation pattern is formed with array geometry and phase shifts at the each array element. Primarily, the transmitting planar array is designed with the intention of maximizing energy radiated towards the sea over wider band so operating frequency can deviate when necessary. Secondly, radiation pattern nulls towards the receiving array must be achieved over entire operation band. In order to achieve those goals elements A and D have a phase shift of 126º from elements B and C from Fig.7.

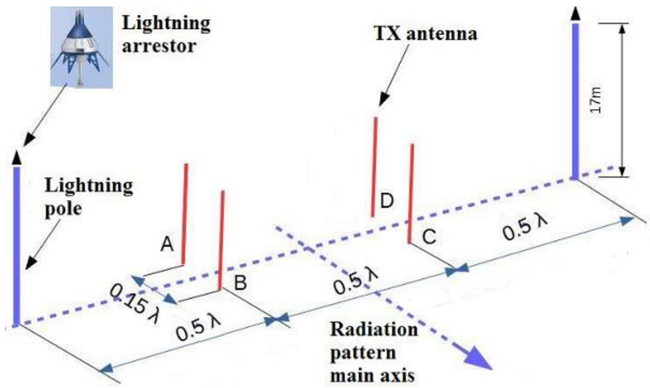

Fig. 7 Transmit array diagram

Lightning poles are placed at ϴ=0º and 180º, 0.75λ from the center of the array, where the nulls are expected to be. It is important to note that lightning poles are a must, since antenna array is towering above the surrounding area. The 3D radiation pattern of the array far field can be seen in Fig. 8, while a horizontal cut at 8º is shown in Fig. 9.

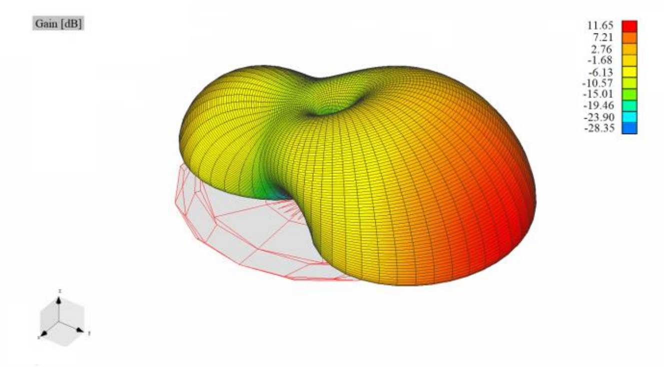

Fig. 8 3D polar plot of transmitting array radiation pattern

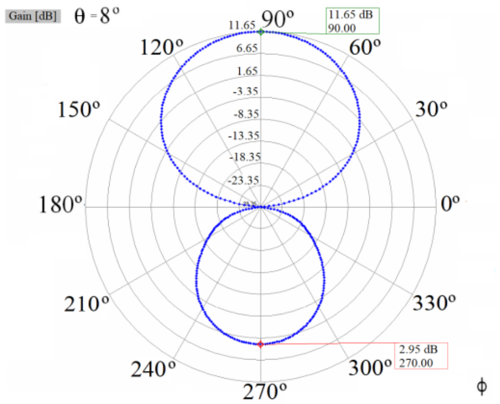

Fig. 9 Radiation pattern of TX array – horizontal cut, ϴ=8º

As shown, the side lobe towards angle ϴ=270º has about 8.7dB lower gain than maxima directed towards ϴ=90º, and the nulls occur toward directions ϴ=0º and ϴ=180º.

4. Signal Processing

This section provides an overview of the signal processing applied to the Vlatacom radar.

Complete signal processing consists of following steps:

1. Range processing,
2. Doppler processing,
3. Beamforming,
4. Constant False Alarm Rate (CFAR) and
5. Target tracking (not subject of this paper)

All these steps are presented in Fig 10.

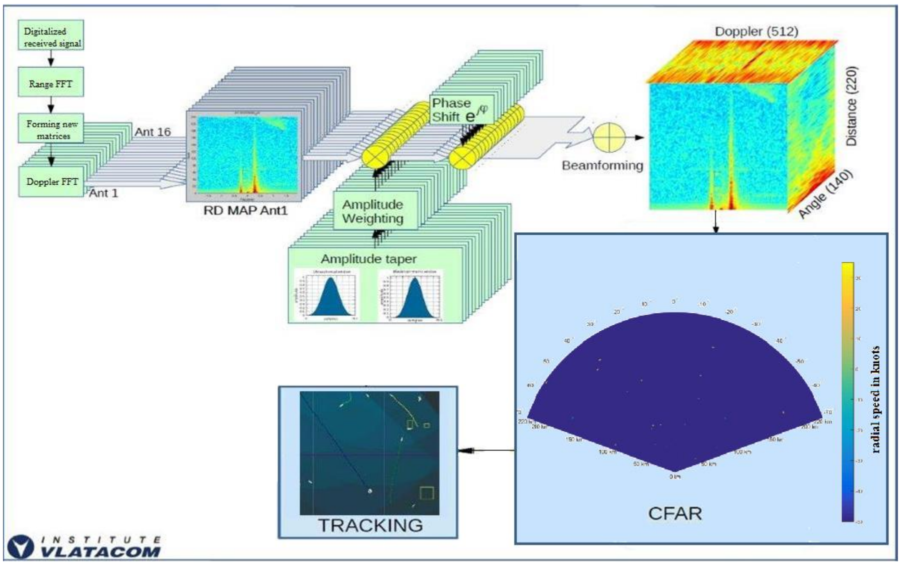

Fig. 10 vHF-OTHR Signal Processing steps

4.1. Range processing

Digitalized complex envelope of received signal translated into the base band (0 to 1000 Hz). The signal form is power relative to time. Digital signal processing starts with the "Range FFT", which is the fast Fourier transform of digitalized received signal. In this way received signal is reshaped into signal level vs range form (Fig. 11).

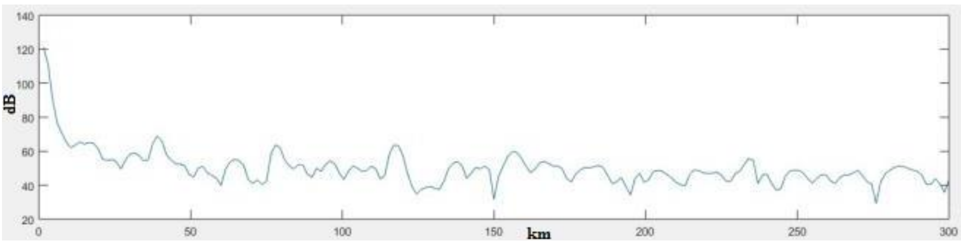

Fig. 11 Signal after the "Range processing" (taken from [5])

4.2. Doppler processing

The first step during Doppler processing is to rearrange data based on range values and RX channels. After data is rearranged into desirable form, it initially is processed by window function before it can be passed to FFT. The Blackman – Harris window function [22] is used here because it suppresses higher order side lobes better than other window functions, while still maintains very good selectivity of the main lobe. The last step is FFT and its outputs the "Range – Doppler maps". These maps are generated for each angle in the HFSWR field of view and represent signal levels dependence on range and speed (Doppler shift) of targets.

Doppler processing is schematically presented in Fig 12.

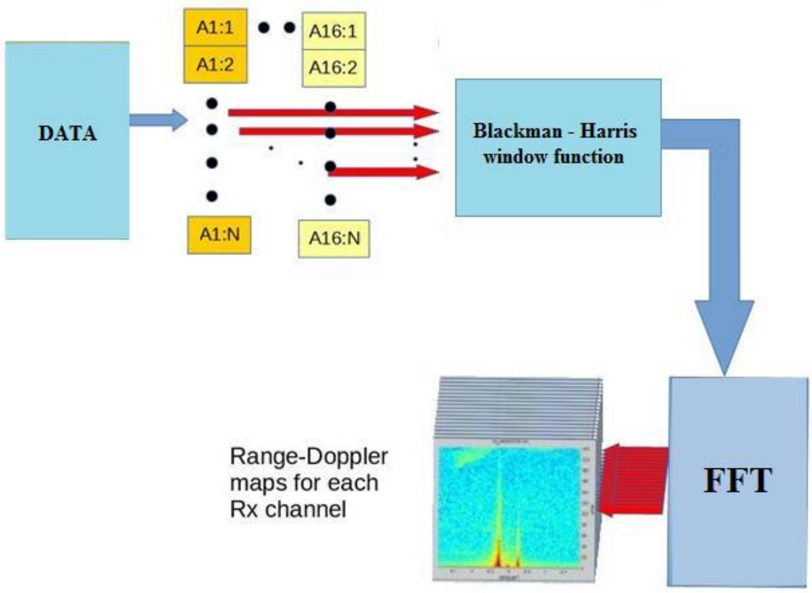

Fig. 12 "Doppler processing" (taken from [5])

4.3. Digital Beamforming

In order to form desired radiation pattern for the receiving array, various summation techniques can be used [23]. Here a conventional phase shift beam former is used for angle calculations, while Orchard algorithm [24] is used for weighting coefficients calculations. Antenna factor of the formed antenna array can be written as:

$$AF = I_n \prod_{n=0}^{N-1} (z - z_n) \tag{1}$$

Where AF represents antenna factor of the formed array, I_n are currents at the each element, N number of elements and z ($z_n = e^{a_n + jb_n}$) is complex variable which defines the array factor. Manipulating a_n and b_n desired antenna factor can be obtained.

Iteratively solving equation system (Eq. 2. – see below) which describes antenna gain in characteristic points (maximums and minimums), a_n and b_n parameters can be obtained. The Beam forming process is described below:

1. a_n are set to 0, while b_n are uniformly distributed between 0 and 2 π. Which gives array gain as a function of $\beta d \cos(\theta)$ as shown in Fig. 13. Where, $\beta = 2\pi/\lambda$ (λ is used wavelength), d represents distance between antenna elements (in this case 0.45 λ) and θ is aspect angle relative to array axis.

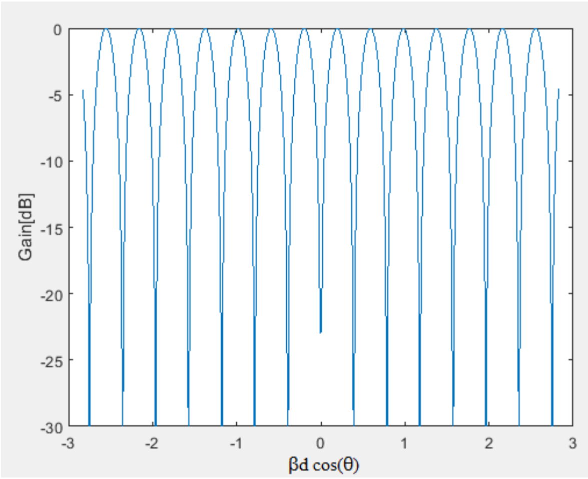

Fig. 13 Starting gain (taken from [5])

2. Desired gain is set and Eq. 2 is solved in order to find a_n and b_n.

$$g^{\sim} + A * \Delta x = g; \tag{2}$$

Where $g^{\sim}$ are current gain values, g are required gain values (defined by shaping function) and Δx is change of x matrix which contains a_n and b_n. It is important to note that there is no closed-form solution to the Eq. 2, but only optimal solutions which can be found using numerical approach. One example can be seen in Fig. 14.

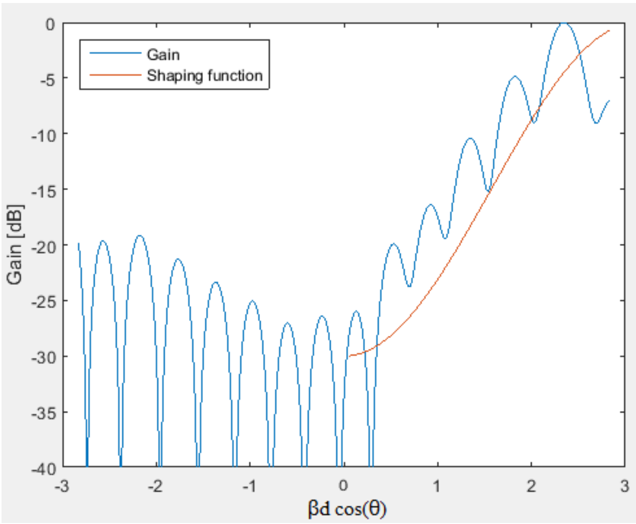

Fig. 14 Intermediate step, obtained during optimization process (taken from [5])

3. It is worth noting that numerical approach using software tools may be suboptimal, as matrix x may become singular when solution reaches some local stationary point. When this happens, some manual tweaking is required in order to reach desired shaping function and thus derive required a_n and b_n. Final result is show in Fig. 15.

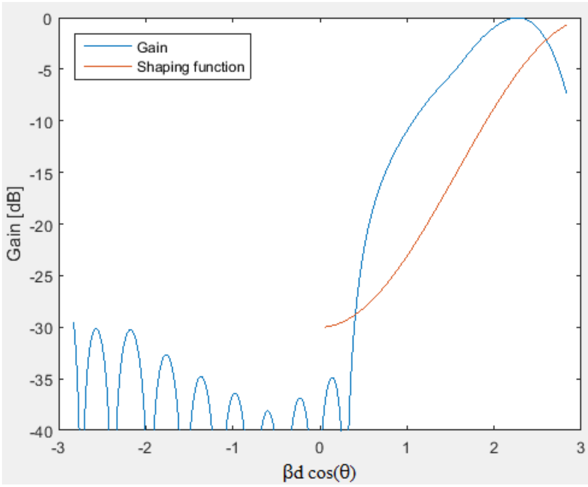

Fig. 15 End of optimization process – fully derived a_n and b_n (taken from [5])

Note that the shift in angle between desired shaping function and obtained radiation pattern is not relevant; since exact position of radiation pattern is achieved through phase shifting coefficients (see Fig. 9.).

End result of beamforming is so called Range – Doppler – Azimuth cube (RDA cube), which contains signal power levels defined by all relevant parameters (range, Doppler shift and azimuth).

4.4. CFAR algorithm

Input data for this processing step are RDA cubes and joint noise/clutter distribution functions. These distribution functions depend on system parameters and environment where system is installed. So, a thorough statistical analysis needs to be done in order to precisely derive required distribution functions.

4.4.1. Statistical Analyses

Firstly, system’s noise distribution function must be derived using data obtained in the laboratory while OTHR transmitter is directly connected to the OTHR receiver and test signal (one lone target) is run. One RD map obtained during such test is shown in Fig. 16.

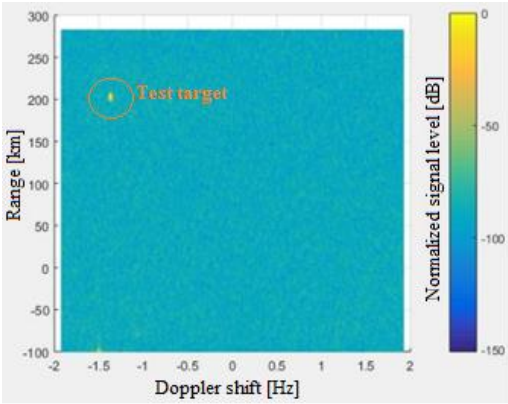

Fig. 16 RD map obtained in the laboratory

Processing all RD maps obtained during this test yields statistical properties of HFSWR system noise. Distribution of the obtained results is shown in Fig. 17

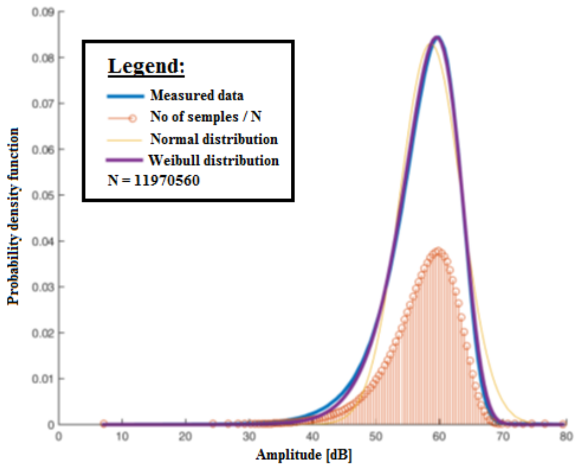

Fig. 17 Statistical properties of system's noise

One RDA cube contains approximately 12 million cells. In one of them a test target is present, while the rest contain only system noise. Orange lines with circles on the top represent number of cells (samples) used to determine the value of the blue line. For example, nearly 120,000 cells had power levels of 50 dB above noise floor, so orange line with circle at the top reached 0.01 (120.000 / 12 million). Distribution of the measured results is shown with blue line, two distributions, Normal and Weibull's, which match measured results the best are shown with orange and purple line respectively. It is clear that the Weibull's distribution matches the measured samples better than the Normal distribution, so it is chosen as statistical model of the system's noise and it is used for further statistical analyses.

Next, clutter and noise introduced by environment will be analyzed. A RDA cube obtained from HFSWR site situated in the Gulf of Guinea is used. One RD map obtained during test is shown in Fig. 18.

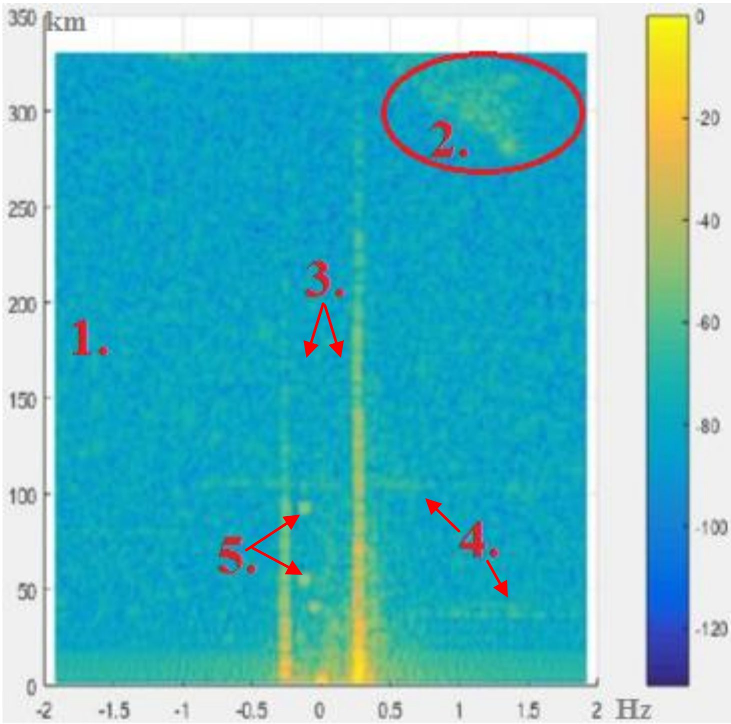

Fig. 18 RD map obtained in the field (Gulf of Guinea)

From Fig. 18. following areas are easily noted:

1. Dominant area, usually containing noise / clutter distribution – primary goal of this analysis. Its distribution function presented in Fig. 17.
2. Ionospheric clutter region, which can mask some distant targets and has distinctive statistical properties, so it will be discussed separately.
3. 1st order Bragg lines [25], representing scattering which is very important for oceanographic measurements, but has no value for vessel tracking, since it introduces blind velocities. Since there is no statistical method, known to authors, which can reliably detect vessels in this region this area is excluded from further statistical analyses. Please note, that although this cannot be solved within CFAR, it can be addressed with frequency diversity.
4. Fast moving targets, such as airplanes, or even returns from D or E ionosphere layers. Since it doesn't have any significant impact on the clutter / noise distributions it will not be discussed further.
5. Potential targets. They are occupying very few cells and have no significant impact on noise / clutter distribution functions.

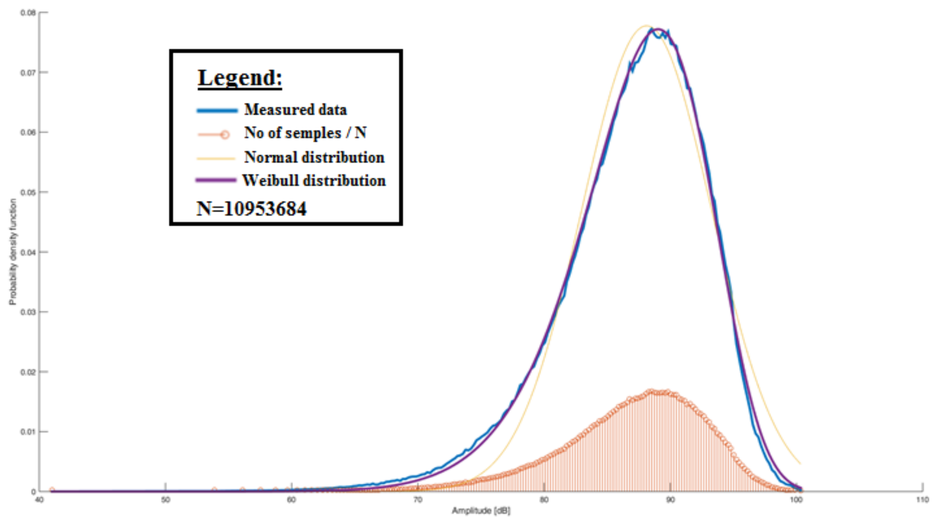

Fig. 19 Statistical properties of the region 4

From Fig. 19. It can be seen that Weibull distribution matches measured data the best and it is adopted for further CFAR modeling.

On the other hand, when ionospheric clutter is present Weibull distribution in the affected area doesn’t matches very well with measured data. As it can be seen from Fig. 20. Log Normal distribution describes that region the best.

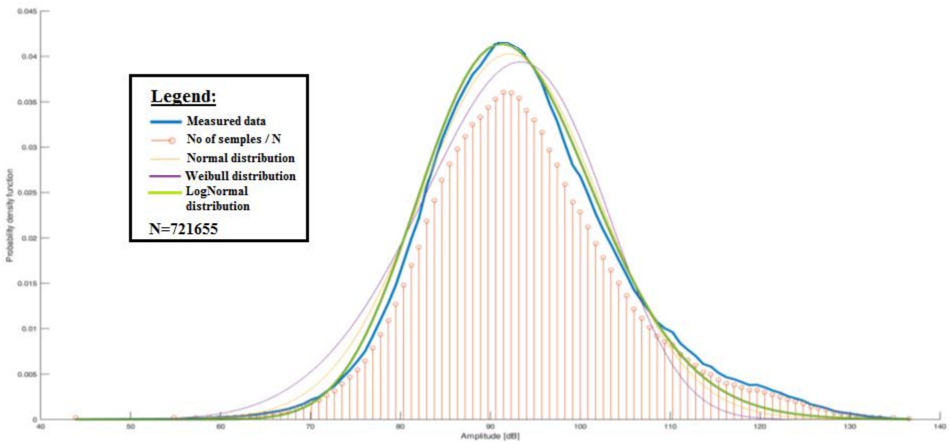

Fig. 20 Statistical properties of the region affected by ionospheric clutter

Please note, obtained distribution functions represent system noise, environmental noise and clutter distribution in the Gulf of Guinea. In some other regions of the World this distribution may vary.

4.4.2. CFAR Algorithm

Analyses presented above suggest usage of an adaptive CFAR algorithm such as [26] or fusion CFAR algorithm [27]. CFAR used here is based on approach present in [27] and represents a slight modification of well know Cell Averaging Greatest Of CFAR (CAGO – CFAR). The only difference lies in the fact that threshold level depends not only on averaged signal level, but also on assumed distribution function presented above.

As in all CFAR detectors "cell under test" is surrounded with guard cells after which come cells used for signal level estimation – training cells (see Fig21). Please note, that for simplicity sake Fig. 21 is draw in 2D, while in reality CFAR operates in 3D (Range, Azimuth, Doppler) estimating each cell in RDA cube.

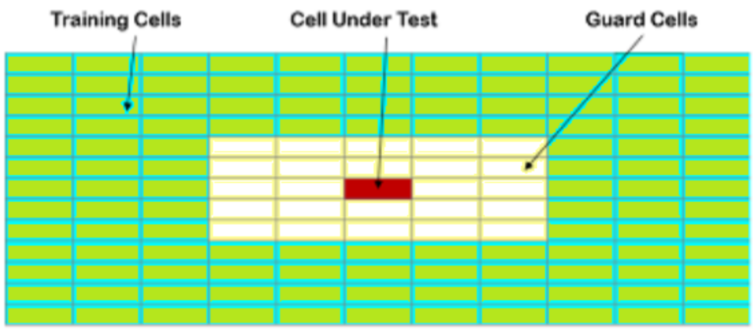

Fig. 21 Cell estimation principle

Mean signal value in training cells is calculated as:

$$\mu = \frac{1}{L}\sum_{TC} y_i \tag{3}$$

Where, μ represents mean signal value, L number of training cells and y_i is signal level in the current training cell. While variance (σ) is calculated as:

$$\sigma^2 = \frac{1}{L}\sum_{TC}(y_i - \mu)^2 \tag{4}$$

Threshold level (T) is calculated as:

$$T = \mu + c\sigma \tag{5}$$

Where, value c is depending on distribution function derived above and its main role is to maintain predefined false alarm ration (see Fig. 22.)

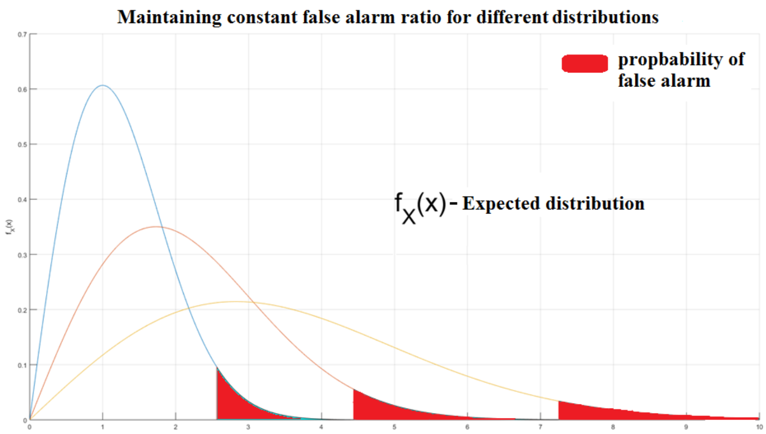

Fig. 22 Maintaining constant probability of false alarm

End result of this processing is list of detected targets. That list is graphically presented in Fig. 23, where all detected targets are plotted in polar diagram. Value of – 50 knots is chosen as figure background because it is highly unlikely that any vessel of interest can reach that speed.

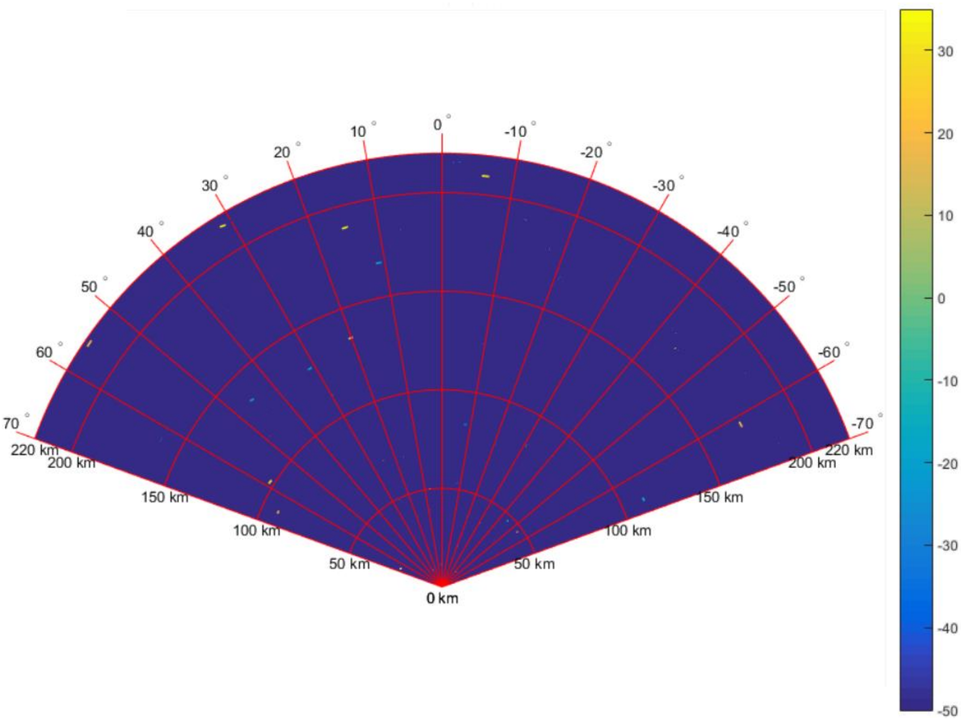

Fig. 23 Detected targets

It is important to note that not all of the detections present at Fig. 23 are necessarily real vessels. On some occasions, especially at the longer ranges, sea clutter can be detected as legitimate target, which may cause false alarms in the C2 system. In order to sort out this issue, all detections are fed to the tracking algorithms which are using track before principle [13] in order to eliminate false alarms. Afterwards, data obtained from multiple radars are fused into single stream of data and integrated with AIS data [15] in order to create unique operational picture. End result of aforementioned process can be seen in Fig. 24. AIS data originating from one vessel are also displayed at the Fig 24 in order to facilitate verification of the vessel detection.

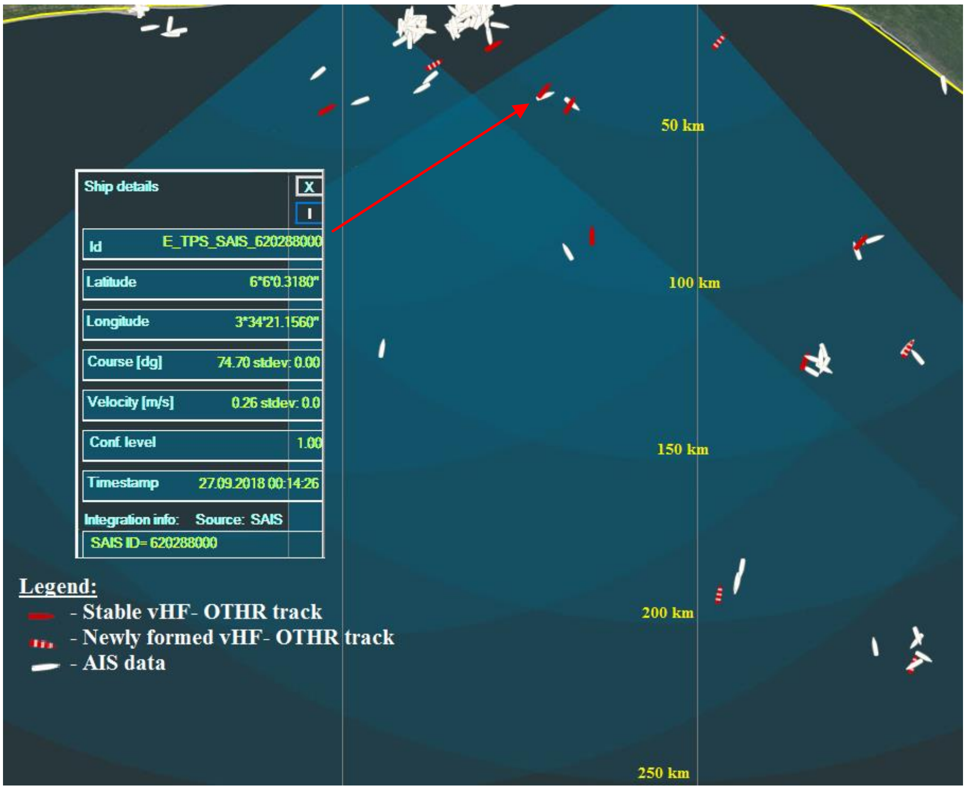

Fig. 24 An example of an operational picture

5. CONCLUSION

With the development of technology, prevention of illegal activities at the open sea is becoming increasingly complex, which further increases the need for more sophisticated solutions for large maritime area monitoring far away from the shore. At ranges well beyond the horizon, constant data availability and affordable price are putting HFSWRs at the forefront of the battle for the safer seas. Unfortunately, unlike microwave radars, HFSWRs are not mass-produced and well established devices. There are many question which demand answers before design process even starts. Most important of those questions, from authors point of view, and according answers are presented in this manuscript. An introduction to HFSWRs that adopt frequency-modulated continuous waves, or FMCW, to measure range, angular position and velocity of remote objects has been made in this article. An elaborate analysis on how the received signal is processed in order to obtain the vessels positions is in the focus of the article, although some other important aspects are discussed as well. During description of the signal processing main focus is given to the Digital Beamforming (DBF) and Constant False Alarm Ration (CFAR) models, but the other steps such as range and Doppler processing are presented as well. In order to better present the design process data obtained from the HFSWR sites operating in the Gulf of Guinea are used. In the future this system development is going multiple in multiple out (MIMO) direction with intention to design one system which consists of multiple interlinked nodes.

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REFERENCES

[1] United Nations, Law of the Sea, Part V – Exclusive Economic Zone. August 2011.
[2] https://news.un.org/en/story/2017/11/570172-un-security-council-urges-comprehensive-response-piracy-somali-coast.
[3] http://eunavfor.eu/mission/.
[4] G. Fabrizio, "High Frequency Over-the-Horizon Radar: Fundamental Principles, Signal Processing, and Practical Applications," London, UK, McGraw-Hill Inc., 2013.
[5] N. Stojkovic, D. Nikolic, P. Petrovic, N. Tosic, N. Lekic, "An Implementation of DBF and CFAR models in OTHR signal processing", In proceedings of the 15th IEEE Colloquium on Signal Processing and its Applications (CSPA 2019), Penang, Malesia, 8-9 Mar. 2019.
[6] L. Sevgi, A. Ponsford, H.C. Chan, "An integrated maritime surveillance system based on high-frequency surface-wave radars. Part 1. Theoretical background and numerical simulations", *IEEE Antennas and Propagation Magazine*, vol. 43, no. 4, pp. 28-43, Aug 2001.
[7] A. Ponsford, A. Ponsford, H.C. Chan, "An integrated maritime surveillance system based on high-frequency surface-wave radars. Part 2. Operational status and system performance", *IEEE Antennas and Propagation Magazine*, vol. 43, no. 5, pp. 52 -63, Oct 2001.
[8] T. Ponsford and J. Wang, "A Review of High Frequency Surface Wave Radar for Detection and Tracking of Ships", Special Issue on Sky- and Ground-wave High Frequency (HF) Radars: Challenges in Modelling, Simulation and Application, Turk J Elec Eng & Comp Sci, vol. 18, no. 3, 2010.
[9] L. Sevgi, "Modeling and simulation strategies in high frequency surface wave radars", *Turk J Elec Eng & Comp Sci*, vol. 18, no. 3, 2010.
[10] A. Ponsford, R. McKerracher, Z. Ding, P. Moo, D. Yee, "Towards a Cognitive Radar: Canada's Third-Generation High Frequency Surface Wave Radar (HFSWR) for Surveillance of the 200 Nautical Mile Exclusive Economic Zone", *Sensors*, vol. 17, no. 7, article no. 1588, 2017.
[11] N. Lekic, D. Nikolic, B. Milanovic, D. Vucicevic, A. Valjarevic, B. Todorovic, "Imapact of Radar Cross Section on HF Radar Surveillance Area: Simulation approach", In Proceedings of 2015 IEEE Radar conference, Johannesburg, RSA, 2015.
[12] Z. Ding, P. Moo, "Design of an IMM-NNJPDA tracker for HFSWR", In Proceedings of the 17th International Radar Symposium (IRS), 2016, pp. 1-5.
[13] N. Stojkovic, D. Nikolic, B. Dzolic, N. Tosic, V. Orlic, N. Lekic, B. Todorovic, "An Implementation of Tracking Algorithm for Over-The-Horizon Surface Wave Radar", In Proceedings of the 24th Telecommunications Forum (TELFOR), Belgrade, Serbia, 22-23 Nov. 2016.
[14] ITU-R Recommendation P.372-11, September 2013.

[15] D. Nikolic, N. Stojkovic, N. Lekic, "Maritime over the Horizon Sensor Integration: High Frequency Surface-Wave-Radar and Automatic Identification System Data Integration Algorithm", *Sensors*, vol. 18, no. 4, article no.1147, 2018.

[16] D. E. Barick, "Theory of Ground-Wave Propagation Across A Rough Sea at Decameter Wavelengths", Battelle Memorial Institute, 1970.

[17] S.V. Vaseghi, "Advanced Digital Signal Processing and Noise Reduction 4th ed", John Wiley and sons ltd., 2008.

[18] G. Chen, Z. Zhao, G. Zhu, Y. Huang, and T. Li, "HF Radio-Frequency Interference Mitigation", *IEEE Geoscience and Remote Sensing Letters*, vol. 7, no. 3, July 2010.

[19] V. Milovanovic, "On Fundamental Operating Principles and Range-Doppler Estimation in Monolithic Frequency-Modulated Continuous-Wave Radar Sensors", *Facta Universitatis, Series: Electronics and Energetics*, vol. 31, no. 4, pp 547-570, 2018.

[20] S.J.Anderson, "Optimizing HF Radar Siting for Surveillance and Remote Sensing in the Strait of Malacca", *IEEE Transaction on Geoscience and Remote Sensing*, vol. 51, no. 3, pp. 1805-1816, Mar. 2013.

[21] M. M. Weiner, "Monopole Antennas," New York – Basel: Marcel Dekker Inc., 2003.

[22] J. O. Smith III, "Spectral Audio Signal Processing," W3K Publishing, 2011.

[23] H. L. Van Trees, "Optimum Array Processing, " John Wiley & Sons, Inc., 2002.

[24] H.J. Orchard, R.S. Elliott, G.J. Stern, "Optimizing the synthesis of shaped beam antenna patterns", In Proceedings of the IEE Microwave, Antennas and Propagation, H 132, Mar. 1985, vol. 1, pp 63 – 68.

[25] O. M. Phillips, "Radar returns from the sea surface—Bragg scattering and breaking waves," *J. Phys. Oceanogr.*, vol. 18, pp. 1065-1074, 1988.

[26] X. Lu, J. Wang, R. Dizaji, Z. Ding, A. M. Ponsford , "A New Constant False Alarm Rate Technique for High Frequency Surface Wave Radar", IEEE CCECE, 2004.

[27] D. Ivković, M. Andrić, B. Zrnić, "Detection of Very Close Targets by Fusion CFAR Detectors, " *Scientific Technical Review*, vol. 66, no. 3, pp. 50-57, 2016.