Fifteen years of HF-Surface-Wave radar for maritime surveillance

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Abstract

The Helzel Over the Horizon radar (OTHR) is an FMCW HF radar for monitoring targets within the exclusive economic zone (EEZ). It has many advantages compared to classical pulsed HF radars like a much lower rf-noise emission, no blind range and less in-band noise. It is originating from the WERA (WEllen RAdar) HF radar for oceanographic applications. We describe the development from the HF radar WERA to the maritime surveillance radar OTHR and basic principles and technologies for this type of HF radar to use it as an instrument in a network of multi sensor trackers. It is an example of technology transfer and ongoing knowledge exchange between scientists, engineers and maritime stakeholders.

Keywords: OTHR, HF, surface wave radar, surveillance, ship detection, WERA

INTRODUCTION

Many different surveillance instruments are monitoring the maritime exclusive economic zone (EEZ). These have all their advantages and limitations. Two main instruments are shore-based radars and satellites. Microwave radars are constantly scanning the area around them with a low data latency but with a limited line of sight and should be installed on a high position. Satellites, on the other hand, are monitoring very large areas but with a high data delay and gaps in time and coverage.

An instrument that is monitoring large areas with a low data latency is the High Frequency radar (HF radar). First HF radars for ship detection work similar to microwave radars in a pulsed mode and their lower frequency allows a longer range but the lower frequency goes hand-in-hand with bandwidth- and noise-problems. Operators of microwave radars get much easier bandwidths than operators of HF radars because the scale for the same bandwidth between both techniques is 1:1000. This means HF operators often need several percent of their frequency as bandwidth while microwave operators are often below one percent. Another disadvantage of pulsed microwave radars is the blind range for the first kilometers resulting from the switching between sending and receiving.

For observation of currents and waves oceanographers are using HF radars with frequency modulated continuous waves (FMCW) instead of pulsed signals for observation of currents and waves to overcome these problems. These specific HF radars are sensitive at small bandwidths and do not have a blind range, albeit there are oceanographic HF radars using FMiCW that still have this blind range. In 1955, Crombie found specific signals from the ocean’s surface when radiating HF waves [1] which were related to the ocean currents. Later, Hasselmann linked these and other specific signals and to ocean waves [2] in 1971. These specific signals are very hard to detect and the hardware has to have a very low noise floor and a long coherent measurement time to extract these hidden information from the ocean. This is possible with FMCW radars that can send and receive at the same time with a low output power that reduces unnecessary noise. Nowadays, HF radars like WERA are the state of the art for observing currents and waves in large areas (120 degrees of azimuth, more than 200km range). The technical development over the last decades lead to a high reliability of this technology [3].

During one of these technical development steps, where Gurgel tried to remove the noise from ships [4], first experiments with the FMCW HF radar WERA for ship detection were made. Over the years the techniques for detecting ships improved. In 2011 Helzel manufactured HF radar for ship detection hardware for OEM partners and in 2017 launched it’s own radar for ship detection, named “Over the Horizon Radar”. This process will be shown in the next section. In a second section we will describe basic principles for ship detection.

HISTORY OF OTHR

OTHR is a successor of WERA that is used for observing oceanographic parameters. WERA had been developed at the University of Hamburg in the 90’s and was later industrialized by Helzel Messtechnik GmbH. Experiments to reduce the noise created by ships led to the idea to spin-off an explicit HF radar for monitoring vessel movements that was later named Over The Horizon Radar (OTHR). Improvements at this radar were made as well as a multi sensor tracker developed that form the basics of the nowadays OTHR.

Table 1: Summary of the development of WERA/OTHR

Date	Development step	Published
1995	First experiments with new low noise radar concept	Yes [5]
1999	First industrialized WERA systems	Yes [6]
2004	First ship detection experiments with WERA by University of Hamburg	Yes [4]
2006	Raytheon used WERA at Germany Bight for ship tracking tests	Classified
2007	Start of Ship detection and tracking software development at HELZEL in co-operation with EADS and University of Hamburg and TU Hamburg-Harburg	Yes [7,8]
2008	French researchers used WERA for ship detection evaluations	Yes [9]
2009	NATO Research center (NURC) starts evaluation with WERA and develops multi sensor tracker	Yes[10, 11]
2010	WERA for ship tracking is registered as Dual-use instrument at German Export Control Authority (BAFA)	-
2011	First OEM contract with another radar manufacturer to use the HF radar core for their product.	No
2011	First export of HF radar system for ship tracking	No
2011	NATO Research (CMRE, successor of NURC) started WERA ship tracking evaluation in German Bight	Yes [12,13]
2013-2014	Ship detection and tracking experiments with 5.3 MHz WERA in the polar region by the Norwegian Navy (FFI)	Classified
2016	Three HF radar systems for ship tracking operational	Classified
2017	Spin-off of OTHR as a specialized HF radar	No
2018	Multi sensor tracker experiments in the Gulf of Guinea	Yes [14]

A group around Essen and Gurgel at the University of Hamburg developed the HF-WERA system in the 90’s. They started in the 80’s with a commercial HF radar from NOAA[16] for measurements of ocean currents in the German Bight and steadily improved the radar’s performance[17]. At some point, the existing hardware wasn’t able to fulfill the requirements of these scientists which lead to a complete redesign of the HF radar: A saw-tooth-like frequency modulated continuous wave (FMCW) replaced the pulsed signal to remove the blind range in the first few kilometers, improved the range-resolution by a factor of ten and increased the sensitivity of the signal to noise ratio (SNR). The antenna-design changed from four antenna square-array to a linear array of 16 antennas allowing using beam-forming algorithms that lead to a significant improvement of azimuthal resolution [5,6] and improved results in heavy ship traffic [18]. For a detailed review about current status of HF radars for oceanographic applications see [19].

This experimental radar was then industrialized by Helzel Messtechnik GmbH in 1999.

Experiments with WERA to reduce noise during wave measurements lead to the byproduct of ship detection. Ships can heavily influence the performance for getting wave and current information. They are creating a static signal on top of a Gaussian noise. These static signals – or ships – can be identified by the Constant False Alarm Rate (CFAR) algorithm [20]. Identifying, allows removing ships from the spectra for better results of wave parameters [4]. This method was applied at 2004 at the University of Hamburg and can be seen as the first ship tracking experiment with a WERA HF radar and the beginning of OTHR.

Between 2005 and 2008 a network of different stakeholders established a monitoring system in the German Bight. This North-Sea Monitoring Project (OMS) was supported by the North-German state Schleswig-Holstein. During this project, several HF radars have been used to monitor this area.

In a cooperation with EADS and ATLAS the ship detection algorithm had been improved and a probabilistic tracker was implemented [7,8] around 2007. To improve the false detection rate, physical parameters, like the range power dependency have been implemented and neighboring grid cells taken into account to create an adaptive power threshold that had a much better performance than the first simple implementation.
These improved detects were used in the first ship tracking algorithm again. This new algorithm was using a Kalman like Alpha-Beta tracker to generate tracking states which consists of position and velocity for possible targets. First comparisons with AIS showed a difference between AIS and radar positions of less than 1 km for 77% for all targets in AIS range.

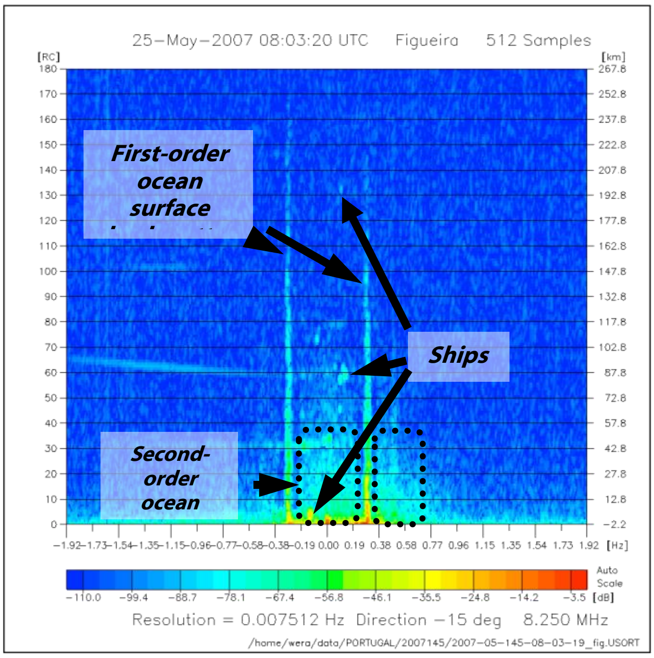

Fig. 1: Typical Range-Doppler map

From 2008 on, French researches started to use WERA for ship detection [9]. They applied the Morphological Component Analysis (MCA) techniques to detect ships. MCA is a technique that allows to extract targets from a spectrum, depending on their geometrical appearance. This algorithm works directly on the Range-Doppler-Map (fig. 1). The research showed that this algorithm has an improved performance compared with CFAR when the background has a lot of noise.

In 2009 the NATO Undersea Research Center (NURC) started as to investigate WERA radars. Their first project was to analyze the dependency between range and signal amplitude of targets, where they found a good fit to a Raleigh distribution and explained discrepancies between distribution and real data with noise sources 10]. In a second project a first kind of multi sensor tracker was established by combining the results of two overlapping WERA systems[11] and comparing it with AIS data.

In the same year, WERA was used especially for Ship Tracking the first time [21].

The Center for Maritime Research and Experimentation (CMRE), successor of NURC, continued to work with data from the German Bight and with two WERA stations at the Ligurian Coast (West Italy) [12,13]. They analyzed the performance of data fusion and two different tracker algorithms for multi target tracking.
Performance of data fusion was measured by comparing single WERA with the combination of two WERA. Here they found a significant improvement of about √2 for the accuracy, False Alarm Rate and Time on Target. The two different tracker algorithms were implemented and compared to the CFAR detection algorithm. The tracker outscored the CFAR detection method in nearly all scenarios and especially the False Alarm Rate by a factor of ten.

In 2017, the gained experiences and scientific research in ship tracking with WERA that took place for over 13 years lead to the decision to spin-off a specialized HF radar from the WERA. This was called Over The Horizon Radar (OTHR). It is a specialized version of an HF radar that is focusing on the techniques to detect ships with specific hardware and software components.

Field experiments from an OTHR-like system show the automatic combination of two HF radars with satellite- and land-derived AIS data [14]. With this technique the software combines HF radar with AIS and marks the ships with the information from AIS[15]. When the ship leaves the coverage of AIS it will be still identifiable with HF radar information. This comes in handy for automated monitoring of the EEZ.

BASIC PRINCIPLES

PHYSICAL Aspects:

Several physical aspects influence the performance of the OTHR. The signal generator creates the signal which is amplified and sent to the transmit antennas. This transmitted signal hits a target, reflects and travels to the receive antennas and then to the receivers where it will be sampled for analyzation.

A simple method to increase the detection range can be achieved by increasing the output power but this has a few drawbacks. The OTHR generates the main signal and amplifies this with the low-noise power amplifier. This amplification results in a power output up of 0.1kW to 1 kW which is quite small compared to pulsed radars that are using several kW peak power. Increasing the output power increases the range but the effect is quite costly: The output power scales to the fourth power of the range [fig. 2]. Another costly factor is the distance between the transmit and receive antennas. Since the OTHR is sending and receiving at the same time, the distance between sending and receiving

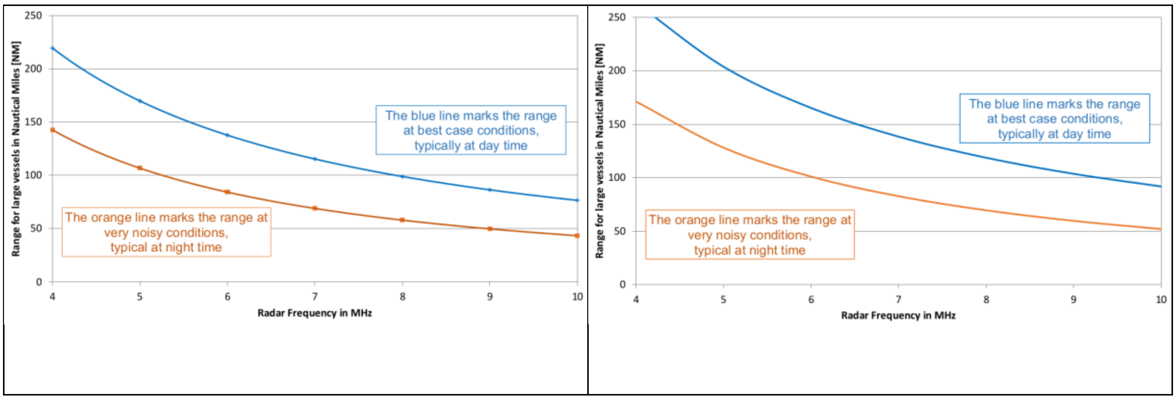

Fig. 2: Typical ranges for detection large ships for 100 (left) and 1000 Watt (right).

antennas has to be increased when power is increasing, otherwise the receiver will drive into saturation by the direct signals from the transmit antennas to the receive antennas.

The design of the transmit and receive antennas has a significant influence on the performance of the radar. A well-tuned antenna-array transmits and receives the electromagnetic waves very good. The receive array consists of a linear array of 16 monopole antennas with a length less than $\lambda/4$ and a distance of $\lambda/2$ that are individually tuned to fit to the environment. Current development allows the use of active broadband antennas that are much smaller in size and do not have to be tuned. The transmit array consists of four $\lambda/4$ monopole antennas that are ordered rectangulary which allows to transmit most of the energy to the ocean and provides a null in the direction towards the receive array.

This specific set-up of receive antennas allows the usage of beamforming algorithms that is the most accurate range-azimuth-resolver algorithm for ship detection at the moment. Another popular set-up of receive antenna array is using much fewer antennas and is using the direction finding method instead of the beamforming method to resolve the location of possible targets. The drawback of this direction finding method compared to beamforming method is a decreased performance in observing oceanographic parameters in the presence of ships [18].

The transmit antenna is radiating a vertical polarized electromagnetic wave. Electromagnetic waves normally propagate in a straight line resulting in shadow zone behind the horizon (space and sky waves) but due to the salt the conductivity in the ocean is much higher than in the air resulting in a wave that is following the curvature of the earth (ground wave) and seeing behind or Over The Horizon.

The frequency of the electromagnetic wave also influences the performance – longer waves have a longer range while shorter waves have a shorter range. HF is defined for wavelengths between 10 (30 MHz) and 100 meters (3 MHz), which results in theoretical ranges between 30 and 500km.

Another frequency related performance impact is the size and orientation of the target. Since the electromagnetic waves of an OTHR are vertically polarized the target has to have some vertical structure that is conductive. The beam then does only see the normal projection (silhouette) of the ship, the radar cross section. This radar cross section heavily depends on the orientation and vertical size of the ship regarding to the radar beam. Apart of simulations there is no deterministic way to guess the radar cross section of a ship. This means that two identical ships in the same distance but with different courses can result in only one detection as well as different sea states change the effective vertical size.

Another important parameter is the radar bandwidth. It is the bandwidth in the frequency allocation, that directly affects the range resolution as well as the noise. Increasing the bandwidth allows the radar to decrease the range-cell depth. The noise automatically decreases for a range cell when its size decreases.

NOISE, Jamming and countermeasures

The OTHR‘s performance is mainly limited by noise. Sources of noise are the the system‘s noise figure and external noise. The system‘s noise figure is already below the environmental noise by design so we only care about external noise. Various techniques exist to identify, remove and avoid same external noise.

The OTHR can detect and differentiate between targets and noise simultaneously [22]. This is possible due to the specific frequency modulation the radar is using. This Radio Frequency Interference (RFI) reduction is the basic technique to remove external noise.

Additional, the OTHR can identify and avoid bands with strong external noise by means of the listen-before-talk method [23]: The radar is scanning the environment before a measurement in the allocated frequency band. Then, the radar may select a reduced bandwidth in this band that has the lowest noise level. This method is especially useful, when noise sources are changing slowly in the order of several minutes.

If the noise source is changing rapidly, eg. due to electronic countermeasure, both mentioned methods to reduce the noise aren‘t sufficient anymore. Then, frequency hopping can be activated. In this case, the radar constantly scans the environment and changes it‘s frequency bandwidth on demand.

External noise sources can be located by using the azimuthal resolution of the radar. If two radars can identify the source, then the location can be derived by triangulation.

MULTI Sensor Tracking

Multi sensor tracking is the combination of several sensors of same or different type. This combination leads to significant improvements in the accuracy and the reliability of the tracker.

From a statistical point of view, the detection of a position from one single source for one target follows a Gaussian distribution. Combining two or more of these detects will improve the accuracy square-root like [24].

It is always preferable not to rely on one system or technique because if one sensor fails the remaining ones still operate – so, from a technical point of view, multiple sensors create redundancy.

Different types of sensors can create an additional level of protection against jamming. If the sensor network is using different frequencies and modulations techniques it is harder to interfere them all simultaneously. If combining different techniques, e.g. radar with optical satellite measurements the level of protection is growing constantly.

Fig. 3: Example of a multi sensor tracker result with OTHR and AIS data. Purple lines are OTHR results and blue lines from AIS. With courtesy of Vlatacom, Serbia [14].

Nowadays, it is standard to combine different radar sources with AIS information in a multi sensor tracker to monitor the exclusive economic zone (fig. 3) [14]. Here, techniques like the suspicious target detection and the seamless combination of AIS and HF data helps operators to classify ships [15].

ENHANCED Antenna Design

The main characteristics of a radar, like the pattern and sensitivity, can be influenced by the antenna layout. The number of antennas with constant spacing defines the effective area and the width of the main lobe, that means the more the better. For an antenna array length of some 100m for 16 antennas, space is often the limiting factor. Modern techniques like MIMO can reduce the required array length by keeping a small footprint. Active antennas are less sensitive than passive antennas but smaller in size which reduces the visual impact (fig. 4) and got other advantages as described below.

Fig. 4: Two different kinds of antennas. Left: active receive antenna with low visual impact, right: passive transmit antenna.

Multiple Input Multiple Output (MIMO) is a common technique in wireless communication systems where multiple transmit antennas and multiple receive antennas are combined. Adding a second transmit array in a

defined distance extends the receive array virtually by this distance. This allows to set up a real receive array of eight antennas that results in eight virtual antennas, summing up to 16 antennas [25] (In practice you build up nines antennas to have one overlapping antenna between real and imaginary antennas).

Another way to enhance the radar's flexibility is to use Dual Frequency, where two different transmit arrays with two different frequencies and one receive array with active broadband antennas can be used to use two frequencies alternating [26]. This method will result in two different radar systems in one: One system with the lower frequency has a better range then the system with the lower frequency, while the system with the higher frequency can probability detect smaller ships than the system with the lower frequency.

Summary

The development of FMCW HF radar for oceanographic observations lead to the usage of this technology for the maritime surveillance.

Many improvements have been made and these from the oceanographic system (WERA) influenced the ship detection (OTHR) and vice versa. It is a good example for knowledge transfer between scientists and engineers.

OTHR is best used as a part of a multi sensor tracker but can also be used solo since it covers the range of the EEZ in nearly real-time without a blind range.

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