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HF Radar WERA Application for Ship Detection and Tracking

High-Frequency (HF) radars are operated in the 3-30 MHz frequency band and are known to cover ranges up to several hundred kilometers. Low power HF radar systems have been developed especially for oceanographic applications. They use electromagnetic surface wave propagation along the salty ocean. The WERA HF radar system transmits an average power of 30 watts but it achieves detection ranges up to 200 kilometers, which are far beyond the conventional microwave radar coverage. Due to external noise, radio frequency interference, and different kinds of clutter, special techniques of target detection using the WERA system have to be applied. For a 12-hour period HF radar data have been recorded and processed. The target locations detected by the HF radar using the proposed adaptive technique are passed to a tracking filter to track the ship position. In order to estimate the performance of the radar detection and tracking techniques, these ship locations are compared with the ship positions recorded by the Automatic Identification System (AIS).

1. Introduction

The high frequency (HF) radar, which is based on surface wave propagation, provides a unique capability to detect targets far beyond the conventional microwave radar coverage. HF radars use the frequency band of 3-30 MHz to provide a large coverage that could extend to more than 200 kilometers in range. These maximum range values are of high interest for many applications including ship detection, tracking, and guidance, as well as search and rescue, distribution of pollutants, fishery and research in oceanography as they appear in consequence of the United Nations Convention on the Law of the Sea established 200 nautical miles as the Exclusive Economic Zone (EEZ). Continuous maritime surveillance of activity within a nation's EEZ is a key question in protection of national sovereignty. These radar systems recently became an operational tool in coastal monitoring worldwide.

It is well known that HF radar's performance depends on its ability to detect and track targets at long ranges. At HF band the environmental noise dominates the pure receiver noise, and the various sources of interference have different characteristics. The main contribution within HF radar echo is due to scattering from the ocean surface. The nature of this signal depends on radar carrier frequency, beam width, polarization

and system configuration. As ocean waves are moving targets, they cause Doppler shifts in any radiation which is scattered from them.

It is supposed that the major mechanism of the interaction between the incident electromagnetic wave and the ocean waves is the so-called Bragg scattering. In case of a monostatic radar, the dominant contribution is produced by scattering from ocean waves having half of the radar wavelength and moving towards and away from the radar site. This first-order resonant scattering effect results in two dominant peaks in the Doppler spectrum called Bragg lines [1]. Second-order scattering is caused by the interaction between crossing sea waves, which leads to side bands around the Bragg lines, also referred to as the second-order continuum. Therefore, the sea clutter can be characterized as a distributed, non-directional source. For ship detection and tracking procedures the sea clutter can be considered to be an unwanted, self-generated interference. One of the important properties of the HF sea echo is its random nature. The external noise and the interference levels will ultimately limit the detection capability of the radar system.

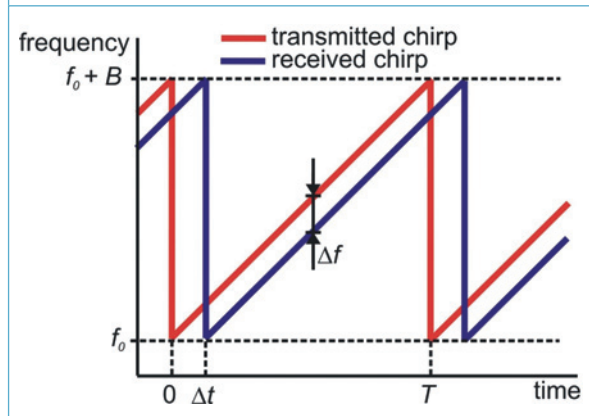
The HF radar system WERA (WEllen RADar) was developed at the University of Hamburg, Germany, in 1996 to allow a wide range of working frequen-

cies, spatial resolution, and antenna configurations in order to operate as a low power oceanographic radar providing simultaneous wide area measurements of surface currents, ocean waves and wind parameters [2]. WERA is based on a modular design that can be easily adopted to the requirements of an actual application. The WERA system has been set to continuous data acquisition mode during a ship detection and tracking campaign for several months [3]. The WERA system installation is shown in Fig. 1.

Figure 1: The HF radar WERA system installation.
a) the transmitting array; b) the receiving array.



Figure 2: Linear frequency chirp signal.



WERA transmits a low power of 30 watts but can achieve a detection range up to 200 kilometers, which is far beyond the conventional microwave radar coverage. It uses frequency modulated continuous wave (FMCW) mode for simultaneous range and Doppler frequency measurements, hence the transmitter and the receiver are operated simultaneously. WERA transmits linear frequency chirps, where the frequency shift Δf between the transmitted and received echo determines the target range (see Fig. 2). The range cell depth is related to the bandwidth B of the chirp signal.

The range resolution is performed by the Fourier transform of each single chirp signal. Thus the range resolution is defined as $\Delta R = \frac{c}{2B}$ where c is the speed of light, B is the frequency bandwidth of the chirp signal. The complex valued Fourier amplitudes of the chirps determine the samples of the slowly varying modulation of the backscattered signal, which contains the information on the ocean surface variability.

The attenuation of the electromagnetic wave traveling along the sea surface depends on the radar frequency and on the conductivity (salinity) of the water. The radar frequency is selected carefully, taking into account the use of the radio spectrum by communication services [4]. The values for the highest possible range resolution of the radar system are limited by the available chirp signal bandwidth (the width of the gaps in the radio spectrum). To find the optimum radar operating frequency and bandwidth, frequency scans are started regularly. In case of a highly occupied radio spectrum, the bandwidth is reduced. A typical bandwidth in the 8 MHz frequency band is

$B = 100$ kHz, which corresponds to a range resolution of $\Delta R = 1.5$ km.

The azimuthal angle covered by WERA is $\pm 60^\circ$ perpendicular to the linear receive antenna array that consists of 16 antenna elements located along the beach as shown in Fig. 1b.

This paper describes a new approach to utilize the WERA system in order to detect and track ships. To evaluate the quality of the radar detections, a data set of GPS acquired ship locations provided by the Automatic Identification System (AIS) was recorded for a 12-hour period.

2. Proposed Ship Detection and Tracking Techniques

2.1 Adaptive Ship Detection Technique

The main interference contribution for the WERA system is due to the sea surface echo signals. In a range-Doppler frequency map the so called Bragg lines are observed permanently and limit the target detection performance. The technical challenge is to detect targets in this strong interference environment and to control the false alarm probability.

Classical target detection using a constant false-alarm-rate (CFAR) algorithm follows the beam forming and fast Fourier transform in a HF radar data processing chain. The typical HF echo signal environment is shown in Fig. 3 and illustrates the complexity of the ship detection process. Most of the observed signal

components are labeled in Fig. 3, which includes sea clutter (resonant scattering of the first and second order), ionosphere interference, radio interference, several ship and aircraft targets. Due to the complexity of the real signal environment it is desirable to employ adaptive procedures in the detection process to adjust to the varying clutter, noise and interference levels.

During a radar run, new radio frequency interference (RFI) may have occurred before the radar carrier frequency and bandwidth are re-adjusted by the next frequency scan. In this case, a special algorithm is used to derive and subtract the RFI's structure from the range-Doppler frequency maps.

We consider a set of processed radar data in range, Doppler frequency (velocity) and azimuthal angle corresponding to a single snapshot collected by the HF radar. We apply the detection algorithm to the range-Doppler power spectrum map for each azimuth beam direction. The range-Doppler map statistics may vary from snapshot to snapshot therefore we have to detect ships against a background signal, which has an unknown distribution of echo signal amplitudes.

Detection of a target echo signal can be expressed with hypotheses H_0 (no target is present) and H_1 (target is present). CFAR methods usually formulate a test statistic for each cell of interest and compare it to some amplitude threshold [5]. The CFAR threshold calculation is usually based on the Neyman-Pearson criterion with a fixed probability of false alarm and a maximum probability of target detection. A detection decision must be processed for each range-Doppler cell individually.

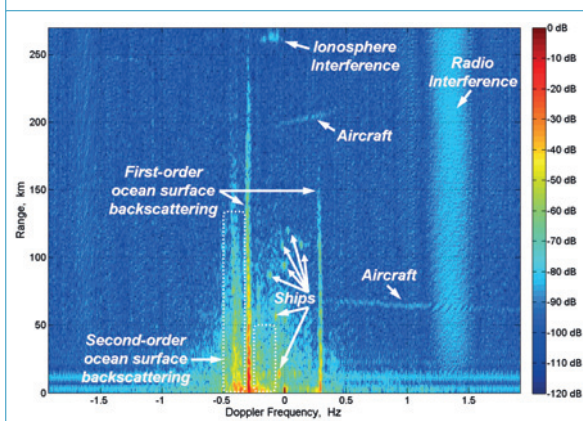
The detection scheme based on the conventional curvilinear regression analysis [6] was discussed in [7] and applied to a logarithmic scaled power spectrum along the range and Doppler cells respectively. The examples of regression curves and their upper confidence bounds are shown in Fig. 4.

The adaptive threshold T at the specified test cell is set as

$$T = \max\{T_{\alpha,R}, T_{\alpha,D}\} \quad (1)$$

where $T_{\alpha,R}$ is the $100(1 - \alpha)\%$ upper confidence bound value for the power regression curve along range, $T_{\alpha,D}$ is the $100(1 - \alpha)\%$ upper confidence bound value for the power regression curve along Doppler frequency.

Figure 3: Example of an HF radar range-Doppler map



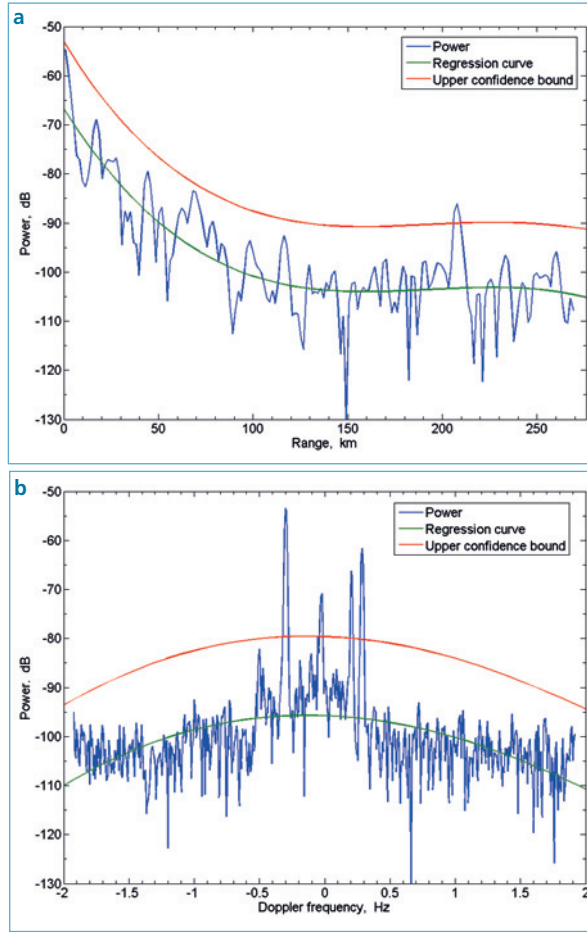


Figure 4: Examples of a power spectrum with the regression curve thresholding procedure
a) along the range cells;
b) along the Doppler frequency cells.

The range-Doppler test cell value Y is compared with the threshold T using the test rule

$$\begin{array}{l} \text{Target} \\ Y > T. \\ \text{No target} \end{array} \quad (2)$$

To reduce the sidelobes due to beamforming, an Ultra Spherical windowing function has been applied and the phases to steer the beam have been calculated to focus to the target location. A Blackman-Harris window function has been used for FFT processing of the range-Doppler power spectrum maps. Due to applying windowing functions in radar data processing and variations in range, angle, and speed of the target, the test decision can be spread over several

adjacent cells. To eliminate this effect an additional technique is applied and based on ordered statistics CFAR to determine local peaks in range, Doppler, and azimuth. Thus an additional rule is proposed

$$\begin{array}{l} \text{Target} \\ Y > \max_{1 \leq i \leq n, 1 \leq j \leq m, 1 \leq k \leq l} \{X_{i,j,k}\} \\ \text{No target} \end{array} \quad (3)$$

where the set of power values $\{X_{i,j,k}\}$ is formed from the cells that surround the test cell Y within a given frame of $n \times m \times l$ cells. The local noise level for an identified maximum Y is taken at 33% of the ordered power values. The test cell Y is accepted as an identified radar target, when it is located in the centre of the frame and its local signal to noise level is at least 6 dB. Range, Doppler, and azimuth values are calculated from the peak indices using a centre of mass algorithm based on the values within the frame. Besides the average, the variance values for range, Doppler, and azimuth are calculated.

It can happen that interference dominates the range-Doppler maps after beam forming, which may even be more powerful than the target echo. In this case we propose to keep all local maxima identified by the detection technique. The false detections due to interference or high side lobes will be identified and deleted in the tracking procedure.

2.2 Proposed Ship Tracking Technique

Using polar coordinates allows performing tracking in the same system from which the radar measurements are obtained. As a final detection from the CFAR we get the range, Doppler frequency (or radial velocity) and azimuth values. Therefore we propose to use the tracking model in polar coordinates.

The range, azimuth and radial velocity values form a plot for each detected target and time measurement scan. The tracking procedure needs to associate each target plot with a track. So we apply a gating technique, i.e. we use the gating statistical distance [8]:

$$d^2 = \left(\frac{R_p - R_o}{\sigma_R} \right)^2 + \left(\frac{\theta_p - \theta_o}{\sigma_\theta} \right)^2 + \left(\frac{V_p - V_o}{\sigma_V} \right)^2$$

where (R_p, θ_p, V_p) is the predicted position, (R_o, θ_o, V_o) is the detected measured position, σ_R^2 , σ_θ^2 and σ_V^2 are the variances of $R_p - R_o$, $\theta_p - \theta_o$ and $V_p - V_o$ respectively.

To make a decision whether we should associate the detected location to a previously formed track, we test if the coordinates and radial velocity of a new plot satisfy the inequality

$$d < \Delta d$$

where Δd is a constant gating threshold. Detected locations are assigned following the nearest neighbour approach.

The tracking filter includes three main steps for a single iteration: measurement, prediction, and update. For the update step we use a scheme similar to the well-known α - β tracker [8], but we extend it to our tracking state vector, which consists of range, azimuth as well as radial and angular velocities.

After each update step we make a test to delete false targets. An assignment counter for each track is incremented by two after a successful assigning a detected location and it is decremented by one, if no location can be assigned. The counter is limited to ten steps. If the track assignment counter drops below -2, then this track will be deleted. This approach allows to bridge short times when the radar detection lost the target. Not-assigned detected locations may form the start of a new track and are added as an initial value.

3. Test Results Using Measured WERA Data and AIS Data

The proposed signal processing techniques for detection and tracking of ships have been tested using the data measured by the WERA HF radar system. An example of a range-Doppler power spectrum map for a specified beam direction is shown in Fig. 5. The coherent integration time of a single snapshot was set to $T_c=133$ s for each range gate. Range-Doppler maps were updated every 33 s. It can be seen in this figure that several kinds of clutter mentioned above are present and the detection task is still complicated to solve in this specific but characteristic environment.

The 95% upper confidence bounds have been set for the regression thresholding along range cells using a 2nd order polynomial and the regression thresholding along Doppler cells using a 3rd order polynomial. In this way the threshold for each range-Doppler cell was calculated using (1). The result after applying the test rule (2), which gives target locations for a selected azimuth, is shown on the range-Doppler map by black crosses (see Fig. 6).

The WERA system was operated continuously for several months. The data shown in this paper have been acquired during a 12-hour period, when ship locations reported by the Automatic Identification

Figure 5: Measured range-Doppler map for the radar beam at -18 degrees azimuth

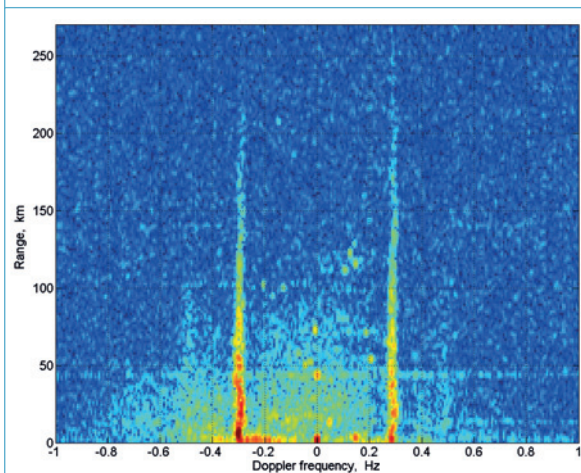
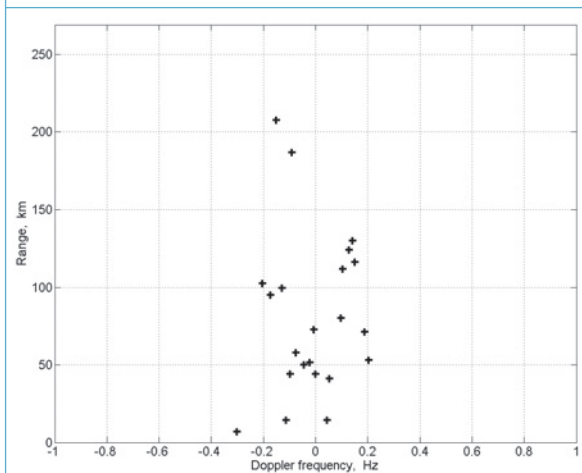


Figure 6: Range-Doppler detection map for the radar beam at -18 degrees azimuth using the proposed detection technique




System (AIS) have been recorded. The detection scheme has delivered plots to the tracking algorithm every 33 seconds, which have been passed to the tracking algorithm. The results of the tracking procedure are shown in Fig. 7. Here the detections and tracks of real moving ships can be observed. The single colorful bullets in the figure show the ship locations observed at the tracker output, where the color indicates the ship's radial velocity measured by the HF radar. The size of the bullet refers to the tracking assignment counter. Large bullets show a constant uninterrupted track, small bullets indicate that the predicted location could not be confirmed at some of the recent tracking steps. The blue tails behind each ship show the recorded track for the last 30 minutes of ship movement. The black crosses correspond to the AIS data indicating the real ship movement in the observed radar coverage. When the radial component of the ship's speed is close to the speed of the Bragg-resonant ocean waves, the crosses

are marked in red indicating that the ship's echo may be hidden. Note that this frequency band around the Bragg lines may shift due to ocean currents.

In many cases, the radar detected a target close to the location reported by AIS. However, there are several ship locations given by AIS, which have not been detected by the radar. The main reasons could be the following:

- The ship's echo strength is below the threshold. To solve this case a better signal-to-noise ratio is required.
- Two or more ships are sailing at the same radial component of the ship's speed within the same resolution cell in range and azimuth. In this case, the strongest echo of only one ship is detected. This case can be solved by increasing the radar's azimuthal and range resolution.





Ocean Data "à la carte"

The new and unique "WERA Permanent" mode allows for optimisation of the data integration time simultaneously for various tasks:

- **OCEAN CURRENTS**
 - in dynamic ocean areas with highest temporal resolution of 3 to 10 Min
 - for ranges of 30 km to more than 200 km
 - with fine spatial resolution
- **WAVES**
 - accurate wave data for each grid point up to 100 km with an integration time of 20 ... 30 min.
 - Significant wave height,
 - directional wave spectra, etc.
- **WIND**
 - Wind Direction up to 200 km
 - Wind Speed* up to 100 km
 - *under investigation

WERA data can be used for various applications:

- Search & Rescue
- Port Authorities
- Met-Offices
- Scientists
- Fishing Industry
- Environmental Protection
- Off-Shore Installations
- Homeland Security
- Disaster Warning

for time critical applications the data update rate can be reduced to less than 1 min.

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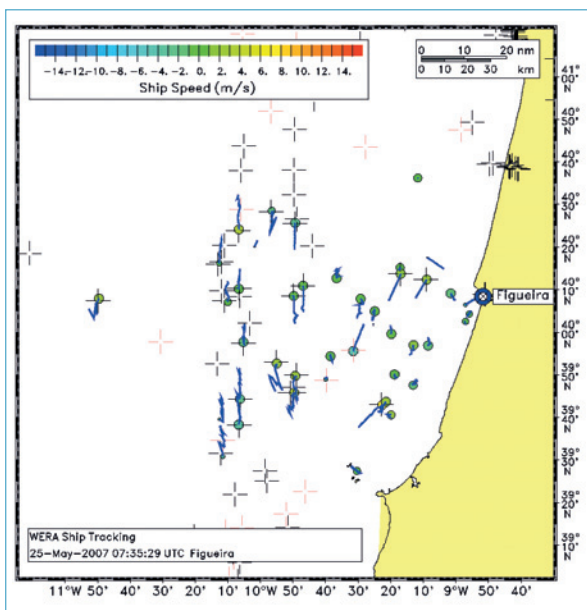


Fig. 7 Detection and tracking results of the WERA system (bullets) and AIS records (crosses)

(Figure by courtesy of Atlas Elektronik GmbH, Germany)

- c) The ship velocity is within the Bragg frequency range and the echo is masked by the sea clutter. In this case, the second radar located about 100 km away will be able to detect the ship due to a different radial speed. Other solutions are either to change regularly the radar's operating frequency band, which shifts the Bragg lines, or to apply an algorithm to remove the strong first-order scatter.

There are also some cases when the radar detected ships, which were not equipped with AIS. These are probably smaller ships, e.g. fishing boats. We are quite sure that these echoes are due to ships, as they move from plot to plot very consistently. As their tracks for the last 30 minutes are quite short, these ships sail at a slow speed or drift during fishing.

Fig. 7 shows also the results of the developed detection and tracking software. A ship, which was tracked by WERA and reported by AIS, can be observed at a range of 170 km off the coast for this example.

To verify the detection and tracking results obtained by the radar, ship locations reported by AIS have been recorded for a 12-hour period. To get the error of the radar measured locations, a table containing the absolute distances between all AIS and all radar detected

locations is set up. Further the minimum absolute distance is obtained from this table to assign an AIS location to a radar track. After this data pair has been stored, these AIS and radar locations are removed from the table and the next minimum is searched. We define a gating distance of 5 km. Once the absolute distance is above this gating distance, we stop the assignment.

Within the 12 hours 1,250 time steps have been analyzed. A total of 17,700 comparisons are available within the gating distance to calculate the statistics. Fig. 8 shows the probability distribution with the normalized frequency for these cases. The cumulative distribution function gives 77% probability for deviations less than 1 km.

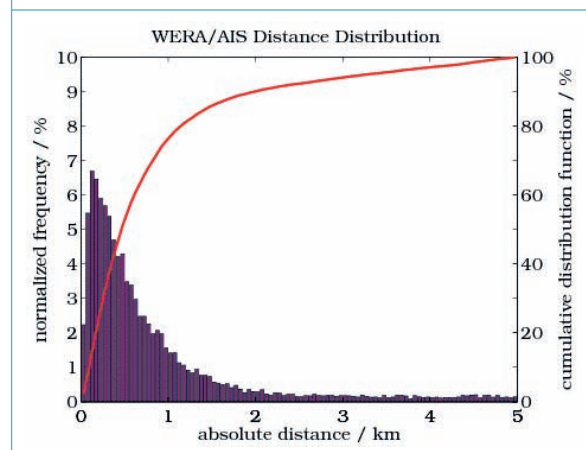
These are preliminary results. To describe the detection and tracking performance of WERA, more comparisons including different sea states and radio interference conditions are required. Also the size of the ships has not been taken into account.

4. Conclusions

This paper presents an approach to utilize the low power HF surface wave radar WERA in order to detect and track ships sailing within the radar coverage area. A new signal processing approach based on an adaptive power regression thresholding and an ordered statistics constant false alarm rate (CFAR) has been implemented.

Fig. 8 Normalized frequency and cumulative distribution functions of the absolute distances between AIS ship locations and ship locations detected by WERA

(Figure by courtesy of Atlas Elektronik GmbH, Germany)



The ship tracking scheme is based on polar coordinates and uses a tracking state vector which consists of range and azimuth as well as its velocities. To analyze the radar detections and tracking results, a data set containing the AIS information about ship movement was recorded for the 12-hour period and compared to the obtained results. Comparisons have been made for a maximum distance of 5 km between AIS and radar detected locations. The deviation between AIS and radar detected locations was below 1 kilometer in 77% of these comparisons. A number of ships was detected and tracked by the radar, but could not be used for comparisons due to the lack of AIS information. The ship detection and tracking results based on the real WERA HF radar data processing show a good performance of the proposed schemes.

Acknowledgment

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