Ocean Surface Current Measurements by HF Radar Under External Radio Frequency Interference

Anna Dzvonkovskaya
Institute of Telecommunications
Hamburg University of Technology (TUHH)
Hamburg, Germany
anna.dzvonkovskaya@tu-harburg.de

Abstract— High-frequency (HF) radar systems located at the coast are well-known as a measurement tool for synoptic on-line mapping of ocean surface current fields. Nevertheless, HF radar performance suffers from external radio frequency interference signals generated by other HF-band users. This paper describes a modified signal processing technique in order to reduce the interference impact on radar power spectra. It allows obtaining the Bragg resonant frequencies masked by interference signals and thus to measure the ocean surface current velocities. The measured HF radar data are used to demonstrate the performance of the developed signal processing technique for different operating radar frequencies.

Keywords - HF radar, interference, ocean current velocity

I. INTRODUCTION

The high frequency (HF) radar, which is based on electromagnetic wave propagation along the salty ocean surface due to conductivity, provides a unique capability to observe far beyond the conventional microwave radar coverage. HF radars use the operating frequency of 5-30 MHz to provide a large coverage that could extend more than 200 kilometers in range. These maximum range values are of high interest for many applications such as ship detection and tracking, research in oceanography, search and rescue, tsunami monitoring, transport and distribution of pollutants, fishery, etc. The HF radar systems recently became an operational tool for coastal monitoring worldwide.

Since the instantaneous HF-band load depends on geophysical environment, periodical diurnal and seasonal variations in ionosphere, and solar activity, these factors have influence to shift the bounds of used frequencies and their bandwidths. The natural interference level at the lower part of HF-band is much above the thermal noise level and depends on daytime and season. Atmospheric interference is usually dominated at frequencies below 10 MHz. Hence the HF-band load density for radio electronic systems varies in time. Broadcasting and long-range communication systems utilizing sky wave propagation use nearly the whole HF-band. The frequency distribution analysis shows that the special band allocation is not provided for HF radar. This usually leads to independent operating channel selection by HF radar itself while adapting to the present electromagnetic environment. Radio communication systems adapt using a frequency grid; however, the HF radar adaptation is based on the continuous analysis of electromagnetic environment and operating radar channel choice with minimal unintentional interference level.

A hard load of HF-band leads to the main radar problem, i.e. a small signal bandwidth can only be chosen resulting in a relatively poor range resolution.

Many interesting techniques have been proposed to overcome the interference challenge. For example, in [1] the HF-band load information processing technique was proposed to select free radio channels together with the existence time and efficiency estimation, which have to be utilized as HF radar operating channels in the presence of sea clutter.

In [2] an approach has been presented to add horizontal dipoles to an HF radar system, which normally uses vertically polarized antennas. The data received from the dipoles were correlated with the data received from the vertically polarized antennas to estimate and to cancel the skywave interference in an adaptive way.

It has been proposed in [3] to consider the spatial diversity of antenna arrays to be utilised to adaptively cancel unwanted radio frequency interference (RFI) whose spatial structure differs from that of the desired signals. The effective removal of nonstationary interference could be achieved through the use of antenna pattern readjustments designed to match the changing spatial properties of the interference prior to Doppler processing.

In [4] a new technique has been discussed to derive the pattern of RFI, which is only available in case of FMCW modulation and an I/Q demodulator for de-ramping. If the radar chirps over the frequency used by a radio service, the de-ramped signal contains a solitary pulse from positive frequencies and then to negative frequencies. This pulse generates a specific structure in the range-Doppler spectra calculated from the radar echoes. The signals from the positive spectrum side of the de-ramped signal can then be used to describe the structure of the RFI on the negative spectrum side.

Nevertheless, the HF interference problem still remains and the low-cost solution has not been found so far.

In this paper an attempt is made to develop an easy way of signal processing under RFI to estimate the Doppler
frequencies generated by the resonant backscatter from ocean surface.

II. SIGNAL PROCESSING FOR SURFACE CURRENTS MEASUREMENTS

It is well-known that a single site of radar system has a capability to provide measurements of Doppler frequency of a moving object, which gives the radial components of its velocity. In this case the moving distributed object is represented by ocean surface in the radar coverage. The dominant contribution for the HF radar system is due to the ocean surface echo signals, which are generated by permanently moving ocean waves. The nature of the ocean surface scattered signal depends on radar frequency, beam width, polarization and system configuration.

Many years ago the first-order HF scattering theory was developed [6]. It introduced the ocean surface as a time-varying quantity based on Bragg scattering as the physical mechanism responsible for electromagnetic scatter from the ocean surface. The dominant contribution of the HF radar backscatter is produced by scattering from ocean waves, which have a wavelength equal to a half of the radar wavelength and move towards and outwards the radar site. Hence, these waves give both positive and negative Doppler frequency shifts. The resonant Bragg peaks are permanently observed in range-Doppler frequency spectra (for example, see Fig. 1) and provide the capability of ocean surface current measurements by HF radar. Depending on the radar operating frequency Bragg-resonant backscattering by ocean waves allows measuring the ocean surface current at distances up to 200 km.

The effect of moving ocean waves on the received monostatic radar spectrum is to produce two strong peaks at so-called Bragg frequencies $f_B$ defined by the linear dispersion relation [7] for propagating ocean waves under the restoring force of gravity

$$f_B = \pm \frac{g}{\pi \alpha} \cdot \tanh \left( \frac{4\pi D}{\lambda} \right)$$

(1)

where $g$ is the acceleration due to gravity at the Earth's surface, $\lambda$ is the radar signal wavelength, $D$ is the water depth. The deviations of spectrum peaks from the theoretical values $f_B$ are an indicator of the ocean surface current because these currents lead to an additional frequency modulation in the radar spectrum.

Modern radars use frequency modulated continuous wave (FMCW) mode for high range resolution. This mode allows the transmitter and the receiver operating simultaneously. It avoids a blind range in front of the radar and simplifies the radar's range resolution modification. It is known that the radar echo signal inside a single chirp is processed by a fast Fourier transform (FFT) to get the target range resolution. The received signal for a single radar antenna element can analytically be described as follows:

$$Z(t) = [\xi_{n,m}(t)]_{N \times M}$$

(2)

where $\xi_{n,m}(t) = a_n(n\Delta R,t)e^{i\phi_m(n\Delta R,t)}$, $m = 1, 2, \ldots, M$ corresponds to a single antenna element in the array, while the index $n = 1, 2, \ldots, N$ describes the number of range cells, $t$ is the time, $a_n$ and $\phi_m$ are the amplitude and the phase of the $m$-th antenna signal respectively, $\Delta R$ is the range cell size, $i$ is the imaginary unit. Following the conventional beamforming technique, the received radar signals (2) can be resolved in beam directions:

$$Y(t, \theta) = Z(t) \cdot B(\theta)$$

(3)

where

$$B(\theta) = [b_{m,k}(\theta_k)]_{M \times K}, b_{m,k}(\theta_k) = \exp \left\{ \frac{2\pi}{\lambda} \frac{(m-1)d}{\sin \theta_k} \right\},$$

$m=1,2,\ldots,M, k=1,2,\ldots,K$ are defined for a uniform linear antenna array with $M$ elements and $K$ beamformed angles $\theta_k$, $d$ is the distance between antenna elements.

Applying the standard technique, the signals (3) would be normally transformed to a frequency domain using the FFT. However, the signals (3) are supposed to contain important information in frequency modulation due to ocean surface backscatter. Therefore the interference amplitude can be destroyed by normalization and only the term with phase information is further used to be processed with a standard signal processing scheme including the windowed FFT to get power spectra of the signals. So the information about ocean surface can be obtained in range, azimuthal angle and Doppler frequency shift (radial velocity).

Afterwards the Bragg peak localization is done separately for positive and negative parts of the resulting spectra. The difference between calculated theoretical frequencies (1) and the arguments of these maxima provide the estimation of radial surface current velocities at each range cell and radar beam angle.

III. RESULTS

The above proposed modification of conventional technique was tested based on the measured range-resolved signals from three different HF radar sites, which were located in South America, the Northern and Southern Europe. The radars were operated at three different frequencies of 22, 12 and 8 MHz respectively. Since the radar systems were run at different parts of the world, they work under various radio frequency interference levels.

All three radar systems belong to the generation of the HF radar WERA (Wave Radar). The radar measurements were provided by Helzel Messtechnik GmbH, the WERA radar manufacturer. The system has a wide range of working frequencies, spatial resolution, and antenna configurations in order to operate as a low power oceanographic radar. It provides simultaneous wide area measurements of ocean surface currents, waves and wind parameters [5]. The WERA system transmits a low power of 30 watts but can achieve a detection range, which is far beyond the conventional microwave radar coverage. This is due to electromagnetic wave travelling along the ocean surface. The attenuation
depends on the radar frequency and on the conductivity (salinity) of the water. The azimuth angle covered by WERA is ±60° perpendicular to the linear receive antenna array that consists of 8, 12 or 16 antenna elements located along the beach. Depending on the radar operating frequency the total radar coverage area occupies more than 20,000 km² of ocean surface.

The WERA radar system is based on a modular design that can be easily adopted to the requirements of an actual application. Most of the signals processing steps are implemented in software and thus the system can be adapted to different needs in a simple way, e.g. simultaneous oceanographic measurements, ship tracking, and tsunami monitoring. This is the reason why the proposed technique was easily tested just modifying the software processing.

Figure 1 shows an example of the normalized HF radar spectrum obtained at the 22-MHz carrier frequency and fixed at a single beam angle. The interference level was about 30 dB above the noise level. It was generated by a pair of periodic interfered signals with pulse blocks of 2.5-sec duration. The transmitting period was 32 sec and a time shift between the pair signals was about 7 sec. The main interest is the resonant Bragg peak locations in the spectrum to estimate ocean surface current velocity. It is obviously seen that over 25-km range the peaks are masked by the interference signals. After having applied the proposed technique to the same radar signals, the normalized spectrum looks different and the spectral peaks are strong enough to be identified at ranges up to 40 km off the coast (see Fig. 2).

The similar signal processing example is shown in Fig. 3 and 4. The normalized HF radar power spectrum was obtained at a frequency of 12 MHz and also fixed at a beam angle. The interference level was caused by a non-periodic chain of transmitting pulses with block length of 11 sec; the pulse amplitude was 40 dB above the noise level. The resonant Bragg peak locations are heavily masked and can be seen not further than 50 km. After having applied the proposed technique to the signals, the spectrum shows the peaks expanding up to 110 km off the coast (see Fig. 4).

Another example of signal processing technique is shown in Fig. 5 and 6. The normalized HF radar power spectrum was obtained at a frequency of 8 MHz and fixed at a beam angle. During the coherent integration time the interference was generated by a set of very short single pulses with duration less than 1 sec and its level was about 30 dB above noise level. The resonant Bragg peak locations are masked starting with a range of 120 km. After having applied the proposed technique to the signals, the spectrum shows the peaks expanding up to 220 km (see Fig. 6).

The results are remarkable in terms of ocean current velocity derivation. After processing the radar data of 22-MHz radar, Figures 7 and 8 show the geographical mapping of estimated radial surface current velocities based on radar spectra in Fig. 1-2. The conventional and proposed techniques are used respectively. The color scale corresponds to the velocity values in meters per second. Both figures show the same measured velocity values. However, the obtained velocity mapping is reduced in range in Fig. 7 because of the RFI; meanwhile in Fig. 8 the surface velocities are derived using the developed technique and expanded up to 20 km further on.

Figures 9 and 10 map the estimated radial velocities with RFI and with reduced RFI influence respectively. The radar frequency was 12 MHz; the radar data are the same as the one used in Fig. 3 and 4. The external interference masks the central part of the observing area. Nevertheless, the new application brings the velocity information back.

Figures 11 and 12 show the mapping example for really over-the-horizon measurements of radial components of ocean surface currents. Since the radar frequency was 8 MHz, the velocities are measured further than 200 km. The radar data are the same as the one used in Fig. 5 and 6. Fig. 11 depicts the reduced observing area caused by the external interference; meanwhile Fig. 12 shows a large extension in surface current information.

IV. CONCLUSIONS

The performance figure of an HF radar system suffers from external radio frequency interference caused by other HF-band radar or radio communication users. This paper describes results after modifying the classical signal processing technique in order to eliminate interference impact on radar power spectra. It allows obtaining the Bragg resonant frequencies masked by interference signals and thus to measure the ocean surface current velocities. The measured HF radar data are used to show the performance of the developed technique for different operating radar frequencies. The same technique could be applied to ship detection tasks; however it should be studied with attention as soon as it tends to give harmonic peaks, which could be counted as false targets. It should be mentioned that the proposed technique doesn’t work satisfactory for ionospheric clutter cancellation.

REFERENCES

Figure 1. Measured range-Doppler frequency power spectrum with external RFI (radar frequency 22 MHz).

Figure 3. Measured range-Doppler frequency power spectrum with external RFI (radar frequency 12 MHz).

Figure 5. Measured range-Doppler frequency power spectrum with external RFI (radar frequency 8 MHz).

Figure 2. Power spectrum with reduced interference impact (the same radar signals as in Fig. 1).

Figure 4. Power spectrum with reduced interference impact (the same radar signals as in Fig. 3).

Figure 6. Power spectrum with reduced interference impact (the same radar data as in Fig. 5).
Figure 7. Radial ocean surface current velocities measured under external RFI (radar frequency 22 MHz).

Figure 9. Radial ocean surface current velocities measured under external RFI (radar frequency 12 MHz).

Figure 11. Radial ocean surface current velocities measured under external RFI (radar frequency 8 MHz).

Figure 8. Radial ocean surface current velocities after reducing interference impact (radar frequency 22 MHz).

Figure 10. Radial ocean surface current velocities after reducing interference impact (radar frequency 12 MHz).

Figure 12. Radial ocean surface current velocities after reducing interference impact (radar frequency 8 MHz).