Experimental Evaluation of the Range-Doppler Coupling on HF Surface Wave Radars

Luigi Bruno, Paolo Braca, Jochen Horstmann and Michele Vespe

Abstract—High-frequency surface wave radar (HFSWR) is used in oceanography to monitor surface wind waves and currents and, more recently, to detect ships in maritime surveillance. The radar accuracy is affected by range-Doppler coupling, which yields a displacement in the measured range proportional to the target radial velocity, i.e. the Doppler shift in the returned pulse. Although in oceanography this effect is usually not accounted for, its relevance grows in ship detection. In this paper we present the results of two experimental datasets showing displacements in the HFSWR range measurements of up to 300 meters and confirming the theoretical analysis. Furthermore, we show that the correction based on theoretical arguments, achieved by the statistical correlation between the range and Doppler measurements, provides remarkable improvement in the radar accuracy.

Index Terms—High-frequency surface wave radar (HFSWR), range-Doppler coupling, ocean remote sensing, ship detection, over the horizon (OTH) radar, frequency-modulated continuous waves (FMCW) waveform

I. INTRODUCTION

HIGH-frequency surface wave radar (HFSWR) is a technology that is being used on an operational basis to monitor ocean surface currents [1], [2], surface waves [3], winds [4] and monitoring of tsunamis is also under study [5]. In the last 3 years the potential of using the HFSWR for maritime surveillance applications has been demonstrated [6]–[10]. In particular radar’s low transmission power (< 50 W) and low cost make it an interesting instrument for monitoring the coast up to a distance of approximately 100 km (depending on the utilized frequency). To obtain a large area with sufficient resolutions HFSWRs typically use a linear chirp as waveform to overcome the power constraints. It is well known that linear chirps are subject to significant range-Doppler coupling [11]. This coupling leads to a Doppler shift in the return pulse, due to a nonzero range rate or radial velocity (with respect to the radar), which in turn will introduce an increment in the time delay. Unfortunately, this effect cannot be distinguished from the changes due to range. For oceanographic applications such as retrieval of ocean surface wind, waves and currents, these effects can be neglected as the velocities of scatterers are small (typically ~ 0.5 m/s) and therefore only leading to small displacements (~ 1.5 m). However, in the case of measuring surface vessel velocities the range is altered by an error of the order of hundreds of meters, which, with respect to ship detection, is no longer negligible. In addition to the range-Doppler coupling, which can be compensated [11], there is a correlation between range and range-rate measurements, which in turn leads to small range displacements that cannot be compensated.

When using HFSWRs for ship detection, comparisons to the reports from the Automatic Identification System (AIS) have shown that HFSWR results suffer from high clutter and a significant amount of miss detections [6]–[10]. To improve the HFSWRs performance with respect to maritime surveillance, proper target tracking algorithms have to be incorporated [7]. For any tracking algorithm the knowledge of the correlation coefficient between range and range rate is a crucial aspect in the design of the tracker and therefore has to be considered [12], [13]. In this paper we are investigating the range-Doppler coupling effect on ship detections retrieved from HFSWR data compared to the associated AIS data. We used the HFSWR data and AIS data collected during an experiment off the Ligurian coast of Italy, which took place between May and December 2009. The HFSWR ship detections were retrieved using algorithms from the University of Hamburg, Germany [9]. Comparison between the HFSWR ship detections and AIS data clearly shows the range shifts due to range-Doppler effects, for which a compensation can then be made.

The range-Doppler coupling effect due to the transmission of a linear chirp is presented in Section II, followed by a description of the Maritime Surveillance HF-Radar experiment as well as the collected data in Section III. In Section IV the range Doppler coupling effects are analyzed and interpreted with respect to the collected experimental data. Finally, in Section V conclusions are presented.

II. RANGE-DOPPLER COUPLING

It is well known that Doppler radars, which employ linear chirp signals, are affected by a strong coupling between the measurements of target range and range rate [11]–[13]. The linear chirp is a continuous wave signal of duration \( t \), during which its frequency \( \Omega \) sweeps linearly between the known values of \( \Omega_1 \) and \( \Omega_2 \), around the center band frequency \( \Omega_0 \). Note that both cases \( \Omega_2 > \Omega_1 \) (upsweep chirp) and \( \Omega_2 < \Omega_1 \) (downsweep chirp) are feasible. Since they are orthogonal signals, they are often used to reduce interferences when two radars scan the same area.

Range measurements, \( r_b \), are retrieved from the measured time delay for the signal to propagate back and forth to the receiver, \( \Delta t \). Moreover, the matched filter on the receiving side adds a further delay dependent on chirp parameters [11]

\[
r_b = \frac{c}{2} \Delta t = \frac{c}{2} \Delta t_0 - \frac{c}{2} \frac{t\Omega}{\Omega_2 - \Omega_1},
\]

where \( c \) is the speed of light and \( t \) is the time delay due to the transmission of the signal.
where $\Omega_r$ is the received center band frequency and $\Delta t_0$ is not dependent on the frequency. Note that the subscript $b$ of the range measurement $r_b$ indicates that the measurement is biased. The coupling between range and range-rate measurements, the latter denoted by $\dot{r}$, is due to the Doppler shift, $\Delta \Omega$, which alters the frequency, $\Omega_0$, of the delivered waveform

$$\Omega_r = \Omega_0 + \Delta \Omega,$$

and it is in turn related to the target range-rate

$$\Delta \Omega = -\frac{2\Omega_0}{c} \dot{r}. \tag{3}$$

By substituting Eqs. (2)-(3) into Eq. (1), we finally obtain

$$r_b = \frac{c}{2} \Delta t_0 - \frac{c}{2} \Omega_2 - \Omega_1 \dot{r} = \frac{c}{2} \Delta t = r + a \dot{r}, \tag{4}$$

where $r$ is the unbiased target’s range and the proportionality coefficient,

$$a = \frac{t\Omega_0}{\Omega_2 - \Omega_1}, \tag{5}$$

has time dimensions and is fully specified by the waveform parameters. Note that the sign of $a$ is positive for upswing chirps and negative for downswing chirps, while the module is unaltered.

The range-Doppler’s tangible effect is that the range measurements show a bias depending on the target’s range-rate, whose correction involves the range-rate measurement instead of the true range-rate and thus introduces statistical correlation between range and range rate measurements. This happens even though the measurements were carried out with independent sensors [12].

Considering an additive noise model [14], the range-rate measurement, $m_\dot{r}$, and the range measurement, $m_r$, after the range-rate compensation, are respectively

$$m_\dot{r} = \dot{r} + n_\dot{r}, \quad m_r = r_b - a m_\dot{r} + n_r, \tag{6}$$

where $r_b$ is defined in Eq. (4), $n_\dot{r}$ and $n_r$ are independent zero-mean random variables with standard deviation $\sigma_\dot{r}$ and $\sigma_r$ respectively. The correlation coefficient, required by the tracker, is defined as [12]

$$\rho = \frac{E[ (m_r - r)(m_\dot{r} - \dot{r}) ]}{E[ (m_r - r)^2]^{1/2} E[ (m_\dot{r} - \dot{r})^2]^{1/2}}, \tag{7}$$

where $E[\cdot]$ is the expected value operator. It is straightforward to compute $\rho$, which is given by the following equation

$$\rho = \frac{a}{\sqrt{a^2 + (\sigma_r/\sigma_\dot{r})^2}}. \tag{8}$$

The correlation coefficient, $\rho$, has the same sign as $a$, and it is consequently positive for upswing chirps and negative for downswing chirps. In Fig. 1 $\rho$ is depicted for several values of $a$ versus the ratio $\sigma_r/\sigma_\dot{r}$.

As a final remark, the affine relation between range and range-rate in Eq. (4) depends uniquely on the use of linear chirp signals. Non-idealities (e.g. distortions) affecting the signal waveform alter that law, requiring different compensations.

### III. The Experiment

In this section the Maritime Surveillance HF-Radar Experiment is described, which was performed by the staff of the Centre for Maritime Research and Experimentation (CMRE, formerly NURC) off the Ligurian coast of Italy in 2009. Within the experiment two WERA HFSWR systems were installed at the coast of the Ligurian Sea, one on Palmaria Island in the Gulf of La Spezia ($44^\circ \ 2' \ 30''$ N, $9^\circ \ 50' \ 36''$ E) and another at San Rossore Park near Pisa ($43^\circ \ 40' \ 53''$ N, $10^\circ \ 16' \ 52''$ E). In Fig. 2 the location of the two sites is shown together with the radars’ fields of view. The geometry of the two sites was selected to enable ocean current, wave and wind retrieval in addition to ship detection. Both setups were operated at a frequency of $\approx 12.4$ MHz (corresponding to a wavelength of $\approx 24$ m).

Each WERA setup consisted of transmitting and receiving antennae arrays, which were separated by approximately 300 m along a straight line parallel to the coast. The transmit array consisted of 4 antennae arranged in a rectangular shape, while the receive array consisted of 16 antennae along the
line perpendicular to the look direction. Electronic control of the arrays was adopted to sweep a 120° angular sector. The system uses a linearly frequency modulated continuous wave (LFMCW), that is a linear chirp with about 100 kHz bandwidth yielding range resolution between 0.3 and 1.5 km. Surface propagation at sea is guaranteed by vertically polarized HF waves, with frequency in the range $\Omega_0 = 3 - 30$ MHz, and thus a wavelength of $\lambda = 10 - 100$ m [1]. The radars in Palmaria and San Rossore adopted orthogonal LFMCWs, that is upsweep and downsweep chirps respectively, whose center band frequency, $\Omega_0$, was tuned within $12.190 - 12.595$ MHz, the band is $|\Omega_2 - \Omega_1| = 100$ kHz, and the chirp duration was $t = 0.26$ s. The coherent processing intervals were composed of 512 samples (about 2 minutes), but a new integration was started every 128 samples ($\approx 33.28$ s). This means that there was a 75% overlap between neighboring integration times, yielding correlated measurements.

The aim is to quantify the effects of range-Doppler coupling on HFSWR measurements. The proportionality constant of Eq. (5) between range bias and range-rate was $\alpha = \pm 0.32$ s, where radars are discriminated by opposite signs and a 4% uncertainty is due to $\Omega_0$ variability. The analysis relies on data collected between May 7 and June 4 2009 (29 days). The ground truth was given by AIS reports collected in the same area and time interval. Ships and vessels exceeding a certain gross tonnage are equipped with AIS transponders and repeatedly broadcast their name, position and other details for automatic display on nearby ships. Although it is possible for a small portion of vessels to not transmit AIS, our analysis was based only on cooperative vessels and AIS position errors were considered negligible when compared to those of the radar. Due to the lack of synchronization between radar and AIS reports, the latter were interpolated to radar time scans. An important problem was how to collocate radar and AIS measurements. We solved the problem by adopting a gating procedure around the positions and velocities reported by AIS. For vessels sending intermittent AIS reports, the data collocation procedure requires some further care to avoid the introduction of uncertainty in the ground truth. Thus, only measurements collected at time instants close enough to AIS reports were selected while contacts which are not reliably associated to any AIS reports are neither processed nor analyzed.

The data collocation was performed using the following
steps:
- Collect all AIS reports pertaining to the same ship (with regard to the unique ship Maritime Mobile Service Identity);
- Interpolate AIS trajectories in order to extract ship’s positions and range-rates that are synchronized with radar scans and manage intermittent AIS as indicated above;
- Gate radar measurements around the interpolated AIS reports by setting thresholds on measurements;
- In the case that more than one measurement falls within the gate, the closest one to the ground truth in terms of Euclidean distance is associated.

About $150 \cdot 10^3$ radar measurements originated by over one thousand vessels, $95 \cdot 10^3$ from the HFSWR at Palmaria and the remaining $55 \cdot 10^3$ from San Rossore, were selected. Then, to eliminate statistical correlation due to the overlapping integration times, a further decimation of measurements distant in time less than 2 minutes from the same vessel was performed, leading to some $80 \cdot 10^3$ collocations.

IV. RESULTS

To demonstrate the technique a track from a 300-m-long cargo vessel is considered. The vessel left the port of La Spezia on May 10 with a southwest course. After passing the island of Palmaria, the vessel headed 135 deg in nearly radial direction to the radar site of Palmaria at a speed of 10 m/s (20 kn). The radial velocity with regards to the radar site at San Rossore has a slightly lower value (8 m/s on average). Fig. 3 (a) shows the vessel trajectory reported from the AIS. Fig. 3 (b lower plot) reports the vessel’s distance from Palmaria versus time, and Fig. 3 (b upper plot) a zoom which resolves a 250-m bias between the range-radar measurement (in red) and the AIS reports (in blue). Applying the theoretical correction, as described in Section III, using $\alpha = 32$ s for the radar in Palmaria and $\alpha = -32$ s for the radar in San Rossore results in Fig. 3 (c)-(d). These plots show the range error histograms prior (blue bars) and after correction (green bars), suggesting that the range bias has been significantly reduced for both sites. Indeed, residual errors and even overcorrections, like slightly happens in Fig. 3 (d), can occur due to the fact that the employed signals can differ from the ideal LFMCW at some extent.

Applying the theoretical correction to the entire data set results in the error histograms shown in Fig. 4 for range, azimuth and range-rate. There is a clear reduction of the spread in the range error histograms for both sites after compensation. In detail the standard deviation of the empirical distributions decrease about 33% and 20% for Palmaria and San Rossore, respectively. Furthermore, as expected, the correction does not influence the histograms of azimuth and range-rates, because the range debiasing procedure does not alter significantly the data association procedure. However, in almost all histograms a residual floor is present, which is caused by points that originate from the signal due to clutter instead of targets. Therefore, the associated measurements are most likely distributed as a mixture between a uniform clutter density (the measurement is not target originated) and the Gaussian-like error density (the measurement is target originated).

Fig. 5 shows the scatter plots of data: x-axis represents the range-rate coordinate of the ground truth (AIS reports), while the y-axis the range error. The range-Doppler coupling effect is quite evident, because a systematic, nearly linear effect is present in panels (a)-(b) with approximately the expected slopes. It is worthwhile to note that the slope reflects one of the ambiguity functions of the LFMCW transmitted waveform. However, the dispersion around the line, on the one hand, is not target originated) and the Gaussian-like error density (the measurement is target originated).

Fig. 6 shows the empirical estimation of the coefficient $a$, based on the least squares estimation of the coefficient $a$ per day and for each radar. The results, arranged in terms of the empirical probability mass function (PMF), are shown in Fig. 6. The PMFs have significant values in the region...
statistical analysis carried out on datasets from two radars. By measurements of as much as 300 meters, as shown by the targets’ velocities led to a displacement in the range to ship detection. In our setup the waveform features and sampling when high-frequency surface wave radars are applied to the range-Doppler coupling, essential to improve the accuracy applying the theoretical correction, we mitigate the effects of tracking algorithms. Minor effects, such as divergences between range and range-rate measurements after the correction was also studied and can be accounted for when tracking algorithms are applied. The residual statistical correlation of the radar waveform from the ideal LFMCW, were not considered in our analysis. The value of the range-Doppler coupling coefficient, $s$, for Palmaria and $\pm 32$ s $s$ for San Rossore; thus, in both cases the PMF assumes nonzero value in the expected range of the range-Doppler coupling coefficient, $a = \pm 32$ s.

V. CONCLUSION

This paper has shown the relevance of range-Doppler coupling when high-frequency surface wave radars are applied to ship detection. In our setup the waveform features and the targets’ velocities led to a displacement in the range measurements of as much as 300 meters, as shown by the statistical analysis carried out on datasets from two radars. By applying the theoretical correction, we mitigate the effects of the range-Doppler coupling, essential to improve the accuracy of tracking algorithms. Minor effects, such as divergences of the radar waveform from the ideal LFMCW, were not considered in our analysis. The residual statistical correlation between range and range-rate measurements after the correction was also studied and can be accounted for when tracking algorithms are applied.

REFERENCES