A NETWORK OF HF SURFACE WAVE RADARS FOR MARITIME SURVEILLANCE: PRELIMINARY RESULTS IN THE GERMAN BIGHT

S. Maresca[†], *P. Braca*[†], *J. Horstmann*[‡], *and R. Grasso*[†]

[†] NATO STO CMRE, La Spezia, Italy; email: {maresca, braca, grasso}@cmre.nato.int.
[‡] Helmholtz-Zentrum Geesthacht (HZG), Hamburg, Germany; email: jochen.horstmann@hzg.de

ABSTRACT

In the context of maritime surveillance, low-power HF surface-wave (HFSW) radars have demonstrated to be a cost-effective long-range early-warning sensor for ship detection and tracking. In this work, multi-target tracking and data fusion techniques are applied to live-recorded data from a network of oceanographic HFSW radars installed in the German Bight (North Sea). This experimentation closely follows the one conducted in the Ligurian Sea (Mediterranean Sea) by NATO Science and Technology Organization (STO) Centre for Maritime Research and Experimentation (CMRE) during the Battlespace Preparation 2009 (BP09) campaign.

Ship reports from the Automatic Identification System (AIS), recorded from both coastal and satellite-based stations, are exploited as ground truth information and a methodology is applied to classify the fused tracks and to estimate system performances. Preliminary results are presented and discussed, together with an outline for future works.

***Index Terms*—** High-frequency surface-wave radar, real data, AIS reports, target detection and tracking, data fusion.

1. INTRODUCTION

Maritime surveillance is an important enabling activity for many national and international communities. In this domain, a variety of sensors can be used, including coastal and ship-borne microwave radars, video, infrared and synthetic aperture radar sensors, as well as the navigation reports provided by the AIS system. In order to have real-time, clear and accurate pictures of wide areas, hierarchical architectures can be considered. Thus, the reports are originated not only from different sensors but can also be broadly divided into high-level (*e.g.* target trajectory, ID, behaviour) and low-level information (*e.g.* radar contacts), and interact within the process at different levels. Data fusion (DF) for surveillance purposes has been widely addressed in the literature [1–4], but it continuously brings on new challenging issues when applied to deployed sensor networks.

This work has been funded by the NATO Allied Command Transformation (NATO-ACT) under the project ACT000215 (Maritime Situational Awareness).

In this context, long-range cost-effective sensors operating on a continuous time basis can play a central role. Among these, low-power HFSW radar systems have demonstrated to be a useful source of data for ship detection and tracking, thanks to their capability of detecting targets over-the-horizon, their continuous-time coverage and direct Doppler velocity estimation. One such system is the Wellen Radar (WERA), developed at the University of Hamburg and intended only for remote sensing applications [5]. Since these systems are set up for oceanic parameter estimation, their configuration is not optimal for target detection and tracking.

These issues have been partially addressed in [6], in which a constant false alarm rate (CFAR) detector and a basic Multi-Target Tracking (MTT) strategy have been proposed. In particular, target detection was performed by a 3D (range-azimuth-doppler) ordered statistics (OS) CFAR algorithm, while track management by the Nearest Neighbor (NN) data association rule in combination with the $\alpha - \beta - \gamma$ filter.

CMRE has conducted a first data acquisition campaign in 2009 during the BP09 program, in collaboration with the Universities of Hamburg and Pisa, in which two WERA systems were deployed in the Ligurian Sea. Initially, different detection strategies, based on the Normalized Adaptive Matched Filter (NAMF), have been considered [7]. Then, an MTT strategy has been presented in [8], based on the Joint Probabilistic Data Association (JPDA) rule followed by the unscented Kalman filter (UKF). To exploit the aspect diversity due to the system geometries, a DF paradigm has been described in [9], while a full statistical characterization of the detection, tracking, and DF performances of the proposed system has been presented in [10, 11]. Sensible gain in terms of performance was achieved w.r.t. the single sensor outputs.

In this work, conducted in collaboration with the HZG of Hamburg, three WERA systems deployed along the German Bight coasts are considered. They are operated within the Coastal Observing System for Northern and Arctic Seas (COSYNA) framework, an operational, integrated observational system that combines observations and numerical modelling for the German shelf sea.

This paper is organized as follows. In Section 2, the German Bight campaign on HFSW radars is presented. Preliminary experimental results are shown and discussed in Sec-

978-1-4799-2893-4/14/$31.00 ©2014 IEEE

tion 3, while conclusions and guidelines for future works are provided in Section 4.

2. THE HFSW RADAR EXPERIMENT

2.1. The Experiment Setup

In the South-Eastern part of the North Sea, known as the German Bight, the HZG is currently installing the experimental COSYNA network. Its main components include in situ instruments and, among these, a network of HFSW radar systems, consisting of three WERA radars installed on the islands of Wangerooge and Sylt, and close to the harbor of Büsum. The locations of the HFSW radars and their areas of coverage (*i.e.* 150 km $\times$ $120°$) are depicted in Fig. 1, together with offshore research platforms, waverider buoys and wind farms (black dots).

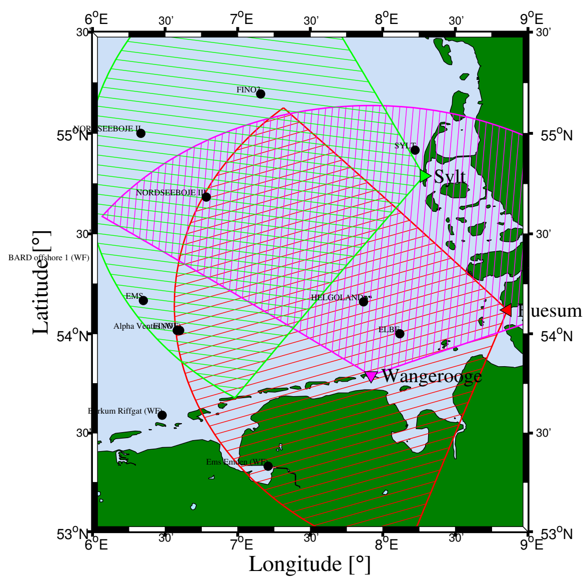

Fig. 1. Setup of the HFSW radars in the German Bight: Sylt (green), Büsum (red), and Wangerooge (magenta).

The HFSW radars

WERA is a bistatic (quasi monostatic) system, whose transmitter (Tx) and receiver (Rx) are made up with $\lambda_0/4$ monopole arrays, where λ_0 is the carrier wavelength. For each system, the Tx has a rectangular arrangement, while the Rx's are made by 12 (for Sylt and Büsum) or 16 (for Wangerooge) elements linear arrays. The distance between Tx and Rx is approximately 300 m. The angles w.r.t. North, namely ϕ_0, of the three array installations are $97.0°$, $5.0°$ and $349.0°$, for Wangerooge, Sylt and Büsum respectively. The azimuth information is extracted via beamforming, using the Hamming window, with a field of view of $120°$ around the broadside direction (*i.e.* $\phi_0 - 90°$). WERA operates at 50 W on average and uses linear frequency modulated continuous wave chirps, whose repetition interval is $T = 0.26$ s. Only Sylt and Büsum share the same operating frequency (*i.e.* $f_0 = 10.8$ MHz), with orthogonal modulating waveforms: the former dowsweep, the latter upsweep. At Wangerooge the frequency channel is selected in the interval $12.2 - 13.5$ MHz, with upsweep chirp. Range resolution is $\Delta R = 1.5$ km for all the systems, with chirp bandwidth $B = 100$ kHz. A range correction due to the Doppler effect is applied cosidering all these factors, as presented in [12]. The setup parameters are summarized in Table 1. At the moment, data from only two radar stations (*i.e.* Büsum and Wangerooge) are available.

	Wangerooge	**Sylt**	**Büsum**
Longitude	$7° \, 55' \, 8''$ E	$8° \, 16' \, 59''$ E	$8° \, 51' \, 28''$ E
Latitude	$53° \, 47' \, 25''$ N	$54° \, 47' \, 19''$ N	$54° \, 7' \, 10''$ N
ϕ_0 [°]	97.0	5.0	349.0
f_0 [MHz]	$12.2 - 13.5$	10.8	10.8
λ_0 [m]	$24.6 - 22.2$	27.8	27.8
T [s]	0.26	0.26	0.26
B [kHz]	100.0	100.0	100.0
sweep sign	up	down	up

Table 1. Setup parameters of the HFSW radars.

The MTT-DF system

Radar observations undergo a quality control and radio frequency interference removal, as described in [13]. Target detection is performed in the FFT domain by the 3D OS-CFAR algorithm [6]. Coherent processing intervals, not statistically independent, are made of 512 samples with an overlap of 75%, *i.e.* a detection occurs every 33.28 s. Detections are associated to tracks by applying the JPDA rule [2, 14], while tracks are updated using the UKF, see [15]. The confirmed tracks generated by the MTT at each site are then combined by means of a track-to-track association and fusion (T2T-A/F) logic [2]. Further information about the algorithms and the parameters can be found in [8, 9, 11].

The AIS ship reports

AIS data are provided by receivers located at each WERA radar site. Fig. 2 depicts the AIS contacts recorded at Büsum and Wangerooge stations on August the 4^{th}, 2013. A total of 620 different AIS-carrying ships (grey) were recorded that day, with 299 only in the fusion region (blue line perimeter). This number is far greater than the maximum one (*i.e.* 91) observed in [11]. The performance assessment procedure requires that the AIS reports are interpolated (black) on the radar timestamps, as described in [11].

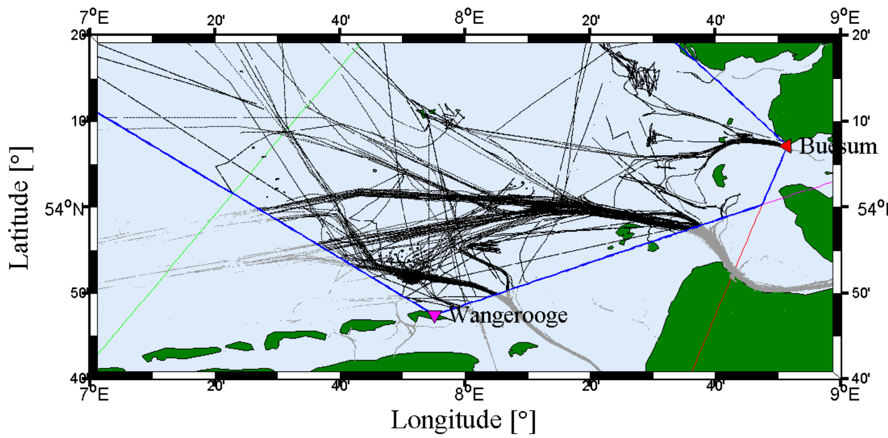

Fig. 2. AIS ship routes recorded on August the 4^{th}, 2013.

3. EXPERIMENTAL RESULTS

Preliminary experimental results are presented for August the 4^{th}, 2013, and are color-coded as follows. The JPDA-UKF outputs at Wangerooge and Büsum are shown in magenta and red, respectively, while the T2T-A/F output in blue. Output track contacts are validated constructing a 3D (range-azimuth-radial speed) performance validation region (PVR) for each AIS contact, following the procedure described in [11].

Analysis of true tracks

Preliminary results are plotted in Fig. 3, for a 2 hours recording interval going from $00:00$ to $02:00$ UTC. As we can observe, there is a good agreement between the estimated tracks and the AIS trajectories. However, the coverage of both radars seems to be limited. At the best of our knowledge, this fact can be partially explained by: *i)* the low sea surface conductivity of the North Sea, less salty than the Mediterranean Sea, *ii)* by the daily tides (*i.e.* the difference between high and low tide is about 2 m on average) which can be responsible of emerging seabed, *iii)* by the strong induced currents, *iv)* by possible severe sea states, and *v)* by the geo-morphology of the region. All these factors could represent an issue for the surface-wave signal propagation, and are currently undergoing further investigations.

A lot of maneuvering ships can be seen moving in front of Wangerooge. The trajectory they depict is circular and, only after a while, they move towards/away the main ship routes. Probably some of these could be cargo ships testing the rudder while waiting to enter the harbor, while the others could be both pilot ships and fishing boats. This situation could require a different tracking algorithm, able to deal also with ship maneuvers. In fact, the nearly constant velocity (NCV) model is the one considered here, which is typical of large ships following commercial ship routes [11]. As already observed, another problem is represented by the density of the high vessel traffic present out of river Elbe and along the two main traffic routes, as shown in Fig. 2. Ship discrimination could be a possible problem for the low-resolution radar system, as well as the JPDA data association rule, which combines probabilistically all the neighboring contacts. However, the available ground truth dataset is still too small to provide a good approximation of the real offshore traffic in the region.

Analysis of false tracks

All the radar tracks (both JPDA-UKF and T2T-A/F outputs) which are not associated to any ship route are labelled as false. However, as pointed out also in [11], only certain ships are required to carry an AIS transponder to communicate their position and other navigation information. In addition to this, we should also consider that the range covered by the AIS receivers is limited (*i.e.* about 20 nm on average to a maximum of 50 nm for high-placed receivers). This means that we do not have a complete map of all the ship traffic crossing the German Bight.

False tracks are plotted in Fig. 4. As we can observe, there is a large amount of false tracks, which are pretty coherent with the main ship routes, see also Fig. 3. Some of these tracks could be easily related to vessels not required to carry the AIS transponder, with the AIS switched off, or simply out of the validation gate. The aim is to optimize, according to

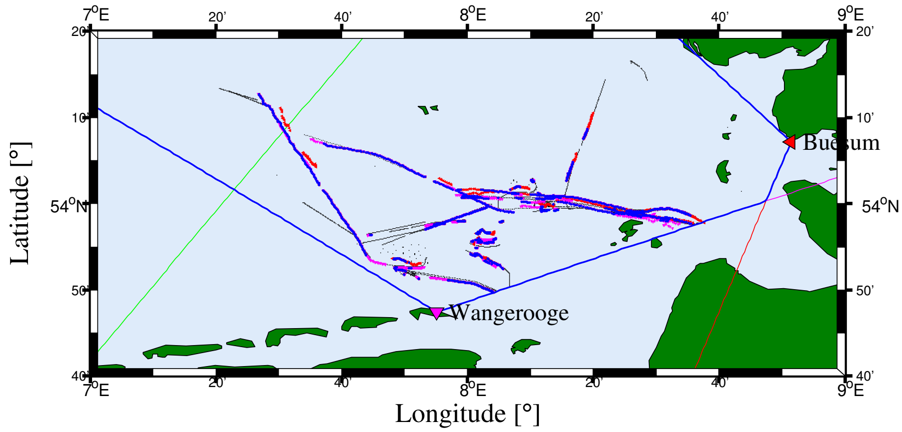

Fig. 3. True HFSW radar tracks and AIS routes on August 4, 2013 in the interval $00:00-02:00$ UTC.

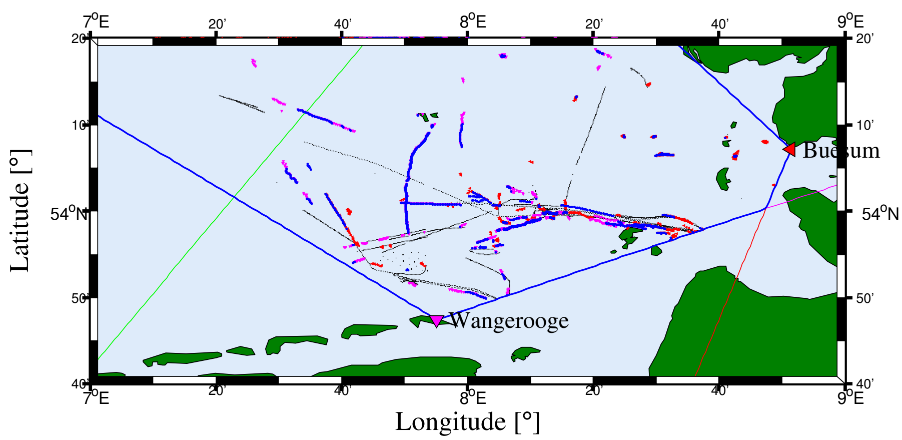

Fig. 4. False HFSW radar tracks and AIS routes on August 4, 2013 in the interval $00:00-02:00$ UTC.

the scenario, all the system and PVR parameters, and, at last, to provide a measure of un-cooperative ship traffic.

4. CONCLUSIONS AND FUTURE PERSPECTIVES

In this work, a surveillance system based on a network of simultaneously operating HFSW radars with overlapping fields of view has been presented and its performance evaluated by means of experimental data recorded in the German Bight. A whole processing chain, going from the OS-CFAR detection algorithm to the a T2T-A/F logic and passing from the JPDA-UKF tracking algorithm, has been considered. A methodology for validating the output tracks has been described. Qualitative results have been presented, showing a good agreement between the estimated tracks and the AIS ground truth data. However, several issues have been raised and their solution is still open. Future research will be focused in this direction.

5. REFERENCES

[1] A. Farina and F. A. Studer, *Radar Data Processing. Vol. II - Advanced Topics and Applications*, Wiley, New York, 1986.

[2] Y. Bar-Shalom, P. Willett, and X. Tian, *Tracking and Data Fusion: A Handbook of Algorithms*, YBS Publishing, Storrs, CT, 2011.

[3] S. Blackman and R. Popoli, *Design and Analysis of Modern Tracking Systems*, Artech House, 1999.

[4] R. Mahler, *Statistical Multisource-Multitarget Information Fusion*, Artech House, 2007.

[5] K.-W. Gurgel, G. Antonischki, H.-H. Essen, and T. Schlick, "Wellen radar (WERA), a new ground-wave based HF radar for ocean remote sensing," *Coastal Engineering*, vol. 37, no. 3, pp. 219–234, Aug. 1999.

[6] A. Dzvonkovskaya, K.-W. Gurgel, H. Rohling, and T. Schlick, "Low power high frequency surface wave radar application for ship detection and tracking," in *Proc. of the IEEE Int. Radar Conference*, Adelaide, Australia, Sept. 2008.

[7] S. Maresca, M. Greco, F. Gini, R. Grasso, S. Coraluppi, and J. Horstmann, "Vessel detection and classification: An integrated maritime surveillance system in the Tyrrhenian sea," in *Proc. of the International Workshop on Cognitive Information Processing (CIP)*, Elba Island, Italy, 2010.

[8] P. Braca, R. Grasso, M. Vespe, S. Maresca, and J. Horstmann, "Application of the JPDA-UKF to HFSW radars for maritime situational awareness," in *Proc. of the* 15^{th} *Intern. Conf. on Inform. Fusion (FUSION)*, Singapore, 2012.

[9] P. Braca, M. Vespe, S. Maresca, and J. Horstmann, "A novel approach to high frequency radar ship tracking exploiting aspect diversity," in *Proc. of the IEEE Intern. Geo. and Rem. Sens. Symp. (IGARSS)*, Munich, Germany, 2012.

[10] S. Maresca, P. Braca, and J. Horstmann, "Detection, tracking and fusion of multiple HFSW radars for ship traffic surveillance: Experimental performance assessment," in *in Proc. of the IEEE Int. Geo. and Rem. Sens. Symp. (IGARSS)*, Melbourne, July 2013.

[11] S. Maresca, P. Braca, J. Horstmann, and R. Grasso, "Maritime surveillance using multiple high-frequency surface-wave radars," *IEEE Trans. on Geo. and Remote Sensing*, (in print).

[12] L. Bruno, P. Braca, J. Horstmann, and M. Vespe, "Experimental evaluation of the range-Doppler coupling on HF surface wave radars," *IEEE Geosci. Remote Sens. Lett.*, vol. 10, no. 4, pp. 850–854, 2013.

[13] K.-W. Gurgel, T. Schlick, G. Voulgaris, J. Seemann, and F. Ziemer, "HF radar observations in the German Bight: Measurements and quality control," in *Proc. of 2011 IEEE/OES* 10^{th} *Current, Waves and Turbulence Meas. (CWTM) Conf.*, March 2011, pp. 51–56.

[14] Y. Bar-Shalom, F. Daum, and J. Huang, "The probabilistic data association filter," *IEEE Control Syst. Mag.*, vol. 29, no. 6, pp. 82–100, Dec. 2009.

[15] S. J. Julier and J. K. Uhlmann, "Unscented filtering and nonlinear estimation," *Proc. IEEE*, vol. 92, no. 3, pp. 401–422, Mar. 2004.