Self-Organized Synchronization Based on a Chirp-Sequence Waveform for an HF Ocean Radar Network

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***Abstract*— HF ocean radars are usually installed along the coast and deliver remote sensing information by transmitting a radio signal with an operating frequency between 3 and 30 MHz. The frequency band allows for a large coverage of ocean surface that could extend more than 200 kilometers offshore depending on the transmit frequency and other operating conditions. To provide a dense coverage of the sea surface, the installation of ocean radars in a radar network may require that the transmitting and receiving units of a radar network demand time synchronization between the units to perform correct space-time measurements of ocean parameters. In this paper, a self-organized synchronization for HF ocean radars is considered without the use of Global Positioning System (GPS) devices. In the case of multiple transmitters, the power peaks are observed in spectra simultaneously for each of the transmitters; hence the time shift can be estimated separately for each of them. The self-organized approach is very useful for the case of multiple transmitters and receivers in a radar network as well as in multiple-input-multiple-output (MIMO) radar configurations, which utilize the feasibility of occupying less space for a HF radar receive antenna while maintaining the high spatial resolution of the radar data.**

Keywords—Ocean Radar, synchronization, MIMO, WERA

I. INTRODUCTION

The principle of high-frequency (HF) ocean radar operation is based on electromagnetic wave propagation along the highly conducting sea surface and the backscatter of this radiation from resonant sea waves. HF ocean radars, operating in the surface wave mode in the 3-30 MHz band, are installed along the coast. The HF band allows for potential coverages of several tens of thousands of square kilometres of the ocean surface to ranges exceeding 200 kilometers, depending on the operating frequency and other considerations such as the ambient noise regime. The HF ocean radar system WERA® was developed as a low-power ocean radar providing simultaneous wide-area measurements of sea surface currents, waves and wind parameters, and tsunami monitoring. This system transmits a power of only 30 Watts, which is harmless to people and the environment but can achieve a total offshore coverage area of more than 20,000 km2 of sea surface.

HF ocean radar systems have become an operational tool for coastal monitoring worldwide. Nowadays there is considerable progress in an international effort to include HF ocean radars into observational coastal networks. Some examples of several WERA systems as a part of such networks are the Australian Coastal Ocean Radar Network (ACORN) [1], the Coastal Ocean Monitoring Prediction System (COMPS) [2] for the West Florida Shelf region, the Coastal Observation System for Northern and Arctic Seas (COSYNA) [3], etc. Figure 1 shows the HF radar network integrated into the COSYNA system for continuous observations of the German Bight.

To provide a dense coverage of the sea surface, the installation of ocean radars in a radar network may require that the transmitting and receiving units of a radar network demand time synchronization between the units to perform correct space-time measurements of ocean parameters.

Since ocean radar systems operate in the short wave radio band, they have to comply with the rules of the International Telecommunication Union (ITU). The 2012 World Radiocommunication Conference (WRC-12) of the ITU allocated a number of frequency bands in the frequency range 3 to 50 MHz to the radiolocation service to be used for oceanographic radar applications as outlined in Resolution 612 (Rev.WRC-12) [4]. Generally, these allocated bands provide very limited bandwidths, which the multiple radar users need to share. Without the synchronization of operating systems in the neighbourhood, the adjacent systems would be seen as radio interference and degrade the signal quality of each radar.

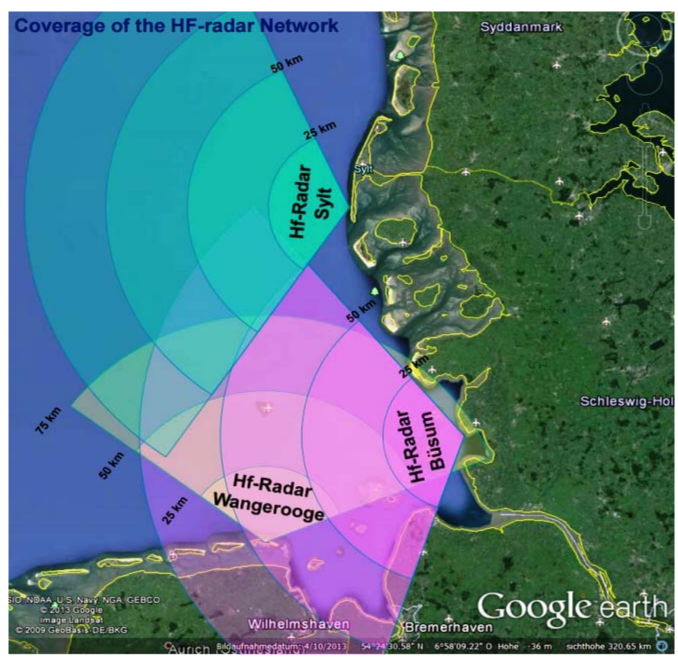

Fig.1. Coverage of three WERA ocean radars providing oceanographic information for the German Bight, Germany [3].

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When all modern ocean radar systems operate in the frequency modulated (FM) continuous waveform (CW) mode with or without gating, it is possible to synchronize the FM sweep signal (chirp) to avoid interference problems.

The ITU has recommended several synchronization methods [4], one of the most effective being the modulation multiplex method (see Fig. 2). This method requires a very high standard to keep the operation frequency and the chirp length stable. A well-known approach is to employ Global Positioning System (GPS) receivers which provide precise time stamps (up to nanoseconds) at both transmitter and receiver sites. However, this technique requires additional costs and is fully dependent on external GPS transmission. Furthermore, the start times need to be synchronised and this requires that the 'master' of a network be defined and that there be an agreement between the operators of adjacent systems. If no external 'master' clock is used for the synchronization, then the internal standards need to have a very high frequency stability of at least 10 ppm per year. For ocean radar applications, it is important to check whether the standard master clocks are suitable for achieving the required stability for the typical duration of the integration cycles of radar measurements, e.g. 10 minutes for sea surface current velocity and 30 minutes for wave spectra estimation.

Bistatic and multistatic radar is gaining more and more interest over the last years. It offers more freedom to separately deploy the transmitters and the receivers along the coasts, which has a special interest in case of HF ocean radar systems [5-7]. A crucial problem associated with bi- and multistatic systems is the synchronisation of time and frequency at the transmitters and receivers for coherent signal processing and range measurement.

Moreover, the multiple-input-multiple-output (MIMO) approach has become a popular technique not only in mobile telecommunications but also in radar applications [8]. For example, the possibilities of using the MIMO FMCW approach in HF ocean radar have been explored in [9-11]. In this technique, the transmitter elements can be operated in the same or partially same frequency band simultaneously and this permits a reduction in the receive array footprint without degrading overall system performance. In particular, for the MIMO application it is essential that, during the integration time, the phase shift between the transmitted signal and the oscillator of the receiver is small enough to ensure an efficient averaging. As it is shown in Fig. 3, for the standard master clocks of a WERA system this requirement is fulfilled up to 30 minutes under worst case conditions. The example in this figure shows that the time drift of internal clocks in the receivers and transmitters is very slow due to the ultra-stable oven-quartz oscillator (OCXO) of the WERA system. This means the errors during the measurements of sea surface current velocity with an integration time of 5-10 minutes will be less than 0.5 mm/s.

II. Self-organized Syhchronization Approach

To implement a self-organised network of ocean radar systems, the characteristics of the FM chirp signals of the already operating systems must first be analysed. These characteristics are the sweep direction (up or down), start and stop frequency with the frequency bandwidth B and the sweep duration T_c (see Fig. 4). Following these basic settings the receiver of a new member in the radar network can start analysing the frequency spectrum and the timing of already existing radar partners. The accuracy of such timing analysis depends on the integration time for the radar measurements and the signal-to-noise ratio (SNR) of the received signals.

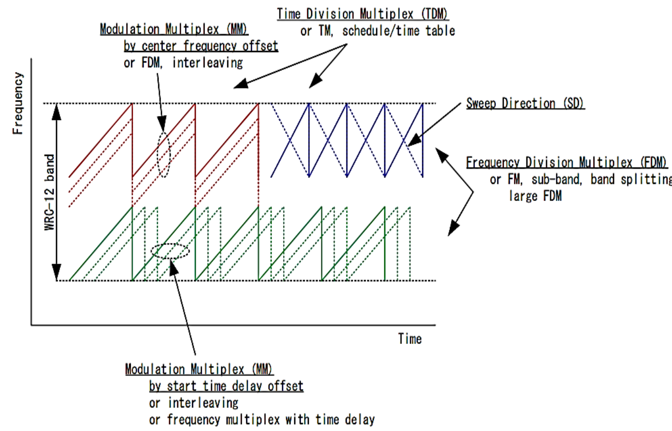

Fig. 2. Synchronisation methods recommended by ITU [4]

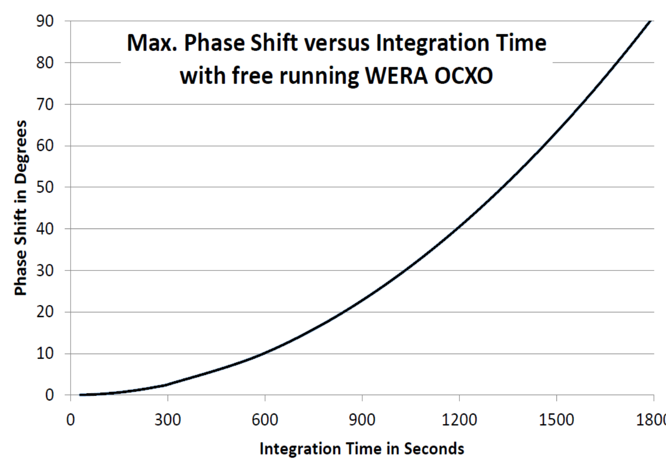

Fig. 3. Worst case of phase shift of free running WERA master clocks

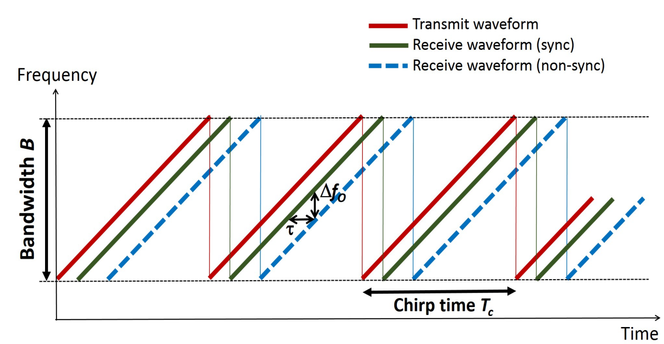

Fig. 4. Chirp-sequence waveform example

Relative to a standard application where the network members need only avoid mutual interference, a simple synchronization with an accuracy of a few milliseconds is sufficient. For more sophisticated methods such as those associated with multistatic or MIMO radar operations, including, for example, when the radar transmitters and receivers are operated simultaneously and continuously without a wired HF connection, the requirements for the synchronisation are much higher. In this case, the received signal coming from the external transmitter needs to be at least within the bandwidth of the receiver, which is typically about 1kHz for an ocean radar. Furthermore, the chirp-sequence waveform is used to derive the information regarding the moving sea surface on a spatial grid. For this task the beat frequency estimation is employed by mixing the transmit and receive signals (see Fig. 3).

In this instance, it is a challenge to provide the time synchronization required for the correct spatial grid mapping of the measured sea parameters. The frequency offset estimation is based on a standard signal processing chain with multiple sequential chirps. If either a start time of the waveforms is different or a transmitter is located significantly far from a receiver (multistatic radar, for example), the power peak from a direct transmit signal indicates a frequency offset Δf_0 in the range-Doppler frequency spectra. As the radar operating bandwidth B and chirp time T_c are known, it is possible to estimate the time shift τ caused by a de-synchronized operation between units using the relationship

$$\tau = \Delta f_o \cdot T_c / B \qquad (1)$$

Optimal data processing is achieved by minimizing the frequency offset Δf_0 to bring the maximum power value to the first range cell with zero Doppler frequency shift.

III. Results from Field Experiments

Field experiments were carried out with a WERA system installed on Sylt island in Germany. The operating frequency was 10.9 MHz with the frequency bandwidth B = 100 kHz and the sweep period Tc = 260 ms. Usually the radar system operates in a quasi monostatic mode utilizing a 12-antenna receive array and an essentially co-located transmit array located 200 m away.

A. Self-synchronization experiment with one transmitter and one receiver in the WERA system.

During this experiment the transmitter was disconnected and driven by an independent WERA transmit unit without cable connection to the receiving unit as it is shown in Fig. 5a. Both WERA units used an independent OCXO oscillator without any kind of synchronization. WERA unit #1 was receiving only and used a synchronisation unit to trigger the start of its sweep generator. This trigger was generated from the received signal transmitted by WERA unit #2. Trigger accuracy had to be precise enough to get the received signal of WERA #2 within the receiver bandwidth of WERA #1. With this first trigger a data acquisition of 2 minutes was carried out and the resulting power spectra allowed for identification of the origin of the received direct path signal from WERA unit #2 as well as the backscattered signal from resonant sea waves. The signal generated the well-documented Bragg lines in the range-Doppler spectra (see, for example, [12]). However, to achieve better accuracy in time synchronization the first synchronization cycle is not sufficient. A restart of the receiving cycle to get the transmit signal closer to zero Doppler frequency followed and the result of this next synchronisation cycle (another 2 min) is displayed in Fig. 6. It shows a frequency offset of 0.68 Hz, which can be easily estimated from the spectrum.

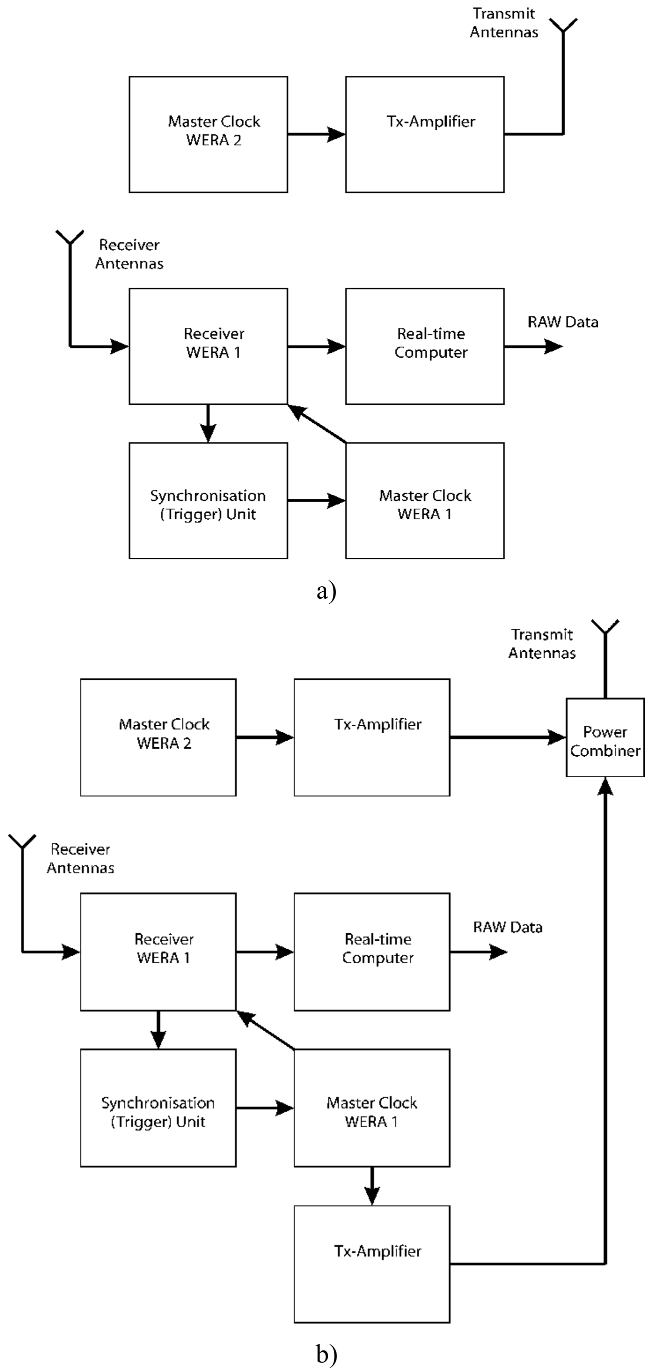

Fig. 5. Experimental set-up with a) disconnected transmit and receive WERA units; and b) two transmit and one receive WERA units.

Using the received radar spectra the radial components of sea surface velocity can be estimated. However, under de-synchronised conditions the velocity measurements are erroneous as it is shown in Fig. 7.

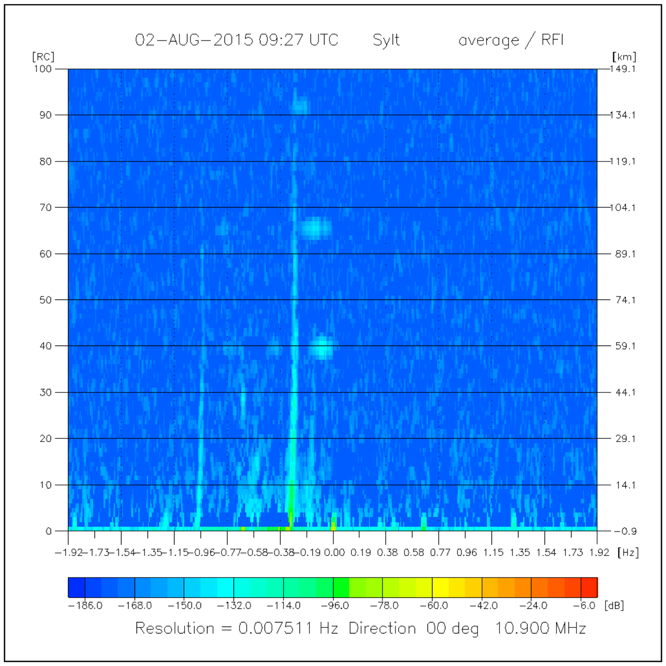

Fig. 6. Range-Doppler frequency spectrum after the first synchronization cycle

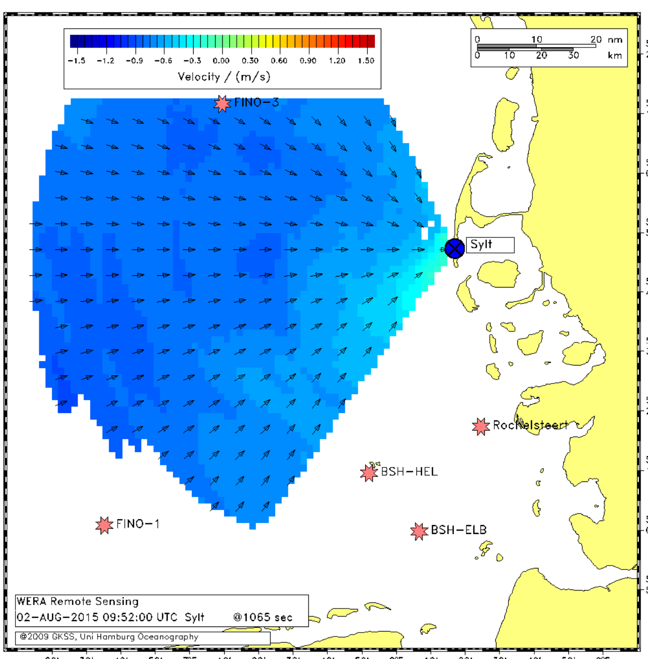

Fig. 7. Map of radial sea surface current velocity with erroneous measurements due to de-synchronized radar operation

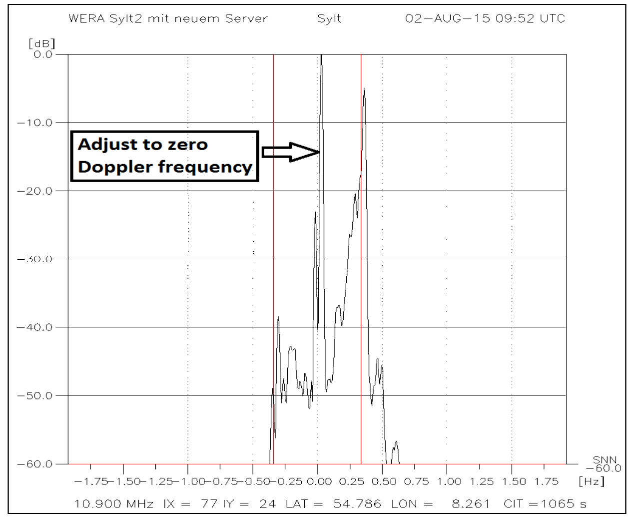

Fig. 8. A spectrum of synchronized acquisition to identify the position of the direct path RF-signal to adjust it to zero Doppler frequency position

Utilizing the received signal and the derived spectra, the more accurate required timing can be set in the next and final synchronization step. With this next receiving cycle the integration time can be increased to the required length, e.g. 20 minutes. If any further fine adjustments of the resulting frequency offset is required, this can be carried out in a near real-time processing step. For this the direct path signal needs to be identified in the Doppler spectrum and used to adjust to zero Doppler frequency (see Fig. 8). The quality of the resulting Doppler spectra needs to be compared with a monostatic radar to check whether the Bragg line width and SNR performance may be degraded by increasing integration periods. Longer integration times are essential to derive good quality wave data.

The results after the final synchronization step are shown in Fig. 9 and 10.

B. Self-synchronization experiment with two transmitters and one receiver in the WERA system.

An additional test was performed with the two radar transmitters to simulate a small radar network which includes both mono- and bistatic operations. The experimental set-up diagram is shown in Fig. 5b. The monostatic transmitter WERA #1 was hard-wired with the receiver system while the bistatic stand-alone transmitter WERA #2 was a free running unit. The WERA #2 unit was synchronized using the method described above. Both transmit signals were combined via a RF-power combiner and fed into one transmit antenna array with 10 Watts total power.

The advantage of this experimental set-up is that the hard wired and self-synchronized data are acquired with the identical system at the same time. The self-synchronized receiver adjusted the external signal to a frequency offset of a quarter of a range cell so that both data are well displayed in one range-Doppler frequency spectrum in Fig. 11 and can further be used for MIMO signal processing. The radial velocities of sea surface currents derived during this specific radar set-up are shown in Fig. 12.

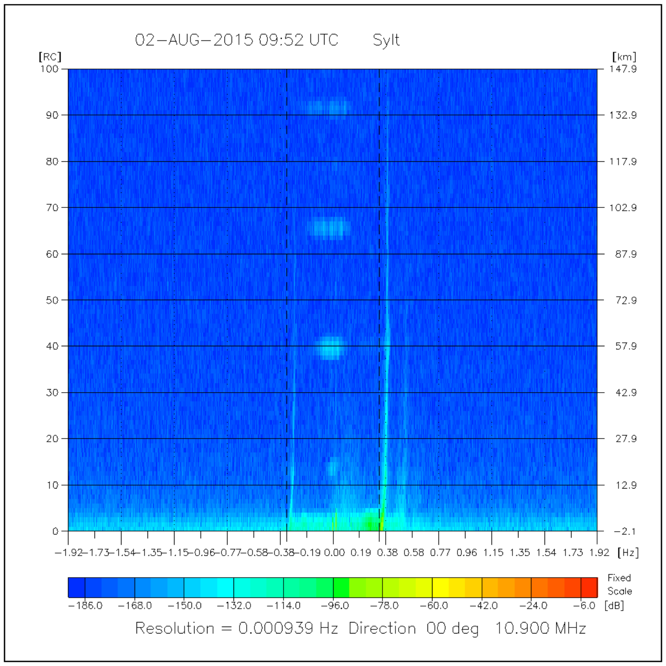

Fig. 9. Range-Doppler frequency spectrum after the second synchronization cycle

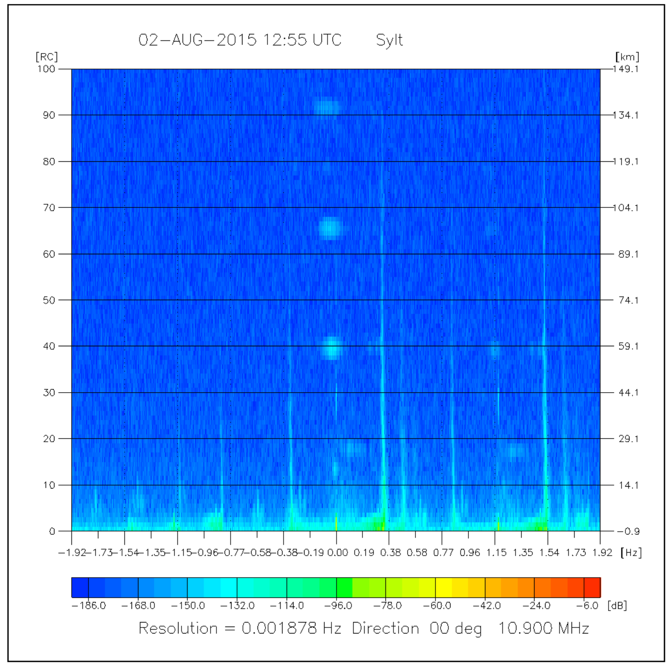

Fig. 11. Range-Doppler map acquired with simultaneously active monostatic and bistatic transmitters during 9-min integration time.

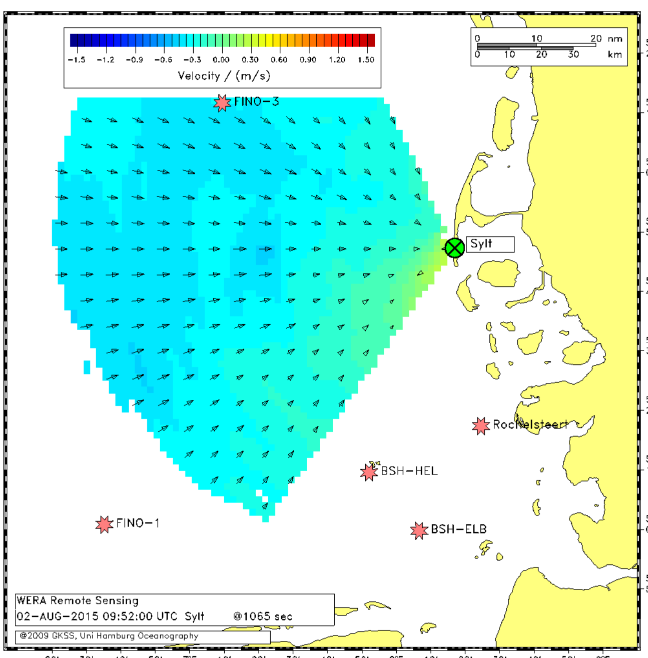

Fig. 10. Sea surface current velocity map with corrected measurements after self-synchronization

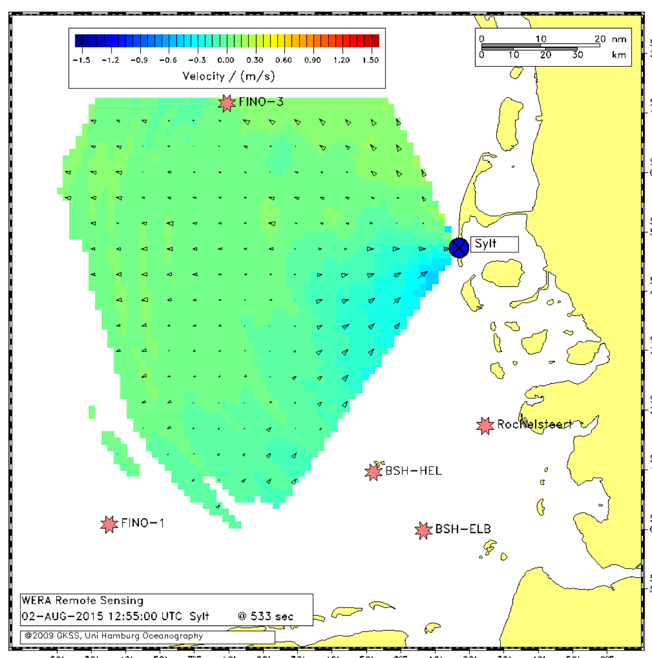

Fig. 12. Radial components of sea current velocity acquired with simultaneously active monostatic and bistatic transmitters.

IV. CONCLUSIONS

This paper has presented an approach for achieving synchronisation between HF ocean radar units without having to rely on external GPS timing. The self-organized approach is very useful for implementation in cases of multiple transmitters and receivers in a radar network as well as in multiple-input-multiple-output (MIMO) radar configurations, which utilize the feasibility of occupying less space for a HF radar receive antenna by maintaining a high spatial resolution of the radar data. Field experiments with existing WERA ocean radar systems were conducted to validate the functionality of the proposed approach.

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REFERENCES

[1] M.L. Heron, L. R. Wyatt, D.P. Atwater, A. Prytz, “The Australian Coastal Ocean Radar Network: Lessons learned in the establishment phase”, IEEE/MTS OCEANS Conference, Yeosu, Korea, 2012, pp.1-5, doi: 10.1109/OCEANS-Yeosu.2012.6263545

[2] C.R. Merz, R.H. Weisberg, Y.Liu, "Evolution of the USF/CMS CODAR and WERA HF Radar Network", Proc. of IEEE/Oceans 2012, pp. 1-5, doi:10.1109/OCEANS.2012.6404947, 2012.

[3] R. Riethmüller, F. Colijn, G. Breitbach, H.-J. Krasemann, W. Petersen, F. Schroeder, and F. Ziemer, “COSYNA, A German inintiative for an integrated coastal observing system”, Proc. of OceanObs'09 Conference, September 2009, Venice, Italy, pp. 1-4.

[4] REPORT ITU-R M.2321. “Guidelines for the use of spectrum by oceanographic radars in the frequency range 3 to 50 MHz”. Document 5B/TEMP/365, 25 November 2014.

[5] E.W. Gill, J. Walsh, “High Frequency Bistatic Cross Sections of the Ocean Surface”, Radio Science, Vol. 36(6), 2001, pp. 1459-1476, doi: 10.1029/2000RS002525.

[6] J. Zhang J, E. Gill, “Extraction of Ocean Wave Information from Simulated Noisy High Frequency Bistatic Radar Data”, IEEE J. Oceanic Eng. Special Issue on HF/VHF Sea Surface Radar, Vol.31, No. 4, 2006, pp. 779-796, doi: 10.1109/JOE.2006.886201.

[7] W. Huang, E. Gill, X. Wu, L. Li, “Measurement of Sea Surface Wind Direction Using Bistatic High- Frequency Radar”, IEEE Trans. on Geoscience and Remote Sensing. Vol .50(10), 2012, pp. 4117-4122, doi: 10.1109/TGRS.2012.2188298.

[8] E. Fishler, A. Haimovich, R. Blum, D. Chizhik et al., “MIMO radar: an idea whose time has come”, Proc. of the IEEE Radar conference, 2004, pp. 71 – 78, doi:10.1109/nrc.2004.1316398.

[9] J.O. Hinz and U. Zoelzer, “A MIMO FMCW radar approach to HFSWR”, Adv. Radio Sci., No. 9, 2011, pp. 159-163, doi:10.5194/ars-9-159-2011

[10] A. Dzvonkovskaya, C. R. Merz, Y. Liu, R. H. Weisberg, T.Helzel, and L. Petersen, “Initial Results of Ship Detection and Tracking Using WERA HF Ocean Radar with MIMO Configuration”, Proc. of Int. Radar Symposium IRS-2014, Gdansk, Poland, June 2014, pp. 317-319, doi: 10.1109/IRS.2014.6869265

[11] A. Dzvonkovskaya, C. R. Merz, Y. Liu, R. H. Weisberg, T.Helzel, and L. Petersen, “Initial Surface Current Measurements on the West Florida Shelf Using WERA HF Ocean Radar with Multiple Input Multiple Output (MIMO) Synthetic Aperture”, Proc. of MTS/IEEE Int. Conf. OCEANS’14, St. John’s, Canada, September 2014, pp. 1-4, doi: 10.1109/OCEANS.2014.7003235

[12] D. Barrick. “First-order theory and analysis of MF/HF/VHF scatter from the sea”, IEEE Trans. Ant. and Prop., vol. AP-20, pp. 2-10, 1972.