Wellen Radar (WERA): a new ground-wave HF radar for ocean remote sensing

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Abstract

HF radars can be used to measure surface currents and wave spectra. The Coastal Radar (CODAR) used by the University of Hamburg was designed for current mapping only. It has been operated for some 15 field experiments during the past 15 years. Recently, a new HF radar called WERA (Wellen Radar) has been developed at the University of Hamburg. One main advantage of the system is the possibility of connecting different configurations of receive antennas. When operated with a linear array, information on the sea state can be obtained via second-order spectral bands. A further advantage is the flexibility in range resolution between 0.3 km and 1.2 km, instead of the fixed resolution of about 2 km of CODAR. This is achieved by transmitting frequency-modulated continuous wave (FMCW) chirps instead of continuous wave (CW) pulses. In addition, this technique avoids the blind range of about 3 km in front of the CODAR. The technical design of WERA is described and first experimental results are presented.

Key words: Ocean remote sensing, HF radar, surface current.

1 Introduction

For some 20 years high-frequency (HF) radars have been used to measure surface currents and wave spectra. The underlying physics is concerned with radar backscattering from a moving rough sea surface which can be described by the theory of wave-wave interaction (Bragg scattering). First-order Bragg scattering is due to surface gravity waves of half of the transmitted HF wavelength propagating towards or away from the radar site. The Doppler shift of the received signal determines the phase velocity of the scattering waves which is composed of the theoretically known portion of surface waves in nonmoving water and a contribution from underlying currents. The difference between the measured and theoretical phase velocity is attributed to the radial velocity (relative to the radar) of the surface current. The spectral distribution of the backscattered energy depends on the surface wave spectrum. While first-order scattering yields information on the scattering waves only, i.e. two discrete spectral lines, second-order scattering reflects the full two-dimensional wave spectrum within certain continuous spectral bands.

HF radars have been operated with frequencies between 7 MHz and 50 MHz. Some of the transmitted HF energy is guided by the sea surface and allows measurements to be made beyond normal radar horizon. Lower frequencies allow greater ranges tu be achieved but at the cost of less spatial resolution. Depending on the transmitted frequency, ranges of up to 200 km may be achieved. More details about the physical limitations of HF ocean sensing are discussed by Gurgel *et al.* [1], this issue. The systems presented in this paper make use of frequencies between 25 MHz and 30 MHz with maximum ranges of some 50 km. The ranges mentioned refer to current measurements. The identification of second-order bands, i.e. the determination of wave spectra, is only possible to about half these ranges.

Barrick *et al.* [2] at NOAA developed the first HF radar with the capability of mapping surface currents. First theoretical investigations on the retrieval of wave information from HF radar backscatter are reported by Hasselmann [3] and Barrick [4]. The University of Hamburg started its work on HF radars in 1980 by adopting the Coastal Radar (CODAR) of NOAA. By 1985 both hardware and software had been modified in order to reduce internal noise, increase sensitivity and optimize processing algorithms. Since then the CODAR has been operated in some 15 field experiments, e.g. Essen et al. [5,6], and from onboard a ship, cf. Gurgel and Essen [7]. Information on the state-of-art of HF remote sensing is presented by Gurgel *et al.* [1], this issue.

Progress in electronics and computer techniques have allowed the design of a new system which avoids some of the shortcomings of the CODAR system. The CODAR four-element receive antenna system does not permit the application of beam-forming techniques which are needed for reliably resolving wave-induced second-order spectral bands, i.e. for measuring surface wave spectra. In addition, longer ranges and higher spatial resolution were desired. Based on these requirements, the new radar WERA (Wellen Radar) has been developed which can be operated with up to 16 receive antennas. The range resolving technique has been changed from the transmitting of continuous (CW) pulses used by CODAR to frequency-modulated continuous wave (FMCW) chirps in the WERA system. As both transmitter and receiver operate continuously, there is no blind range in front of WERA.

WERA has been developed within the European project SCAWVEX (surface current and wave variability experiment). The first field experiments were carried out in 1996 on the Dutch coast. In the spring, two CODAR and two WERA systems were installed north and south of the Rhine mouth. Surface current monitoring by CODAR extended over six weeks, whilst WERA was operated only for the last two weeks. Comparisons of the performance of both systems are presented. In the fall of 1996, a second experiment was carried out some 100 km north of the Rhine mouth. The objective was to test the wave-monitoring capability of the WERA system, which was operated from two sites over a period of six weeks.

This paper reports on experience with current measurements only. One radar measures the radial current speed relative to its position. I.e., at least two stations at different sites are necessary for determining the two-dimensional current vector. Horizontal averaging depends on the range and azimuthal resolution of the radar and is between some 0.1 km^2 and 10 km^2. Vertical averaging occurs in a natural manner due to the penetratation depth of the scattering surface waves and is about 0.5 m. Temporal averaging is performed by the measurement time of 9 or 18 min.

Surface currents are hard to measure by conventional means. The unique advantage of the HF radar is the ability to map the horizontal variability of currents which is needed for several applications. Eddy dynamics, such as propagation and decay, can be studied, cf. Essen *et al.* [6], as well as the spatial variability of tidal currents, cf. Prandle [8]. Maps of surface currents yield ground truth for satellite remote sensing. Examples are the comparison with satellite-measured sea-surface temperature (SST) fields, cf. Essen [9], or with current velocities as extracted from interferometric synthetic aperture radar (INSAR), cf. Graber *et al.* [10]. The capability of measuring surface-wave spectra by means of WERA is discussed by Wyatt *et al.* [11], this issue.

2 Techniques of spatial resolution

HF radars transmit electromagnetic waves to the sea surface and record the backscattered signal which contains information on surface currents and waves. In order to locate the scattering area, spatial resolution has to be achieved in range and azimuth. For this pupose, CODAR and WERA apply different techniques. These techniques as well as the hard- and software components of the WERA are described. Additional physical and technical problems which arise by both range and azimuthal resolution are discussed by Gurgel *et al.* [1], this issue.

2.1 Range resolution

The CODAR system transmits short CW pulses and resolves the range by means of the travel time. The spatial resolution is determined by the pulse length. In order to not disturb the receive signal, successive transmit pulses have to be separated by a period of the order of 100 pulse lengths. Because of the relative short transmit time, a high peak power is needed. The main advantage of this kind of range resolution is the simple technical design. The CODAR of the University of Hamburg uses a carrier frequency of 29.85 MHz. The length of the tapered pulse is 16 μs, which corresponds to a range resolution of about 2 km. As no echos are expected from distances larger than some 80 km, a pulse repetition period of 512 μs has been chosen. The received signal is phase-coherently demodulated. The resulting slowly varying in-phase and quadrature time series are A/D converted with a sampling rate of 8 μs which corresponds to range sampling of 1.2 km. After averaging 128 time samples, the temporal sampling becomes 0.262 s, which is appropriate for the sea-surface variability.

WERA transmits linear frequency chirps, where the frequency shift between the transmitted and received echo determines the range. The range cell depth is related to the bandwidth of the chirp. This technique is known as FMCW (frequency modulated continuous wave). The transmit signal is,

$$s(t) = \sin[2\pi(\nu_o + \frac{b}{2T}t)t], \tag{1}$$

where during the chirp period T the frequency (i.e. the derivative of the phase with respect to time) linearly increases from ν_o to $\nu_o + b$. After reaching the maximum frequency, the chirp is repeated. The received signal is a superposition of HF waves, which have been backscattered at different distances from the radar,

$$r(t) = \int \alpha(\tau) \sin[2\pi(\nu_o + \frac{b}{2T}(t-\tau))(t-\tau) + \varphi(\tau)]d\tau, \tag{2}$$

where τ is the propagation time from the radar to the scattering area and back, i.e. a measure of the range. The amplitude $\alpha(\tau)$ and phase $\varphi(\tau)$ change slowly with time due to variations of the scattering surface waves, but can assumed to be constant during a chirp period. After phase-coherent demodulation, the in-phase and quadrature time series are composed of a complex series,

$$z(t) = \int \frac{\alpha(\tau)}{2} \exp[i(-2\pi\frac{b\tau}{T}t + \phi(\tau) + \varphi(\tau))]d\tau. \tag{3}$$

Range resolution is performed by Fourier-transforming each single chirp. The resolution of the frequency $\nu = b\tau/T$ is determined by the length T of the chirp, $\Delta\nu = 1/T$. Thus the resolution of the propagation time $\Delta\tau$, and in turn range Δr, becomes,

$$\Delta\tau = \frac{T\Delta\nu}{b} = \frac{1}{b}, \quad \Delta r = \frac{c}{2}\Delta\tau = \frac{c}{2b}, \tag{4}$$

with c being the speed of light. It should be mentioned that the Fourier transform requires some caution. Due to the leakage problem in spectral analysis, near-range high-energy spectral lines may mask far-range lines of low energy. This problem is accounted for by applying a window filter to the chirps prior to the Fourier transform, cf. Gurgel *et al.* [1], this issue.

The complex Fourier amplitudes of the chirps determine the samples of the slowly varying modulation of the backscattered signal, which contains the information on the sea-surface variability. After sorting into range cells, it becomes,

$$v(n\Delta r, t) = \alpha(n\Delta\tau, t)\exp[i\varphi(n\Delta\tau, t)], \tag{5}$$

where n counts the range cells. This result is equivalent to that of CODAR. It contains the backscattered signals from a certain range cell, but is a superposition of backscattered waves from different azimuthal directions at each single antenna.

Transmit frequencies of WERA between 27 MHz and 30 MHz were used during the test experiments. However, other frequencies are possible with some simple modification of the system. Range resolutions of 1.2 km, 0.6 km and 0.3 km can be selected. The chirp length determines the sampling rate of the surface variability and is T = 0.26 s. For a given range resolution, a specific bandwidth of the radar signal is needed, e.g. 125 kHz for 1.2 km resolution. This bandwidth is independent of the technique applied, pulses or chirps.

Advantages of range resolution FMCW technique are the possibility of altering the range cell depth by just modifying the width of the chirp, omitting the blind range in front of the radar, and a lower data rate to be processed in the receiver. However, transmitter and receiver must be designed for extreme dynamic range and linearity, as the superimposed near-range high-energy and far-range low-energy signals have to be separated.

CODAR, as developed by Barrick *et al.* [2] makes use of four antennas arranged in a square. Azimuthal resolution is performed in the frequency domain by means of the complex Fourier components of the time series in Eq. (5). This procedure is called direction-finding. Theoretically, two waves of the same Doppler shift, but different direction, can be resolved from the four complex Fourier components. However, a method accounting for phase differences only, is more robust, but allows the resolution of one direction only, cf. Leise [12], i.e. the azimuthal resolution is based on the assumption that the radial speed uniquely depends on the azimuthal direction. The algorithm developed at the University of Hamburg enables the detection and discarding of ambiguous data. It has been found that in some cases the processing of overlapping shorter partial time series yields better performance. In general, the direction-finding method worked well for all the data collected with the CODAR of the University of Hamburg.

The main advantage of the four-antenna configuration is the small space needed, i.e. for operation from a rocky coast, cf. Essen *et al.* [6] or from on-board a ship, cf. Gurgel and Essen [7]. Disadvantages are possible failures of the direction-finding algorithm due to ambiguities and more important, second-order Doppler lines from a certain azimuthal direction are masked by first-order lines from deviating directions. The second-order Doppler spectrum contains most of the information on the sea state.

WERA allows the operation of up to 16 receive antennas which can be installed arbitrarily with respect to experimental requirements, e.g. WERA may be operated with the four-element CODAR array. Another method of angular resolution is beamforming which WERA permits by means of the receive antennas. For operation from the coast, i.e. receiving signals from a semicircle only, the most appropriate antenna configuration is a linear array. Beamforming is performed in the time domain by adding the weighted and phase-shifted signals, Eq. (5), of all antennas. The weighting reduces side lobes and the phase shift steers the beam to the desired direction. The beam width depends on the aperture, i.e. the overall length of the array. The main disadvantage of the linear array is the space needed (length of $15 \times \lambda/2$) instead of a square of $\lambda/2$ in diameter of the CODAR array, where $\lambda \approx 10$ m is the wavelength of the radar signal. Additional problems associated with beamforming are discussed by Gurgel *et al.* [1].

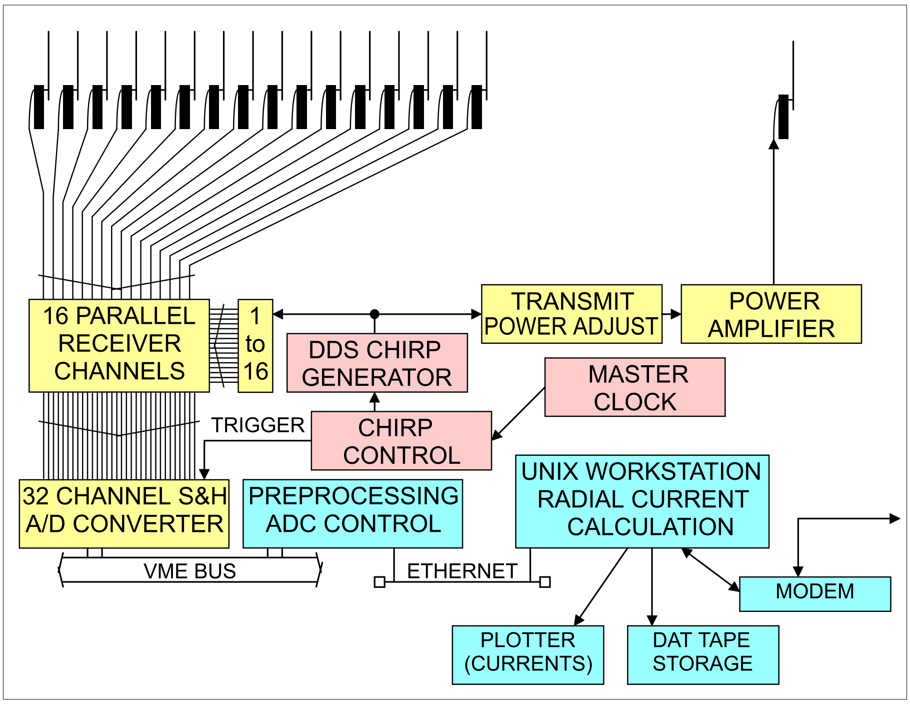

Figure 1. Block diagramm of WERA system.

3 Technical design of WERA

The design of WERA is based on standard industry components whenever possible. This helped to reduce both development costs and time which was one year. Components not available on the market were built around smaller modules. The aim was to use state-of-the-art techniques in order to achieve the highest dynamic range and linearity possible. WERA is using FMCW modulation for range resolution, which implies simultaneous transmit and receive operation of the radar. The design involves a combination of hardware and software solutions.

3.1 Hard- and software components

The most crucial component of a FMCW radar is the chirp generator. Advantages of the Direct Digital Synthesizer (DDS), used by WERA, are high flexibility and optimum realisation of a linear chirp at low phase noise. The chirp is used by both transmitter and receiver. A block diagram of the hardware is presented in figure 1. The DDS is controlled by a high speed counter. Start and stop frequency can be easily changed, which permits modifications of mean carrier frequency and range resolution. The system master clock is a stable synthesizer (HP 3335A). Its long- and short-term stability and low phase noise is essential for good performance.

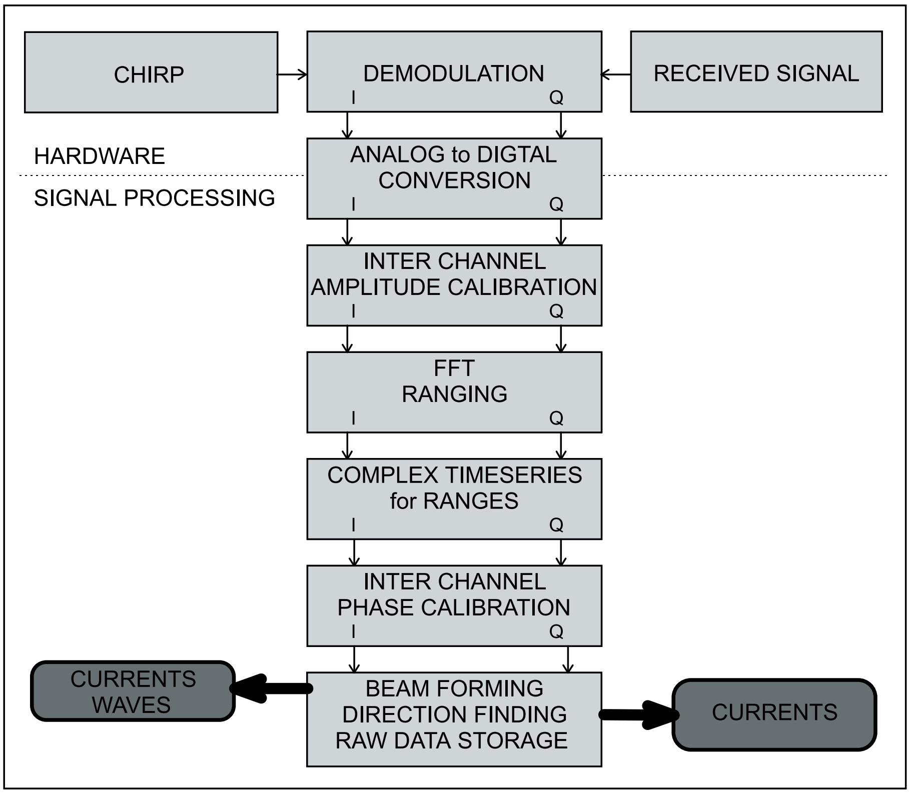

Figure 2. Signal processing implemented in WERA.

The generated chirp is split into 17 channels. One controls the transmitter and is amplified to 47 dBm. The others are needed for the phase-coherent I/Q demodulation of the backscattered signals. This is performed by 16 independent direct-conversion receivers connected to the receive antennas. Before A/D conversion a low pass filter (7-pol, -3 dB at 700 Hz) suppresses frequencies above the Nyquist frequency and a high pass filter attenuates the strong signals received directly from the transmit antenna. The characteristics of the filters have been measured and are compensated for by software during data analysis. In order to extend the dynamic range of the 16-bit A/D converter, the signal is oversampled 13 times. The next steps of signal processing are implemented in software.

The A/D converters are connected to a VME-bus and controlled by a DEC AXPvme CPU running the VxWorks operating system. This CPU performs all processing steps in real time during the measurement. The VME-bus system is connected to a Digital Unix workstation by an ethernet line. Measured raw data are directly stored on the workstation's disk by NFS protocol. Final processing, i.e. store data, form beams and calculate the surface current velocity, is done on the workstation.

Figure 2 illustrates the signal processing implemented in WERA. After A/D conversion of the complex demodulated signal, an inter-channel amplitude calibration is applied to compensate for gain variations of the 16 receivers. Range resolving Fast Fourier Transforms (FFT) are then applied to all channels. A windowing function as described in Gurgel *et al.* [1] has to be used in this context. After sorting of the data into range cells, the complex time series of Eq. (5) are available. An inter-channel calibration of the phase is performed and the data are stored for further processing. Amplitude and phase calibration is crucial for the accurate performance of azimuthal resolution techniques.

3.2 Data processing

Data processing of CODAR is based on the Fourier transforms of the demodulated complex time series, which are available from four antennas at each range cell. Within the signal range, the Doppler lines are attributed to varying radial speeds at different azimuthal directions, i.e. the information used is distributed over a broad frequency range. When operating WERA with a linear array of receive antennas, data processing is based on beamforming in the time domain. Considering a certain range cell and a selected azimuthal direction, the time series should contain two major frequency components which are due to Bragg scattering waves running toward or away from the radar site. The shift relative to the theoretical Bragg lines determines the radial speed of underlying currents.

In the case of beamforming, the radial surface current speed is determined by two single frequency lines, cf. Gurgel *et al.* [1]. In general, the frequency spectrum is computed by means of Fourier analysis. However, publications of Khan [13] and Martin and Kearney [14] show that parametric spectral estimation methods can lead to significantly improved spectra, which reveal higher accuracy and larger working range.

4 Experimental results

4.1 Comparison of CODAR and WERA

In spring 1996, both CODAR and WERA systems were installed at two sites North and South of the Rhine mouth. At each site CODAR and WERA were operated alternately with measuring periods of CODAR and WERA of 18 min and 9 min, respectively. This experiment permitted a comparison of the performance of the two systems. In Particular, the methods of azimuthal resolution are compared direction-finding in Fourier domain (CODAR) and beamforming (WERA). The CODAR was equipped with the four-antenna square array,

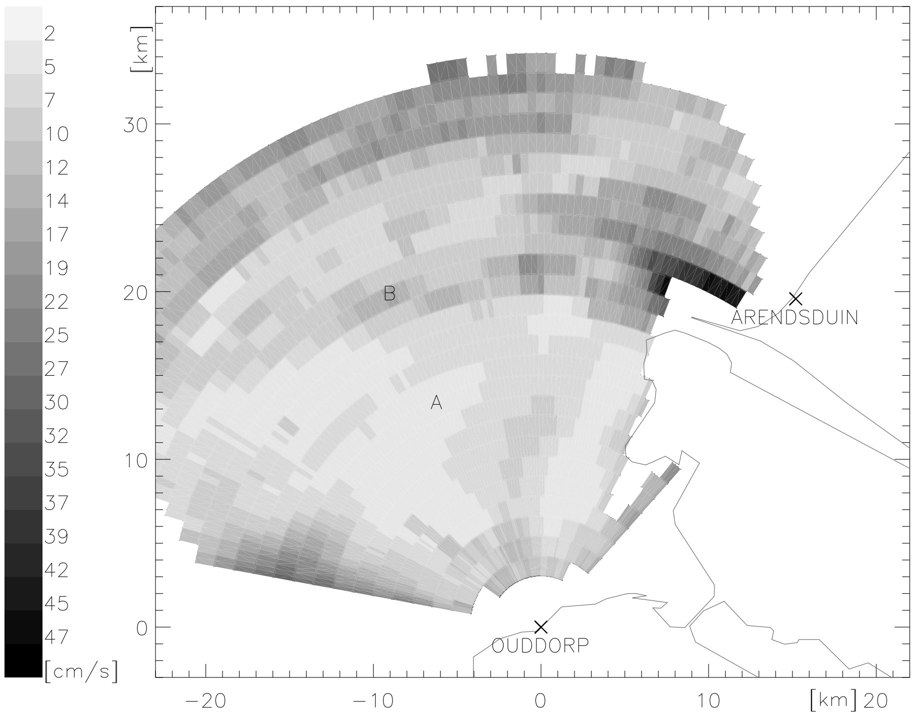

Figure 3. Radar sites Ouddorp and Arendsduin at the Rhine mouth, and rms differences in grey-scale between radial speeds measured by CODAR and WERA.

while the 16 receive antennas of WERA were separated into a 12-antenna linear array and a 4-antenna square array.

Figure 3 shows a map of the experimental site and displays the rms difference of radial speeds measured by CODAR and WERA. The data set covers 382 successive measurements of CODAR and WERA, taken every 1/2 h between 17-March, 21:00 UTC and 25-March, 17:00 UTC. During this period the sea state was moderate. Some of the differences may be due to deviating spatial resolution, 2.0 km and 1.2 km, and temporal averaging, 18 min amd 9 min, for CODAR and WERA, respectively, or due to currents changing between the two successive measurements. However, most of the deviation must be attributed to measurement errors. Up to 25 km the rms difference is less than 10 cms^{-1}. At larger distances, there are areas with unexpected high rms differences.

In the literature, Graber *et al.* [16] found a range of rms differences of 4 - 20 cms^{-1} between HF radar current measurements and those observed by conventional means. However, the quantities measured by radar and current meters differ. While the radar measures surface currents averaged of serveral km^2, current metres are located a few metres below the surface and perform point measurements. Investigating the statistics of radial speeds measured by CODAR in several experiments, we estimated an accuracy of about 5 cms^{-1}. This is in accordance with errors found for the 25.4 MHz Ocean Surface Cur-

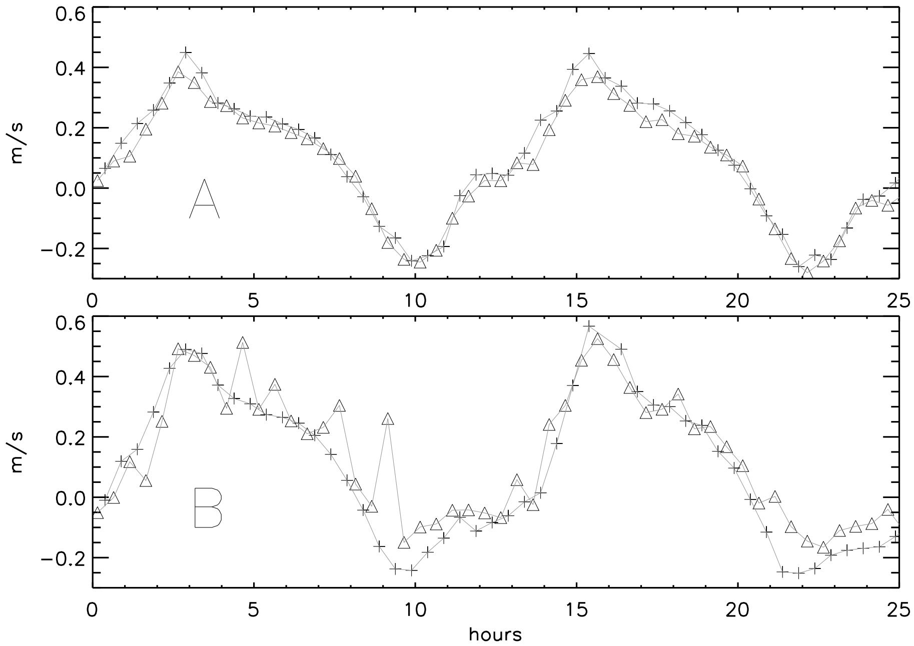

Figure 4. Radial speeds measured by CODAR (triangles) and WERA (crosses) at position A (upper panel) and B (lower panel) of Figure 3.

rent Radar (OSCR), cf. Graber *et al.* [16]. It should be mentioned that the error depends on the signal-to-noise ratio and increases with increasing range.

Figure 4 displays radial speeds measured by CODAR and WERA at the two positions A and B in Figure 3. The time series extend over two M2 tidal cycles with 1/2 h sampling. At position A both measurements agree well with a rms difference of less than 5 cms^{-1}. At position B, the CODAR measurements reveal some spikes within the almost continuos time series, whereas the WERA time series is stable. Position B is situated within the main shipping route towards Rotterdam harbour. For this reason, we conclude that the CODAR direction-finding algorithm is less robust than the beamforming with respect to perturbations by ship traffic. This finding is confirmed by investigations of the signal-to-noise ratio of both measurements, cf. Gurgel *et al.* [15].

4.2 Current measurements

The experiment in spring 1996 was aimed at measuring the circulation in front of the shipping channel to Rotterdam harbour. This area is characterized by high oceaongraphic variability due to the inflow of fresh water from the Rhine which, because of tidal influences, changes periodically. Plumes are generated and propagate along the coast to the north. Special wind situations can generate current structures, which interfere with the ship traffic. The experiment lasted from 18-February to 26-March 1996, CODAR was operational for the

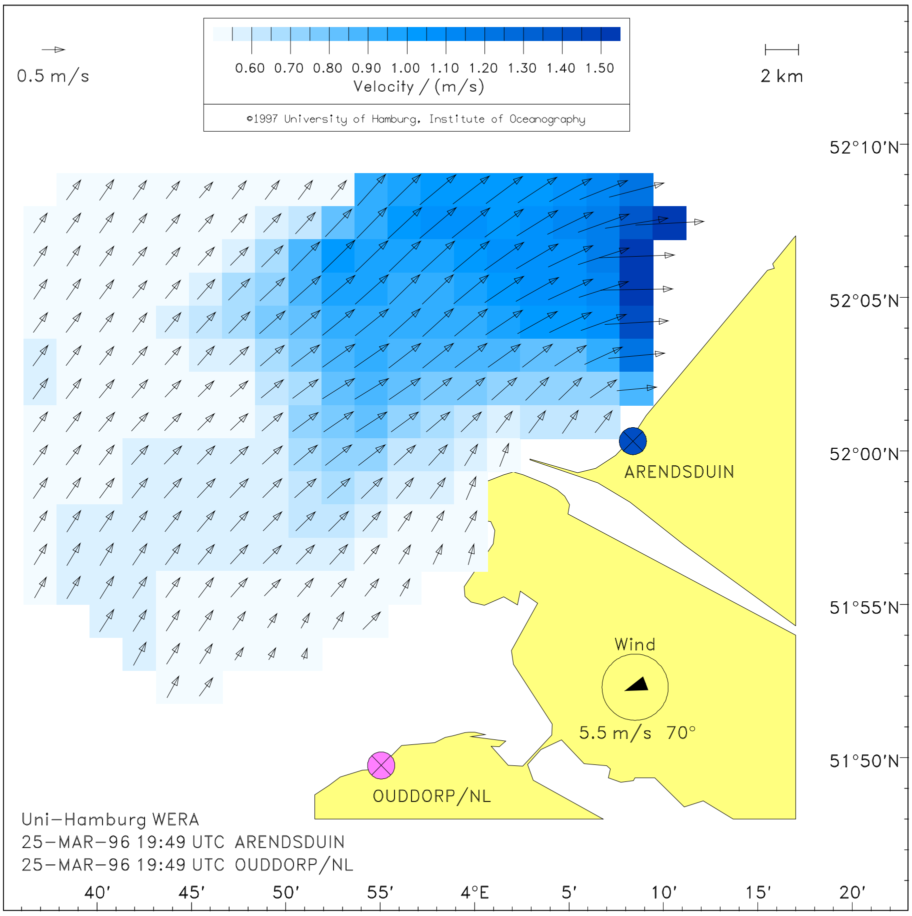

Figure 5. Surface current measured by WERA. Arrows represent current speed and direction, grey shading refers to the current speed.

whole time, WERA only the last two weeks.

Figure 5 presents an example of WERA measured surface currents. WERA was equipped with a linear array of 12 receive antennas. The two radar sites were operated simultaneously, the start time is indicated. The grid spacing is 2 km. The arrows represent speed and direction of the current. Figure 6 shows the current field measured by CODAR 10 minutes later. The integration time of CODAR is 18 min, that of WERA 9 min, which means that the effective delay between the two measurements is about 15 min. In general, there is a good agreement. Maximum tidal currents are shifted somewhat towards north. Strong differences occur in the shallow area just south of the Rhine outflow close to the coast. This area is not covered by beamforming because the view direction is almost parallel to the antenna array. On the other hand, the propagation from the Arendsduin HF site is partly over land and both WERA and CODAR measurements may be distorted. Distortions may be caused by refraction at shore, higher attenuation over land than over sea, and obstructions from metal constructions in the Rotterdam harbour area.

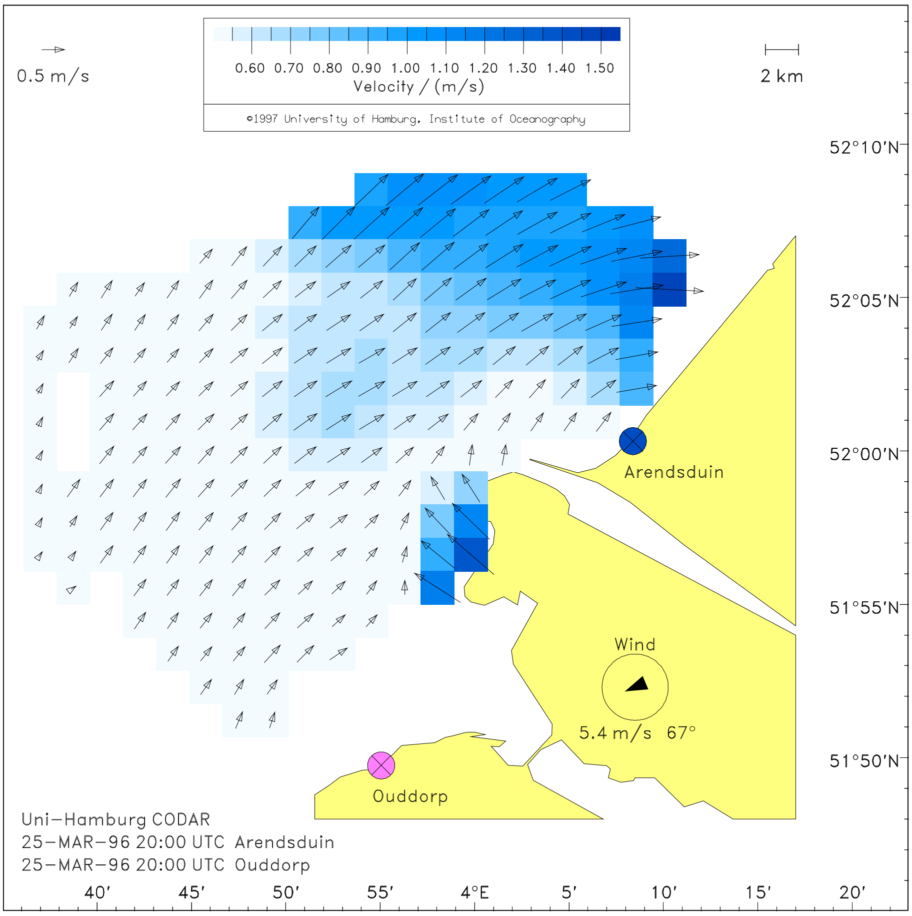

Figure 6. Surface current measured by CODAR. Arrows represent current speed and direction, grey shading refers to the current speed.

The surface currents presented have been computed by considering the shallow-water dispersion relation. The bathymetry used takes into account actual tide gauge measurements. However, the two-dimensional current vectors presented are not affected by the bathymetry. Changes of the phase velocity of the scattering Bragg wave (about 5 m wavelength) are less then 1 cms^{-1} if the water depth exceeds 2.2 m.

Surface currents could be measured within an area of 30 km $\times$ 30 km for the whole measuring period, independent of sea state. WERA revealed somewhat larger working ranges than CODAR. However, the mean working range was less than expected from former experiments. The most probable reason for this finding is the wide beach between antennas and the sea, combined with the low height of the antennas above the sea surface. In addition, the relative fresh Rhine water tends to remain at the surface and causes higher HF attenuation.

The main objective of the second experiment in fall 1996 was the measuring of wave parameters by means of WERA. The area selected was near Petten on the Dutch coast (figure 7), which is highly exposed to the sea and situated south of the island Texel. Standard buoy supported wave measurements have been performed on a long term basis by the Dutch hydrographic institution Rijkswaterstaat. In order to realize a sufficient signal-to-noise ratio for the second-order wave signals, the radar sites were deployed only 10 km apart. This configuration is not optimum for current measurements of up to 40 km off shore. Narrow angles between two radial components used for composing a two-dimensional vector considerably reduce its accuracy.

Both WERA sites were operated with the 16-element linear receive array, and beam-forming technique was applied for azimuthal resolution. The experiment lasted from 29-October to 7-December 1996. The measuring period was 9 min. In order to avoid interference, the two sites were operated successively, and repeated every 20 min. A range resolution of 1.2 km was chosen for most of the experiment and reduced to 0.3 km for the last two days. In the high-resolution mode, the amount of data constrained the working range to 38.4 km, although the signal-to-noise ratio allowed ranges of up to 50 km for current measurements. Wyatt *et al.* [11] analysed the data for wave spectra by making use of inversion techniques, cf. Wyatt and Ledgard [17].

Vectors of surface currents, measured with 1.2 km range resolution, have been evaluated on a grid with 2 km spacing. The azimuthal resolution is some 6^o and, in terms of km, increases with increasing range, i.e. becomes coarser than the grid spacing at ranges larger than 20 km. Unfortunately, the radar at Petten suffered from radio interference with the wave buoys. The wave buoys worked like transponders by receiving the radar signal, modulating and retransmitting it. Distortions of parts of the chirp signal lead to missing data of some ranges. However, in most cases the gaps could be filled by interpolation. Depending on the sea state, working ranges varied between less than 30 km and more than 50 km.

Figure 7 shows an example of surface currents measured with 1.2 km resolution on 20-Nov-1996. A jet with maximum speed of 1.2 ms^{-1} propagates along the coast. This jet is a well known phenomenon caused by the Rhine outflow some 100 km further south. Figure 8 displays surface currents measured with 0.3 km resolution on 7-Dec-1996 at about the same tidal phase as the measurement of figure 7. The gaps are due to the interference problem discussed before. The azimuthal resolution of the antenna array used is about $\pm 3^o$, i.e. only in the near range of the same order as the 0.3 km range resolution. Due to the site locations the high resolution applies mainly to the direction perpendicular to the coast. Again the jet is visible. At its edge the current shear is 0.5 ms^{-1} within 300 m, i.e. ≈ 0.002 s^{-1}. This unexpected high value confirms the necessity of measuring with high spatial resolution in coastal waters, in order to understand ocean dynamics.

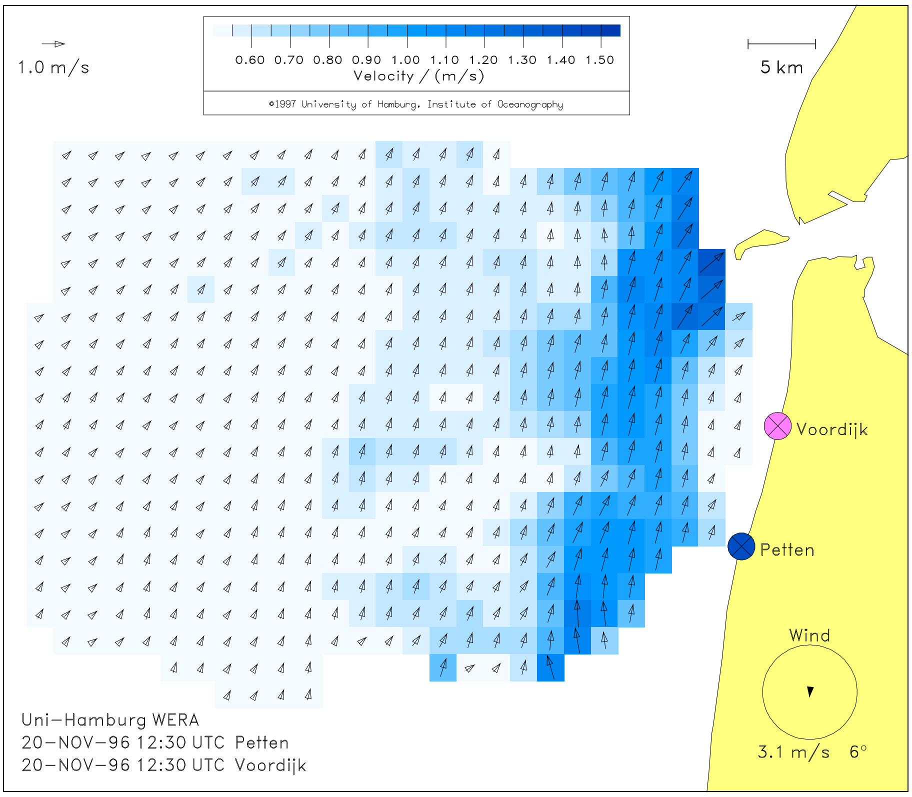

Figure 7. Surface current measured by WERA with 1.2 km resolution on a 2 km $\times$ 2 km grid. Current speed is encoded in grey-scale, current direction indicated by arrows.

5 Conclusion

Compared to CODAR, the new design of WERA offers increased flexibility in spatial resolution and allows both beamforming and direction-finding techniques, as required by the application. Within the EC project SCAWVEX, the WERA system measured surface currents and wave height directional spectra simultaneously, using the University of Hamburg current algorithm and the University of Sheffield wave algorithm, respectively. This is a further step in research on current-wave interaction. With respect to current measurements the high-resolution mode of WERA (0.3 km) is advantegeous for studying near-shore ocean dynamics and for the interpretation of space-borne synthetic aperture radar (SAR) images.

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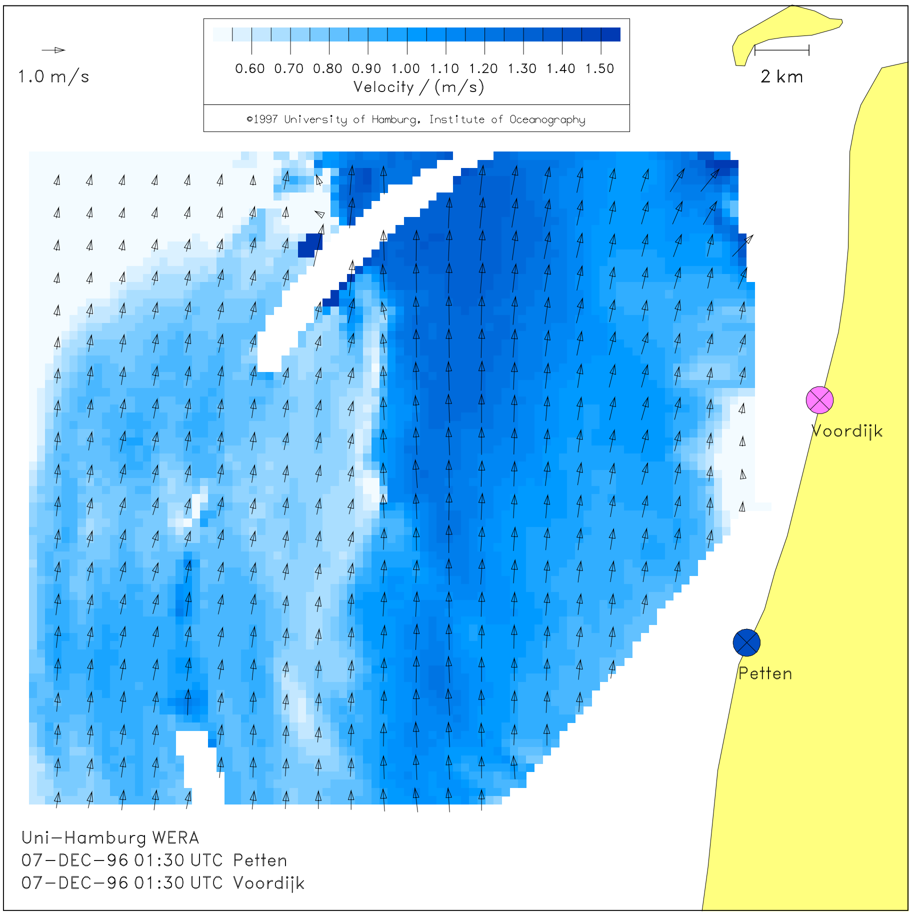

Figure 8. Surface current measured by WERA with 0.3 km resolution on a 0.3 km × 0.3 km grid, with each 4th vector displayed. Current speed is encoded in grey-scale, current direction indicated by arrows.

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