Applications of Coastal Radars for Monitoring the Coastal Zone

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Abstract

Coastal radars for monitoring the coastal zone have been developed for some 20 years taking advantage of improved electronics and computer techniques. The term 'Coastal Radar' is normally connected to High-Frequency (HF) radars which use ground-wave propagation to remotely sensing ocean surface currents and sea state over large areas. In a broader sense, also microwave radars operated from the coast can be called 'Coastal Radars'. Microwave radars have the advantage of simple installation, but do not cover the large areas as possible with HF radars. As many applications need forecast information, these 'Coastal Radars' can be used to measure maps of surface current and wave spectra, which then are assimilated into models.

1 Introduction

Remote sensing of current and wave information at the coastal zone got more and more important during the last decades. Applications like coastal management and ship guidance require increased data density compared to single point measurements with current meters and wave bouys. Remote sensing techniques also have the advantage of no need to install a mooring in the open sea, which can be damaged by bad weather conditions or ships passing too near.

Radars, as used by ships or satellite remote sensing, operate in the microwave band with wavelengths of some centimeters. In the past 20 years, algorithms have been developed to measure the wave directional spectra within a 1 km^2 patch of the sea using a nautical radar; e.g. the WaMoS system developed by the GKSS Research Centre now is commercially available from Ocean SensWare [17]. These systems are quite small and easy to install and operate. Using satellites like ERS-1/2 in costal monitoring have the disadvantage of poor temporal coverage, i.e. one image every 35 days.

High-frequency (HF radars) use frequencies between 3 MHz and 30 MHz with wavelengths of 100 m to 10 m. For remotely sensing the ocean, HF radars are mostly operated from the coast, except for a few attempts at ship-based operations. Remote sensing by means of HF radar is based on skywave or ground-wave propagation. Refraction by the ionosphere allows a large propagation range to be achieved. However, the ionosphere undergoes temporal changes and modulates the signal from the sea surface. This paper deals with ground-wave propagation only. The advantage of HF radars is the possibility of

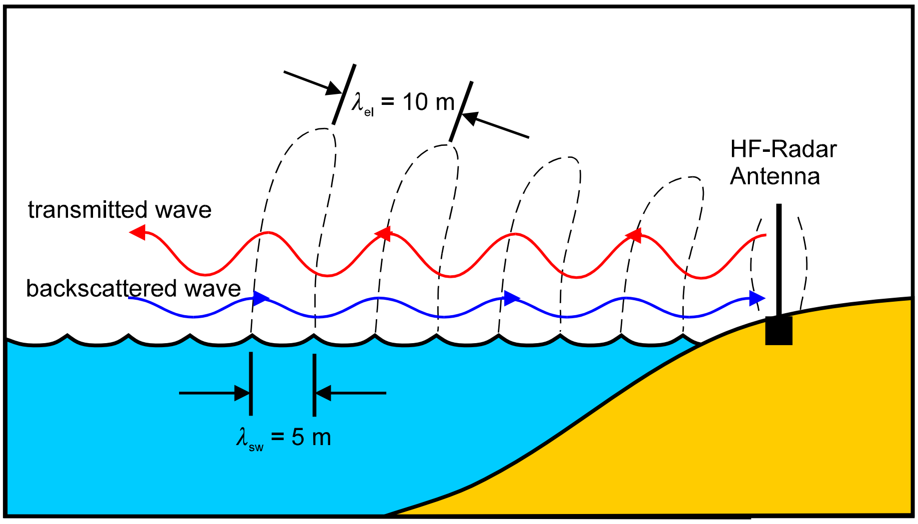

Figure 1: Backscattering of electromagnetic waves at a wavelength λ_{el} from ocean waves of half the electromagnetic wavelength by Bragg scattering.

continuously mapping surface current and ocean waves over large areas, i.e. 40 km$\star$40 km with a resolution down to 300 m. The University of Hamburg recently developed a new HF radar for coastal applications called WERA (WEllen RAdar).

2 Basic physics and performance of HF radars

2.1 Propagation and scattering of electromagnetic waves

HF remote sensing is based on the scattering of electromagnetic waves from the rough sea surface. As the ocean wave spectrum nearly always contains sea wavelengths of the order of the radar wavelength, the Bragg scattering theory is applicable. In the case of a monostatic configuration, i.e. transmitter and receiver at the same position, first-order Bragg backscattering is due to ocean waves of half of the radar wavelength travelling towards or away from the radar site (figure 1). Thus, the Doppler spectrum (figure 2) of the backscattered signal contains two lines, the frequencies of which are determined by the phase velocity of the scattering ocean waves. Deviations from the theoretically known values in nonmoving water are attributed to an underlying surface current. This is the way, a HF radar measures the radial component of the surface current vector. The strengths of the Doppler lines reflect the spectral density of the two first-order scattering ocean waves. The full ocean wave spectrum is involved in second-order scattering and generates side-bands in the HF-Doppler spectrum. These can be used for determining, by means of inversion techniques, the two-dimensional wave-height spectrum.

Ground wave propagation strongly depends on the conductivity of the sea water. The conductivity mainly is a function of temperature and the salinity of the water. The

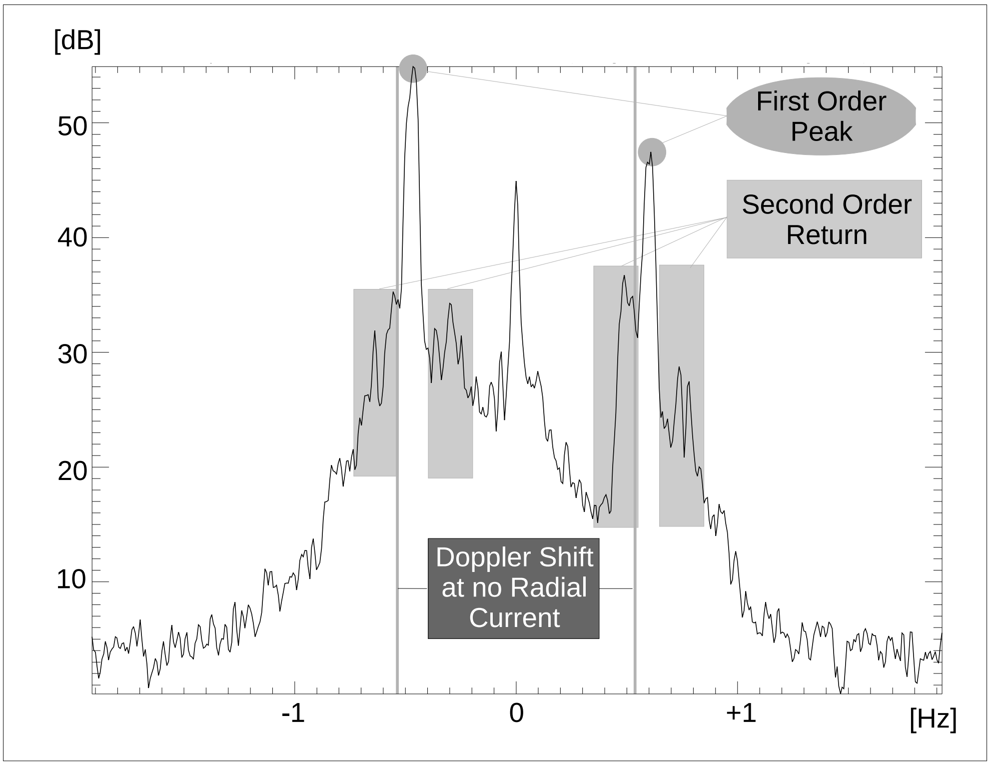

Figure 2: The spectrum of the sea echos from a selected patch of the sea surface. The first order Bragg peaks and the second order sidebands are indicated.

University of Hamburg has experience in operation of HF radars at 25 MHz to 30 MHz under a wide range of conditions:

- In the Dead Sea, the salinity is extremly high and only a low transmitter power is needed to cover the complete area.
- In the North Sea, the salinity is about 35 PSU. This corresponds to a conductivity of $G \approx 45$ mmho/cm, which is the normal working condition for oceanographic HF radars.
- In the Baltic Sea, the salinity varies between 14 PSU in the west to 7 PSU around Bornholm and nearly 0 PSU in the east. At 7 PSU, the conductivity is around $G \approx 7$ mmho/cm, which reduces the working range of the HF radar by about 50 %.
- A test in a fresh water lake showed that the HF radar did not measure any sea echos.
- Ice coverage also reduces the working range by damping the Bragg-scattering ocean waves and in addition decreasing the salinity due to freezing.

More detailed information on this topic can be found at [10].

2.2 Measurement of the 2-dimensional surface current

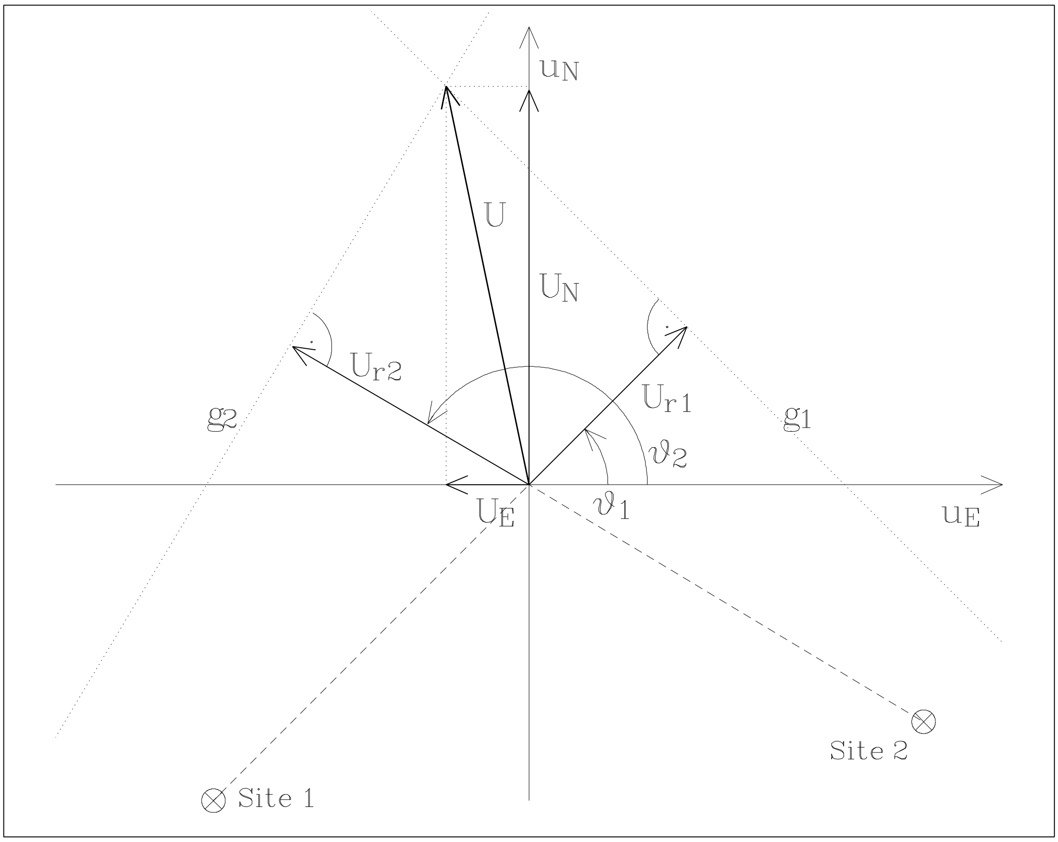

Figure 3: Calculating the 2-dimensional surface current vector U from two radial components U_{r1} and U_{r2} measured at site 1 and site 2.

In principle, radar systems measure in polar coordinates. Spatial resolution has to be achieved in range and azimuth. The radial component of surface current velocity relative to the radar site is calculated from the HF radar backscatter spectrum. At least two radars are needed for detecting the 2-dimensional vector of current velocity. If more than two radial components are available, a least-squares algorithm can be used to increase the accuracy of the 2-dimensional surface current vector.

2.3 Examples of surface current maps measured at the Dutch coast

Within the EC MAST-2 project SCAWVEX[1], WERA was operated during two experiments at the Dutch coast. The first experiment was aimed to measure the circulation in front of the shipping channel to Rotterdam, which is heavily effected by the inflow

[1]Surface Current And Wave Variability EXperiment

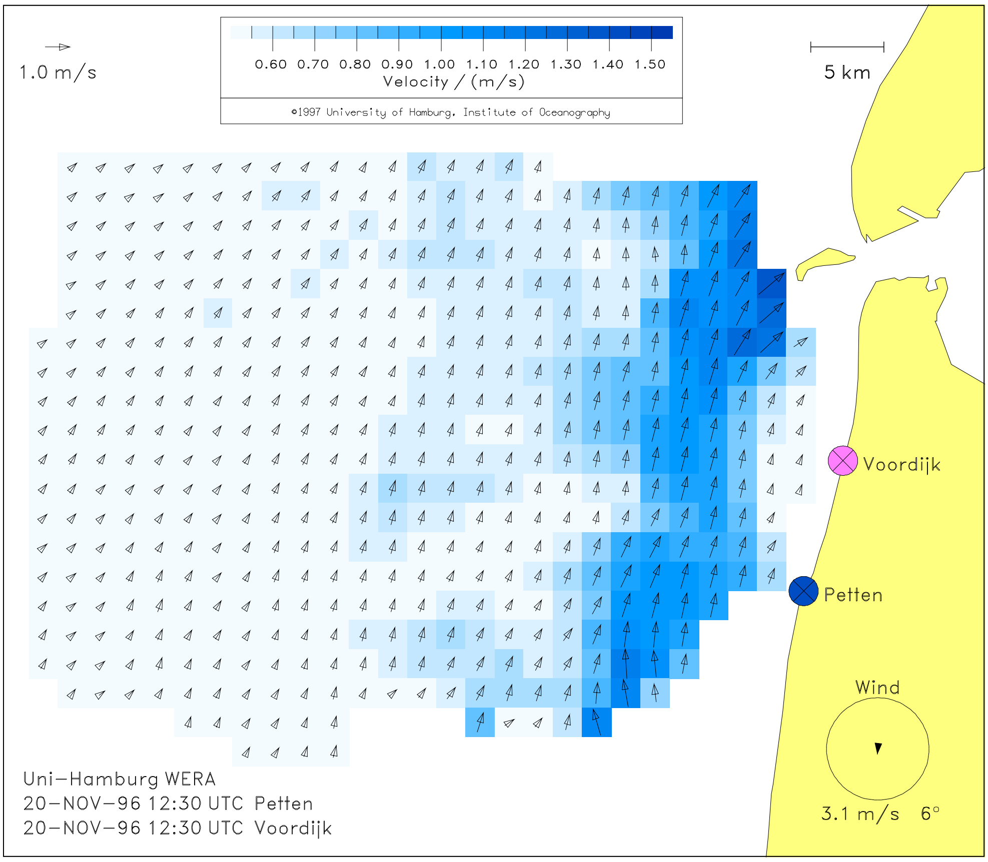

Figure 4: A surface current field measured on a 2 km x 2 km grid by two WERA radars at Petten and Voordijk. The absolute value of the current velocity is encoded in gray-scale. A coastal jet with current velocities of up to 1.2 m/s propagates along the coast.

of large amounts of fresh water from the Rhine. The second experiment was mainly aimed to demonstrate the wave measurement capabilities of HF radar. The area selected for this experiment was near Petten, which is strongly exposed to the sea and situated south of the island Texel (a the northeast edge of figure 4). Standard oceanographic wave measurements have been carried out in this area on a long term basis by the Dutch Rijkswaterstaat. This includes a number of directional waverider bouys moored on a line perpendicular to the coast from the dike at Petten to 10 km off the coast.

To ensure a sufficient signal-to-noise ratio for the wave measurements, the two radar sites have been selected only 10 km apart at Petten and Voordijk. This setup is not optimal for current measurements, as narrow angles between the radars reduce the accuracy of the 2-dimensional vector. A second problem was interference of the radar with the wave bouys deployed directly in front of the radar. Due to insufficient shielding inside the bouys, they picked up the transmitted radar signal, modulated it with their telemetry data, and retransmitted it to the receiving antenna of the radar. This finally lead to a

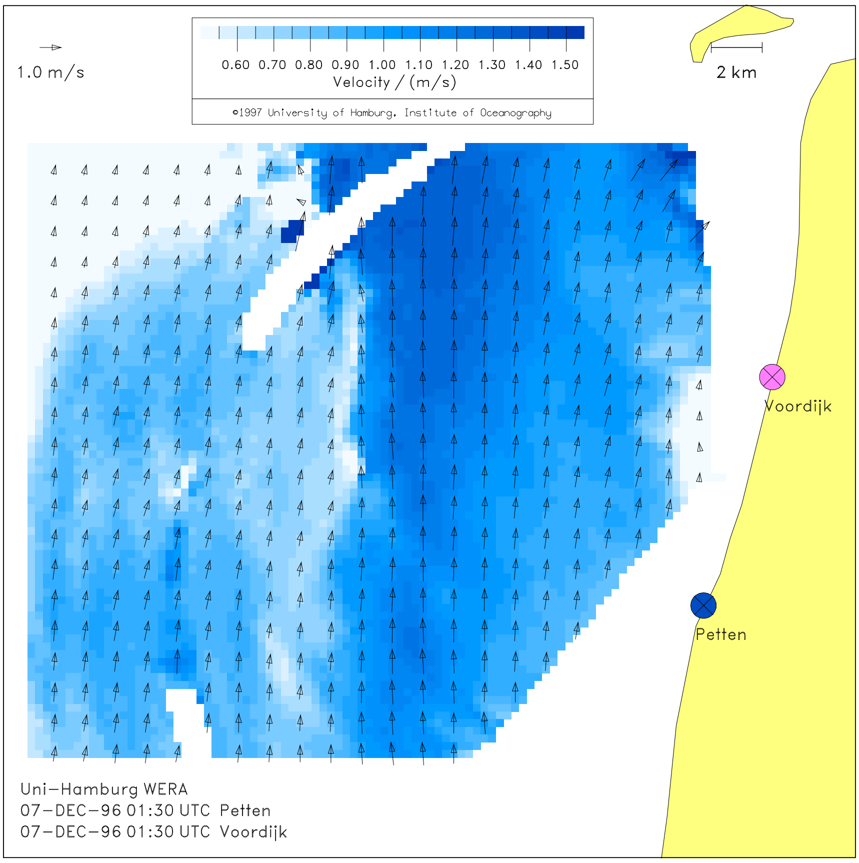

Figure 5: A surface current field measured on an 300 m x 300 m grid by two WERA radars at Petten and Voordijk. The absolute value of the current velocity is encoded in gray-scale. For clearity, only every 4th arrow indicating the direction is shown. The oceanographic front can be seen more detailed. Gradients in current velocity up to 50 cm/s within 300 m can be observed. The gaps in the measurement are due to interference at the Petten site (see text).

few distorted ranges in the measurements of the WERA radar operated at Petten. In these cases, measured radial components of the surface current from the Voordijk WERA are available, and if the spatial gap is not too wide, the missing data from the Petten WERA have been interpolated.

Figure 5 again shows the coastal jet. This time, WERA has been operated in high resolution mode. The oceanographic front can be seen in more details. Gradients in current velocity up to 50 cm/s within 300 m are observed. The tidal phase is similar to figure 4, 17 days ago; the current again is directed along the coast to the north. This measurement shows, that the spatial variability and the gradients of the surface current in this area are much higher than expected.

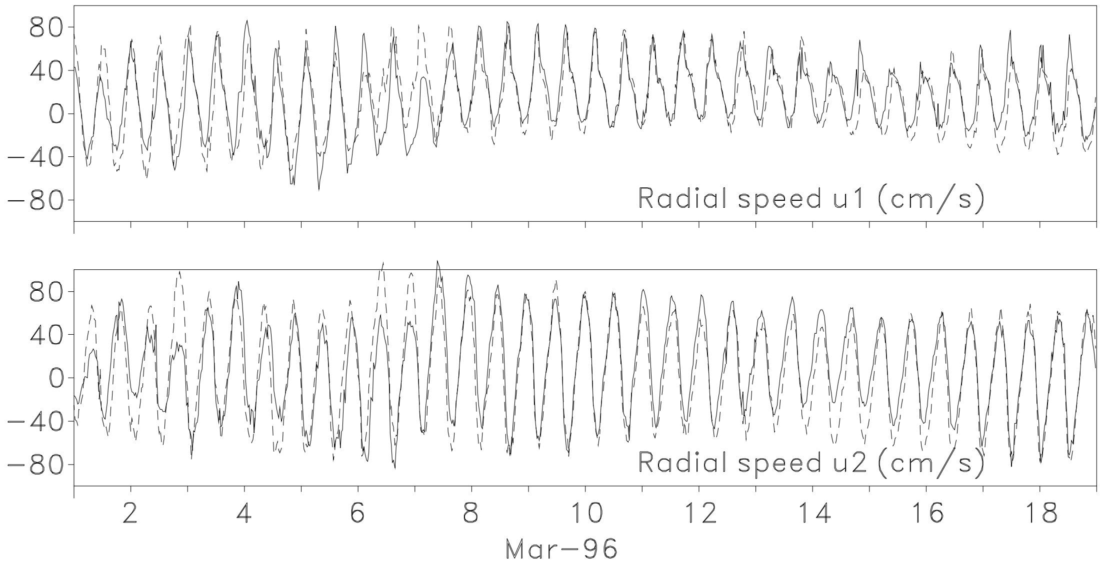

Figure 6: Comparison of radial speeds measured by CODAR (full lines) with the projections of the S4-current measurements onto these components (dashed lines). The sampling intervall is 1/2 h.

2.4 Comparison of currents measured by HF radar and a S4-current meter

Fig. 6 compares the HF radar measurements with data of an electromagnetic current meter (S4), deployed 1 m below the sea surface. The HF radar radial speeds are averages over 3 range cells and an azimuthal section of 9^0. This results in an area extending 3.6 km in range and 3.4 km in azimuth around the position of the current meter. The overall rms-differences of the radial components u1 and u2 are 18 and 21 cms^{-1}, respectively. Some single days reveal much better agreement, e.g. 10-March with rms-differences of 8 and 9 cms^{-1} of the two radial components.

Most of the rms difference is due to some events where the S4 measures higher tidal amplitudes than the CODAR and occasional phase shifts between the tides of the order of 1 hour. These deviations are reproduced by several successive 1/2-hourly samples. For this reason, we conclude that some portion of the rms difference is due to horizontal averaging performed by the HF radar in contrast to the point measurement of the S4. The experimental area is influenced by the Rhine outflow which causes current shears both horizontal and vertical.

3 Basic physics and algorithms of WaMoS

(Figure and text supplied by K. Reichert, Ocean SensWare)

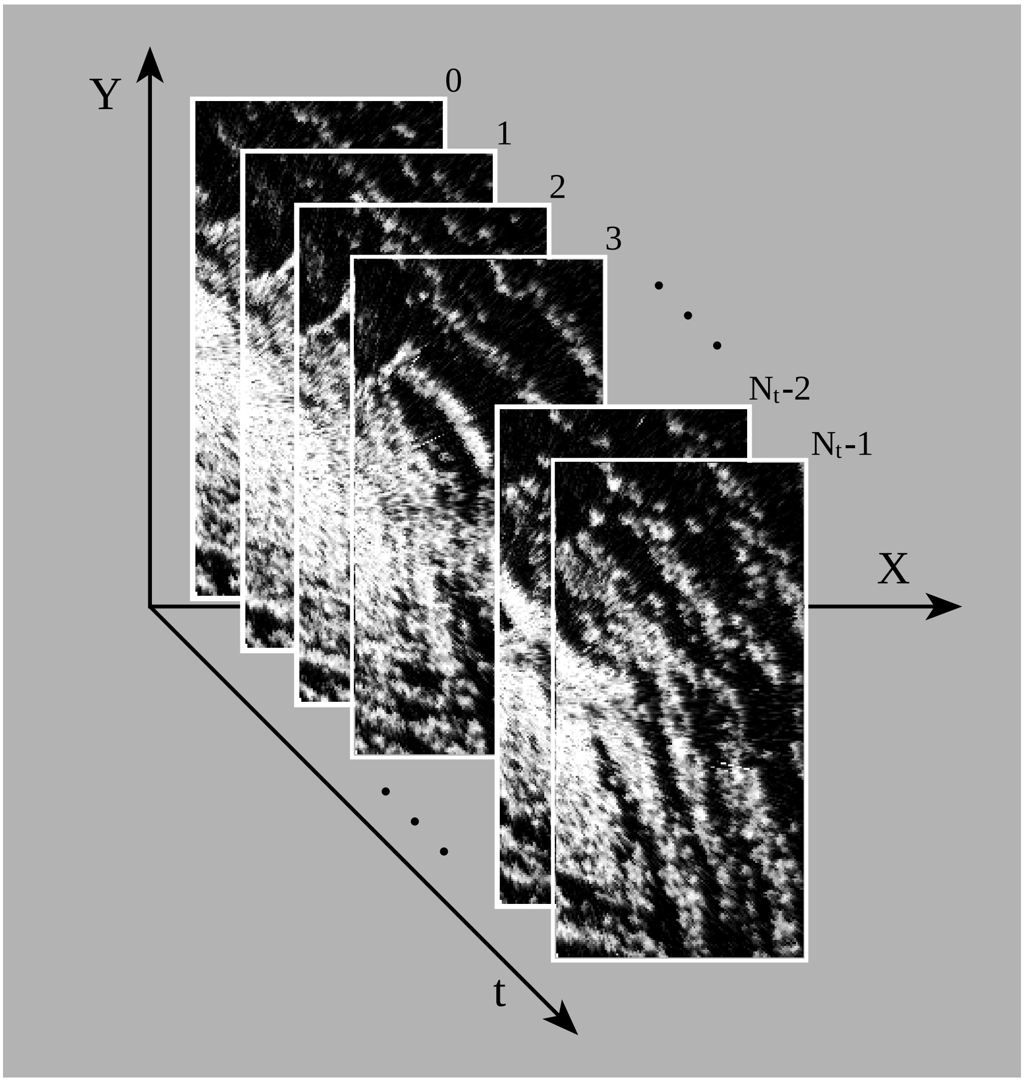

Figure 7: A sequence of images recorded from a nautial radar showing sea clutter. WaMoS uses these sequences to retrieve wave and current information.

The measurement of ocean waves and surface currents with a nautical radar is based on the spatial and temporal structure analysis of radar images of the sea surface. These radar images are generated by the interaction of HH-polarized electromagnetic waves with the sea surface ripples at grazing incidence. In these radar images (figure 7) the sea surface is visible as sea clutter. The spatial and temporal variability of the sea clutter information is analyzed in order to extract the unambiguous directional wave spectrum and further sea state parameters, such as significant wave height and peak period.

4 Existing HF radar systems

Table 1 summarizes the specifications of existing HF radar systems. The data refer to a non-directional transmit antenna and sea water of 35 PSU. The antenna size presented is the extent of a linear array of receive antennas, though some of the systems referred to make use of other configurations (see below).

There is no interference from long range radio sources with VHF frequencies higher than 50 MHz. Disturbances can only arise from near-by radio stations. Broad bandwidths can be used to realize high spatial resolutions. However, the working range at these frequencies is strongly reduced because of the high attenuation of the HF ground-wave.

Table 1: Working range for current measurement and range resolution of existing HF-radars in dependence of transmit frequency. Working range for wave measurements is less because of more severe signal-to-noise requirements.

Operating frequency		Working range	Frequency bandwidth	Range resolution	Antenna size	Radio interference
6.75 MHz	[13]	200 km	20 kHz	7.5 km	≈870 m	very high
7 MHz	[18]	200 km	20 kHz	7.5 km	≈200 m	very high
25 MHz	[2, 20]	60 km	125 kHz	1.2 km	≈90 m	variable
27 MHz	[11]	40 km	500 kHz	0.3 km	≈83 m	low
27 MHz	[11]	55 km	125 kHz	1.2 km	≈83 m	low
30 MHz	[8]	50 km	125 kHz	1.2 km	≈75 m	low
55 MHz	[15]	15 km	600 kHz	0.25 km	≈83 m	low

Table 2 summarizes the techniques as applied by HF radar systems presented in the literature. Respective working ranges and range resolution are listed in Table 1. The original CODAR developed at NOAA performes range resolution by means of pulses and uses a 4-element square array with direction finding for azimuthal resolution. The OSCR makes use of a linear array and beam forming. The PISCES radar is based on FMICW modulation for range resolution and beam forming provided in hardware by switchable cables used as phase shifters. FMICW introduces transmit / receive switching to overcome dynamic range limitations. The C-CORE Cape Race system provides a high azimuthal resolution by a 40-element linear array, which is some 1 km long. This is a very large permanent installation for research, i. e. the tracking of icebergs. The Australian COSRAD radar (Coastal Ocean Surface Radar) developed at James Cook Univerisity is operated at 30 MHz and uses pulses of 20 μs duration which yield 3 km range resolution. In contrast to the other systems mentioned, which perform illumination of the measurement area by a wide angle transmit antenna, a common antenna array for transmit and receive is used to perform beam forming. This has the advantage of squared sidelobe directivity performing a narrower beam and increases the signal-to-noise ratio. However, as the different directions are scanned step by step, the azimuthal surveillance is slow and technical problems in switching the antenna between transmitter and receiver arise. The SeaSonde is a very small portable system using FMICW for range resolution. Azimuthal resolution is provided by a very small loop antenna combined with a special direction finding algorithm different from the one described in this paper. Finally, WERA uses FMCW (without transmit / receive switching) for range resolution and beam forming or direction finding techniques for azimuthal resolution as described in this paper, depending on the application's requirements.

Table 2: Range- and azimuthal resolution of existing HF radar systems as well as the illumination by the transmit antenna (wide angle or narrow beam).

System	Pulse	FM(I)CW	Transmit **w**ide/**b**eam	Direction finding	Beam forming
CODAR / NOAA [2]	X		w	X	
OSCR [16]	X		w		X
PISCES [18]		(I)	w		X
C-CORE [13]		(I)	w		X
COSRAD [12]	X		b		X
SeaSonde [14]		(I)	w	X	
WERA [11]		X	w	X	X

5 Monitoring the coastal zone by an integrated remote sensing / model system

As indicated in the preceding paragraphs, remote sensing methods offer a synoptic view on the oceanographic processes in the coastal zone. Many applications, however, require not only on-line information, but a forecast on the next 3 to 6 hours to properly react on special events. Examples are shiping channels which are effected by eddies or the management necessary after accidents e.g. with oil tankers. To cover these requirements, a combined remote sensing / model system is needed. Currently, such a system is developed within the EU-EuroROSE project[7]. Information on EuroROSE is also available on the Web at http://ifmaxp1.ifm.uni-hamburg.de/EuroROSE/index.html

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