

Radar Remote Sensing of ocean surface waves may in general be defined as measuring characteristics of the sea surface by means of electromagnetic waves so that the sea surface is itself not disturbed. The electro-magnetic waves transmitted by the radar antenna are scattered back from the sea surface, modulated in amplitude and phase or frequency by the interaction with the sea surface in motion. This modulation carries information about sea-surface characteristics, surface waves and currents. Oceanographic data is extracted from the backscatter signal by sophisticated signal processing and data analysis.

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Wave Radars

A comparison of concepts and techniques

Why remote sensing? Surface ocean waves may be measured by a large number of differing techniques and a lot of instruments are commercially available. Instruments based on radar remote sensing techniques have become of particular interest in applications where it is important to avoid direct contact with the water surface and avoid structural interference. A typical case is wave measurements from an offshore platform in deep waters, with the presence of high currents making the mooring of a wave buoy enormously difficult. Another interesting case is a ship in transit, where having instruments in the sea is highly impractical and interference from the ship's hull must be avoided.

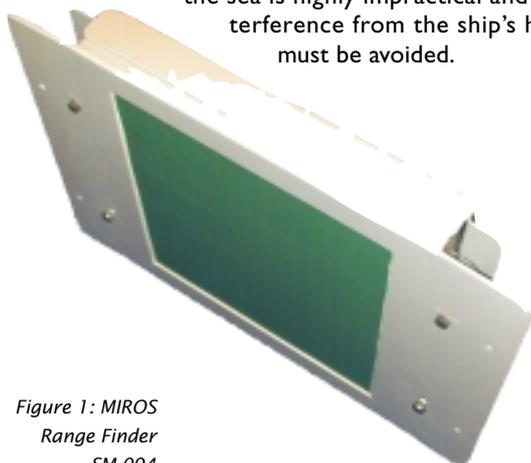


Figure 1: MIROS
Range Finder
SM-094

An internet search using key words like 'radar+remote+sensing' results in thousands of hits on publications dealing with the processing of radar images collected from space by satellite-borne Synthetic Aperture Radars (SAR) and very little of anything else. SAR is apparently what the scientific community has been concerned with in recent years. This paper is not about SAR. In practical everyday life, ground-based radar sensors are dominating the arena and several commercial instruments based on a variety of different concepts and techniques are available to the user. A great problem from the users point of view is that many of these instruments are commonly denoted 'Wave Radars'; this is quite imprecise and often misleading, as their operation may be based on very different principles, giving the instruments different qualities.

How to select the right instrument for a given application? Obviously, some knowledge about the basic principles of operation of the various sensors is required, as well as some basic understanding of the requirements of the application in question. With this knowledge, one should be able to read and understand the instrument data-sheet and specifications and

hopefully be able to decide which instrument qualities are important.

In this paper a brief description is given of some ground-based radar remote sensing techniques and their advantages and disadvantages. Examples of commercially available sensors are also provided.

RRS – Terms and Definitions

A wide range of radio wavelengths may be used for remote sensing of sea waves, ranging all the way from InfraRed (IR) to MicroWave (MW) and High Frequency (HF). Basically, there are two different classes of radar remote sensors for waves: direct and indirect sensors.

- The direct sensor measures directly some relevant parameter of the wave system (like surface elevation or water particle velocity)
- Indirect sensors observe the surface waves via the interaction with some other physical process as, for example, the radar cross-section of the sea surface. This greatly complicates interpretation of the measurement results

Microwave radars may be used in two different 'modes':

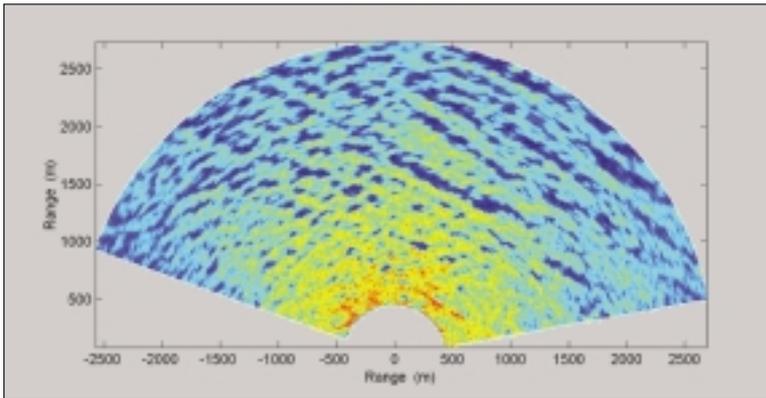


Figure 2: Polar sea echo image of marine navigation radar shows gravity wave modulation pattern

- In the near-vertical mode the radar echo is generated by specular reflections from the sea surface
- In the low-grazing angle mode the radar echo is generated by Bragg scattering, hence surface ripple (Bragg waves) must be present

If not, measurements cannot be done. The backscattered signal will be modulated in amplitude and frequency, primarily due to tilting, hydrodynamic interaction and shadowing of the surface ripple by large-gravity waves. Hence, gravity wave information is derived from the modulation of the backscattered signal only. The nature of the surface ripple (Bragg waves) is not important as long as the echo contains sufficient energy to conquer the thermal noise of the sensor.

When microwave radar is to be used as a wave probe, the radial and azimuthal extent of the surface area to be illuminated by the radar (radar footprint or resolution cell) must be small in comparison with all ocean wavelengths of interest. The band-

width of the radar signal and the beamwidth of the radar antenna together determine spatial resolution. The beam of a microwave antenna is dispersive; consequently, the resolution becomes a function of range. The beam of IR radar (laser) is non-dispersive; the radar footprint is therefore independent of range. HF radar utilises the Bragg scattering mech-

anism and always operate at very low grazing angles. Due to the low frequency of operation, the radar waves are backscattered directly from the gravity waves, and surface ripple need not be present.

Radar transceivers may be coherent or non-coherent. Coherent radar measures Doppler-modulation as well as amplitude modulation, while non-coherent radar measures only amplitude modulation. Consequently, a non-coherent radar echo contains less information about sea-surface properties. Examples of non-coherent radar are conventional marine navigation radar.

The radar transmitter waveform may be either unmodulated Continuous Wave (CW), modulated or pulsed. Unmodulated CW radar has no range resolution but can resolve targets on the basis of different velocity, while a modulated or pulsed radar can resolve echoes from different ranges. The radar waveform plays a very important role in radar theory.

The above discussion illustrates why the term 'Wave Radar' is not very precise. Wave Radar performance is highly dependent on:

- Mode of operation or measurement geometry (vertical or grazing)
- Class of system (direct or indirect)
- Frequency of operation

- Radar waveform (unmodulated CW or modulated/ pulsed)
- Type of transceiver (coherent or non-coherent)
- Radar antenna properties

Remote Sensing Techniques

Vertical Radar

These sensors transmit a modulated radio signal in a narrow beam and measure the delay before the echo from the sea surface is received. The delay is easily converted to range. Based on a time-series of the sea surface elevation, a non-directional (point) wave spectrum can be calculated. If the sensor is sufficiently stable it can be used to measure water level and air-gap as well as waves.

One frequently occurring problem with vertical radar is the effect of interference from the structure on which they are mounted. The wave field to be measured will be disturbed and the resulting measurement error will depend on wave direction.

Low-cost vertical radar designed to be used as level-gauges are generally not suitable for wave measurement applications. The main problems are high sensor noise levels requiring large averaging intervals and large footprints due to wide antenna beams. This may be overcome partially by using transfer functions. Three different types of vertical radar suitable for measurement of non-directional or point wave spectra are described. By arranging three (or more) vertical radar in a suitable geometrical pattern, a directional wave spectrum similar to the measurements of a directional heave, pitch and roll buoy can be obtained.

Laser altimeters are small, lightweight and operate in the infrared (IR) frequency band. They normally use pulsed waveforms and perform direct measurements of sea surface elevation that can easily be converted to wave amplitude. The laser beam is very narrow and almost non-dispersive. The footprint is small and almost independent of range. Due to the high frequency of operation, laser altimeters are prone to interference from natural sources of IR emission. Salt and soot deposits on the optical window great-

Figure 3: Two dimensional wave spectrum derived from sequence of polar marine navigation radar images

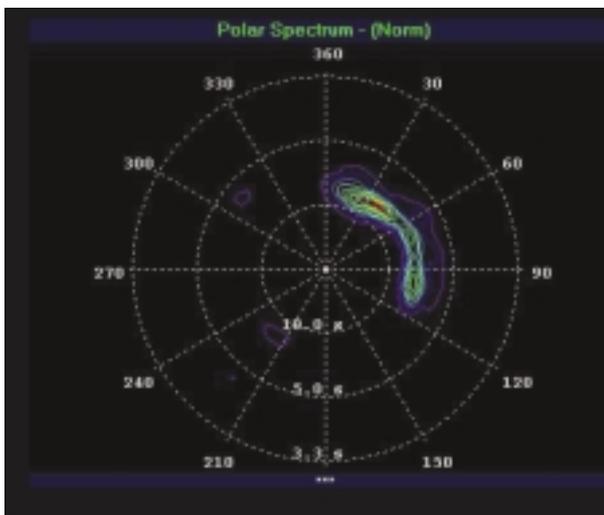


Figure 4: MIROS Wave and Current Radar MkIII with mounting pedestal, shock absorbers and junction box



ly deteriorate measurement performance. The sensor easily locks onto fog and water spray, and it will quite frequently be unable to track the sea surface. The Canadian-based Optech Incorporated provides laser sensors suitable for wave measurements.

Microwave Range Finders normally operate at GHz frequencies. Due to the much lower frequency, the microwave range finder is not as affected by fog and water spray as the laser altimeter. A linear CWFM (continuous wave frequency modulated) radar waveform is normally used to provide range resolution. The microwave antenna must be quite large to generate a narrow beam. The Miro's Microwave Range Finder SM-094 operates at 10GHz with an antenna diameter of 35cm (Figure 1). The antenna beam is about 5 degrees wide. The beam is dispersive, hence the size of the footprint increases linearly with range. At a range of 50m the footprint is about 4 metres in diameter. Hence, at this range the sensor cannot properly measure sea waves shorter than approximately 16m, corresponding to 3.2 s period.

Another example of a Microwave Range Finder is the Saab Tank Radar REX, also used for wave measurement applications. Microwave CW Doppler Radar use a coherent continuous wave waveform to measure the Doppler shift caused by the velocity of the sea surface relative to the radar. The Doppler measurement is directly related to wave height by simple integration. This radar cannot be used to measure range (i.e. water level or air-gap). The performance of the CW Doppler radar depends greatly on the stability of the signal source, except for very short measurement ranges. The footprint is entirely determined by the antenna pattern. This means that CW Doppler radar can only be used at near-vertical angles if the conditions of a small footprint are to be met. An accelerometer may be used to remove ship or platform vertical motion from the Doppler measurement. A commercial example of a motion compensated CW Doppler Wave sensor is the TSK Shipborn Wave Height Meter.

Three, vertically arrayed radar in triangular configuration may be used to measure a directional

wave spectrum. Algorithms and signal processing software similar to that used in the processing of heave, pitch, roll buoys have been developed in a number of research projects, see for example the WaDiRA (Wave Directional Radar Array) project. A commercial system called Directional WaveGuide is available from the Dutch Radac.

Marine Navigation Radar

The sea-clutter image of conventional navigation radar contains a pattern that resembles a sea-wave pattern. The radar sea-echo amplitude depends on wind-generated 'roughness' of the sea surface. Gravity waves and currents form images on the radar display because they modulate the sea-surface radar cross-section by angular modulation, hydrodynamic interaction and shadowing (Figure 2). By digitising the radar video signal it can be processed by a digital computer. With the use of appropriate algorithms, a full three-dimensional wave spectrum and the magnitude and direction of near surface currents may be calculated on the basis of these digitised radar images (Figure 3).

Marine navigation radar utilises only the non-coherent radar backscatter modulation. Navigation radar is a typical example of an indirect-wave sensor, because there is no direct relation between wave-height and radar backscatter modulation amplitude. The calculated wave spectrum is basically unscaled with respect to wave energy. Additional measurement of the non-directional wave spectrum may be required for calibration purposes, or an empirical method of calibration, relating some parameter derived from the measured data to the real wave-height, may be employed. Several empirical cal-

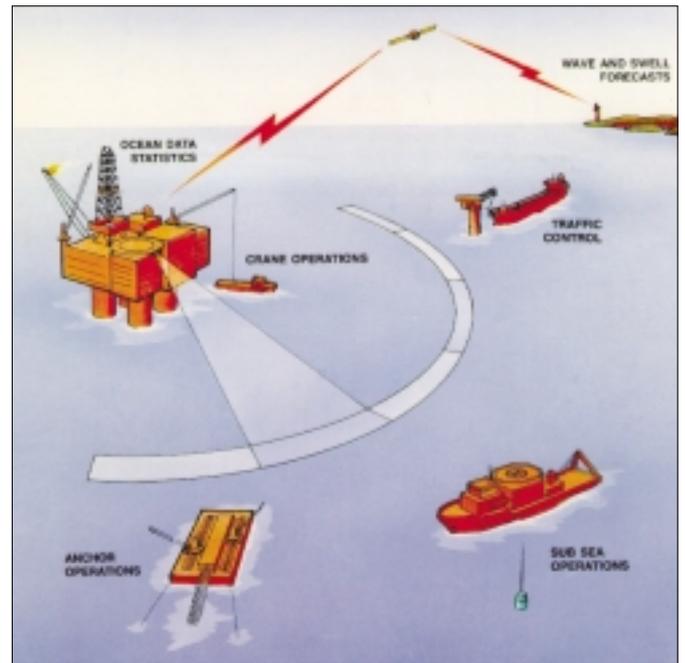


Figure 5: Measurement geometry of Miro's Pulsed Doppler Wave and Current Radar

ibration methods exist. These work well under most conditions but may occasionally fail completely. It is therefore impossible to quote reliable, wave-height performance figures valid for all conditions.

However, marine navigation radar-based wave sensors are excellent tools for wave-direction measurements. Marine navigation radar may also provide a tool for surface current measurements. Point measurements of the current vector, as well as current maps up to a distance of a few kilometres from the platform, with a resolution of 50 to 100m, can be provided. As marine navigation radar works at low grazing angles, surface ripple (Bragg waves) must be present. If not, measurements cannot be done. Work on the application of marine radar sea-echo images for estimation of the sea wave spectrum and surface current has been undertaken at many universities and research institutes over the past 20 years but, amazingly, few

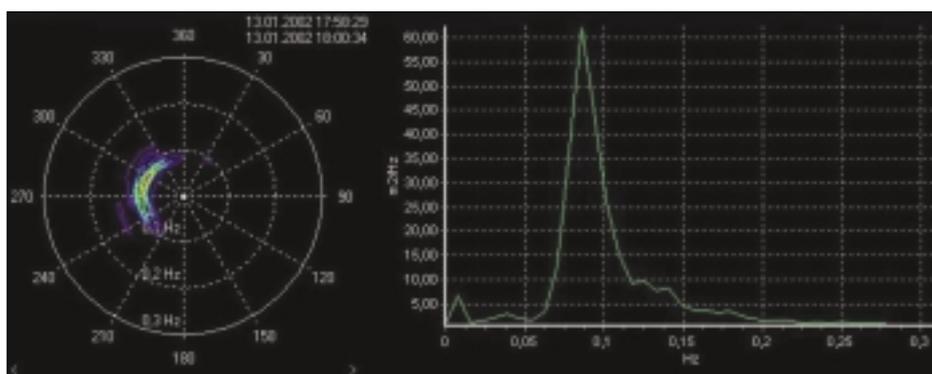


Figure 6: 2D wave spectrum (left) and point spectrum (right) measured by the Miro's Wave and Current Radar



Figure 7: Miros Wave and Current Radar MkII - offshore installation

commercial sensors have come into being. MIROS Wavex has been commercially available since 1996. The main area of application is directional wave measurement from moving ships. Another example of a marine radar-based system is Oceanwaves Wamosll.

Range-gated Pulsed Doppler Microwave Radar

A range-gated pulsed Doppler radar can be used at low grazing angles. This uses a coherent transceiver. The radar footprint is narrow in range (due to pulsing and receiver range gating) and several sea wavelengths wide (determined by antenna beam width and range). This has the effect of restricting the response to a narrow range of sea-wave direction of travel. The Doppler shift of the radar echo is proportional to the horizontal component of water particle velocity. By using several antennae (or a scanning antenna), the range-gated pulsed Doppler radar may be used as a directional wave sensor, basically measuring a directional water particle velocity spectrum. This is directly related to the wave-height spectrum by a mathematical model based on linear wave theory, and accurate measurements of the wave spectrum (Figure 6) can be provided under most conditions.

The Miros Wave and Current Radar is the only commercially available wave sensor based on the range-gated pulsed Doppler radar technique. The frequency of operation is 5.8GHz and an array of six horn antennae covers an included angle of 180 de-

grees (Figure 4). A dual footprint technique is used to provide a full directional wave spectrum covering 360 degrees. Measurements are taken at a distance from the platform on which it is mounted (Figure 5). The wave field is therefore almost undisturbed by interference from the platform structure. Like the marine navigation radar, this radar also works at low grazing angles and surface ripple (Bragg waves) must be present. If not, measurements cannot be done.

Dual-frequency Microwave Radar

In dual-frequency microwave radar, two microwave frequencies are simultaneously transmitted. The frequency separation is chosen to give a 'spatial beat' length, which is in the range of the water waves of interest. The dual-frequency radar may be considered a microwave equivalent of the High Frequency (HF) radar (see below) and is suitable for the measurement of surface current. As far as wave measurements are concerned, the processes of backscatter are too complicated (and not well enough understood) to allow the attainment of useful measurement accuracy.

The range-gated pulsed Doppler technique for wave measurements and the dual-frequency technique for surface current measurements are both implemented in the Miros Wave and Current Radar. Miros Wave and Current Radar provides a point measurement of the current vector.

High Frequency (HF) Radar

The HF radar is well established as a powerful tool for sea current measurements up to a range of about 30km. It operates in the MHz frequency band, corresponding to a radar wavelength in the range of 10 to 300m. The Doppler shift of the first order Bragg lines of the radar echo is used to derive sea-current estimates in very much the same way as for the Dual Frequency Microwave Radar (see above). For wave measurements, a more complex second-order mechanism of backscatter is used.

Although it has been claimed that HF

radar can measure wave spectra at very long ranges, its success as a wave sensor has in the past been limited for very much the same reason as for the microwave dual-frequency radar (see above). One great disadvantage of HF radar is the size of many of their antennas. Attempts have been made to make the antennas smaller, but probably at the cost of greatly reduced antenna efficiency.

The Codar Sea Sonde is the only commercially available wave and current sensor based on HF-radar techniques. Codar Sea Sonde uses a patented direction-finding antenna, an elegant solution to the above-mentioned problem of HF antenna size. A Sea Sonde installation may provide current maps up to a distance of 70km from shore, with a resolution down to 300m. Two radar installations are required, looking at the same patch of the sea surface from different angles.

Conclusion

This paper has presented a number of different radar techniques suitable for sea-wave and surface current measurement. These techniques are implemented in a number of currently available commercial wave and current sensors. The sensors differ both in complexity and performance. In order to select the 'right' sensor, the user must have an understanding of the requirements imposed by the application in question, as well as the working principles of the different sensors. It must be emphasised that no sensor is 'best' under all conditions. Price and performance should be carefully matched to the requirements of the actual application.

Biography

Øistein Grønlie holds a M.Sc degree in electrical engineering and a Ph.D degree in communication theory. He has taken additional courses in radar theory and project management. In 1982 he joined A/S Informasjonskontroll as a senior scientist doing theoretical work on remote sensing of ocean waves and currents using radar techniques. Has held various positions at MIROS A/S since 1984.

Editor's Note: The submitted article included many references; the author is very willing to send interested readers the article with references included. ■