Journal of Oceanography and Marine Science Vol. 1(1). pp. 001-010, January, 2010
Available online http://www.academicjournals.org/joms

Full Length Research Paper

An overview of recent technologies on wave and current measurement in coastal and marine applications

P. Kasinatha Pandian[1]*, Osalusi Emmanuel[2], J. P. Ruscoe[2], J. C. Side[2], R. E. Harris[2], S. A. Kerr[2] and C. R. Bullen[2]

[1]Department of Civil Engineering, Tagore Engineering College, Chennai 600048, India.
[2]International Centre for Island Technology, Heriot-Watt University (Orkney Campus), Stromness, Orkney, Scotland, KW16 3AW, United Kingdom.

Accepted 5 December, 2009

The coastal ocean is the most important zone for the maritime countries for recreation, mineral and energy exploitation, weather forecasting and national security. Understanding of coastal and oceanic processes is mostly based on field measurements and laboratory experiments. Most coastal processes occur over relatively long time spans and have large spatial extents. They also involve or are impacted by a variety of factors such as waves, wind, tide, storm surges, currents, beach sediment properties, etc. Measurements of waves, both on site and in wave flumes, are carried out using different techniques. This article reviews the different technologies available and presently adopted in wave and current measurements. Different instruments for wave and current measurement have its own advantages and disadvantages depending on the applications and needs. A detailed overview of various studies carried out in worldwide locations on wave and current measurements is presented. Various instruments, their application, advantages, disadvantages and accuracy are discussed in this article. It is essential to choose the type of instrument most appropriate to the application, based on the requirements, necessitating a thorough knowledge of the instruments available, the funding and duration of the project.

Key words: Measurements, waves, currents, buoys, ADCPs, radars, remote sensing.

INTRODUCTION

Most coastal processes occur over relatively long time spans and have large spatial extents and involve or are impacted by a variety of coastal factors such as waves, wind, tide and storm surge, currents and beach sediment properties. Consequently the cost of field measurements can be high. Routine monitoring of waves and currents in the offshore and nearshore regions is of great interest to both coastal and scientific communities. The measurement of waves and in particular their direction, has been one of the most difficult problems in observational coastal engineering and oceanography (Strong et al., 2000). There are many techniques adopted for measuring waves such as wave rider buoys, Acoustic Doppler Current Profilers (ADCP) and remote sensing including High Frequency Radar. In wave measurements, directional wave data are made with a wide variety of instrumentation techniques. The nature of these instruments dictates that most wave measurements be made in coastal areas. The cost in physical effort and money to maintain an operating wave gauge is relatively high. However, for a variety of reasons, the percentage of time that worthwhile data are obtained is commonly much less than 100% (Sorensen, 1997). Although there are many aspects to the collection of data from the marine measurement, this article only deals with wave and current measurements and their problems, advantages and disadvantages and reviews the different techniques and instruments used by various researchers worldwide.

*Corresponding author. E-mail: pknp2020@gmail.com.

Wave rider buoys

Wave rider buoys have been in use since 1966 and are the principal instrument for national wave measurement programmes for many countries. It has frequently been assumed that the wave rider sensitivity remains within 3% of the specified one volt $m^{-1}$of wave elevation throughout its useful life. During the earlier years of wave rider use, no calibration apparatus was available, although approximate calibrations over a limited range of period of vertical motion could be obtained by suspending the buoy from an elastic cord or spring and maintaining vertical motions manually (Ribe, 1983). In support of their respective wave climate programmes, researchers in the United States, Canada and United Kingdom developed apparatus to calibrate wave riders on a rotating-arm, vertical circle of motion. In Venezuela, a device using pure vertical motion, based on the Scotch-yoke principle has been developed. Such apparatus has enabled improvement in ocean wave measurement accuracy by as much as 5%. Resultant correction factors are a function of period or frequency and, therefore, must be applied to sinusoidal, Fourier components of a wave elevation time series or, as a square of the transfer function, to the coefficients of the variance spectra. The wave rider buoy has a unique accelerometer design consisting of a cantilever-beam sensor mounted in the electrical field of an electrolytic fluid. The fluid conductivity is carefully adjusted to provide the desired wave rider sensitivity and the associated electronic circuitry is designed to match the characteristics of each individual accelerometer. Effects of fluctuations of temperature of the fluid can be considered negligible. However, an increase in the electrical conductivity of the electrolyte of some wave rider buoys has caused a corresponding decrease in sensitivity and has rendered the assumption of insensitivity to temperature fluctuations invalid. This has increased the importance of applying corrections to wave rider measurements.

Magnusson and Donelan (2000) looked at simultaneous measurements taken from both wave rider and vertical lasers at the same location with storms analysed. They discussed the effect of buoy correction and the propagation effect on statistics of highest crests and wave heights from both instrument types. Once the corrections were made, skewness and steepness values from the buoy were seen to converge toward laser measurements. Original records from the wave rider were subsequently corrected for the quasi-Lagrangian behaviour of the buoy and found to similarly converge toward laser measurements. Wikramanayake (2006) investigated the wave climate of Sri Lanka in increasing detail and sophistication over the last two decades. The actual measured wave time series were transformed using a transformation matrix. Comparison of measured and transformed time series showed that there were significant differences between the measurements made using wave rider buoys (used between 1983 and 1997) deployed near the shore and the WAVEC deep water buoy used in the directional measurement programme. Wikramanayake observed that the wave rider buoys are not able to measure the higher waves; particularly the sea waves and, therefore concluded that this under-estimation may be due to the rigidity of the mooring used for the near-shore buoys.

Acoustic doppler current profilers (ADCPs)

Historically the technology for measuring waves and currents has required separate instrumentation for each, but recently it has become possible to measure wave height, wave direction and current from conventional ADCPs. The need to also measure currents frequently confronts the practitioner with the necessity of deploying two instrument systems, such as a data buoy and an ADCP. And because, the ADCPs combine the required functionality to measure both waves and currents in a single compact package, there has been considerable interest in exploring their efficacy as a wave sensor. Pinkel and Smith (1987) and Krogstad et al. (1988) have demonstrated that a Doppler sonar using horizontally-projected beams could provide a high quality measurement of wave direction (Smith, 1989). Most existing ADCPs utilize the Janus beam geometry and do not incorporate a pressure sensor. Terray et al. (1999) proved that it is possible in shallow water to estimate both wave height and direction from a conventional bottom-mounted, upward-looking ADCP. They proved that height and direction spectra compare with a co-located array of pressure gauges. They used the iterative version of Capon's "Maximum Likelihood Method" (Capon, 1969) known as the IMLM (Krogstad et al., 1988). Pawka (1983) estimated the direction of multiple echo arrivals using sparse arrays. Like all high resolution direction-of-arrival estimators, the IMLM is model based and requires a relation between the frequency-direction spectrum and the array covariance. A bottom-mounted, upward-looking ADCP provides a robust means of determining wave height and direction in coastal and deep waters. When equipped with a pressure sensor, the ADCP yields three independent estimates of the non-directional wave height spectrum and hence provides an internal consistency check on the performance of the instrument. Directional spectra obtained from the ADCP tend to be sharper than those from point measurements, such as pressure velocity (PUV) triplets or directional wave buoys and because of the greater number of degrees of freedom in the measurement, the ADCP can resolve complex multi-directional wave distributions. These conclusions were arrived at by Strong et al. (2000) after comparing and analysing of different data sets of ADCPs collected from many parts of the world.

Deepwater current profiling requires a low-frequency

ADCP operating at 38 or 75 kHz. Traditionally these large systems have been hull mounted mostly deployed on research vessels. Utmost care should be taken to ensure the system operates in a low-noise and bubble free environment. Towing an ADCP system offers an attractive alternative to vessel mounted ADCPs. A towed system can be used in ships for different purposes, allows easy maintenance and provides remedies to several problems of vessel-mounted systems. Kaneko et al. (1990) first introduced a towed ADCP. They obtained detailed velocity measurements of the Kuroshio Current with an ADCP mounted inside a sled. The sled was towed behind a ship about 7 m beneath the surface. Internal ADCP sensors measured the heading, pitch and roll of the sled. Vessel-mounted ADCPs have become a standard tool on many research vessels (Joyce, 1989). In addition to the limitations inherent in the ADCP system itself (Chereskin et al., 1989; Chereskin and Harding, 1993), air bubbles near the transducer heads and compass biases (King and Cooper, 1993) often degrade shipboard ADCP observations. New (1992) reported that as the ship heaves, a cloud of air bubbles entrained under the hull of the ship. Monchow et al. (1995) attempted different techniques in which all the measurements utilize the ADCP bottom-tracking capability and an upward-looking self recording 614 kHz ADCP which provides velocity observations of the water column above the towed body. The downward-looking 153 kHz ADCP was connected to a shipboard computer. In this towed ADCP system they found two separate sources of error that is surface gravity waves and compass biases and concluded that this towed ADCP system returns data of at least the same quality as vessel mounted ADCP system.

Towed ADCP systems have been used by many researchers, for example, Anderson and Matthews (2005) developed a towed ADCP system used to support operational monitoring of deepwater currents. The towed body configuration provides a quiet and stable sensor platform that can be readily relocated and deployed from different vessels. High-frequency ADCPs are used in towed bodies for several shallow water applications. The unique Towfish system employed a 75 kHz RDI Long Ranger ADCP packaged in a large Endeco/YSI type 850 V-Fin and was used in the Gulf of Mexico to survey upper ocean currents. The system calibrations were found to be very robust and stable. Towfish was deployed at nominally 20 m depth with tow speeds of 1 to 3 ms^{-1}. One disadvantage of the towed body approach was that the ADCP would be deployed deeper than a hull or side mounted system and as a result, a single down-looking ADCP would not be able to sample the very near surface. Placing a second ADCP configured in an up-looking direction into the V-fin would allow profiling to the surface. ADCPs operating at 300 kHz to 1.5 MHz have been successfully used in towed bodies for some time now and have performed quite well (Anderson and Matthews, 2005).

High frequency radars

HF Radar system is a shore based remote sensing system using the over the horizon radar technology to monitor ocean surface currents, waves and wind direction. Oceanographic High Frequency Radars are simple in concept: electromagnetic waves (EM) sent to the ocean are backscattered on surface waves of exactly half the radio wavelength, just like X-rays are scattered in crystals. Since the ocean is generally covered by waves of many different wavelengths and directions (continuous spectrum), there are always trains of waves propagating toward and away from the radar. The return signal from either train will be Doppler-shifted by the wave velocity, which is known exactly by the gravity wave dispersion relationship. Thus the spectrum of the return echoes consists of two peaks, symmetric with respect to the transmit frequency and in the absence of currents. This long range, high resolution monitoring system operates with radio frequencies 5 - 50 MHz. A vertical polarised electromagnetic wave is coupled to the conductive ocean surface and will follow the curvature of the earth. The rough ocean surface interacts with the radio wave and due to the Bragg Effect back-scattered signals can be detected from ranges of more than 200 km (HELZEL, 2004). This effect was first described by Crombie (1955) and the first radar system using that effect was developed at NOAA in 1977 by Barrick (1977). The WERA HF Radar system was developed at the University of Hamburg by Gurgel et al. (2000) which is operating in a frequency modulated continuous wave mode (FMCW). When a continuously swept rf-signal is transmitted, the reflected signal has a frequency offset compared to the actual transmitted signal, thus the range is frequency coded.

In recent years the evolving capability to use shore based high-frequency (HF) radar systems to continuously monitor vast stretches of coastal ocean surface currents has presented a new possibility for improving our understanding and monitoring capabilities in these marine environments (Paduan and Graber, 1997). HF radar networks exploit radio wave backscatter in the frequency band 3 - 30 MHz to map ocean surface currents. Most systems operate in the range of 12 - 25 MHz and are capable of producing maps up to 60 km from shore with horizontal resolutions of 1 - 3 km (Paduan and Rosenfeld, 1996; Graber et al., 1997). At lower frequencies (around 5 MHz), ranges of 200 km are possible using shore-based systems with horizontal resolution of 5 - 10 km (Barrick, 2003). A major advantage with HF radar systems is that they are unaffected by weather, clouds or changing ocean conditions.

Remote sensing cannot always be counted on to provide timely observations of the sea surface and is not a direct measurement of ocean currents. Remote sensing of near-surface currents with high frequency (HF) radar was demonstrated more than three decades ago by Stewart and Joy (1974). Subtraction of the theoretical phase velocity of the ocean waves gives radial current velocities (hereafter referred to as radials). Multiple radars are typically deployed so radials have enough angular separation to resolve both the north-south and east-west velocity components referred as totals (Ohlmann et al., 2007). 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. HF radars have been operated with frequencies between 7 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. Depending on the transmitted frequency, ranges of up to 200 km may be achieved (Gurgel et al., 2000).

Two HF radar technologies are commonly used for oceanographic research. Beam-forming radars electronically point linear arrays of receiving antennas to determine bearing over the sea surface. Examples include the Ocean Surface Current Radar and the Wellen radar (Gurgel et al., 1999). Direction-finding radars rely on directional properties of antenna elements to determine bearing. The most commonly employed direction-finding radar is the Seasonde, which uses two directional antennas and a monopole antenna (Barrick and Lipa, 1997). Spatial coverage of HF radar measurements varies according to transmit frequency. For the ~ 25 and ~ 12 MHz systems, maximum ranges are ~ 42 and ~ 83 km, respectively (Ohlmann et al., 2007). The SeaSonde HF radar system by CODAR Ocean Sensors provides real-time data over large coverage areas, with ranges up to 200 km. The SeaSonde is a compact, non-contact surface current and wave measurement system that can be deployed and maintained easily and can perform even during extreme weather conditions such as hurricanes. CODAR Ocean Sensor's FMCW eliminates the range aliasing and antenna wind-vibration noise inherent to other HF system designs (CODAR, 2008). In recent years, the utility of HF radar-derived surface velocity fields as input to data-assimilating numerical circulation models has been the focus of several studies. The potential benefits of HF radar data are large, particularly in light of the dearth of real-time observations from the marine environment. These data are also potentially important because they can cover significant portions of coastal ocean model domains. They make it possible, for the first time, to track the location and movement of mesoscale oceanic features in a fashion analogous to the superior capabilities provided by data inputs to numerical weather forecast models (Paduan and Shulman, 2004).

The unique advantage of the HF radar is the ability to map the horizontal variability of currents which is needed for several applications (Gurgel et al., 1999). Eddy dynamics, such as propagation and decay, can be studied (Essen et al., 1989), as well as the spatial variability of tidal currents (Prandle, 1987). The capability of measuring surface-wave spectra using WERA has been discussed by Wyatt et al. (1998). Compared to CODAR, the new design of WERA offers increased flexibility in spatial resolution and allows both beam forming 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 advantageous for studying near-shore ocean dynamics and for the interpretation of space-borne synthetic aperture radar (SAR) images (Gurgel et al., 1999). Essen et al. (2000) investigated the accuracy of surface current velocities measured by HF radar. Data from the two radar systems of the University of Hamburg CODAR (Coastal Radar) and WERA (Wellen Radar) were compared with *in situ* data. In one experiment, CODAR and a near surface current meter were operated simultaneously over a 19 day period. In addition, WERA was operated for 6 days during that period. In another experiment, WERA and a bottom mounted current meter were operated simultaneously over a 35 day period. Both radars used frequencies of about 30 MHz where backscattering which was due to ocean waves of 5 m wavelength. The influence of the orbital motion of underlying longer waves on radial velocity errors was investigated. In accordance with the theory the measured standard deviations of HF-measured current velocities depend on the sea state. In dependence of the sea state, estimated errors ranged from 3 to 10 cm and explain only part of the RMS difference of 10 to 20 cm found between HF and *in situ* current measurements. The rest was assumed to be due to the differences of the quantities measured, e.g. the spatial averaging.

The wave radar system is a very useful tool for the measurement of waves over a wide area with real-time observation, but it still lacks a method to check its accuracy. The Okinawa Subtropical Remote-sensing Center has developed a new high-frequency ocean radar system called Long Range Ocean Radar (LROR). LROR is a kind of Doppler radar using an HF radio wave; it has the capability to monitor a broad area of the ocean surface, surface currents, waves, etc. LROR has been located in Yonaguni Island and Ishigaki Island; an area vulnerable to serious typhoons every year. It is very difficult to measure waves in the open ocean during a typhoon and as a result, very few accurate measurements are available. More than 20 experimental observations have been made in Japan using HF ocean surface radar system in collaboration with various institutes and universities since 1989 (Koterayama et al., 2003).

Alfonso et al. (2006) compared the CODAR SeaSonde HF Radar data with data collected by wave rider buoys between November, 2005 and February, 2006 from Galician Coast, Spain. They concluded that the statistical results were well correlated with indexes of 0.8 in current U component, 0.7 in current V component and up to 0.9 in wave height. They identified the radar information coverage was rather good in waves (97%) but low in currents (72%) in relation to the buoy. Wave period estimations from radar measurements were very stable but may have been too smooth and seemed incapable of reproducing sudden changes in periods. They also found that some strange oscillations that appeared in radar wave directions might be related to tidal effects. The accuracy of HF radar measurement in the Tsushima Strait located between Japan and Korea has been investigated by Yoshikawa et al. (2006). A comparison between radial velocities measured by HF radar and an ADCP, which provides an upper bound of HF radar measurement error, showed from their study that the root-mean-square (RMS) velocity difference obtained from the principal component analysis was 6.62 ~ 11.3 cms^{-1}. A comparison of velocities measured by two facing HF radars, which provides a lower bound of HF radar measurement error, showed that the variance error of hourly radial velocity was 5.75 ~ 13.3 cms^{-1}. The bias error of HF radar measurement was also found to be reasonably small through a comparison of tidal ellipses estimated from 1 year of HF radar data with those from 5 years of ADCP data. They concluded that the variance error of HF radar measurement was the dominant source of the velocity difference found between ADCP and HF radar.

HF radar derived velocities (radials and totals) compared with velocity estimates from large numbers of simultaneous drifter observations by Ohlmann et al. (2007). Drifter averages were obtained within an area observed by HF radar, thus allowing comparison of velocity estimates on similar time and space scales. The primary goal of their study was to quantify the effects of spatial averaging, over various scales, on measurement differences between HF radar and drifter velocities. They used the HF radar data in the Santa Barbara Channel collected by up to five SeaSondes from 1997 to 2006. Moored current meter and profiler data were also used for validation. Differences between HF radar and current meter-derived velocities near 10 - 15 cms^{-1} have been reported by Holbrook and Frisch (1981), Janopaul et al. (1982) and Schott et al. (1986). Chapman et al. (1997) used shipborne current meter data to suggest that the upper bound of HF radar accuracy is 7 - 8 cms^{-1}. Paduan and Rosenfeld (1996) used both ADCP and drifter data to show that RMS differences with HF radar data are 10 to more than 20 cms^{-1}. The most recent comparisons between HF radar velocities and point measurements show RMS differences between 7 and 19 cms^{-1} (Kohut and Glenn, 2003; Emery et al., 2004; Kaplan et al., 2005; Paduan et al., 2007).

Remote sensing

The high-resolution properties of space borne synthetic aperture radar (SAR) systems, as well as their independence of light and cloud conditions, make SAR imagery a crucial source of information for a number of marine and coastal applications. SAR observations have also demonstrated their ability to routinely monitor different ocean-surface parameters, such as, swell direction and amplitude (Beal et al., 1983; Hasselmann and Hasselmann, 1991). The modification of short surface waves by surface layer winds, air/sea temperatures changes over water masses, the presence of surface currents, surface slicks, bathymetry changes, or coastal plumes have also enabled the identification of atmospheric and oceanic features from SAR images. However, challenges remain in uniquely interpreting such a wealth of high-resolution identified patterns in terms of physical processes in the upper ocean and the atmospheric boundary layer (Kerbaol and Collard, 2005). Hydrodynamic modulation of the surface roughness resulting from wave-current interaction also makes possible the observation of oceanic features, such as current fronts (Marmorino et al., 1994), eddies (Johannessen et al., 1996), internal waves (Alpers, 1985), etc. More recently, ongoing research led to progress in more emerging SAR applications, such as Doppler-based surface current measurements (Chapron et al., 2004) and oceanic and atmospheric features identification, which offers new insights for the observation and modelling of mesoscale meteo-oceanic processes.

SAR is an active microwave instrument producing high-resolution imagery of the Earth's surface, regardless of cloud, dusty and solar illumination. The spatial resolution of space borne SARs typically ranges between a few meters and more than hundred meters, depending on the product type (that is continuous or burst mode). Accordingly, the spatial coverage varies between approximately 100 x 100 km (standard image mode) to 500 x 500 km (wide swath or ScanSAR mode). Presently, three spaceborne SARs namely, ERS-2, Envisat and Radarsat-1 are available. Higher radar frequencies are theoretically expected to be more responsive to wind-speed variations. However, lower radar frequency may be less sensitive to roughness saturation at highest wind speeds. The wave-imaging capability is mostly limited by the so-called SAR azimuth cutoff, which is driven by the root mean square (RMS) of the line-of-sight components of the sea-surface orbital velocities (Kerbaol et al., 1998) weighted by the range-to-velocity ratio. In theory, a lower

Table 1. Various instruments and their functions.

Devices	Function		Remarks
Wave Rider Buoy	To measure near surface waves and currents.	1	Position is not fixed in space in the horizontal direction.
		2	Prone to damage from larger waves, ice, vessel traffic or from vandalism.
		3	Prone to errors in accelerometer due to pitch and roll of the buoys
Acoustic Doppler Current Profilers	Provides a robust means of determining wave heights and direction in shallow and deep waters.	1	Operating at frequencies between 38 kHz and 1.5 MHz.
		2	Directional spectra sharper than data obtained from point measurements
High Frequency Radar	To measure ocean surface waves and currents.	1	Radio wave backscatter in the frequency band if 3 - 30 MHz:
	Electromagnetic waves sent to the ocean are backscattered on surface waves of exactly half the radio wavelength	2	Range: 42 - 83 km from shore with Horizontal resolution of 1 - 3 km in 12 - 25 MHz: 200 km with less horizontal resolution of 5 - 10 km in 5 MHz
Remote Sensing	Synthetic Aperture Radar: a microwave instrument producing high resolution imagery regardless of clouds, dusty conditions and solar illumination.	1	For surface currents, oil slicks, ship detection, bathymetry, wave fields, etc.
		2	Spatial coverage: 100 x 100 km to 500 x 500 km
		3	Spatial Resolution: Between few metres and >100 km

radar frequency should minimize this effect, as a smaller range of wave number components will contribute to the integration of the RMS of the orbital velocities (Kerbaol and Collard, 2005).

DISCUSSION

The various instruments available for the measurement of waves and currents and their functions are presented in Table 1. In addition to traditional sensors, like pressure gauges, wave rider buoys or electric level gauges, radar altimeters are being deployed more frequently in wave monitoring. In comparison to traditional sensors, the radar level gauge, being a remote measuring system, has the benefit of no direct contact with the water (corrosion free and no wave attack on the sensor) (Brumbi, 1995). Nevertheless there are some problems in using standard radar level gauges in wave monitoring such as: (1) Mounting is needed (in contrast to the wave rider buoy); (2) Salinity of the water and sea-ice coverage influences the penetration of the radio-wave pulse into the water; (3) The footprint of the radar has an averaging effect and (4) Reflection of the radio-wave pulse depends on the slope of the water surface.

Wave rider buoy measurements have problems, particularly in breaking seas, where surface-floating instruments are subjected to large accelerations. Under such conditions, wave rider measurements may overestimate or underestimate the actual wave heights. The wave rider buoy measurements are also prone to missing data due to shore-station problems, or damage to the buoy arising from collisions with vessels or sea ice, or due to vandalism. Overall, acoustic-based range measurements offer a promising means of measuring ocean waves from the comparative safety and stability of the ocean floor. Problems with wave rider buoys can be eliminated through use of a better mooring system that minimizes instrument tilt and vertical movements.

It is recognized that wave rider buoys fail to adequately measure many non-linearities and asymmetries in the sea-state (Arhan and Plaisted, 1981; LeBlond, 1982). This is most likely due to the fact that the buoy position is not fixed in space in the horizontal direction, as would be a wave staff device. The slack in the mooring is of the order of the depth and therefore of the wave length or greater in many cases. The buoy probably tends to follow the circular or elliptical path of the water particles under the wave and is thus tending toward some sort of Lagrangian measurement on the scale of a wave length as opposed to the Eulerian measurement made by a wave staff. Care must therefore be taken in attempting to extract information on steepness and wave lengths from the surface elevation signal from the wave rider. Any problems of a decrease in sensitivity of the wave rider buoy due to aging of the accelerometer fluid was found to be either nonexistent in some cases or sufficiently slow that wave programs with a regular calibration schedule should be able to detect and respond to the problem. The wave rider buoy should not be expected to produce the same time history as a wave staff and the data should be integrated accordingly (Wilson and Taylor, 1983).

Extreme wave crests have been of special interest for fixed platforms, since their designs are directly connected to the crest heights and the water velocities. Some activities on the platforms also depend on what crest heights can be expected in a given sea state while in operation. Extreme statistics are usually made from point measurements, but waves often appear in wave groups. Due to the dispersive nature of the waves, these groups can have different maximum crests at different positions along the direction of travel. If the waves ride on an ocean current, the return signal is further Doppler-shifted by the radial component of the current, which can be readily estimated. With two radars some distance apart along the coast, vector currents can be computed. This is a precise concept, which surprisingly has taken more than three decades to be accepted by the oceanographic community (HELZEL, 2004). Yet unlike ADCPs, the scattering targets are well known, and well understood theoretically in HF Radars. ADCPs deployed on ships provide the most viable way to survey ocean current profiler (Anderson and Matthews, 2005).

Different instruments for wave and current measurements have their own advantages and disadvantages depending on the applications and needs. Advantages of wave rider buoys include: (1) Real-time telemetry is facilitated by adding the appropriate wireless antenna and telemetry hardware. In this case there is no need for a cable to shore, or acoustic modems. Depending on the installed telemetry option, the receiving station could even be thousands of kilometers away; (2) Solar power can be employed to maintain power; (3) Attenuation of wave-induced properties (such as pressure, velocity) is not an issue, since the measurements are made at the water surface; (4) Deployment can be relatively simple; e.g. hoist buoy into water and release; hoist anchor into water and release; (5) Inexpensive, easy to handle and accurate for small waves.

Disadvantages include: (1) Buoys are subject to vessel or debris impact; (2) Visibility can lead to vandalism problems; (3) Environmental mooring loads are more severe, since mean flows, wave-induced flows, and winds all act on the buoy; (4) Mooring system requires servicing; (5) Internals (incl. batteries) are under constant acceleration loads, although this has not created problems to date; (6) Fixed, bottom mounted gear (such as up-looking ADCP) provides higher rated accuracy for measurement of mean flows, compared to buoy equipped with down-looking ADCP; (7) Measurement of water depth or tidal range is typically not feasible. Noise in accelerometers may make measurement of low frequency energy problematic; (8) Buoys are not able to measure the higher waves, particularly sea waves; (9) Buoyancy will be inadequate to keep it on the ocean surface during storm in measuring larger waves.

In ADCP, measurement of long term data is a major problem in establishing the effect of wave-current impact, particularly on the marine energy converters. Air frequency measurement is required greater than 1 Hz for a good study. It is difficult to measure data for longer duration which requires larger memory. It is very expensive for long term measurement of air frequency, which requires at least for one year continuous data. It involves continuous deployment deal with harsh turbulent marine environment, make the process difficult. Long term air frequency data is essential as an input for validating theoretical modelling. Therefore, working with short term data will not give good representation of dynamics of marine structures. In ADCPs, aliasing of unwanted high-frequency noise signals such as orbital velocities into the frequency band of interest can be characterised by the variance of an individual recorded ensemble average. In practical situations it is common to deal with noise signals such as waves that are either inherently broadband or must be treated as effectively so due to variability in the peak frequency.

Alternatively, very small gradients and low value currents, which are inferred from sea-surface heights estimated from satellite altimetry, are already routinely used in the global circulation models. However, this approach does not allow direct measurements of sea-surface displacements nor does it achieve the spatial scales that may be obtained from SAR (Kerbaol and Collard, 2005). Sequences of sea-surface temperatures and ocean-colour data can be used either in the Maximum Cross Correlation method (Emery et al., 1986) or the Optical Flow method (Vigan et al., 2000; Yang and Parvin, 2000). Although these methods allow absolute measurements of current vectors, they do not achieve the spatial resolution of SAR-based methods and they are limited by the solar-illumination and cloud-cover conditions. Finally high-frequency (HF) radars offer a very interesting opportunity to retrieve the full vector of sea-surface currents with a temporal sampling of a few minutes. However, the coverage area is more limited than the spaceborne SAR coverage. Furthermore, the deployment and maintenance of such systems often induce additional costs and administrative difficulties. Nevertheless, such a system may be well suited for local measurements and validation purpose (Kerbaol and Collard, 2005).

Many questions still exist, however, about the details and effectiveness of HF radar-derived surface currents as sources for data assimilation. On one level, data descriptors needed to define the requisite error covariance functions are not yet well known. Errors in HF radar-derived currents arise from a variety of sources, including electromagnetic interference, ships, and poorly constrained inversion algorithms. Some insight into these errors can be obtained comparing with data from in situ moored current meters or drifting buoys (Laws et al., 2001). Despite several tasks, it is clear that two-dimensional maps of surface currents from HF radar networks represent a useful and unique resource for the improvement of coastal ocean circulation models, particularly in the critical depth range encompassing the euphotic zone (Paduan and Shulman, 2004).

Differences between surface current velocities from HF radar and other platforms are: (1) measurements from HF radar, drifters, and current meters are all inexact. The frequency resolution of computed radar cross-spectra, which depends on FFT length, limits radial velocity resolution to ~ 5 and 2.5 cms^{-1} for 12- and 25-MHz systems, respectively. Drifters can slip at ~ 1 to 2 cms^{-1} from the ocean water they follow (Ohlmann et al., 2005);

Table 2. Comparison of velocity measurements between various instruments.

Instruments	Parameters	Errors	Authors and Remarks
HF Radar Vs ADCP	RMS velocity difference	6.62 ~ 11.3 cms^{-1}	Yoshikawa et al. (2006): Major error of radial velocity of HF Radar is Variance error rather than bias error
	Variance error of hourly radial velocity	5.75 ~ 13.3 cms^{-1}	
	Bias error	Reasonably small	
HF Radar and Current meter	Velocity	10 - 15 cms^{-1}	Holbrook and Frisch (1981), Janopaul et al. (1982) and Schott et al. (1986)
HF Radar vs. Ship-borne current meter	Velocity	7 - 8 cms^{-1}	Chapman et al. (1997)
HF Radar vs. ADCP and Wave Rider Buoy	RMS velocity difference	10 - 20 cms^{-1}	Paduan and Rosenfield (1996)
		7 - 19 cms^{-1}	Kohut and Glenn (2003), Emery et al. (2004), Kaplan et al. (2005) and Paduan et al. (2007)
HF Radar vs. Single Drifter	RMS velocity difference	10 cms^{-1}	Ohlmann et al. (2007): Minimum of ~ 5 cms^{-1} when 15 – 30 drifter observation averages.

(2) vertical scales of measurement differ. The HF radar gives vertically integrated values from the surface, drifters give integrated values over their drag elements, and current meters give values for specific depths or depth bins; (3) Horizontal scales of measurement differ. Typically, HF radars average over extensive horizontal areas (up to several km^2), while other platforms give point measurements or limited spatial measurements following motion; (4) Measurements are not necessarily coincident in time and Stokes drift may not be reconciled consistently among platforms (Ohlmann et al., 2007).

Velocity measurements using different instruments are compared from different works carried out by various researchers and presented in Table 2. The reduction in RMS velocity differences in the San Diego data with measured antenna patterns supports results of Kohut and Glenn (2003) and Paduan et al. (2007), who attribute errors of more than 10 cm cms^{-1} to poorly known antenna patterns (Ohlmann et al., 2007). Large changes in radar radials, relative to drifter velocities, may not necessarily be evident in RMS difference, for example where the bias (difference) between platforms goes from positive to negative without changing magnitude. The occasional use of drifter comparisons to determine both bias and RMS difference can indicate errors related to antenna patterns, ultimately improving the quality of HF radar data provided to users.

The complicated signal processing for extracting surface currents from backscattered radar signals (de Paolo and Terrill, 2007) yields radial velocities on polar coordinate grid points centered by each antenna location. Radial velocities measured by multiple antenna installations have been combined into current vector field using unweighted least squares fitting (Lipa and Barrick, 1983). The maps of ocean surface currents are incomplete in space and time for the following reasons (Kim et al., 2007); 1. The algorithm on the measured Doppler spectrum does not provide a solution for all bearing angles; 2. Estimate of current vectors along the baseline between two radars where the measurements of radial velocities are nearly aligned suffers from poor geometrical dilution of precision (GDOP), and frequently results in spurious current vectors. The region with radial velocities crossing at angles less than 15 - 20° between two radars is commonly considered to produce unusable current vectors and; 3. Hardware or software problems can lead to the temporary shutdown of individual radar sites.

Relevant applications of surface currents require time and space-continuous data, which requires the interpolation of the incomplete observations to a regularly spaced product. A variety of remote sensing tools have been housed in artificial satellites, which are very useful for monitoring the global environments. Sensors and software for measuring water temperature, wind velocity, current velocity, wave height and chlorophyll on the sea surface have been developed and installed on satellites. Remote sensing using satellites is most effective in its breadth and simultaneity, but it must be calibrated by direct measurements. Ocean engineers have been charged with developing vehicles and buoys for these direct measurements (Koterayama et al., 2003). Surface current measurement by interpretation of radio waves backscattered from surface gravity waves is quickly maturing as an oceanographic observational tool whose data is useful to a broad range of users. The shore-based antenna approach can provide continuous temporal and broad spatial surface current observations, facilitating the delivery of data in near real-time for various applications (Kim et al., 2007).

The SAR is, so far, the only satellite-borne instrument that can measure the directional characteristics of the ocean wave field. In the early 1990s, the derivation of a closed-form expression for the ocean-to-SAR spectral transformation, as well as the formulation of the inversion procedure (Hasselmann and Hasselmann, 1991), significantly improved the understanding about the SAR imaging of ocean waves. A new SAR inversion algorithm for Envisat ASAR Level 2 wave-mode products was developed by Engen et al. (2001). Preliminary results support the fact that the significant wave height estimated from SAR is less than 40 cm in 50% of the cases and the RMS on wave direction is about 30 (Kerbaol et al., 2004). As an example, the detection of current features, including current fronts, internal waves, and eddies, are generally based on the use of the wavelet transform (Wu and Liu, 2003). The future research will focus on understanding the dynamic mechanisms by which surface velocity information impacts subsurface model currents and to explore the sources of error in the HF radar data itself in order to improve error covariance models of data assimilation. Future model improvements should include tidal forcing and special handling of velocity assimilation near the coastal boundary.

SUMMARY

Wave rider buoys have proven to be a cost effective means of collecting ocean current observations. However, buoys report only near surface currents and a Lagrangian technique does not provide a means of activity targeting and monitoring a specific site or area. Acoustic Doppler Current Profilers mounted on moorings and platforms can provide real-time current information but are not always optimally located. HF Radars provide data for a wider area but only of the surface waves/ currents perspective. SAR data provide wider spatial coverage through satellite sensors. It is essential to choose the type of application based on the needs and importance. It is concluded that each of the instrumentation/applications have their own advantages and disadvantages. A thorough knowledge of the particular instrument to be used is essential before it is deployed. Cost may also be an issue, depending on funding availability and duration of project.

ACKNOWLEDGEMENTS

This work is carried out under SRDG/MREDS programme funded by the Scottish Funding Council. The authors are thankful to the Scottish Government for the support and funding provided to the ICIT, Heriot-Watt University, Edinburgh, United Kingdom.

REFERENCES

Alfonso M, Alvarez E, Lopez J.D (2006). Comparison of CODAR SeaSonde HF Radar operational waves and currents measurements with Puertos del Estado buoys. Final Report, March, 32p.

Alpers W (1985). Theory of radar imaging of internal waves. Nature. 314(6008): 245–247.

Anderson SP and Mathews P (2005). A Towed 75 kHz ADCP for Operational Deepwater Current Surveys.

Procs. IEEE/OES Eighth Working Conference on Current Measurement Technology. pp. 46 - 49.

Arhan M, Plaisted RO (1981). Non-Linear deformation of sea-wave profiles in intermediate and shallow water. Oceanologia Acta. 4: 107-115.

Barrick D (2003). Proliferation of SeaSonde coastal current-mapping radars. Hydro Int., 7(1): 30- 33.

Barrick DE (1977). Ocean surface current mapped by radar. Science, 198: 138-144.

Barrick DE, Lipa BJ (1997). Evolution of bearing determination in HF current mapping radars. Oceanography, 10: 72–75.

Beal R, Tilley D and Monaldo F (1983). Large and small-scale spatial evolution of digitally processed ocean wave spectra from Seasat Synthetic Aperture Radar. J. Geophys. Res., 88(C3): 1761–1778.

Brumbi D (1995) Measuring Process and Storage Tank Level with Radar Technology. IEEE Int. Radar Conf., Alexandria, VA, USA.

Capon J (1969). High-resolution frequency - wavenumber spectrum analysis. Proc. IEEE, 57: 1408-1418 also Corrigendum in Proc. IEEE (Lett.), 59, 112 (1971).

Chapman RD, Shay LK, Graber HC, Edson JB, Karachintsev A, Trump CL and Ross DB (1997). On the accuracy of HF radar surface current measurements: Intercomparison with ship-based sensors. J. Geophys. Res. 102 (C8): 18737–18748.

Chapron B, Collard F, Kerbaol V (2004). Satellite synthetic aperture radar sea surface Doppler measurements. Proc. 2nd Workshop Coastal and Marine Applications Synthetic Aperture Radar (SAR), Svalbard, Norway, (ESA SP-565). Noordwijk, Netherlands, pp. 133-140.

Chereskin TK, Firing E, Gast JA (1989). Identifying and screening filter skew and noise bias in acoustic Doppler current profiler measurements. J. Atmos. Oceanic Technol., 6: 1040-1054.

Chereskin TK, Harding J (1993). Modeling the performance of an acoustic Doppler current profiler. J. Atmos. Oceanic Technol. 10: 42-63.

CODAR (2008). Retrieved from the website of CODAR Ocean Sensors, http://www.codaros.com.

Crombie DD (1955). Doppler spectrum of sea echo at 13.56 Mc/s. Nature 175: 681-682.

De Paolo T, Terrill E (2007). Skill assessment of resolving ocean surface current structure using Compact-Antenna style HF RADAR and the MUSIC direction finding algorithm. J. Atmos. Oceanic Technol, in press.

Emery BM, Washburn L, Harlan JA (2004). Evaluating radial current measurements from CODAR high-frequency radars with moored current meters. J. Atmos. Oceanic Technol., 21: 1259-1271.

Emery W, Thomas A, Collins M, Crawford W, Mackas D (1986). An objective method for computing advective surface velocities from sequential infrared satellite images. J. Geophys. Res. 91(C11): 12865-12878.

Engen G, Johnsen H, Høgda K, Chapron B (2001). Envisat ASAR Level 2 Wave Mode Product Algorithm Specification-Software Requirement Document. Technical report. NORUT IT. Doc. 650/1-01.

Essen HH, Gurgel KW, Schirmer F (1989). Surface currents in the Norwegian Channel measured by radar in March 1985. Tellus, 41A: 162-174.

Essen HH, Gurgel KW, Schlick T (2000). On the accuracy of current measurements by means of HF Radar. IEEE J. Oceanic Eng. 25: 4.

Graber HC, Haus BK, Chapman RD, Shay LK (1997). HF radar comparisons with moored estimates of current speed and direction: Expected differences and implications. J. Geophys. Res. 102: 18:749 - 18,766.

Gurgel KW, Antonischski G, Essen HH, Schlick T (1999). Wellen radar (WERA): A new ground wave radar for remote sensing. Coastal Eng. 37: 219–234.

Gurgel KW, Essen HH, Kingsley SP (2000). HF Radars: Physical limitations and recent developments. Elsevier Publications (and in www.helzel.com).

Hasselmann K, Hasselmann S (1991). On the nonlinear mapping of an ocean wave spectrum into a synthetic aperture radar image spectrum and its inversion. J. Geophys. Res., 96(C6): 10713–10729.

HELZEL (2004). Retrieved from the website of Wellen radar. http://www.helzel.com.

Holbrook JR, Frisch AS (1981). A comparison of near surface CODAR and VACM measurements in the Strait of Juan de Fuca, August

1978. J. Geophys. Res. 86: 10 908-10 912.
Johannessen J, Shuchmann R, Digranes G, Lyzenga D, Wackerman, C, Johannessen O, Vachon P (1996). Coastal ocean fronts and eddies images with ERS-1 synthetic aperture Radar. J. Geophys. Res. 101(C3): 6651–6667.
Janopaul MM, Broche P, de Maistre JC, Essen HH, Blanchet C, Grau G, Mittelstaedt E (1982). Comparison of measurements of sea currents by HF radar and by conventional means. Int. J. Remote Sens. 3: 409-422.
Joyce TM (1989). On in situ calibration of ship-board ADCPs. J. Atmos. Oceanic Technol., 6: 169-172.
Kaneko A, Koterayama W, Honji H, Mizuno S, Kawatate K and Gordon RL (1990). Cross-stream survey of the upper 400 m of the Kuroshio by an ADCP on a towed fish. Deep sea Res. 37: 875-889.
Kaplan DM, Largier J, Botsford LW (2005). HF radar observations of surface circulation off Bodega Bay (northern California, USA). J. Geophys. Res, 110, C10020, doi:10.1029/ 2005JC002959.
Kerbaol V,Collard F (2005). SAR-Derived Coastal and Marine Applications: From Research to Operational Products. IEEE J. Ocean. Eng. 30(3): 472-486.
Kerbaol V, Chapron B, Vachon P (1998). Analysis of ERS-1/2 SARwave mode imagettes. J. Geophys. Res. 103(C4): 7833–7846.
Kerbaol V, Johnsen H, Chapron B, Rosich B (2004).Quality assessment of ENVISAT ASAR wave mode products based on regional and seasonal comparisons with WAM model outputs. Proc. ESA ERS/ENVISAT Symp. Salzburg, Austria.
Kim SY, Terrill E, Cornuelle B (2007). Objectively mapping HF radar-derived surface current data using measured and idealized data covariance matrices. J. Geophys. Res., 112(C06021): 1-16.
King BA, Cooper EB (1993). Comparison of ship's heading determined from an array of GPS antennas with heading from conventional gyrocompass measurements. Deep Sea Res. 40: 2207-2216.
Kohut JT, Glenn SM (2003) Improving HF radar surface current measurements with measured antenna beam patterns. J. Atmos. Oceanic Technol. 20: 1303–1316.
Koterayama W, Nakamura M, Sato K, Ikebuchi T (2003). Model and Field Experiments on a Wave Observation Buoy. Int. J. Offshore Polar Eng. 13: 1.
Krogstad HE, Gordon RL, Miller MC (1988). High resolution directional wave spectra from horizontally-mounted Acoustic Doppler Current Meters. J. Atmos. Oceanic Technol., 5: 340-352.
Laws K, Fernandez DM, Paduan JD (2001). Simulation-based evaluations of HF radar ocean current algorithms. J. Oceanic Eng. 25: 481– 491.
LeBlond PH (1982). A preliminary review of non-spectral wave properties: grouping, wave breaking and freak waves. Can. Contract. Rep. Hydrogr. Ocean Sci. 1: 66.
Lipa BJ, Barrick DE (1983). Least squares methods for the extraction of surface currents from CODAR crossed-loop data: Application at ARSLOE. IEEE J. Oceanic Eng. 13(2), pp.507– 513.
Magnusson AK, Donelan MA (2000). Extremes of waves measured by a wave rider buoy and vertical lasers. Proc. Rogue Waves 2000, Brest. 17: 231-245.
Marmorino G, Jansen R, Valenzuela G, Trump C, Lee J, Kaiser J (1994). Gulf stream surface convergence images by synthetic aperture radar. J. Geophys. Res., 99(C9): 18315–18328.
Monchow A, Coughran CS, Hendershott MC, Winant CD (1995). Performance and Calibration of an acoustic Doppler current profiler Towed below the Surface. J. Atmos. Oceanic Technol., 12: 345-444.
New AL (1992). Factors affecting the quality of shipboard acoustic Doppler current profiler data. Deep Sea Res., 39: 1985-1992.
Ohlmann JC, White PF, Sybrandy AL, Niller PP (2005). GPS-cellular drifter technology for coastal ocean observing systems. J. Atmos. Oceanic Technol. 22: 1381–1388.
Ohlmann C, White P, Washburn L, Terrill E, Emery B, Otero M, (2007). Interpretation of coastal HF Radar derived surface currents with High-Resolution Drifter data. J. Atmos. Oceanic Technol., 24: 666-680.
Paduan JD, Graber HC (1997). Introduction to high frequency radar: Reality and myth. Oceanography 10: 36- 39.
Paduan JD, Rosenfeld LK (1996). Remotely sensed surface currents in Monterey Bay from shore-based HF radar (CODAR). J. Geophys. Res. 101: 20,669–20,686.
Paduan JD, Shulman I (2004). HF radar data assimilation in the Monterey Bay area. J. Geophys. Res. 109(C07 S09): 1-17.
Paduan JD, Kim KC, Cook MS, Chavez FP (2007). Calibration and validation of direction-finding high frequency radar ocean surface current observations. IEEE J. Oceanic Eng. in press.
Pawka SS (1983). Island shadows in wave directional spectra. J. Geophys. Res. 88: 2579-2591.
Pinkel R, Smith JA (1987). Open ocean surface wave measurement using Doppler sonar. J. Geophys. Res. 92: 12,967-12,973.
Prandle D (1987). The structure of nearshore tidal and residual circulations revealed by HF radar surface current measurements. J. Phys. Oceanography with High-Resolution Drifter data. J. Atmos. Oceanic Technol. 24: 666-680.
Ribe RL (1983). Accuracy characteristics of the electronics of Wave Rider Buoys used in the ARSLOE. IEEE J. Ocean Eng. OE-8(4) 212-214.
Schott FA, Frisch SA, Larsen JC (1986). Comparison of surface currents measured by HF Doppler Radar in the western Florida straits during November 1983 to January 1984 and Florida current transports. J. Geophys. Res., 91: 8451 – 8460.
Smith JA (1989). Doppler sonar and surface waves: Range and resolution. J. Atmos. and Oceanic Technol., 6: 680-696.
Sorensen RM (1997). Basic Coastal Engineering. Chapman and Hall, New York, 301p.
Stewart RH, Joy JW (1974). HF radio measurements of surface currents. Deep Sea Res. 21: 1039–1049.
Strong B, Brumley B, Terray EA, Stone GW (2000). The Performance of ADCP-Derived Wave Spectra and Comparison with Other Independent Measurements, www.rdinstruments.com/library.html.
Terray EA, Brumley BH, Strong B (1999). Measuring waves and currents with an upward-Looking ADCP. Proc. IEEE 6th Working Conference on Current Measurements, IEEE, pp. 66 - 71.
Vigan X, Provost C, Bleck R, Courtier P (2000). Sea surface velocities from sea surface temperature image sequences, 1. Method and validation using primitive equation model output. J. Geophys. Res. 105(C8) 19499–19514.
Wikramanayake N (2006). The coastal wave-climate of Sri Lanka: Measurements and Modeling. Procs. 7th International Workshop on Indian Ocean Research and Ocean Hazard/ Tsunami, Guangzhou, China.
Wilson JR, Taylor JD (1983) Experiences with wave rider buoys in the Canadian wave climate study. Oceans. 15: 254-257.
Wu S, Liu A (2003). An automated ocean feature detection, extraction and classification algorithm for SAR imagery. Int. J. Remote Sens. 24: 935–951.
Wyatt LC, Thompson SP, Burton RR (1998). Evaluation of HF radar wave measurements. Coastal Engineering and in www.helzel.com .
Yang Q, Parvin B (2000). Feature based visualization of geophysical data. Proc. Computer Vision and Pattern Recognition (CVPR), Hilton Head Island, SC, 2: 276–281.
Yoshikawa Y, Masuda A, Marubayashi K, Ishibashi M, Okuno A (2006). On the accuracy of HF radar measurement in the Tsushima Strait. J. Geophys. Res. 111(C04009): 1-10.