On Shipboard Marine X-Band Radar Near-Surface Current “Calibration”

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ABSTRACT

The ocean wave signatures within conventional noncoherent marine X-band radar (MR) image sequences can be used to derive near-surface current information. On ships, an accurate near-real-time record of the near-surface current could improve navigational safety. It could also advance understanding of air–sea interaction processes. The standard shipboard MR near-surface current estimates were found to have large errors (of the same order of magnitude as the signal) that are associated with ship speed and heading. For acoustic Doppler current profilers (ADCPs), ship heading errors are known to induce a spurious cross-track current that is proportional to the ship speed and the sine of the error angle. Conventional mechanical gyrocompasses are very reliable heading sensors, but they are too inaccurate for shipboard ADCPs. Within the ADCP community, it is common practice to correct the gyrocompass measurements with the help of multiantenna carrier-phase differential GPS systems. This study shows how a similar multiantenna GPS-based ship heading correction technique stands to improve the accuracy of MR near-surface current estimates. Changes to the standard MR near-surface current retrieval method that are necessary for high-quality results from ships are also introduced. MR and ADCP data collected from R/V Roger Revelle during the Impact of Typhoons on the Ocean in the Pacific (ITOP) program in 2010 are used to demonstrate the MR currents’ accuracy and reliability.

1. Introduction

Marine X-band radars (MRs) have been widely used for ship navigation since the mid-twentieth century. The radar backscatter from the sea surface, commonly referred to as sea clutter, was first investigated as a source of noise because it may obscure radar targets like small ships (e.g., Croney 1966). While it was soon discovered that the sea clutter contains valuable surface gravity wave and current information (Oudshoorn 1960; Ijima et al. 1964), it took another three decades for oceanographic MR applications to garner substantial traction.

In the early 1990s, modern computer technology was first employed toward the digitization, storage, and processing of radar imagery in near–real time (Ziemer and Dittmer 1994). This development has paved the way for today’s broad range of oceanographic (and meteorological) MR applications, which include the retrieval of surface wave spectra and currents (Young et al. 1985a; Senet et al. 2001), bathymetry (Bell 1999), individual wave parameters (Nieto Borge et al. 2004), wind speed and direction (Dankert et al. 2003; Lund et al. 2012), and internal wave properties (Ramos et al. 2009; Lund et al. 2013), to name a few.

MRs operate by emitting pulses of microwave radiation (~3-cm wavelength) at grazing incidence. The microwaves are scattered back to the antenna by sea surface roughness elements. Oblique incidence radar returns arise primarily due to Bragg scattering, induced by ocean waves of half the radar wavelength (Barrick...
1968; Wright 1968). But Bragg theory, which predicts a reduction of the backscatter intensity with increasing incidence angle, was found to underestimate grazing incidence backscatter measurements, suggesting the existence of additional scattering mechanisms (Valenzuela 1978). It is now widely accepted that a significant contribution to grazing incidence backscatter comes from breaking wave events at a variety of scales, generating so-called sea spike echoes (e.g., Trizna et al. 1991).

Equipped with a rotating antenna, MRs can scan the sea surface at high temporal (~1.4 s) and spatial (~10 m) resolution, up to a maximum range of ~4 km (when operated in short-pulse mode). In the presence of surface gravity waves, the resulting images exhibit bands of enhanced and weakened backscatter, which correlate strongly with the waves’ crests and troughs (Nieto Borge et al. 2004). Figure 1 gives an example of an MR image collected from R/V Roger Revelle showing two prominent crossing wave systems (one is approaching the ship head on, the other is coming from a slight port-side angle). MRs image ocean waves through three mechanisms: tilt modulation (the waves’ influence on the local incidence angle), hydrodynamic modulation (the waves’ orbital motion modulating the radar scattering elements), and shadowing (wave crests blocking the radar energy in the areas behind) (Alpers et al. 1981a; Wetzel 1990). After transforming a sequence of MR images to Fourier space, the near-surface current can be retrieved from the three-dimensional (3D) image spectrum by measuring the current-induced Doppler shift of the surface wave signal (Young et al. 1985a; Senet et al. 2001).

In situ near-surface current measurements are accompanied by many difficulties (e.g., Yoshikawa and Masuda 2009). Surface gravity waves induce a significant orbital motion that is superposed on the (typically weaker) mean near-surface current. To measure the (mean) near-surface current, this wave signal must be removed, which may lead to errors. The measurements are subject to further contamination by wave-induced instrument motions. Near-surface acoustic Doppler current profilers (ADCP) measurements are error prone due to bubbles (e.g., caused by breaking waves), which can act as a shield that inhibits sound transmission (Teledyne RD Instruments 2011). Conventional non-coherent MR-based systems like OceanWaveS’ Wave and Surface Current Monitoring System (WaMoS) are capable of delivering near-surface current estimates in close to real time without wave contamination. Another advantage of remote current measurements is that they are immune to flow distortions by the instrument (Mueller 2015).

The validity of land-based MR currents has been established in several studies, most recently by Hessner et al. (2014), using data from a tidally dominated coastal region near Wellington, New Zealand. Their MR-based current estimates show good agreement with results from a hydrodynamic model. Bell et al. (2012) deployed an MR at a tidal energy test site in the northern isles of Orkney, known for their extreme current environment. They reported a good agreement between their MR near-surface current results and ADCP measurements made within the radar field of view (FOV).

Aboard ships, knowledge about the near-surface current is likely to improve navigational safety. For example, it could prepare the crew for coastal jets at narrow harbor entrances, or be used to guide search and rescue efforts in a passenger overboard situation. It could also contribute to environmental protection, for example, by enabling the tracking of surface pollutants. Finally, scientific field experiments stand to benefit from accurate near-surface current data. To give one example, air–sea momentum flux measurements require information on the surface current. This is because the bulk momentum flux is proportional to the relative difference between the wind and current velocities (Edson et al. 1998). Or, another example, MR near-surface current measurements could be used to investigate the wind-driven surface flow (i.e., the speed factor and deflection angle), which is still incompletely understood (Yoshikawa and Masuda 2009). In view of these (potentially lifesaving) benefits, how can it be that shipboard MR near-surface current sensors are so poorly established? And why does the scientific literature offer little to no evidence of successful shipboard MR current retrieval campaigns? We believe this is because the MR current estimates’ dependency on accurate ship heading has been ignored.
Here, issues that are specific to the retrieval of near-surface currents from shipboard MR data are investigated. We have been involved in multiple research cruises aboard MR-equipped vessels, and have repeatedly found that the standard near-surface current estimates have significant errors that depend on ship speed and heading. Here, we demonstrate how a combination of gyrocompass inaccuracies and offsets between radar image and ship heading triggers the observed ship track dependency of our near-surface current estimates. Borrowing from the expertise of the shipboard ADCP community, we propose a multi-antenna GPS-based heading correction and water-track “calibration” technique. (Note that we put the word *calibration* in quotation marks to emphasize the fact that no external reference sensors are needed. For ease of reading, the quotation marks will be omitted hereafter.)

In addition, we present improvements to the standard MR current retrieval approach from underway ships. Using shipboard MR and, for reference, ADCP data, we show that the proposed methods yield reliable and accurate near-surface current results, which are completely independent of the ship track.

This article is organized as follows. Section 2 describes our 3D fast Fourier transform (FFT)-based MR near-surface current retrieval algorithm, with a particular focus on the challenges and solutions for shipborne data. An overview of the data used for this study is given in section 3. Section 4 illustrates the consequences of ship heading errors for the MR-based near-surface current estimates, and introduces our new heading correction technique. In section 5 we demonstrate the method’s effectiveness using MR and ADCP data from two research cruises. The section also investigates the causes for MR–ADCP differences. The paper ends with a summary of results and conclusions in section 6.

2. Shipboard marine X-band radar near-surface current retrieval

Section 2a revisits the standard MR near-surface current retrieval. The methods described in this subsection apply equally to fixed platform (e.g., on lighthouses) and shipboard MR installations. Section 2b discusses supplemental processing steps that are necessary to ensure high-quality results from moving platforms (i.e., ships). Section 2c explains how we refined the MR near-surface current retrieval in order to better estimate the measurements’ effective depth.

a. Standard current retrieval revisited

The near-surface current retrieval from conventional noncoherent MR backscatter data is based on the ocean waves’ radar signatures (Young et al. 1985a). For sea clutter to be present, a minimum significant wave height of \( \sim 0.5 \text{ m} \) and wind speed of \( \sim 3 \text{ m s}^{-1} \) is required (Hatten et al. 1998). It is assumed that sea state is a linear, zero-mean, Gaussian process that is homogeneous in space \( \mathbf{r} = (x, y) \) and stationary in time \( t \) (Nieto Borge et al. 1999). Figure 2 gives an example of a radar image sequence. On the image cube’s \( t-y \) face, individual waves propagating in the negative direction of the \( y \) axis are clearly visible.

A 3D FFT is employed to convert a sequence of MR images \( I(x, y, t) \) to the spectral density (also called periodogram or power spectrum):

\[
P(k_x, k_y, \omega) = \frac{1}{dk_x dk_y d\omega} |\text{FFT}[I(x, y, t)]|^2,
\]

where \( \mathbf{k} = (k_x, k_y) \) is the wavenumber vector, \( \omega \) is the angular frequency, and \( dk_x, dk_y, d\omega \) are the spectral resolutions. The Nyquist frequency \( \omega_N \) (here, \( \sim 2.2 \text{ rad s}^{-1} \)) defines the spectrum’s upper-frequency limit and is determined from the antenna rotation period \( T_a \) (\( \sim 1.4 \text{ s} \)) by \( \omega_N = \pi/T_a \).

In the absence of a current, the wave signal’s location in 3D Fourier space is defined by the linear dispersion relationship,

\[
\zeta = \pm \sqrt{gk \tanh kh},
\]

where \( \zeta \) is the intrinsic frequency, \( k = |\mathbf{k}| \) is the wavenumber, \( g \) is the acceleration due to gravity, and \( h \) is the water depth. As expressed by (2), the wave signal is located on a surface that resembles an inverted cone, the
so-called dispersion shell. It is perfectly symmetric in wave-number space, with its center at \( k_x = k_y = 0 \text{ rad m}^{-1} \). The impact of a current \( \mathbf{U} = (\mathbf{u}, \mathbf{v}) \) is to add the Doppler term \( \omega_D = k \cdot \mathbf{U} \) to the intrinsic frequency, giving the absolute frequency,

\[
\omega = \omega_0 + \omega_D,
\]

where \( \omega_D \) distorts the dispersion shell’s symmetric structure, giving it an elongated shape. Figure 3a illustrates the still water dispersion shell. Figure 3b illustrates the dispersion shell’s distortion in the presence of a 1 m s\(^{-1}\) current in the negative direction along the \( x \) axis.

To determine the MR near-surface current, one must identify the coordinates within the 3D image power spectrum that are associated with the surface waves. The wave signatures represent the dominant signal within the MR image sequences. This facilitates discriminating the waves’ spectral coordinates from the nonlinearities and the background noise components. (The most prominent nonlinearity within the 3D power spectrum is the group line, which is believed to arise due to modulations by the wave field’s group structure; a detailed discussion of the different spectral components can be found in Nieto Borge et al. (2008) and Lund et al. (2014). Typically, all spectral coordinates above a certain power threshold are attributed to the waves (e.g., Senet et al. 2001).

Once the waves’ 3D spectral coordinates are known, a least squares fitting algorithm that was first proposed by Young et al. (1985a) is utilized to obtain a first estimate of the near-surface current vector. This algorithm adjusts the near-surface current such that the distance of the selected spectral coordinates from the dispersion shell is minimized. Note that, to yield an accurate current vector, this method requires the wave energy spectrum to have significant directional spread. This condition is generally fulfilled under natural sea states (e.g., Rogers and Wang 2007).

To determine the final near-surface current, we follow Senet et al.’s (2001) iterative approach, which begins with the result from the Young et al. (1985a) algorithm as a first guess. In essence, they showed that the MR near-surface current results improve significantly if one accounts for aliasing effects and the higher harmonics of the dispersion relation. The aliasing issue is illustrated by Fig. 3. Both graphs mark the wavenumbers whose frequencies, as defined by (3), are within the \( \omega_{Ny} \) limit. Wavenumbers with frequencies greater than \( \omega_{Ny} \) are subject to aliasing; that is, the corresponding waves are temporally undersampled. This is a common occurrence for MRs with slow antenna rotation speeds. The Doppler shift associated with strong currents exacerbates this issue. The higher harmonics are mainly due to the nonlinearity of the MR imaging mechanism, especially shadowing effects, and are given by

\[
\omega_p = \pm (p + 1) \sqrt{\frac{gk}{p + 1} \tanh \frac{kh}{p + 1}} + \omega_D,
\]

where the factor \( p \) is the order [\( p = 0 \) yields (3), referred to as the fundamental mode]. For additional details, the reader is referred to Senet et al. (2001).

Figure 4 illustrates the wave signal within the 3D image power spectrum that was derived from a \( \sim 12 \text{ min-long} \) sequence of MR images that includes the data shown in Figs. 1 and 2. Figure 4a shows the wavenumber–frequency slice through the spectrum at \( k_x = 0 \text{ rad m}^{-1} \) and \( 0 \text{ rad m}^{-1} \leq k_y \leq k_{Ny} \), where the Nyquist wavenumber...
is given by $k_N y = \frac{\pi}{\delta r}$, with $\delta r$ being the range cell size (here, 7.5 m). Figure 4b shows the frequency slice at 1.12 rad s$^{-1}$. The curves corresponding to the dispersion relation’s fundamental, first harmonic, and second harmonic modes are shown in black, red, and blue, respectively. The Doppler-shifted dispersion curves are dashed, and the still water ones are solid. The white-to-red color scale is logarithmic.

The figure prompts a number of observations. First, the influence of the near-surface current on the wave signal within the spectrum becomes clearly visible by comparing the still water and Doppler-shifted dispersion curves in both graphs. The curves that account for the current coincide almost perfectly with the distinct local peaks of spectral energy. Second, it is noteworthy that short waves experience a much stronger Doppler shift than long ones, which is why they are particularly important for MR near-surface current retrieval (see Fig. 4a). Third, a wave signal can be observed over a broad range of frequencies (Fig. 4a) and directions ($\theta = \arctan k$; Fig. 4b). The requirement of sufficient directional spread is thus fulfilled. And, finally, while the dominant signal is located on the fundamental mode dispersion curves, group line and higher harmonic contributions are also visible.

b. Adaptations to shipboard applications

The standard MR near-surface current analysis method revisited in the previous subsection treats the radar backscatter recorded during each antenna rotation like a spatiotemporal “snapshot” of the sea surface (Young et al. 1985a; Senet et al. 2001). This means, the data are processed with the assumption that the radar instantaneously scans the sea surface in all directions. The MR platform is then allowed to move during the “sampling gap” that is equal to the antenna rotation period $T_a$. This is clearly a simplification of the real situation, where the MR transmits horizontally narrow pulses of microwaves from a steadily rotating antenna. The radar transceiver is affixed to a platform that may itself be moving at varying velocities. MR images are built from a sequence of such microwave pulses. In a space–time frame of reference, the MR backscatter data therefore resembles a spiral staircase that is tilted in accordance with the ship motion. For fixed platforms, the errors resulting from the snapshot simplification are limited to the time domain, and have proven to be acceptable. This is assuming that the analysis is carried out over a relatively small window of the radar sweep, in which case the maximum error will be only a fraction of $T_a$.

On ships, however, the snapshot assumption may lead to additional errors. For example, an MR image recorded from a ship that was traveling at 6 m s$^{-1}$ will have mapping errors of $\approx 8$ m, given a $T_a$ of $\approx 1.4$ s. In the context of MR near-surface current retrieval, such seemingly small errors (of the order of a single range resolution cell) will have a significant impact on the results. Under the snapshot assumption, ship heading changes that occur during the period of an antenna rotation lead to mapping errors that are even more important: at maximum range ($\approx 4$ km), a 1° heading change results in a mapping error of $\approx 70$ m. Bell and Osler (2011), who used shipboard MR data to retrieve coastal bathymetry, suggest that inaccuracies in their ship heading measurements degraded the higher-frequency
wave signal to such extent that a current fit was no longer possible.

Another issue is that the standard MR near-surface current retrieval method uses a platform-based coordinate frame. This means, on ships the analysis windows are positioned at a constant range and angle relative to the bow. To determine the near-surface current, the known ship motion is simply subtracted from the radar-derived encounter current (i.e., the sum of ship motion and near-surface current) (Young et al. 1985a; Senet et al. 2001). This approach may further deteriorate the MR near-surface currents, because our assumption of a spatially homogeneous and temporally stationary wave field is fulfilled only if the ship assumes a steady speed and heading throughout the entire analysis period (of the order of minutes). In real sea conditions this is nearly impossible, since the ship will always experience some yaw under wave and current loading. What is more, any course change undertaken during a measurement period will severely degrade a near-surface current measurement, if not render it useless.

To overcome the numerous inaccuracies associated with the standard approach, we decided to forgo the traditional ship-based reference frame and, instead, georeference our radar backscatter data. A comparable approach has already been adopted by Bell and Osler (2011) as part of their shipboard MR bathymetry retrieval and by Ludeno et al. (2014), who retrieved surface wave information. However, neither study did away with the snapshot simplification, which we believe is necessary for accurate near-surface current retrieval. To this end, we use the navigation data (longitude and latitude) from the ship’s GPS receiver and heading at high temporal resolution (1 s), making sure that all instruments (MR, GPS, and compass) are synchronized with the ship network's time server. (Note that this article’s main subject, the heading correction technique, is instrumental for accurate mapping of the MR backscatter measurements, as will become clear in section 4.)

We then use linear interpolation techniques to estimate time, heading, and position for every radar pulse. Subsequently, we trilinearly interpolate our raw polar backscatter data to Cartesian coordinates, accounting for each polar grid point’s location (in geographic coordinates) and time. We do not yet consider the ship’s pitch and roll. This could be done in the future using either a shipboard GPS-based attitude-measuring system or a conventional motion pack (Hill 2005). The output grid size we chose for our trilinear interpolation matches the range sampling resolution $\delta_r$ in space $(x, y)$ and the mean $T_a$ in time. The image sequences that result from this operation are subsequently used within the Fourier analysis that ultimately yields our near-surface current estimates. In contrast with the standard method, our results are fully attributed to the near-surface current, since the georeferencing effectively removes the ship motion.

The georeferencing of our shipboard MR data through trilinear interpolation eliminates all of the issues that were raised above. We no longer make the snapshot simplification, and course changes—assuming the navigation data are accurate—no longer have detrimental effects on the results. In addition, georeferencing has the advantage that aliasing is greatly reduced. Finally, note that our shipboard MR currents correspond to a spatiotemporal average over the entire radar FOV (here, $\sim$2 km in all directions from the radar antenna) and analysis period ($\sim$12 min). Our results are thus representative of a larger area when the ship is underway than when it is stationary.

c. Effective depth of measurements

The observed current is a superposition of tidal currents, geostrophic currents, wind drift, and wave-induced currents (i.e., Stokes drift) (Alpers et al. 1981b). The wave signal’s Doppler shift is induced by the near-surface current down to the waves’ penetration depth, which is approximately half the waves’ wavelength (Dean and Dalrymple 1991). For high-frequency (HF) radar, Stewart and Joy (1974) show that the current measurement is a weighted mean current over the upper layer of the ocean. Their result has been extended by Young et al. (1985a) to consider the full current vector. Assuming a current that is small compared with the wave speed, the current-induced Doppler shift can be expressed as

$$ \hat{U}(k) = 2k \int_0^h U(z) \exp(-2kz) \, dz, \quad (5) $$

where $U(z)$ is the near-surface current as a function of the vertical coordinate $z$. For the special case of a linear current profile, it can be shown that the radar senses the current at an effective depth of $(2k)^{-1}$, or about 7.8% of the ocean wavelength (Stewart and Joy 1974). If the current profile is logarithmic, then the radar probes the current at an effective depth of approximately 4.4% of the ocean wavelength (Ha 1979). For example, the effective depths of MR currents derived from ocean waves with lengths of 50 and 30 m are 3.9 and 2.3 m, respectively, for a linear profile, or 2.2 and 1.3 m, respectively, if the profile is logarithmic. In principle, MR imagery can therefore be used to determine near-surface vertical current shear, as has already been demonstrated for multifrequency HF radars (e.g., Teague 1986).
The least squares analysis proposed by Young et al. (1985a) and further developed by Senet et al. (2001) uses data from all wavenumbers. Their depth-integrated current is therefore an average over the exp(−2kz) weighting functions (5) for the wavenumbers that contain energy above some threshold. Young et al. (1985b) report that during their experiment near the German island of Sylt, most energy was concentrated in the band \( k = 0.10–0.15 \text{ rad m}^{-1} \). This observation led them to conclude that the current sensed by the radar is representative of values in roughly the upper 6 m of the ocean.

The uncertainty as to what depth the MR near-surface current estimates correspond to is an important point of criticism. In this work, we partially address this issue by reporting \( \mathbf{U} \) for a specific wavenumber, which we chose to be 0.225 rad m\(^{-1} \) (i.e., a wavelength of 28 m). For a linear (logarithmic) profile, the resulting current corresponds to an effective depth of 2.2 m (1.2 m). This choice of effective depth (or wavenumber) is a sensible compromise between the need for a high signal-to-noise ratio, on the one hand and a Doppler shift that is sensitive to small current speed changes, on the other hand (the signal-to-noise ratio tends to decrease with wavenumber, while the strength of the Doppler shift increases). The details of our method are beyond the scope of this article and will be covered in a forthcoming paper, where we explore the possibility of measuring MR near-surface vertical current shear (B. Lund et al. 2015, manuscript submitted to J. Geophys. Res. Oceans, hereafter L15; which discusses a new technique for the retrieval of near-surface vertical current shear from marine X-band radar images).

3. Data overview

The data used for this study were collected during the Impact of Typhoons on the Ocean in the Pacific (ITOP) experiment, which took place in the western North Pacific from August to October 2010. The multi-institutional ITOP program coordinated meteorological and oceanic observations from a broad range of platforms, including several ships, two C-130 aircraft, a DOTSTAR Astra, a moored buoy array, two Extreme Air–Sea Interaction (EASI)/Air–Sea Interaction Spar (ASIS) buoy pairs, and a variety of drifters. The program also had a significant satellite and modeling component. As its name suggests, ITOP aims to investigate the impact of tropical cyclones on the ocean, with a special emphasis on the ocean’s long-term recovery from storm-induced cold wakes. Detailed measurements of three typhoons and their ocean interactions were made during the experiment (D’Asaro et al. 2014).

Our focus lies on data we collected from R/V Roger Revelle during the EASI/ASIS deployment and recovery cruises in August (RR1010) and October (RR1015) 2010. The two buoy pairs were deployed in the Philippine Sea, east of Taiwan, at 21.28°N, 126.88°E (5450-m depth) and at 19.68°N, 127.38°E (5500 m). At both sites, a 60-m wire rope tethered an ASIS to an EASI buoy that was moored to the seabed (Grabert et al. 2000; Drennan et al. 2014). Because of heavy weather during RR1015 (it coincided with Typhoon Chaba), the buoys could not be recovered until March 2011. Figure 5 shows a map of the ship tracks during the two cruises. The gray crosses indicate the two EASI/ASIS sites. The mooring sites were also the locations of four CTD casts (one at the northern site and three at the southern site). The map includes bathymetric information from IOG et al. (2003). During most of the ITOP experiment, R/V Roger Revelle was based in Kaohsiung, Taiwan. Figure 6a shows a picture of R/V Roger Revelle in Kaohsiung harbor.

R/V Roger Revelle is equipped with two MR systems, one for navigation and one for science. Here, we use the science MR, which was installed in June 2010. The science MR is located on the main mast above the pilot house, just under the navigation radar (see Fig. 6b). The reason for a designated science MR is that oceanographic applications such as ocean wave and near-surface current retrieval require that the radar be operated in short-pulse mode, in order to achieve a sufficiently high range resolution. This cannot always be guaranteed if the navigation MR is used.

The science MR is a Furuno FAR2117BB that was set to operate at a pulse length of 0.07 µs (i.e., short-pulse mode), providing a range resolution of 10.5 m. It has an 8-ft antenna with an antenna rotation period \( T_a \) of \( \sim 1.4 \text{ s} \).
and a pulse repetition frequency of 3 kHz. The antenna’s horizontal beamwidth is 0.75° (the MR range and azimuth resolution improve with a shortened radar pulse and a lengthened antenna, respectively). It is operating at 9.4 GHz (X band) with HH polarization and grazing incidence angle. Like any conventional MR, it is fitted with a logarithmic amplifier to increase the video signal’s dynamic range.

The science MR was connected to a WaMoS radar data acquisition board by OceanWaveS. WaMoS consists of an analog-to-digital converter, a personal computer for data storage and analysis, and a screen to display results (Dittmer 1994; Ziemer 1994). To capture backscatter intensity images, the system requires four signals from the radar transceiver: (i) a heading marker, which signals each full revolution of the antenna; (ii) a trigger pulse, signaling the emission of a microwave beam; (iii) a bearing pulse, carrying information on the antenna look direction; and (iv) the demodulated, logarithmically compressed video signal. Figure 7 shows a diagram of the WaMoS hardware and data flow.

WaMoS was set to store the logarithmically amplified radar return over a range from 247.5 to 2152.5 m at a sampling frequency of 20 MHz. On average, the system sampled the backscatter from 1/3.5 microwave pulses transmitted by the radar. The resulting polar MR images have a cell size of 7.5 m in range (δ_r) and ~0.3° in azimuth. The radar return is captured at a 12-bit image depth, that is, digitized backscatter intensities range from 0 to 4095. The measured backscatter intensities were not radiometrically calibrated, which is typical for conventional MRs. The radar’s technical specifications and WaMoS settings are summarized in Table 1.

Two ADCPs, the Ocean Surveyor 75 kHz (OS75) and the Narrowband 150 kHz (NB150), both manufactured by Teledyne RD Instruments, are mounted on the hull of R/V Roger Revelle. The University of Hawaii Data Acquisition System (UHDAS) acquires the ADCP data and processes them using the Common Ocean Data Access System (CODAS) (Firing and Hummon 2010). The CODAS processing, which includes transforming the measured current speeds from instrument to Earth coordinates and removing the ship motion, yields the final product, that is, the ocean velocity as a function of depth. Here, we use the NB150, which provides higher range resolution than the OS75 and is therefore well suited for studying the upper ocean. Depending on its mode of operation, NB150’s depth bins range from 21 to 413 m, in 8-m increments, or from 19 to 215 m, in 4-m increments.

Last, both WaMoS and the ADCPs require navigation parameters. Heading information is obtained from both a Sperry MK-37 MOD D/E gyrocompass and an Ashtech ADU-2 GPS-based 3D position and attitude determination system. Ship position data come from a Trimble GPS receiver.
TABLE 1. MR and WaMoS technical specifications for the installation on R/V Roger Revelle.

<table>
<thead>
<tr>
<th>MR/WaMoS parameter</th>
<th>Value</th>
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<tr>
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<tr>
<td>WaMoS sampling range (m)</td>
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</tbody>
</table>

4. Near-surface current calibration

Section 4a reviews the existing knowledge of how heading errors affect shipboard ADCP measurements, and it demonstrates that shipboard MR currents are equally dependent on accurate heading. In section 4b, borrowing from the shipboard ADCP community’s expertise, we introduce a heading correction scheme that is based on multiantenna GPS measurements. Section 4c discusses the water-track calibration that corrects for any remaining (constant) heading offsets. The heading correction technique proposed here is directly analogous to an approach that is well established within the shipboard ADCP community. Readers who are familiar with this methodology (and not interested in the radar-specific adaptations) may therefore wish to skip to section 5.

a. Shipboard current retrieval’s dependency on heading

For shipboard ADCPs, it has long been known that their measurements of water velocity over ground require highly accurate ship heading data (e.g., Pollard and Read 1989). This is because heading errors induce a spurious cross-track current,

\[ U_\perp = U_s \sin \theta_e, \]  

that is proportional to the ship speed (through the water) \( U_s \) and the sine of the error angle \( \theta_e \). The resulting along-track error is given by

\[ U_\parallel = U_s (1 - \cos \theta_e) \]  

and typically negligible. For example, R/V Roger Revelle has a transit speed of 11.7 kt, where 1 kt = 0.51 m s\(^{-1}\). For underway data, a bias of only 1° in the ship’s heading sensor introduces an error of 0.1 m s\(^{-1}\) (i.e., 1.7% of the ship’s speed) in the cross-track component of the current. In contrast, \( U_\parallel \) is only 0.001 m s\(^{-1}\). While gyrocompasses are very reliable (i.e., they provide periodic measurements independent of outside conditions like weather or GPS satellite availability), they have been shown to be insufficiently accurate for shipboard ADCP applications. In their shipboard ADCP manual, Firing and Hummon (2010) suggest that heading sensors must provide \( O(0.1°) \) accuracy. This would limit heading-related errors aboard research vessels to ~1 cm s\(^{-1}\).

However, the errors of conventional mechanical gyrocompasses can be 2°–3° or more. Moreover, they vary with latitude, heading, and ship speed. A detailed discussion of the principles of operation and errors of gyrocompasses can be found in Bowditch (2002).

King and Cooper (1993) and Griffiths (1994) propose a ship heading correction method that uses multiantenna differential GPS carrier-phase measurements. They found that GPS-based attitude-measuring systems, though not as reliable as gyrocompasses, can provide the desired heading accuracy of 0.1° or better. The Ashtech system on R/V Roger Revelle, which is based on differential carrier-phase measurements between four antennas, provides attitude angles (i.e., heading, pitch, and roll) as accurate as one milliradian (0.057°) or better (Thales Navigation 2000). For an in-depth description of the GPS interferometric attitude and heading determination, the reader is referred to Van Graas and Braasch (1991). Potential error sources are discussed by Firing and Hummon (2010).

For shipboard ADCP measurements, it is now common practice to determine heading using at least one gyrocompass and one multiantenna GPS compass (Firing and Hummon 2010). In the following, we present a sensitivity study to demonstrate that an accurate ship heading signal is equally crucial for the MR near-surface current retrieval as it is for ADCP measurements. We selected a ~2-h period during which R/V Roger Revelle made a maneuver that was followed by a course change. Before the maneuver the ship was traveling approximately north at 5 m s\(^{-1}\), afterward it went at full steam (~6 m s\(^{-1}\)) on a westward course. To assess the sensitivity to ship heading, we introduced constant offsets from ~2° to 2°, stepped in 1° increments, into the multiantenna GPS-corrected gyrocompass measurements (details on the correction are given in the following subsection). The resulting five cases were subjected to our near-surface current retrieval analysis (see section 2).

Figure 8a shows a time series of the MR near-surface current retrieval results for our five cases. The results were rotated to a ship coordinate system; that is, the cross- and along-track (or port–starboard and fore–aft, respectively) current components are shown. Each near-surface current estimate was obtained from ~6 min of
radar data (all subsequent MR current results were determined with an analysis period of 12 min). The ship maneuver that separated the northward from the southward course lasted for about 20 min, starting at 0.75 h. The cross-track currents vary significantly with the offsets, and the errors increase linearly with ship speed. At full speed the error is 0.1 m s\(^{-1}\) (1°)\(^{-1}\) offset. The along-track current remains largely unaffected by the offsets. The solid lines in the graph show the errors we would expect according to (6) and (7), which are in excellent agreement with the actual measurements. (The near-surface current was not accounted for in the error projections, which explains some of the remaining differences.) The MR current retrieval thus obeys the same heading error equations as shipboard ADCPs.

Figure 8b shows a time series of the same current data but as speed and direction in an Earth reference frame. In addition, as a first-order reference, the figure shows (heading corrected and calibrated) shipboard ADCP data from the 21-m bin, which is the closest to the surface. The figure exemplifies to what extent heading errors contaminate the MR near-surface current record. The ADCP data show best agreement with the MR results for the 2°-offset case, suggesting the possibility of a misalignment in the radar or heading sensor reference frame relative to north. This issue will be explored further in section 4c. The difference in current speed, most notable in the first half of the study period, may be explained by the fact that MR and ADCP measure the current in different layers of water.

b. Gyrocompass correction by multiantenna GPS

On R/V *Roger Revelle*, the gyrocompass signal is logged at 1 Hz with 0.1° precision. The Ashtech system’s measurements are stored at the same rate as the gyrocompass signal, but with a precision of 0.01°. In addition to heading, pitch, and roll, the multiantenna GPS provides the attitude-phase measurement and baseline length root-mean-square errors (mrms and brms, respectively) as quality control parameters. Here, data points with mrms and brms values greater than the Ashtech-recommended thresholds of 5 mm and 3.5 cm, respectively, were disregarded (Thales Navigation 2000). In addition, measurements where pitch or roll had values greater than 5° were discounted. This threshold is based on the histograms of these parameters, following King and Cooper (1993). As a result of this quality control, 17.5% of the Ashtech data from cruises RR1010 and RR1015 were sorted out. During RR1015, a 40-min period had to be flagged manually due to abnormal variability in the gyro–Ashtech heading differences. Another 12-min period was flagged due to a sudden jump in the Ashtech data that was followed by a slow drift back to normal. Last, for a 4.5-h period during RR1015, no Ashtech data were available.

As the previous paragraph made clear, the more accurate multiantenna GPS data are not always available. For the two cruises considered here, 25.7% of gyrocompass measurements were lacking a GPS-based counterpart. This is why the Ashtech system cannot fully replace the gyrocompass. Figure 9 shows a time series of the gyro–Ashtech heading differences covering both cruises. On top of the instantaneous data, the

![Figure 8](image-url)

**Fig. 8.** Time series of MR near-surface current retrieval results for varying ship heading offsets. (a) Results and projection estimates in ship coordinates. (b) MR and ADCP current speeds and directions in Earth coordinates. The data correspond to a 2-h period starting at 0630 UTC 31 Oct 2010.
constant. This means α needs to be determined just once, but accurately. To determine α, we adopt the water-track calibration technique proposed by Joyce (1989) for shipboard ADCP. Note that this method is completely independent of any external current information.

The MR-derived near-surface current components in Earth coordinates (x, y) are

\[
\begin{align*}
    u_w &= u_x + u'_d \cos \alpha - u'_y \sin \alpha \\
    v_w &= v_x + u'_d \sin \alpha + u'_y \cos \alpha.
\end{align*}
\]  

(8)

Here, \((u'_d, v'_d)\) represent the measured velocity components in the radar’s \((x', y')\) coordinate frame, which is rotated counterclockwise by the unknown angle \(\alpha\) from the \((x, y)\) frame. The subscripts \(w, s, d\) and \(d\) are used to denote water, ship, and Doppler, respectively. Note that, for simplicity, we dropped the tilde that we used in section 2 to indicate that MR currents are a function of wavenumber [which can be related to an effective depth via (5)]. Finally, remember that we georeferenced our MR images (see section 2). For (8) to be valid, we therefore need to subtract \((u_s, v_s)\) from \((u'_d, v'_d)\).

For the water-track calibration to work, we must assume that the near-surface current velocity before and after a ship maneuver (i.e., a course change, acceleration, or deceleration) remains the same to within some noise level \(\varepsilon\):

\[
\begin{align*}
    u_w &= \langle u_w \rangle + \varepsilon_x \\
    v_w &= \langle v_w \rangle + \varepsilon_y,
\end{align*}
\]  

(9)

where the angle brackets denote the ensemble average of the pre- and postmaneuver measurements. The idea is to determine the \(\alpha\) that minimizes the difference in the near-surface current velocity before and after the ship maneuver. Now let us define

\[
\delta u = u - \langle u \rangle
\]  

(10)

for each of the velocity components in (8). Using (9), we obtain

\[
\begin{align*}
    \delta u_w &= \delta u_x + \delta u'_d \cos \alpha - \delta u'_y \sin \alpha = \varepsilon_x \\
    \delta v_w &= \delta v_x + \delta u'_d \sin \alpha + \delta u'_y \cos \alpha = \varepsilon_y.
\end{align*}
\]  

(11)

The goal is to solve (11) such that \(\varepsilon^2 = \varepsilon_x^2 + \varepsilon_y^2\) is minimized. Taking the dot product of (11) with itself yields an equation for \(\varepsilon^2\). The least squares estimator for \(\alpha\) is subject to the condition that

\[
\frac{\partial \langle \varepsilon^2 \rangle}{\partial \alpha} = 0,
\]  

(12)

c. Water-track calibration

The in situ calibration of shipboard ADCPs requires determining errors of two types: sensitivity and alignment. Sensitivity errors arise due to small errors in the beam geometry. If a multiantenna GPS-based heading correction is implemented, then the alignment error \(\alpha\), as per its name, corresponds to an error in the orientation of the ADCP transducer/multiantenna GPS relative to the true heading. There is no MR equivalent to the sensitivity error. The calibration of shipboard MR near-surface current measurements thus requires determining \(\alpha\) only. It corresponds to an unknown error in the radar/multiantenna GPS reference frame. Assuming solid radar and heading sensor installations, \(\alpha\) is
which finally yields the desired alignment error:

\[
\tan \alpha = \frac{(\delta u_x' \delta u_y - \delta v_x' \delta v_y)}{(\delta u_x' \delta u_y + \delta v_x' \delta v_y)}. 
\]

(13)

Individual estimates for \(\alpha\) tend to be noisy, since our assumption of a current that remains unchanged during the calibration period is not always true. However, assuming good MR and heading measurements, the noise is random and the errors will average out.

We limited our water-track calibration to cruise RR1015. Calibration opportunities arise during ship maneuvers that are preceded and followed by a steady course for at least one analysis period (\(\sim 12\) min). Using the navigation data, we identified a total of 18 such opportunities during RR1015. Of the 18 opportunities, 2 were excluded from the ensemble average, since their respective \(\alpha\) estimates differed from the mean by more than four standard deviations. In the following analysis, we use the ensemble average of all (valid) \(\alpha\) values, which is \(2.21^\circ\) with a standard deviation of \(0.50^\circ\). This means that the radar coordinate frame needs to be rotated counterclockwise by an angle of \(2.21^\circ\). It is difficult to determine which of the two systems—multiantenna GPS or MR (or both)—is responsible for this error. However, a constant offset of this magnitude is perfectly plausible. For example, a GPS antenna array might inadvertently get “bumped” out of its original position (Firing and Hummon 2010). Finally, note that this calibration result is in good agreement with our sensitivity study, where we observed qualitatively that the MR and reference ADCP data are in best agreement if a \(2^\circ\) bias is introduced in the heading data (section 4a; Fig. 8b).

5. Results and discussion

In the following, our shipboard MR near-surface current estimates are validated using concurrent measurements from the NB150 shipboard ADCP. Here, the MR near-surface current estimates were retrieved from surface waves with a length of \(\sim 28\) m, corresponding to an effective depth of \(2.2\) m (\(1.2\) m) for a linear (logarithmic) profile (see section 2c). The ADCP measurements stem from the topmost bin at a depth of \(21\) m. As discussed in section 4, the MR results were obtained using a multiantenna GPS-corrected heading signal. Furthermore, a \(2.21^\circ\) alignment error was removed from the heading measurements. The CODAS processing of shipboard ADCP data includes a similar heading correction, as well as sensitivity and alignment error corrections. We screened the ADCP velocities for egregious outliers, which resulted in the removal of 24 out of a total of 4150 measurements. In contrast, all MR near-surface current results are included in the analysis.

Figure 10 shows a time series of the MR and ADCP current speed and direction for RR1010 (from 1200 UTC 5 Aug 2010 until 0540 UTC 11 Aug 2010) and RR1015 (from 1935 UTC 26 Oct 2010 until 1300 UTC 31 Oct 2010). Each MR data point represents \(\sim 12\) min; the ADCP data are 10-min averages.

Scatterplots and comparison statistics for the same MR and ADCP currents are shown in Fig. 12. For a total of 1153 data pairs, the standard deviations of the current speed and direction differences are \(0.09\) m s\(^{-1}\) and \(30.17^\circ\) with negligible biases of \(0.02\) m s\(^{-1}\) and \(-2.43^\circ\), respectively. The correlation coefficient of 0.93 for the current speeds, and the mean directional difference length of 0.90 for the current directions confirm good MR–ADCP agreement. (The mean directional difference length is the length of the vector mean of the set of unit vectors, each of which is oriented by the difference in angles between the two series; a value of 1 means perfect correlation and 0 means no correlation at all.) A rotary spectral analysis by L15 of acoustic Doppler velocimeter measurements from the southern ASIS buoy
shows the presence of strong baroclinic tidal and inertial motions. The amplitude of near-inertial motions is nearly constant within the mixed layer but decreases rapidly below (e.g., Weller 1982). These observations indicate that the circulation in the study area is driven by nonlocal dynamics that are homogeneous in the upper-ocean mixed layer.

Despite the overall good agreement between the MR and ADCP currents, some differences exist. In what follows we investigate physical explanations for the MR–ADCP differences. In contrast to the large-scale flow, the (typically relatively weak) instantaneous wind- and wave-driven currents are much stronger at the near surface sampled by the MR than at the ADCP’s shallowest subsurface bin. Figure 13 shows a time series of the MR–ADCP current differences in terms of speed and direction. It also includes the corresponding sonic anemometer wind measurements from R/V Roger Revelle, adjusted to 10 m above the sea surface. The near- and subsurface difference flow is generally weak compared with the total flow, and it tends to go to the right of the wind, in agreement with Ekman dynamics (Ekman 1905). Hence, differences between the MR and ADCP measurements can for a large part be explained by wind- and wave-induced current shear. The MR–ADCP difference flow displays 1.5 clockwise rotations during the first 2 days of RR1010. These are most likely inertial motions (at 19.68°N, the latitude of the southern EASI/ASIS site, the inertial period is 35.54 h). The near- and subsurface differences at this early stage of the experiment are due to a relatively shallow mixed layer (as discussed further in the next paragraph). The fact that the MR currents correspond to an area, while the corresponding ADCP data were acquired along a transect through only parts of that area, may explain further differences between the two datasets.

If we look at the comparison statistics for the two cruises separately, they improve for RR1015 and deteriorate for RR1010. For the RR1015 current speed and
direction differences, the standard deviations are 0.08 m s\(^{-1}\) and 17.42\(^{\circ}\), with a correlation coefficient of 0.96 and a mean directional difference length of 0.96, respectively. For RR1010, the standard deviations are 0.10 m s\(^{-1}\) and 36.30\(^{\circ}\), with a correlation coefficient of 0.92 and a mean directional difference length of 0.86, respectively. One explanation might be that the alignment error, that we determined using data from RR1015 only, had changed between the two cruises. However, our analysis of the gyro–Ashtech differences (see section 4b; Fig. 9) does not indicate any significant changes. Instead, we believe that the differences in the RR1015 and RR1010 comparison statistics are due to different stratifications. Stratification is relevant for determining how deep wind-induced currents can penetrate the upper ocean (Ralph and Niiler 1999). Figure 14 shows representative CTD profiles of temperature and salinity from each of the two cruises. The CTD cast from RR1015 yielded nearly constant temperature and salinity values around 27.5\(^{\circ}\)C and 34.45 PSU up to a depth of ~60 m, respectively, leaving no doubt that the MR and ADCP sampled the same well-mixed body of water. This high degree of mixing can be explained by the recent passage of Super Typhoon Megi and other tropical cyclones. In contrast, during RR1010 both temperature and salinity differ significantly between the 21-m bin sampled by the ADCP and the near-surface waters sensed by the MR.

6. Summary and conclusions

Shipboard MR near-surface currents complement ADCP measurements, which typically start at a greater depth. They offer a unique opportunity to improve both navigational security and our understanding of air–sea interaction processes. Our shipboard MR near-surface current retrieval method is largely based on a method that was first proposed by Young et al. (1985a) and later refined by Senet et al. (2001). However, to improve performance on ships, we account for the horizontal ship motion and heading changes that occur during a radar sweep by georeferencing each radar pulse; that is, we
make away with the assumption that the ship and sea surface are static during the time required for one antenna rotation. Also, while previous investigators used a broad range of wavenumbers to obtain their MR near-surface current estimates, ours were made from surface waves with a length of \( \sim 28 \text{ m} \). This allows us to better estimate the currents’ effective depth, which is 2.2 m for a linear profile or 1.2 m for a logarithmic profile.

This article introduces a new heading correction method for shipboard MR near-surface current meters. We showed that shipboard MR current retrieval requires a highly accurate heading signal. Small offsets in the ship heading may lead to significant errors in the current estimates’ cross-track component. The error is proportional to the ship speed and the sine of the error angle. For a ship that is steaming at 6 m s\(^{-1}\), a heading bias of only 1° results in a cross-track current error of 0.1 m s\(^{-1}\). The same dependency on accurate heading exists for shipboard ADCP (Joyce 1989; King and Cooper 1993).

To limit the error to \( \sim 1 \text{ cm s}^{-1} \), a heading sensor accuracy of \( O(0.1°) \) is required. Gyrocompass measurements are highly reliable but insufficiently accurate for shipboard MR current retrieval. While multiantenna GPS-based heading sensors are not as reliable as gyrocompasses, they reach the desired accuracy. The heading correction requires two heading sensors: a gyrocompass to ensure a continuous signal and a multiantenna GPS for accuracy. The quality-controlled multiantenna GPS signal is used to remove biases within the gyrocompass signal. Gaps are filled using linear interpolation. Remaining constant offsets in the heading signal are identified by water-track calibration. This calibration technique is based on the assumption that the near-surface current velocity before and after a ship maneuver remains unchanged. The alignment error \( \alpha \) is obtained by minimizing the difference in the near-surface current velocity before and after the maneuver. The assumption of a constant ocean velocity pre- and post-maneuver is not always true, but the resulting noise averages out if \( \alpha \) is determined multiple times.

A heading correction technique similar to the one proposed here for MR has long been put into practice by the shipboard ADCP community. In fact, our approach follows the work of Firing and Hummon (2010), who developed and maintain the well-established UHDAS + CODAS shipboard ADCP data acquisition and processing packages. We applied the heading correction to MR data that were acquired from R/V Roger Revelle during two cruises as part of the 2010 ITOP field campaign in the Philippine Sea. We found that our multiantenna GPS-corrected gyrocompass signal was offset by \( \alpha = 2.21° \). To remove this error, the radar coordinate frame needed to be rotated counterclockwise by an angle of 2.21°.

We used shipboard ADCP measurements from the topmost bin (21 m) to validate our MR-retrieved near-surface currents. For a total of 1153 MR–ADCP data pairs, we found the standard deviations of the current speed and direction to be 0.09 m s\(^{-1}\) and 30.17°, respectively, with high correlations and negligible biases. This good agreement is due to the fact that the currents in the study area are driven by large-scale tidal and inertial motions. Differences between the near- and subsurface measurements were shown to be mostly due to wind- and wave-induced vertical current shear.

To conclude, our results indicate that shipboard MRs can yield reliable and accurate near-surface currents, provided that the proposed improvements to the shipboard MR current retrieval are implemented, and our heading correction technique is employed. We hope that, in the future, these techniques will be adopted by the existing operational shipboard MR current retrieval systems. Once they become common practice, efforts can be focused on improving our understanding of the air–sea interaction processes driving the observed near-surface currents. For example, one of the research questions we intend to address in the future concerns the influence of tropical cyclones on upper-ocean circulation.

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REFERENCES


