Vertical Current Shear Retrieval from Shipboard Marine X-band Radar

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Outline

1. Data Overview

2. Radar-based Near-surface Vertical Current Shear Measurement Principles


4. Results from ITOP Field Campaign
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1 Data Overview

2 Radar-based Near-surface Vertical Current Shear Measurement Principles

3 Shipboard Marine Radar Near-surface Current Profiling Methodology

4 Results from ITOP Field Campaign
A science marine radar (MR) system consists of a standard navigation X-band (9.4 GHz) radar that is connected to a PC equipped with a data capture board and analysis software (e.g. WaMoS).

System hardware:

Radar antennas:

R/V Roger Revelle:

Cruise tracks and mooring locations:
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Quasi-Eulerian and Wave-induced Current

The radar-based current is a superposition of a quasi-Eulerian (wind drift, tidal, geostrophic, and inertial motions) current \( U_E \) and a wave-induced current \( U_{Sf} \) (Ardhuin et al. 2009):

\[
U_R = U_E + U_{Sf}.
\]

\( U_E \) for deep water linear waves is (Stewart and Joy 1974):

\[
U_E(k_D) = 2k_D \int_0^h U(z) \exp(-2k_D z) dz.
\]

\( U_{Sf} \) is given by:

\[
U_{Sf}(k_D, \theta_D) \simeq U_{SS}(f_D) \cdot e_{\theta_D} + 4\pi k_D \int_{f_D}^{\infty} \int_0^{2\pi} f \cos(\theta - \theta_D) E(f, \theta) d\theta df.
\]

\( U_{SS} \) is the Stokes drift vector for waves with frequencies up to \( f_D \):

\[
U_{SS}(f_D) = 4\pi \int_0^{f_D} \int_0^{2\pi} f k(f) E(f, \theta) df d\theta.
\]
Effective Depth

Depth weighting function for $U_E$:

$U_E$ represents a weighted-mean of the upper ocean currents.

Linear current profile:
Effective depth is 7.8% of ocean wave length

Logarithmic profile: 4.4%
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[Wave and] Current Analysis

Processing steps:
- Backscatter ramp correction
- Pulse-by-pulse georeferencing and trilinear interpolation
- Standard near-surface current retrieval
- Heading correction and current “calibration”
- From 3D spectral density to SNR
- Current profiling
Backscatter Ramp Correction

Goal: Reduce backscatter dependency on range and azimuth.

12-min averaged radar image:

Corresponding Fourier-fitted ramp:
Backscatter Ramp Correction

Goal: Reduce backscatter dependency on range and azimuth.

12-min averaged radar image:

After ramp subtraction:
Georeferencing and Trilinear Interpolation

Polar radar images are transformed from ship to geographical coordinates and trilinearly (i.e. in space and time) interpolated.

MR image spiral:  

After trilinear interpolation:
Linear dispersion relationship:

\[ \omega = \sqrt{gk \tanh kh} + \mathbf{k} \cdot \mathbf{U} \]

- \( \omega \) Angular frequency
- \( g \) Acceleration due to gravity
- \( k \) Wavenumber
- \( h \) Water depth
- \( \mathbf{k} \) Wavenumber vector
- \( \mathbf{U} \) Current vector
Doppler-shifted 3D Dispersion Shell

Wave energy location in 3D wavenumber-frequency space ("dispersion shell"); with current \((\mathbf{U} = \langle -1, 0 \rangle \text{ ms}^{-1})\):

Linear dispersion relationship:

\[ \omega = \sqrt{gk \tanh kh} + \mathbf{k} \cdot \mathbf{U} \]

- \(\omega\)  Angular frequency
- \(g\)  Acceleration due to gravity
- \(k\)  Wavenumber
- \(h\)  Water depth
- \(k\)  Wavenumber vector
- \(\mathbf{U}\)  Current vector
Aliasing occurs if a signal is temporally undersampled ($\omega > \omega_{Ny}$). Higher harmonics appear mainly due to nonlinearities in the imaging mechanism (Senet et al. 2001).

Dispersion relationship with higher harmonics:

$$S_{p}^{\pm} = \pm (p + 1) \sqrt{\frac{gk}{p+1}} \tanh \left( \frac{k_{h}}{p+1} \right) + k \cdot U$$

Aliasing symmetry conditions:

$$P(k_{x}, k_{y}, \omega) = P(k_{x}, k_{y}, \omega + n\omega_{Ny})$$
$$P(k_{x}, k_{y}, \omega) = P(-k_{x}, -k_{y}, -\omega)$$

$S$  Angular frequency
$p$  Integer for harmonic order
$P$  3D image power spectrum
$n$  Integer for frequency intervals
Spectral Signal of Near-surface Current

Current fit minimizes distance of 3D dispersion shell from wave signal (Young et al. 1985; Senet et al. 2001).

Frequency slice through 3D spectrum (1.12 rad$^{-1}$):

Wavenumber-frequency slice from 3D spectrum ($k_x = 0$ rad m$^{-1}$ and 0 rad m$^{-1} \leq k_y \leq k_{Ny}$):

**Graph 1:**
- Still water
- $U = (0.12, 0.52)$ ms$^{-1}$
- Fundamental mode
- First harmonic
- Second harmonic

**Graph 2:**
- Still water
- $v = 0.52$ ms$^{-1}$
- Fundamental mode
- First harmonic
- Second harmonic
- Group line
Shipboard current measurements require accurate heading data. Errors induce a spurious cross-track current: \( U_\perp = U_s \sin \theta_e \) (Pollard and Read 1989).

In geographic coordinates:

In ship coordinates:
Solution: (1) Correct gyro heading using multi-antenna GPS (King and Cooper 1993), and (2) perform water-track “calibration” to determine (constant) radar–compass misalignment angle (Joyce 1989).

Ship maneuver offering calibration opportunity:

Alignment error: \[ \tan \alpha = \frac{\langle \delta u'_d \delta v_s - \delta v'_d \delta u_s \rangle}{\langle \delta u'_d \delta u_s + \delta v'_d \delta v_s \rangle} \]

<table>
<thead>
<tr>
<th>(u_s)</th>
<th>(v_s)</th>
<th>(\delta u_s)</th>
<th>(\delta v_s)</th>
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<td>-0.164</td>
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<td>-0.089</td>
<td>-2.181</td>
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<td>0.008</td>
<td>0.089</td>
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<table>
<thead>
<tr>
<th>(u'_d)</th>
<th>(v'_d)</th>
<th>(\delta u'_d)</th>
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<tbody>
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<td>-0.135</td>
<td>3.662</td>
<td>-0.001</td>
<td>2.13</td>
</tr>
<tr>
<td>-0.133</td>
<td>-0.597</td>
<td>0.001</td>
<td>-2.13</td>
</tr>
</tbody>
</table>
Background noise as $f(k, \omega)$ is estimated from spectral half with lowest standard deviation of spectral density over $k$. 

(a) 

(b) 

(c) 

(d)
Goal: Identify wave signal over broad range of directions and wavenumbers.

Power thresholding:

SNR thresholding:
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Time series of MR (0.225 radm$^{-1}$ or ~2 m) and ADCP (21 m) currents.
Shipboard Marine Radar versus ADCP Currents II

Scatter plots and statistics for MR–ADCP comparison.

Current speed:

- N = 2391
- r = 0.93
- Bias = 0.01 ms$^{-1}$
- RMS = 0.08 ms$^{-1}$
- $\sigma_{xy} = 0.07$ ms$^{-1}$

Current direction:

- N = 2391
- R = 0.91
- Bias = 0.65°
- RMS = 28.08°
- $\sigma_{xy} = 28.07°$
Example of MR near-surface vertical current shear measurements with WW3-based filtered Stokes drift.
Near-surface Current Profile Examples II

“Parallel flow” and “clockwise forcing”.

REV, 10/22/2010, 04:33:00.4-04:45:11.8 UTC

REV, 10/18/2010, 05:19:03.2-05:31:23.7 UTC
Near-surface Current Profile Examples III

“Counter flow” and “counter-clockwise forcing”.

REV, 08/08/2010, 12:26:34.7-12:38:46.1 UTC


H_s = 2.65 m
U_{ADCP} = 0.58 ms^{-1}
U_{wind} = 12.6 ms^{-1}

H_s = 5.94 m
U_{ADCP} = 0.31 ms^{-1}
U_{wind} = 13.4 ms^{-1}
Near-surface Current Profile Examples IV

“Parallel flow” transitioning f/ “counter-” to “clockwise forcing”; flow reversal.


REV, 08/07/2010, 23:19:34.3-23:31:46.0 UTC
Time series of differences between MR (0.11 rad m⁻¹ or ~4.5 m) and ADCP (21 m) currents.
Choice of Background Current Depth II

Time series of differences between MR (0.11 radm$^{-1}$ or ~4.5 m) and ADCP (101 m) currents.
Stokes and Ekman Drift

Mean background-current-corrected MR profiles.

- Stokes drift
- Radar
- Radar–Stokes drift

Depth [m]

Deflection angle [°]

Speed factor

0.004 0.006 0.008 0.010 0.012 0.014 0.016

-80 -60 -40 -20 0
Conclusions & Outlook

- Compared MR near-surface currents with ADCP reference measurements
- MR currents are in good agreement with reference
- Presented first MR near-surface current profiles
- Near-surface current profiles’ response to wind and wave forcing agrees with our physical expectations (flow to the right of the wind, speed decays, deflection angle increases with depth)

Future work / outlook:

- Determine exact effective depths of near-surface current profiling results through numerical inversion of $U_E(k_D)$
- Validate MR near-surface current profiles, e.g. using drifters
- Apply methodology to further MR data sets to study Stokes drift and Ekman dynamics
Acknowledgment

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References:

Spectral Sensitivity to Currents

Technique’s sensitivity, in terms of wavenumber resolution cells:
Spectral Sensitivity to Bathymetry

Sensitivity to bathymetry:
Mean deviations of MR currents from 5th degree polynomial fit:
Mean SNR across dispersion curve

Mean SNR along lines covering a range of radial distances from the dispersion curve, for different frequencies:

Mean signal-to-noise ratio

Angular frequency [rads⁻¹]

Distance from dispersion curve [waven. res. cells]
Marine Radar Current Shear Measurements

Current shear fit example:

Frequency = 1.729 rads$^{-1}$

Mean signal-to-noise ratios:

- With shear
- Without shear

Wavenumber cells perpendicular from dispersion curve

Mean signal-to-noise ratio
Anemometer winds, sub-surface currents, filtered Stokes drift, and peak wave parameters.
Conventional mechanical gyro compasses are reliable but have errors of $O(1^\circ)$ depending on ship speed, heading, and latitude (Bowditch 2002).

Difference between ASHTECH multi-antenna GPS and gyro compass:

Gyro compass error dependency on heading:
ITOP Experiment


Air-Sea Interaction Spar (ASIS) buoy (Graber et al. 2000):

- CO2 and H2O vapor
- Wind speed and direction
- Marine aerosol
- Air temperature, relative humidity
- Beacon
- Wave wires

Extreme Air-Sea Interaction (EASI) buoy (Drennan et al. 2014):

- Wind speed and direction
- CO2 and H2O (closed and open path)
- Marine aerosol
- Air temperature, relative humidity
- Solar radiation

R/V Roger Revelle with ASIS-EASI buoy pair:

Photo credit: Hans C. Graber
ASIS / EASI graph credit: Henry Potter
Wind-driven currents are heavily affected by stratification (Price et al. 1987; Price and Sundermeyer 1999).

During RR1010 near EASI-N:
20.63°N, 127.43°E; 08/05/2010, 13:12:15 UTC

During RR1015 near EASI-S:

**EASI-S–WW3:**

- Scatter plot
- Parameters:
  - $N = 2641$
  - $r = 0.91$
  - Bias = -0.03 ms$^{-1}$
  - RMS = 0.04 ms$^{-1}$
  - $\sigma_{xy} = 0.03$ ms$^{-1}$

**EASI-N–WW3:**

- Scatter plot
- Parameters:
  - $N = 2809$
  - $r = 0.91$
  - Bias = -0.04 ms$^{-1}$
  - RMS = 0.05 ms$^{-1}$
  - $\sigma_{xy} = 0.03$ ms$^{-1}$
WAVEWATCH III peak wave parameters, 12 August 2010, 12:00 UTC.

Significant wave height, currents (black arrows) and winds (white):

Peak wave period and direction:
JCOPE-T ocean model – a regional tides resolving version of POM (Miyazawa 2012) – output for vertical (color code) and horizontal current (arrows) at 2 m, 12 August 2010, 12:00 UTC.
Time series of ADV (4 m) and ADCP (21.22 m) measurements:
Scatter plots and statistics for ADV–ADCP comparison.

**Current speed:**
- **ADV current speed** [ms$^{-1}$]
- **ADCP current speed** [ms$^{-1}$]
- $N = 2104$
- $r = 0.96$
- Bias = -0.02 ms$^{-1}$
- RMS = 0.07 ms$^{-1}$
- $\sigma_{xy} = 0.07$ ms$^{-1}$

**Current direction:**
- **ADV current direction** [°]
- **ADCP current direction** [°]
- $N = 2104$
- $R = 0.85$
- Bias = -15.33°
- RMS = 41.13°
- $\sigma_{xy} = 38.16$°
Spectral Analysis of ASIS-S ADV Data

Rotary ADV spectra (Gonella 1972); the inertial period is 35.54 h: