Vertical Current Shear Retrieval from Shipboard Marine X-band Radar

[1]Björn Lund, [1]Hans C. Graber, [2]Clarence O. Collins III,
[3]Hitoshi Tamura, and [3]Sergey Varlamov

[1]Rosenstiel School of Marine and Atmospheric Science
University of Miami
[2]Naval Research Laboratory
Stennis Space Center
[3]Yokohama Institute for Earth Sciences
Japan Agency for Marine-Earth Science and Technology

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Outline

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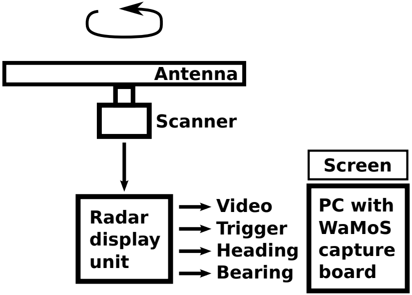
1. **Data Overview**
2. Radar-based Near-surface Vertical Current Shear Measurement Principles
3. Shipboard Marine Radar Near-surface Current Profiling Methodology
4. Results from ITOP Field Campaign

Marine X-band Radar System

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:



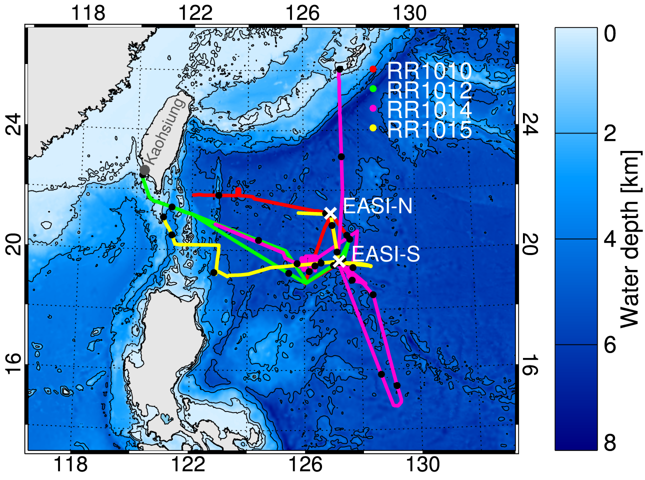
Radar antennas:

R/V Roger Revelle:

ITOP Experiment

Impact of Typhoons on the Pacific (ITOP), western Pacific, 2010.

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 $\mathbf{U}_E$ and a wave-induced current $\mathbf{U}_{Sf}$ (Ardhuin et al. 2009):

$$\mathbf{U}_R = \mathbf{U}_E + \mathbf{U}_{Sf}.$$

$\mathbf{U}_E$ for deep water linear waves is (Stewart and Joy 1974):

$$\mathbf{U}_E(k_D) = 2k_D \int_0^h \mathbf{U}(z)\exp(-2k_D z)\mathrm{d}z.$$

$\mathbf{U}_{Sf}$ is given by:

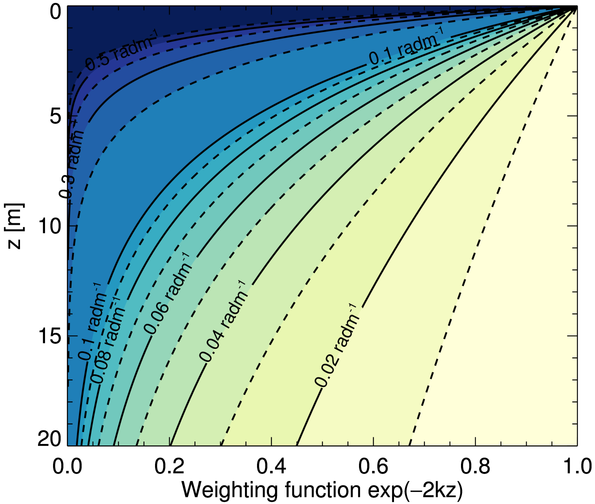
$$\mathbf{U}_{Sf}(k_D, \theta_D) \simeq \mathbf{U}_{SS}(f_D) \cdot \mathbf{e}_{\theta_D} + 4\pi k_D \int_{f_D}^{\infty} \int_0^{2\pi} f \cos(\theta - \theta_D) E(f, \theta) \mathrm{d}\theta \mathrm{d}f.$$

$\mathbf{U}_{SS}$ is the Stokes drift vector for waves with frequencies up to f_D:

$$\mathbf{U}_{SS}(f_D) = 4\pi \int_0^{f_D} \int_0^{2\pi} f \mathbf{k}(f) E(f, \theta) \mathrm{d}f \mathrm{d}\theta.$$

Effective Depth

Depth weighting function for $\mathbf{U}_E$:



$\mathbf{U}_E$ 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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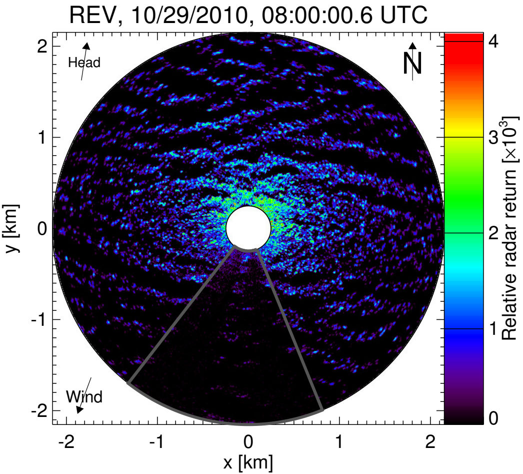
[Wave and] Current Analysis

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

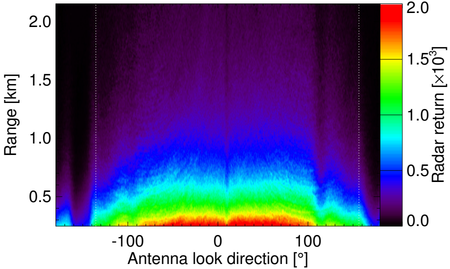
Radar image example:



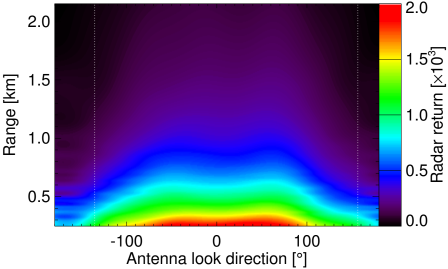
Backscatter Ramp Correction

Goal: Reduce backscatter dependency on range and azimuth.

12-min averaged radar image:



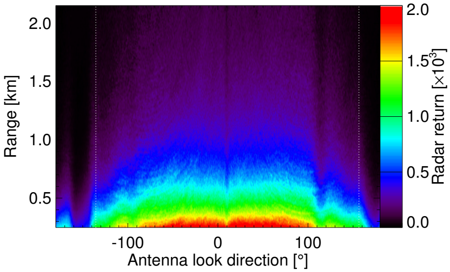
Corresponding Fourier-fitted ramp:



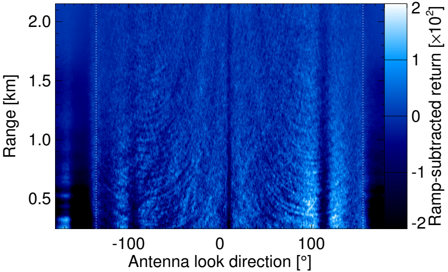
Backscatter Ramp Correction

Goal: Reduce backscatter dependency on range and azimuth.

12-min averaged radar image:



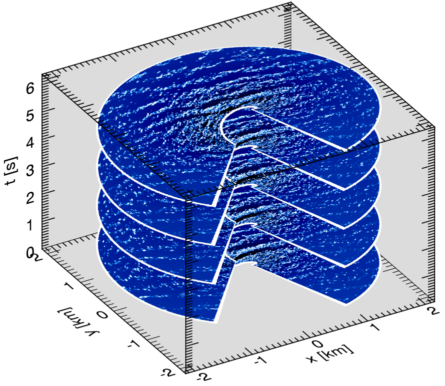
After ramp subtraction:



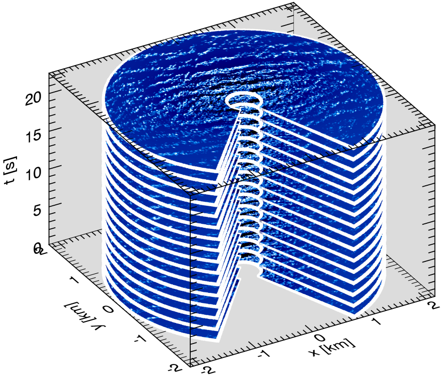
Georeferencing and Trilinear Interpolation

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:



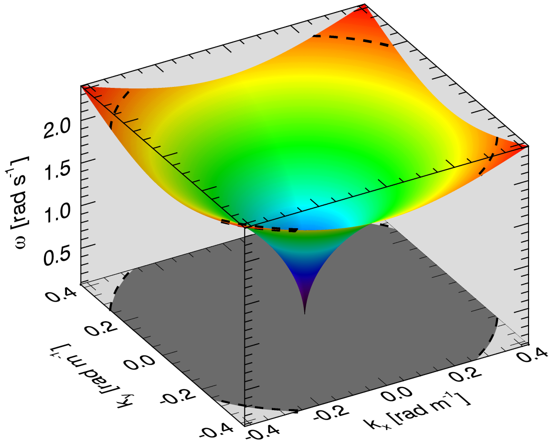
3D Dispersion Shell

Linear dispersion relationship:

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

ω	Angular frequency
g	Acceleration due to gravity
k	Wavenumber
h	Water depth
$\mathbf{k}$	Wavenumber vector
$\mathbf{U}$	Current vector

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



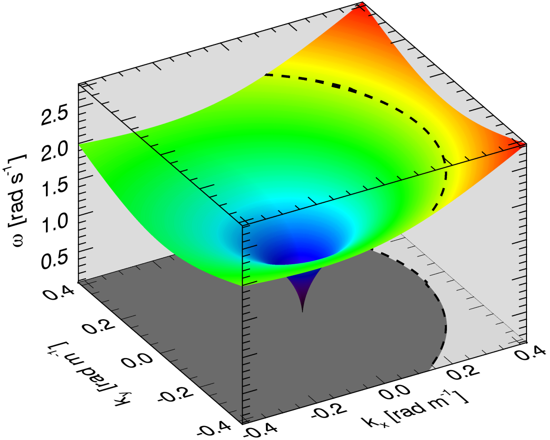
Doppler-shifted 3D Dispersion Shell

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

Linear dispersion relationship:

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

ω	Angular frequency
g	Acceleration due to gravity
k	Wavenumber
h	Water depth
$\mathbf{k}$	Wavenumber vector
$\mathbf{U}$	Current vector



Aliasing & Higher Harmonics

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:

$$S_p^{\pm} = \pm(p+1)\sqrt{\frac{gk}{p+1}\tanh\left(\frac{kh}{p+1}\right)} + \mathbf{k}\cdot\mathbf{U}$$

Aliasing symmetry conditions:

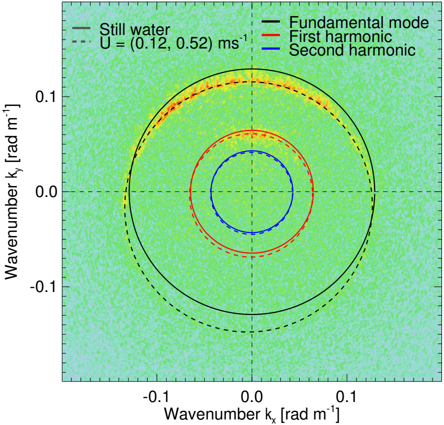
$$P(k_x, k_y, \omega) = P(k_x, k_y, \omega + n\omega_{Ny})$$
$$P(k_x, k_y, \omega) = P(-k_x, -k_y, -\omega)$$

S	Angular frequency
p	Integer for harmonic order
P	3D image power spectrum
n	Integer for frequency intervals

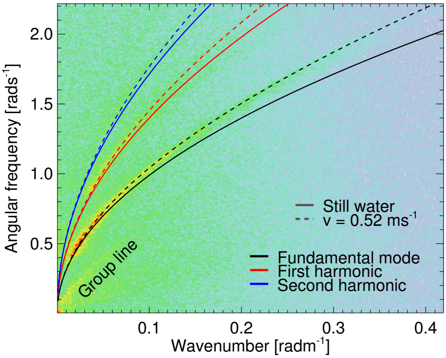
Spectral Signal of Near-surface Current

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 rads^{-1}):



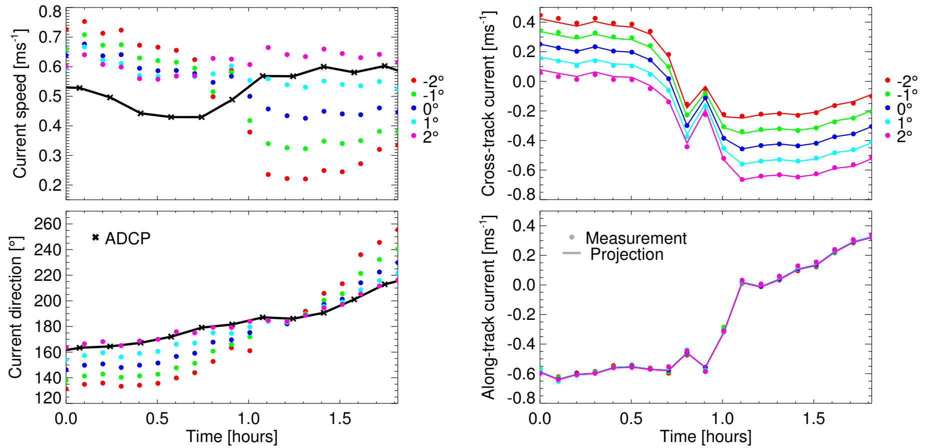
Wavenumber-frequency slice from 3D spectrum ($k_x = 0$ radm^{-1} and 0 radm$^{-1} \leq k_y \leq k_{Ny}$):



Ship-track Dependent Current Errors I

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).

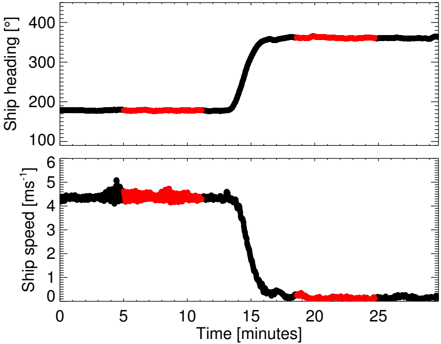
In geographic coordinates: In ship coordinates:



Ship-track Dependent Current Errors II

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:



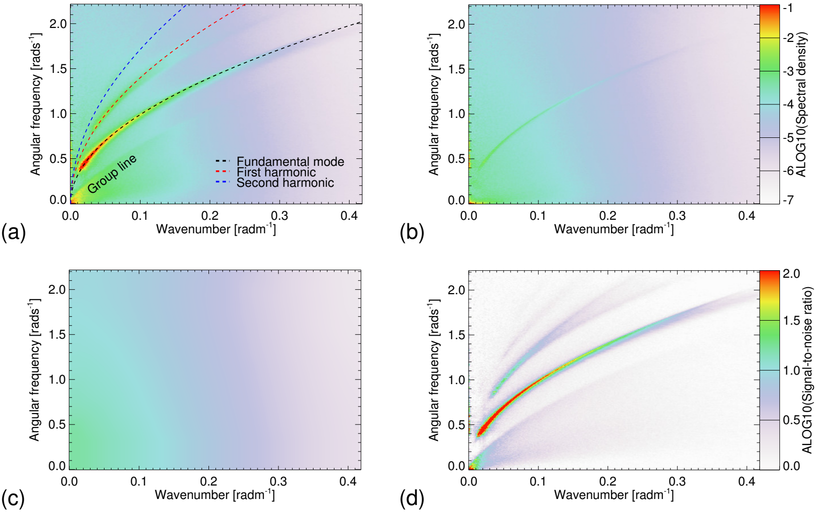
Alignment error: $\tan\alpha = \frac{\langle \delta u'_d \delta v_s - \delta v'_d \delta u_s \rangle}{\langle \delta u'_d \delta u_s + \delta v'_d \delta v_s \rangle}$

u_s	v_s	δu_s	δv_s
–0.164	**–4.354**	**–0.089**	**–2.181**
0.015	**0.008**	**0.089**	**2.181**

u'_d	v'_d	$\delta u'_d$	$\delta v'_d$
–0.135	**3.662**	**–0.001**	**2.13**
–0.133	**–0.597**	**0.001**	**–2.13**

From 3D Spectral Density to Signal-to-Noise Ratio I

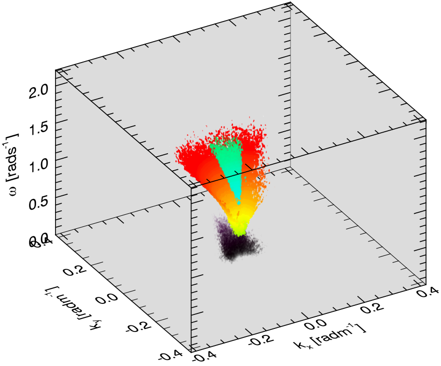
Background noise as $f(k,\omega)$ is estimated from spectral half with lowest standard deviation of spectral density over k.



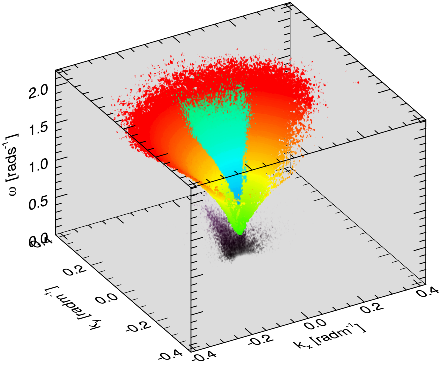
From 3D Spectral Density to Signal-to-Noise Ratio II

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

Power thresholding:



SNR thresholding:



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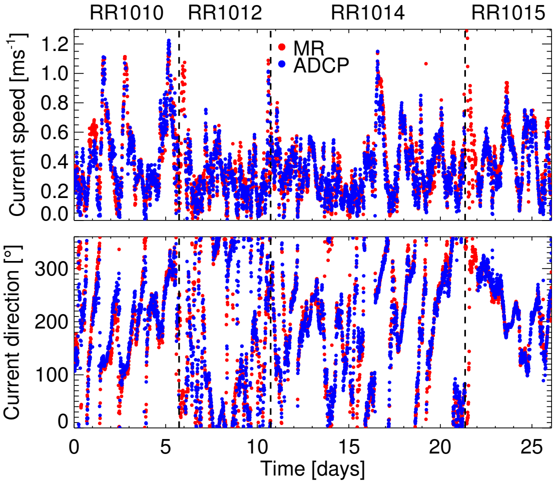
Shipboard Marine Radar versus ADCP Currents I

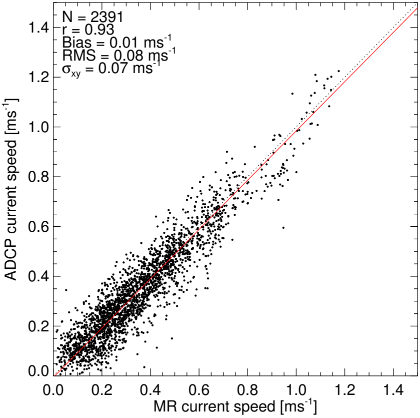
Time series of MR (0.225 radm^{-1} or ~2 m) and ADCP (21 m) currents.



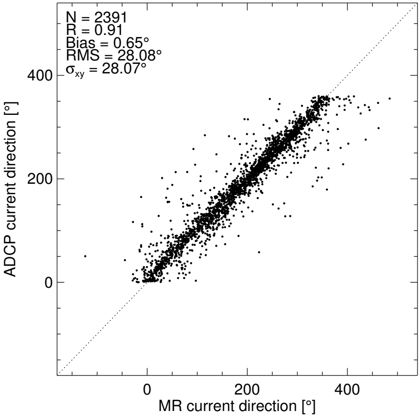
Shipboard Marine Radar versus ADCP Currents II

Scatter plots and statistics for MR–ADCP comparison.

Current speed:



Current direction:



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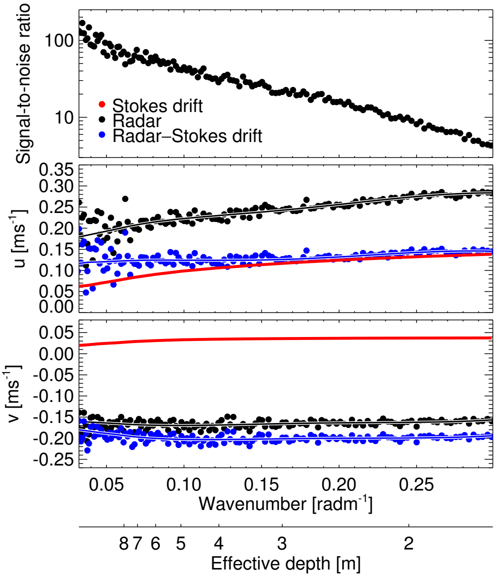
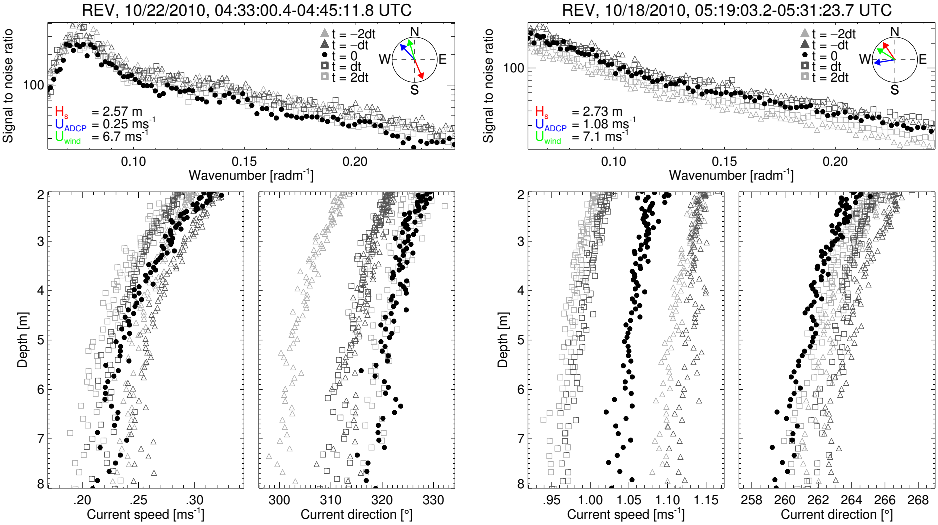
Near-surface Current Profile Examples I



Example of MR near-surface vertical current shear measurements with WW3-based filtered Stokes drift.

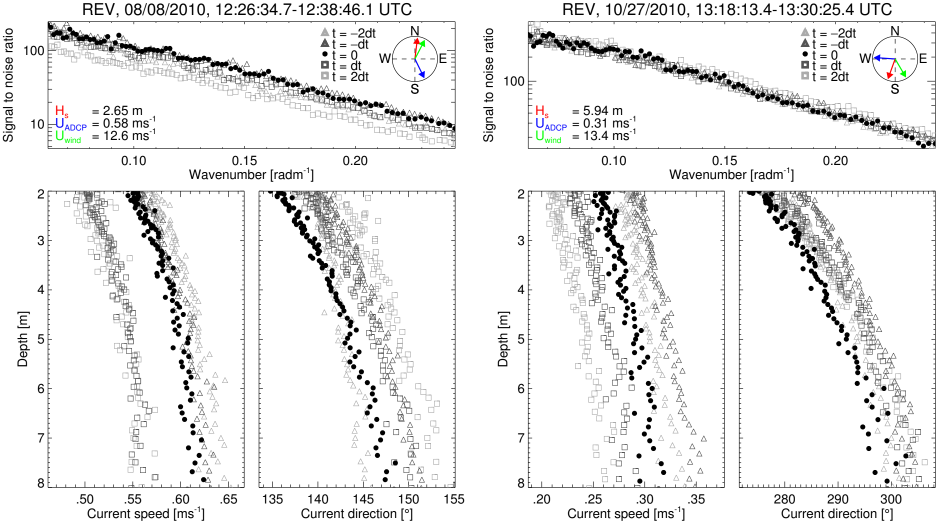
Near-surface Current Profile Examples II

"Parallel flow" and "clockwise forcing".



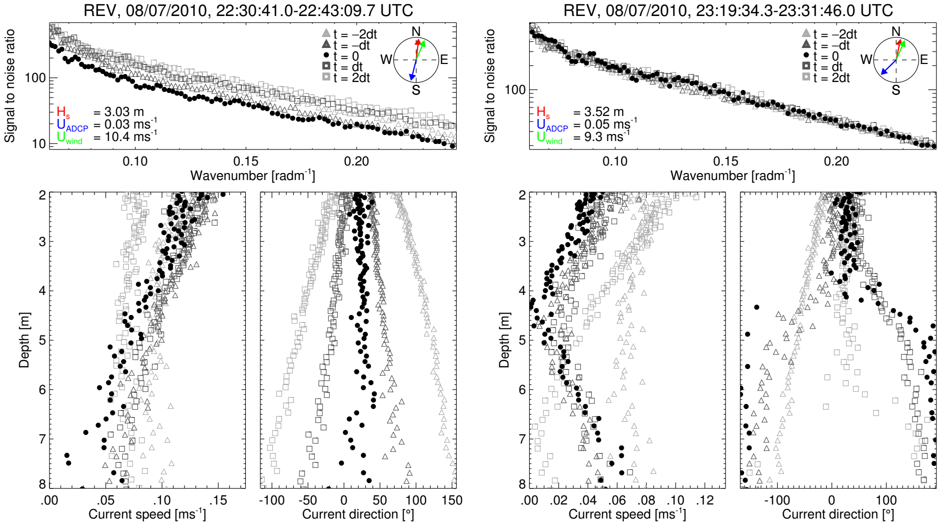
Near-surface Current Profile Examples III

"Counter flow" and "counter-clockwise forcing".



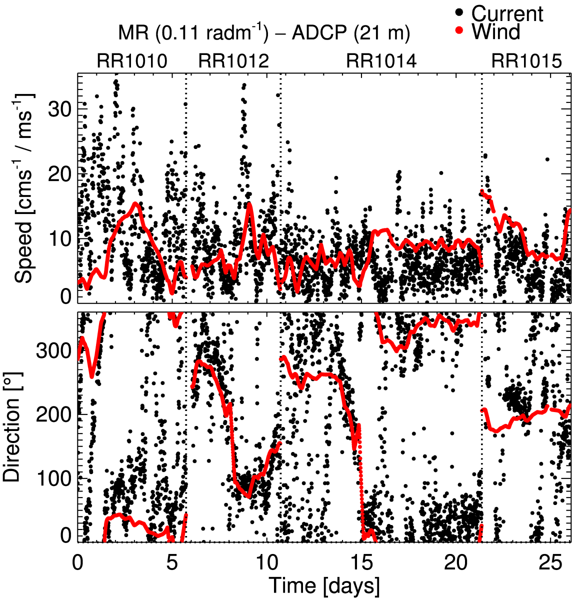
Near-surface Current Profile Examples IV

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



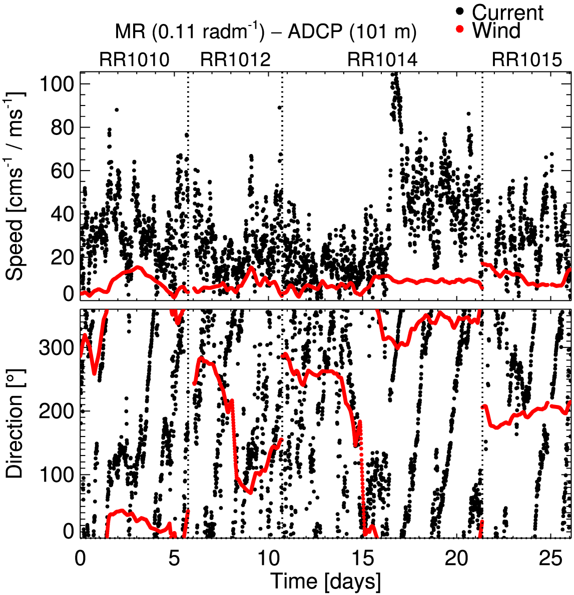
Choice of Background Current Depth I

Time series of differences between MR (0.11 radm^{-1} or ~4.5 m) and ADCP (21 m) currents.



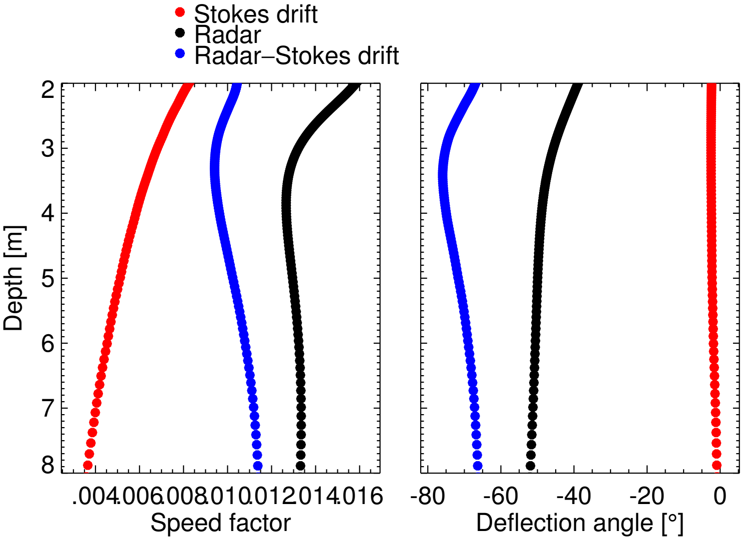
Choice of Background Current Depth II

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.



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 $\mathbf{U}_E(k_D)$
  - 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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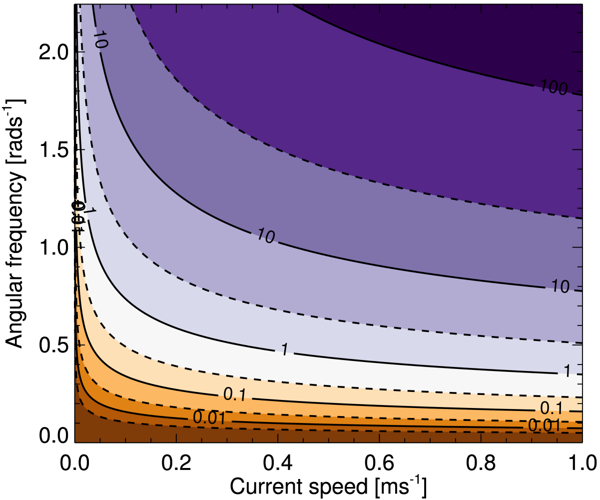
References:

- Lund, B.; Graber, H. C.; Hessner, K. & Williams, N. J.: On shipboard marine X-band radar near-surface current "calibration". Manuscript submitted for publication, 2015
- Lund, B.; Graber, H. C.; Tamura, H.; Collins III, C. O. & Varlamov, S. M.: A new technique for the retrieval of near-surface vertical current shear from marine X-band radar images. Manuscript submitted for publication, 2015
- Lund, B.; Collins III, C. O.; Graber, H. C.; Terrill, E. & Herbers, T. H. C: Marine radar ocean wave retrieval's dependency on range and azimuth. Ocean Dynam., 2014, 64, 999-1018

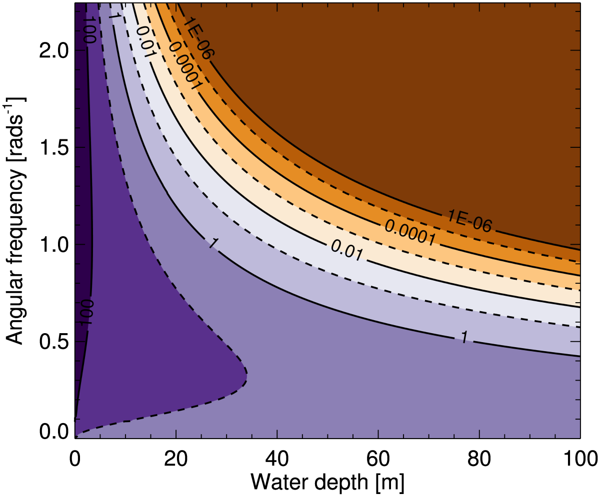
Spectral Sensitivity to Currents

Technique's sensitivity, in terms of wavenumber resolution cells:



Spectral Sensitivity to Bathymetry

Sensitivity to bathymetry:



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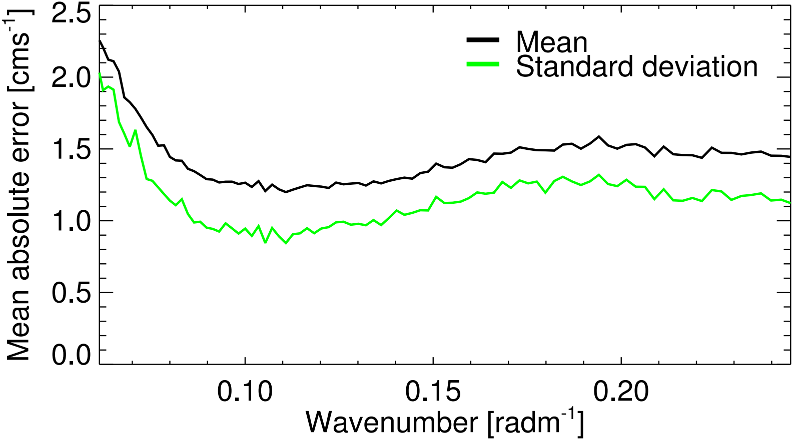
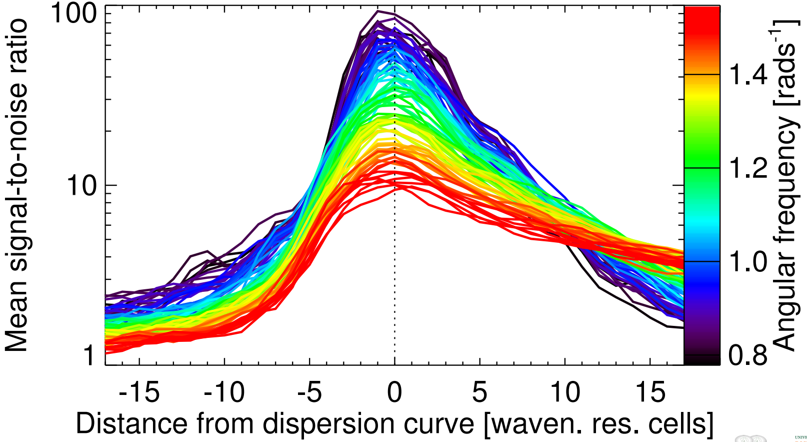
MR Near-surface Current Profile Accuracy

Mean deviations of MR currents from 5th degree polynomial fit:



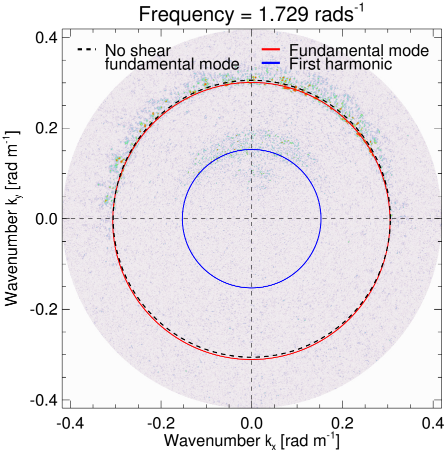
Mean SNR Across Dispersion Curve

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

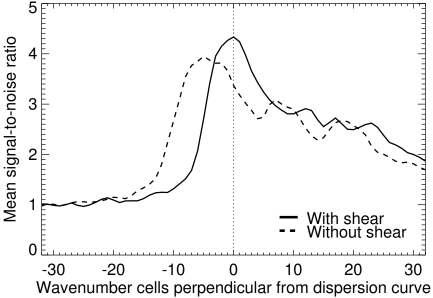


Marine Radar Current Shear Measurements

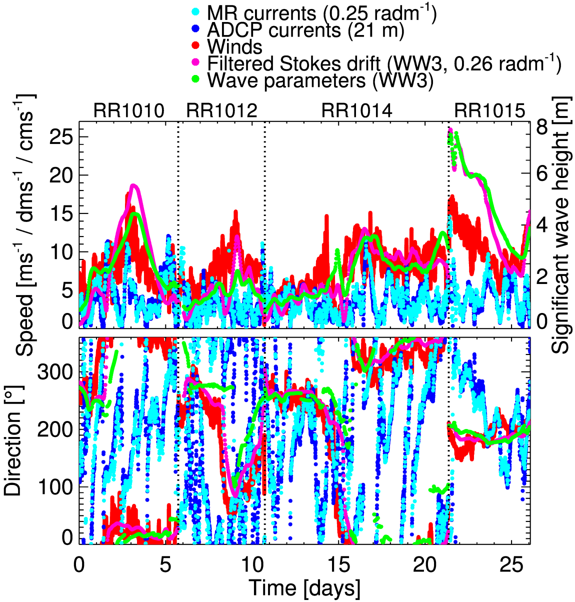
Current shear fit example:



Mean signal-to-noise ratios:



Currents, Winds, and Waves

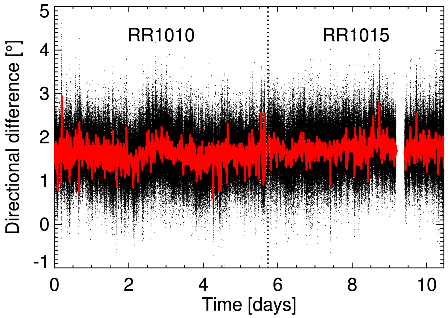


Anemometer winds, sub-surface currents, filtered Stokes drift, and peak wave parameters.

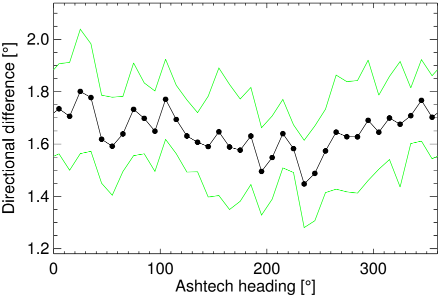
Shipboard Marine Radar Current "Calibration"

Conventional mechanical gyro compasses are reliable but have errors of O(1°) depending on ship speed, heading, and latitude (Bowditch 2002).

Difference between ASHTECH multi-antenna GPS and gyro compass:



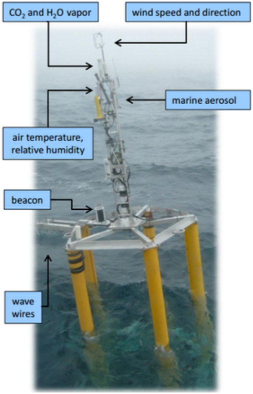
Gyro compass error dependency on heading:



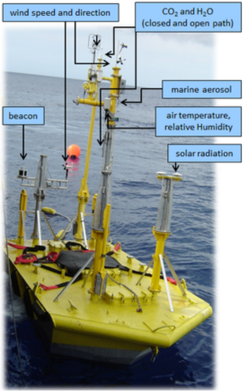
ITOP Experiment

Impact of Typhoons on the Pacific (ITOP), western Pacific, 2010.

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



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



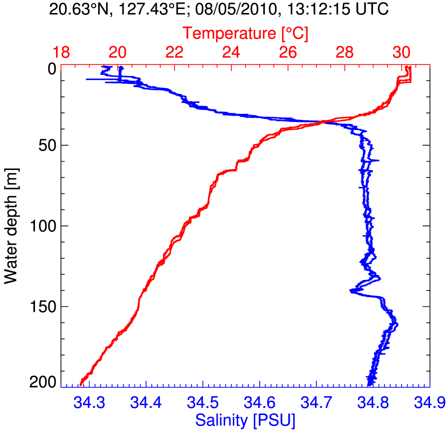
R/V Roger Revelle with ASIS-EASI buoy pair:

Photo credit: Hans C. Graber
ASIS / EASI graph credit: Henry Potter

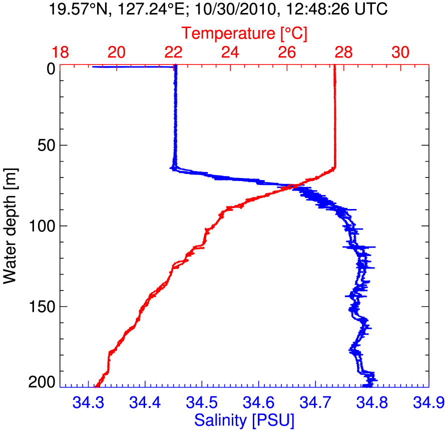
Stratification

Wind-driven currents are heavily affected by stratification (Price et al. 1987; Price and Sundermeyer 1999).

During RR1010 near EASI-N:



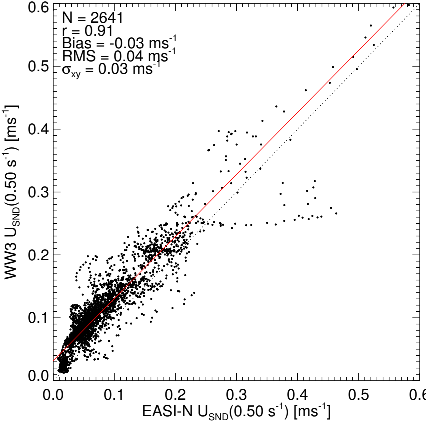
During RR1015 near EASI-S:



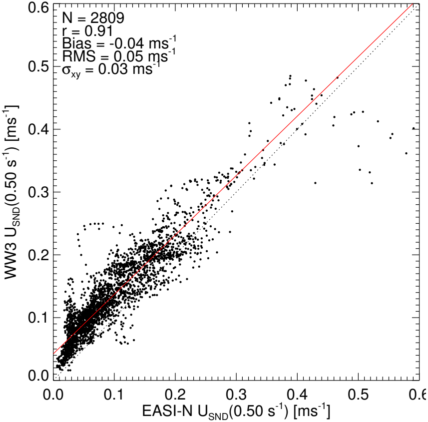
Stokes Drift Estimated from WAVEWATCH III

Scatter plots and statistics for EASI-N– and EASI-S–WW3 non-directional Stokes drift speed comparison (Ardhuin et al. 2009).

EASI-S–WW3:



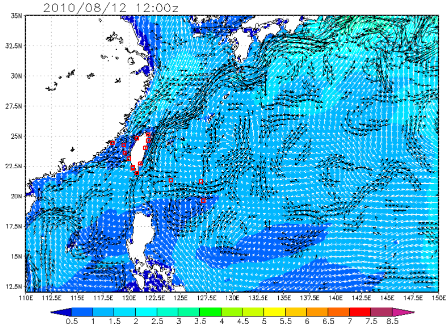
EASI-N–WW3:



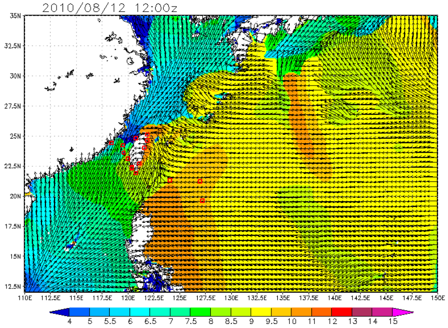
WAVEWATCH3 Modeling Example

WAVEWATCH III peak wave parameters, 12 August 2010, 12:00 UTC.

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

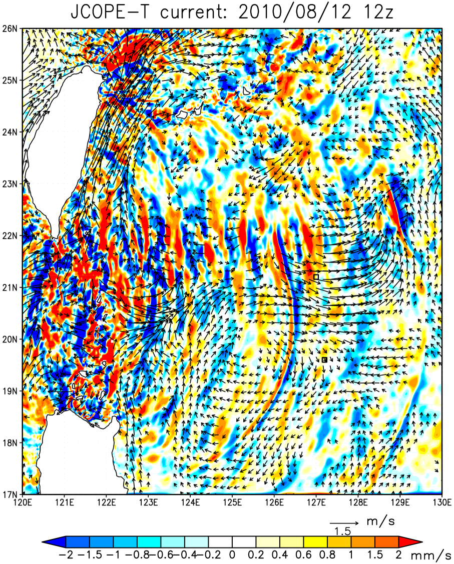


Peak wave period and direction:



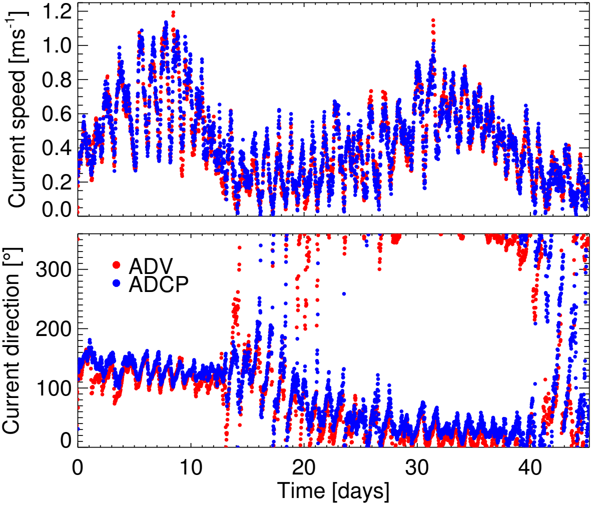
JCOPE-T Modeling Example

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.



ASIS-S Near-surface Current Measurements I

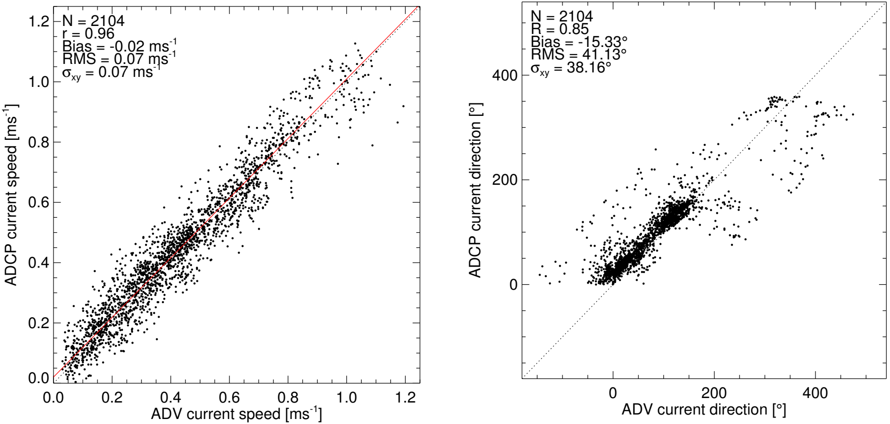
Time series of ADV (4 m) and ADCP (21.22 m) measurements:



ASIS-S Near-surface Current Measurements II

Scatter plots and statistics for ADV–ADCP comparison.

Current speed: Current direction:



Spectral Analysis of ASIS-S ADV Data

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