

Velocity Measurements from Gliders (with ADCPs)

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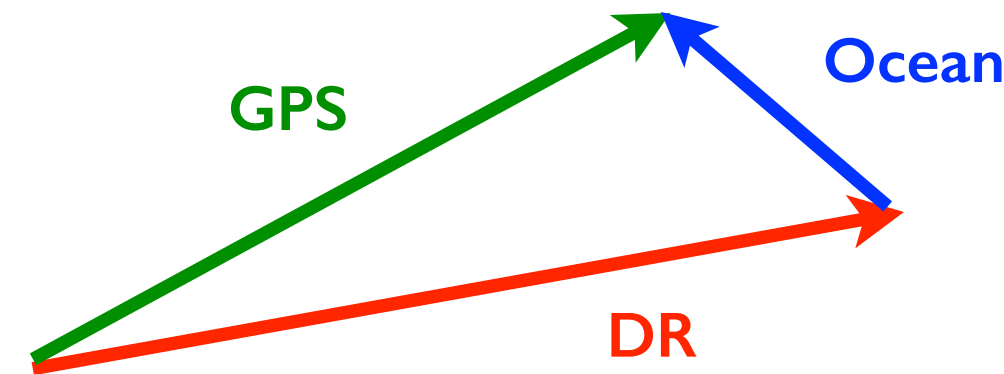
Presenters: Robert E. Todd (WHOI), Emma Heslop (SOCIB)

Velocity Measurements from Gliders

Three Distinct Methods:

1. Depth averaged absolute currents

- Estimate horizontal displacement through water from heading, pitch, depth, and flight model (DR)
- Measure displacement over ground with GPS
- Difference is due to integrated currents (Ocean)



2. Geostrophic Shear

- Derive density gradient from CTD measurements
- Limited to scales larger than ~30 km/1 day
- Cross-track component only

3. Water velocity relative to glider with ADCP

- Glider-mounted Doppler current profiler measures relative water velocity within ~20 m of glider
- Many overlapping profiles of relative (u,v,w)

Need absolute reference!

Two red arrows originate from the text 'Need absolute reference!'. One arrow points towards the '2. Geostrophic Shear' section, and the other points towards the '3. Water velocity relative to glider with ADCP' section, indicating that these methods require an absolute reference for accurate velocity measurement.

Workshop Overview

1. Depth Averaged Currents

- A. Compass calibrations
- B. Accuracy and limits
- C. Corrections from ADCPs
- D. Best practices

2. Velocity Profiling with ADCPs

- A. Sampling
- B. Inverse method
- C. Constraints
- D. Bias Correction
- E. Accuracy

3. Panel Discussion

Depth Averaged Velocities

COMPASS CORRECTION

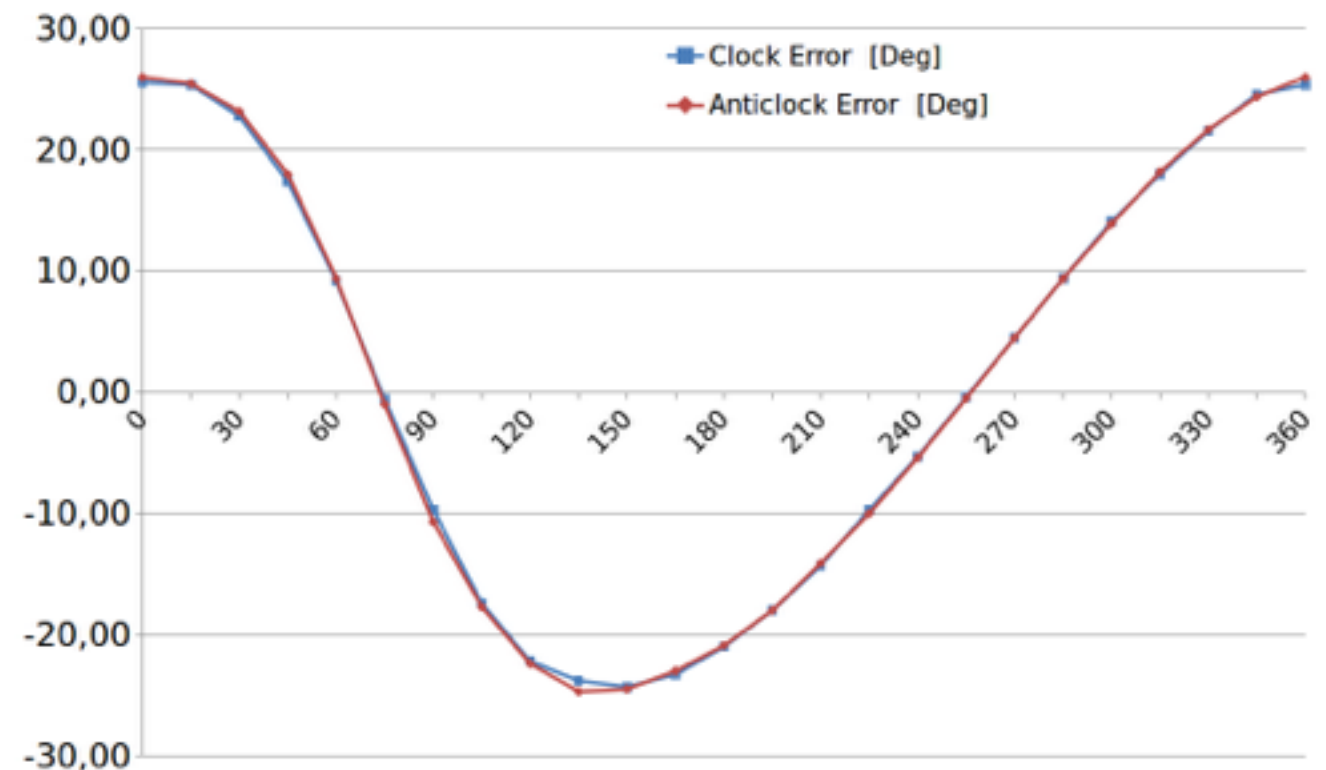
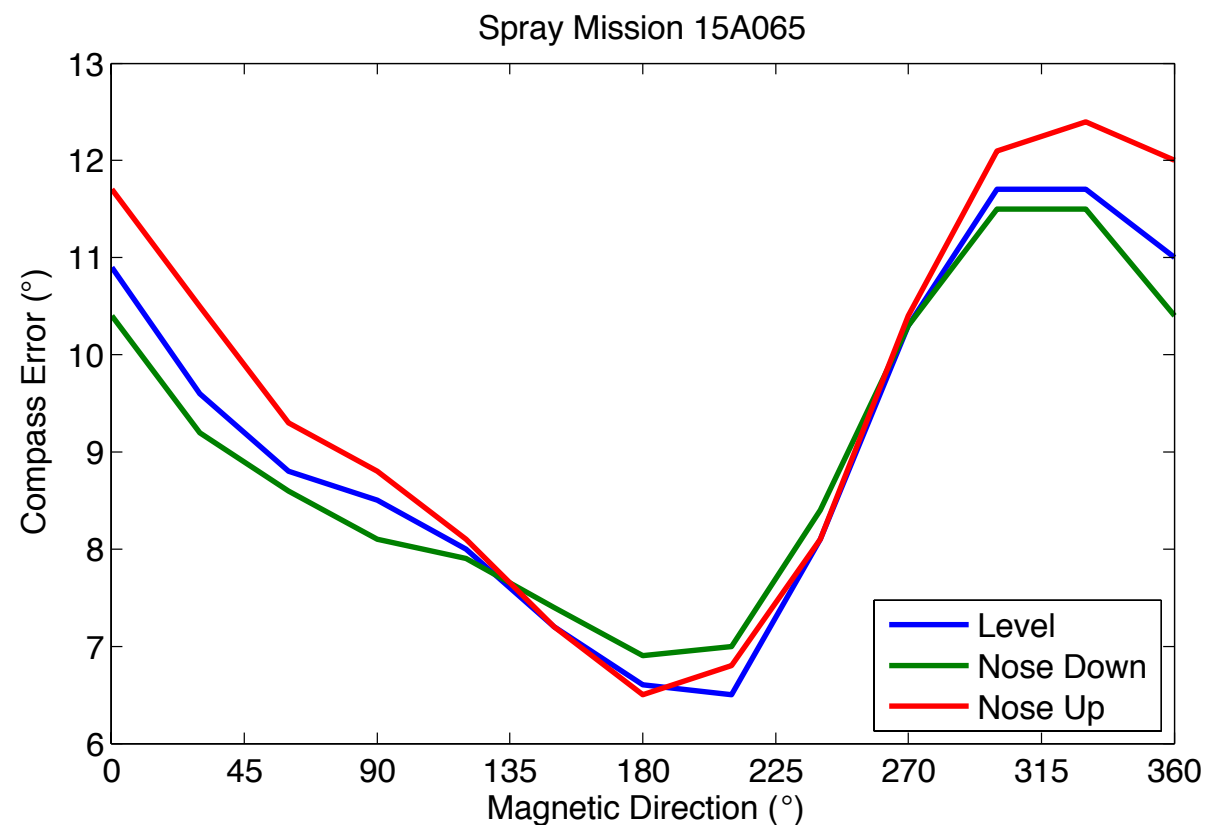
- Glider internal compass has an associated heading dependent error
- Find correction by ‘swinging’ the glider to points of the compass
- Find difference between external (correct) and glider internal compass heading
- Methods to ‘swing’ glider:
 - Specific apparatus/cradles
 - Hanging glider in trees
 - In the ocean



Cradle for compass correction procedure (SOCIB)

Depth Averaged Velocities

- Compass correction 'curves'
- Error varies each mission – perform each mission
- Recommend 15-30 degree intervals, nose up/down
- Can be large 20 – 30 degrees

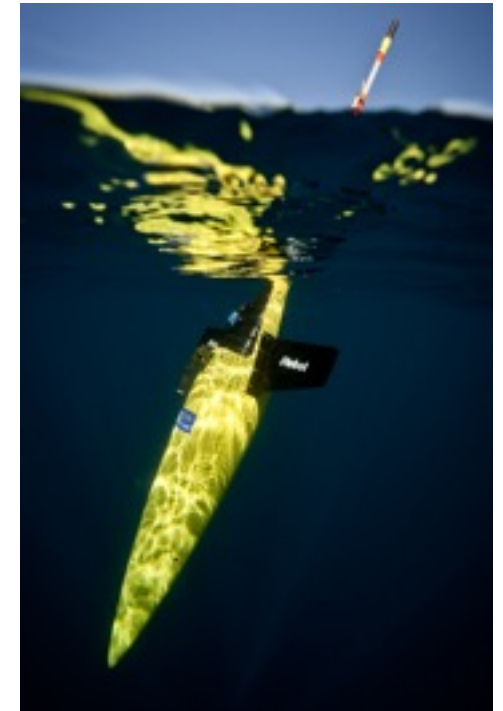


Examples of compass correction curves Spray (left) and Slocum (right)

Depth Averaged Velocities

POST-PROCESSING DEPTH AVERAGE CURRENTS

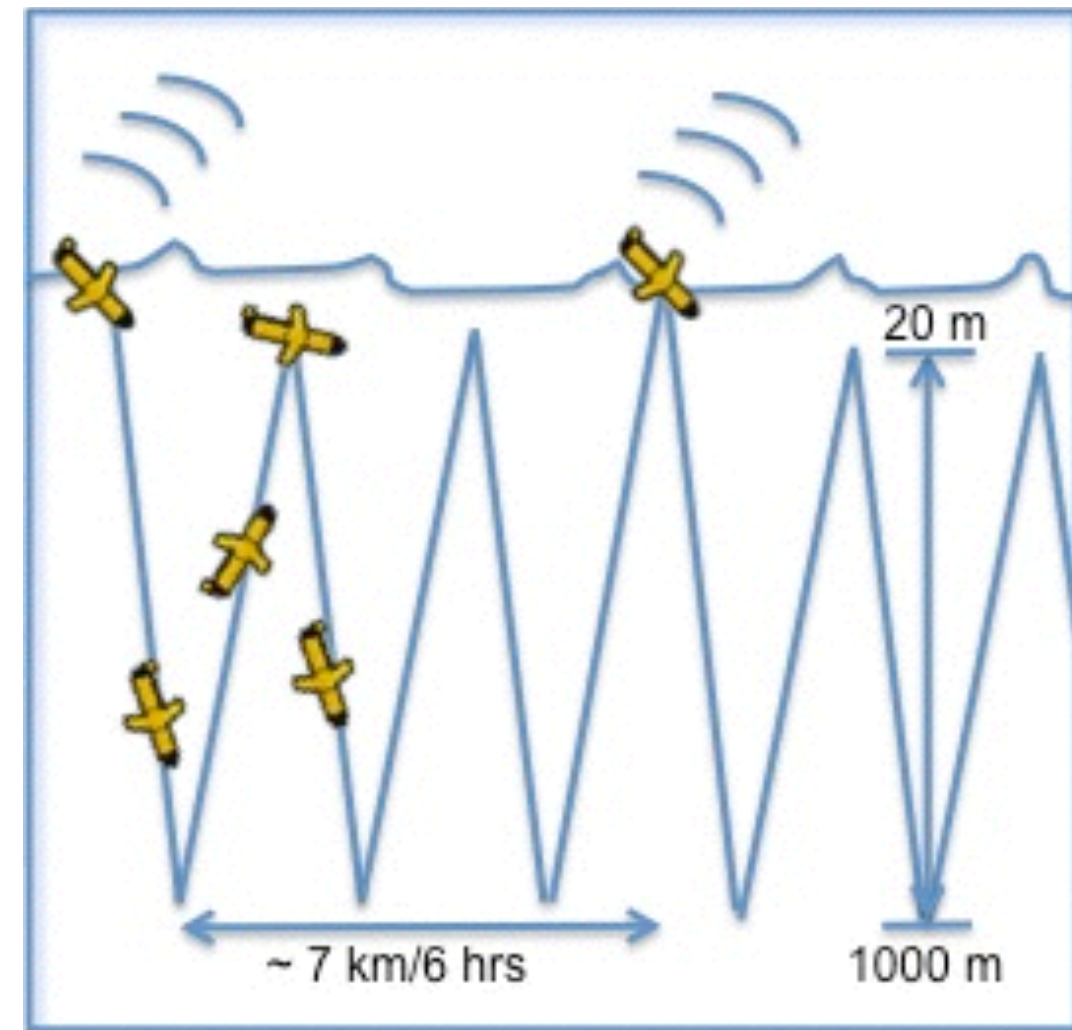
- Re-estimate dead reckoned position (horizontal displacement of glider from heading, pitch, depth and model of glider flight).
- Subtract the drift at the surface before gaining a GPS fix to find the actual surfacing position.
- The difference between actual and dead reckoned position represents the depth average velocity for the previous segment
- Merckelbach et al 2008, Rudnick et al., (2015), Todd et al., (2016) submitted
- Bouffard et al., (2010) - calculate the difference between mean velocity (u, v) for the segment with and without compass error, subtract average error in velocity to estimate a corrected DAV



Depth Averaged Velocities

ACCURACY AND LIMITS

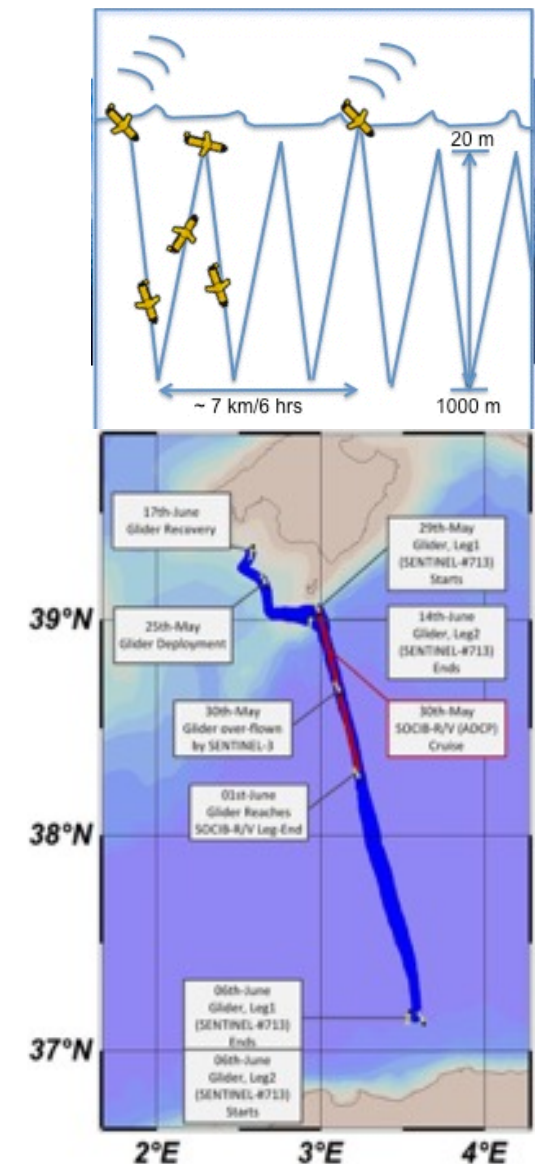
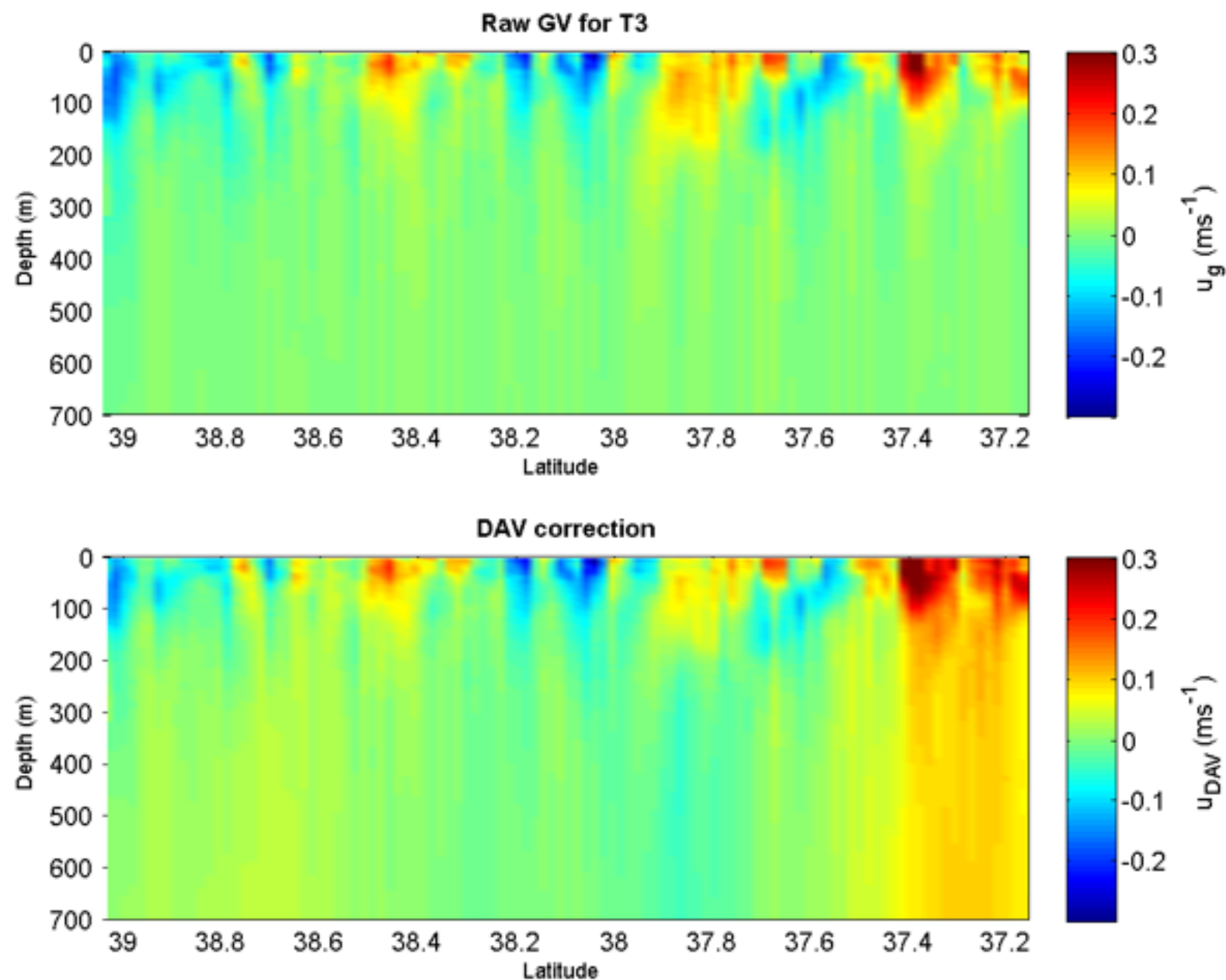
- Depth Averaged Velocity calculation is accurate to within 0.01 m s^{-1} (Todd et al., 2011), $2 - 3 \text{ cm s}^{-1}$ (Merckelbach et al., 2008)
- Use difference on either side of (many) turns to evaluate accuracy (Todd et al. 2011)
- The DAV for a segment – could contain multiple and/or short profiles – only know location of first and last profile
- Changing bathymetry – how representative is one depth average velocity for features along slope edge
- Contains all signals, e.g. inertial, geostrophic, Ekman



Depth Averaged Velocities

ACCURACY AND LIMITS – EXAMPLE

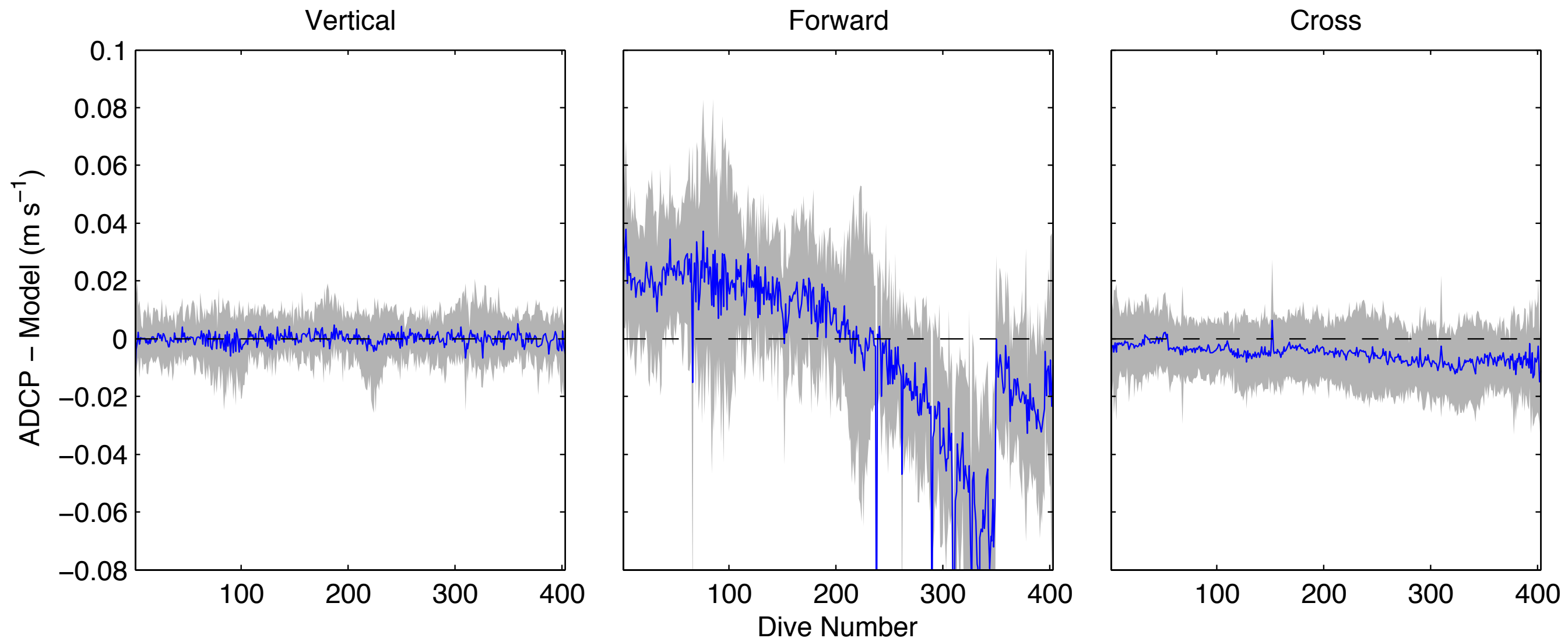
- Using Depth Average Velocities to provide a reference bottom velocity for geostrophic



Algerian Basin
Mission
May 2016

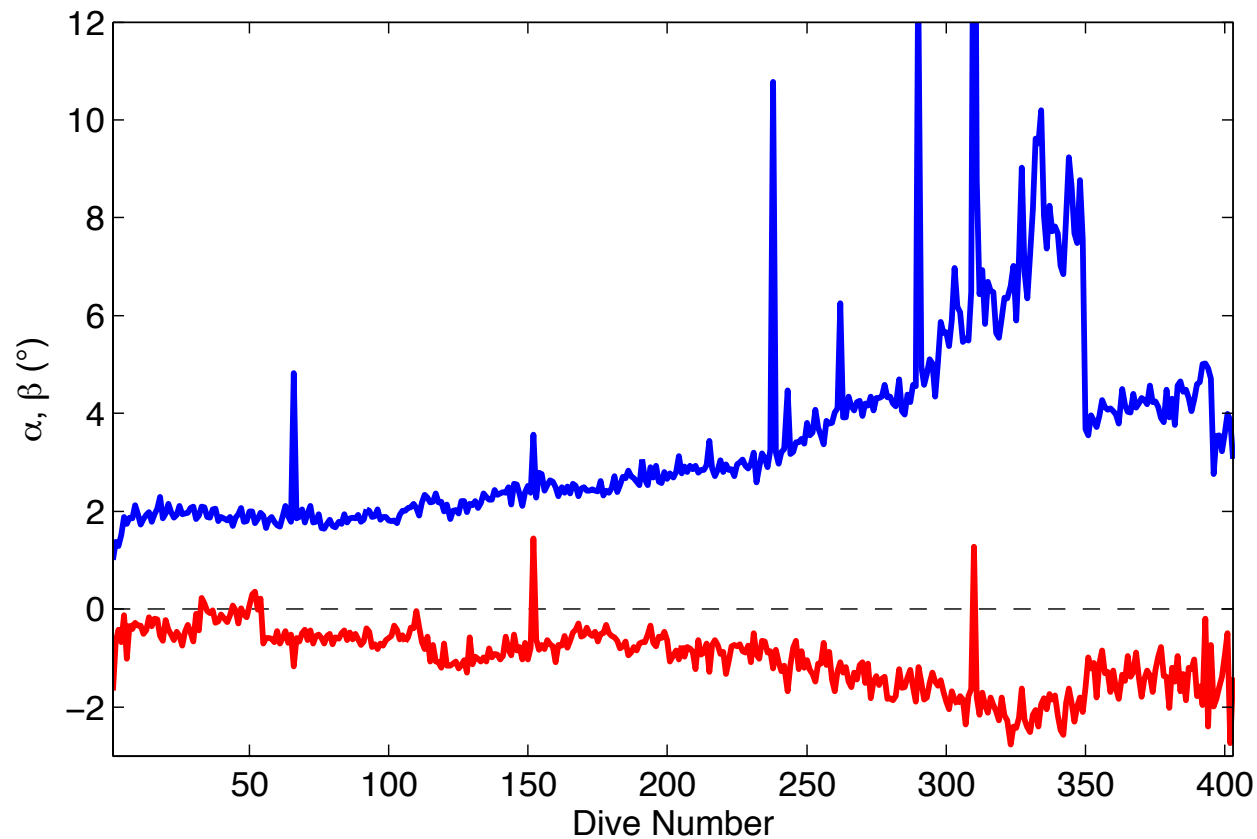
ADCP vs. Model of Glider Velocity

- Nearest ADCP cell (~ 1 m range) captures glider velocity through water.
- Basic model cannot capture changing drag (e.g., due to biofouling)

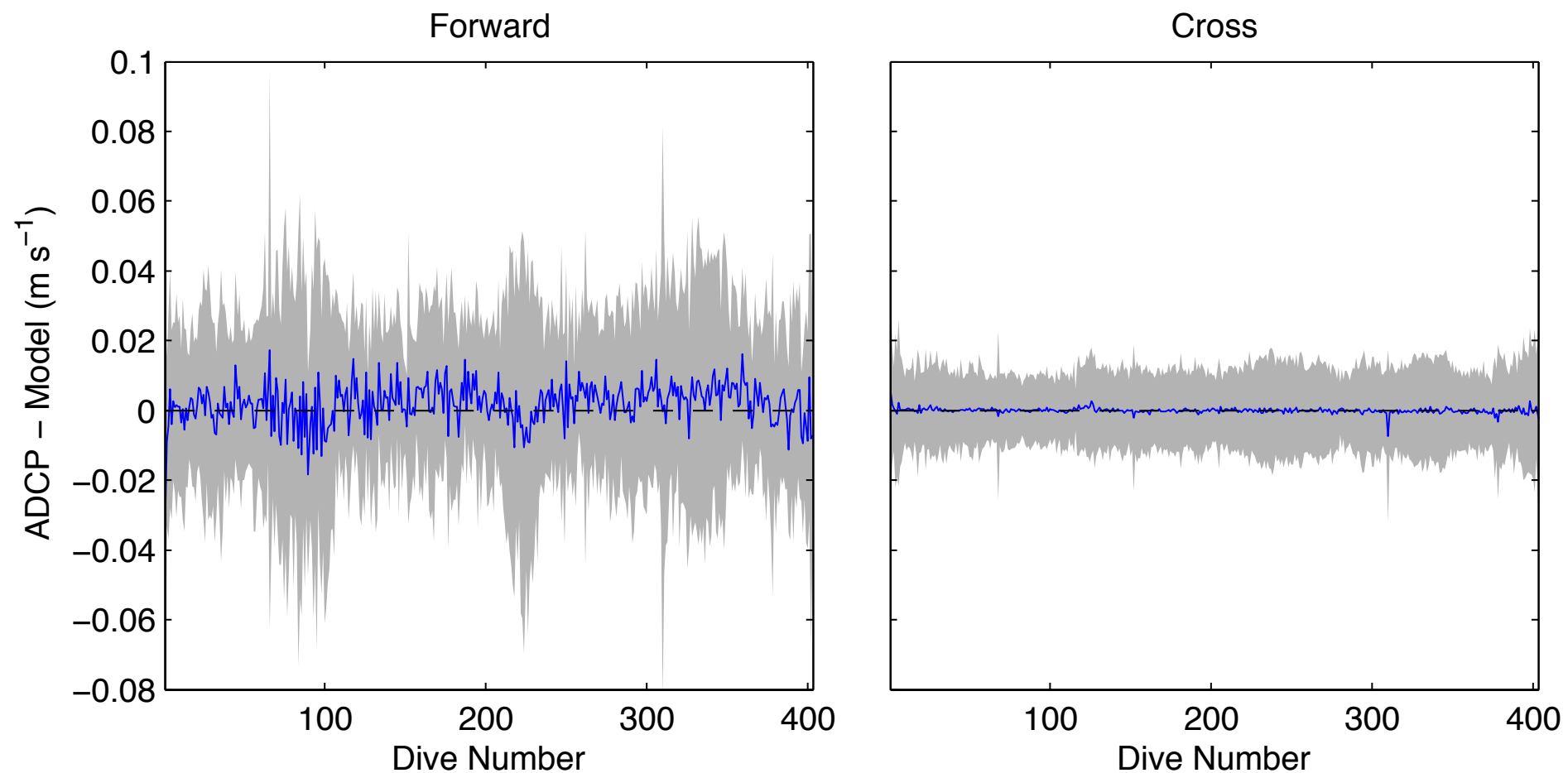


[Example from Spray mission I52058 in eastern Equatorial Pacific]

Correcting DAV with ADCPs

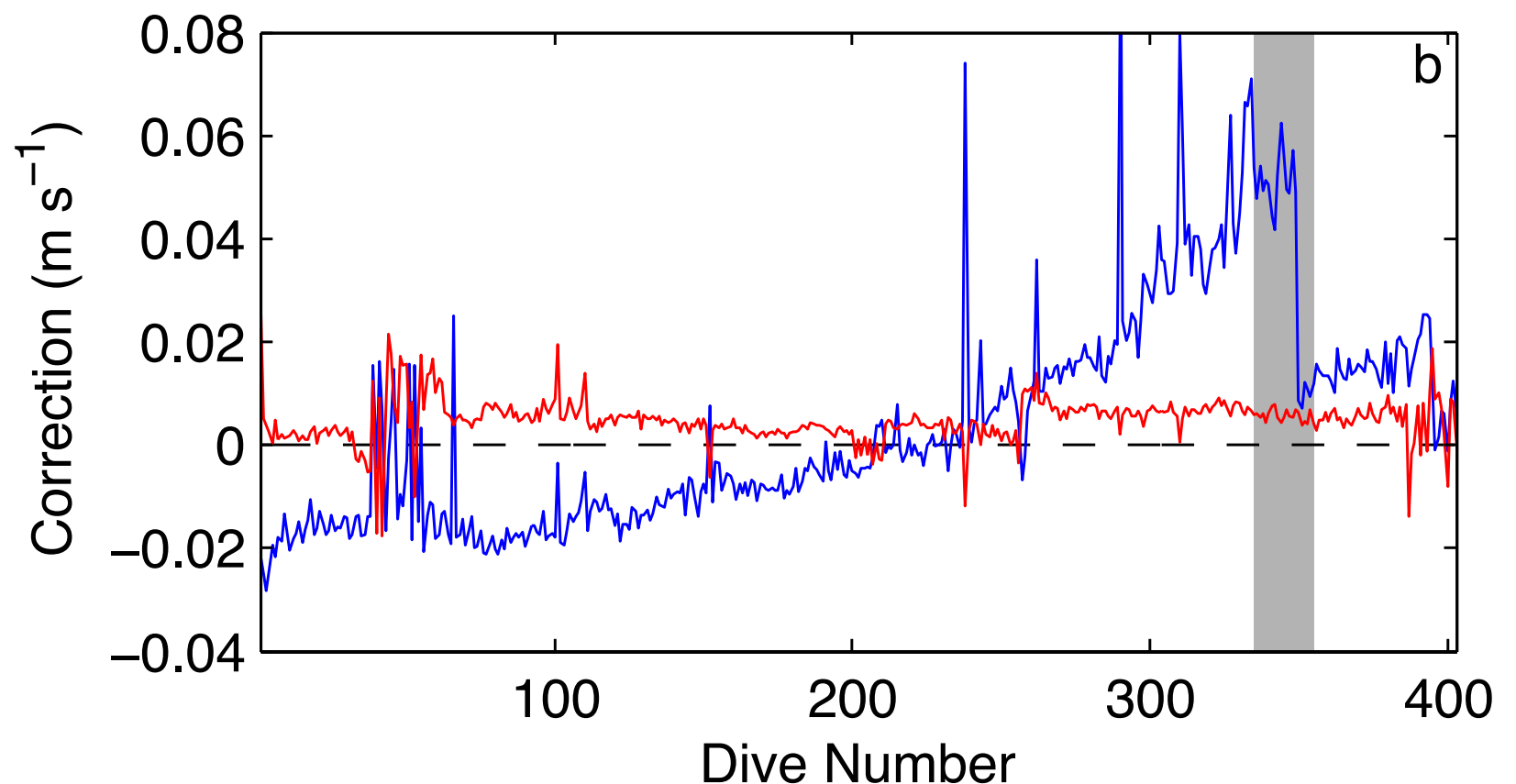
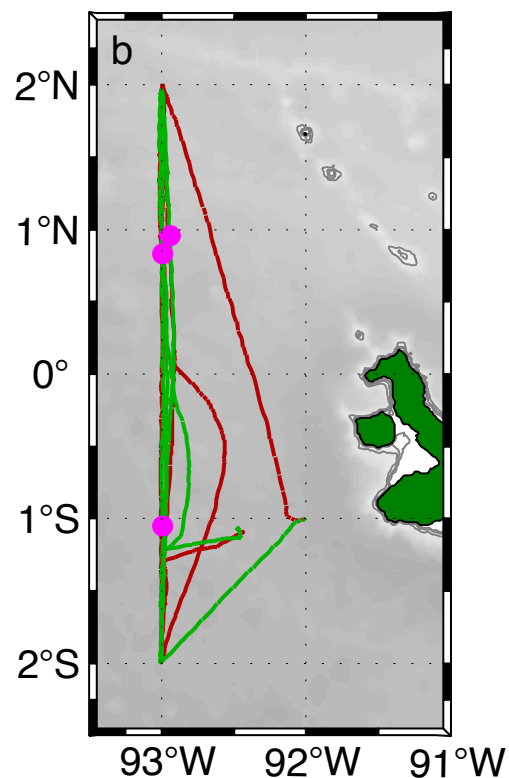
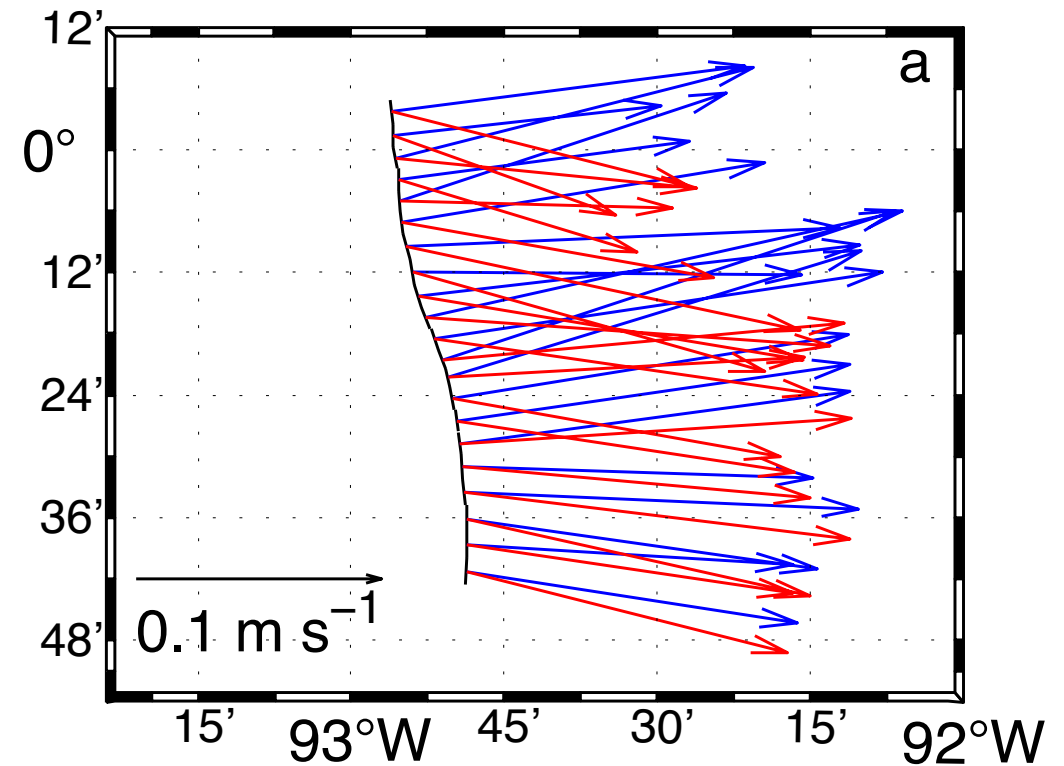


- Too costly to run ADCP all the time
- Infer variable **angle of attack** (α) and **sideslip** (β) from ADCP measurements
- Apply to flight model



Correcting DAV with ADCPs

- Recalculate dead-reckoned displacement with modified flight parameters
- Resulting depth averaged current estimates account for varying flight performance



Depth Averaged Velocities

BEST PRACTICES

- ‘Swing’ glider compass before/after each mission – 15-30° interval, vary pitch
- Consider surfacing each dive/climb ‘V’ - more accurate profile position, more DAVs
- Nearest-cell measurements from ADCPs on glider can be used to changing infer flight characteristics, which can improve velocity estimates.
- Apply a 25 – 30 km filter to the depth average velocity field for geostrophic reference

Workshop Overview

1. Depth Averaged Currents

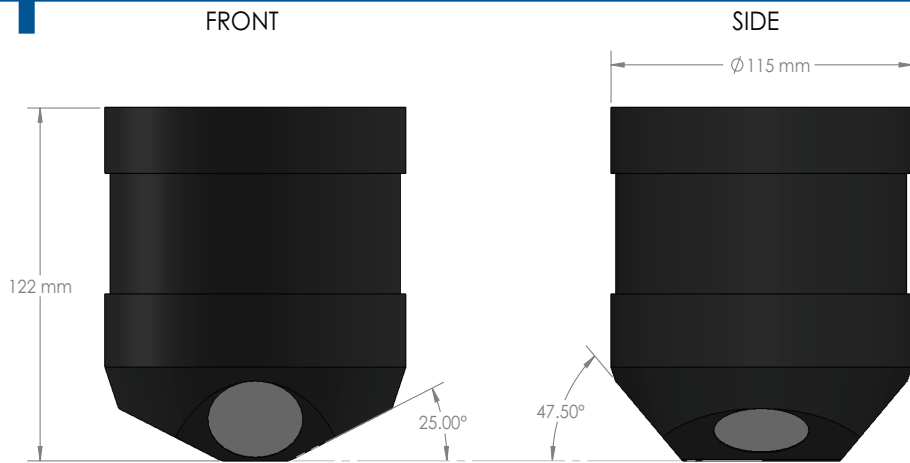
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2. Velocity Profiling with ADCPs

- A. Sampling
- B. Inverse method
- C. Constraints
- D. Bias Correction
- E. Accuracy

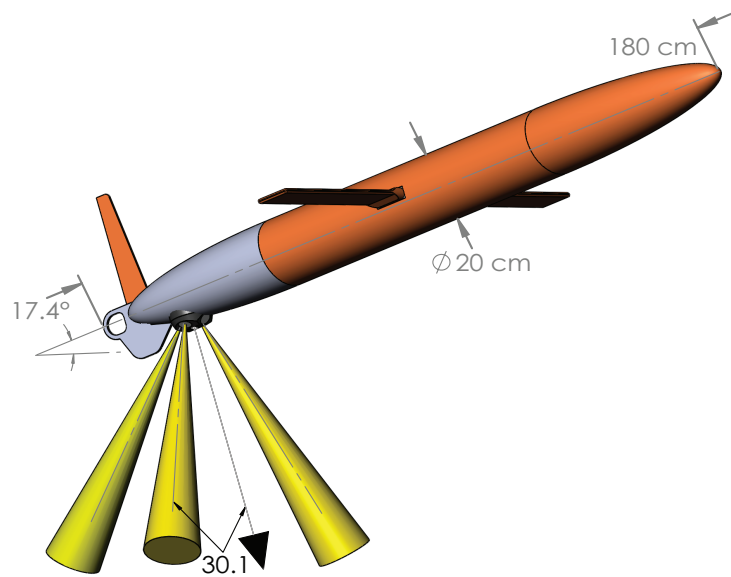
3. Panel Discussion

ADCP Sampling from Gliders



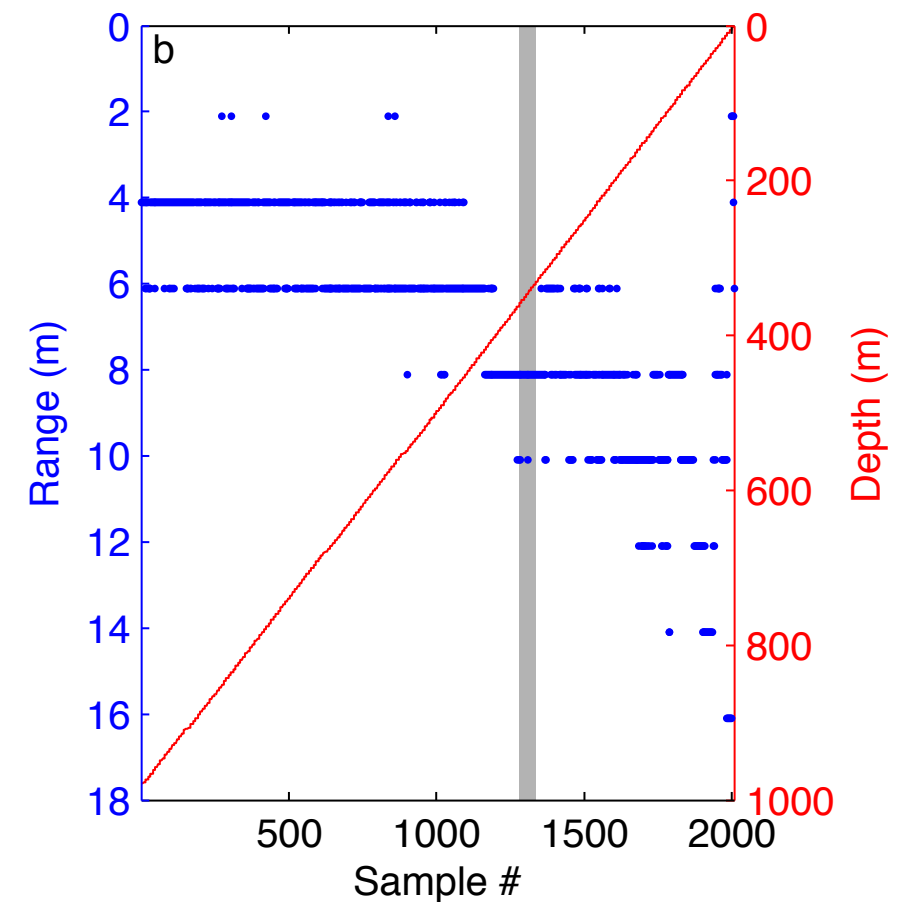
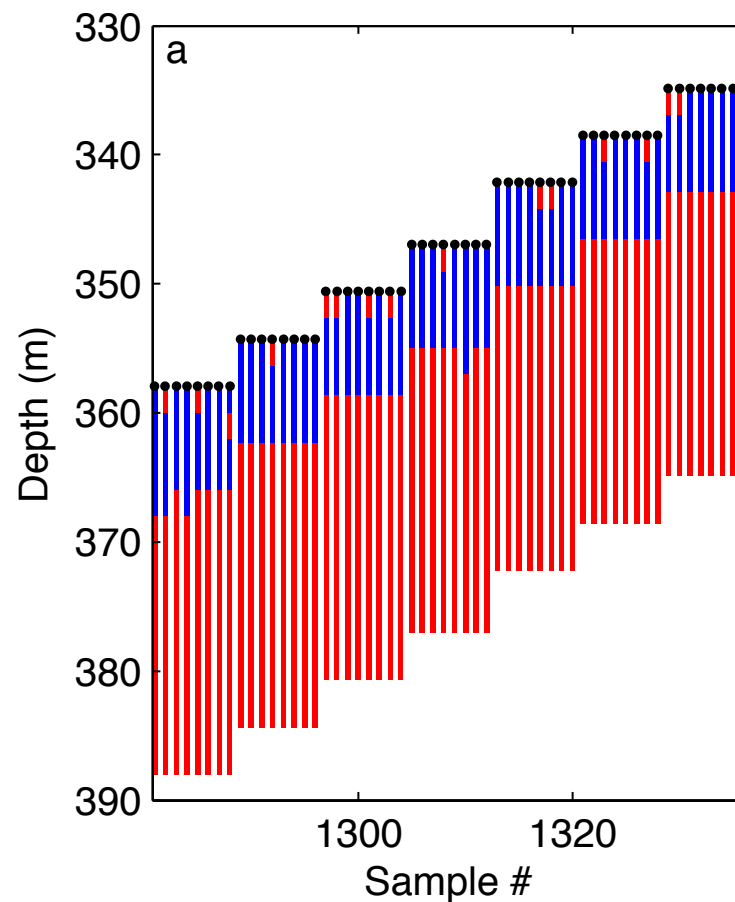
(a)

(b)



(c)

- Downward-looking Nortek AD2CP (1-MHz)
- 8-ping ensemble every 30 s during ascent
- 110-day endurance
- 15 cells of 2-m vertical extent
- Effective range after QC of 6-12 m



Inverse Method: ADCP Measurements

- Each ADCP measurement of relative velocity gives an equation of the form:

$$(u, v)_r = (u, v)_w - (u, v)_g$$

- Write system of equations in matrix form:

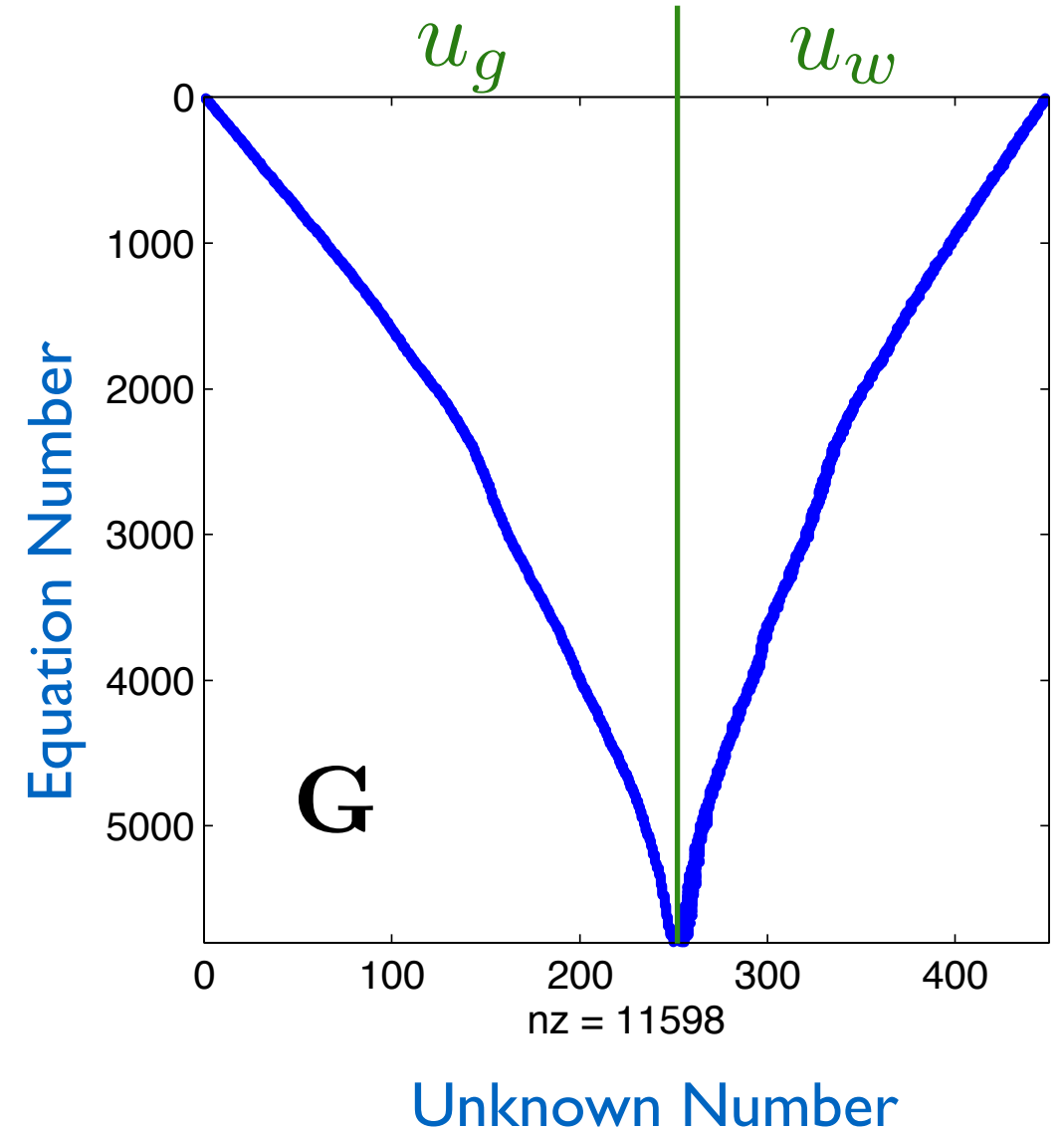
$$\mathbf{d} = \mathbf{G}\mathbf{m} + \mathbf{n}$$

- Vector of unknown glider and water velocities over the ground is:

$$\mathbf{m} = \left[\begin{array}{cccc|cccc} u_{g,1} & \cdots & u_{g,N} & u_{w,0} & u_{w,1} & \cdots & u_{w,M} \end{array} \right]^T$$

- Solution by least squares is:

$$\mathbf{m} = (\mathbf{G}^T \mathbf{G})^{-1} \mathbf{G}^T \mathbf{d}$$



Need absolute reference!

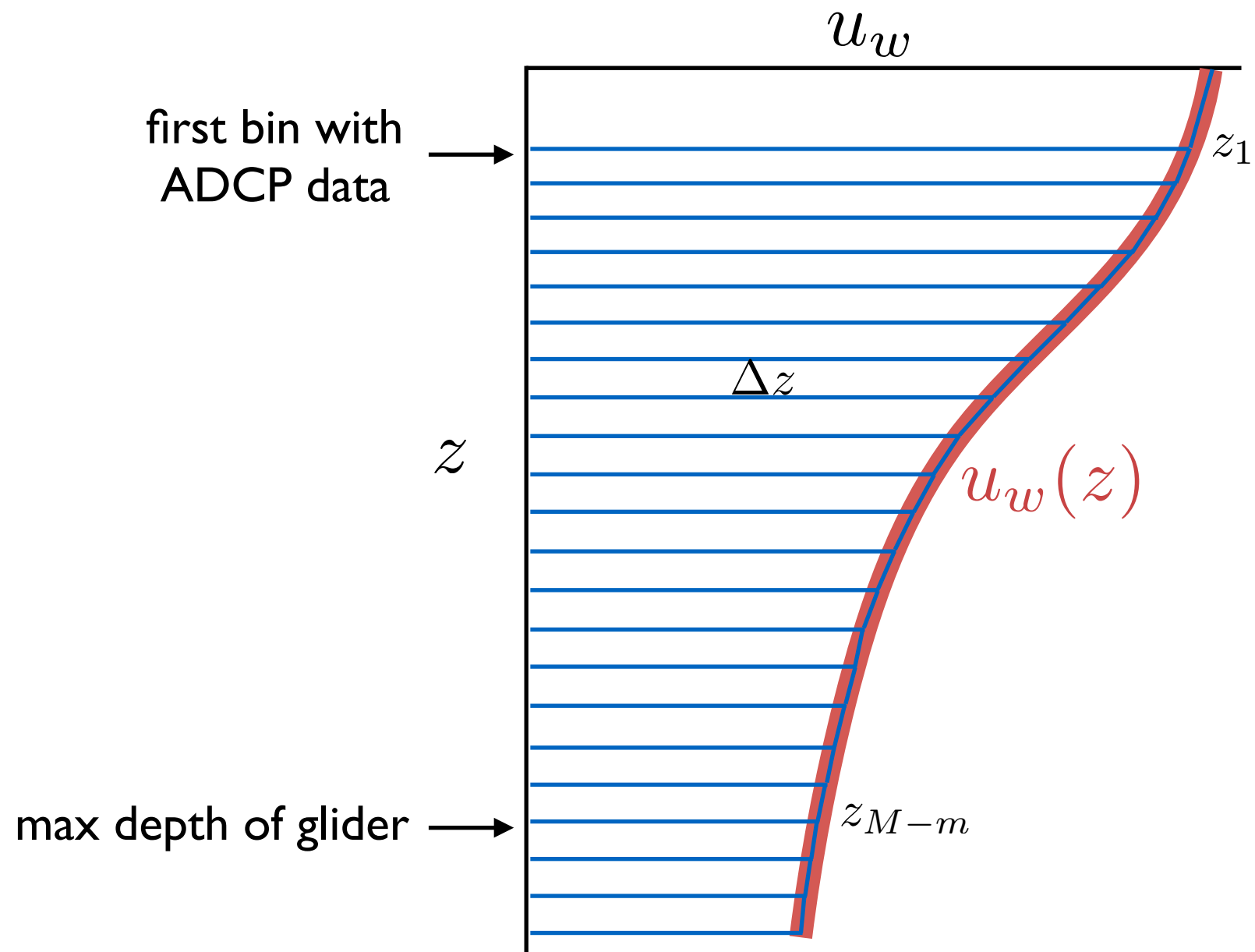
Inverse Method: Depth Averaged Constraint

- Use trapezoid rule to write depth average of unknown water velocity.
- Constrain to equal glider-based measurement.
- Element added to $\mathbf{d}$:

$$CU$$

- Equation added to $\mathbf{G}$ is:

$$\frac{C}{z_{M-m}} \times \left[\begin{array}{c|cccccccccccc} 0 & \dots & 0 & \frac{z_1}{2} & \frac{z_1}{2} + \frac{\Delta z}{2} & \Delta z & \dots & \Delta z & \frac{\Delta z}{2} & 0 & \dots & 0 \end{array} \right]$$



Inverse Method: Surface Constraint

- Estimate surface velocity from glider drift between dives ($\sim 0.05 \text{ m s}^{-1}$ accuracy).
- Constrain velocity profile to match drift estimate at surface:

$$u_{w,0} = u_{\text{surf}}$$

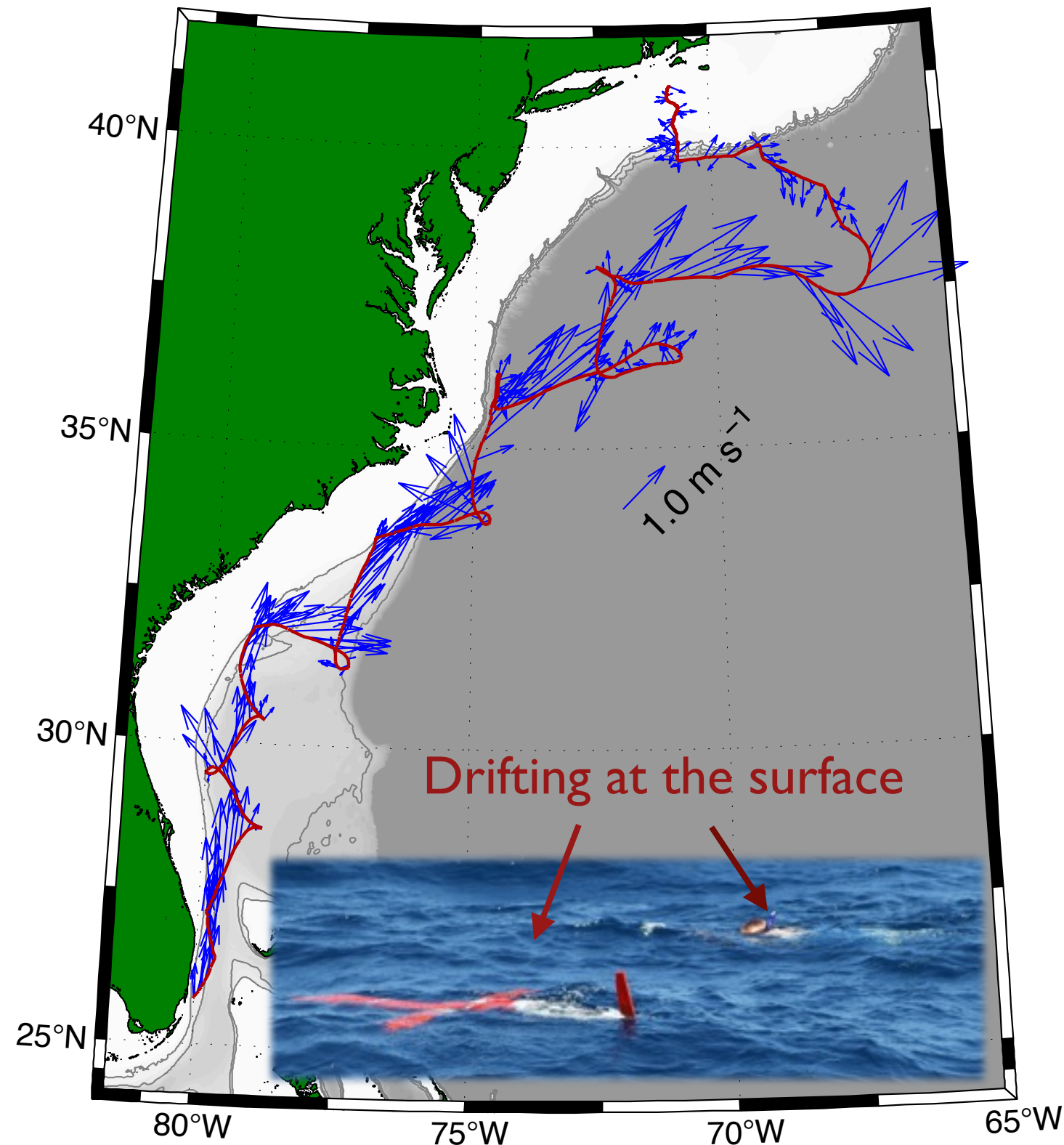
- Equation added to $\mathbf{G}$:

$$\left[\begin{array}{cccc|ccccc} 0 & \dots & 0 & 1 & 0 & \dots & 0 \end{array} \right]$$

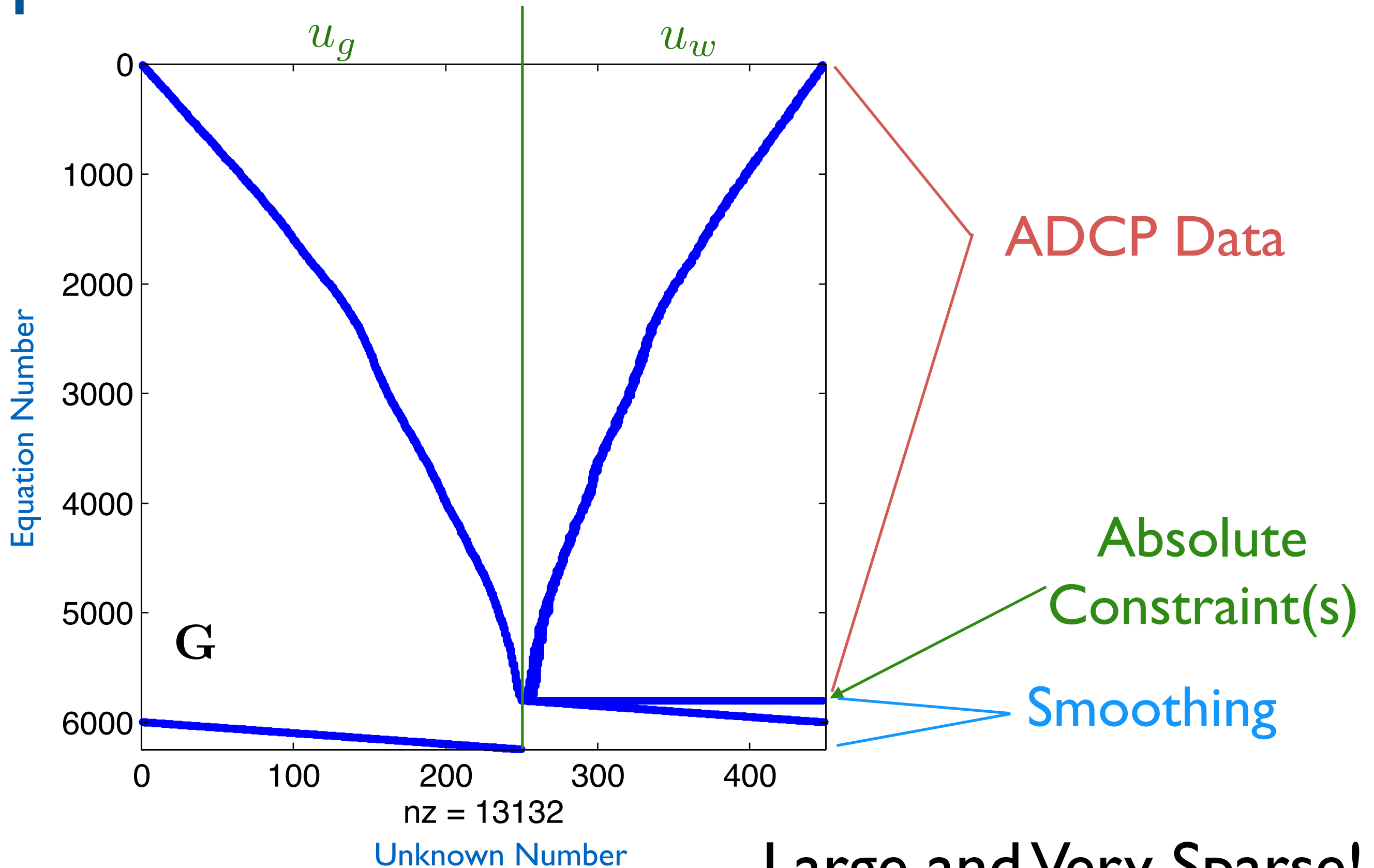
- Element added to $\mathbf{d}$:

$$u_{\text{surf}}$$

- Need weights for absolute constraints.

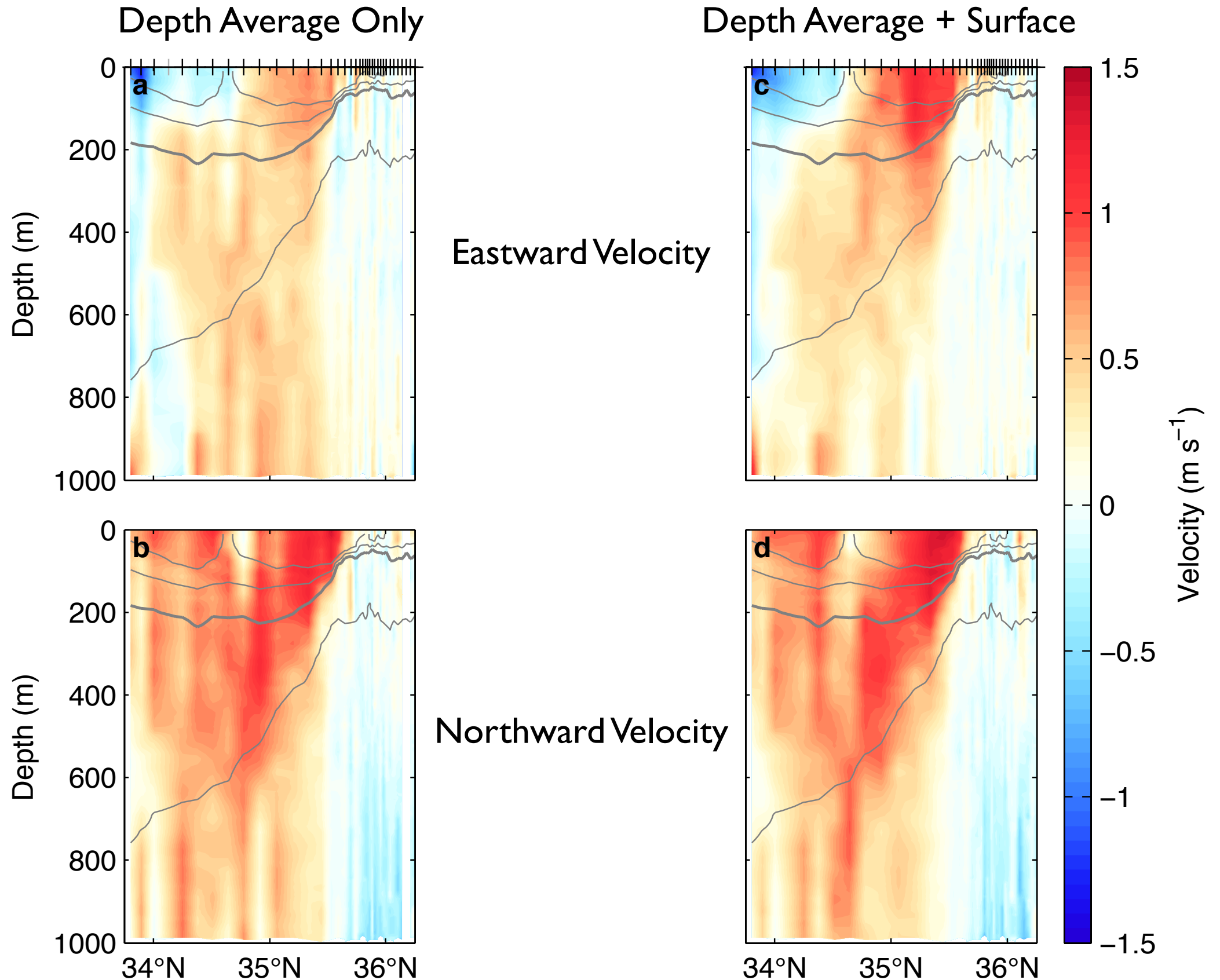


Inverse Method: Complete Problem

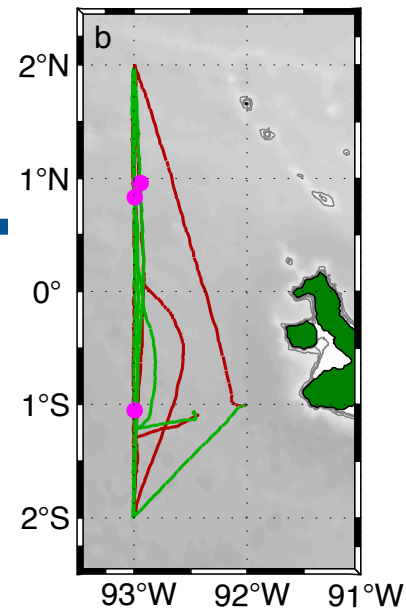
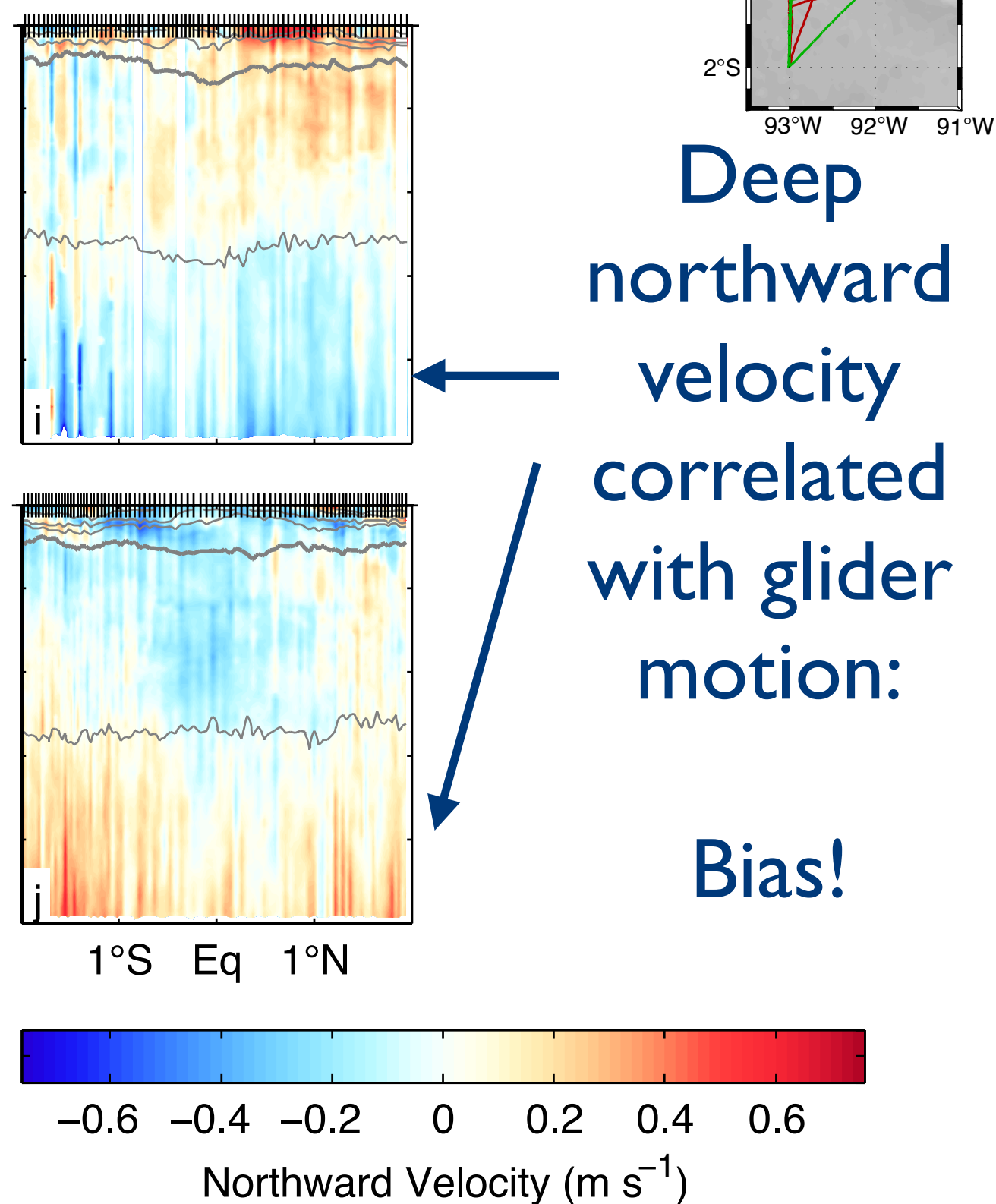
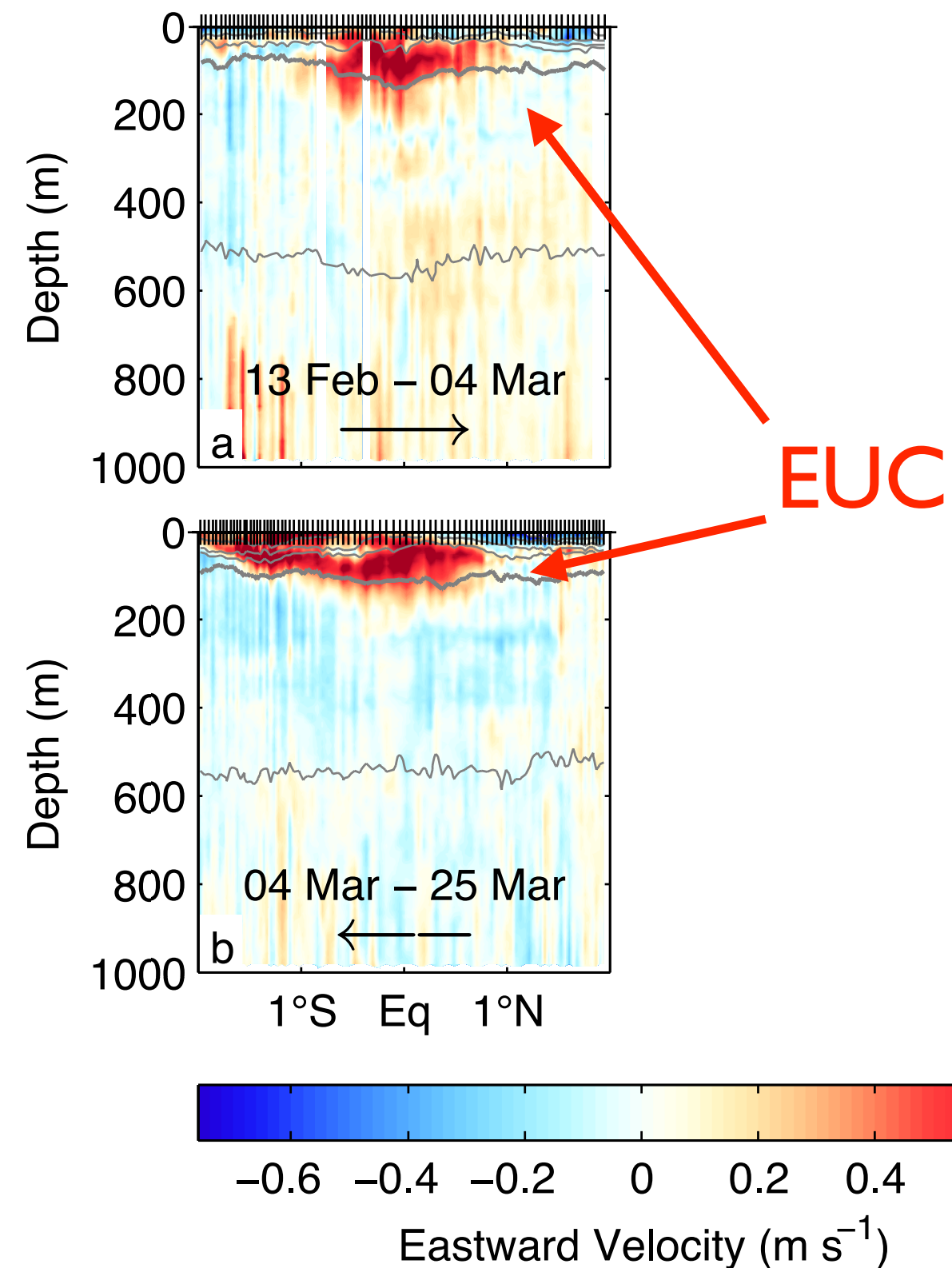


Large and Very Sparse!

Example: Gulf Stream near Cape Hatteras

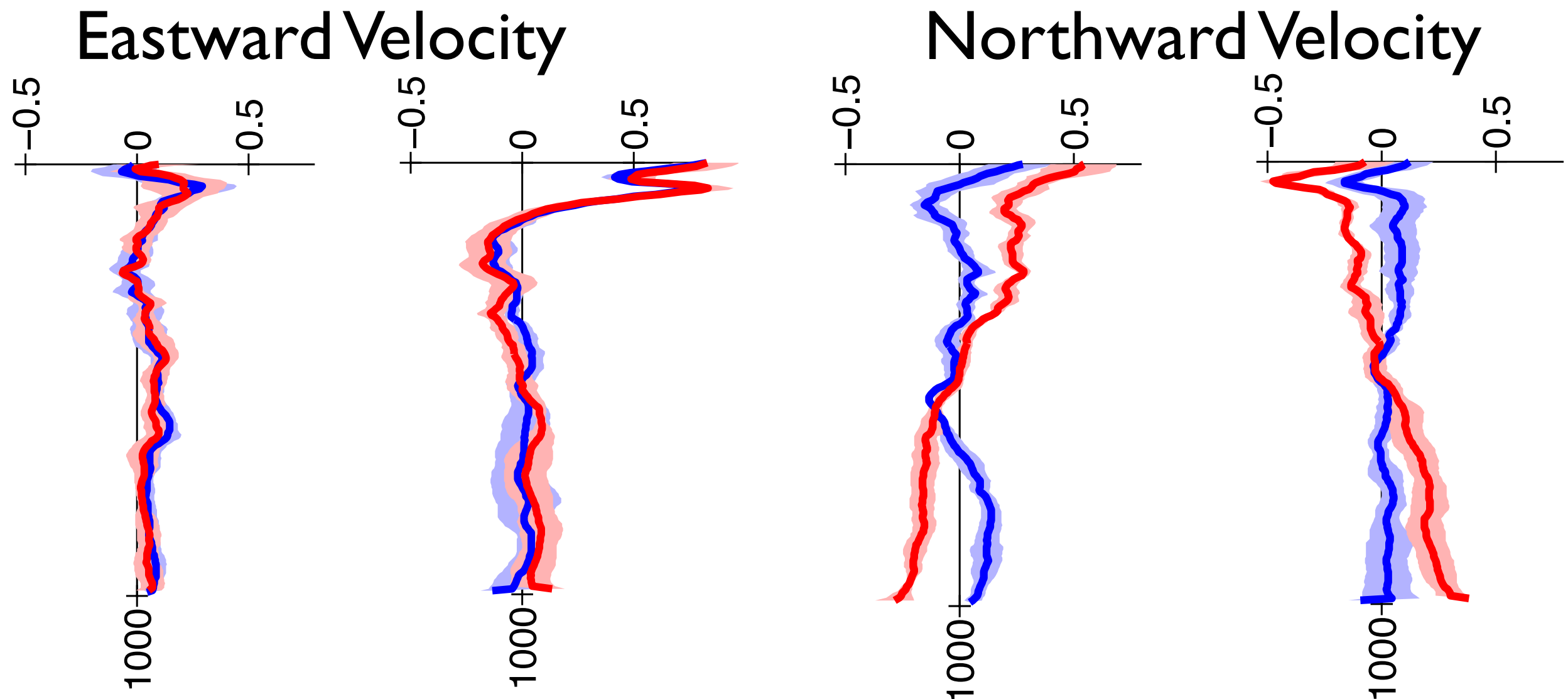


Example: Eastern Equatorial Pacific



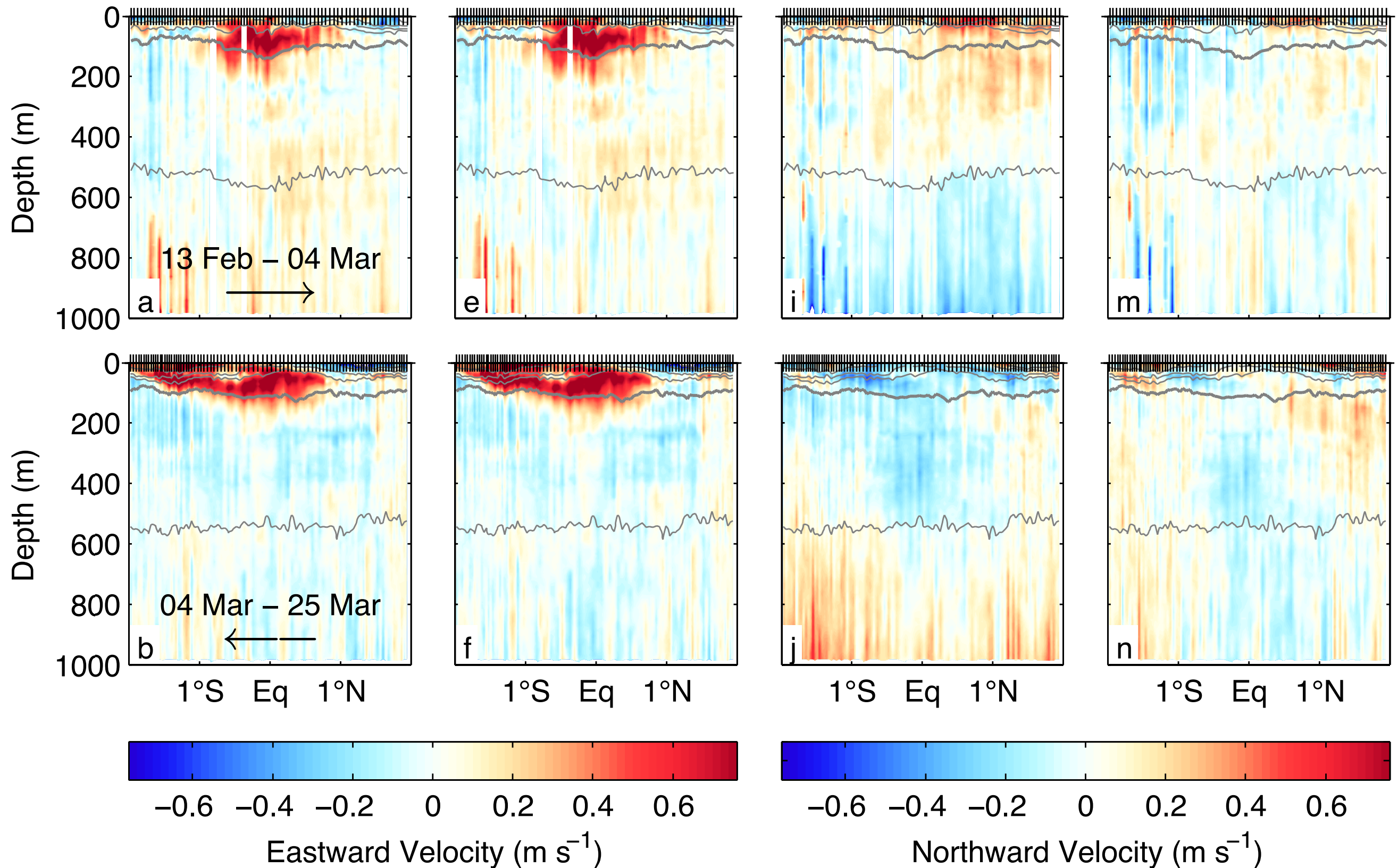
Heading Dependent Error

Eastward (cross-track) agreement between independent gliders.
Northward (along-track) disparity between independent gliders.

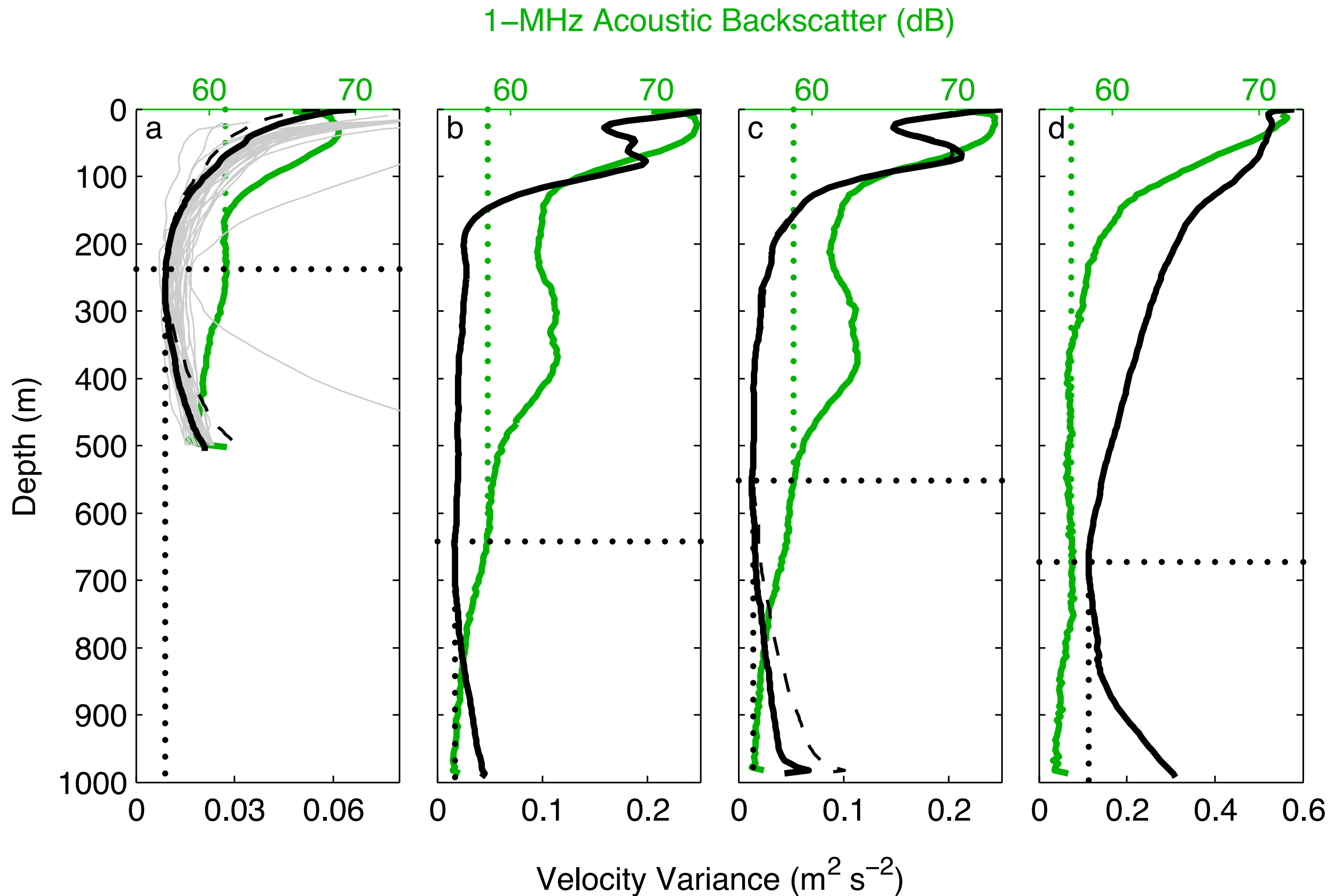


Bias Correction: Remove linear profile in glider frame of reference with slope chosen to minimize deep variance.

Example: Eastern Equatorial Pacific



Assessing Profile Accuracy

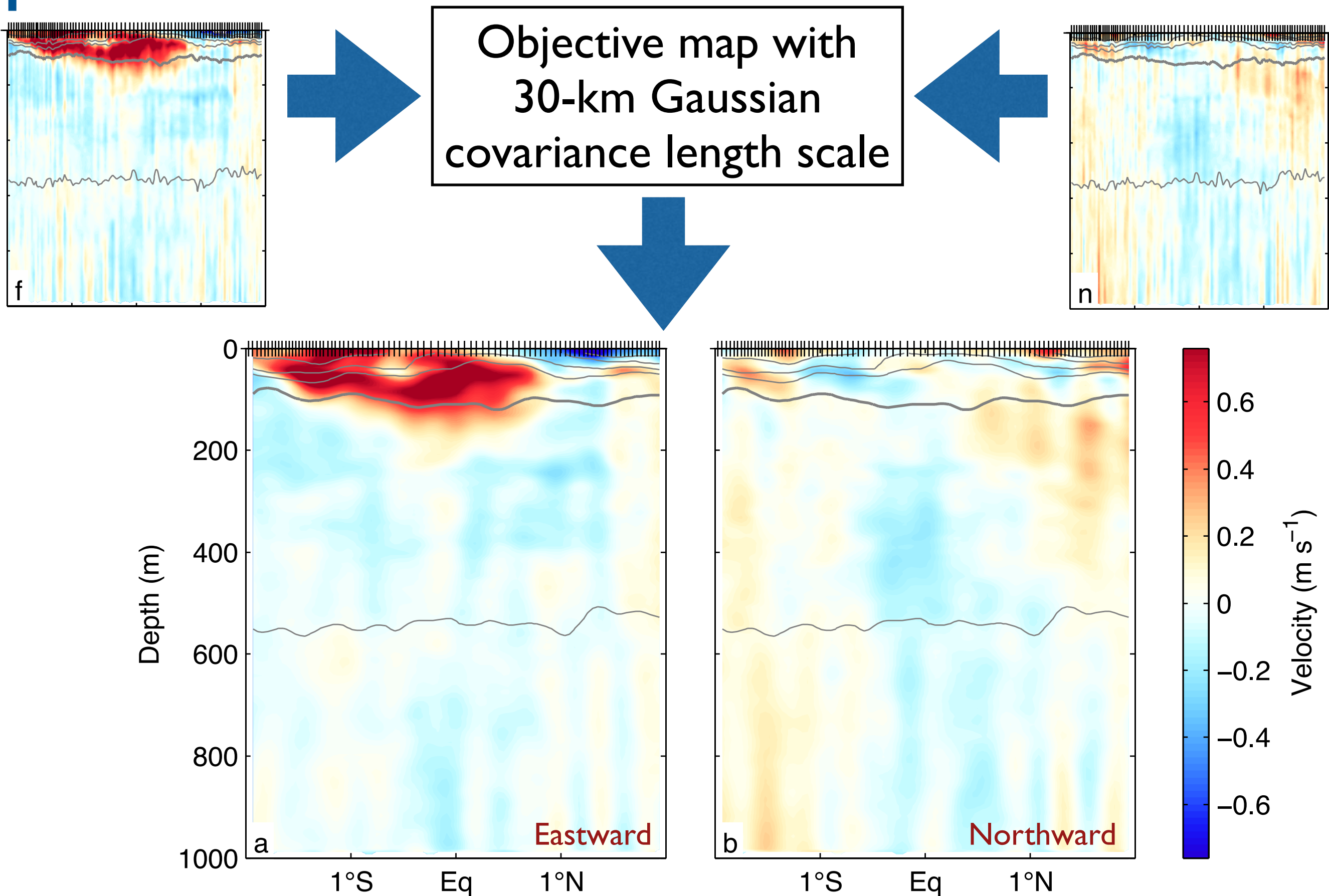


Bias and Accuracy Estimates

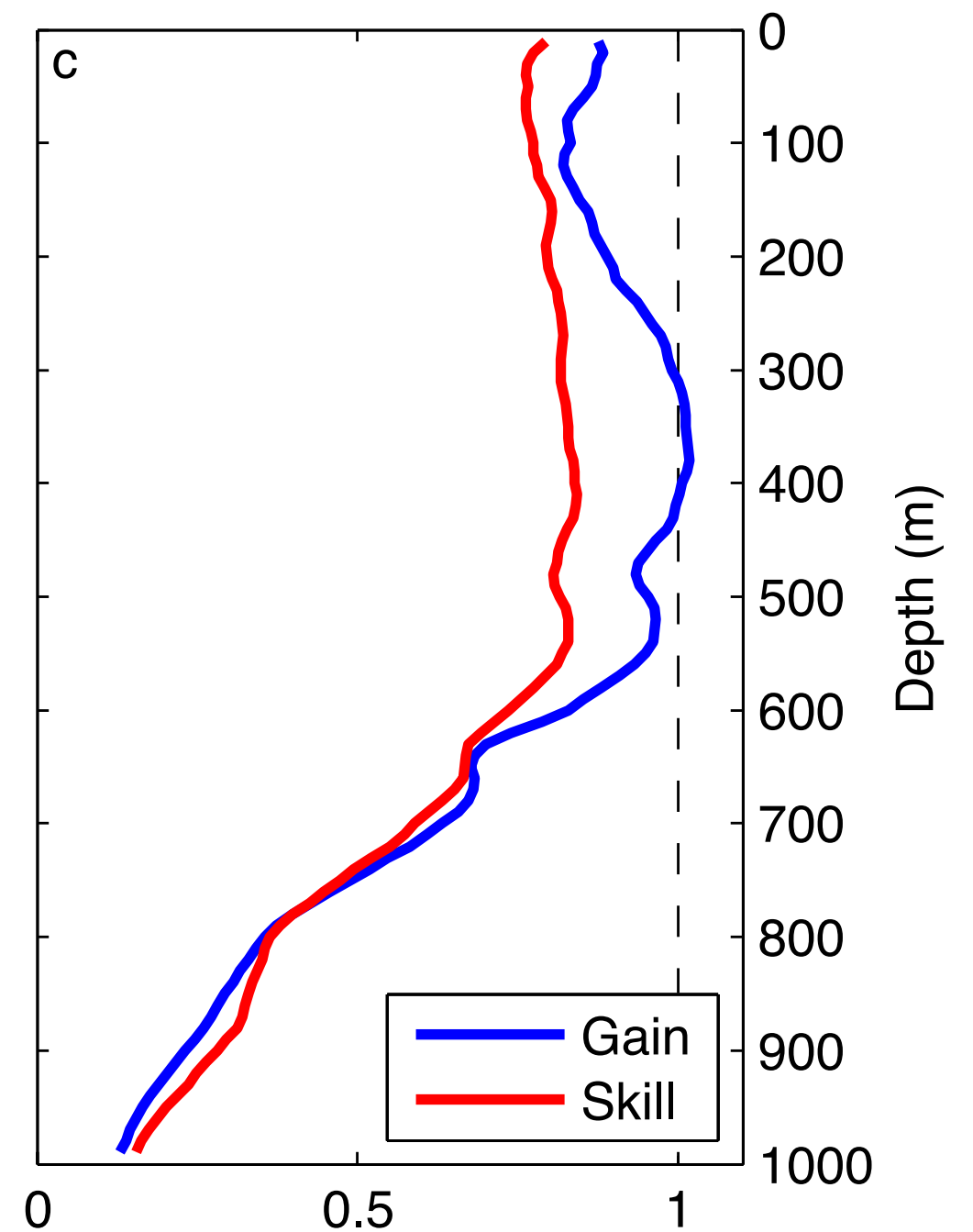
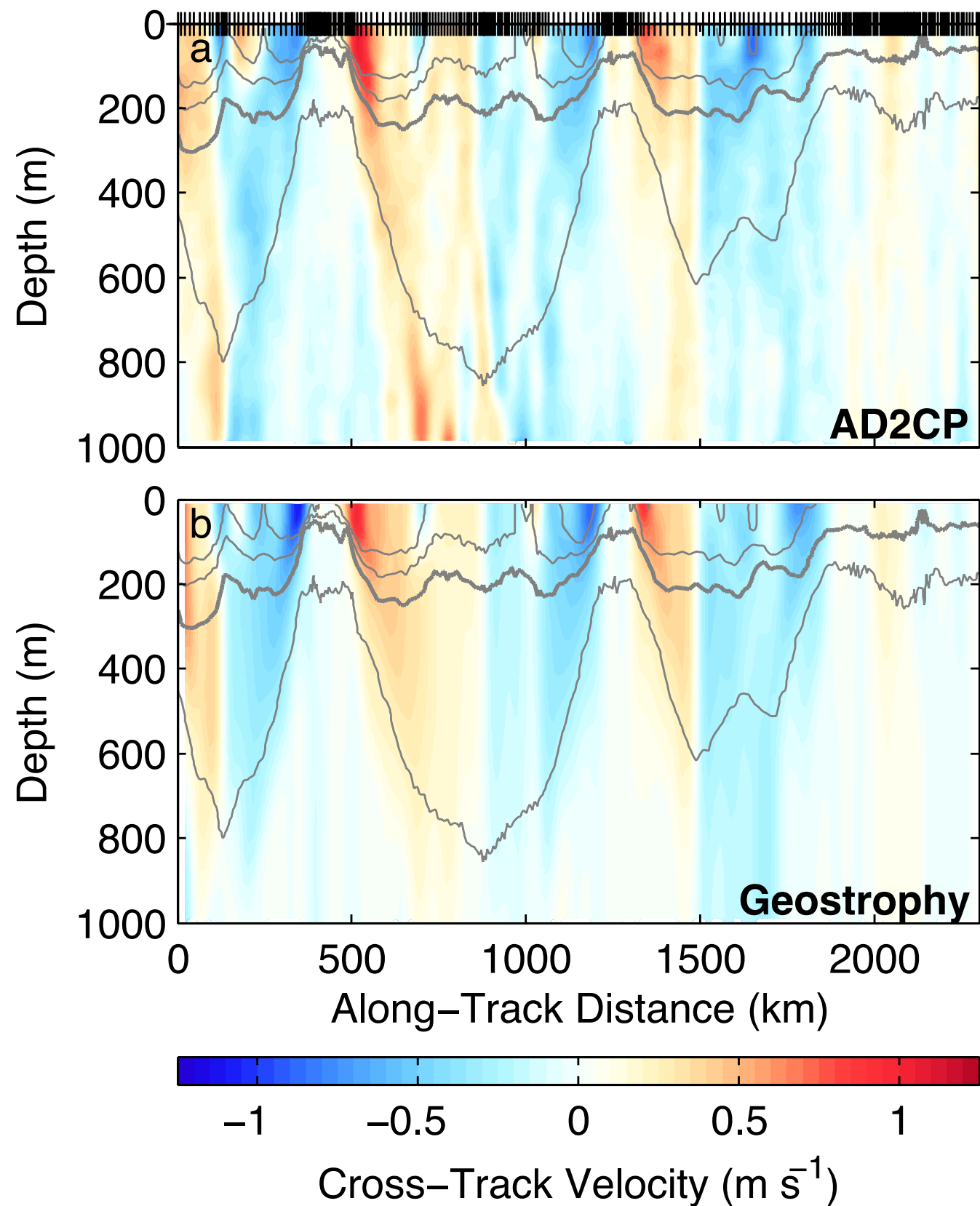
Mission	Location	Along-Glider Shear Bias	RMS Error at Depth
15030	California (500 m)	-0.46 m/s/km	0.11 m/s
152057	Galápagos (1000 m)	-0.09 m/s/km	0.17 m/s
152058	Galápagos (1000 m)	-0.41 m/s/km	0.23 m/s
15A065	Gulf Stream (1000 m)	-0.08 m/s/km	0.44 m/s

Often need to combine profiles to improve accuracy.

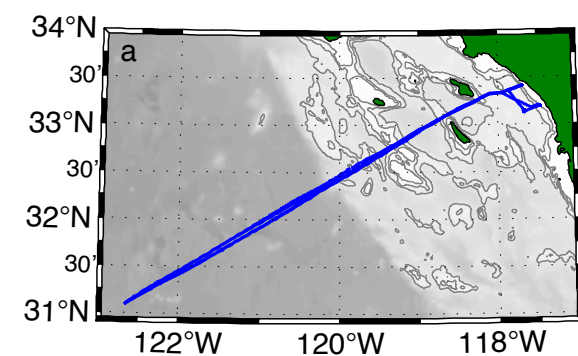
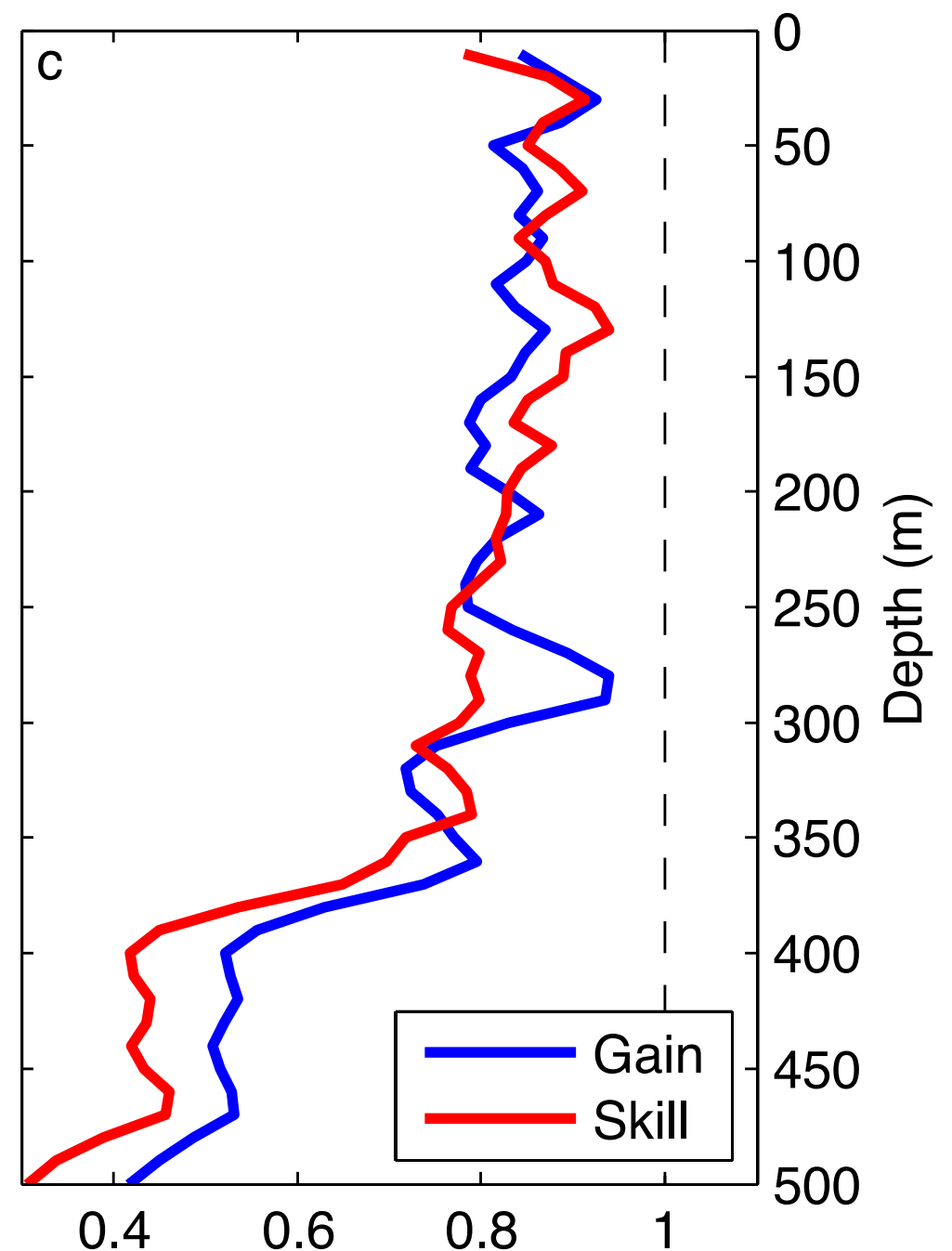
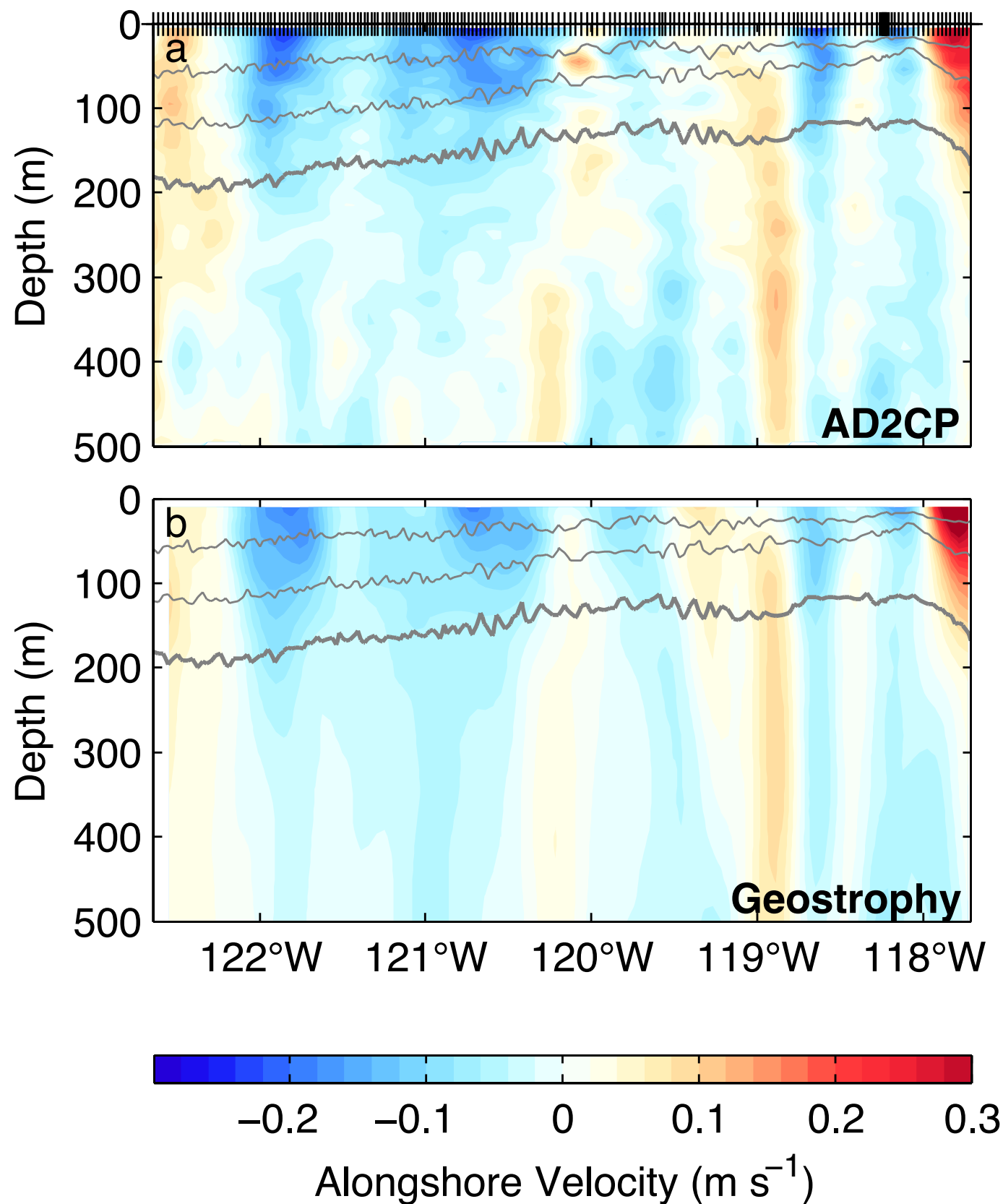
Averaging profiles



Comparisons to Geostrophy



Comparisons to Geostrophy



References

- Merckelbach, et al. (2008, IEEE Current Meas. Tech.): DAV, geostrophic, vertical velocity
- Davis (2010, J. Marine Res.): ADCP shear method
- Bouffard, et al. (2010, J. Geophys. Res.): Reference levels
- Todd, et al. (2011, J. Geophys. Res.): DAV accuracy, ADCP processing
- Frajka-Williams, et al (2011, J. Atmos. Oceanic Res.): Vertical velocity
- Rudnick, et al. (2013, J. Geophys. Res.): Vertical velocity
- Todd, et al. (2016, J. Atmos. Oceanic Tech., in review): ADCP processing, DAV correction, profile accuracy

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- Robert Todd, Woods Hole Oceanographic Institution
- Emma Heslop, SOCIB
- Atle Lohrmann, Nortek
- Charlie Eriksen, University of Washington