Seaglider ADCP Processing

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Seaglider

Seagliders are small, reusable, long-range autonomous underwater vehicles designed to glide from the ocean surface to as deep as 1000 m and back while collecting profiles of temperature, salinity, and other oceanic variables. Gliders steer through the water by controlling attitude (pitch and roll) and can thus navigate between waypoints to execute survey patterns. Typical horizontal speed is about 20 km per day. Mission durations depend largely on ambient stratification, profile depth, and instrument power, sometimes extending to nearly a year. Because the vehicles are relatively small and light, special handling gear is not required and field teams typically consist of one or, at most, two individuals. Standard sensor suites include pressure, temperature, and conductivity.

Seagliders surfaced at the end of every dive cycle, downloading new commands and uploading data to a base station located at the University of Washington via Iridium satellite telemetry. Initial processing is performed in near real-time. The different responses of temperature and conductivity sensors are accounted for and corrected through an analytical physical model (Charles Eriksen, personal communication; Morison et al., 1994; Lueck and Picklo, 1990) integrated into the base station.

A hydrodynamical flight model (Bennett et al., 2019) uses data from the glider's attitude sensors and from the environment to estimate glider speed through the water, and thus location during the dive. The hydrodynamical model provides an estimate of the horizontal distance travelled through water in an ocean at rest, which, when compared to the actual positions at the beginning and end of the dive, provides and good estimate of the depth-averaged current (or, more accurately, ocean current averaged along the underwater trajectory of the glider). Repeated GPS fixes obtained during the surface drift, before and after every call to the base station, provides an estimate of ocean surface velocity.

AD2CP processing

A Nortek Signature 1000 specifically designed for gliders has been integrated onto Seaglider, and other types of gliders (Spray; SeaExplorer; and Slocum). This is a 1 MHz ADCP with four transducers. The forward and aft beams are oriented with an angle of 40.5°, while the port and starboard beams are oriented at 25°. This asymmetry in the beam orientations allow to optimize solutions during the dive (using aft and side beams all have similar angles relative to the horizontal plane) or the climb (using the forward beam).

Typically, Seaglider collects ADCP data both on the descent and the climb, with 15 bins and a cell size of 2 m. Raw ensembles are recorded every 15 seconds (in beam coordinated). Data are also transformed in vehicle coordinate in real time and averaged every minute. These vehicle-coordinate averaged velocities are sent back in near-real time.

Inverse problem

The processing for the glider ADCP generally follows the steps described in Todd et al. (2017), which is based on L-ADCP processing (Visbeck, 2002) and subsequent developments (Todd et al., 2011; Thurnherr et al. 2015). Andrey Shcherbina (APL/UW) also worked on this problem during CABAGE and for the Lagrangian Float and shared his code.

One important, and perhaps confusing, difference is that in the Spray and LADCP processing, the inverse solves for the total vehicle velocity (U_{total}) and the ocean velocity (U_{ocean}), while our processing solves for the vehicle velocity through the water (U_{ttw}) and the ocean velocity (U_{ocean}). The total vehicle velocity is equal to the sum of the vehicle velocity plus the ocean velocity evaluated at the location of the glider (also referred as the drift in some case). They are exactly equivalent, but it makes more sense to put all ocean velocity together in order to choose the constraints better.

The ADCP measures the velocity of the water relative to the glider. In Earth coordinate, this is $U_{relative}(t,z) = U_{ocean}(z) – U_{total}(t,z0)$, where $U_{ocean}(z)$ is the ocean velocity at the location of the measurement cell and $U_{total}(t,z0)$ is the total vehicle velocity (relative to the Earth), which is itself equal to the velocity of the glider through the water and the ocean velocity at the location of the glider (z0), i.e., $U_{ttw}(t)+U_{ocean}(z0)$. That is Eq. 3 of Todd et al. 2017. We setup the inverse problem **d** = **Gm**, with the solution **m** = $(\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\mathbf{d}$, with the measurement matrix **m**:

$$\mathbf{m}= [u_{ttw,1}\ u_{ttw,1}\ ...\ u_{ttw,N}\ |\ u1_{ocean,1}\ u1_{ocean,2}\ ...\ u1_{ocean,M}\ |\ u2_{ocean,1}\ u2_{ocean,2}\ ...\ u2_{ocean,M}],$$

where N is the number of ensembles (timeseries of $U_{ttw}(t)$) and M is the number of vertical bins in the gridded ocean velocity $U_{ocean}(z)$. Because Seaglider typically sample the ADCP both on the descent and on the climb, we calculate two ocean velocity profiles ($u1_{ocean}$ and $u2_{ocean}$).

The data matrix **d** consists of all the measurements from the ADCP (N ensembles of 15 bins each):

$$\mathbf{d}= [u_{1,bin1}\ u_{1,bin2}\ ...\ u_{1,bin15}\ u_{2,bin1}\ ...\ u_{N,bin15}].$$

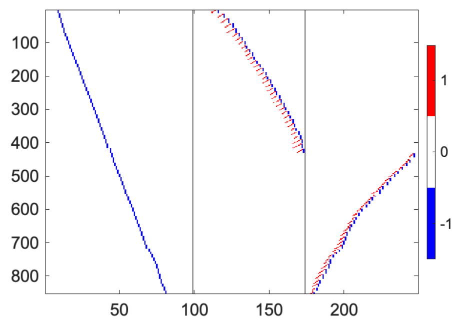
Note that both **m** and **d** are column vectors, written here as row vector for clarity. As explained above, each ADCP measurements (in the Earth coordinate) is the sum of the speed of the glider through the water and of the relative ocean velocity, for example:

$$u_{1,bin1}(t)= -U_{ttw}(t) + U_{ocean}\ (z_{bin1}) - U_{ocean}(z_{glider})$$

The matrix G consist of two parts: (1) the “ttw” part, which multiplies the vehicle speed part of **m** and which consists of a matrix selecting the vehicle ttw velocity at the time of each ADCP measurement, **Av** in the code. (2) The “ocean” part, which multiplies the ocean speed part of **m** (here $u1_{ocean}$ and $u2_{ocean}$ since we solve for the down and up ocean profile separately), corresponding the relative ocean velocity, obtained from a matrix **AiM** assigning the vertical (ocean profile) grid to the measurement position; and a matrix assigning the vertical grid to the vehicle position expressed at every measurement position, **AiG.** The latter is obtained by multiplying a matrix assigning the vertical grid to the vehicle position **Ai0** by **Av**. Since the ADCP bins nor the vehicle position exactly match the ocean grid, we use fractional index to indicate how much each ocean bin contributes to the measurements. In the end, sum(AiM,2)=1 and sum(AiG,2)=1.

The measurement matrix **G** is therefore a bit different than that of Todd et al. 2017 (and Visbeck 2002), as it includes the ocean velocity at the glider position, because we solve for the vehicle velocity through the water (U_{ttw}) as opposed to the total velocity (U_{ocean} + U_{ttw}).

For example (dive 4 of SG171 EKAMSAT_Apr24 real-time data), with N=99 (number of ensembles), M = 75 (ocean grid points), our matrices **G_adcp, m,** and **d** looks like:

G_adcp=		$\boldsymbol{m} = \begin{bmatrix} u_{ttw,1} \\ u_{ttw,2} \\ \dots \\ u_{ttw,N} \\ u1_{ocean,z1} \\ \dots \\ u2_{ocean,z1} \\ \dots \\ u2_{ocean,zM} \end{bmatrix},$	$\boldsymbol{d} = \begin{bmatrix} u_{1,bin1} \\ u_{1,bin2} \\ \dots \\ u_{1,bin15} \\ u_{2,bin1} \\ \dots \\ u_{N,bin1} \\ \dots \\ u_{N,bin15} \end{bmatrix},$
	Ndata x (N + M +M)	(N + M + M) x 1	Ndata x 1

Here the first 99 columns correspond to - $U_{ttw}(t)$, and the next two groups of 75 columns correspond to the two ocean profiles, with both the (positive) values of the ocean velocity at the bin minus the ocean velocity at the glider (negative blue). Rows are each valid ADCP measurements, roughly the number of ensembles times the number of bins (Ndata ≈ N x 15, here 854 instead of 1485 after removing the bad ADCP measurements). The first and last few ensembles in this case contain no valid measurements, hence the lack of values in the first 13 columns of **G_adcp**.

The constraints are included by adding additional rows to the **G** matrix.

A constraint for the total displacement of the glider during the dive obtained from gps positions before and after the dive can be enforced by ensuring that the average total speed ($U_{ttw}(t)$+ U_{ocean} at the glider) matches the mean speed from the pre and post-dive position.

G_dac= [**w** **w**×**Ai0**]	$\boldsymbol{d}_{\mathrm{dac}} = \mathrm{UV}_{total}$
1 x (N + M +M)	1 x 1

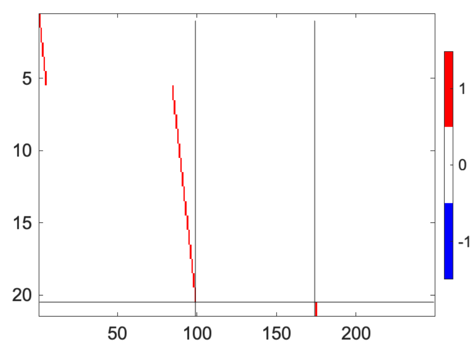
where w is a 1xN matrix that is non-zero during the dive, with elements that make it a time-average using trapezoid rules. Recall that **Ai0** is the matrix assigning the vertical grid to the vehicle position. **w**×**Ai0** is therefore the contribution of the ocean velocity at the location of the glider to the time averaged total velocity. UV_{total} is the distance between the gps positions divided by their time interval.

The smoothness constraints for $U_{ttw}(t)$ and $U_{ocean}(z)$ are the same as in the L-ADCP case (Visbeck 2002).

Dv= $\begin{bmatrix} -1 & +2 & -1 & +0 & \dots & 0 \\ 0 & -1 & +2 & -1 & \dots & 0 \\ 0 & 0 & -1 & +2 & \dots & 0 \\ 0 & 0 & 0 & 0 & \dots & -1 \end{bmatrix} \begin{vmatrix} 0 & \dots & 0 \\ \dots & \dots & \dots \\ 0 & \dots & 0 \end{vmatrix} \begin{matrix} 0 & \dots & 0 \\ \dots & \dots & \dots \\ 0 & \dots & 0 \end{matrix}\Bigg]$	$\boldsymbol{d_{smooth}} = \begin{bmatrix} 0 \\ \dots \\ 0 \end{bmatrix}$
Ndata x (N + M +M)	(N + M + M) x 1

… and similarly for the smoothness of the ocean profile, **Do**, where the (-1 , 2 , -1) smoothness operator is applied to the ocean columns (last two blocks of M columns).

Separating the vehicle velocity through the water from the total velocity allows to more easily apply other constraints. We enforce that $U_{ttw}(t)$ is zero during the surface drift. U_{ocean} is also (weakly) constrained to be like the surface drifts estimated from gps.

G_sfc=		$\boldsymbol{d_{sfc}} = \begin{bmatrix} 0 \\ \dots \\ 0 \\ U_{gps} \end{bmatrix},$
	21 x (N + M +M)	21 x 1

Here the first 6 and the last 14 ADCP ensembles are when the glider is at the surface, and therefore $U_{ttw}(t)$ is constrained to be zero during that time (first 20 rows of **G_sfc**). For this particular dive, the only additional GPS constraint available is at the end of the dive, so the top bin of the second ocean profile (column M+N+1) is constrained to be the speed estimated from gps fixes during the surface drift.

Similarly, $U_{ttw}(t)$ is constrained to be zero at the bottom of the dive, by building a **G_deep** matrix with non-zero values only in the first N columns corresponding to the apogee, and zero in the **d_deep** matrix (similar to the first 20 rows of **G_sfc** and **d_sfc**).

When we build the final G matrix, all the constraints are weighted relative to each other by multiplying both the **G** matrices and their corresponding **d** matrix by a given weight. This allows us to enforce these constraints with relative importance (e.g., surface ocean velocity doesn't exactly have to be the gps drifts).

The two ocean velocity profiles are also constrained to be similar, with a weight that decreases as the time interval between measurements increases (i.e., weight is maximum at the bottom, minimum at the top).

We tried to constrain $U_{ttw}(t)$ to be close to the flight model, but it seems to create more problems than helping to constrain the solution. However, if only the down or up profile is available (for energy saving reason, or any problem with part of the dive), we enforce that the vehicle velocity (U_{ttw}) is close to the flight model when ADCP data are not available, and that the two ocean profiles (U_{ocean}, dn and up) are the same.

Vertical velocity inverse

In addition to the traditional inverse for (horizontal) speed through the water and (horizontal) ocean velocity profile, I also add an inverse to estimate the vertical velocity of the glider through the water, and the vertical ocean velocity. The inverse is very similar, but with less constrains. One additional constraint is that the depth-average vertical velocity has to be zero.

Raw data processing

The program *ADCP_inverse_example.m* shows the processing steps. Data for this example are saved in the processing directory. Data from the glider (profile netcdf file) and raw ADCP data (in beam coordinates) are loaded and cleaned. It seems that the ADCP pressure might have offsets, so we use the glider pressure. Weights for the various constraints are set, and the inverse is done by *ad2cp_inverse4.m* A lot of the code to load and transform the data originates from Andrey Shcherbina and others, so dependencies are a bit messy (hence all the other programs in the folder).

Figure 1 and Figure 2 show the results for this particular dive.

The inverse solution for the total vehicle speed over ground (UVveh_solution) can be integrated to estimate the displacement of the glider while underwater (Fig 4). This is an improvement over the more typical underwater track, estimated by adding a uniform depth-averaged current to the flight model results. Ocean advection of the glider is greater near the surface.

This processing is done for all the dives in a given mission(Fig 4).
ADCP_inverse_dn_up_mission_2023.m

Realtime data processing

The glider netcdf includes the near-realtime data, processed onboard and telemetered during the mission. The realtime data has already been transformed in earth coordinates and averaged (60 sec averages). However, it seems that the data is different enough to produce a different solution – perhaps because of the way the glider averages. This need to be tracked down. Stay tuned.

Also, because we only return the 1-min averages in earth coordinates, the inverse transformation to calculate the velocities in the glider frame of reference (if we wanted to use them for the flight model, say) is not very accurate.

Data structure

For each dive, the results for the inverse solution in structure arrays "D" (time series) and "profile". The latter structure is a version of the timeseries gridded on the regular vertical grid.

D is a structure array with fields:

- Mtime: time in matlab day (on the ADCP time sampling grid)
- UV: horizontal velocity in Earth coordinates measured by the glider as a function of range and time.
- W: vertical velocity in Earth coordinates measured by the glider as a function of range and time.

- Z: depth of each ADCP bins (as a function of range and time).
- Z0: depth of the glider as a function of time.
- upcast: 0 for downcast, 1 for updast.
- UVttw_model: flight model estimate of horizontal velocity of the glider through the water on ADCP time.
- UVmodel_total: flight model + flight model estimate of dac (uniform) on ADCP time grid
- Wttw_model: flight model estimate of vertical velocity of the glider through the water on ADCP time.
- T: temperature as a function of time at the glider location
- UVocn_solution: Inverse solution of horizontal ocean velocity at the location of the glider.
- UVttw_solution: Inverse solution of horizontal glider velocity through the water
- UVveh_solution: Inverse solution of the total glider velocity (throught the water + ocean drift)
- UVocn_adcp: Estimate of ocean velocity from ADCP (measurements minus glider motion).
- UVerr: Estimate of the error of the solution
- Wttw_solution: Inverse solution of vertical glider velocity at the location of the glider
- Wocn_solution Inverse solution of vertical ocean velocity at the location of the glider

profile is a structure array with fields:

- z:
- UVocn
- UVttw_solution:
- UVttw_model:
- time:
- UVerr
- Wocn
- Wttw_solution:
- Wttw_model

When processing the whole mission, the “profile” structure arrays for each dive are accumulated in a adcp_grid_raw or adcp_grid_realtime array, gridded in depth (and profiles), with the same fields. In addition, for raw data processing, we also save:

timeseries_adcp is a structure array with fields:

- time: adcp time grid
- Ux: measured relative velocity in the “x” axis of the glider coordinate (forward, tail to nose).
- Uy: measured relative velocity in the “y” axis of the glider coordinate (towards port).
- Uz: measured relative velocity in the “z” axis of the glider coordinate (towards top of glider).
- speed_ttw_solution: speed of the glider through the water from the inverse solution. Vector sum of UVttw_solution and Wttw_solution

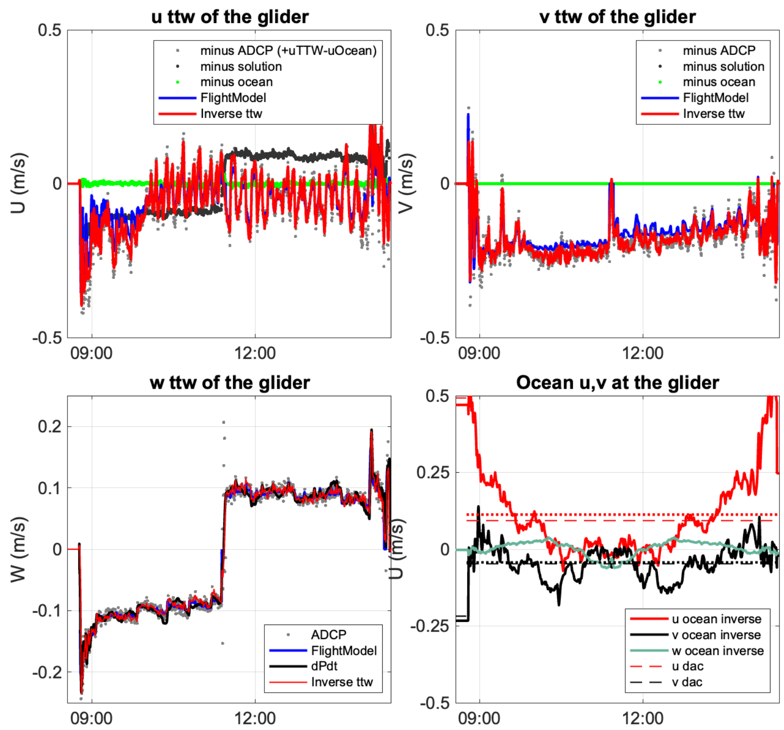


Figure 1: Example of the results for SG219 dive 275 during SMODE1, across a front. Here the vehicle velocity through the water (ttw) and the ocean velocity at the glider are plotted as timeseries.

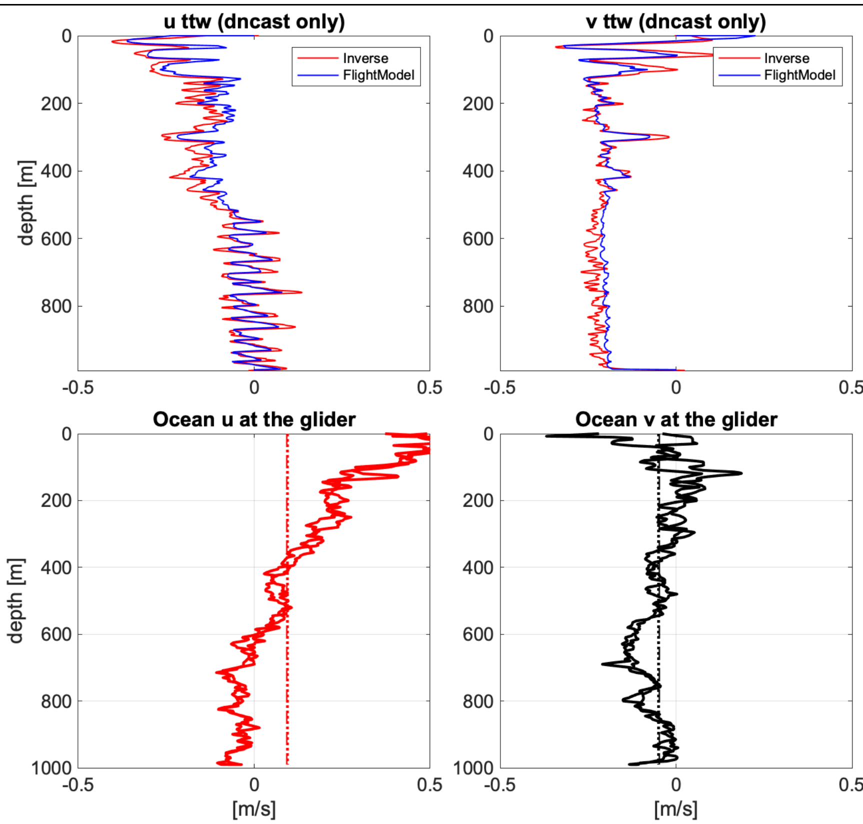


Figure 2: Vertical profiles of horizontal glider velocities (top) and horizontal ocean velocities (bottom).

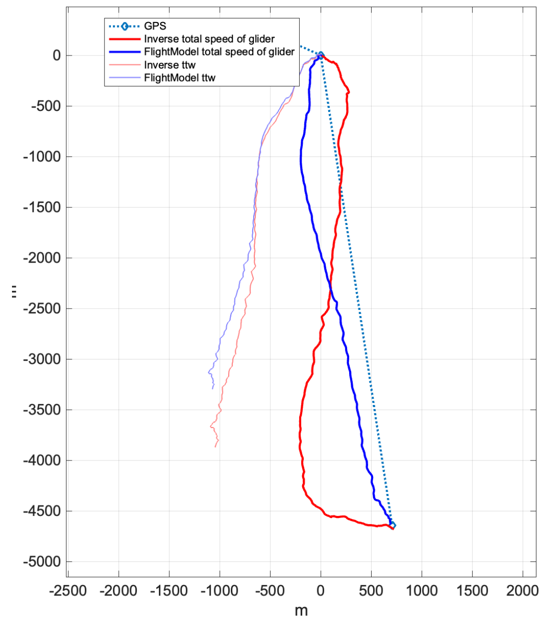


Figure 3: Displacement of SG219 as a function during dive 275 during S-MODE1 (2021). Estimate of total displacements over ground is shown by the thick lines for the flight model (blue) and the ADCP inverse solution (red). Displacements through the water are shown by thin lines.

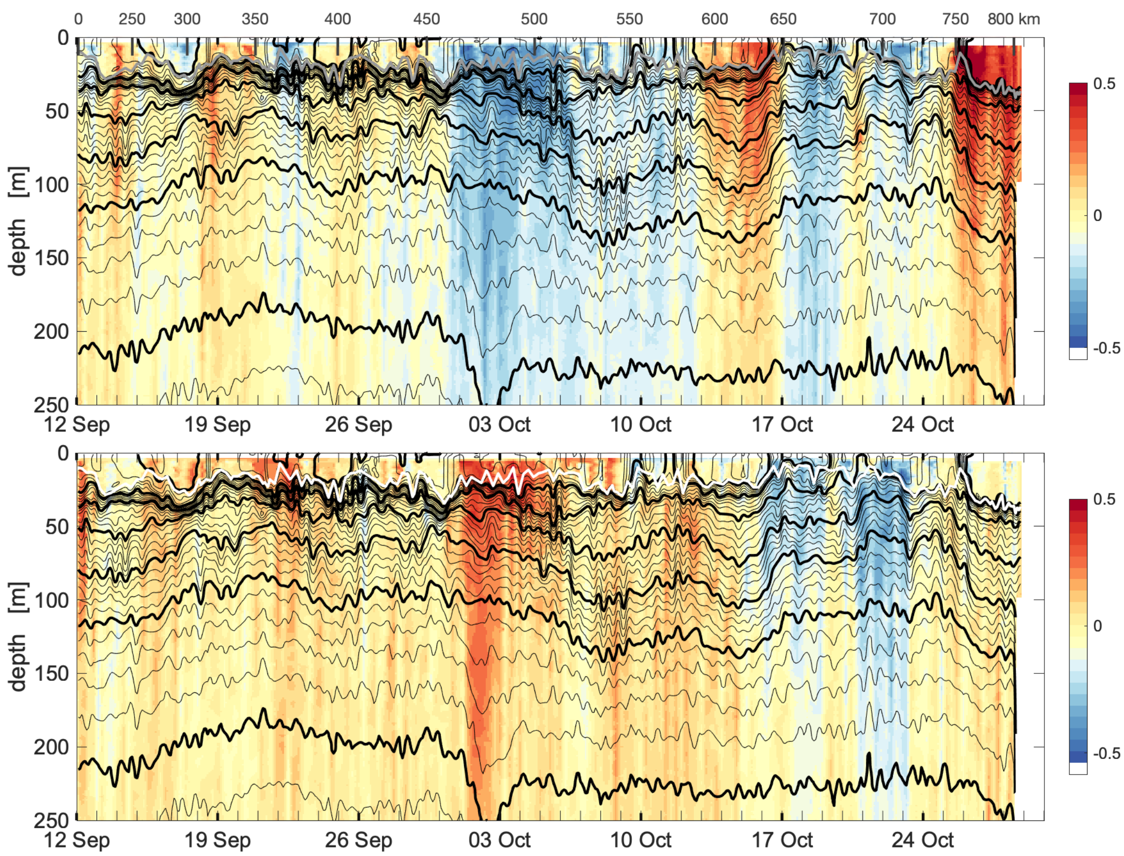


Figure 4: Time series of east (top) and north (bottom) velocity from SG219 as a function of depth and time during S-MODE1 (2021). Only the top 250m out of 1000m are plotted. Black contours are isopycnals (0.1 kg m^{-3} intervals, 0.5 in bold), with the mixed layer depth in white. Cumulative track distance is plotted along the top axis. Dive 275 (Figs 1,2) is on 29 Oct, near the end of the deployment.

References

Thurnherr, A. M., D. Symonds and L. St. Laurent, 2015. Processing explorer ADCP data collected on slocum gliders using the LADCP shear method, IEEE/OES Eleveth Current, Waves and Turbulence Measurement (CWTM), St. Petersburg, FL, USA, 2015, pp. 1-7, doi: 10.1109/CWTM.2015.7098134.

Todd, R. E., D. L. Rudnick, M. R. Mazloff, R. E. Davis, and B. D. Cornuelle, 2011: Poleward flows in the southern California Current System: Glider observations and numerical simulation. J. Geophys. Res., 116, C02026, doi:10.1029/2010JC006536.

Todd, R. E., Rudnick, D. L., Sherman, J. T., Owens, W. B., & George, L. 2017. Absolute Velocity Estimates from Autonomous Underwater Gliders Equipped with Doppler Current Profilers, Journal of Atmospheric and Oceanic Technology, 34(2), 309-333.

Visbeck, M., 2002. Deep velocity profiling using lowered acoustic Doppler current profilers: Bottom track and inverse solutions. J. Atmos. Oceanic Technol., 19, 794–807, doi:10.1175/