# 2021 GO-SHIP A20 LADCP Post-Cruise QC Report

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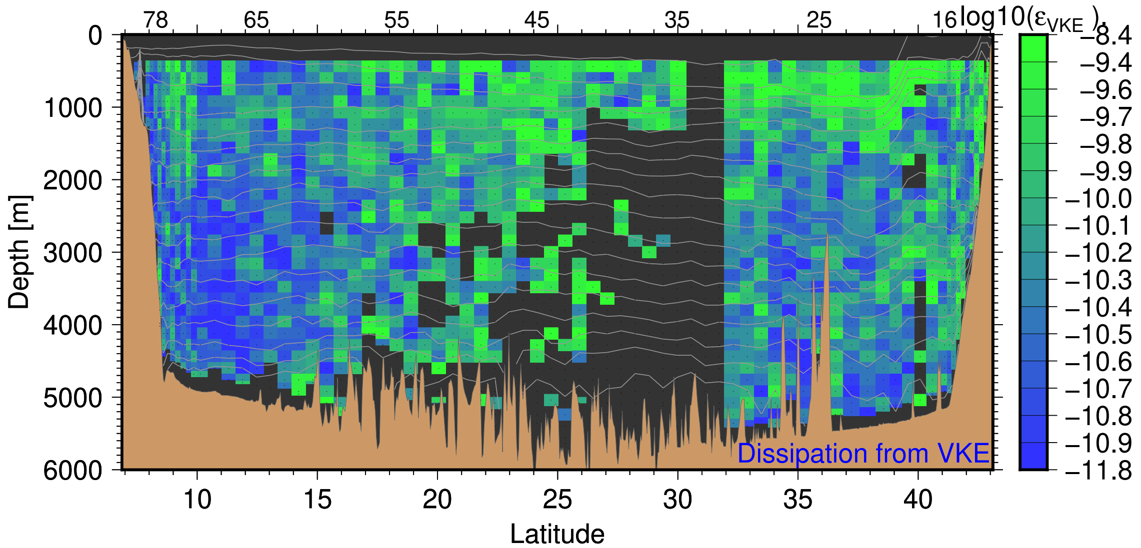


Figure 1: Kinetic energy dissipation in units of $\mathrm{W \cdot kg^{-1}}$ from a finescale parameterization based on vertical kinetic energy ($\epsilon_{\mathrm{VKE}}$) overlaid with $\sigma_2$ potential-density contours. VKE in the upper 300 m are contaminated, perhaps by moving organisms. Gaps below that depth, indicating fewer than 2 spectral estimates in a window, are mostly caused by insufficient instrument range. The figure was produced from the default output of the `LADCP_w` software, version 2.1, applied to the A20 LADCP data, without any manual filtering or modification of the default processing parameters. See Section 7 below for a discussion of the main spatial patterns apparent in this figure.

## 1 Summary

This report describes the results from the post-cruise quality control of the LADCP data collected during the 2021 GO-SHIP re-occupation of the A20 repeat hydrography section with the UNOLS vessel R/V *Thomas G. Thompson.* Using two ADCPs installed on the CTD rosette, one looking downward (DL) and the other upward (UL), as well as an independent IMU, full-depth profiles of all three components of the oceanic velocity field were collected at all stations. The cruise track crosses

a region with extremely low acoustic backscatter, causing gaps in the LADCP data coverage. For the horizontal velocities, the data gaps had to be determined manually and removed from the profiles before archiving. For the vertical velocities the processing software automatically filters out the bad data, implying that no user interaction is required to produce the final data set, including the section of parameterized turbulence levels shown in Figure 1. Outside the region of low backscatter where no LADCP velocities are available, the quality of both horizontal and vertical velocities is excellent, as indicated by the agreement with shipboard ADCP velocities for the former, and by high correlations between the measurements taken with the two instrument for the latter. Additional LADCP plots, as well as information about the LADCP data acquisition on this cruise can be found in the main cruise report.

# 2 Instrumentation

Several different ADCPs were used during this cruise. A single 300kHz TRDI Workhorse Monitor ADCP (WH300, s/n 12734), fitted with a custom self-recording accelerometer/magnetometer package (called IMP), was installed as the uplooker during all casts. In contrast, several different instruments were installed as downlookers during different casts. For the shakedown cast (900) a prototype Nortek Signature 100 ADCP (Sig100) was installed for testing. Since this instrument did not provide good data, it was replaced with a 150kHz TRDI Workhorse ADCP (WH150, s/n 19394). While the WH150 performed reasonably well, some of the processing diagnostic from the uplooker WH300 were noticeably cleaner. Therefore, for station 018 the WH150 was replaced with a second WH300 (s/n 24497). This instrument performed very similar to the WH150. As there was no apparent difference in the quality of the processed profiles before and after station 018 the WH300 (s/n 24497) was left installed until profile 031. In the mean time, the Nortek prototype was modified with guidance from the manufacturer and reinstalled for three casts on stations 032–034. While the data had improved from the shakedown cast, the quality of the recorded velocities was still considerably worse than those from the TRDI instruments. Therefore, the Sig100 was removed from the rosette after profile 034 and replaced by the WH150 used before on stations 1–17. While this instrument performed well for a few casts its range deteriorated gradually but quite quickly to the point of not returning any bins with valid velocities at depth on station 041. The instrument was therefore replaced (again) for station 042 with the WH300 s/n 24497 which had been used before on stations 018–031. While this instrument yielded very good data, several profiles showed strange echo-amplitude anomalies affecting a small number of the recorded ensembles. When, on station 052, the data from this instrument additionally contained an unexplained gap of 1.5s, it was decided to swap the downlooker with another spare (WH300 s/n 24477). This final instrument performed well and was left in place for the remainder of the cruise (profiles 053-090).

After the cruise, the data from the IMP (magnetometer and accelerometer) were downloaded and processed as described by Thurnherr et al. (J. Tech., 2017), and the resulting replacement time series of pitch, roll and heading were merged with the raw ADCP data files, which are suitable for processing with standard software. Figure 2 shows the heading-dependent errors of the two ADCP compasses in a random profile.

# 3 Sampling Conditions

Figure 3 shows the maximum depths as well as the number of net rotations experienced by the CTD package during each profile. Apart for the continental slopes at either end, the average profile depth is ≈5000 m with smooth abyssal plain topography in the north and south bracketing topographically

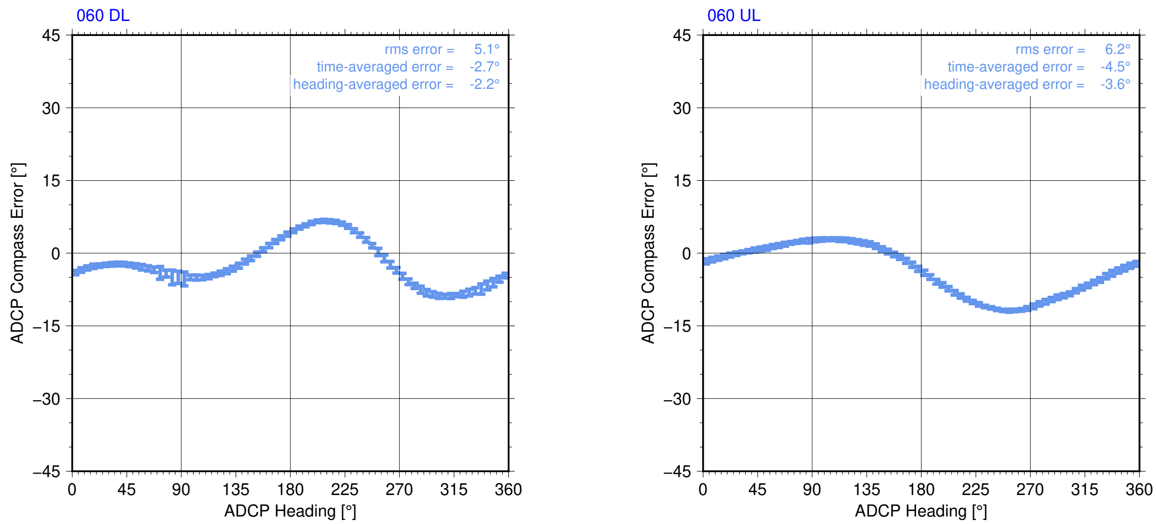


Figure 2: Heading dependent errors of the two ADCP compasses in a random profile; it is these errors that are corrected for by using external magnetometer data.

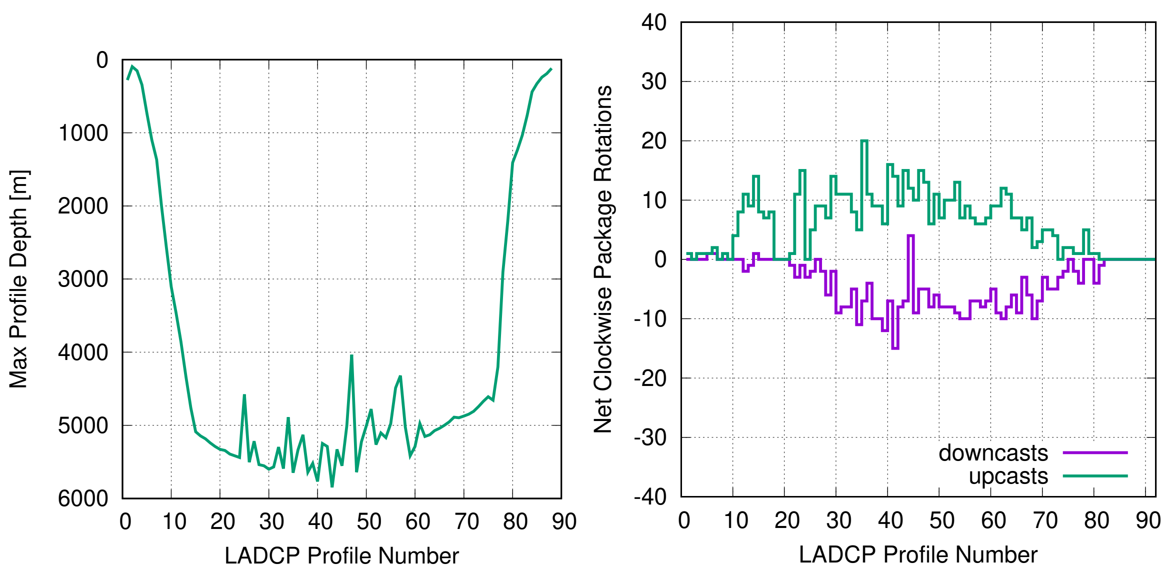


Figure 3: Profiling properties. Left panel: Maximum profile depth. Right panel: Net package rotations, positive indicating clockwise when viewed from above.

rough MAR-flank topography in the middle (left figure panel). Except for the first 20 profiles in deep water (stations 10–30) CTD package rotations were approximately balanced, with similar numbers of downcast counterclockwise and upcast clockwise rotations (right panel), indicating that the wire was fully adjusted to the load.

The most important parameter affecting the quality of horizontal LADCP velocities is the mea-

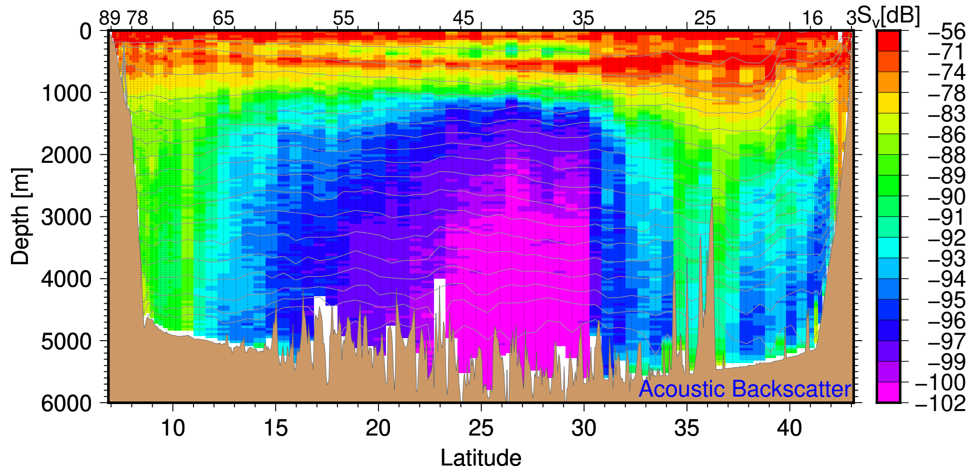


Figure 4: Downcast acoustic backscatter coefficient $S_v$ from the UL data, calculated using the vertical-velocity processing software. Based on the data from this cruise, the lower limit for collecting LADCP profiles with a dual Workhorse LADCP system is $\approx -97$ dB.

surement range of the instrument which, for a given instrument, depends primarily on the acoustic backscatter environment. Along the track of A20 the backscatter environment below about 1000 m is extremely variable with backscatter approaching zero at depth between 21° and 30°N (Figure 4). Note the extremely sharp transition in backscatter between stations 034 and 035. Other noteworthy features include the layered vertical structure in the upper 1000 m, as well as the full-water-column elevation of backscatter over the seamounts near 35°N.

The weak acoustic backscatter below 1000 m in the middle third of the section causes the measurement range of WH300 ADCPs to drop below 65 m (Figure 5, left panel), which is an empirical limit for processing of single-head LADCP profiles for horizontal velocity. While the range of the 150 kHz instrument was consistently longer than the range of the 300 kHz Workhorses, the quality of the velocity data collected with the low-frequency instrument in the region of low backscatter is poor (see below). Note that on stations 018 and 019 the DL ADCP was accidentally set to wide-band mode, which improves the single-ping velocity measurement accuracy with a penalty in instrument range. While the processed profiles from these two stations are of high quality, there is evidence from other cruises that range is more important than single-ping accuracy for horizontal LADCP velocities.

Sea state can also affect LADCP data quality with some LADCP installations; in the right panel of Figure 5 sea state is quantified as the *rms* vertical package acceleration. Conditions during the cruise ranged from calm (around $0.15\,\mathrm{m\cdot s^{-2}}$) to stormy (around $0.3\,\mathrm{m\cdot s^{-2}}$ or greater).

# 4 Horizontal Velocity QC

The overall quality of the horizontal LADCP velocities is assessed by processing all profiles with the LDEO_IX implementation of the velocity-inversion method without using the SADCP velocities to constrain the solutions, and then comparing the two independent velocity profiles in the upper

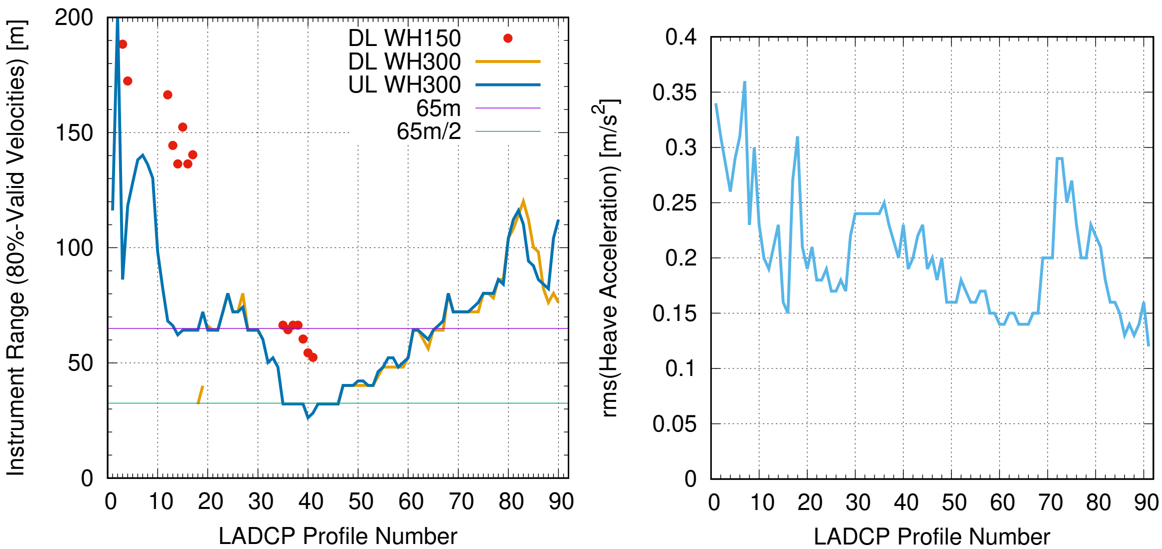


Figure 5: Left panel: Instrument ranges, with the horizontal lines indicating the minimum ranges typically required for successful processing of full-depth LADCP profiles from a dual/single 300 kHz TRDI Workhorse ADCP systems. Right panel: *rms* vertical acceleration due to vessel heave (sea state).

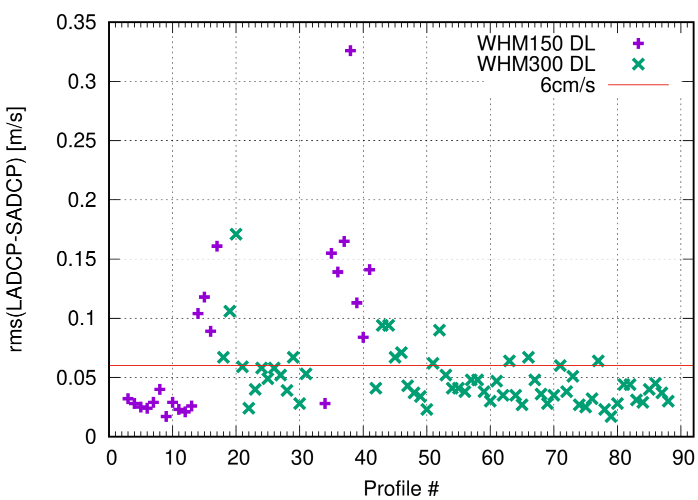


Figure 6: *rms* LADCP-SADCP horizontal velocity differences; low values indicate good agreement; overall *rms* is $4.8\,\mathrm{cm \cdot s^{-1}}$, $2\,\mathrm{mm \cdot s^{-1}}$ lower than the corresponding value from processing without the external magnetometer/accelerometer. The horizontal line indicates an empirical limit for high-quality profiles collected in regions of not-very-strong near-surface currents.

ocean; Figure 6 shows the profile-averaged *rms* velocity differences from this cruise. Based on data from many other cruises, high-quality LADCP profiles constrained with GPS and BT data typically agree with the corresponding SADCP velocities within 3–6 $cm \cdot s^{-1}$ when averaged over a few profiles. In case of the A20 data there are two profile ranges where this limit is clearly exceeded: The first encompasses profiles 014–021 collected in the Gulf Stream (see Figure 7 below), where large near-surface velocities contribute to the velocity differences. Inspection of the diagnostic processing figures from these profiles reveal no apparent anomalies, however, indicating that the final processed profiles (constrained with GPS, BT and SADCP data) across the Gulf Stream are of high quality. The large velocity discrepancies in profiles 035–041 are caused by the low backscatter in that region (Figure 4). Noting that the velocity differences remain somewhat elevated up to about profile 055 indicates that additional checking should be carried out for profiles where the backscatter coefficient drops below $-97$ dB.

Based on instrument range (Figure 5, left panel), profiles 035-046 are potentially problematic. Inspection of the processing log files, diagnostic figures, and velocity profiles from this region indicates that horizontal LADCP velocities of profiles 032–041 are bad below 1000 m with three additional profiles (042-044) having bad horizontal velocities below 3000 m. In contrast, there are no indications that any of the profiles in the range 045–055 are significantly affected by the low backscatter. What this means is that the combined GPS and BT constraints are sufficient to overcome the noise due to low backscatter in the lower half of the water column in these profiles. Since the fully processed profiles additionally use the SADCP data in the upper ocean to constrain the LADCP velocities, the errors in the archived data set are smaller than the values shown in Figure 6.

The small magnitudes of the velocity discrepancies outside the Gulf Stream and the low-backscatter region indicates that the quality of the 2021 horizontal velocity LADCP profiles is excellent. Notably, there are no indications that either vessel motion during storms or the wide-band setting of the DL in profiles 018 and 019 has adversely affected the quality of the corresponding horizontal velocity profiles. Additional notes:

1. For archiving the LADCP data were re-processed for horizontal velocity using all available referencing constraints, including the SADCP velocities. As a result, the final velocity uncertainties are smaller than those shown in Figure 6. Profiles 032–044 with the bad velocities at depth were not included in the archive, both because it is not clear how to chose an appropriate depth cut-off and because the barotropic component of the LADCP solution is likely contaminated by the bad data at depth.

2. As part of the quality assessment of the 2021 A20 LADCP data, the velocity profiles were compared to archived LADCP data collected during previous occupations of the A20 section. Unfortunately, this revealed bad velocities at depth in the archived data from previous occupations in the same region of weak acoustic backscatter. Is it not clear how to address this problem.

3. The velocity profiles collected with the WH150 instrument in the region of weak backscatter are clearly worse than the velocity profiles collected with the WH300 (Figure 6), providing strong support for the decision to swap instruments on profile 042. Based on the clearly inferior performance of several WH150 ADCPs during recent GO-SHIP cruises, this instrument type will likely not be used for US GO-SHIP LADCP work in the future.

# 5 Horizontal Currents

Figure 7 shows sections of zonal and meridional velocity from the LADCP. The full-depth eastward current in profiles 019–021 is the Gulf Stream. Between the Gulf Stream and the northern continental

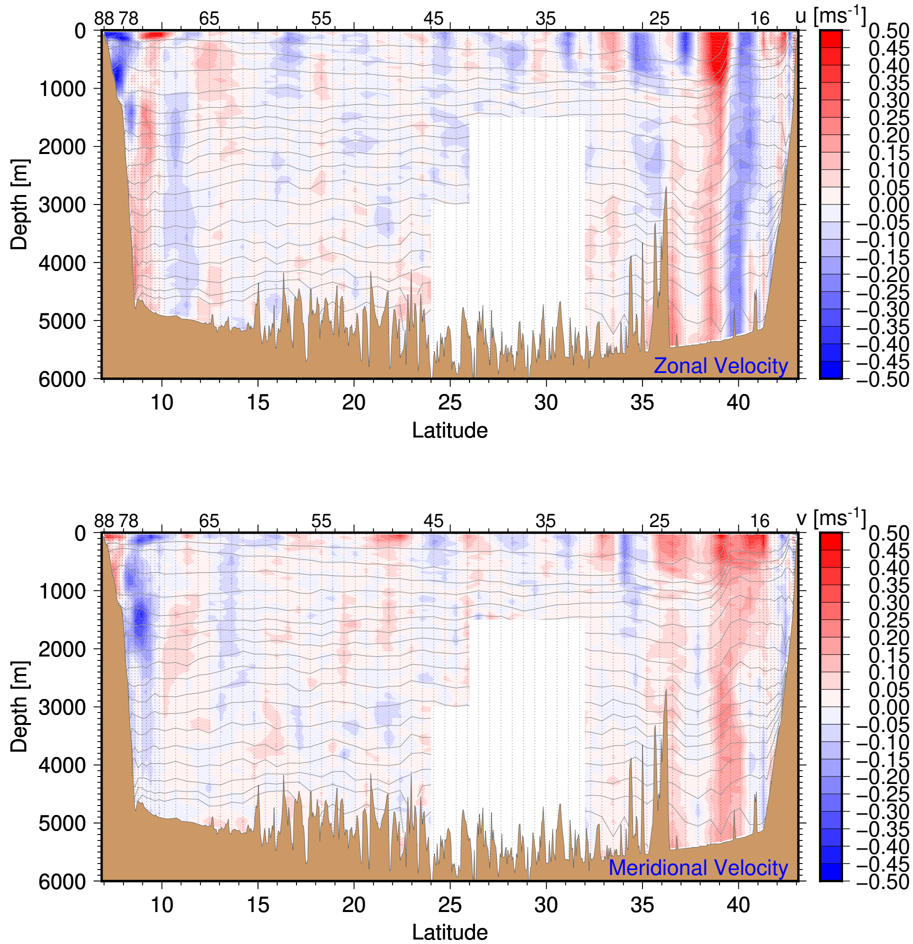


Figure 7: Zonal (upper panel) and meridional (lower panel) velocities from the LADCP. As explained in Section 4 the partial depth-profiles are not included in the archive.

slope there is evidence of a standing eddy that is distinct but likely related to the northern recirculation gyre described in the literature. South of the Gulf Stream there is evidence for several rings and other mesoscale eddies, primarily in the upper 1000 m of the water column. Near the southern boundary the current structure is complex with the Brazil Current flowing north-westward along the coast. Off shore from the Brazil Current, there is full-depth south-eastward flow extending out to about 10°N, flanked by another region of north-westward flow to the north. The similarity of the vertical structure of the outer two of these currents suggests that they may be the signature of a deep-reaching eddy.

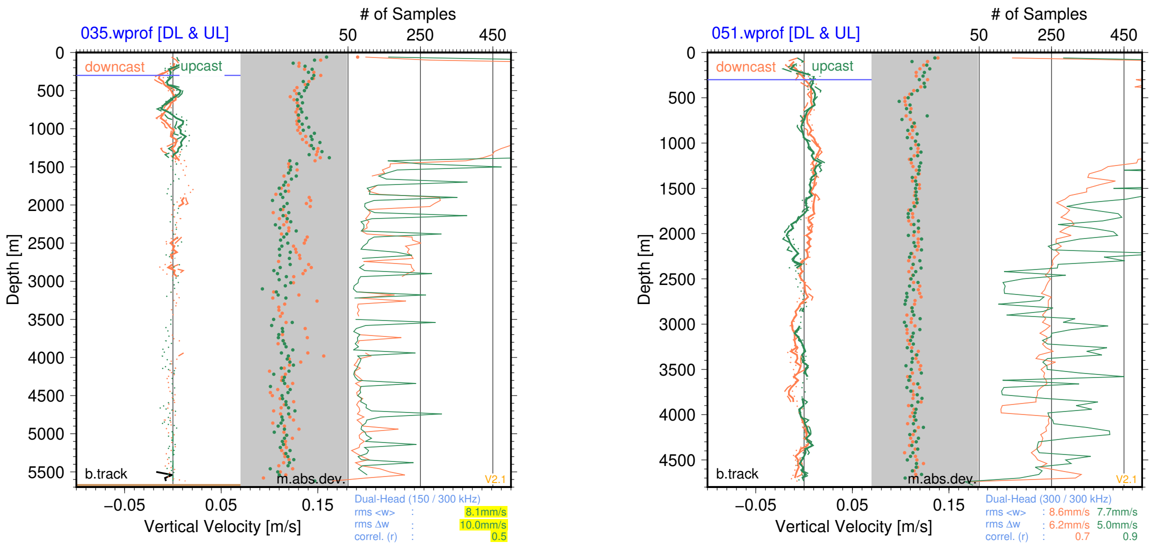


Figure 8: Example diagnostic figures from two vertical velocity profiles. Left panel: Profile 035, collected in a region with insufficient backscatter below 1300 m. Right panel: Profile 051, collected in a region with mostly sufficient backscatter and with significant internal-wave motion. Each panel shows (from left to right) vertical ocean velocity (dashed: DL, dotted: UL, combined: heavy), mean-absolute-deviation in each $w$ bin (bullets), as well as number of samples in each bin (lines).

# 6 Vertical Velocity QC

For processing the LADCP data for vertical ocean velocity the `LADCP_w` software, version 2.1, was used. With two ADCPs measuring the vertical velocity field QC is based primarily on comparisons between the two largely independent[1] $w$ measurements. In contrast to horizontal velocity, which can only be derived from full profile data, the effects of measurement errors due to insufficient backscatter, excessive instrument motion, etc., on vertical velocity are localized and can be removed during processing, causing gaps in the resulting profiles. The example profile shown in the left panel of Figure 8 was collected in the region with weak backscatter, resulting in a partial-depth profile covering the upper 1400 m of the water column. In contrast, in the profile shown in the right figure panel there was sufficient acoustic backscatter for both instruments to produce nearly complete downcast profiles, and a large portion of the upcast data was also successfully sampled by both ADCPs. Where data from both instruments are available there is good agreement between the two. The vertical velocity variability with scales of hundreds of meters and amplitudes of about $2\,\mathrm{cm \cdot s^{-1}}$ in both profiles is qualitatively consistent with high-frequency internal waves.

In order to try to quantify this visual assessment, UL-DL correlation coefficients were calculated in 320 m-thick windows (Figure 9). Where there is data from both instruments, the correlations are mostly positive, indicating that the vertical velocities are dominated by the signal, rather than by measurement errors and noise. Inspection of individual profiles indicates that many of the negative correlations are from windows with approximately uniform $w$, i.e. where the signal is small, without indications for measurement problems. While this problem can be mitigated by increasing the window

[1] The same portion of the water column is sampled at different times by the two ADCPs. Only biases related to the CTD pressure measurements are common to the vertical velocity measurements from both instruments.

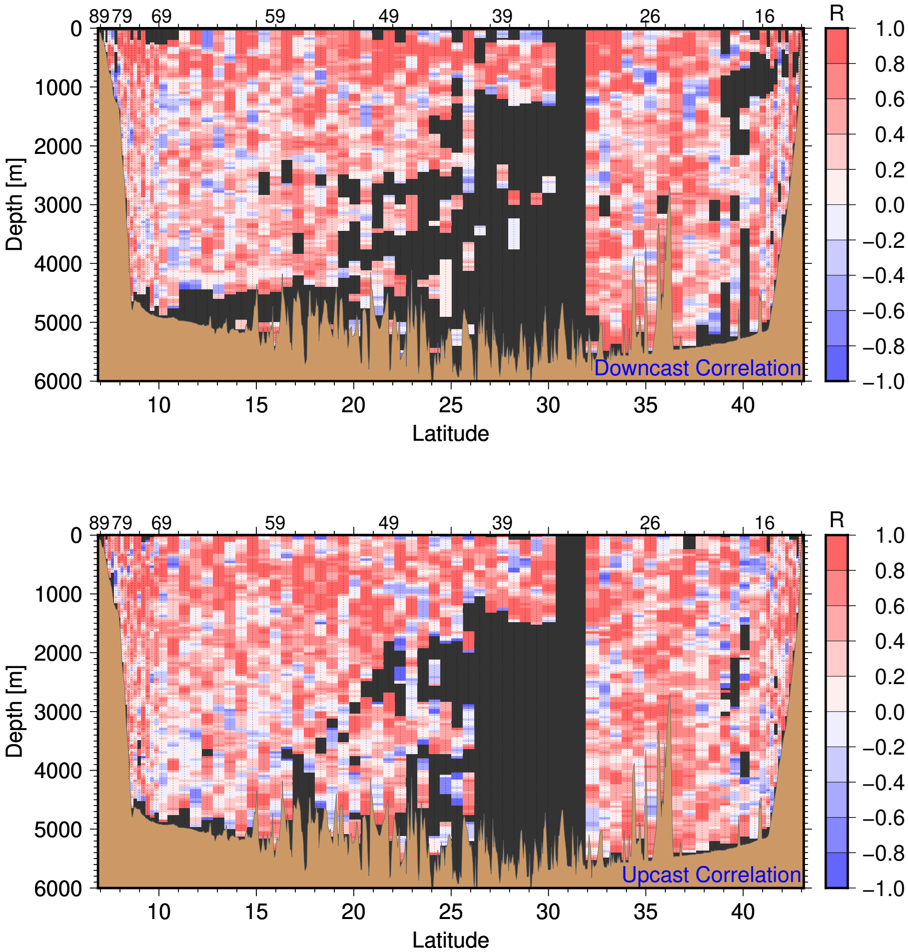


Figure 9: Correlations between the vertical-velocity measurements from the two ADCPs in 320 m-thick windows; a minimum of 6 samples are required for each correlation. Regions without correlation coefficients are shaded dark; there are no DL data in profiles 032–034. Upper panel: Downcast data. Lower panel: Upcast data.

size for the correlations, 320 m is a popular choice for quantifying "finescale" internal-wave properties (e.g. Figure 1), which is the main use of the LADCP-derived vertical velocity measurements to date.

There is a prominent data gap below ≈1200 m in the region of weak backscatter (profiles 035–041) in both down- and upcast data. (There are no good DL data from profiles 032-034.) South of this region there are gaps in particular in the downcast data of many profiles. Most of these gaps are caused by insufficient sampling. Near the seabed, sampling is reduced in both UL and DL data primarily because of sidelobe interference from the seabed. The two quasi-horizontal bands in mid water are caused by interference from the seabed reflection of the previous pings; there are two bands because staggered pinging (alternating ping intervals) was used. In addition to those profile gaps, there is a prominent block of no data near 1000 m in many of the downcast profiles up to station

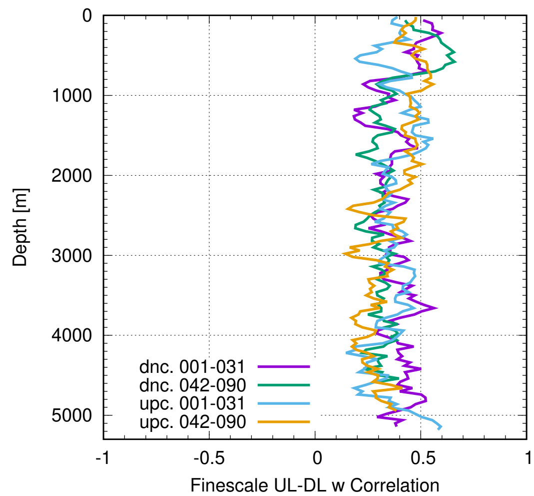


Figure 10: Average correlation profiles north and south of the region of low backscatter; only bins with 10 or more samples are shown.

020. Inspection of the diagnostic figures of the affected profiles indicates that the downcast gaps in this region is caused by inconsistent DL data, most likely due to large horizontal acceleration of the instruments (two different ADCPs show the same behavior), which was installed ≈1.5 m below the CTD termination, assumed to be the pivot point of the rosette. There are no apparent anomalies in the corresponding data from the UL, which was installed close to the CTD termination.

With sufficient averaging, correlations between the finescale vertical velocities measured by the two ADCPs are around $0.4 \pm 0.1$ (Figure 10), apparently without much vertical or meridional structure, which suggests that the data editing of the `LADCP_w` software is adequate and that finescale spectra of vertical kinetic energy are not dominated by measurement noise.

# 7 Vertical Kinetic Energy and Parameterized Dissipation

The `LADCP_w` software includes the `LADCP_VKE` tool, which is used to estimate vertical kinetic energy (VKE) and, implementing a finescale parameterization based on high-frequency internal waves, kinetic energy dissipation $\epsilon_{\mathrm{VKE}}$ (for details, see Thurnherr et al., GRL 2015). When applied to the A20 data this parameterization results in physically reasonable patterns (Figure 1). In particular:

1. Turbulence levels are generally elevated over the topographically rough flank of the Mid-Atlantic Ridge (c.f. Polzin et al., 1997).

2. In the Gulf Stream region, turbulence levels in the upper 2000 m are generally elevated with particularly high values parallel to density surfaces in the main front (019–021).

3. South of the MAR turbulence levels are generally low over the abyssal plain and continental slope, except for the retroflection of the Brazil Current (070-075) where turbulence is elevated in the upper 2000 m of the water column.

4. There is evidence for elevated turbulence in the BBL on the abyssal plain near the southern end of the section.

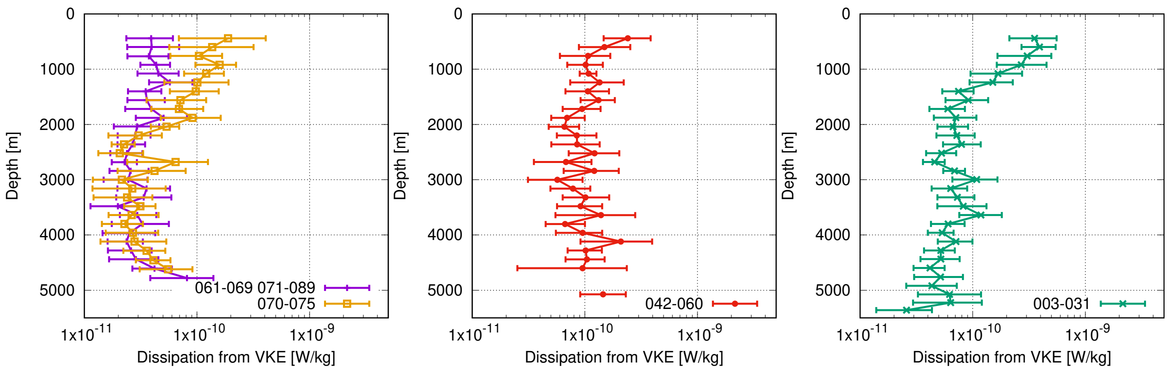


Figure 11: Regionally averaged profiles $\epsilon_{\mathrm{VKE}}$; error bars show 95% confidence intervals from bootstrapping. Left panel: Profiles from the southern margin, showing elevated turbulence in the Brazil Current retroflection. Middle panel: Profile over the MAR flank, showing moderately elevated turbulence throughout the entire water column. Right panel: Profile from the northern margin, showing the elevated turbulence associated with the Gulf Stream.

Regionally averaged mean profiles support and clarify these inferences and indicate that the differences between the turbulence levels in the different regions are statistically significant (Figure 11).