2019 GO-SHIP I6S LADCP Post-Cruise QC Report

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1 Summary

This report describes the results from a post-cruise quality control of the LADCP data collected during the 2019 GO-SHIP occupation of the I6S repeat hydrography section with the R/V *Thomas G. Thompson.* Using two ADCPs installed on the CTD rosette, one looking downward (DL) and the other upward (UL), full-depth profiles of all three components of the oceanic velocity field were collected at all 55 stations. In spite of poor performance of the 150 kHz ADCP installed as the DL during the first half of the cruise, high-quality horizontal velocities are available from all but two of the stations, with the data from an external magnetometer/accelerometer significantly improving a handful of profiles collected with large package tilts in a region of strong near-surface currents. Hardware problems with the CTDs used on the cruise prevent vertical-velocity processing of many of the I6S LADCP profiles with available software. Significant effort was therefore expended to develop and test an algorithm to correct 24 Hz CTD files for dropped scans, clock jitter, and excessive clock drift. The algorithm was implemented in the CTD pre-processing tool that is part of the public-domain vertical-velocity processing software. Using CTD time series corrected with the new algorithm yields high-quality vertical velocity and VKE-parameterization profiles at 48 out of the 55 I6S stations occupied during this cruise.

2 LADCP Instrumentation

Three ADCP instruments were used during the cruise: A TRDI WHM150 (serial #24544), a standard TRDI WHM300 (#24477), as well as a modified WHM300 (#12734) with a self-recording accelerometer/magnetometer instrument installed inside the pressure housing. On the first 9 stations, the WHM150 was used as the DL and the unmodified WHM300 was used as the UL. For the remainder of the cruise (profiles 10–55), the modified WHM300 was installed as the UL, implying that there are magnetometer and accelerometer data available for these profiles.[1] On profile 35 the DL WHM150 was replaced with the unmodified WH300, because of concerns about the data quality of the 150 kHz instrument. Post-cruise processing confirmed that the performance of the 150 kHz instrument was not satisfactory. This is most easily apparent in the vertical velocity differences between the two ADCP's (Figure 1). For final processing for the archive, water track data from the WH150 ADCP were therefore not used. However, since there are indications that the poor performance of the instrument is related to weak acoustic backscatter, (post-processed) bottom-track data from the WH150 were used as a referencing constraint for the horizontal velocities.

[1] The DL file from profile 36 has embedded garbage bytes, which prevent patching with the accelerometer/magnetometer data.

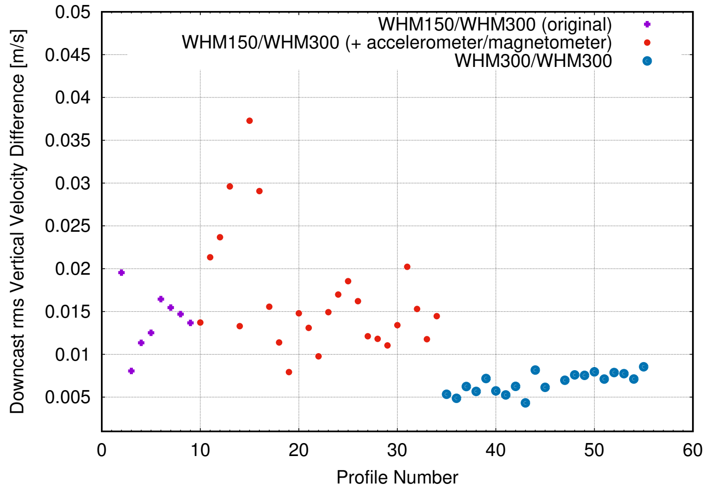

Figure 1: Root mean square downcast vertical velocity differences below 500 m between the two ADCPs vs. profile number. Different colors indicate different instrument combinations; see text for details.

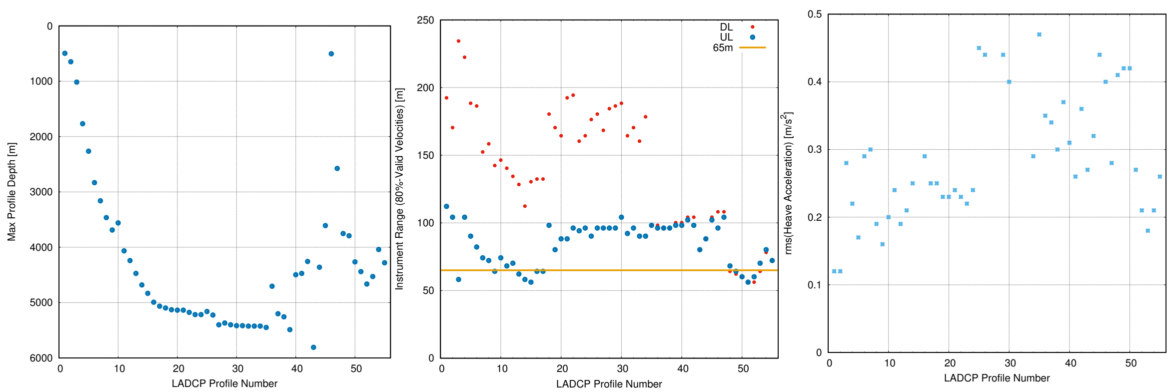

Figure 2: Left panel: Maximum profile depth. Middle panel: Instrument range, with the horizontal line indicating the minimum range (65 m) typically required for successful processing of full-depth LADCP profiles from a single 300 kHz TRDI Workhorse ADCP for horizontal velocity. Right panel: *rms* vertical acceleration due to vessel heave, a measure of sea state.

3 Sampling Conditions

Figure 2 shows the maximum profile depths, instrument range, as well as the sea state during each cast. Most profiles extend below 3000 m with the deepest profile reaching nearly 6000 m (left figure panel). LADCP data quality is sensitively dependent on instrument range (middle panel), which depends on the acoustic scattering environment. While at most of the stations from this cruise the range of the UL was above 65 m, which an approximate empirical limit for minimally sufficient LADCP range, weak acoustic backscatter was encountered in profiles 3, 9, 13–17, as well as 49–

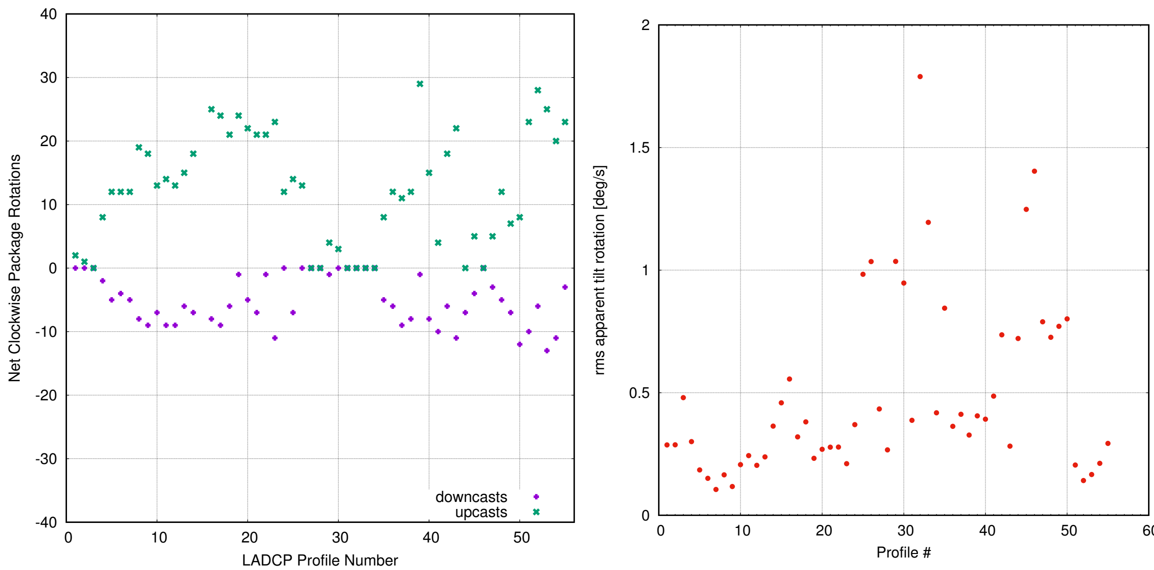

Figure 3: Left panel: Net package rotations, positive indicating clockwise when viewed from above. Right panel: *rms* apparent package tilt (pitch/roll) rotation.

52. For the last group of profiles this is not an issue because they were collected with two working ADCPs, which, when combined, provide sufficient range. However, the early profiles with short range were collected without a good DL, implying that their quality is suspect. Consistent with this interpretation, the vertical velocity differences between the two ADCPs were particularly large in profiles 11–16 (Figure 1). In addition to instrument range, sea state is also known to affect LADCP data quality in some cases; in the right panel of Figure 2 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), with most of the rough seas encountered between profiles 25 and 50.

4 CTD Rosette Behavior

Figure 3 shows the net horizontal rotation experienced by the CTD rosette during each down- and upcast (left panel), as well as the *rms* apparent package tilt rotation (i.e. the time-derivative of the tilt angle) for each profile (right panel). There was significant horizontal package rotation in all profiles with consistently net counterclockwise/clockwise rotation during the down-/up-casts, respectively (left figure panel). During the entire cruise the rosette performed a net total of 402 clockwise rotations, which is similar to the rosette rotation on some previous cruises.

During I6S, the CTD package exhibited a range of different tilting motions (right panel of Figure 3 and Figure 4). During the profiles collected in calms seas in regions of weak oceanic flows the rosette remained close to vertical and with smoothly varying tilt angles (top panel in Figure 4). This is in marked contrast to the profiles collected in heavy seas in regions of weak currents, which show numerous large spikes in the instrument tilts (middle panel). A few profiles were collected in regions with very strong near-surface velocities, which resulted in package tilts exceeding the capabilities of the TRDI Workhorse compasses (bottom panel). While the time series of tilt from profile 32 looks visually extreme, similar spikes, although typically of lower magnitude, have been

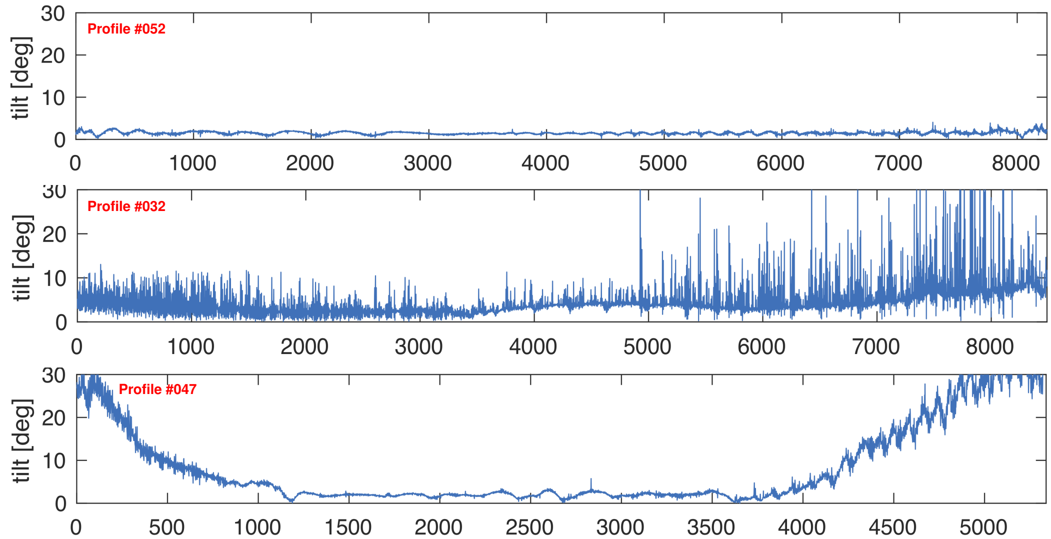

Figure 4: Example time series of tilt (ordinate is ensemble number) from three profiles. Top panel: Profile 52 collected in calm seas with weak currents. Middle panel: Profile 32 collected in rough seas with weak currents. Bottom panel: Profile 47 collected in intermediate seas with very strong ($1\,\mathrm{m{\cdot}s^{-1}}$ near the sea surface) currents.

observed in numerous previous LADCP cruises, including many repeat-hydrography occupations. While the spikes appear as tilt angles in the ADCP and accelerometer measurements, horizontal instrument acceleration also contributes to the spikes in apparent instrument tilt. In order to obtain true instrument tilt, gyroscope data are required in addition to the accelerometer measurements. While this option will be explored in the future it is important to note that in spite of significant efforts to establish the contrary with data from multiple cruises, no significant effect of spikes in the tilt time series on the quality of processed LADCP profiles has been found. This is likely due to the fact that filters based on tilt velocity are used for data editing during processing for both horizontal and vertical velocities.

5 QC of Horizontal Velocity

The overall quality of the horizontal LADCP velocities is assessed by processing all profiles with the velocity-inversion method without using the SADCP velocities to constrain the solutions, and comparing the resulting LADCP velocities in the upper ocean to the corresponding SADCP velocities. Based on data from other cruises, high-quality LADCP profiles constrained with GPS and BT data typically agree with the corresponding SADCP velocities within $3\text{–}6\,\mathrm{cm{\cdot}s^{-1}}$ when averaged over a few profiles. In Figure 5 profile-averaged *rms* differences between the SADCP and LADCP velocities from three different processing runs are shown with different colors: *Brown:* Using all LADCP velocity data from both instruments, as well as pitch, roll and heading recorded by the ADCPs. *Red:* Using water-track velocities only from the 300 kHz instruments (i.e. discarding the water velocities from the DL in profiles 1–34), as well as pitch, roll and heading recorded by the ADCPs. *Blue:* Using water-track velocities only from the 300 kHz instruments, and using pitch, roll and heading from the

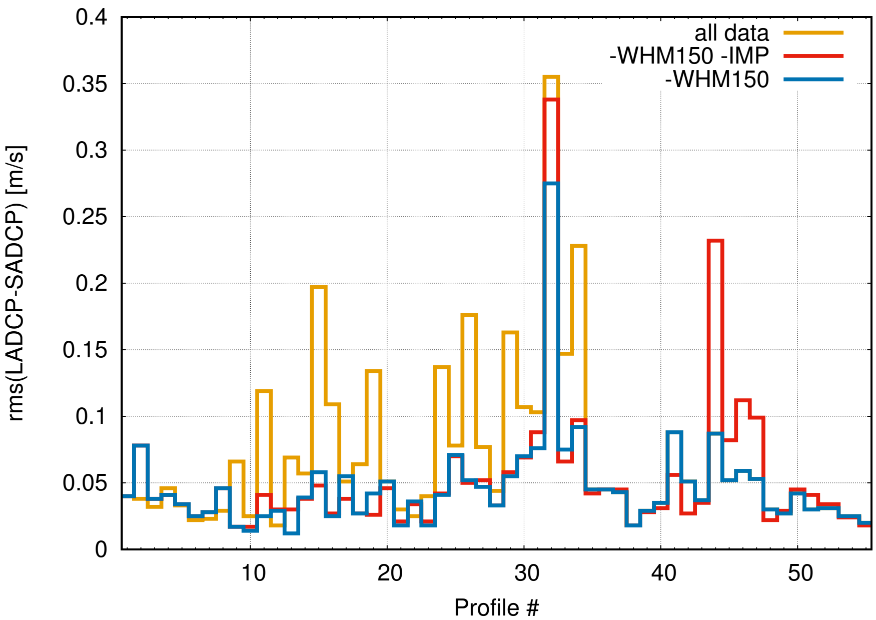

Figure 5: *rms* LADCP-SADCP horizontal velocity differences; low values indicate good agreement. Solutions plotted in brown show results from processing run using all data from both ADCPs, including pitch/roll/heading. Solutions plotted in red show solutions from processing after discarding all water-track velocities from the 150 kHz ADCP. Solutions plotted in blue show solutions from processing after discarding all water-track velocities from the 150 kHz and replacing the ADCP pitch, roll and heading data with the corresponding measurements from the accelerometer and magnetometer.

self-recording accelerometer/magnetometer. The worst of these three processing runs is clearly the run that includes the water-track velocities from the 150 kHz ADCP (brown), which degrade many of the profiles between 9 and 34. The reason this contamination is not apparent in the profiles before 9 is likely related to the fact that these were collected over the continental slope, where the water was comparatively shallow and acoustic backscatter was comparatively strong (Figure 2). When processed without the water-track velocities from the 150 kHz ADCP[2] (red) all of the contaminated profiles are significantly improved, leaving only a handful of profiles (32, 44–47) with unacceptably large velocity differences. Inspection of the diagnostic figures produced during processing reveals that these profiles were collected at comparatively high instrument tilt (pitch and/or roll) angles. Consistent with the observation that the 2-D TRDI Workhorse ADCP compasses do not perform well at angles greater than about 10–15° the best overall agreement between the LADCP and SADCP velocities (blue) is achieved when the ADCP pitch, roll and heading data are replaced with the corresponding measurements from the independent accelerometer and magnetometer installed in the uplooker. In this processing run only profile 32 shows an *rms* discrepancy between L- and S-ADCP velocities exceeding $10\,\mathrm{cm{\cdot}s^{-1}}$ — the errors in this profile are nearly 3× larger than the errors in any

[2]While the `LDEO_IX` processing software is capable of processing the UL water track velocities together with the DL BT data this unusual combination causes significant anomalies in the diagnostic plots showing BT data, in particular in profiles 1, 2, 5 and 9.

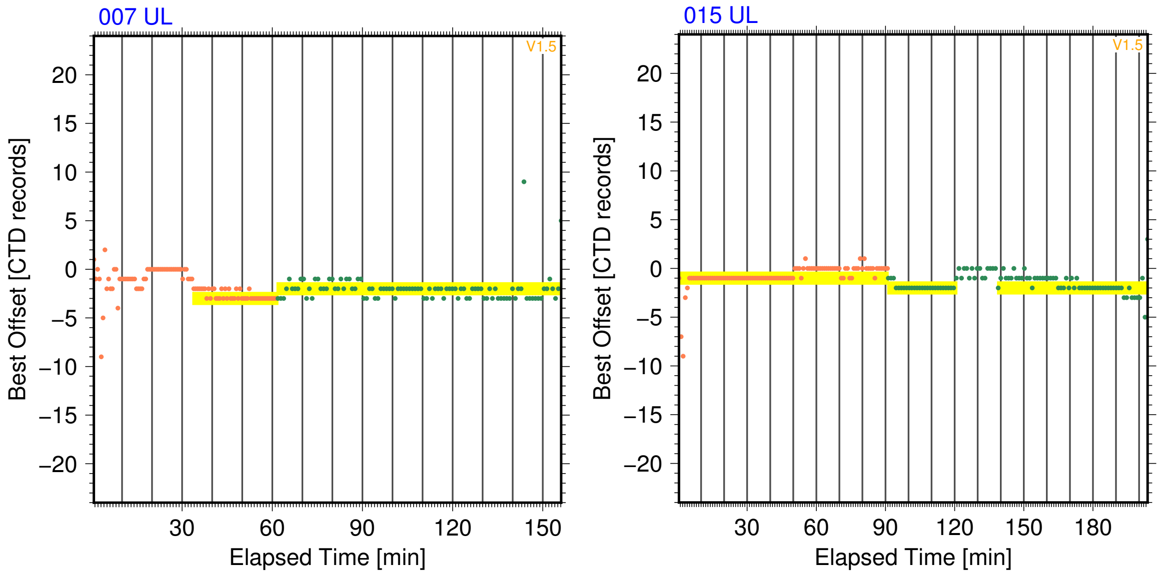

Figure 6: Time-lagging diagnostic plots (c.f. Figure 7) from two example CTD time series with time-lagging anomalies. See text for details.

of the other profiles. Inspection of the diagnostic figures from this profile indicates that the combined effects of fairly unidirectional currents causing almost complete weather-vaning of the rosette, as well as extreme spikes in the package tilts due to heavy seas (Figure 4) cause severe contamination of the ADCP velocity measurements. The horizontal velocities from this profile are therefore not included in the archived data set.[3] Also missing from the archive are the horizontal velocities from profile 53, which cannot be processed with the `LDEO_IX` software for unknown reasons. (When processed with the GPS constraint it creates a solution for u but not for v and when processed without the GPS constraint, the abyssal velocities are unrealistically large; there are no apparent anomalies in the GPS time series.) While inspection of the diagnostic processing figures does not reveal similarly glaring problems in any of the other profiles, it is important to note that the expected errors in profiles 1–34, which are derived from a single ADCP, are likely somewhat larger than those in profiles 35–55, for which data from two good-quality ADCPs are available. Nevertheless, Figure 5 indicates that most of the profiles form this data set are of high quality.

6 QC of Vertical Velocity and VKE

6.1 CTD Problems

Three different CTDs were used during I6S. For profiles 1–19, two different SIO SBE9plus underwater units were deployed, with both showing indications for pressure problems (J. Gum, *personal communication).* With regards to LADCP processing many of the profiles in this range show indications for irregularities in the CTD system time with amplitudes of maybe 1/5th of second or so, as shown with

[3]Interestingly, there are no indications in the diagnostics from vertical-velocity processing of the data from profile 32 indicating any data quality issues (Section 6). This suggests that the problem is likely more due to the weather-vaning than to the tilt spikes.

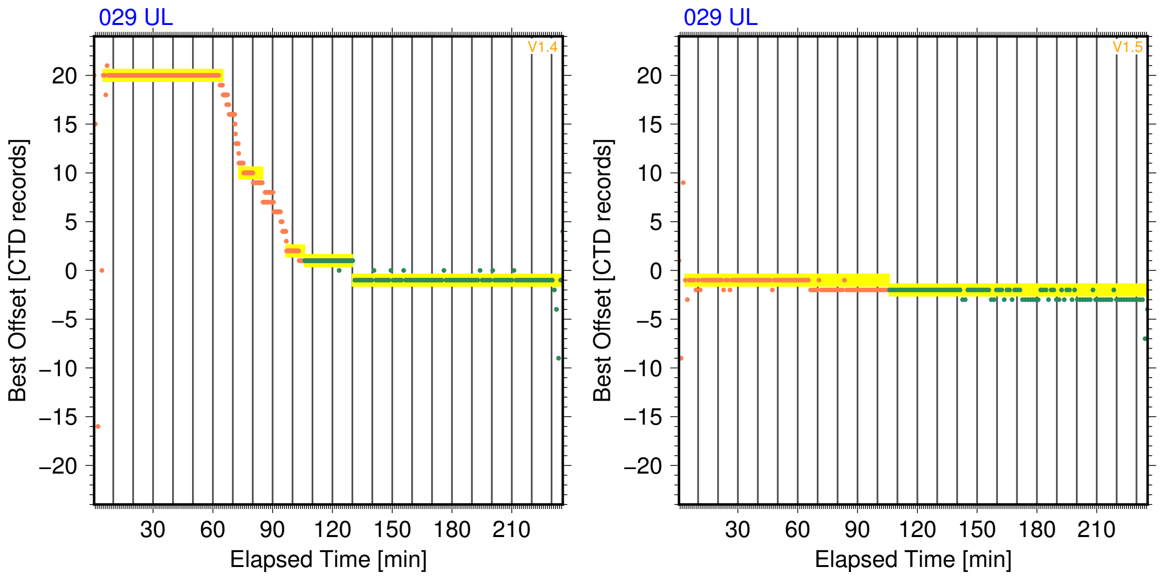

Figure 7: Time-lagging diagnostic plots from vertical-velocity processing of an example profile with multiple dropped CTD scans. Optimal lags for matching the LADCP to the CTD data are calculated from many small sections of the data. For profiles without clock- and data transmission problems there should be a single optimal offset for the entire profile. Left panel: Processing carried out with original CTD file; steps and slopes in this plot indicate times when CTD scans were lost. Right panel: Processing carried out with CTD file after correction for dropped scans. The shallow slope in this panel (beginning offset -1 CTD record; ending offset -3 CTD records) indicates a slight drift of the LADCP clock with respect to the CTD system clock (1/3th of second over 4 hours).

two example diagnostic figures from w processing in Figure 6: Rather than horizontal and straight (c.f. Figure 7, right panel), the time lags in the figure are "wavy". Possible reasons for this problem include i) a bad CTD; ii) a bad deck box; or perhaps iii) an upside-down deck-box orientation (J. Gum, *personal communication).* While there are no indications that the timing and/or pressure problems contaminate the horizontal velocities (Section 5), the vertical velocities of some of the affected profiles are clearly anomalous. Based on an inspection of all diagnostic processing figures, w profiles 6–8, 13, and 15–17 were determined to be bad and are not included in the archive.

From station 20 onward, a SBE9plus CTD from the ship was used instead. While this unit did not show any pressure or timing issues, many of the profiles up to 39 are affected by significant CTD data transmission problems, resulting in numerous dropped scans, which typically prevent merging of the unmodified CTD and LADCP data at the high temporal resolution (6 Hz time series are typically used) required for w processing (Figure 7, left panel). However, inspired by an approximate algorithm developed by Gerd Krahmann to fill gaps in 1 Hz CTD files required for horizontal-velocity LADCP processing, a significantly more complex but also more accurate algorithm to fill CTD data gaps was developed and implemented in version 1.5 of the `LADCP_w` software, which was used for processing (right figure panel). [The 1 Hz CTD time series required for horizontal velocity processing can easily be derived from the 6 Hz files obviating the need for any changes in the `LDEO_IX` software.] The new gap-correction algorithm requires the `timeY` and `modError` fields to be present in the 24 Hz CTD files.

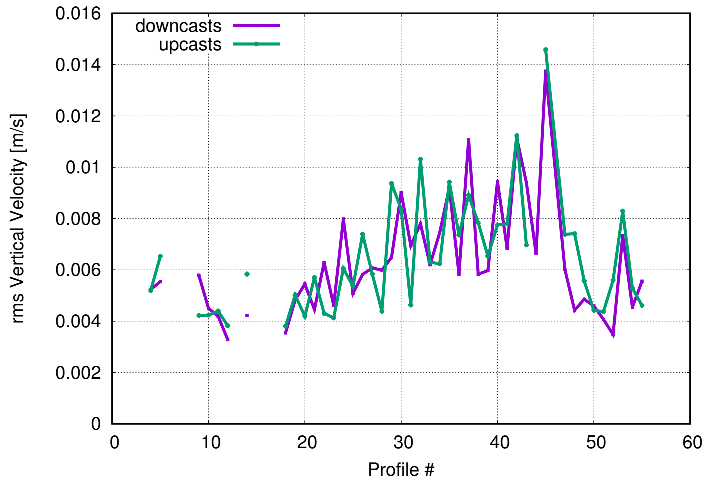

Figure 8: *Rms* vertical velocity below 500 m vs. profile number. Profiles with fewer than 20 deep samples, and profiles with CTD problems (6–8, 13, 15–17; Section 6.1) are not shown.

6.2 Vertical Velocity QC

For LADCP data collected with dual ADCPs, the *rms* differences between the DL and UL velocities provide a direct and easy-to-interpret measure of the quality of the resulting velocities. In the case of I6S, Figure 1 shows i) that the water-track velocities from the 150 kHz instrument are badly contaminated, and ii) that a minimum range of ≈50 m (Figure 2) for the 300 kHz instruments is sufficient for w processing. This implies that high-quality w profiles should be available from all I6S stations not affected by CTD problems (Section 6.1).

While DL/UL velocity differences are the most direct method for assessing the quality of LADCP-derived vertical velocity measurements, in the case of I6S the main result is that the data from the WH150 ADCP are bad. Directly comparing down- and upcast velocities is not a viable alternative for assessing vertical-velocity quality because of the fast time scales associated with the near-N internal waves that dominate the w signal. However, *rms* vertical velocities averaged over vertical scales much greater than the vertical wavelengths of individual waves are a measure of the energy content of the internal wave field, which is not expected to vary significantly over the time scales associated with the collection of a single profile, i.e. the resulting down- and upcast estimates are expected to agree. Figure 8 shows the profile-averaged *rms* vertical velocities below 500 m for the profiles with sufficient deep samples that are not affected by CTD problems. The dc and uc velocities from all remaining profiles agree within about $2\,\mathrm{mm\cdot s^{-1}}$, confirming that the LADCP w measurements are not noise dominated. Across the I6S section depth-averaged VKE varies regionally by about an order of magnitude, with profiles 12 and 45 containing the lowest and highest internal-wave energy, respectively (Figure 9).

6.3 Vertical Kinetic Energy and VKE-Derived Dissipation

From all vertical velocity profiles that pass the QC finescale VKE wavenumber spectra were calculated and a VKE-based finestructure parameterization method was applied to derive estimates of kinetic energy dissipation ϵ_{VKE}. The bottom panels in Figure 9 show results for the profiles with the lowest

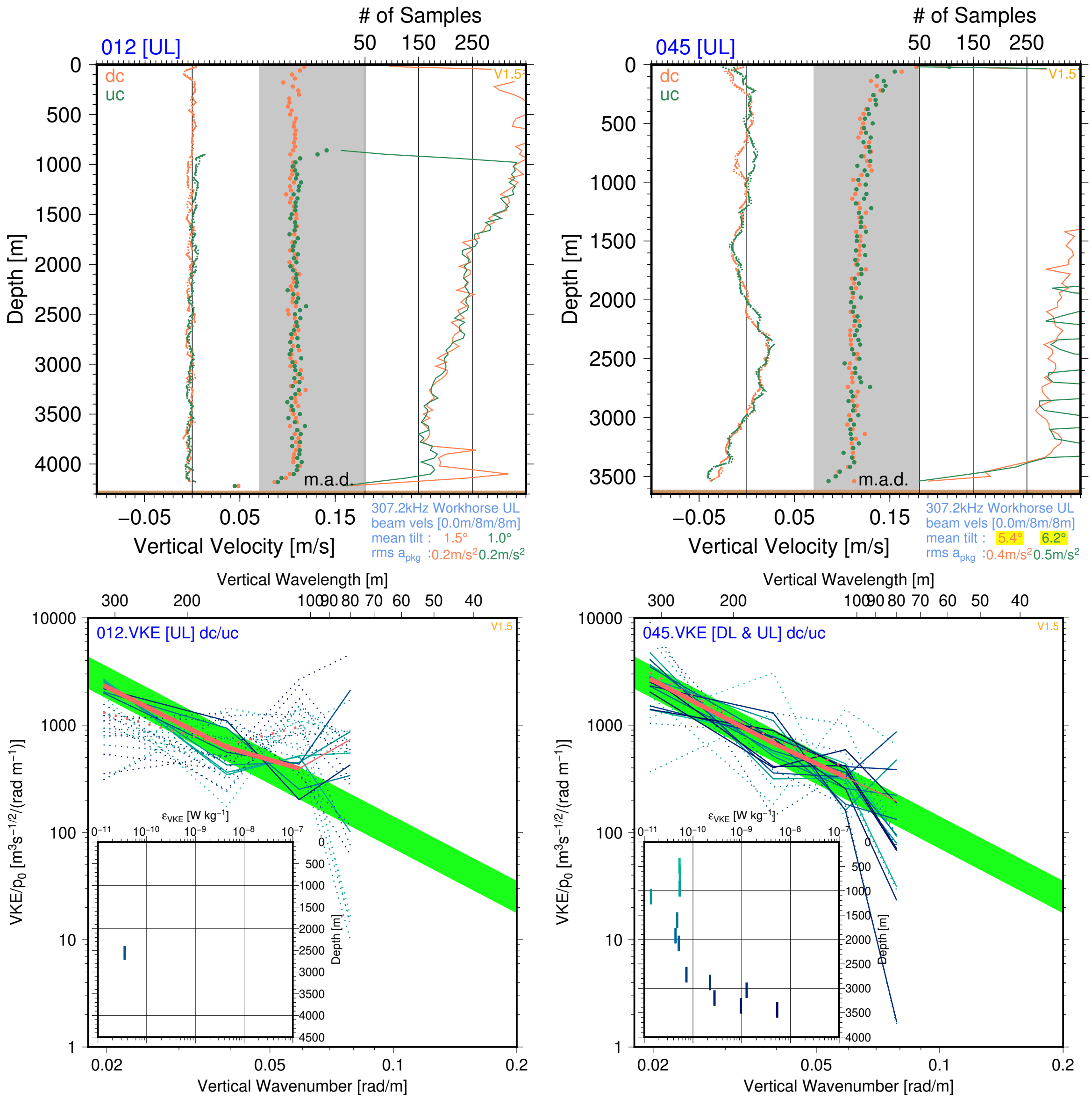

Figure 9: Diagnostic figures from processing the two profiles associated with (left column) the lowest and (right column) the highest VKE in this data set. Top row: Vertical velocities (leftmost curves in both panels). Bottom row: (main panels) VKE spectra, and (inset) dissipation estimates from VKE parameterization.

and highest VKE levels. Note that ϵ_{VKE} is only estimated from spectra with slopes of ≈-2 (solid lines in the main figure panels) — at oceanic background levels, the w spectra become noise dominated and flatten (dotted curves) to the point where the parameterization does not work any more. Profile 45 with the highest VKE (right figure panels) looks similar to a typical ACC jet profile, with dissipation decreasing from a maximum of $\approx 10^{-8}\,\mathrm{W \cdot kg^{-1}}$ near the seabed to background levels ≈ 2000 m above.

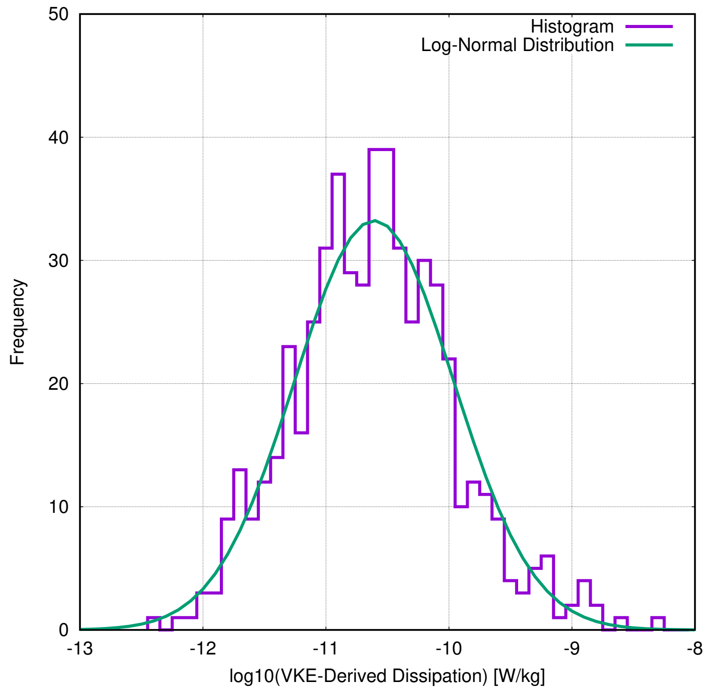

Figure 10: Distribution of the VKE-derived dissipation estimates below 500 m in log space (purple) and corresponding log-normal distribution with the same area, mean and standard deviation.

In the I6S vertical-velocity profiles there are 1388 half-overlapping 320 m-wide spectral windows, including bottom windows, for which ϵ_{VKE} estimates can potentially be derived. Out of these, 645 (≈46%) yield valid ϵ_{VKE} estimates, while the remainder either does not have sufficient velocity data or the spectra do not pass the consistency checks built into the processing software. Over the entire section, the valid ϵ estimates below 500 m follow an approximately log-normal distribution centered at $3 \times 10^{-11}\,\mathrm{W{\cdot}kg^{-1}}$ with a standard deviation of about factor 5 (Figure 10). The anomalously high tail with dissipations above $10^{-9}\,\mathrm{W{\cdot}kg^{-1}}$ is due to profile 45 (Figure 9).