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**QUALITY CONTROL OF ADCP DATA WITH PRESSURE SENSOR AND EXTRACTION OF THE TOPMOST DEPTH STRATA**

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This report describes the quality control (QC) procedure of moored Acoustic Doppler Profiler (ADCP) data with pressure (depth) measurements available (pressure QC) and the extraction of current data at constant depth strata from the surface. The post-processing procedures and flagging are described. We recommend the inclusion of the tilting test as well as the correction of the bin depth for tides and tilting before applying the echo intensity and correlation tests. We describe an alternative test for the echo intensity criteria based on the normalized echo intensity profile (in dB). The temporal variation of the side-lobe contaminated cells as a function of the total depth is also taken into account.

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# 1. Introduction

Previous tests have shown that information about the temporal variation of the total depth (pressure measurements) above the ADCP head is crucial for the data quality-control (Mantovanelli et al., 2014; first Report). In this report, a detailed description is given of the quality-control (QC) procedure when pressure (depth) measurements are available. Although this procedure was designed and tested for four-beam broadband ADCPs (RDI Workhorse; Teledyne Instruments) of different operating frequencies (76.8 kHz, 153.6 kHz, 307.2 kHz and 614.4 kHz), it provides a methodology that can be adapted to other Doppler Profiles. ADCP data sets applied here were obtained from Australia’s Integrated Marine Observing System (IMOS) database(<http://www.imos.org.au/>) for the Queensland Great Barrier Reef (GBR, Q-IMOS) and Northern Australia (NA, WAIMOS) moorings. A total of 14 deployments including both shallow (20-60 m) and deep (100-470 m) water moorings are analysed and compared.

The temporal variation of the depth above the ADCP is used to identify the dry cells (i.e., measurements performed in air when the instrument range is larger than the local depth) and to estimate the surface layer contaminated by side-lobe reflection. Further, changes of the depth of each bin in relation to surface owed to tidal variations are considered for the horizontal (*u*, *v*) and vertical (*w*) velocity components when bin mapping is enabled. Although the RDI ADCP bin mapping algorithm takes into account the variations of the bin depth due to instrument tilting when reporting the velocity components (*u*, *v*, *w*) and error velocity, the tilting is not corrected when reporting the some of the ADCP performance descriptors (i.e., echo intensity and correlation).

Previous tests have shown that GBR and WAIMOS moorings are subjected to large tilting angles at some instances of time, and the instrument tilting is increased at peak tides particularly for the shallow water moorings; tilting can cause variations between the actual (i.e., tilted) and nominal (i.e., vertical) depths up to 3 bins (Mantovanelli et al., 2014; first Report). Therefore, we proposed here the inclusion of the correction for tilting when reporting of the ADCP quality descriptors (i.e. echo intensity and correlation). Further, both velocity and instrument performance descriptors (echo intensity, correlation and percent of good) are remapped into uniform depth strata for compatibility and accurate outlier flagging. Large tilting angles render the velocity measurements unreliable, and therefore, the inclusion of a tilting test as a QC test is strongly recommended.

The post-processing and flagging QC procedure presented here consists of 16 steps, some of which need to be performed in the right order to achieve the desired results. Particularly, the first 9 steps are strongly recommended. Some additional flagging (the correlation, echo intensity, percent of good, error velocity and vertical velocity) are also recommended and their cut-off limits may be set according to user’s requirements. These flags are used to quantify the total amount of data that failure each QC test in the analysed deployments, allowing to identify the most relevant tests as well as of the tests that can be flagging potentially good data.

## 2. Instrumentation set-up

### 2.1. Data sets

ADCP data sets applied here were obtained from Australia’s Integrated Marine Observing System (IMOS) data base(<http://www.imos.org.au/>) for the Queensland Great Barrier Reef (GBR, Q-IMOS) and Northern Australia (NA, WAIMOS) moorings (Figure 1; Table I), including: (*i*) three shallow GBR mooring stations (~45-60 m deep), namely Heron Island North (HIN), Heron Island South (HIS), One Tree Island (OTE); (*ii*) the 100 m-deep Pilbara station (PIL, Western Australia); (*iii*) one NA station located in waters ~470 m deep (TIS, Timor South); and (*iv*) Darwin National Reference Station Buoy (NRSDAR, ~20 m deep).

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**Figure 1.** Location of the Queensland Great Barrier (Q-IMOS GBR) and Northern Australia (WAIMOS-North) mooring stations (left panel) and schematic ADCP mooring diagram (right panel). The upward-looking ADCP is deployed a few meters from the bottom and a subsurface buoy array holds the mooring line in a vertical position; additional temperature sensors (SBE) are present in most of the stations.

### 2.2. ADCP set-up

Table I summarises the instrument model, set-up configuration and the deployment period for each mooring site. All mooring were equipped with four-beam broadband ADCPs (RDI Instruments) with beam angles slanted at 20° in Janus configuration. The coordinate transformation option (Coord Xform (EX) 11111) was enabled to use tilting corrections, three beams solution and bin mapping which transforms the internal coordinate ADCP system (system XYZ) into an Earth coordinate system referred as ENU (East/North/Up) with correspondent velocity components denoted by (*u*, *v*, *w*).

The broadband ADCPs retrieve many samples per ping, which are typically averaged over a period of a few minutes (burst) to obtain reliable readings; these ping averages are termed ‘ensembles’. ADCP deployments lasted for about 6 months; the interval between ensembles (sampling rate) and number of pings per ensemble are specified in Table I. ADCPs were deployed in an upward-looking configuration a few meters above the bottom (Figure 1 right), with the number and size of bins (or depth cells) varying for the different deployments (Table I).

Table I. Site name, the first and last good measurement for each deployment (day/month/year, hour:minutes in UTC time) are indicated in the first/second columns and the correspondent binary file in the last column. Details of instrument specifications (ADCP frequency in kHZ, beam angle), ADCP model, configuration (number of cells, cell size, sampling rate and number of pings per ensemble), site depth and distance of ADCP from the bottom, site location (latitude and longitude) for each analysed deployment. Deployments without pressure measurements were excluded.

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| site | first good | last good | frequency  (model) | bin number  x size (m) | sample rate  (min) | pings/  ens. | MD  (°) | depth/  off-bed  (m) | latitude/longitude | binary file (.000) |
| HIN (1) | 16/10/09 04:00 | 19/04/10 0:35 | 614.4 (1) | 50 x 1 | 30 | 170 | 9.71 | 45/ 4 | -23.3835°/ 151.9869° | HIN01000b |
| HIN (2) | 22/04/10 23:23 | 30/08/10 22:30 | 614.4 (1) | 50 x 1 | 30 | 170 | 9.70 | 46/ 4 | -23.3827°/ 151.9875° | HIN02000 |
| HIN (3) | 02/09/10 02:04 | 10/03/11 04:37 | 614.4 (1) | 50 x 1 | 10 | 60 | 9.70 | 44.5/ 4 | -23.3804°/ 151.9873° | HIN03000b |
| HIS (1) | 26/04/10 04:54 | 31/08/10 01:50 | 614.4 (1) | 54 x 1 | 30 | 170 | 9.72 | 45/ 0.5 | -23.5128°/ 151.9542° | HIS02000 |
| HIS (2) | 03/09/10 05:43 | 08/03/11 05:13 | 614.4 (1) | 28 x 2 | 10 | 60 | 9.72 | 45/ 0.5 | -23.5132°/ 151.9548° | HIS04000b |
| HIS (3) | 09/03/10 22:23 | 13/08/11 03:40 | 614.4 (1) | 28 x 2 | 10 | 60 | 9.71 | 45/ 1 | -23.5136°/151.9553 | HIS05000 |
| OTE (1) | 12/10/09 03:00 | 19/04/10 23:26 | 614.4 (1) | 54 x 1 | 30 | 160 | 9.78 | 59/ 5 | -23.4836°/ 152.1722° | OTE01000b |
| OTE (2) | 05/09/10 05:06 | 10/03/11 02:19 | 307.2 (1) | 16 x 4 | 10 | 30 | 9.76 | 56/ 3 | -23.4836°/152.1727° | OTE03000 |
| OTE (3) | 14/03/11 23:37 | 16/08/11 04:10 | 307.2 (1) | 15 x 4 | 10 | 40 | 9.75 | 60/ 8 | -23.4831/ 152.173 | OTE04000 |
|  |  |  |  |  |  |  |  |  |  |  |
| TIS(1) | 30/05/11 04:10 | 10/01/12 06:45 | 76.8 (2) | 46 x 10 | 20 | 20 | 2.50 | 469/ 7 | -9.8176 °/127.5540° | TIS03000 |
| TIS(2) | 11/01/12 02:00 | 21/07/12 22:18 | 76.8 (2) | 46 x 10 | 20 | 22 | 2.50 | 465/ 9 | -9.8174 °/127.5541° | TIS04000 |
|  |  |  |  |  |  |  |  |  |  |  |
| PIL | 20/02/12 10:00 | 19/08/12 01:33 | 153.6 (3) | 12 x 8 | 10 | 42 | 1.28 | 100/ 8 | -19.6944 °/116.1115° | P1001000 |
|  |  |  |  |  |  |  |  |  |  |  |
| NRSDAR(1) | 02/01/11 07:10 | 25/06/11 06:00 | 614.4 (1) | 40 x 0.75 | 10 | 120 | 3.23 | 23/ 1 | -12.3380 °/130.6965° | NEMO\_NRSDAR1101\_  CURRENTS\_CONCATENATE |
| NRSDAR(2) | 14/01/12 07:08 | 26/07/12 22:31 | 614.4 (1) | 40 x 0.75 | 10 | 60 | 3.19 | 22/ 1 | -12.3381 °/130.6964° | NRSDAR1201\_  RDI\_CONCATENATED |
|  |  |  |  |  |  |  |  |  |  |  |

ADCP model: (1) RDI Workhorse Sentinel, (2) RDI Workhorse Longranger, (3) RDI Workhorse Quartermaster

## 3. ADCP quality control procedure

The QC procedure presented here was designed for four-beam broadband ADCPs (RDI Workhorse) and tested for instruments with different operating frequencies (76.8 kHz, 153.6 kHz, 307.2 kHz and 614.4 kHz). Sixteen sequential steps are performed to eliminate data points that are assuredly known to be unreliable and flagging suspicious data (Figure 2). Both systematic and random ‘bad data’ and coarse outliers identified in steps 1-9 are replaced with NaN by an automated routine implemented in MATLAB. Steps 10-16 generate flag matrices but do not removed the data; users can elect the set of flags and cut-off limits to be applied. Ten flag matrices are generated to quantify the data rejected by the designed QC test (Figure 2), namely: RDI test (flag 0), tilting test (flag 7), side lobe test (flag 8), outlier test (flag 9), normalized echo intensity top layer only (flag 12top\_half), normalized echo intensity whole water column (flag 12), echo intensity difference that flags only the shallowest half of the water column (flag 12b), correlation test (flag 13), percent of good (flag 14), error velocity (flag 15a,b) and vertical velocity (flag 16).

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**Figure 2**. Steps for the ADCP post-processing (right side) and selected flags (left side). The flags with dotted line balloons indicate a new or modified flag from the currently applied IMOS flag, the flags with solid line balloons are the same as applied by IMOS.

All the flags described above are prescribed in a matrix of uniform size with N (instants of time) x M (depth strata), which include dry cells only. The measurements performed in air were previously removed (Steps 5 and 10). Each flag test produces an individual matrix, where each data point has either value of 1 (if it failures the test) or 0 (if it passes the test). The sum of all values of each flag matrix gives the total number of data points rejected in each test. The sum of the flag matrix is divided by the total number of points (M**.** N) and multiplied by 100 to furnish the percentage of rejected points in each test (Table II). Some overlap may occur among the different flags, and therefore, the amount of data flagged by each additional flag after the applying Steps 1 to 9 plus flag 0 is also quantified to assess the relative importance of each test (Table III). The flag 0 refers to horizontal (*u*, *v*) and vertical (*w*) velocity component data removed (replaced with NaN) a priori by the RDI software testing. Note that for the error velocity matrix may have more flagged values by the RDI testing than the velocity matrices because the error velocity cannot be calculated for the 3 beams solution.

### 3.1. Reading the ADCP binary files

The ADCP binary file is read (‘readWorkhorseEnsembles’ MATLAB code; <http://code.google.com/p/imos-toolbox/>) to extract some variables of interest extracted: the east (*u*), north (*v*) and vertical (*w*) components of current velocity; the error velocity; pitch and roll angles; acoustic backscatter intensity (echo intensity) and (*iv*) correlation magnitude of the four beams; percent of good (field 4); bottom temperature; pressure; the number and size of the depth cells (bins); distance to the centre of the first depth cell; time (UTC or as setup).

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### 3.2. Step 1 – magnetic declination correction and direction test

The magnetic declination has to be corrected before the averaging the horizontal (*u*, *v*) velocity components. ADCPs are equipped with an internal fluxgate compass such that the *v*-component aligns with the magnetic north. In order to convert the magnetic direction to a true (geographical) north, the coordinate system must be rotated by an amount given by the local magnetic declination (Brook *et al*., 2007), which changes with geographical location and time. Estimations of magnetic declination can be manually obtained at Geoscience Australia website (<http://www.ga.gov.au/oracle/geomag/agrfform.jsp>) or from NOAA Geomag automated software (http://www.ngdc.noaa.gov/geomag/models.shtml). An averaged value of magnetic declination was adopted here for each deployment and inputted to the code (*mag\_decl*).

In the code, the four-quadrant inverse tangent MATLAB function (atan2) is applied to reconstruct the azimuth angle (clockwise from North) from east and north velocity components, being 360° added to the negative angles. After this, azimuthal angles outside the 0 to 360° range are removed (current direction test). Positive to east (negative to west) magnetic declinations (*MD* in degrees) are added (subtract) to uncorrected azimuthal angle (*D* in degrees) yielding to a corrected azimuthal angle (*D*±*MD*). The corrected azimuthal angle is used to calculate the anticlockwise angle between the *x*-axis and the vector ( in radians, Equation 1) and to re-calculate the *u*- and *v*- velocity components (Equation 2).

(1)

, , (2)

where is the current speed magnitude (m s-1) which has the same value before and after the magnetic declination correction.

### 3.3. Step 2 – in and out the water test

Each deployment record contains information about time when the instrument was first in place (first good measurement; input start\_t) and when it removed for maintenance (last good measurement; input end\_t; see http://www.aims.gov.au/imosmoorings/). This information is used to remove the outside the water measurements from the current velocity data (*u*, *v*, *w*), error velocity and total depth. A flag\_4\_out\_position stores values equal to 1 for data points that failure, and values equal to 0 for data points that pass in this test.

### 3.4. Steps 3 and 4 – distance from the surface to the centre of each depth cell

The distance of each depth cell (bin centre) along the beams is fixed in relation to the ADCP head. However, the depth of each cell varies as the total depth (*DT*) changes with tides and mooring tilting (Figure 3). Considering a classical logarithmic velocity profile with depth, then a particular depth cell may be sampling at different vertical positions within this profile in different instances of time. The bin-mapping algorithm supplied by RDI Instruments (the manufacturer) corrects the velocity components (*u*, *v*, *w*) and error velocity data for tilting when bin-mapping and Earth Coordinates set-up are enabled. The RDI ADCP bin-mapping algorithm aligns measurements vertically from the instrument head (Darryl Symonds, *pers. comm*.), selecting the range cell in each beam calculated to lie closest to the nominal (i.e., vertical) position of the depth cell (no interpolation is done; Gordon, 1996).

When bin mapping is used, time-dependent vertical depth (*SD*, m) of the *nth* depth cell (*n* = 1, 2…*N =* number of bins) is calculated as:

, for upward looking ADCP

, for downward looking ADCP (3)

where *DT* (m) is the total depth from the ADCP head to the surface, calculated from the measured pressure of the instrument (*p*, dbar) using the TEOS-10 algorithm (IOC *et al*., 2010) and its Matlab toolbox ([www.teos-10.org](http://www.teos-10.org)). Further, values of total depth (*DT*) larger than the averaged depth during each deployment plus or minus five times its standard deviation are removed (Step 3; Figure 2). This step is important to avoid spurious values when estimating the depth strata for re-mapping the currents (Step 6 in Figure 2; item 3.4).

The *DHC* (m) is the distance from the head of the ADCP to the centre of the *nth* depth cellgiven by:

, (4)

where *R1* is the distance to the centre of the first depth cell*, CL* is the cell length (bin size) and *n* is the depth cell number (*n* = 1, 2, …*N*). This simple calculation of depth is applicable to velocity and error velocity measurements only. The bin-mapping algorithm is not applied to the performance descriptors (echo intensity and correlation magnitude) supplied with the ADCP data (Darryl Symonds, *pers. comm.*). Proper quality control of the data using the ADCP QC fields requires the depths of each bin to be corrected for tilt (as described in item 3.9.1).

### 3.5. Steps 5 and 6 – placing data into uniform depth strata

At each instant of time, the velocity data (*u*, *v* and *w* components), error velocity and percent of good data are placed into uniform depth strata by inspecting the distance of a particular bin to the surface. Usually only one data point is located in each depth stratum, and data are averaged if more than one data point lies in a particular depth stratum. Air cells are removed before defining the depth strata by replacing any negative depth (*SDn*) with NaN (Step 5; Figure 2). Only wet cells are kept in order to generate matrices of uniform size for flagging (see item 3.9). The depth strata are defined as: where *CL* is the bin size (or cell length),, is the maximum number of wet cells estimated based on the maximum vertical depth () observed during a particular deployment. Therefore, the first column of all averaged matrices corresponds to the deepest cell and the last column the shallowest cell.

### 3.6. Step 7 – tilting angle test

Self-contained RDI ADCPs furnish heading and pitch and roll angles. These orientation angles are used to transform data from XYZ to ENU. If the pitch and roll angles are nil, each beam pair sample the same depth cell. However, correspondent nominal depth cells of a tilted ADCP move up and down relative to one another (Figure 3). The bin-mapping algorithm cannot accurately correct tilting if angles are larger than ±20°, a physical limit imposed by the tilt sensor output, excepting for the RDI Workhorse LongRanger with maximum output of ±50° and the new Sentinel V ADCP that provides tilt over complete ± 180 ° (Darryl Symonds, *pers. comm*.).



**Figure 3**. Tilting and correspondent change in the cell depth (highlighted) of a four-beam bottom-mounted upward-looking ADCP (adapted from Gordon, 1996).

The tilting test aims at eliminating data points subjected to large instrument tilting (above *angle\_cutoff* = 20° for most instruments and *angle\_cutoff* = 50° for the RDI Workhorse LongRanger). The tilt angle (*T*) can be estimated from the measured pitch (*P*) and roll (*R*) angles (Equations 5 and 6). Equation 5 was adapted from Equation 5 in Woodgate and Holroyd (2011), assuming beam angle equal to zero ( = 0) that is equivalent to calculate the tilting between the main axis of the instrument pointing up (*z-axis*) and the vertical.

(5)

(6)

Equation 5 assumes thatpitch is the angle of the axis through beam 4 and beam 3 to the horizontal, with positive pitch for beam 3 head higher than beam 4; roll is the angle of the axis through beam 2 and beam 1, with positive roll for beam 2 head higher than beam 1 (Woodgate and Holroyd, 2011). A flag7\_tilting\_angle matrix stores values equal to 1 for data points along all depth cells at instants of time with tilting angle larger than the specified limit (*angle\_cutoff*) and 0 when instrument tilting is within the acceptable range.

### 3.7. Step 8 –side lobe test

After calculating the depth of each cell to the surface (item 3.4), the cells lying outside the water (*i.e.*, ***SD***(*n*, *t*)< 0; dry cells) are removed (Step 5; Figure 2). Dry cell measurements occur when the sampling range is larger than the local depth, a common set-up of the GBR and WAIMOS moorings. A second layer of spurious data is present below the dry cells, which results from side lobe contamination near the sea surface. The reflections from ADCP side lobes produce echoes stronger than those returning from ocean scatters which overwhelm the transducer side lobe suppression. The width of the side-lobe contaminated layer (*SLW*) and the number of depth cells contaminated by side lobe (*n\_SL*) are given by (Gordon, 1996):

(7)

, (8)

where is the beam angle (equal to 20°), *ceil* is a MATLAB function that rounds the number to the nearest larger integer; *DT* (m) and *CL* (m) were previously defined. Current velocity data (*u*, *v*, and *w* components) from dry and side lobe contaminated depth cells are removed. A flag8\_side\_lobe stores values equal to 1 either for the side-lobe contaminated cells and 0 for the remaining cells.

### 3.8. Step 9 – coarse outlier removal

The time-averaged (each deployment) value of velocity magnitude (*V* as described in item 3.2) for each depth strata plus 5 times (user defined*; ts\_lim* = 5 by default) its standard deviation is set as the cut-off limit above which values are removed (Step 9). This filter is applied twice. This criterion is based on the measured currents at each location/deployment instead of fixed cut-off limits. If an extreme event of short duration (such as a cyclone) occurs during the deployment, the data set should be carefully investigated during the period and different *ts\_lim* tested.

### 3.9. Additional flags

The additional flags (echo intensity, correlation magnitude, percent of good, error velocity and vertical velocity; Figure 2) are generated to identify potentially bad data. The standard processing bythe RDI Instruments software reports the echo intensity and correlation magnitude as bins along the beams (Darryl Symonds, *pers. comm.*), and the tilting correction is not applied in this case (bin-mapping is only applied for *u*, *v*, *w* and error velocity; see section 3.4). Therefore the surface hit, identified as a peak in the echo intensity signal, will occur at different bins for each beam when the instrument is tilted. The instrument tilting has to be corrected when estimating the vertical depths from the sea surface to the centre of each cell depth for each beam. This correction is also required to ensure that the echo intensity and current velocity data correspond to the same depth layer before removing outliers on the current velocity matrices.

#### 3.9.1. Tilting correction for the different beams

The distances from the sea surface to the centre of the depth cells along each ADCP beam (*SD\_B1*, *SD\_B2*, *SD\_B3*, *SD\_B4*) are calculated as:

(9)

,

where *DT* is the distance from the head of ADCP to the surface, *Ra* is the range distance to the centre of the ‘*n*’ depth cell defined as , is defined in Equation 4 and is the beam angle. The cosines of the angle of all beams (*B1*, *B2*, *B3*, *B4*) to the vertical including tilting are given by (Woodgate and Holroyd, 2011):

(10)

where *B1*, *B2*, *B3* and *B4* represent the angles of each one of the four beams to the vertical and the other parameters were previously defined (Figure 4). After correction of the depth strata, the echo intensity and correlation magnitude data are placed into uniform depth strata using the same depth strata range defined in item 3.5. Following, the specific tests for each criterion are applied to generate each flag.



**Figure 4**: Schematic representation of beam 1 (*B1* = 35 °) and beam 2 (*B2* = 5 °) angles to the vertical after instrument tilting (*T* = 15 °) and correspondent distances from the centre of each depth cell to the surface (*SD*\_B1, *SD*\_B2) and to the ADCP head (hB1 = *Ra* *cos* *B1*, hB2 = *Ra* *cos* *B2*).

The Figure 5 shows the depth (*SD*\_*B1*, *SD*\_*B2*, *SD*\_*B3*, *SD*\_*B4*) and the echo intensity profiles for each one of the four beams (on top) when the instrument tilting is large (~19°; Figure 5a) and small (~1°; Figure 5b). Large tilting causes the different beams to cross the surface (zero) at different depth cells (bins), and just before the correspondent echo intensity peaks (Figure 5a). Conversely, all beams cross the surface approximately at the same depth cell when pitch and roll angles are small (Figure 5b). Values of correlation magnitude for each beam are also plotted.

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**Figure 5**: The recorded echo intensity (*E*, in counts; RSSI), correlation magnitude and the distances from the sea surface to the centre of the depth cells for the different beams (*SD\_B1*, *SD\_B2*, *SD\_B3*, *SD\_B4*) for (**a**) large tilt angle (19.2°) and (**b**) small tilt angle (1.3°). Beam 1 (black line), Beam 2 (blue line), Beam 3 (green line) and Beam 4 (red line). Example is for HIN02000.000 (HIS02, k=231,k=685).

#### 3.9.2. Range normalized echo intensity (RE) test

The echo intensity (*EI*), *i.e.* the signal strength of the echo returning from scattering of the transmitted pulse, is the most indicative parameter for data quality, and useful to verify if the returning signal from scatters is larger than the ambient noise level (Shih *et al*., 2001) and to locate the surface, the bottom, or an obstruction (Symonds, 2006). The relative backscatter intensity (*RE*) produces a range-normalized echo intensity profile, supressing the reduction of the echo intensity towards the sea surface (for a bottom mounted ADCP) and generating an approximately straight *RE* profile (Figure 6b). The use of the range-normalized echo intensity profiles facilitates the identification of spurious values.For operational purposes, the range normalized echo intensity (*RE*, dB) can be defined as the sum of the echo intensity and the two-way transmission loss (Thevenot *et al*., 1992):

(11)

Replacing in Equation 7 yields:

(12)

where *E* is the recorded echo intensity (in counts), termed as Reflected Signal Strength Indicator (RSSI); *Kc* is a scale factor that converts RSSI from counts to decibels (dB), being *Kc* = 0.45 dB/LSB adopted here (Deines, 1999); *Er* is the baseline (in counts) which is the reference level for the echo intensity when no signal is present (Deines, 1999) and *TL* is defined in Equation 13. In the code, minimum values of echo intensity during the whole deployment are calculated for each beam and the larger value among them is stored (*minecho*). The instrument baseline (*Er*) corresponds to the smallest value between *minecho* and a user defined value (*instrument\_baseline* = 45 is default), being the same baseline values is adopted for the four beams. Typical baseline values are 40-48 counts (Deines, 1999; Kim *et al*., 2004). Values of echo intensity (*E*, counts) inferior than the baseline are removed. The transmission loss (*TL*) is calculated as:

(13)

where *Ra* (m) is the radial (slant; item 3.9.1) distance from the transducer to the centre of the depth cell and is the absorption coefficient for water (dB/m; described in the Annexe 1). The first and second terms on the right side of Equation 13 account for the geometrical spreading (i.e., a logarithmic loss in echo intensity with increasing range, *Ra*) and absorption losses (Annexe 1), respectively (Figure 6a). The near-field correction of the geometrical spreading disregarded.

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| C:\Users\Mumma Kim\Documents\MATLAB\AIMS\surfacereference_QC_new\fig5a.png |  |  |

**Figure 6:** (**a**) Linear increase of absorption (ABS = *2 α Ra*; black line), logarithmic increase beam spreading (GS= *20 log Ra*; blue line) and transmission loss (*TL*; red line) with depth above the ADCP head; (**b**) depth profile of echo intensity (*E* in counts, black line) for Beam 3, the *E* profile after removing the dry cells (blue line), and the normalized relative echo intensity (*RE* in *dB*, red line); (**c**) *RE* profile over depth strata before (green line) and after applying the echo intensity QC criterion (red line). The accepted values are within the range indicated by the dotted lines applying cut-off limits of plus or minus 10 dB and 15 dB for the top layer and bottom layers, respectively (*echo\_lim\_top* = 10 dB; *echo*\_*lim*\_*bottom* = 15 dB). Example for Heron Island North (HIN) deployment (HIN02000.000; beam 1; 24/04/2010 19:55 UTC; k=125).

#### 3.9.2.1. Echo intensity criterion (flag 12)

Echo intensity profiles of each beam (*B1*, *B2*, *B3* and *B4*) are range-normalized by applying Equation 12, and then, placed onto uniform depth strata using surface distances calculated in Equation 9 for flagging. The mean value of the range-normalized echo intensity (*RE* (*t*)) over the water column is calculated at each instant of time, and a constant offset in dB (user defined) is both added and subtracted to the mean value to furnish a range of acceptable *RE*(*t*) values. In Figure 6c, this range is represented by dotted lines, with different limits for the top (*echo\_lim\_top* = 10 dB) and bottom layers (*echo\_lim\_bottom* = 15) been applied. The value used for these ranges are user defined, and different limits can be applied for the different deployments. The range normalized echo intensity test is run for each beam separately, and if two or more beams failure the test (i.e., they have the data points outside the specified range), a flag equal to 1 (failure) is attributed to the tested depth cell at that instant of time, otherwise the flag is equal to 0 (pass). Two flag matrices are generated: one that applies this test just to the top half of the water column and a second one that tests the whole water column. Note that the dry cells are previously removed before averaging the *RE* along the profile and they are not included in this test.

#### 3.9.3. Echo intensity vertical gradient test (flag 12b)

The raw echo intensity values (*E*, in counts) placed into uniform depth strata are used in this test. The difference between two successive echo intensity values (*E*) along the water column is tested against a limit (usually 25-30 counts) and all the data points above the depth cell (shallower in the upward configuration) that exceeded the set limit are also flagged as 1 (failure). Note that this test is only applied to the top half of the water column. The test is performed independently for each beam and if two or more beams failure the test (i.e. sum of the individual flags is larger or equal to 2) then the final flag matrix will store a value of 1 (failure), otherwise the flag will be equal to 0.

#### 3.9.4. Correlation magnitude test (flag 13)

Correlation magnitude is a measure of the pulse-to-pulse correlation in a ping for each depth cell showing a slightly variable value throughout the depth profile, and reflecting good data quality (high signal to noise) for high values and bad correlation for a zero value (Symonds, 2006). The correlation test (flag 13) is applied individually to each beam attributing flag = 1 (failure) when 2 or more beams fall below a minimum limit (64 by default). Correlation values below 64 usually relates to the “flattening out” of the echo intensity, indicating that the ADCP has reached its noise floor and cannot pick out the signal (Symonds, 2006).

#### 3.9.5. Percent of good (flag 14)

Percent good reports the percentage (0 to 100) of good data collected for each depth cell of the velocity profile, and data rejection is based on low correlation, large error velocity and fish detection (false target threshold; Symonds, 2006). Percent good is related to the expected noise (standard deviation) of your data but cannot detect the surface (echo intensity test) or if the data has good confidence (correlation test; Symonds, 2006). Here the percent of good (field 4) placed in uniform depth strata is tested against a minimum acceptable value (50 by default) and data points below this value are rejected (flag = 1) and above are accepted (flag = 0).

#### 3.9.6. Error velocity (flag 15)

Each pair of beams measures one horizontal velocity component and one vertical velocity component. The error velocity is the difference between two independent estimates of vertical velocities from each pair of beams, therefore it can only be reported when the 4 beams solution is applied (Gordon, 1996). Error velocity allows you to evaluate whether the assumption of horizontal flow homogeneity is reasonable, and the error velocity approaches to zero when the flow is homogeneous (Symonds, 2006; QARTOD, 2013). The error velocity test (Flag 15a) rejects (flag = 1) data points with error velocity higher than ±0.15 m s-1 and a second test uses as cut-off limit twice this values (i.e., ±0.3 m s-1; Flag 15b). Note that this flag does not count values of error velocity removed by the RDI software (replace by NaN) when the 3 beams solution was applied.

#### 3.9.7. Vertical velocity flags (flag 16)

Data points with error velocity higher than ±0.20 m s-1 (by default) are rejected (flag = 1), otherwise flag = 0.

## 3.10. Extraction of the topmost valid depth cell

The nearest-to-the-surface (topmost) valid velocity data were extracted for each analysed deployment after placing the data in uniform depth strata using the surface as reference (see item 3.4 and 3.5). Both the topmost depth cell with a minimum of 50% of data temporal coverage during the deployment and the depth cell immediately below it were analysed.