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# *A spar buoy-mounted ADCP measurement station in the Ligurian Sea: a metrological approach to correct current measures for bias effects and evaluate uncertainties*

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***Abstract*—Since the '70s, the ENEA Marine Environment Research Centre of S. Teresa has been involved in monitoring and analysis of physical, chemical and biological processes in marine environment. In order to provide a deeper view of the real marine dynamics, based on the integrated use of data and models, some of these activities have been recently focused on the measurement of current profiles in the open sea. A dedicated experimental methodology and data analysis were carried out to design and install a system for measuring current profiles in the surface layer in the Ligurian Sea: the measurement station, based on an Acoustic Doppler Current Profiler (ADCP) mounted on the surface buoy of W1-M3A (Western 1 Mediterranean Moored Multisensor) weather-oceanographic observatory, led to the acquisition of a time series of data continuously acquired for five months (from April to August 2017). The collected dataset, together with the implemented post-processing techniques, were aimed to realize a monitoring system able to support (and verify by comparison) marine current numerical models, with the final purpose of improving their performances. Main object of this work are both the correction of bias effects due to the buoy influence on ADCP measures and the evaluation of the overall uncertainty associated with the current velocities. In the following, an overall view of the performed experimental activity is briefly reported, ranging from the design of the measuring station to its implementation, from recovery to preliminary data processing and uncertainty analysis applied to a sub-set of data, used as a test case.**

***Keywords—ADCP; spar buoy; current profiles; bias correction; uncertainty analysis***

## I. INTRODUCTION

With the purpose of both monitoring sea conditions and providing a method to verify the reliability of numerical models related to surface circulation in open sea [1], an ADCP (Acoustic Doppler Current Profiler) was mounted on the damping disc of the Ocean Data Acquisition System (ODAS) Italia 1 spar buoy, part of the open ocean W1-M3A (Western 1 Mediterranean Moored Multisensor) observatory [2], placed in the centre of the Ligurian Sea (simply indicated as Buoy, in the following); the site was selected in order to take advantage of this well-known open sea infrastructure [3, 4], so avoiding the installation of a proper, dedicated fixed mooring (with all the maintenance costs that would have been derived from this).

The ADCP, placed at the depth of about 37 m and facing upwards, allowed to acquire a time series of data five months long (from April to August 2017): data consisted in current velocities measured along the overlying water column, with a vertical resolution of 4 m, at a frequency of sampling of 0.5 hours. An *ad hoc* data-analysis method was developed and applied on a subset of collected data, used as a test case. Current profiles measured by ADCP needed to be post-processed taking properly into account the following two effects, both attributable to the Buoy action on the ADCP:

- alterations of the ADCP compass due to the local distortion of the Earth's magnetic field induced by the metal structure of the Buoy (that consists of a tubular steel structure, 600 mm diameter): such distortion was not constant over time as a result of the rotation of the Buoy itself due to winds, waves and currents;
- fictitious currents measured by ADCP due to displacements of the Buoy following the action of currents: owing to the very long mooring line (1900 m), the buoy is indeed left free to move around the anchor with a radius of about 0.5 NM.

Uncertainty analysis was then implemented on ADCP post-processed data by applying the standard framework for uncertainty evaluations, as prescribed by [5, 6].

## II. MATERIALS AND METHODS

In the following, the various phases in which the experimental activity was designed and implemented are described, respectively.

## A. *The platform for the measurement station*

The W1-M3A observatory, composed of the spar Buoy ODAS Italia 1 combined with a subsurface mooring (central point of the working area about 43° 48.90' N, 09° 06.80' E), is a remarkable example of offshore laboratory (Fig. 1). The observatory is located in the open sea about 40 NM from Genoa, on a 1270 m deep sea bed in the Ligurian-Tuscan and Provençal basin: the surface spar Buoy is 51 m long, of which about 37 m immersed, and has a weight on the ground of about 12 tons (Fig. 2).

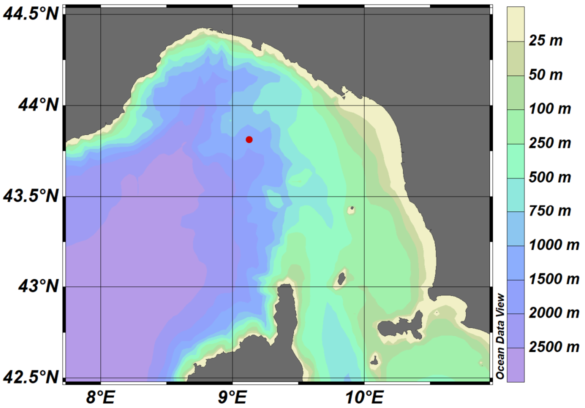


Fig. 1. Map and bathymetry of the Ligurian Sea. The red dot marks location of the W1-M3A Buoy.

Fig. 2. Images of the Buoy in its entirety on land and in operation at sea.

The Buoy is a completely autonomous laboratory, which draws energy from renewable sources of sun and wind, and communicates with the outside world by a satellite connection. Equipped with a set of sensors dedicated to weather and marine parameters, the Buoy allows to collect and transmit useful data to national and international meteorology centers, thus contributing to the realization of the weather forecast and allowing to develop comparisons between the observations from satellite and measures collected directly at sea.

## B. *The ADCP*

The ENEA S. Teresa Centre manages two different ADCPs, respectively with three (Nortek manufacturer) and four (RDI manufacturer) acoustic beams: due to Buoy features, in order to prevent its structure from interfering with one of the beams, it was decided to use the three-beam ADCP (using the other one as a reference, in the context of some preliminary comparison tests).

The general characteristics of the instrument are reported in Table I, referring to literature for a more exhaustive description of the technical details and the operating principle underlying the Doppler measurements of current profiles [7, 8]:

TABLE I. ADCP GENERAL CHARACTERISTICS

| Parameter | Value |
|---|---|
| Model | Nortek Aquapro |
| Acoustic frequency | 400 kHz |
| Max working depth | 200 m |
| Max profiling range: | 60-90 m |
| Cell size | 2-8 m |
| Beam width | 3.7° |
| Min blanking distance | 1 m |
| Max number of cells | 128 |
| Velocity range | ± 10 m/s |
| Declared accuracy | 1 % of measured values ± 0.005 m/s |
| Max sampling rate | 1 Hz |

Despite their widespread use, combined with technological developments and application advances, no standard procedure has been adopted or accepted for calibration of ADCP until today [9]. ADCPs are not individually calibrated for velocity, however the transducers are tested at factory to be within specification on the transmitted and received frequencies, which is somehow equivalent to testing the velocity measurements (as declared by the manufacturer [10]). In this context, a custom ADCP characterization was carried out at ENEA by means of dedicated sea tests. The operations performed and the results achieved in this preliminary phase are briefly presented in the following.

## C. *ADCP preliminary characterization: comparison with a reference four-beam ADCP*

In order to verify the correct functioning of the chosen ADCP, before it was mounted on the Buoy, both ADCPs were tested by comparison in the field to measure current profiles from the bottom to the top, from a depth of about 37 m (comparable with the damping disc depth of the Buoy).

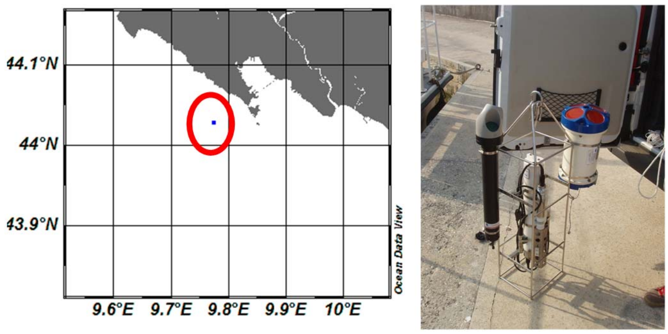


Fig. 3. Comparison test between two ENEA ADCPs: working area (left) and mechanical assembly (right).

In Fig. 3 the site point in which the test was performed and the assembly configuration are shown: the two ADCPs (the Nortek on the left and the RDI on the right, respectively) were assembled on the frame of a CTD probe so that their reference beams (beam X for the Nortek, beam no. 3 for the RDI) pointed in the same direction. The configuration of the reference systems for both ADCPs was the ENU type (East-North-Up coordinates), with automatic correction of Roll, Pitch and Heading. Specifically, the Nortek ADCP was configured to divide the profile into 20 cells of 2 m; compatibly with some minor differences (i.e. blanking distance, estimated error on the measured speed, etc.), the RDI ADCP was configured with the same number of cells of the same size, too.

The test consisted in the acquisition of six measures of current profiles at five minute intervals, with an acquisition time window of 120 s. Current profiles of both the ADCPs, in terms of East and North components, respectively, are shown in Fig. 4.

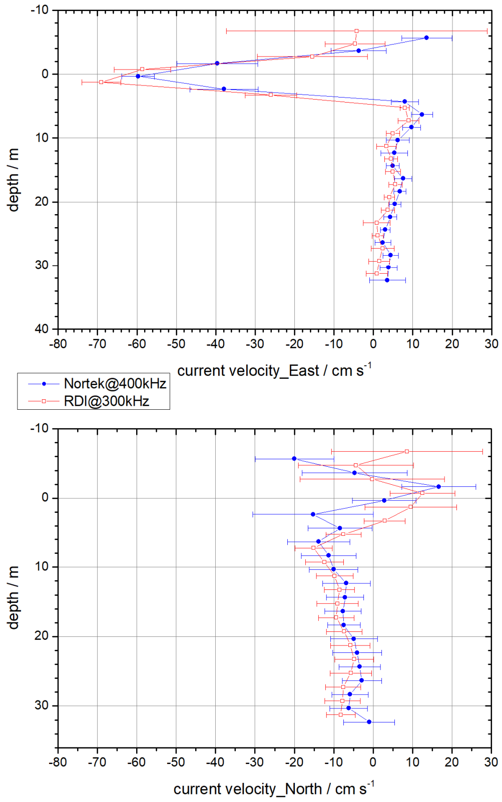


Fig. 4. Comparison test between two ENEA ADCPs: mean profiles for East (top) and North (bottom) components.

The results provided a reasonable compatibility of the measures between the two ADCPs and their response dynamics: in particular, the water-air interface band and the so-called side-lobe error (which determines the maximum extent of the measurability interval) were well identified.

*D. ADCP preliminary characterization: qualitative verification of the ADCP operating in ENU configuration*

Some other tests were carried out in the S. Teresa bay, during which the correct functioning of the ADCP (in this case oriented downwards) in ENU configuration was verified. Actually, the measured current was "fictitious", as it was generated by translating the ADCP at an almost constant speed (in practice, walking slowly on the pier shown in Fig. 5 and taking the ADCP pushed out). The test allowed to verify how the ADCP carries out the conditioning of the acquired acoustic signals on board, providing as output an already correct result according to ENU reference system.

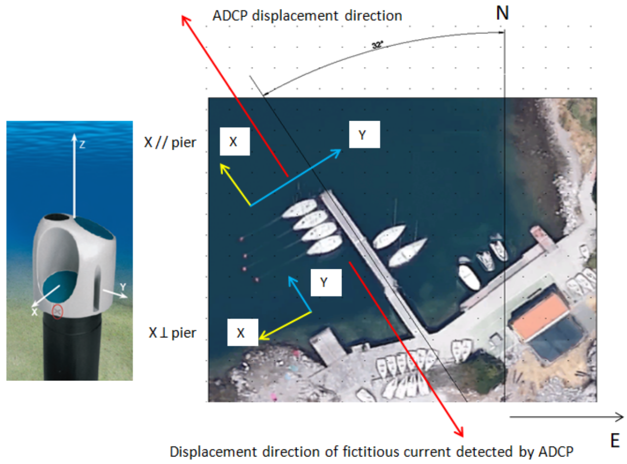


Fig. 5. Bay test: ADCP (facing down) translated to measure a fictitious current. On the left, the ADCP Cartesian axis reference system is shown.

These considerations were useful to choose the ENU system for the ADCP once mounted on the Buoy: the ENU system indeed proved to be suitable for carrying out corrections on ADCP data for the effects of magnetic distortion and rotary translation in the plane, characteristic of the Buoy itself. It has to be noted that in the Bay test ADCP was operated in “fast” sampling rate, so that accuracy related to velocity and direction are significantly lowered; anyway, measured mean velocity of (0.67 ± 0.23) m $s^{-1}$ and direction of (146 ± 29)° proved to be reasonably comparable with expected values (equal to about 0.8 m $s^{-1}$ and 148°, respectively).

*E. Final measurement configuration of the ADCP and mounting on the Buoy*

As a consequence of the preliminary tests, the ADCP was set in order to supply a ten-cell current profile each 1800 s (900 s average interval, 10 s compass update rate), being 4 m the cell size and 0.006 m $s^{-1}$ the (nominal) horizontal velocity precision, respectively. The ADCP mechanical mounting on the Buoy was designed in order to avoid any interferences among the acoustic beams and the Buoy structure itself (Fig. 6).

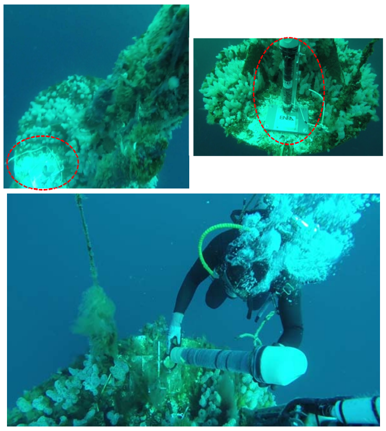

Fig. 6. ADCP installation on the Buoy. At the top, mounting on the damping disk of the Buoy: overview (left) and detail (right). Below, re-installation after the battery replacement.

## III. TEST CASE: DATASET AND POST-PROCESSING

The overall experimental activity can be divided into three steps:

- installation of the ADCP, on 2017/03/30;
- battery replacement and re-installation, on 2017/07/07;
- recovery of the ADCP, on 2017/08/29 (after 152 day of continuous data acquisition).

In addition to the data acquired by the ADCP, the values of orientation and position registered by the Buoy were acquired, too. These data, hourly averaged and related to the direction of the Buoy detected by the on-board compass (Heading) and to its GPS position, are necessary for the corrections of the current profiles measured by the ADCP. In the present work the following subset of the overall dataset was taken into consideration as a test case: current profiles measured every 0.5 hours by the ADCP starting from 2017/03/30 (10:00:00 UTC) to 2017/05/24 (08:00:00 UTC), for a total of 2637 profiles in 55 days. In order to verify that the signals recorded on the three acoustic beams of the ADCP did not show anomalies, the mean values (over time) of the counts on the three beams were compared, as a function of the cell depths (Fig. 7). All three beams behaved homogeneously (within the associated standard deviations), with correctly decreasing signals towards the surface of the sea (as the distance from the sensor emitting/receiving head increases). This homogeneity was found to a greater extent for the cells from the 2 to 7. Furthermore, as expected for the measurement configuration adopted, cells 10, 9 and 8 were not considered in the analysis of current profiles: in particular, cells 10 and 9 were respectively positioned directly in the air and at the water-air interface. Cell 8 showed an anomaly relative to the number of counts (excessively high for all three beams, if compared with the previous cells): hence this cell was also considered as affected by the disturbing action of the water-air interface. Furthermore, echo amplitude, describing the relative strength of the backscattered signal, was strong enough to maintain the signal-to-noise ratio (SNR) at satisfactory levels (Fig. 7).

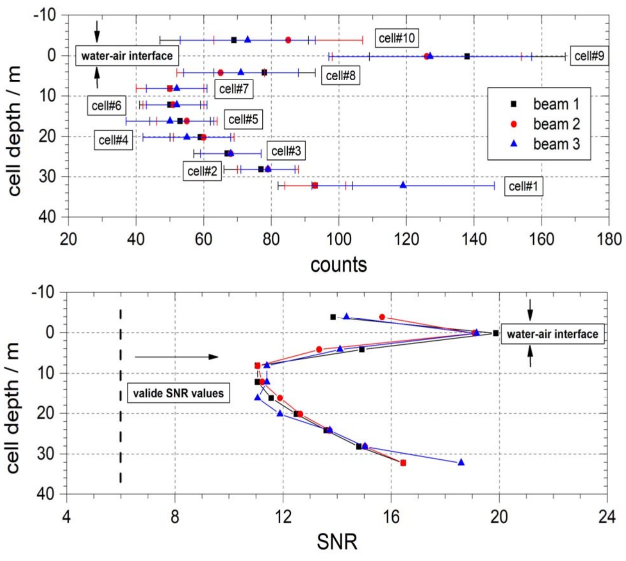


Fig. 7. Top: average counts of the three ADCP beams vs. cell depths along the profile. Bottom: corresponding SNR values.

### A. *Involved quantities and their standard uncertainty*

In the following, quantities measured by ADCP and Buoy at the $i$-th moment ($1 < i < 2637$) and at the $j$-th depth (or cell, $1 < j < 7$) are defined, together with their associated standard uncertainty:

- ADCP quantities:
  measured velocity $\boldsymbol{v}_{i,j}$, characterized by a modulus $v_{i,j}$ and a direction $dir_{i,j}$. The standard uncertainty (expressed in m s$^{-1}$) associated with $v_{i,j}$ was calculated in accordance with Table I (values declared by the manufacturer [7]), as:

$$u(v_{i,j}) = \sqrt{(0.01 \times v_{i,j})^2 + 0.005^2} \qquad (1)$$

  The standard uncertainty (deg) associated with $dir_{i,j}$ was derived from declared values of accuracy and resolution of ADCP compass (Heading [7]):

$$u(Head\_ADCP_i) = \sqrt{(2)^2 + \left({}^{0.1}/_{\sqrt{3}}\right)^2} \qquad (2)$$

  so that $u(dir_{i,j})$, for each $j$-th depth, can be expressed (in accordance with Par. II-E) as follows:

$$u(dir_{i,j}) = {}^{u(Head\_ADCP_i)}/_{\sqrt{90}} \qquad (3)$$

  where 90 indicates the number of compass values acquired in correspondence of the $i$-th measurement. Furthermore, pressure values $p_i$ measured by ADCP were used to evaluate the mean ADCP depth, in order to correctly scale the depths associated with the centers of the individual profile cells: mean depth for cell#1 was calculated as (32.18 ± 0.62) m (other cells are scaled of 4 m, with same standard uncertainty,up to the last valid cell, cell#7, whose associated depth is 8.18 m ).

- Buoy quantities:
  the Buoy compass (Heading) values were characterized by the following standard uncertainty (deg):

$$u(Head\_Buoy_i) = \sqrt{(2)^2 + \left({}^{0.5}/_{\sqrt{3}}\right)^2} \qquad (4)$$

  where accuracy and resolution terms (deg) reported in [11] are properly combined.
  Uncertainties of GPS values in terms of Longitude and Latitude (deg) were respectively:

$$u(Lon_i) = 0.00004/1.96 \qquad (5)$$
$$u(Lat_i) = 0.00003/1.96 \qquad (6)$$

  as calculated from a maximum error of 3 m on the distance at a 95 % level of confidence (as declared by the manufacturer [12]), close to the Buoy.

*B. Post-processing and correction for bias effects due to Buoy*

In the following, a list of the steps performed to analyze the data is reported:

1) <u>interleave action on the Buoy Heading and GPS data to match them to the ADCP data</u>: to guarantee the correct data matching, it was necessary to interleave Buoy data. This means that they were doubled, inserting the values (for the Date & Time [UTC], Lon, Lat and Heading parameters) at half an hour as the average of the data referring to the immediately preceding and following hours (for the Date & Time parameters, Lon and Lat the arithmetic mean can be applied directly). As regards the *i*-th average of the pair of angles associated with the Buoy Heading, values had to be averaged in vectorial terms;

2) <u>estimation of the velocity vector (modulus and Bearing) associated with Buoy displacement between two successive pairs of its GPS coordinates</u>: the distance $d_{i+1}$ (m) traveled by the Buoy was calculated between two successive pairs (indicated with the label *i* and *i*+1, respectively) of its GPS coordinates (acquired at a time interval of 0.5 hour) with the formula called spherical law of cosines [13] (considering the values of *Lon* and *Lat* in radians and the mean Earth radius in the spherical approximation of the Earth close to the Buoy, *R*, equals to 6367922 m):

$$d_{i+1} = \arccos(\sin(Lat_i) * \sin(Lat_{i+1}) + \cos(Lat_i) * \cos(Lat_{i+1}) * cos(Lon_{i+1} - Lon_i)) * R \tag{7}$$

The module of the velocity vector (m s$^{-1}$) associated with the displacement of the Buoy is then calculated by dividing each *d* by the time in seconds (1800 s) passed between two successive positions on which *d* itself was calculated. Once the module of the Buoy displacement was calculated (and consequently the module of its velocity), its angle $\gamma_{i+1}$ (rad) with respect to the North direction (what is referred to as Bearing) can be determined, according to the following formula (where the values of *Lon* and *Lat* are again expressed in radians [13]):

$$\gamma_{i+1} = \mathrm{atan2}(\cos(Lat_i) * \sin(Lat_{i+1}) - \sin(Lat_i) * \cos(Lat_{i+1}) * cos(Lon_{i+1} - Lon_i),\ sin(Lon_{i+1} - Lon_i) * \cos(Lat_{i+1})) \tag{8}$$

3) <u>first correction of ADCP values: Heading correction</u>. Since the value of the ADCP compass is influenced by the presence of the metallic body of the Buoy, the *Head_Buoy* value is adopted as a reference value and consequently the mean Heading error *EH* (deg) to be adopted on the *i*-th measure of the ADCP is evaluated as follows:

$$EH_i = Head\_ADCP_i - (Head\_Buoy_i + 180) \tag{9}$$

where the fact that the reference axis of Buoy and ADCP are oriented with a difference angle of 180° was taken properly into account. The value of $dir_{i,j}$ (deg) can so be corrected as follows:

$$dir\_HC_{i,j} = dir_{i,j} - EH_i \tag{10}$$

where the term *HC* indicates that the Heading correction was applied (cell by cell and profile by profile). The mean value of *EH* was about 16°. In Fig. 8 a comparison of ADCP values before and after Heading correction is reported as an example for cell#4.

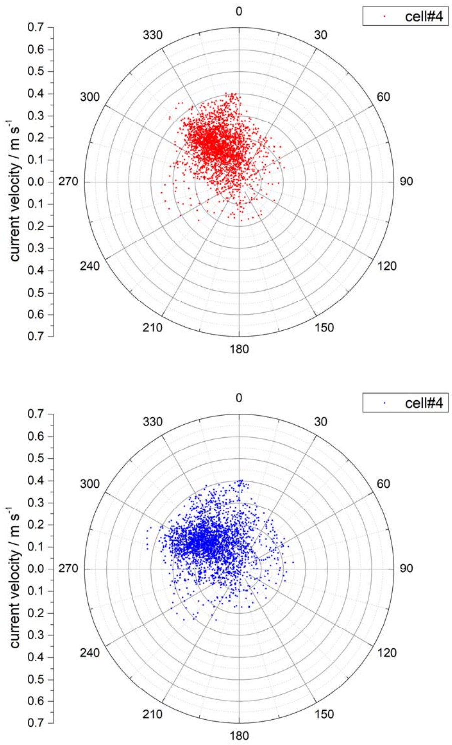


Fig. 8. Heading correction: example of application of the Buoy Heading correction. Current values measured at the cell#4 first (top diagram, in red) and after the correction (bottom diagram, in blue).

4) <u>second correction of ADCP values: correction for offset currents induced by the Buoy movement</u> (<u>*dummy* currents</u>). Since the Buoy, in addition to the rotation on its axis, shows a displacement on the plane (induced by current and/or winds), the ADCP will suffer from fictitious currents for which the measured current profiles need to be corrected. This correction can be implemented simply by vectorially composing the Buoy and ADCP velocity vectors (as calculated in step 2), cell by cell and profile by profile. In Fig. 9 an overall view of ADCP current velocities, cell by cell, is shown in comparison with the estimated Buoy velocities (ADCP values were already re-calculated taking into account the Heading correction).

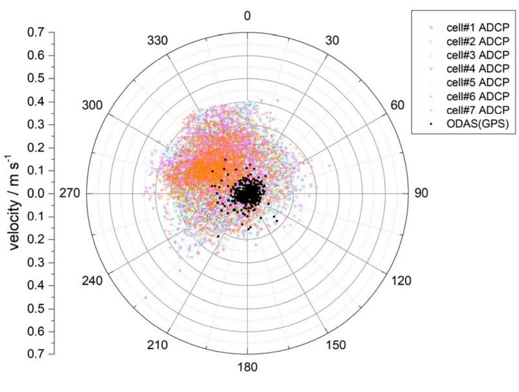


Fig. 9. Velocity comparison among cell-by-cell measured currents (already corrected for Buoy Heading, coulored symbols) and fictitious current values (black dots).

By implementing all the previous steps, the final result was obtained, i.e. the set of current velocity profiles corrected for both bias effects (e.g. data representation shown in Fig. 10).

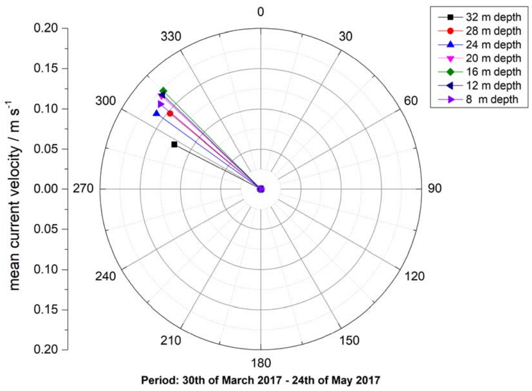


Fig. 10. Mean (corrected) current profile, cell by cell, in the test case.

The procedure here described needs a dedicated uncertainty analysis, taking properly into account the contributions due to each involved quantities and the way by which they are combined.

### *C. Evaluation of standard uncertainties associated with corrected current velocities: preliminary results*

Up to Heading correction (10), standard uncertainty on *dir_HC* can be calculated according to the law of uncertainty propagation [5]. On the other side, due to non-linear model by which finally corrected current velocities and their directions are obtained, their standard uncertainties were calculated as a by-product of the propagation of the Gaussian probability distributions modeling each input quantities, i.e. *Lon*, *Lat*, *d*, $\gamma$, *v* and *dir_HC* (Monte Carlo method [6]). The simulation was performed in R ambient [14], randomly generating M = $10^6$ data for each input quantities: Gaussian distributions, centered in the measured values of the respective input variable, had standard deviation equal to the uncertainty calculated with the formulas described in Par. III. From the probability density functions numerically obtained for both corrected *v* and *dir*, the associated uncertainties were taken as the corresponding standard deviations. Final results are shown in Fig. 11 and Fig. 12, for velocity modules and directions, respectively.

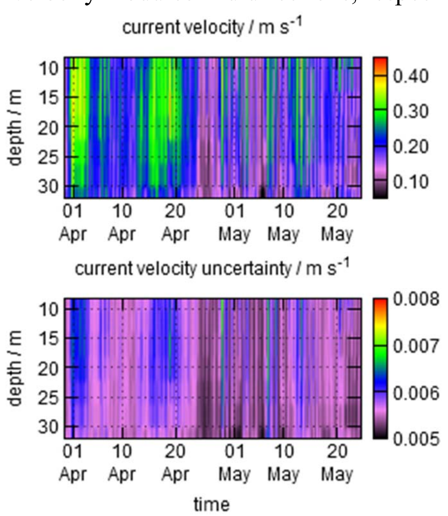


Fig. 11.Corrected velocity modules and their standard uncertainty vs time.

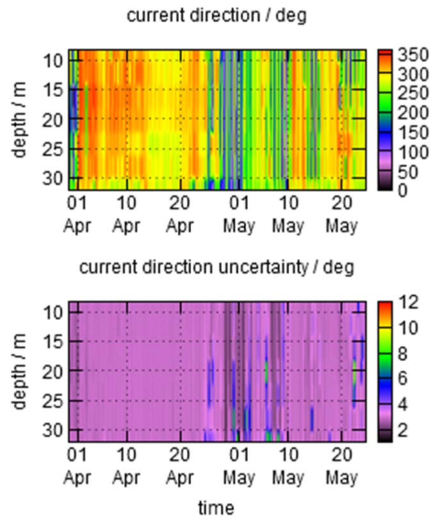


Fig. 12.Corrected velocity directions and their standard uncertainty vs time.

## IV. CONCLUSIONS

An ADCP station for current profile measurements in the surface layer was planned and installed on a spar buoy in deep sea, together with the development of a proper post-processing and data analysis procedure. The *ad hoc* methods adopted for the corrections of both the magnetic influence (exerted by the buoy body on the ADCP compass) and the displacement of the buoy itself (causing fictitious currents detectable by the ADCP) were at the same time considered in a proper uncertainty evaluation by means of Monte Carlo method. The work here presented can be considered as a (suggested) technique to both collect current velocity data and assess their measurement reliability by a proper uncertainty analysis: the data set can so be exploited for both the phenomenological analysis and the comparison with data supplied by numerical models.

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