Estimating ocean vertical velocities using an autonomous multipurpose profiler

Jean-Luc Fuda
Mediterranean Institute of Oceanography
Centre National de la Recherche Scientifique
Marseille, France
jean-luc.fuda@mio.osupytheas.fr

Stéphanie Barrillon
Mediterranean Institute of Oceanography
Centre National de la Recherche Scientifique
Marseille, France
stephanie.barrillon@mio.osupytheas.fr

Caroline Comby
Mediterranean Institute of Oceanography
Aix-Marseille Université
Marseille, France
caroline.comby@mio.osupytheas.fr

Andrea Doglioli
Mediterranean Institute of Oceanography
Aix-Marseille Université
Marseille, France
andrea.doglioli@mio.osupytheas.fr

Patrice Le Gal
CNRS-IRPHE
Aix Marseille Université
Marseille, France
patrice.le-gal@univ-amu.fr

Anne Petrenko
Mediterranean Institute of Oceanography
Aix-Marseille Université
Marseille, France
anne.petrenko@mio.osupytheas.fr

***Abstract*— A low-cost multipurpose oceanographic vertical profiler is described. Its application to the measurement of vertical currents, inspired by ocean glider flight-model methods, is presented. Preliminary results of the BioSWOT-Med campaign, carried out in April-May 2023, illustrate the instrument's ability to capture weak signals, potentially linked to sub-mesoscale oceanic structures.**

Keywords — autonomous profiler, vertical currents

I. INTRODUCTION

The vertical distributions of fundamental oceanographic parameters (e.g., temperature, salinity, fluorescence, dissolved oxygen, turbidity, …) are generally obtained using a CTD rosette winched vertically from research vessels. Most of the time, this imposing device (several hundred kilograms) is electrically powered through an electromechanical cable, which makes it possible to receive and display the sensors signals with respect to depth in real time, as well as to close remotely seawater sampling bottles, at chosen depths. Off-the-shelf commercial devices can sample the water column over several thousand meters depth, at very high frequency (24Hz), at a cost of several tens of thousands of euros.

During large-scale campaigns, the ship often has to remain stationed at a specific location for a whole day, in order to massively sample the site with different types of instruments, taking into account natural biogeochemical cycles. During a station, it is therefore common to operate various instruments for completing the CTD casts, such as, for instance, plankton net tows, punctuated by standby episodes dedicated to emptying bottles and analyzing samples. During these phases, the vertical profiles of the basic parameters are not recorded since the CTD cannot generally be operated, mainly because it is not possible for practical or safety reasons to winch or operate several instruments simultaneously from the ship.

The autonomous profiler that we have developed makes it possible to complete and enrich conventional CTD rosette data thanks to continuous and high-frequency sampling throughout the duration of a station, at the level of the upper layers which are dynamically the most energetic, and often the crucial ones for physical-biological interactions [1]. Once deployed, the profiler autonomously performs, over several hours, a series of successive descent/ascent cycles to a preset depth, drifting in the ship's vicinity. It is accurately located each time it surfaces, thanks to a commercial stand-alone SPOT GPS tracker (https://www.findmespot.com/en-gb/products-services/spot-trace). In addition, the profiler drift allows to collect precious information about the horizontal current field around the vessel and the re-positioning of the ship-based measurements in a Lagrangian reference frame [2].

It is worth pointing out that the use of this lightweight profiler can be advantageously extended to various coastal applications, as it operates freely, without any cable. It can therefore be deployed and recovered using a modest boat, provided an internet connection is available through the local mobile phone network to locate it through the SPOT website.

Here below, we describe the general design of the profiler, before presenting an application dedicated to the measurement of ocean vertical currents in the framework of the BioSWOT-Med oceanographic cruise [3].

II. GENERAL DESIGN

The profiler consists mainly of the following mechanical and electronical components, marketed by Blue Robotics: a 4-inch diameter sealed cylindrical container in anodized aluminum (max depth 500 m), a rechargeable 260 Wh Li -Ion battery, a **bar30** pressure sensor (max depth 300 m) and a 20 N-max-thrust **T200** electric propeller which is the heart of the system. These components are mechanically associated with buoyancy elements, so that the profiler floats as long as the vertically mounted propeller is at rest. When the propeller is turned on with adequate thrust (ie = drag + buoyancy), the profiler is driven down to the set depth. The propeller is then stopped hence the profiler rises under the sole effect of its positive buoyancy. Once at the surface, it remains in stand-by during a few minutes, in order for the SPOT tracker to get and send GPS data to the onland mapping and monitoring SPOT website. The cycle then repeats until the programmed mission time is reached or the battery is exhausted.

The control electronics consist of a classic ARDUINO Uno board interfaced with the **bar30** pressure sensor. The C++ Arduino sketch manages the propeller behavior, depending on the 4 possible states of the profiler, namely "out of water" (when the ARDUINO board is powered up on deck), "on surface", "descending" and "ascending". These states are evaluated in real-time thanks to the continuous measurements of the **bar30** pressure sensor at ~ 1 Hz. In addition to these basic functionalities, safety actions are also implemented, such as stopping the propeller in the event of contact with the bottom (i.e. pressure remaining constant), or if the battery voltage becomes too low. A watchdog is also activated, in order to reboot the system and switch off the propeller in case of any hardware failure, so that the profiler can come back safely to surface in abort mode.

Additionally, a 3 axis-accelerometer and a storing shield (both Adafruit modules) are connected to the Arduino, to record and monitor pitch and roll during the descent/ascent cycles. Incidentally, the accelerometer can be used for sampling waves whenever the profiler stands by in surface between dives.

The user must enter 3 parameters for configuring the mission: the total duration (up to 8 hours), the terminal depth (max 300 m, imposed by the bar30 depth limit) and the stand-by delay in surface between 2 consecutive dives.

The total cost of the system is less than 1.5 keuros.

Currently, the associated scientific payload is a commercial autonomous CTD, but it can be any off-the-shelf autonomous logger of reasonable size, attached to an adapted (in terms of hydrodynamics and residual buoyancy) floating frame, and equipped with the above-described universal system which is simply composed of an electronic enclosure and a propeller.

We present hereafter an adaptation of that system for measuring ocean vertical velocities, using a RBR Concerto CTD (max depth 750 m).

III. ESTIMATING OCEAN VERTICAL VELOCITIES

Based on the above-described general design, we have imagined and developed an original instrument, called the VVP (Vertical Velocity Profiler) for measuring ocean vertical velocities during the BioSWOT-Med oceanographic cruise carried out in April-May 2023, during the calibration phase of the newly launched SWOT (Surface Water Ocean Topography) satellite [3]. The vertical component of ocean currents is generally very weak (a few mm/s), and their in-situ measurement represents a real technical challenge, even with state-of-the-art instruments such as ADCPs, mainly because of the noise induced by the motions of their supporting platforms.

The oceanic fine scales (1-100 km) associated to sub-mesoscales structures (eddies, fronts, filaments) are the subject of study of the SWOT-ADAC international consortium (www.swot-adac.org) of which the BioSWOT-Med cruise is part. They have relatively short lifetimes (days to weeks) and limited spatial extension (1-100km) but crucially affect ocean physics and ecology up to the climate scale, due to the strong gradients created by their energetic dynamics [4]. These gradients are associated with strong vertical transport connecting the ocean's upper layer to its interior, with major impacts on biogeochemical cycles [5], biodiversity [6], fish distribution [7], and even foraging strategies of the mega-fauna [8].

The VVP was inspired by several published works which exploit the difference between the actual vertical speed *Wr* of an ocean glider (estimated as the temporal difference ~ dP/dt, from the onboard pressure sensor, see details below) and its theoretical vertical speed *Wth* computed from a flight model [9] [10]. The oceanic vertical speed *Woc* is thus expressed by their simple difference (*Woc* = *Wr* - *Wth*) at any sampling point along the vehicle trajectory in the water column.

The main components of the VVP are shown in Fig.1. The upper part consists of a 0.5 m diameter friction disc under which are fixed 8 ellipsoidal trawl floats (buoyancy 0.78 kg, each). The watertight enclosure which contains the electronics and the battery is encased in the center. The SPOT tracker and a safety flashlight are positioned at the top of the enclosure, just below the somital acrylic transparent dome. The bottom chassis is a stainless-steel cage that houses the T200 propeller and a high quality self-contained RBR Concerto CTD, able to sample and record pressure, seawater temperature and electrical conductivity at 2 Hz. Four fins are fixed on the cage, 90° apart, to stabilize the profiler when it rises back to the surface (see below). The height of the system is 1.27 m.

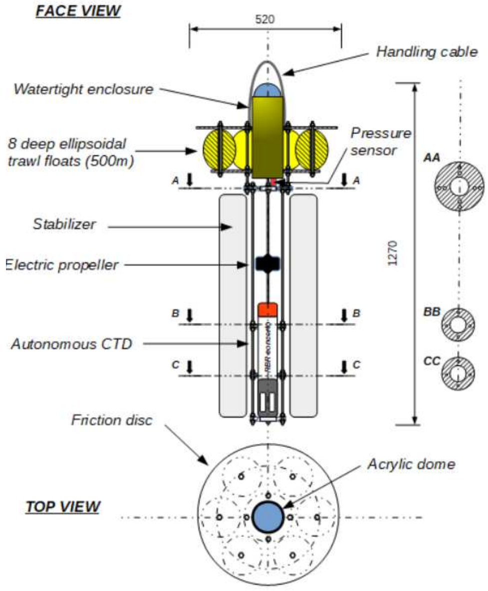

Fig. 1. Overview of VVP components

The profiler needs to be accurately ballasted at the lab, so that its net positive buoyancy in the field, just below the surface, is 0.30 kg +/- 0.05 kg, while its total weight in air is 20.00 kg. With those settings, only the acrylic dome emerges a few cm above the surface, thus minimizing wind drift, as done also by the cross-mounted fins which act as a drogue (sea anchor).

Only the ascending phases are used for estimating the ocean vertical velocities, as the pulling force of the propeller cannot be accurately measured during descending phases. In ascending phases, the profiler undergoes only 3 mechanical forces: its weight, the Archimedes thrust and the hydrodynamic drag. Expressing the mechanical static balance between these forces, one can infer the theoretical ascending vertical velocity *Wth* of the profiler in still water:

$$W_{th} = \sqrt{2\,\frac{\rho\, V\, g\; -\; M\, g}{\rho\, \pi\, R^2\, Cd}} \qquad (1)$$

where ρ stands for seawater density (kg/m^3), V the total VVP volume (m^3), M (kg) its mass, g the gravity acceleration (9.81 m/s^2), R the friction disc radius (m), and Cd the drag coefficient.

M is directly measured at the lab with an accurate KERN electronic weighing scale (50g accuracy).

The volume V is depending on pressure through the compressibility coefficient β (dbar^{-1})

$$V = V_0\,(1 - \beta P) \qquad (2)$$

where V_0 stands for the VVP volume at $P = 0$ (atmospheric pressure).

The actual vertical velocity of the profiler can be estimated as the difference in time of the measured pressure:

$$W_r = \frac{d\left(\dfrac{P}{\rho\, g}\right)}{dt} \qquad (3)$$

Finally, the ocean vertical velocity *Woc* is obtained by the difference:

$$Woc = Wr - Wth \qquad (4)$$

V0 is obtained by ballasting, namely by weighing with high quality KERN spring scales the VVP totally immersed in a dedicated water tank (Fig. 2)

The seawater density ρ is derived accurately from the pressure, temperature and conductivity in-situ measurements made by the RBR concerto CTD using the TEOS10 equation of state [11].

Fig.2. Ballasting the VVP at the SAM (Service Atmosphere et Mer) technical facility of the MIO (Mediterranean Institute of Oceanography)

One of the problems we encountered in designing the VVP was its susceptibility to a fluid-structure interaction causing parasite vertical oscillations [12]. To annihilate these oscillations, we first studied the wake of the profiler in a wind tunnel. Choosing the Reynolds number in the air flow equal to the one met when rising in still water, we have been able to determine the frequency of the emitted vortex street of its wake. In dimensionless units, this frequency is measured by the Strouhal number which takes a classical value between 0.15 and 0.17. The fact that this value is close to the value of the Strouhal number calculated for the oscillation observed at sea, proves that the VVP was subject to a fluid-structure instability. Therefore, in a second step, we studied the behavior of the VVP when rising in water in a 10 m deep pit. As can be observed on Fig. 3-a, there is a clear lateral oscillation about 1 m in amplitude and with a period around 40 s. This periodic displacement is associated with a vertical oscillation at half the period (20 s) (Fig. 3-b). To annihilate the spurious vertical velocity oscillations, we decided to equip the VVP with 4 stabilizers in order to damp the VVP lateral motions. Figure 3-d proves that the presence of these fins is very efficient to recover a smooth rising as expected.

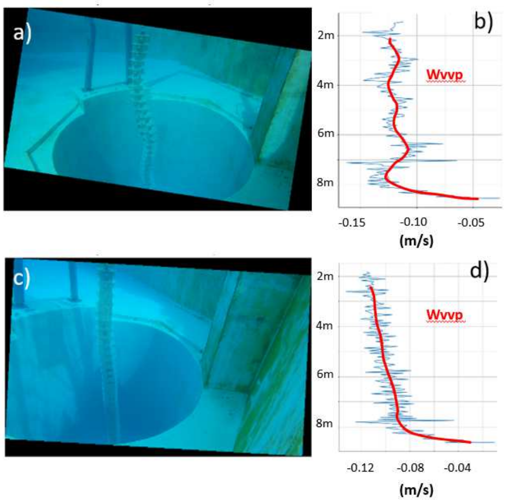

Fig. 3. a) Superimposition of video images of the VVP rising in the 10m deep pit showing the fluid-structure instability. b) records of its rising velocity with the spurious oscillations associated to the observed instability. In red the filtered signal with instrumental noise removed, c) as per a) with the stabilized VVP. Note the absence of lateral motions. d) records of rising velocity where the spurious oscillations have disappeared and leave a signal with only instrumental noise with a RMS of ~ 7 mm/s. Note the slight acceleration of the VVP due to the change of volume of its different hollow pieces; this effect can be easily corrected.

This done, the determination of *Cd* and β have requested numerous sea trials. Having measured all other parameters at the lab, as explained before, the method consists in finding the best [*Cd*, β] couple which zeroes the averaged |*Woc*| over the greatest number of profiles. It is adapted from the approach described in [9] and [10]. The underlying hypothesis, physically justified, is that the average of vertical velocities over depth and over time should finally go to zero.

Such computations, made over numerous but short subsets of profiles collected at sea in different places and at different times lead to values of **$Cd \sim 3.2$** and **$\beta \sim 5.8\text{e-}5\ \text{dbar}^{-1}$**.

IV. PRELIMINARY RESULTS FROM BIOSWOT-MED CAMPAIGN

We propose in this section a brief illustration of the VVP data obtained during the BioSWOT-Med oceanographic cruise which was carried out in the region of the North Balearic Front (Western Mediterranean Sea) from April 21 to May 14, 2023.

12 VVP missions of 5-7 hours were performed during this 1-month cruise, representing more than 45 profiles down to 200 m. The instrument could always be deployed using a release hook from the A-Frame of the 80 m-long R/V Atalante, but a rubber-boat was necessary to recover it at the end of each mission, as shown by Fig. 5.

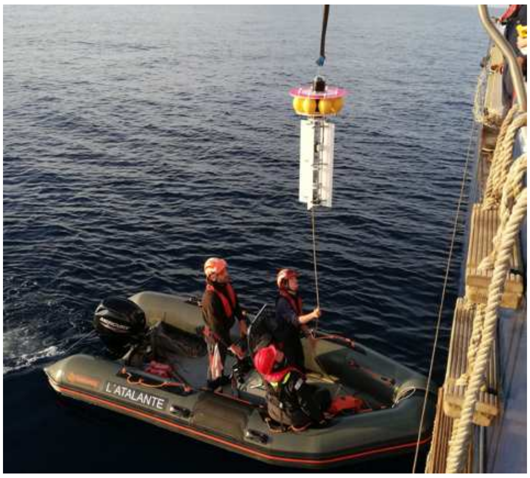

Fig.5. Recovery of the VVP after a 6-hour mission, using the rubber-boat of R/V Atalante.

Fig. 6 hereafter displays the results of a 5-hour mission performed on May 4. Four successive dives were performed by the VVP, with an average ascending speed of ~ 0.08 m/s (~ 0.06 m/s at 200 m and ~ 0.1 m/s below the surface) calculated using equation 3), as shown by the blue lines on Fig. 6-b). The four superimposed green lines, undistinguishable from each other, represent the theoretical ascending speed in still water, calculated using equation 1) with the density profiles measured by the RBR Concerto CTD, shown on Fig. 6-a. The resulting ocean vertical velocities on Fig. 6-c highlight dramatic low-frequency oscillations (long wavelength) over the vertical, with amplitudes up to 15 mm/s, i.e. twice the fluctuation RMS seen in Fig. 3d.

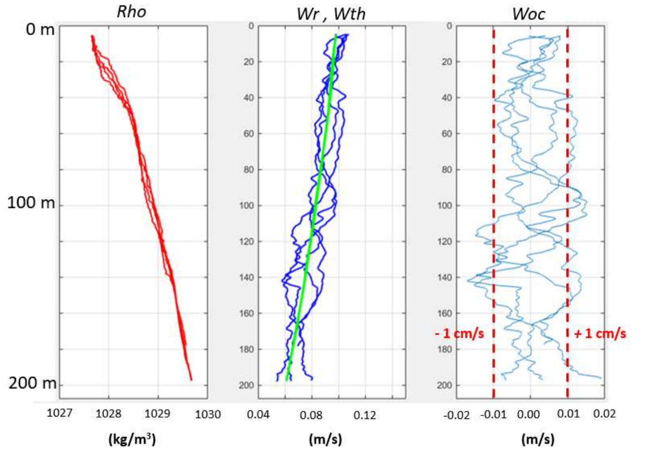

Fig.6. a) Vertical profiles of density, b) actual *Wr* (blue) and modeled *Wth* (green) ascent speed of the VVP, c) resulting ocean vertical velocity *Woc*.

Even though the scientific interpretation of these events is obviously premature and beyond the scope of this paper, these features evoke the permanence of energetic internal waves, as also suggested by the fluctuations of density profiles on Fig 6-a. Interestingly, the contour plot shown in Fig. 7 also suggests a coherent downward propagation of the ocean vertical velocities extrema. To what extent are such characteristics related to the sub-mesoscale structures targeted by the BioSWOT-Med campaign? This is a central question that should be thoroughly investigated in our future analyses.

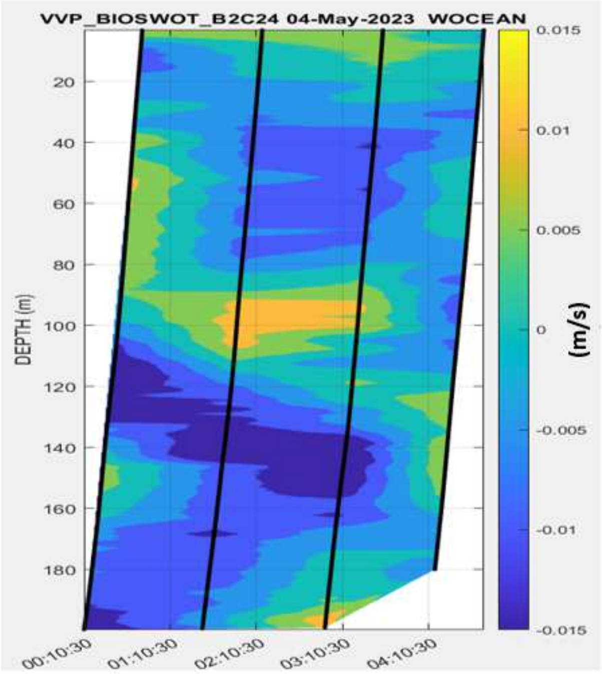

Fig.7. Contour-plot of ocean vertical velocities *vs* depth (vertical axis [0-200 m]) *vs* time (horizontal axis: [0:10 am 4:30 am] on May 4). The black lines represent sampling points, individually undistinguishable due to the 2 Hz high-resolution sampling rate.

V. CONCLUDING REMARKS

We have developed a lightweight autonomous profiler and adapted it to measure vertical velocities in the ocean, inspired by previous work done with ocean gliders. The profiler performed more than 45 deep profiles during the BioSWOT-Med campaign in spring 2023, with very promising preliminary results.

Beyond this unique application, the profiler is a universal tool that can provide significant added value during offshore stations aboard oceanographic vessels. Indeed, it can supply continuous high-resolution vertical profiles in parallel with conventional measurements, while drifting close to the ship, which is particularly relevant for Lagrangian studies. In this specific context, the simultaneous deployment of several profilers will also allow to document the deformation of the short-scale current field around the sampled station. The very low cost of the instrument makes it possible to envisage future deployments in such flotillas.

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