Performance of pumped and un-pumped CTDs in an underwater glider

Alberto Alvarez, Richard Stoner, Alain Maguer
NATO Centre for Maritime Research and Experimentation (CMRE)
La Spezia, Italy

***Abstract*—The salt content of seawater is determined by observations of seawater conductivity and temperature done in special cells called CTD sensors. The thermal inertia of the sensor body induces temperature differences between the environment and the flow through the cell (known as thermal lag), degrading the quality of sampled values of conductivity. Adequate corrections to the thermal lag effect can be obtained if the velocity of the flow inside the cell is known. For this reason, CTD sensors are equipped with pumping systems that provide stable working conditions. Pumped CTD sensors for gliders have just been developed. An open question is the improvement in accuracy that these sensors offer when compared to the traditional un-pumped CTD sensors, where the flow inside the cell depends on the velocity of the platform. This article analyses the data collected on July 19th -20th 2012 offshore La Spezia by a Slocum glider equipped with both a pumped and an un-pumped CTDs. Results indicate that degradation of salinity estimation could be up to fifty times bigger than the accuracy of the un-pumped CTD "SBE 41CP" operating under controllable conditions (0.002 psu). However, the pumped CTD sensor is more robust due to the constant internal flow conditions imposed by the pumping system. An inter-comparison between salinity data gathered from the pumped and un-pumped CTDs on board the glider and a ScanFish along a 8 km transect is also presented in the paper. Summarizing the results, pumped CTD sensors on board gliders would be preferred for accurate salinity determination in near surface ocean layers.**

Keywords—CTD; glider; thermal lag correction

I. INTRODUCTION

Observational oceanography is transitioning from ship based capabilities to the networking of autonomous platforms. Due to their long autonomy at sea, underwater gliders are envisioned to play a significant role in this new observational approach [1] [2]. They are autonomous underwater vehicles that make use of their hydrodynamic shape, wings and buoyancy change to induce yo-yo motions in the water column with net horizontal displacements. The energy consumption of the buoyancy engine is very small and thus gliders can remain at sea for very long periods without human intervention.

A wide variety of scientific sensors can be hosted in gliders. The Conductivity, Temperature and Depth (CTD) sensor is probably the most common among them. This sensor samples the basic physical variables from which the density of the field and dynamical magnitudes can be derived. In essence, a CTD comprises by a temperature sensor, a pressure gauge and a conductivity cell. The latter is a hollowed circular cylinder of about 0.004 m radius and 0.2 m length where a set of electrodes are placed along the walls of the cylinder. A potential difference is applied to the electrodes to determine the conductivity of the fluid media filling the space between electrodes. The refreshment of the fluid inside the conductivity is usually induced by the motion of the platform or by pumping systems that ensure constant flow rates inside the sensor. In both cases, determining the conductivity of the fluid inside the sensor can have difficulties. A major source of discrepancies is the so called thermal-lag effect. This is generated by the diffusion of the heat stored in the sensor walls into the water in the vicinity of the conductivity cell, producing errors in the conductivity measurements (conductivity depends also on the temperature of the water parcel). Lueck and Picklo [3] and Morison et al. [4] characterized these errors in terms of a fluid thermal anomaly, a relaxation time constant and the flow speed inside the cell. The analysis procedures derived from their work are now standard in processing CTD data. Hydrodynamic and geometric effects can also have a significant impact on conductivity measurements.

This article investigates the differences in the performance of pumped and un-pumped CTDs on board a Slocum glider. It is organized as follows: Section II described the data and methodology employed in this study while results are summarized in Section III. Finally, conclusions are presented in Section IV.

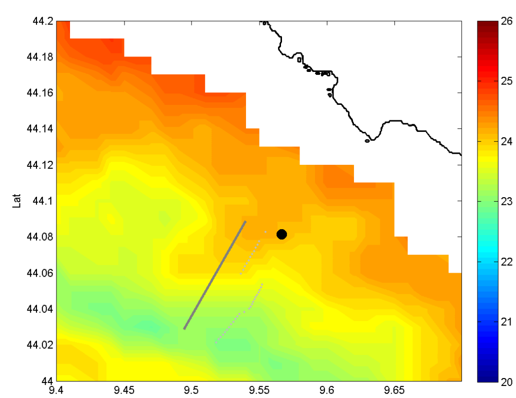

Fig. 1. Location of CTD profiles (black circle) done on July 19th and ScanFish (dark gray) and glider (ligth gray dots) transects performed during July 20th. Colors represent the sea surface temperature in ºC obtained from satellite.

This work has been funded by the NATO Allied Command Transformation-ACT and the EU project GROOM FP7-284321.

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II. DATA AND METHODS

A. Data

A field experiment was conducted on July 19th-20th 2012 offshore La Spezia (located at the northwestern coast of Italy) to evaluate the differences in the performance of pumped and un-pumped CTD sensors in a Slocum glider, Fig. 1. A special scientific payload section was built for the glider with the purpose to simultaneously host an un-pumped CTD "SBE 41CP" and a pumped CTD "SBE Slocum Glider Payload CTD". CTD sensors were symmetrically located on both sides of the hull. To enable future comparisons with a reference CTD, a special frame was designed to attach a Slocum glider onto the protection structure of a Seabird SBE 911plus CTD. The frame allows inclinations of -3^o , 0^o and 3^o of the glider platform to consider usual operating conditions characterized by angles of attack (AoA) of -3^o and 3^o. The experiment was conducted in two phases. During July 19th, a total of 10 profiles up to 130 m depth have been done for each inclination with the dual CTD glider attached to the structure of the Seabird SBE 911plus CTD. The field experiment concluded on July 20th measuring with the dual CTD glider and a ScanFish equipped with a Seabird SBE 49 FastCAT CTD, the salinity field along a 8 Km section.

B. Methodology

Thermal lag correction has been applied to compute the salinity from the conductivity and temperature sampled by the CTD sensors involved in the experiment. Specifically, a corrected temperature T_c was computed from the sampled temperature, T, using the recursive relationship [3][4]:

$$T_c^{\,n} = b\, T_c^{\,n-1} + a\, (T^{\,n} - T^{\,n-1}) \qquad (1)$$

$$a = 4 f \alpha \tau \,/\, (1 + 4 f \tau), \;\; b = 1 - 2\, a \,/\, \alpha \qquad (2)$$

Where α and τ are the thermal fluid anomaly and relaxation time constants, respectively, and f is the Nyquist frequency corresponding to the different CTD sensors (6, 4, 0.5 and 0.25 Hz for the SBE 911 plus, SBE 49 FastCAT, un-pumped and pumped CTDs respectively). Standard values of $\alpha = 0.0245$ ^{o}C and $\tau = 9.5$ s were considered to process the SBE 911plus data [3]. Instead, three procedures have been employed to estimate the value of these parameters for the CTD sensors on board the glider. In a first approach, α and τ parameters were determined for each profile by minimizing the root mean square error (RMSE) of the resulting salinity with respect to the ground truth profile. A second estimation of these parameters was obtained using the empirical relationships suggested by [3] and [4]:

$$\alpha = 0.0264 \,/\, V + 0.0135 \qquad (3)$$

$$\tau = 2.7858 \,/\, V^{0.5} + 7.1499 \qquad (4)$$

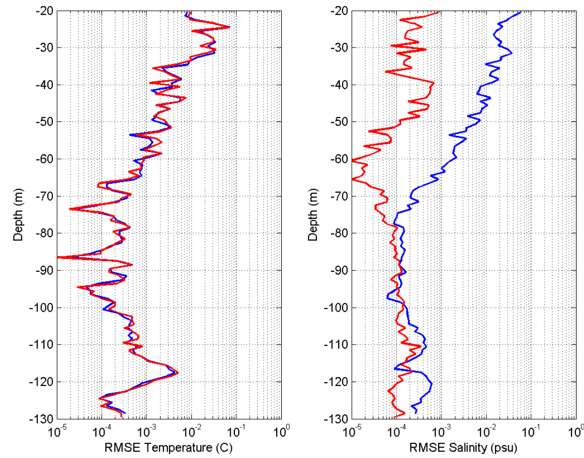

Fig. 2. AoA=0^o, Left panel: RMSE in temperature from the un-pumped (blue) and pumped (red) CTD sensors; Right panel similar than the left panel but for the salinity.

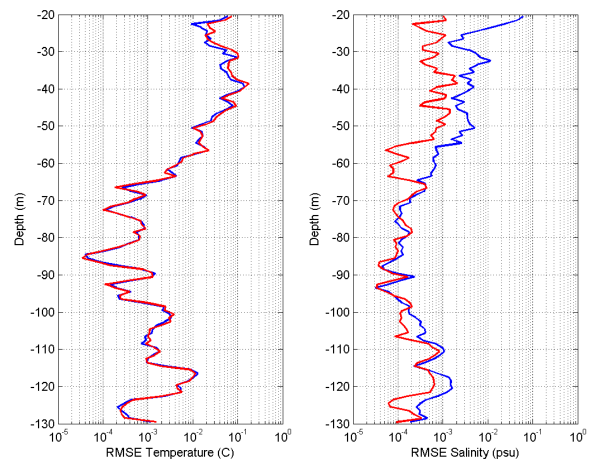

Fig. 3. Similar to previous figure but for AoA=3^o.

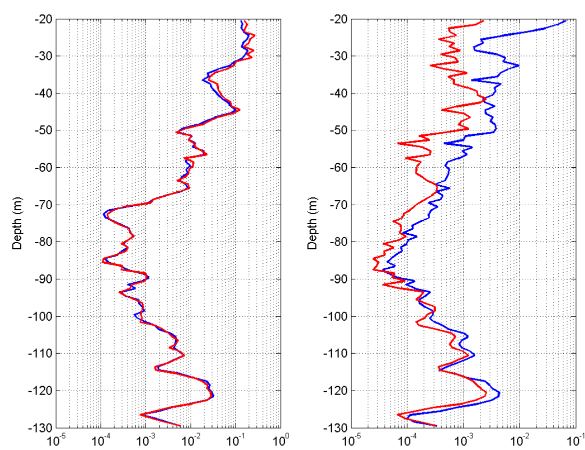

Fig. 4. Similar to previous figure but for AoA=-3^o.

Where V is the descending speed. The third procedure just considers the average value of the parameters obtained from the first approach.

In the second part of the experiment, the profiles gathered with the SBE 49 FastCAT were corrected using $\alpha = 0.03$ °C and $\tau = 7$ s [5]. Data from pumped and un-pumped CTDs on board the glider were processed using a similar technique to that proposed in [6]. Specifically, parameters α and τ were estimated by minimizing the differences between each pair of consecutive down-up casts. This approach provided better results than considering fixed parameters for the full set of profiles.

III. RESULTS

As it has been previously indicated, 10 profiles were simultaneously done with the dual CTD glider and the SBE 911plus, from surface to 130 m depth for each AoA configuration. Mean descending speeds for the different set of configurations were close to 0.4 ±0.05 m/s, which is the usual speed of Slocum gliders through the water column. Environmental conditions derived from the SBE 911plus CTD, vary during the realization of each set of profiles. Specifically, changes were observed in the salinity profile between the first set of measurements corresponding to the case of AoA of 0° and the other two cases considered. This variability is associated with a core of relative low saline water masses flowing between 30 and 60 m depth. Temperature profiles remained stable during the sampling period.

Results obtained from correcting the dataset with the parameters derived from RMSE minimization with respect to the ground truth are first presented. Figs. 2, 3 and 4 compare the RMSE in temperature and salinity derived from the pumped and un-pumped CTD sensors for the different AoA configurations. As would be anticipated, no substantial differences in the temperature are found in the three configuration cases for both CTD sensors. Conversely, results indicate that uncertainties in the salinity are significantly different between both CTD sensors. Specifically, Fig. 2 shows that at AoA= 0°, errors associated to the pumped CTD sensor vary consistently through the water column. In contrast, salinity errors derived from the un-pumped CTD sensor are not consistent and both show a decreasing behavior from the sea surface where thermal gradients are bigger. The pumped CTD outperforms the un-pumped one in the most surface layers while the RMSE from both CTD sensors are similar at layers well below the thermocline. The maximum uncertainty in the salinity field derived from the pumped CTD is 0.001 psu while the one corresponding to the un-pumped sensor is 0.057 psu.

The pumped CTD sensor also performs better than the un-pumped one for AoAs different from zero, Figs. 3 and 4. Again, performances of both sensors are similar in the deepest layers where thermal gradients are small. In both cases, maximum uncertainties are found at the most surface layers with values of 0.002 and 0.060 psu for the pumped and un-pumped CTDs, respectively.

A ground truth is not available for each glider profile in usual working operations. Thus, α and τ parameters in (2) cannot be optimally determined by minimizing the differences with respect to a reference profile. Instead, their values need to be defined a priori or estimated using (3) and (4). For this reason, it is important to analyze the modifications in the RMSE when a more realistic operational framework is considered. Fig. 5 compares, for the un-pumped CTD sensor, the RMSE obtained when the analysis is done with α and τ parameters derived from the minimization procedure, or

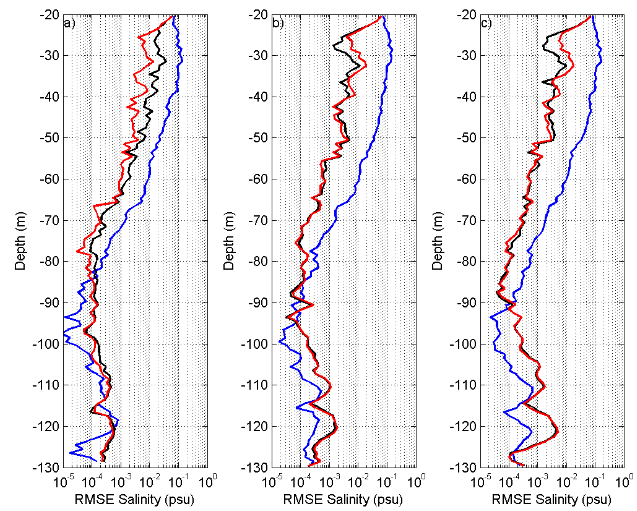

Fig. 5. a) RMSE in salinity for the un-pumped CTD at AOA=0° resulting from α and τ parameters obtained from optimization (black), from (3) and (4) (blue) and averaged values (red); b) and c) are similar to a) but for AoA=3° and -3°, respectively.

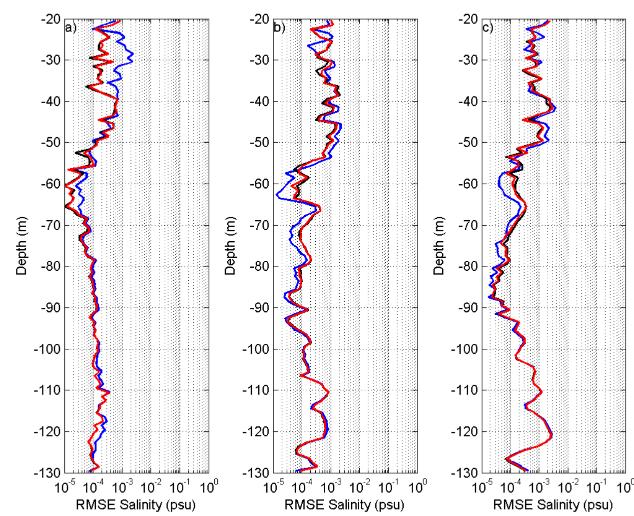

Fig. 6. Similar to Figure 5 but for the pumped CTD sensor

computed from (3) and (4) considering the mean descending speed for each profile, or obtained from their average value in the 10 profiles defining the dataset of each AoA configuration. Fig. 5 reveals that errors of up to 0.1 psu can be produced above the thermocline when parameters are computed from (3) and (4). Average error is around 0.05 psu in the first 70 m of the water column. A similar comparison has been done for the pumped CTD. In this case, the velocity required in (3) and (4) was found assuming a Poisuille flow inside the CTD pipe with the flow rate of the pumping system ($1e^{-5}$ m^3/s). Fig. 6 reveals that results from the pumped CTD sensor are robust to the modifications considered. This latter result is presumed to be attributable to the near constant flow conditions provided by the pumping mechanism inside the sensor.

Fig. 7 displays the salinity field along the 8 Km section, reconstructed from the up and down casts of the pumped and un-pumped CTDs. All field reconstructions show similar physical features in the water column. A core of relative low saline water masses (identified as Modified Atlantic Waters-MAW) flows between 20 and 60 m depth at the most onshore locations. A second patch of these water masses disconnected from the core is found at offshore locations and deeper depths. More saline waters characteristic of open sea conditions are identified in the surface layers at these offshore locations. While sharing the same physical picture, differences are evident between the different assessments. Regarding the un-pumped CTD, Figs. 7 a and b show that estimates from the downcast glider profiles at the shore locations produces higher salinities at surface than the corresponding reconstruction derived from the upcasts. Conversely, the latter overestimates salinity at the bottom boundary of the surface saline waters at the offshore stations. This is hypothesized as an artifact generated by the thermal lag correction when the platform transits across the thermocline located at 30 m depth. Patches of MAW are now less saline than in the reconstruction resulting from downcast profiles. Differences in the shape of the MAW patches are attributed to interpolation effects due to the different location of the up-down profiles. This is supported by the fact that similar differences are found between the shape of the salinity structures obtained from the down and up cast profiles with the pumped CTD, Figs. 7 c and d. As would be expected, both salinity fields show a higher level of agreement than in the un-pumped case. Finally, Fig. 8 displays the salinity field along the section with the ScanFish. Salinity features similar to those previously reported are found below the thermocline. Unlike in the previous cases, saline waters above 38.2 psu cover the surface layers all along the section. This discrepancy is hypothesized to be generated by the different location of the glider and ScanFish sections, being initially separated by 500 m for safety issues. This initial separation increased along the section due to the effect of the local currents on the glider navigation, Fig. 1.

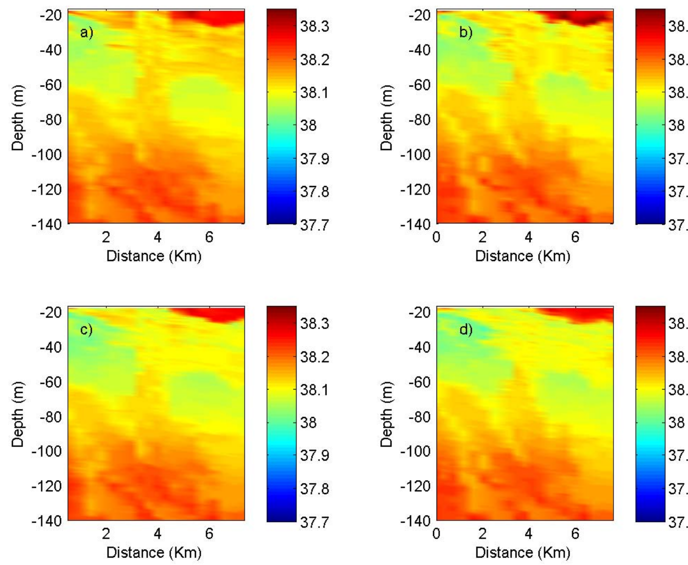

Fig. 7. Salinity field (psu) along the 8 Km section obtained with the un-pumped CTD from glider a) downcasts and b) upcasts; c) and d) are similar to a) and b), respectively, but for the pumped CTD.

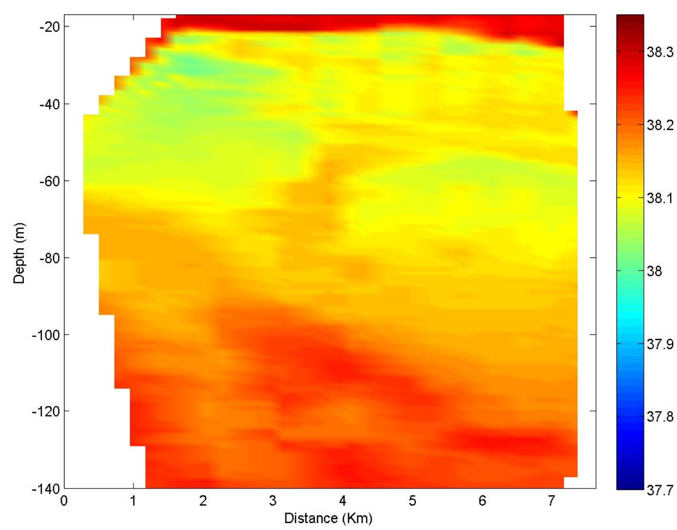

Fig. 8. Salinity field (psu) along the 8 Km section obtained with the ScanFish platform.

IV. CONCLUSIONS

Underwater gliders are becoming a popular ocean observing platform in oceanography. Their maneuverability and long endurance allow persistent and sustained monitoring of the interior ocean. This is achieved by a high level of autonomy and low power consumption. Because the latter, glider platforms usually host simplified versions of diverse oceanographic instrumentation. The CTD sensor is among them. Taking advantage of the motion of the platform to induce a water flow through the conductivity cell has been a common practice for CTD sensors in gliders. This procedure avoids the use of a pumping system in the sensor but strongly couples the quality of the measurement of salinity to the dynamics of the platform. Flow conditions can vary significantly inside the conductivity cell in un-pumped CTD sensors. This would prevent discernment of which percentage of the sampled conductivity is due to the salt concentration in the seawater.

Recent technological developments allow gliders to be equipped with low-powered but pumped CTD sensors. The benefits, if any, of using pumped instead un-pumped CTD sensors in gliders has been investigated in this article. In a first experiment, a glider hosting pumped and un-pumped CTD sensors was lowered simultaneously by a SBE 911plus CTD sensor and the resulting measurements confronted. The RMSE computed from the 10 profiles refereed to the ground truth represented by the samples gathered by the SBE 911plus CTD sensor, was employed as a performance metric. Reported results reveal (with optimum selection of the thermal fluid anomaly and relaxation time parameters) that the RMSE derived at surface layers from the pumped CTD sensor is around an order of magnitude smaller than the RMSE corresponding to the un-pumped CTD sensor. The performance of the un-pumped CTD sensor strongly depend on dynamical aspects of the platform like the velocity and so, determination of the thermal fluid anomaly and relaxation time parameters becomes a significant challenge. This is evidenced by the RMSE obtained when the correction parameters are computed under usual operational conditions (using (3) and (4)). Degradation of performance could then be up to order 0.1 psu in water layers with strong thermal gradients. However, the pumped CTD sensor is more robust to this variability due to the constant internal flow conditions imposed by the pumping system.

Although under less controllable conditions, the inter-comparison of measurements along a marine section brings new information into the data processing. This is represented by the CTD up-casts that were not considered in the previous experiment due to technical difficulties to implement simultaneous down-up casts. The existence of contiguous down-up casts allows the possibility to derive the thermal fluid anomaly and relaxation time parameters by minimizing the difference found between both profiles. This approach was used to compare the salinity field along a 8 Km transect resulting from the pumped and un-pumped CTD sensors. Samples gathered from a ScanFish were used as ground truth in this case. Results corroborate previous findings. No significant differences have been found in the performance of pumped and un-pumped CTD sensors under weak thermal gradients. Again, performance of the un-pumped CTD sensor is degraded at the thermocline and most surface ocean layers where thermal gradients are located. Differences are not only with the ground truth but they also arise between down and up casts of the un-pumped sensor. Degradation of the performance of the un-pumped CTD is hypothesized to originate from the unsteady conditions inside the conductivity cell induced by the motion of the platform. Specifically, the proximity of the inflection depth to the thermocline, speed modifications due to density changes in the surrounding water, pitch control procedures etc., modify flow conditions inside the sensor making prescribed correction parameters inadequate. The impact of these dynamical processes is less noticeable under homogeneous environmental conditions. Instead, the pumped CTD sensor is clearly uncoupled from the dynamics of the platform, being more robust and stable. Given these results, the use of pumped CTD sensors is recommended for studies that require accurate salinity determination in the surface and near surface ocean layers.

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