Physical Oceanographic Data from Seaglider Trials in Stratified Coastal Waters Using a New Pumped Payload CTD

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***Abstract*—The Seaglider, developed by the University of Washington with ONR (Office of Naval Research) funding and licensed to iRobot in 2008, is an autonomous underwater vehicle used for a wide variety of oceanographic research. Science payloads installed on gliders typically include temperature (T) and conductivity (C) sensors, or a CTD (Conductivity-Temperature-with-Depth profiler), in which the T and C measurements are used to derive salinity, density and other important physical parameters. Free-flushed CTDs by Sea-Bird Electronics, referred to here as the CT Sail, were the first science payload installed in the Seaglider. While these are still in use on many Seagliders, they are being phased out in favor of a modular, low-power pumped CTD, referred to as the GPCTD (Glider Payload CTD), also by Sea-Bird Electronics. Data gathered during field trials of the Seaglider integrated with the new GPCTD alongside Seagliders with the free-flushed CT Sails offer an opportunity to evaluate and compare the data quality between the two CTD types. Data provided by iRobot come from June 2011 mission trials conducted in the stratified waters along the coast off Massachusetts. Comparisons of dive profiles made simultaneously by pairs of Seagliders indicate the raw pumped GPCTD data show improved data quality with less salinity spiking and conductivity cell thermal mass errors compared to the free-flushed CT Sail data. Applying consistent corrections to the GPCTD data for sensor measurement alignment and time-dependent conductivity cell thermal mass errors further improves accuracy. Corrections to GPCTD data are simple in comparison to the unpumped CT Sail data, because the GPCTD pumped flow produces a steady T-C sensor response, and the GPCTD data acquisition system provides a constant sample-rate time series necessary for these time-dependent corrections.**

Keywords- Seaglider, CTD, Salinity, AUVs, Wave Gliders, Temperature, Conductivity

I. Introduction

A. CT Sail – Free-flushed CTD Payload on Seagliders

The first science payload installed on the Seaglider consisted of separate, free-flushed T (temperature) and C (conductivity) sensors, called a CT Sail, installed on the upper side of the glider pressure hull and integrated with the internal glider data acquisition and flight control system. On the CT Sail, the temperature sensor is positioned beneath and parallel to the conductivity sensor (Fig. 1). The conductivity sensor itself is placed inside a protective metal guard with hole-cutouts to allow for flushing. The T-C sensors are not connected (ducted) and are free-flushed, therefore the CT Sail cannot guarantee that the water sample measured by the thermistor will be the same that enters the conductivity sensor. On the Seaglider, the pressure sensor is located about 38.5 cm in front of the thermistor, requiring a slight spatial alignment with the CT Sail sensors, e.g., pressure values should be reduced by 0.4 dbar on the down-dives, and increased by the same amount on up-dives.

Installing the CT Sail requires opening the pressure hull and de-soldering/soldering the wires between the CT Sail and the electronics board. Care is required as the soldering process can alter the factory T-C calibrations. Installation is usually done by the glider manufacturer rather than by the glider operator. In order to conserve power for mission endurance, Seaglider does not supply a pump for flow-control of T-C sensors on the CT Sail. Therefore, flow past the T-C sensors on the Seaglider CT Sail relies solely on the glider movement.

The onboard Seaglider processor is responsible for logging data from the nonautonomous science payload sensors, e.g., the CT Sail. The processor is not always able to provide a constant sample-rate time series of T-C and other payload sensor data,

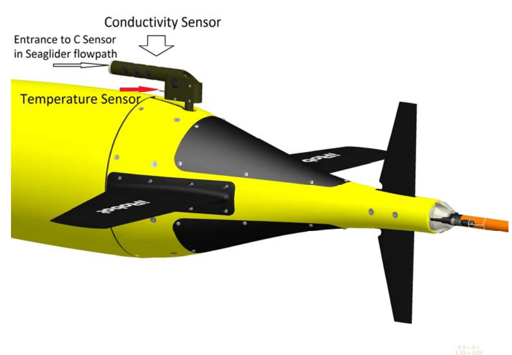


Figure 1. Schematic diagram of the iRobot Seaglider with the free-flushed payload CTD CT Sail installed on the upper-side of the pressure hull.

because it is a single thread processor (i.e., can only do one task at a time), and the glider controls for the buoyancy pump, and pitch and roll motor movements take precedence over data sampling. As a result, for any given dive, the sample rate of the sensors will not be continuous or constant (Fig. 2). The user has some control over the data acquisition, such as how often to take a measurement from a payload sensor. However, achieved sample rate depends on the number of sensors being polled at any given time, as well as the frequency of operations going on with the control system.

The data upload from the Seaglider to the shore-side command center (called the basestation) is an automated process. The CT Sail data, transferred as raw frequencies, are included in the same data stream as the glider control data and any other nonautonomous sensor data (e.g., Aanderaa Optode and the WET Labs EcoTriplet.). Data conversion to engineering units using sensor calibration equations and factory calibration coefficients from Sea-Bird is completed once the CT data are uploaded. Derived parameters, such as salinity, can then be computed from the converted T and C data.

B. Glider Payload CTD – Modular, Flow-Controlled CTD Payload on Seagliders

In 2010, Sea-Bird Electronics launched the GPCTD (Glider Payload Conductivity-Temperature-with-Depth profiler) for use on autonomous platforms, including buoyancy and internally powered AUVs and wave gliders. The GPCTD is a self-contained CTD with memory and an integrated pump and replaces previous glider CT Sail installations. The motivations behind the development of the GPCTD were to simplify the physical integration of the CTD with the glider, to make data handling and processing easier, and to improve overall data quality, both in the raw data output as well as after simple post-processing corrections when so desired. It also allows for the integration of a flow-controlled oxygen sensor directly in-line with the T-C sensors (e.g., SBE 43 electrochemical sensor, or the SBE 63 optical oxygen sensor).

The integrated pump was added to the glider CTD, because having a steady flow through the conductivity cell is desirable, as proven on ship-lowered CTD systems. This is because of two critical conductivity sensor response issues:

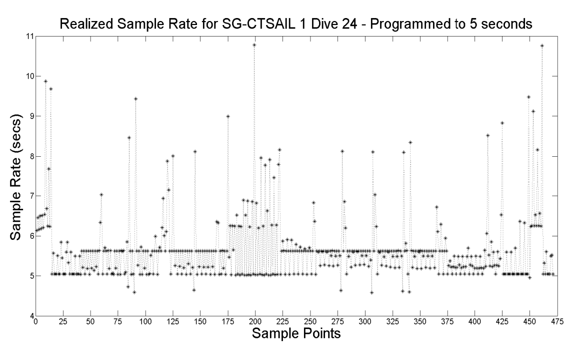


Figure 2. Example of the sample rate of the T-C data from the Seaglider SG-CTSail1, dive 24, where the onboard glider processor was programmed to sample payload sensors every 5 seconds.

1) Conductivity sensors have a response-time dependence on the water volume flow rate through the sensor; and 2) Conductivity sensors experience a temporal lag in response while traversing temperature gradients due to heat stored in the sensor materials, and this can cause incorrectly reported values because conductivity is highly temperature dependent. The latter effect is referred to as a cell thermal mass error in conductivity values, and leads to errors in subsequent derived parameters (e.g., salinity). To illustrate, as the CTD moves from warm to cold water, heat stored in the walls of the conductivity cell causes the conductivity measurement to be high of correct, resulting in high of correct computed salinity. The opposite happens when moving from cold to warm water. The amplitude of this error for a Sea-Bird 9*Plus* CTD, which pumps a volume rate of 30 ml/s, is on the order of 0.03 psu for a 1 deg C step change in temperature. The lag is the time required for the diffusive heat transfer to occur between the conductivity cell and the ambient water sample, which for the 9*Plus* CTD is about 7 s. The flow rate through the sensor determines the initial amplitude of the error and the time lag (e.g., a 30 ml/s flow rate will have a slightly smaller amplitude and shorter lag than a 10 ml/s flow rate). With a steadily pumped flow, T-C responses can be matched, and the amplitude and lag period of the cell thermal mass error can be quantified and corrected for in the data. The major drawback with the free-flushed glider CT Sail configuration, is that it depends solely on glider motion to flush the sensors. Because glider speeds can vary substantially, so can the flow rates past the sensors, including the flow-dependent conductivity sensor. This produces variable T-C responses and inconsistent thermal mass errors that are difficult to correct for.

From a practical standpoint, the self-contained CTD module offers more flexibility to the end-user. Glider manufacturers as well as operators can exchange GPCTDs without opening the pressure hull of the glider. On the Seaglider, the GPCTD's electronic module is installed between the pressure hull and the fairing in the aft flooded payload bay (Fig. 3).

The T-C sensors are ducted and pumped on the GPCTD, with the intake situated on the exterior of the aft fairing, positioned to minimize measurement errors caused by the vehicle's thermally contaminated boundary flow. This configuration offers a significant data quality advantage.

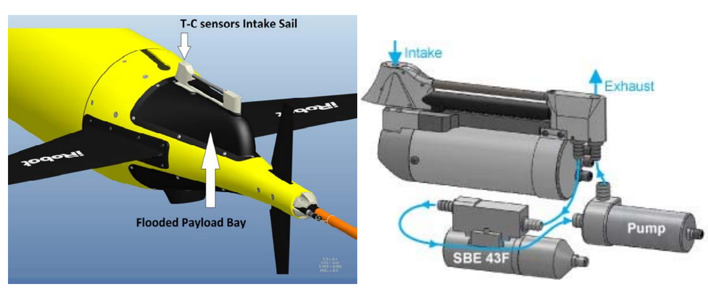


Figure 3. Left image: Schematic of the iRobot Seaglider showing the location of the GPCTD. Right image: Schematic of the Sea-Bird GPCTD, with pump and optional oxygen sensor.

The plumbed and connected T-C sensors (and optional oxygen) are guaranteed to sample the same water parcel, which is necessary for temporal measurement alignment between sensors. Unlike the CTD Sail, there is no protective metal guard surrounding the conductivity sensor on the GPCTD. This reduces the thermal mass around the sensor and provides better access to external flushing. Seagliders with the GPCTD have the pressure sensor co-located with the GPCTD, optimizing T-C measurement spatial alignment with respect to pressure.

The internal memory in the GPCTD module can record a continuous time series at a fixed rate up to 1 Hz, and the operating system offers more flexible sampling choices to the glider operator. It provides a variety of options to conserve power while maintaining a continuous time series, e.g., reducing the sample rate and pumping intermittently between sample points. Data are stored directly in the GPCTD during a dive, bypassing the glider data acquisition and control system's busy schedule. The internal memory is 8 gigabytes, and can store, for example, 699,000 samples of T-C and pressure data sampling at 1 Hz, which is equivalent to 194 hours (~8 days). As the Seaglider surfaces, the data are offloaded from the GPCTD, either as raw frequencies or in engineering units, through the Seaglider 'clothesline' to the basestation.

The power consumption required by the GPCTD pump is significantly reduced by using a specially designed impellor and constant but slower flow-rate through the CTD sensors (10 ml/s). The power required is now a factor of two less than shipboard CTD pumps. A continuously pumped GPCTD consumes only 175 mw while recording 1 Hz data. To put this in perspective, the energy contained in one Lithium DD cell will provide 24 days of continuous down-up profiling at 1 Hz with continuous pumping.

II. METHODS

During June13-16, 2011, Seaglider trials were conducted along the New England coast in the vicinity of Wildcat Knoll off of Scituate, Massachusetts. Three Seagliders were tested, two with the free-flushed CT Sail configurations (Seagliders SG-CTSail1 and SG-CTSail2), and the third Seaglider with the new GPCTD (SG-GPCTD). The flight patterns were varied, but for the most part, dives made by all the Seagliders were completed within a 10 km radius region (Fig. 4).

The start time of each Seaglider dive is included in each CTD dive file for both CT Sail and GPCTD data. SG-CTSail1 was deployed outside of the cluster of trajectories, but entered the same sampling area after dive 15 on June 14, 2011. Given the three Seagliders were in the same general vicinity, the criteria for pairing dives used for comparisons were based on dives made after SG-CTSail1dive 15, and dives from each Seaglider that were initiated within 10 minutes of each other.

Data on the SG-GPCTD were recorded at 1 Hz with continuous pumping, while the SG-CTSail Seagliders were programmed to sample at 0.2 Hz (every 5 secs). The realized sample rate for the SG-CTSail data varied much over the course of the dive, as seen for SG-CTSail1 dive 24 (Fig.2).

For brevity, data comparisons presented in this paper are restricted to data from Seagliders SG-Sail1 and SG-GPCTD. Data are plotted as raw variables in temperature (deg C),

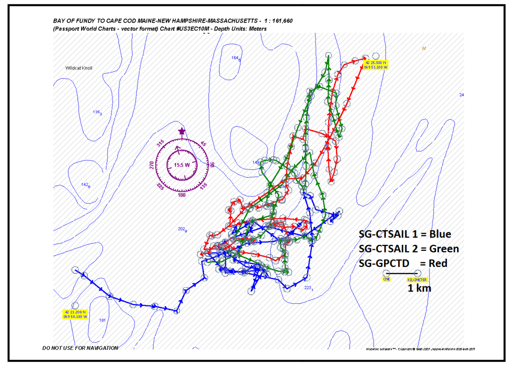


Figure 4. Map showing Seaglider trajectories from June 13-16, 2011 off of Wildcat Knoll, Masasachusetts. Seagliders SG-CTSail1 (Blue) and SG-CTSail2 (Green) were equipped with CT Sail payload CTDs. Seaglider SG-GPCTD (Red) was equipped with the new GPCTD. Arrows show dive starting points and direction of Seaglider trajectories.

conductivity (S/m) and computed practical salinity. GPCTD data were additionally processed following standard Sea-Bird protocols for temperature and conductivity measurement alignment and cell thermal mass corrections [1]. The corrected GPCTD data are shown and discussed separately. Temperature and conductivity measurements were advanced +0.5 and +0.4 seconds relative to pressure, respectively. Alignment corrections were based on the transit time between the T-C sensors, the temperature response time, and the estimated response time of the conductivity sensor in a 10 ml/s flow. The applied cell thermal mass corrections were derived using data from prototype glider CTD measurements sampling at 0.5 Hz with a pumped flow rate of 10 ml/s. The cell thermal mass correction used for the amplitude (alpha) was 0.06 with a time lag of 10 seconds. Further details on conductivity cell thermal mass correction determinations can be found in [1], [2], [3], and [4]. Attempts at correcting CT Sail data were not made in this exercise, given the complexity of the processing that would be required due to the nonconstant sample-rate, and the lack of a clear time-dependent cell thermal mass correction scheme for variable glider-induced flows through the conductivity sensor. Therefore, only the converted variables from the CT Sail raw data are presented.

III. RESULTS

The down-up profiles from the time-paired Seaglider dives were assumed to be completed within the same water mass. This assumption is supported by the short horizontal excursions in rountdrip dives being under 0.5 km on average (Fig. 4), and also by observed well-matched down-up dive data profiles in the Seaglider dive pairs selected for evaluation. From the far-field viewpoint, the general patterns observed in the paired Seaglider dive plots indicate that both gliders successfully measured the same large-scale and significant features in the water column, as demonstrated by SG-GPCTD dive 18 and SG-CTSail1 dive 24 (Fig. 5).

Viewing the data in closer detail, the effects of mismatched T-C measurements (spiking) and thermal mass error on computed salinity become more evident in the CT Sail data. The shallow down-up dive from SG-CTSail1 (Dive 2) illustrates this well (Fig. 6). Despite the T-C roundtrip profiles being in good agreement, there is a clear gap in the down-up

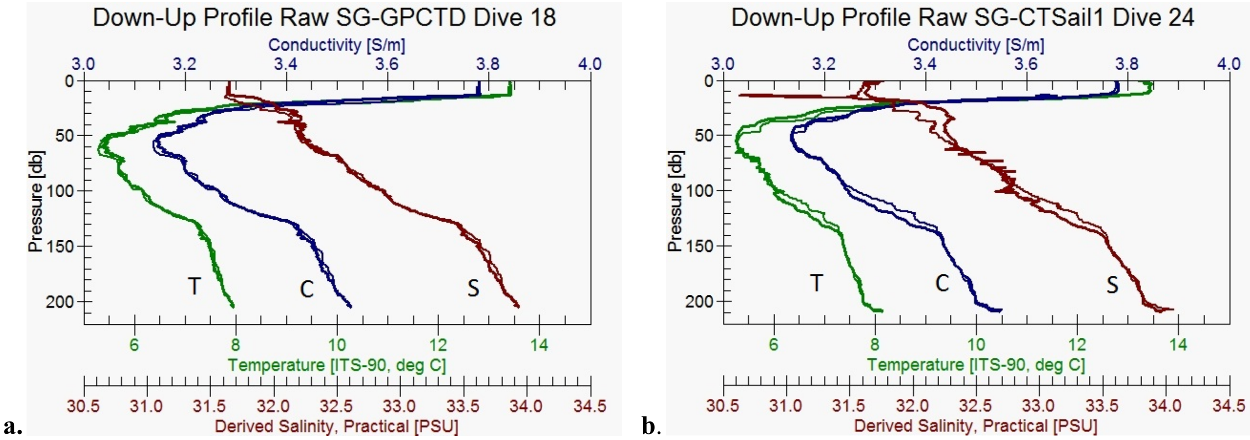


Figure 5. Down-up dive vertical profiles of temperature (green-T), conductivity (blue-C) and computed salinity (red-S) from Seagliders: a. SG-GPCTD dive 18, and b. SG-CTSail1 dive 24.

salinity profiles not easily explained by any significant discrepancies in T-C. The glider moves from warm to cold water on the down cast in this example, which in terms of the time-dependent cell thermal mass effect, would cause the conductivity sensor to read warm of correct for several seconds. The high of correct conductivity measurements cause high of correct salinity computations, and as in this case, is observed throughout the water column. The opposite occurs on the ascent, moving from cold to warm water, resulting in low of correct salinity computations. As the water column T-C structure stops changing sharply with depth, as seen here in the upper 10 m, the salinity differences between down-up dives decrease.

Using the same Seaglider pair shown in Fig. 5, but focusing on the thermocline region in the upper 60 dbar, cell thermal mass errors are evident in both SG-CTSail1 and SG-GPCTD salinity profiles (Fig. 7). On the down dive (denoted by solid lines), the salinity consistently reads higher than the up dive (dotted lines). The SG-GPCTD salinity below 30 dbar, where T-C agreement between the down-up dives is best, shows very good down-up profile salinity agreement. In contrast, a more significant gap develops in the down-up salinity profiles observed by the SG-CTSail1 starting at 60 dbar. The cell thermal mass effect appears larger in amplitude and longer lived in the SG-CTSail1 data throughout the water column.

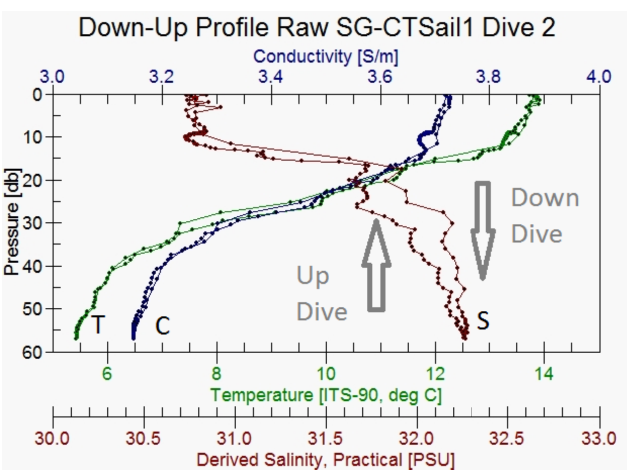


Figure 6. Illustration showing typical down-up dive profiles from the SG-CT Sail1 dive 2. Dots mark sample points in the profile.

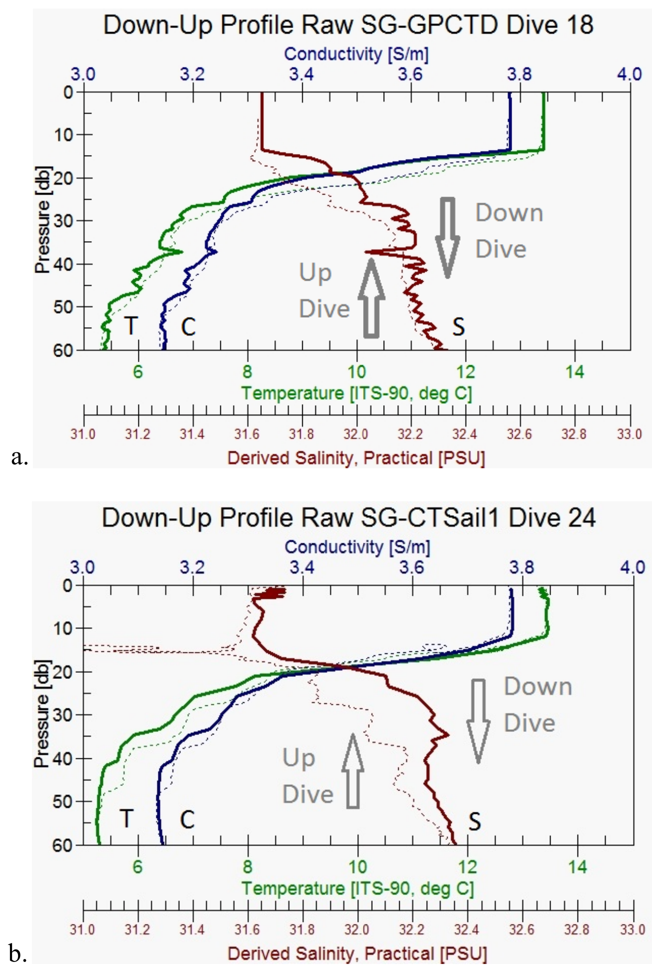


Figure 7. Down-up dive vertical profiles from the upper 60 dbar of temperature (green-T), conductivity (blue-C) and computed salinity (red-S) from Seagliders: a. SG-GPCTD dive 18, and b. SG-CTSail1 dive 24. Solid lines denote the down dive; dotted lines denote the up dive.

Applying a consistent T-C alignment and cell thermal mass correction to the SG-GPCTD data reduces salinity spiking, and improves the down-up dive salinity agreement in the region of highest thermal gradients (~10-35 dbar). The small down-up difference observed near the step change (15 dbar) is not a residual error, rather a real change in the sharp gradient depths between down and up dives (e.g., the depth of the T-C and salinity step change is more shallow on the down cast by ~4 m) (Fig. 8).

Seaglider pairs assumed to be profiling in the same water masses, should exhibit similar TS (temperature-salinity) relationships. To examine general patterns in TS-relationships, down-up profile data from six of the dives selected from the coincidental time pairs are plotted for SG-CTSail1 and SG-GPCTD (Figs. 9 a,b, respectively). The six dives were all completed within one day on 14 June 2011. Both sets of Seaglider data show a tight TS relationship for salinities greater than 32.5 psu (the deeper water column). The SG-CTSail1 data exhibit more salinity variability in the warmer surface thermocline region (upper 60 dbar), and some salinity spiking near the temperature minimum and again near the bottom of the dive (33.8-34.4 psu). The TS relationships between the down and up dives from the SG-GPCTD, especially in the thermocline, are more repeatable than those observed from SG-CTSail1, despite the fact that both Seagliders were sampling at the same time in the same water mass. Small differences are expected between down-up dive data profiles, given the gliders were not moving straight up and down in the water column, rather were travelling with a forward trajectory on descent and ascent. However, more salinity spiking and a larger cell thermal mass error is evident in the SG-CTSail1 data, especially in the upper water column where temperature is changing most.

Applying T-C alignment and cell thermal mass corrections to the six dives from the SG-GPCTD makes modest improvements in the TS relationships for down-up dives, and further demonstrates the direct improved data quality coming straight off the GPCTD (Fig. 10).

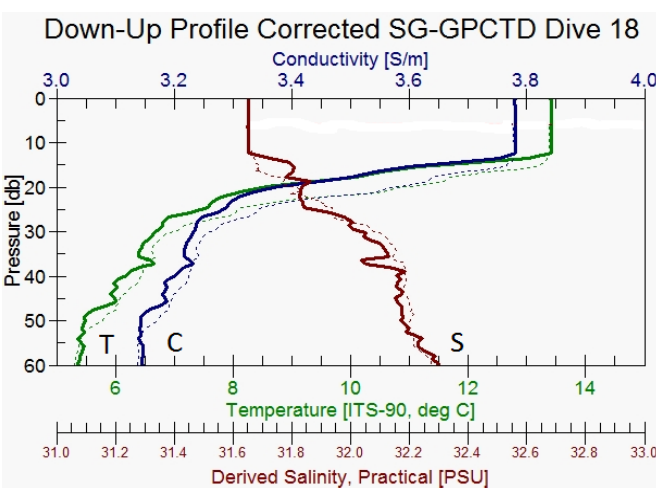
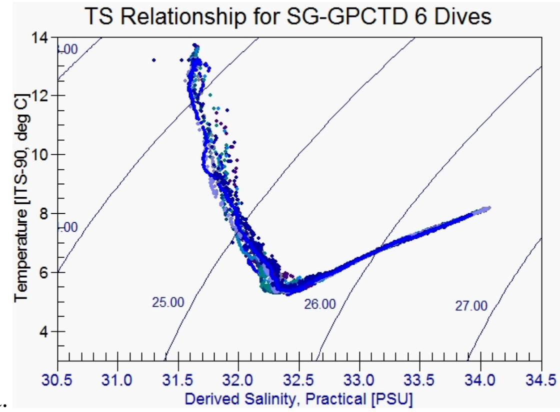
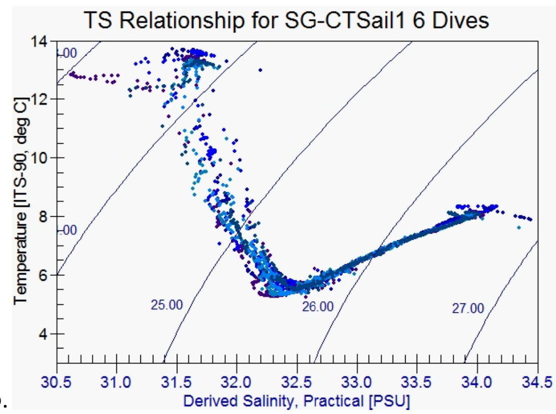


Figure 8. Down-up dive vertical profiles from the upper 60 dbar of T-C aligned and cell thermal mass corrected SG-GPCTD data; temperature (green-T), conductivity (blue-C) and computed salinity (red-S) from SG-GPCTD dive 18. Solid lines denote the down dive; dotted lines denote the up dive.



a.



b.

Figure 9. TS diagrams from each Seaglider using six combined down-up dives. a. SG-GPCTD raw data derived TS relationship. b. SG-CTSail1 raw data derived TS relationship. Different shades of blue represent the different dives.

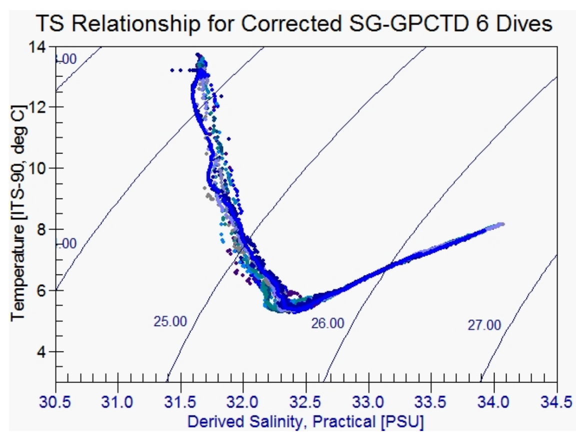


Figure 10. TS realtionships for six down-up dives from SG-GPCTD, with aligned T-C data and cell thermal mass corrected conductivity and computed salinity. Different shades of blue represent the individual roundtrip dives.

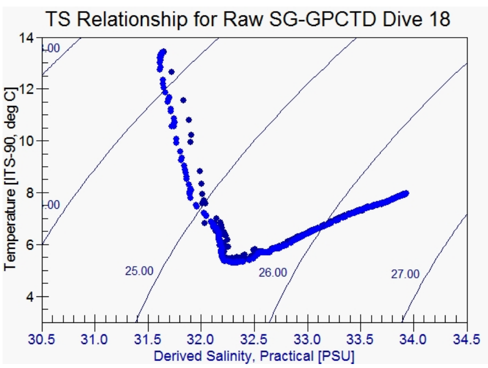
Using the same dive pair as shown in Fig. 5, (SG-CTSail1 dive 24 with SG-GPCTD dive 18), the TS relationships show the down profile salinity registers higher than that on the up profile for both Seaglider CTDs (Fig. 11 a,b). This is the general pattern seen on most of the individual dive pairs, though the thermal mass variants (amplitude and lag) in the SG-CT Sail data are typically larger and depend on the speed of the Seaglider, as well as on the steepness of the temperature gradient encountered. Applying the prescribed corrections to the SG-GPCTD data rectifies the conductivity thermal mass-induced salinity errors (Fig. 11c).

IV. CONCLUSIONS

Simultaneous observations of temperature, conductivity and computed salinity from two different payload CTDs (one pumped, the other free-flushed) were made on several iRobot Seagliders deployed in stratified coastal waters. Data from both CTDs show high qualitative agreement in mapping important large-scale hydrographic features in the water column. However, the new modular-pumped GPCTD data show immediate improvements in raw, uncorrected data quality, a result of fixed-rate flushing and hardware changes (e.g., ducted T-C sensors) that significantly reduce salinity spiking and the effect of cell thermal mass errors on the conductivity and salinity data. Any residual errors in the GPCTD data are also easily corrected by following standard Sea-Bird data processing protocols for T-C sensor alignment and cell thermal mass corrections. The simplified corrections are made possible, because of the fixed-rate flow past the T-C sensors producing a consistent T-C response, and the ability to gather a constant sample-rate time series required for accurately making the time-dependent cell thermal mass corrections.

In contrast, the CT Sail raw data show more frequent salinity spiking, and a larger and longer cell thermal mass response, most noticeable in regions of rapidly changing temperature. A major cause of the salinity spiking is the non-ducted T-C sensors on the CT Sail. A factor contributing to the cell thermal mass error includes the lack of a steady flow through the conductivity sensor, where flow helps diffuse heat from the sensor materials. Another is the metal guard protecting the conductivity sensor, which may reduce external flushing and further enhance the thermal mass error experienced by the conductivity cell. Sample resolution differences between the Seagliders (from 1 Hz to 0.2 Hz) do not appear to be a major player in the discrepancies in mapping the hydrographic features, likely because the Seagliders were moving slow enough to measure the spatial gradients in the water column. However, the lack of a constant sample rate in the time series impedes clear corrections for the CT Sail data. This poses a problem to the data end-user in terms of data quality, because the data correction options for these free-flushed sensors are not consistent for a given data set or even a roundtrip down-up dive cycle. Variable Seaglider transit speeds control and produce variable flow rates through the conductivity sensor, making determination of the T-C response and cell thermal mass corrections difficult. The discontinuous sample-rate time series coming from the free-flushed Seagliders further complicates any time-dependent corrections.

The benefits now available with the new GPCTD are expected to improve ease of use by the glider operator, and as demonstrated here, will simplify data handling by the end-user while producing higher quality data, with or without post-processing corrections.



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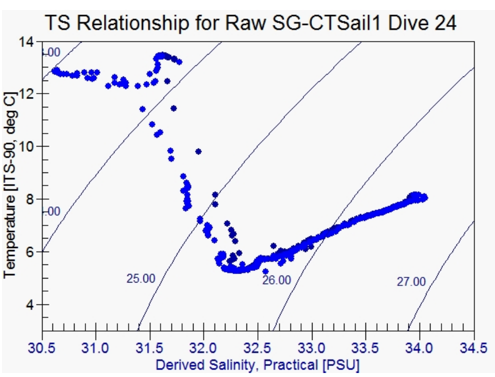

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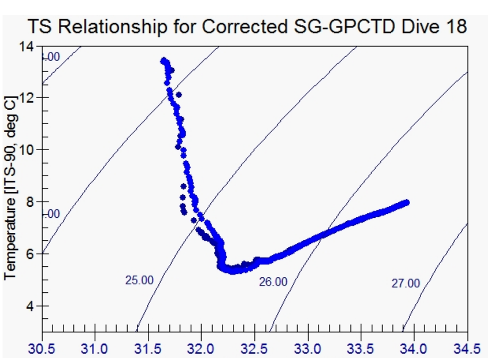

c.

Figure 11. Raw data TS relationship for a rountrip dive from a. SG -GPCTD dive 18, and b. SG-CTSail1 dive 24; c. TS diagram for SG-GPCTD dive 18 after T-C alignment and cell thermal mass corrections applied. In this figure, Royal blue denotes the up-dive, and Navy blue the down-dive.

REFERENCES

[1] Sea-Bird Electronics, Inc., SEASOFT V2: SBE Data Processing CTD Data Processing and Plotting Software for Windows 2000/XP. 153 p., 2011. (http://www.seabird.com/pdf_documents/manuals/SBEDataProcessing_7.21d.pdf)

[2] R.G. Lueck, "Thermal Inertia of Conductivity Cells: Theory," Journal of Atmospheric and Oceanic Technology (JAOT), vol. 7(5), pp. 741-755, 1990.

[3] R.G. Lueck and J.J. Picklo, "Thermal Inertia of Conductivity Cells: Observations with a Sea-Bird Cell," Journal of Atmospheric and Oceanic Technology (JAOT), vol. 7(5), pp. 756-768, 1990.

[4] J. Morison, R. Andersen, N. Larson, E. D'Asaro, and T. Boyd, "The Correction for Thermal-Lag Effects in Sea-Bird CTD Data," Journal of Atmospheric and Oceanic Technology (JAOT), vol. 11(4), pp. 1151-1164, 1994.