

# RBR

## Onboard processing of dynamic corrections for the RBRargo3

### Introduction

There are two types of dynamic errors affecting salinity measurements <sup>[1]</sup>:

- Response time and sensor misalignments: a time lag between temperature and conductivity measurements.
- Thermal mass errors: the thermal mass of the conductivity cell impacts the temperature of the water volume where the seawater conductivity is measured.

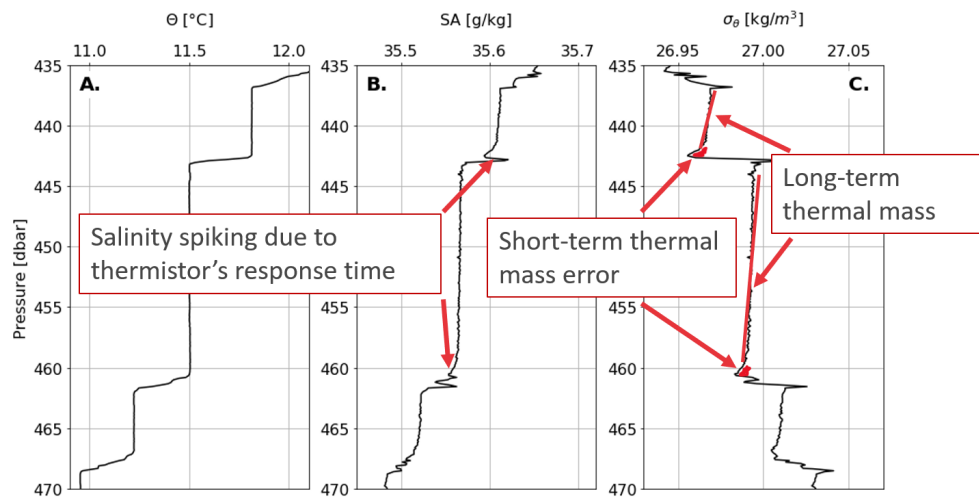


Figure 1. A review of dynamic errors with data from ALAMO float 9139 in a Caribbean Sea Staircase <sup>[2]</sup>

### Response time and sensor misalignments

"Salinity spiking" <sup>[3-5]</sup>, or C-T lag, often refers to the misalignment between temperature and conductivity measurements. It is generated by two separate mechanisms:

- the physical separation between the thermistor and the conductivity cell, as it takes time for the sampled water to travel from the thermistor to the conductivity cell. The RBRargo<sup>3</sup> C.T.D has been specially designed to minimize the spatial separation between the two sensors to reduce this effect.
- the inherent response time of the thermistor. The thermistor responds slower than the conductivity cell when the RBRargo<sup>3</sup> C.T.D profiles through a temperature interface. This difference in response time introduces a time lag between the two sensors and results in spiking in the computed salinity <sup>[3]</sup>.

## Thermal mass errors

Thermal mass errors occur when the RBRargo<sup>3</sup> C.T.D travels through a temperature gradient. Heat is exchanged between the conductivity cell and its surrounding water, thus changing the temperature of water sampled by the conductivity cell<sup>[6-7]</sup>. Thermal mass errors affecting conductivity measurements from the RBRargo<sup>3</sup> C.T.D present two main separate timescales (Figure 1):

- a long-term thermal mass error, corresponding to how the conductivity cell responds to thermal gradients on timescales of minutes.
- a short-term thermal mass error, which describes the response of the conductivity cell to thermal gradients on timescales of seconds.

Both timescales are rooted in the different properties of the materials used in the conductivity cell and the ascent rate of the instrument.

## Ascent rate estimation

[1] has shown a strong dependence of the dynamic errors on the speed, at least for short-term and long-term thermal mass errors. In practice, the ascent rate of an Argo float can not be constrained to a constant ascent rate during its ascent for technical reasons. Furthermore, for operational purposes, it is often required that the targeted ascent rate of a float changes over the course of the deployment. It is then necessary to estimate dynamically, onboard the RBRargo<sup>3</sup> C.T.D, the actual ascent rate and derive accordingly coefficients for thermal mass error correction.

# Implementation

A complete study of the dynamic effects and how to correct them has been published in [1]. The following describes the actual implementation of such correction in the latest firmware of the RBR<sup>argo</sup>3 C.T.D and in the publicly available microcontroller-targeted library libRBR.

## Nomenclature and definitions

The following nomenclature follows and extends the nomenclature used in [1].

	Variable	Description
<b>Measurements</b>	$T_{meas}$	Water temperature as measured by the marine thermistor (°C)
	$C_{meas}$	Conductivity as measured by the conductivity cell (mS/cm)
	$P_{meas}$	Measured sea pressure (dbar)
	$T_{cond}$	Temperature measured inside the conductivity cell (°C)
<b>CT lag</b>	$T_{cor}$	Seawater temperature corrected for the C-T lag (°C)
<b>Short-term thermal mass</b>	$T_{short}$	Temperature adjustment for short-term thermal mass inferred from Lueck and Picklo (1990)'s algorithm (°C)
<b>Long-term thermal mass</b>	$T_{long}$	Temperature adjustment for long-term thermal mass (°C)
<b>Corrected temperature</b>	$T_{cell}$	Corrected seawater temperature corrected (°C)
<b>Ascent rate</b>	$V_p$	Estimated ascent rate capped for validity range of dynamic correction
	$V_{p_{est}}$	Estimated ascent rate not capped for validity range of dynamic correction

<b>Salinity</b>	$S$	Salinity computed from $C_{\text{meas}}$ , $T_{\text{meas}}$ , and $P_{\text{meas}}$
	$S_{\text{cor}}$	Salinity corrected for thermal mass errors. Computed from $C_{\text{meas}}$ , $T_{\text{cell}}$ , and $P_{\text{meas}}$

Other intermediary variables:

	<b>Variable</b>	<b>Description</b>
<b>Sampling</b>	$f_S$	Sampling rate (Hz)
	$f_N$	Nyquist frequency, half of sampling rate (Hz)
<b>C-T lag</b>	$\Delta t$	C-T lag (s)
<b>Short-term thermal mass</b>	$\alpha$	Magnitude of short-term thermal mass correction.
	$\tau$	Time constant of the short-term thermal mass correction (s)
<b>Long-term thermal mass</b>	$ctcoeff$	Magnitude of the long-term thermal mass correction.

And coefficients:

	<b>Coefficient</b>	<b>Description</b>
<b>Short-term thermal mass</b>	$\alpha_a$	Coefficient for $\alpha$ estimation
	$\alpha_e$	Coefficient for $\alpha$ estimation
	$\tau_a$	Coefficient for $\tau$ estimation

	$\tau e$	Coefficient for $\tau$ estimation
<b>Long-term thermal mass</b>	$ctcoeff_a$	Coefficient for $ctcoeff$ estimation
	$ctcoeff_e$	Coefficient for $ctcoeff$ estimation
<b>Ascent rate</b>	$V_{pfc}$	Frequency cut of ascent rate estimation low pass filter (Hz)
	$V_{pmin}$	Minimum of ascent rate's validity range (m/s)
	$V_{pmax}$	Maximum of ascent rate's validity range (m/s)

## Response time and sensors misalignment

The misalignment between temperature and conductivity measurements (i.e., C-T lag) introduced by the slower time response of the thermistor is corrected by applying a constant optimal lag determined in [1]

$$T_{cor}(t) = T_{meas}(t + \Delta t)$$

based on this equation, one could derive the following implementation:

$$T_{cor}(n) = (1 - \phi) * T_{meas}(n + N) + \phi * T_{meas}(n + N + 1)$$

with:

$$\phi = F_s * [\Delta t \text{ mod } 1/F_s]$$

and:

$$N = \lfloor F_s * \Delta t \rfloor$$

## Thermal mass errors

### Long-term thermal mass error

The long-term thermal mass error correction is characterized using an experimental setup in the laboratory, and the correction is based on the conduction equation in steady-state, suggesting that the temperature anomaly is proportional to the temperature gradient [1]:

$$T_{long} = ctcoeff * (T_{cond} - T_{cor})$$

Using a coefficient based on the instantaneous estimated ascent rate of the float:

$$T_{long}(n) = ctcoeff(n) * (T_{cond}(n) - T_{cor}(n))$$

With:

$$ctcoeff(n) = ctcoeff_a * V_p(n)^{ctcoeff_e}$$

## Short-term thermal mass error

This thermal mass error has long been identified in profiling CTD data and addressed by a recursive filter developed by Lueck<sup>[6]</sup>, and refined by Lueck and Picklo<sup>[8]</sup> and Morison et al. <sup>[9]</sup>:

$$T_{short}(n) = -b(n) * T_{short}(n-1) + a(n) * [(T_{cor}(n)) - (T_{cor}(n-1))]$$

The two coefficients a and b are computed using:

$$a(n) = \frac{4f_N\alpha\tau}{1 + 4f_N\tau}$$

$$b(n) = 1 - 2\alpha^{-1}a(n)$$

Using coefficients adjusted for the actual ascent rate of the float, it becomes:

$$a(n) = \frac{4f_N\alpha(n)\tau(n)}{1 + 4f_N\tau(n)}$$

$$b(n) = 1 - 2\alpha(n)^{-1}a(n)$$

Where coefficients are calculated based on the instantaneous ascent rate:

$$\alpha(n) = \alpha_a * V_p(n)^{\alpha_e}$$

$$\tau(n) = \tau_a * V_p(n)^{\tau_e}$$

## Corrected Salinity

The inferred actual water temperature seen by the CT cell is:

$$T_{cell} = T_{cor} + T_{long} - T_{short}$$

and the corrected Salinity is then calculated as:

$$S_{cor} = pss78(C_{meas}, T_{cell}, P_{meas})$$

The figure below is a comparison of data before and after all dynamic corrections were applied<sup>[10]</sup>:

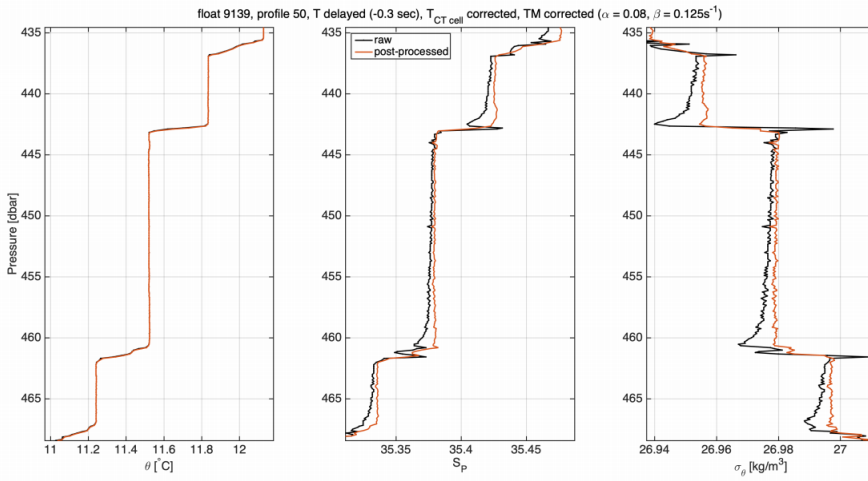


Figure 2: Same profile as in Figure 1 collected from ALAMO float number 9139. Solid black line shows the raw data ( $T_{meas}$ ,  $S_{meas}$ , and  $\sigma_{meas}$ ). Red line shows the corrected data ( $T_{cor}$ ,  $S_{cor}$ , and  $\sigma_{cor}$ ).

## Estimated ascent rate

The ascent rate is estimated using an IIR low pass filter on the instantaneous pressure difference:

$$\tilde{V}_{p_{est}}(n) = (1 - a) * \tilde{V}_{p_{est}}(n - 1) + a * (P_{meas}(n - 1) - P_{meas}(n)) * f_S$$

$$a = 1 - e^{-2 * \pi * i * V_{p_{fc}} / f_S}$$

The estimated ascent rate is then constrained to be in the validity range obtain in [1]:

$$\tilde{V}_p(n) = \min\{\max\{\tilde{V}_{p_{est}}(n), V_{p_{min}}\}, V_{p_{max}}\}$$

## Recommended coefficients for RBRargo<sup>3</sup> C.T.D (2000dbar)

The recommended coefficients for the RBRargo<sup>3</sup> C.T.D (2000 dbar) in the context of an Argo float can be directly deduced from [1]:

	<b>Coefficient</b>	<b>Recommended value</b>
<b>Short-term thermal mass</b>	$\alpha_a$	<b>0.00323</b>
	$\alpha_e$	<b>-1.03</b>
	$\tau_a$	<b>4.93</b>
	$\tau_e$	<b>-0.26</b>
<b>Long-term thermal mass</b>	$ctcoeff_a$	<b>0.00139</b>
	$ctcoeff_e$	<b>-1.00</b>
<b>Ascent rate</b>	$V_{pfc}$	<b>0.04</b>
	$V_{pmin}$	<b>0.03</b>
	$V_{pmax}$	<b>0.45</b>



# Available implementations

## Derived channel in the instrument

Firmware 1.145 introduced dynamic correction onboard the RBR<sup>3</sup> C.T.D as derived channels. Channels corresponding to  $T_{cor}$  and  $S_{cor}$  can be exposed alongside the salinity without dynamic correction  $S$ .

Refer to the [RBR Logger3 command reference](#) <sup>[11]</sup> for details (sections *Integrating with a profiling float*).

## libRBR example for dynamic correction

libRBR is an open-source C library maintained by RBR. It provides an interface for simplified communication with RBR instruments. Refer to <https://bitbucket.org/rbr/librbr> for more details.

libRBR contains source code for a dynamic correction library. It is provided with various examples of how to apply the dynamic correction:

- (1) to streamed data from an RBR<sup>3</sup>
- (2) to downloaded data from an RBR<sup>3</sup>
- (3) to a comma-separated values (.csv) file

Below are test-runs for each example:

## Apply dynamic correction to the instrument streamed data

```
$ cd <PATH>/librbr
$ make

$ cd <PATH>/librbr/examples/posix
$ make exampledynamiccorrection

$ ls /dev/tty*
/dev/tty /dev/ttyS5

$ ./posix-stream-dynamiccorrection.exe /dev/ttyS5

./posix-stream-dynamiccorrection: Instrument is stopped, not logging. I'm going to start it.
2000-01-01 05:13:51.000, 34.487500, 24.174500, 19.932600, 22.050400, 0.457800
2000-01-01 05:13:51.125, 34.487500, 24.174300, 19.926000, 22.050500, 0.457800
2000-01-01 05:13:51.250, 34.487600, 24.173800, 19.917300, 22.050800, 0.478200
2000-01-01 05:13:51.375, 34.487600, 24.174100, 19.954300, 22.050700, 0.457800
timestamp(s) | T_cor(°C) | P_meas(sea pressure, dbar) | S_cor(PSU) | T_cond(°C): 0.000, 24.17403984, 9.80009270,
30.63297844, 0.45780000
2000-01-01 05:13:51.500, 34.487700, 24.174600, 19.923900, 22.050500, 0.457800
timestamp(s) | T_cor(°C) | P_meas(sea pressure, dbar) | S_cor(PSU) | T_cond(°C): 0.125, 24.17450142, 9.79349327,
30.63294220, 0.45780000
2000-01-01 05:13:51.625, 34.487700, 24.173800, 19.952100, 22.050900, 0.457800
timestamp(s) | T_cor(°C) | P_meas(sea pressure, dbar) | S_cor(PSU) | T_cond(°C): 0.250, 24.17395973, 9.78479290,
30.62295532, 0.45780000
2000-01-01 05:13:51.750, 34.487700, 24.173700, 19.963000, 22.050900, 0.478200
```

```

timestamp(s) | T_cor(°C) | P_meas(sea pressure, dbar) | S_cor(PSU) | T_cond(°C): 0.375, 24.17371941, 9.82179260,
30.63310432, 0.47819999
2000-01-01 05:13:51.875, 34.487700, 24.173800, 19.930400, 22.050900, 0.478200
timestamp(s) | T_cor(°C) | P_meas(sea pressure, dbar) | S_cor(PSU) | T_cond(°C): 0.500, 24.17378044, 9.79139328,
30.63321495, 0.47819999
2000-01-01 05:13:52.000, 34.487800, 24.174300, 19.963000, 22.050700, 0.457800
...

```

## Apply dynamic correction to EasyParse format data file downloaded from the instrument

- i** EasyParse format means "memformat type = calbin00" for RBR instruments. [libRBR](#) is provided with a sample EasyParse dataset (dynamiccorrection-sample.bin) alongside this example. To run this example with a different data file, the provided code assumes the following channel order:
- channel 1: Conductivity (mS/cm),  $C_{meas}$
  - channel 2: Marine temperature (°C),  $T_{meas}$
  - channel 3: Sea pressure (dbar),  $P_{meas}$
  - channel 4: Internal temperature of the conductivity cell (°C),  $T_{cond}$

```


$ cd <PATH>/librbr
$ make

$ cd <PATH>/librbr/examples/posix
$ make exampledynamiccorrection

$ ./posix-parse-file-dynamiccorrection.exe ../sampledata/dynamiccorrection-sample.bin 4
./posix-parse-file-dynamiccorrection: Using libRBR v1.2.0 (built 2021-10-14T11:09:57-0400).
-----
timestamp(s) | T_cor(°C) | P_meas(sea pressure, dbar) | S_cor(PSU) | T_cond(°C)
-----
0.000, 10.00000000, 450.00000000, 35.00887299, 10.00000000
0.500, 10.00000000, 449.79998779, 35.00895691, 10.00000000
1.000, 10.00000000, 449.60000610, 35.00905228, 10.00000000
1.500, 10.00000000, 449.39999390, 35.00914001, 10.00000000
2.000, 10.00000000, 449.20001221, 35.00922394, 10.00000000
2.500, 10.00000000, 449.00000000, 35.00931931, 10.00000000
3.000, 10.00000000, 448.79998779, 35.00940323, 10.00000000
3.500, 10.00000000, 448.60000610, 35.00949860, 10.00000000
4.000, 10.00000000, 448.39999390, 35.00959015, 10.00000000
4.500, 10.00000000, 448.20001221, 35.00968552, 10.00000000
...

```

## Apply dynamic correction to a comma-separated values file

 libRBR offers a .csv test data file in ./examples/sampleddata folder for a test run.

```
$ cd <PATH>/librbr
$ make libdynamiccorrection

$ cd <PATH>/librbr/examples/dynamicCorrection
$ make

$ ./dynamicCorrection-example.exe ../sampledata/dynamiccorrection-sample.csv

sampling rate is 2.000
Correction written to ../sampledata/dynamiccorrection-sample_corr.csv
```

and the expected output in dynamiccorrection-sample\_corr.csv is (showing only the first 10 rows of data) :

```
# timestamp(s), T_cor(°C), P_meas(sea pressure, dbar), S_cor(PSU), T_cond(°C)
0.000, 10.00000000, 450.00000000, 35.00887299, 10.00000000
0.500, 10.00000000, 449.79998779, 35.00895691, 10.00000000
1.000, 10.00000000, 449.60000610, 35.00905228, 10.00000000
1.500, 10.00000000, 449.39999390, 35.00914001, 10.00000000
2.000, 10.00000000, 449.20001221, 35.00922394, 10.00000000
2.500, 10.00000000, 449.00000000, 35.00931931, 10.00000000
3.000, 10.00000000, 448.79998779, 35.00940323, 10.00000000
3.500, 10.00000000, 448.60000610, 35.00949860, 10.00000000
4.000, 10.00000000, 448.39999390, 35.00959015, 10.00000000
4.500, 10.00000000, 448.20001221, 35.00968552, 10.00000000
...
```

## References

- [1] Dever M., S.Wijffels, B. Owens, C.Richards, I.Shkoverts, M.Halverson, and G.Johnson, Static and dynamic performance of the RBRargo3 (2022).
- [2] Sanabia, E. R. and Jayne, S. R. (2020). Ocean observations under two major hurricanes: Evolution of the response across the storm wakes. AGU Advances, 1(3):e2019AV000161.
- [3] Horne, E. P. W. and Toole, J. M. (1980). Sensor Response Mismatches and Lag Correction Techniques for Temperature-Salinity Profilers. Journal of Physical Oceanography, 10(7):1122–1130.
- [4] Dever, M., Freilich, M., Farrar, J. T., Hodges, B., Lanagan, T., Baron, A. J., and Mahadevan, A. (2020). EcoCTD for Profiling Oceanic Physical–Biological Properties from an Underway Ship. Journal of Atmospheric and Oceanic Technology, 37(5):825–840.
- [5] Ullman, D. S. and Hebert, D. (2014). Processing of Underway CTD Data. Journal of Atmospheric and Oceanic Technology, 31(4):984–998.
- [6] Lueck, R. G. (1990). Thermal Inertia of Conductivity Cells: Theory. Journal of Atmospheric and Oceanic Technology, 7(5):741–755.

[7] Halverson, M., Siegel, E., and Johnson, G. (2020b). Inductive-conductivity cell a primer on high accuracy ctd technology. *Sea Technology*, 61(2):24–27.

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

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

[10] RBR document: RBR#0008228revA Dynamic corrections for the RBRargo CTD 2000dbar.

[11] RBR document: RBR#0005199 Logger3 command reference.

## Revision Log

Rev	Revised by	Date	Description of Change
A	Xiaowei Yang	Oct 20, 2021	Initial release.
B	Jean-Michel Leconte	Nov 24, 2021	Revision of recommended values for 10cm/s ascent rate.
C	Xiaowei Yang	May 09, 2022	Revision of recommended values.
D	Jean-Michel Leconte	Oct 21, 2022	Dynamic ascent rate.