RBR

Conductivity pressure correction for 2000dbar conductivity cell

1 Summary

In 2016 several new models of conductivity cell were released by RBR. Those new conductivity cells are called combined CT cells and are available in three versions: 1000dbar, 2000dbar, and 6000dbar.

The 1000dbar version uses a pressure vessel made from POM and ceramic while the 2000dbar and 6000dbar models use OSP and ceramic. Until recently, the pressure correction of conductivity was done using a parameter derived empirically from an earlier design of the cell. In situ comparisons of RBR data to bench top salinometer data showed that higher accuracy could be achieved with a new calibration equation which extends the pressure dependency from first to third order in the case of the 2000dbar combined CT cell. Firmware version 1.093 and higher, available since September 2018, uses the updated correction, but the new compensation can be retroactively applied to data collected with previous firmware versions as detailed below.

The new pressure correction equation, making conductivity accurate to within ±0.003 mS/cm, together with temperature measurements accurate to within ±0.002°C, result in a salinity accurate to within Argo standards.

2 Conductivity calibration

Although electrode based conductivity cells are simple to characterise in terms of pressure sensitivity, particularly when the electric field is entirely self-contained and the cell shape is a geometric primitive (hollow cylinder) with isotropic material properties, the mechanical behaviour of an inductive cell under pressure can be more complex to understand. The electric field in an inductive cell forms a toroid that passes through the centre of the cell (typically also a hollow cylinder, though one with a much lower aspect-ratio than the electrode-based counterpart) but then out and around the exterior volume of the cell. This may also be a geometric primitive (a larger cylinder) and in cells designed for moored applications, this is the most efficient form factor as hydrodynamic concerns are less significant. However, for cells intended for profiling use, considerable design effort is expended in order to achieve optimal flushing of the cell due to the movement of the host platform. This results in a cell exterior which does not have an easily calculated physical deformation as a function of hydrostatic pressure.

The RBR combined CT cell (where the thermistor housing and the conductivity cell are manufactured as a single combined unit) is of such a shape.

3 First order correction

3.1 Original linear x2 coefficient

The equation that produces a conductivity value using a linear pressure correction is as follows:

$$C_{corrected} = \frac{C_{uncorrected} - x_0 \cdot (T - x_3)}{1 + x_1 \cdot (T - x_3) + x_2 \cdot (P - x_4)}$$

where **P** is the absolute pressure (dbar), **T** is the internal temperature of the conductivity cell (°C). Coefficients **x0** ((mS/cm)/°C) and **x1** (°C^{-1}) are the temperature correction coefficients, **x2** (dbar^{-1}) is the pressure correction coefficient, **x3** is the temperature during calibration (°C), and **x4** is always 10 (dbar), indicating the nominal pressure during calibration.

The pressure sensitivity is modelled as a simple first order dependence, and has no effect to the nominal conductivity calibration performed at 10 dbar (**x4**, atmospheric pressure).

In instruments shipped for the past few years, **x2** was set to 4e-7 dbar^{-1}. This value was determined empirically through sea trials on board the R/V "Thomas G. Thompson" (TN298 cruise) in 2013 using the old conductivity cell design. However, our results with the combined cell have shown a consistent bias to high salinity using that value. This can be seen in buddy-float deployments, rosette casts, and WOA comparisons. Comparing data from three RBR*argo* Teledyne Apex floats to such reference data indicates that the salinity bias at 2000dbar is +0.05 psu (C = 31 mS/cm).

The bias results from applying the conductivity pressure correction developed for the moored cell to the combined RBR*argo* CT cell. The RBR*argo* CT cell pressure correction term is different because its construction differs from that of the moored cell.

3.2 Provisional linear x2 coefficient

The realization that an updated pressure compensation was necessary became clear after analyzing salinity from Second Institute of Oceanography RBR*argo* Apex float WMO 2902730. As a temporary solution, RBR calculated a new linear pressure correction coefficient of **x2** = 1e-6 $dbar^{-1}$. This value was derived by matching salinity from RBR*argo* profiles to the local average WOA salinity at 2000 dbar. In fact, Argo China applied this new compensation to the Second Institute of Oceanography RBR*argo* Apex float WMO 2902730 in April 2018.

4 Third order correction

In the summer of 2018, RBR worked with JAMSTEC and DFO Canada, to assess whether the pressure correction *model* itself should be changed, either as an increased order polynomial or a power law. In addition, a large salt water pressure tank (1.4m deep by 0.7m diameter) was used to provide more controlled evaluation of these terms.

The saltwater pressure tank study provided the best data for deriving a new correction because of the tightly controlled, constant salinity environment. The main result of this study is that the optimal correction factor is a cubic polynomial instead of a linear function of pressure. F-tests showed that increasing the polynomial degree beyond three does not increase the explained variance in a statistically significant way. Quantitatively, the F-test statistics, when changing from a polynomial of degree *n* to *n+1* ($F_{n,n+1}$), are $F_{1,2}$ = 223, $F_{2,3}$ = 112, and $F_{3,4}$ = 0.008 ($F_{3,4}$ is well below the 99% significance level).

With a cubic pressure correction, the conductivity calibration equation now looks like:

$$C_{corrected} = \frac{C_{uncorrected} - x_0 \cdot (T - x_5)}{1 + x_1 \cdot (T - x_5) + f(P - x_6)}$$

$$f(P - x_6) = x_2 \cdot (P - x_6) + x_3 \cdot (P - x_6)^2 + x_4 \cdot (P - x_6)^3$$

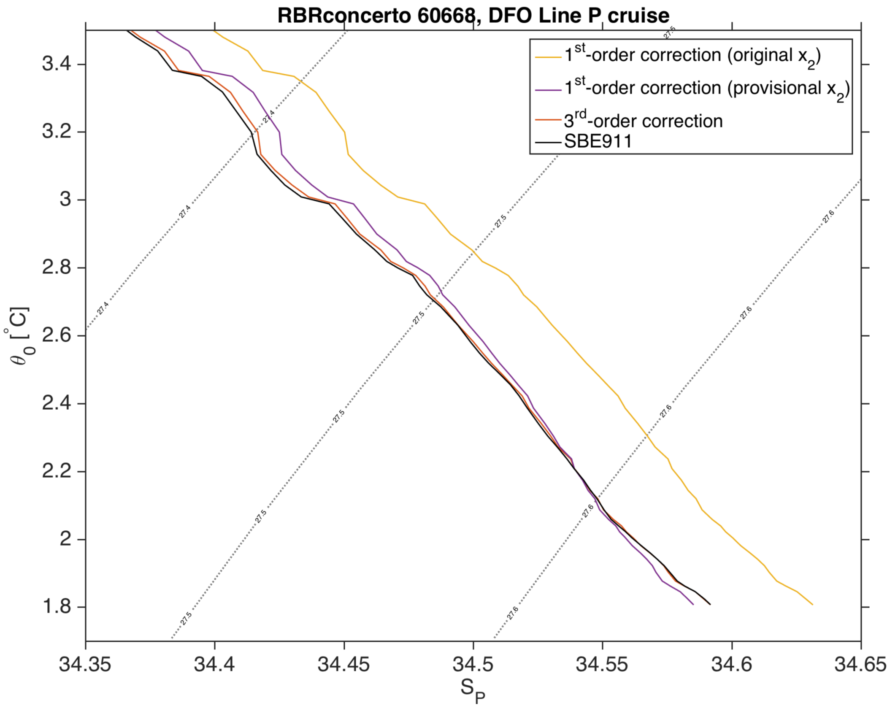
The new pressure compensation equation was incorporated into the RBR*argo* CTD firmware version 1.093 released in September 2018.

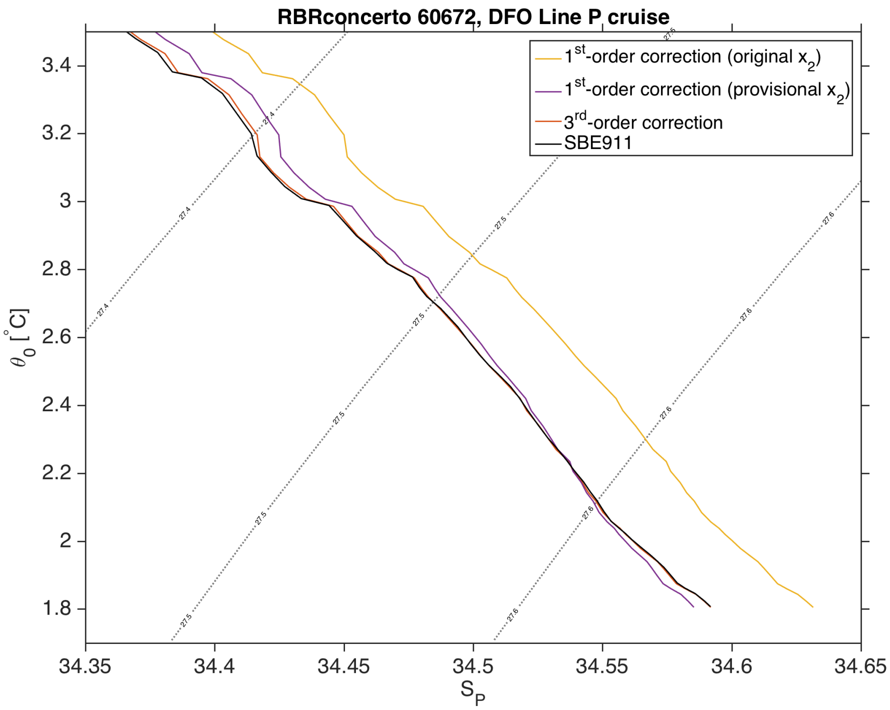
5 Comparison of original first order, provisional first order, and third order conductivity corrections

5.1 DFO Canada rosette comparison

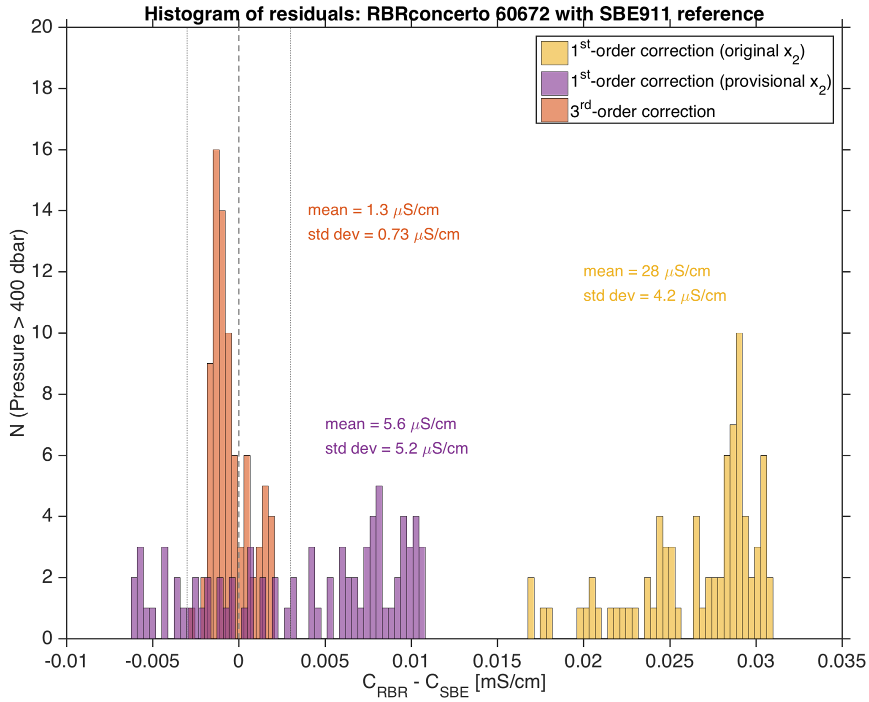
RBR equips its autonomous loggers (e.g., RBR*concerto*) with the same conductivity cell found on profiling floats, and therefore it is straightforward to assess the cell's performance by mounting it on a rosette water sampler. In June 2018, two RBR*concerto* 2000dbar CTDs were profiled on a rosette during the DFO Canada Line P cruise in the North Pacific. Pressure compensation coefficients computed from the saltwater pressure tank testing were applied to the RBR*concerto* data.

The difference between the conductivity when corrected with the new cubic correction, the original linear **x2** coefficient, and the provisional **x2** coefficient, is seen in the following T/S diagrams. The focus is on θ_0 < 3.5 °C (P>1000 dbar), where stratification is weak and the pressure effect dominates thermally-driven dynamic errors. The salinity error (RBR - reference), when using the original linear correction, ranges from 0.03 to 0.05 as pressure increases from 1000 dbar to 2000 dbar. The provisional linear correction reduces the error to 0.011 to -0.007 over the same pressure range. The third order correction brings the salinity to within ±0.003. Furthermore, the errors are consistent between two different 2000dbar RBR*concerto* CTDs.





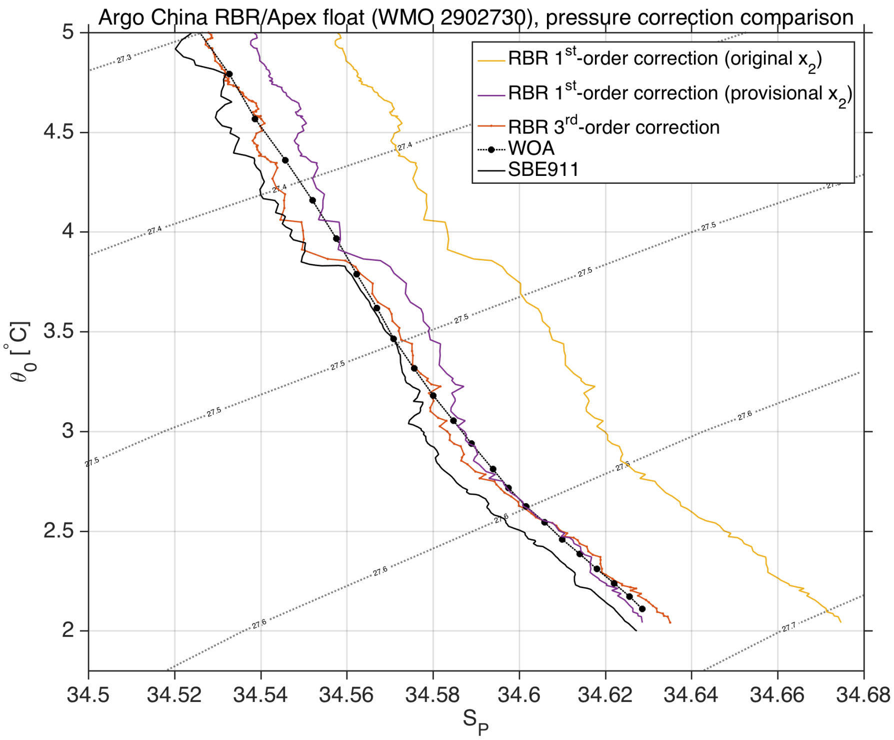
A more detailed and quantitative look at the impact of the various pressure compensation functions can be seen by analyzing the residual conductivity, which is defined as the difference between the RBR*concerto* and a Seabird SBE911. Conductivity is averaged into 20 dbar bins, and data from above 400 dbar are excluded because the strong stratification there causes dynamic errors that dominate the pressure signal. The histograms show that the original linear term effectively biased the measurements too high and increased the range of the errors, while in comparison, the provisional linear correction term reduced the bias but retained the scatter. The third order correction reduces both the bias and the scatter: the average conductivity difference is 0.001 mS/cm, and one standard deviation of the residuals is 0.0007 mS/cm.



5.2 Argo China float comparison

Next, we use the first profile taken by Argo China float 2902730 to illustrate the evolution of the correction terms. Although Argo China applies the *provisional* **x2** coefficient, we also show the original coefficient, **x2** = 4e-7 $dbar^{-1}$, because all floats shipped to date were configured with this value. The reference data in this case is a SBE911 profile taken when the float was deployed, and the nearest grid point of the ¼° World Ocean Atlas mean T/S over the years 2005 - 2012.

The T/S diagram shows the bottom 1000 dbar of the water column ($\theta_0 < 5$°C), where it is seen that the salinity computed from conductivity using the original **x2** value is too salty by 0.03 to 0.04 relative to the WOA. The provisional linear correction brings the salinity very close to WOA values below about 3°C, however it overestimates salinity by 0.01 between 4°C and 5°C (there appears to be a salinity anomaly 3°C and 4°C, so no conclusion is drawn there). Applying the cubic correction brings the salinity below 5°C to within 0.005 of the WOA mean salinity. The average difference below 5°C is less than 0.001 mS/cm, while the standard deviation is 0.0026 mS/cm. While the provisional correction brought the deep values very close the WOA mean, the advantage of the cubic correction is that it minimizes the error over a wide pressure range.



5.3 JAMSTEC rosette comparison

This section will be completed when the JAMSTEC data is made available.

6 Updating the pressure correction

Changing the pressure compensation applied on floats that used the original linear coefficient is easy in Matlab or any other suitable tool. The following example uses the Gibbs Seawater Matlab toolbox because on most floats it is necessary to back out conductivity from temperature and salinity.

Matlab script to apply new cubic corrrection

```
% old pressure compensation factor for conductivity
x2_orig = 4e-7;

% new coefficients for non-linear compensation
x2 = 1.8732e-06;
x3 = -7.7689e-10;
x4 = 1.489e-13;

% create an anonymous function to compute the correction.  P = sea pressure
fp = @(P) x2.*P + x3.*P.^2 + x4.*P.^3;

% calculate conductivity from salinity, temperature, and sea pressure
conductivity = gsw_C_from_SP(salinity,temperature,seapressure);

% remove previous pressure compensation
conductivity = conductivity.*(1+x2_orig.*seapressure);

% apply new pressure compensation coefficient
conductivity = conductivity./(1+fp(seapressure));

% re-derive salinity
salinity = gsw_SP_from_C(conductivity,temperature,seapressure);
```