Advantages in performance of the RBR conductivity channel with Delrin^{TM}/ceramic inductive cell.

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***Abstract* – This paper demonstrates several key advantages of the inductive conductivity sensor. In calibration the sensor has a linear response and may be calibrated with direct traceability to primary standards without assumptions about the salinity scale; one calibration can be used for a wide range of salinities and temperature compensation can be directly measured independently. In the field it has demonstrably superior passive exchange of measurand within the sensor and this is confirmed by the comparative TS plots when used simultaneously with an electrode based sensor.**

I. INTRODUCTION

At the time of introduction of CTD systems to oceanographic practice 50 years ago, there were two major methods for conductivity measurements: the inductive and contact conductometry principles and both are still in use today. It should be emphasised that that the pioneer of CTD system development, Neil Brown, examined these different approaches throughout his career, and produced practical implementations of both. Historically, the choice between these methods always relied on the balance between required technical specifications of the CTD measurements and ability of the extant technology to satisfy those requirements. It is important to realise that the selection of a technology for conductivity measurements must be based not only on a particular conductivity cell, but also on the overall performance of the conductivity channel, i.e. cell design, electronics circuit performance, signal processing and metrological traceability of the measurements.

The requirements for modern oceanographic observation platforms for conductivity measurement must meet the specifications for the CTD systems seen in the UNESCO IOC Manual and Guides 26 "Manual of Quality Control Procedures for Validation of Oceanographic Data" [1]:

Range:	1-65mSm/cm
Accuracy:	±0.005mS/cm
Resolution:	0.001mSm/cm
Stability/month:	~0.003mSm/cm

In the 2007 Alliance for Coastal Technologies (ACT) Workshop "State of technology for *in situ* measures of salinity using conductivity-temperature sensors" [2] a goal was set for the improvement to salinity measurement accuracy to 0.01 over the calibration interval of 12 months.

Both alternative technologies for the measurement of conductivity are offered on the oceanographic instrumentation market and there is a competition between the manufacturers in order to satisfy customers' requirements to meet these specifications. Moreover, a variety of mooring designs and environmental conditions of the deployment requires an additional evaluation of the performance of existed technologies for specific conditions and to find an optimal ratio between cost of deployment and value of achieved data.

The UNESCO CTD systems specification requirements were chosen as a target for the conductivity channel developed in RBR Ltd. In addition to this it was also desired to ensure reliability and ease of use.

This paper presents the results of tests of the RBR conductivity channel in controlled temperature and salinity laboratory conditions as well as *in situ* comparison with an alternate instrument using an electrode sensor in the North Atlantic dynamic environment.

RBR Ltd is a company which has manufactured oceanographic instruments for over 30 years. In recent years the method for measurement of conductivity has received considerable scrutiny and review in order to provide a robust and accurate conductivity channel for RBR XR and XRX series CTD instruments. In 2006 an inductive conductivity cell was developed with the body completely made of high performance plastic, Delrin™, then in 2008 it was modified with ceramic insert (inset, right), which significantly reduced temperature and pressure effect on the cell. Taking in account that external body of the inductive cell is made from the Delrin™, overall durability and flexibility of the cell remains at the same good level, but the metrological parameters of the conductivity channel were considerably improved.

Construction

The RBR Delrin/ceramic inductive conductivity cell has a rated depth range of 740m and has been successfully deployed in many areas with harsh environmental conditions. In a situation of high sediment load and current the robustness of the sensor was illustrated by the recovery of a logger with the Delrin conductivity cell still in reasonable condition, whilst the third party turbidity sensor was completely destroyed by the intense abrasion.

Performance

Work on improvement of the conductivity electronic circuit has resulted in significant reduction of noise level to below 0.001 mSm/cm rms and gives a true linear conductivity channel with non-linearity deviation less than ±0.002mS/cm. For every instrument with a conductivity channel, RBR performs a linearity test with 8 points of conductance simulated with a resistance calibrator. This test can only be done for the inductive conductivity cell technology, where the input conductance can be simulated with a resistance loop. The linear form of the conductivity calibration makes it possible for the users to perform a two-point calibration of the RBR conductivity channel. Taking into account that one point can be at zero conductivity, and hence may be measured in the air, then a calibration may be performed using just one seawater point. For the factory conductivity calibration, this point is taken in a well-stirred uniform seawater bath with salinity close to 35psu and temperature close to 15ºC. Salinity in the bath is controlled by the ratiometric Micro-salinometer (RBR Model MS-310 [3]), set at a temperature of 15ºC. The practical salinity Sp of a sample of seawater, is defined by the Practical Salinity Scale 1978 (PSS-78) [4] in terms of the ratio K_{15} of the electrical conductivity of the seawater sample at the temperature of 15°C and the pressure of one standard atmosphere, to that of a potassium chloride (KCl) solution, in which the mass fraction of KCl is 32.4356E-3, at the same temperature and pressure. The K_{15} value exactly equal to 1 corresponds, by definition, to a practical salinity exactly equal to 35. The practical salinity Sp is defined in terms of ratio K_{15} by the following equation:

$$Sp=f(K_{15}). \tag{1}$$

Conversion of the practical salinity and temperature to conductivity is performed by using the iteration of the PSS-78 equations, after salinity samples are measured ratiometrically with Micro-salinometer MS-310. The ratiometric principle of direct ratio conductivity measurement allows the MS-310 to measure the sample conductivity ratio Rt at temperature 15ºC, maximizing closeness to the temperature of standardisation (calibration) of the IAPSO standard seawater to the KCl primary standard (K_{15}) [5].

Following this sequence of calibration, the transfer of units of the conductivity provides the best way to ensure traceability from the primary conductivity standard to the calibrated conductivity channel at the almost same temperature 15ºC and conductivity ratio $Rt=K_{15}$.

Temperature drift

There is a residual temperature drift in any measurement channel. It is possible to estimate the correction coefficients for this drift in the inductive conductivity channel for each manufactured logger, separately for offset and slope components of the dependence of conductivity on temperature. The pressure correction of the cell was estimated at seagoing trail by comparison with salinity samples taken from the different depths. These correction coefficients for temperature and pressure are stored in the instrument for derivation of the corrected conductivity using an equation of the form [6]:

$$Ccor = \frac{Co+C1*Vc - b*(T-Tc)}{1+a*(T-Tc)+c*P} \qquad (2)$$

where:

Co and C1 - linear regression calibration coefficients;
Vc - raw conductivity channel voltage ratio output;
P - hydrostatic pressure, dBar
Tc - temperature at calibration point, at manufacturing Tc=15ºC
a - conductivity slope temperature correction coefficient, typically 1.5E-5 1/ºC;
b - conductivity offset temperature correction coefficient, typically ±2E-4mS/cm*°C;
c - conductivity pressure correction coefficient, typically 7E-7 1/dBar

Verification of this equation was performed in a temperature controlled conductivity bath, filled with artificial seawater with mass fraction of the salts approximately 0.035. Changing the temperature in the bath from 35ºC to 0ºC with 5 ºC steps, leads to conductivity range from 64mS/cm to 29mS/cm. It needs to be highlighted that this simulation method of the conductivity input quantities is used only for validation of calibration characteristic at fixed salinity 35 in the range of temperatures, but not directly for the estimation of the conductivity calibration coefficients, for example as a cubic polynomial regression. Uncertainties of the reference method of the simulation of the input conductivities by changing temperature of the seawater can be comparable with initial accuracy of a calibrated conductivity channel. Due to the strong correlation between conductivity and temperature parameters of seawater, traceability of the conductivity measured with conductivity channel, directly calibrated only at constant salinity using polynomial regression, leads to significant uncertainties in conductivity (salinity) measurements in the natural waters with salinity different than 35. This method is commonly used for contact cell conductivity calibration and according to the recommendations of manufacturers, for use in the water with salinity different than 35, a conductivity sensor needs to be re-calibrated at working salinity. In the conditions of variable salinities and temperatures, this recommendation makes it impossible to perform conductivity measurements *in situ* with the precision given after calibration. The independence of conductivity calibration from the bath salinity temperature-conductivity correlations is a cornerstone of the metrological traceability of the oceanographic conductivity measurements. Metrological comparability of the oceanographic conductivity measurements to the SI-units can be done only at temperature 15 ºC and practical salinity 35. The RBR inductive conductivity channel accommodates this point for calibration in the seawater bath, and traceability chain transfers the conductivity units from the primary standard KCl through the reference IAPSO standard seawater salinity 35 to the conductivity channel at the same temperature 15 ºC and the same practical salinity 35. This procedure is termed the “calibration by T15S35 bath”.

The reproducibility of the calibration point T15S35 is also a very good and independent test of the reproducibility of the bath seawater over the dynamic temperature range, i.e. uncertainties originated by changing in chemical composition of the seawater. Verification of the stability of the conductivity channel in the same T15S35 bath enables the determination of drift of the RBR conductivity channel to be as low as 0.005mS/cm per year. Typically, when the instrument is used in accordance with the manual and a conductivity cell is mechanically cleaned to restore the original cell geometry (for example in case of biofouling), the stability of the conductivity calibration characteristic at reference point T15S35 is better than 0.01mS/cm per year.

Another important parameter of the conductivity cell design is a flushing factor of the cell. This is a very important factor when measurements are made in conditions of dynamic change of the salinity of the water masses, e.g. for measurements in polar areas, estuaries and other areas of saltwater-freshwater interaction. The best parameter of the conductivity cell flushing property is a diameter-to-length ratio (hole ratio). The hole ratio of RBR Delrin/ceramic conductivity cell is 0.39, which allows water to easily flush the cell. For comparison, the SBE contact cell has a hole ratio equal to 0.02, i.e. almost 20 times less. In a dynamic salinity environment, pumping water through such a cell is the only way to perform proper measurements, which is not suitable in the cases when power consumption is a key factor. This factor needs to be taken into consideration at the time of planning of the observation experiment setup.

In the laboratory we performed comparison of the flushing ability of the RBR inductive conductivity cell and SBE-37 contact cell. Both instruments were submersed in well stirred 100L seawater bath in a similar position. A portion of 100mL of distilled water (equal to reducing the salinity by 0.03) was added into the bath and conductivity (salinity) response was recorded.

An opportunity for the comparison of the RBR inductive cell with SBE-37 contact cell conductivity technology in a real oceanographic observatory conditions of the North Atlantic was given during cruise 298 RRS “Discovery”, when on the mooring E near Cape Farewell (Greenland) both instruments were deployed for a year period at depth 182m. An RBR XR-420CT and a SBE-37 were fixed on the legs of the lander (inset) with the distance of 1m from each other at the same height. Comparison of the collected data was performed both in time scale, and in a form of the T-S diagrams, which reflects the harmonization of the C-T measurement in an instrument design.

III. RESULTS

Calibration

Laboratory testing of the RBR conductivity channel shows very good metrological characteristics. Statistics of the manufacturing calibration of the conductivity channels shows that conductance non-linearity never exceeds 0.002mS/cm with standard deviation less than 0.0007 mS/cm. Typical non-linearity is shown in Fig. 1.

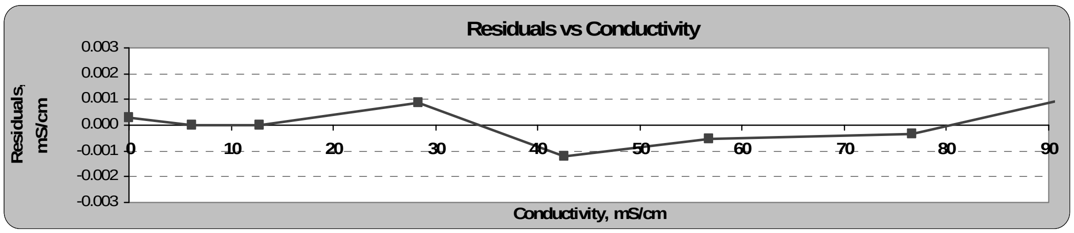

Fig. 1. Residuals after calibration

Measurements in the T15S35 bath are shown in Fig 2. The calibration process at RBR includes a repeatability test, which consists of two movements of the logger out of and back into the calibration bath, so-called conductivity-temperature shocks. It is well-seen that changing of the bath CT-conditions by heat emission from the operators hands, does not affect salinity readings (blue line) due to well-harmonized CT-measurements. Noise level for the conductivity measurements is within 0.0007 mS/cm rms, which is equal to 0.0006 rms for the practical salinity determination.

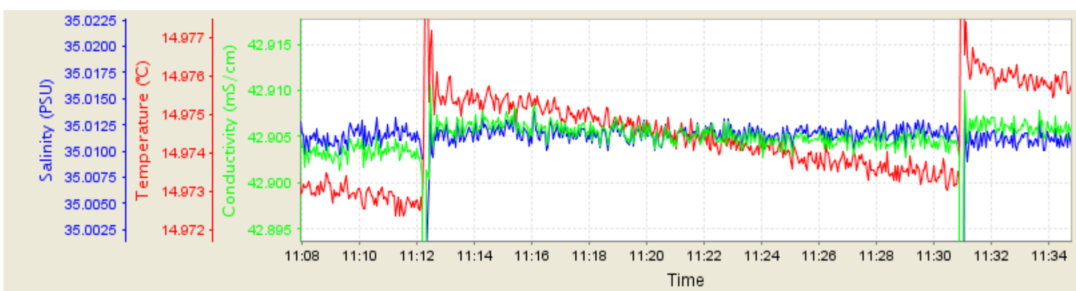

Fig. 2. Measurement in T15S35 bath

The temperature dependence of the conductivity channel is typically less than 0.01% per ºC and each instrument is supplied with its own conductivity-to-temperature correction coefficients. Fig. 3 shows the residuals after temperature correction for conductivity measured in the S35 CT-bath over a temperature range of 35° to 5°C. As we can see in this figure, the temperature compensation works well, minimizing the conductivity error in full temperature range to acceptable level. Maximum of residuals of up to ±0.005 mS/cm could be caused by the variations in dynamic range of the temperature dependence of the conductivity channel and the methodical uncertainties of this method of the conductivity simulation, which may include chemical composition of the seawater, presence of dissolved gases, formation of bubbles, accuracy of the temperature and salinity references etc.

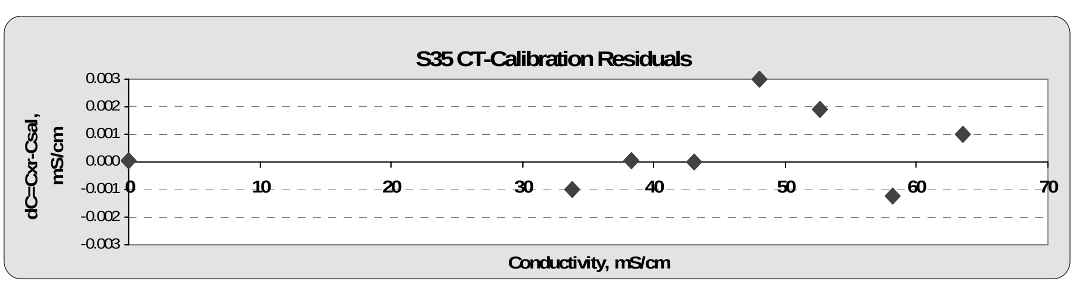

Fig. 3. Conductivity residuals after temperature correction

Time response

The comparison of the response of an RBR XR-420CT and a SBE-37 to an aliquot of distilled water added to the well-stirred S35 bath is presented in Fig. 4. In this it is seen that the reaction to the freshwater input is significantly different. Taking into account the actual time for homogenization of the bath seawater, XR-420CT conductivity readings came to stable conductivity value in 4 seconds after adding distilled water. For SBE-37 this process takes almost 1min for stabilization of readings and magnitude of changing in conductivity reading is 2.5 times bigger. Ratio of the RBR XR-420 and SBE-37 conductivity cells flushing times (1:15) is nearly proportional to the ratio of the hole ratios (1:20) and indicates the superior ability of the inductive conductivity cell to respond adequately to dynamic changes of the environmental salinity.

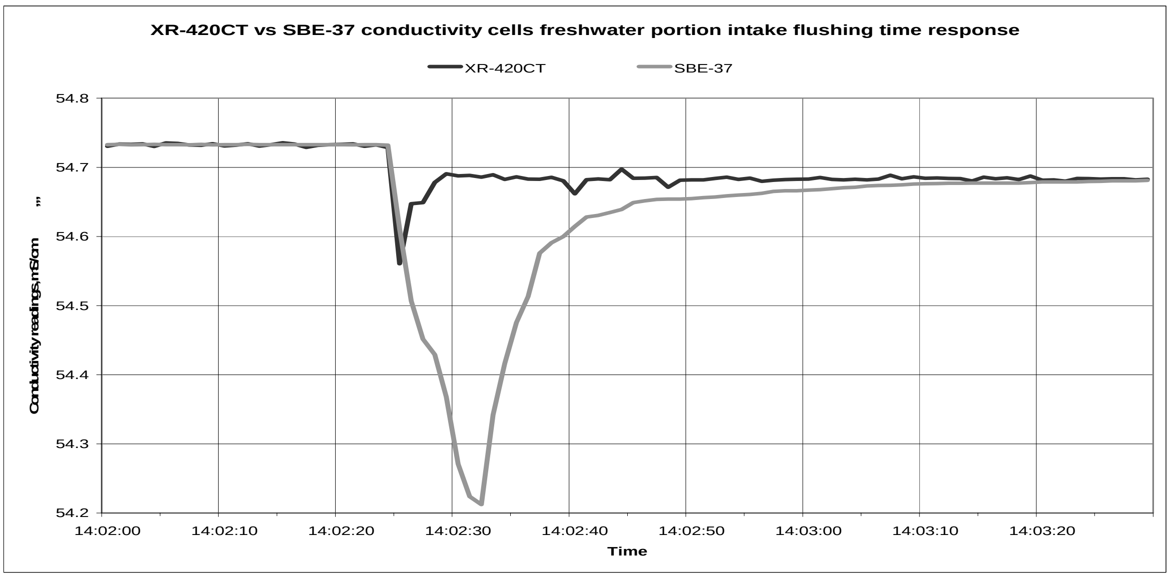

Fig. 4. Comparison of the response of an RBR XR-420CT and a SBE-37 to an aliquot of distilled water added to the well-stirred S35 bath

Deployment Results

Performance of different conductivity measurement technologies in the real ocean observatory conditions of the North Atlantic was performed on the Mooring E, on the bottom of the Greenland shelf, near Cape Farewell. This area is characterized by intense freshwater fluxes and very dynamic thermohaline structure of water masses

Fig. 5 presents a time plot of the salinity measurements in the event of the rapid increase of the salinity of water masses. As well seen, data before and after step changing of water masses are in good agreement, but transition period behaved differently. Lag in time response of the SBE-37 salinity was caused by poor flushing rate of the conductivity cell. It required more then an hour for complete cell flushing and to reach the XR-420 salinity readings.

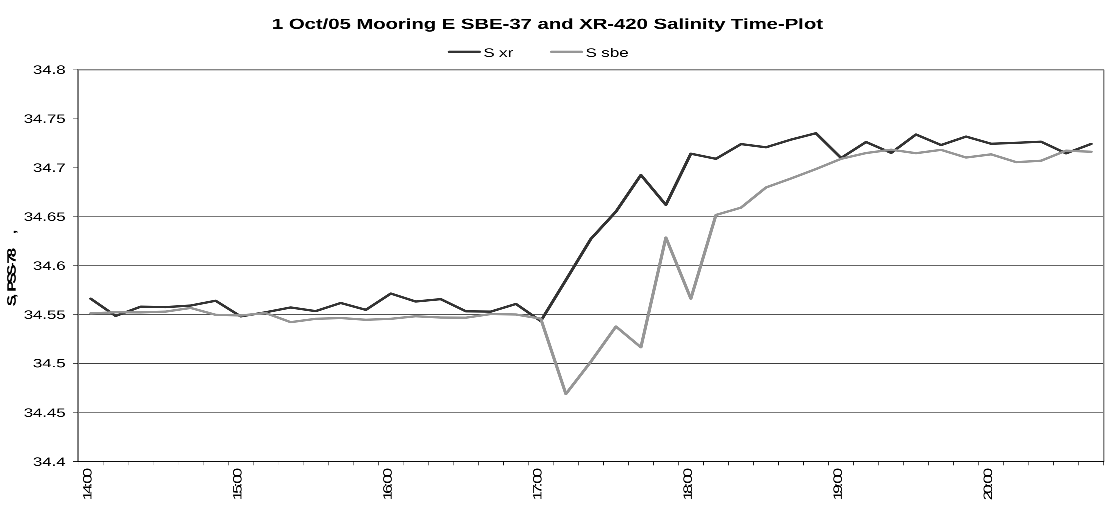

Fig. 5. Time course of response to rapid increase in salinity

The comparison in the time domain can be sensitive to positioning of the compared instruments, dynamic factors of water masses and sample synchronization. To avoid time and dynamic factors, a comparison based on TS-diagrams is used, as shown in Fig 6. From this graph, it may be seen that correlation of the TS relationship for the same period of time is much better for XR-420 (R^2xr=0.99, R^2sbe=0.78) and indicates better harmonization of the CT-measurements made with XR-420.

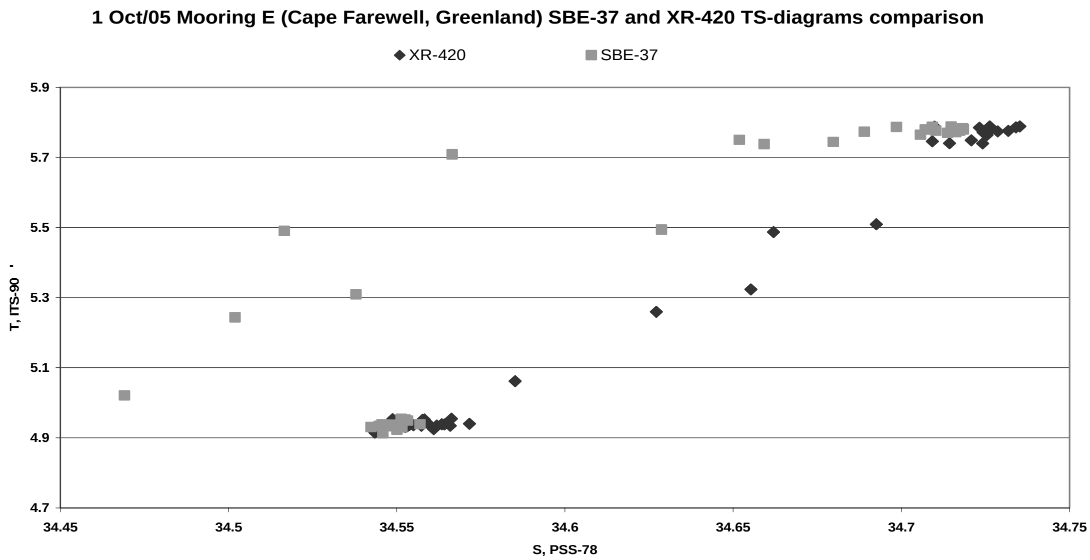

Fig. 6. T-S plot for XR-420CT and SBE-37CT

A more dramatic salinity record with temporal disturbance is presented in the time domain plot of Fig.7. Again, it is very difficult to interprete a comparison of the salinity time plot in conditions of the dynamic fluctuations of water masses. It was assumed that the water in the SBE-37 conductivity cell did not reach a fully flushed condition if the periodicity of the fluctuations was less then one hour compromising the exchange of water within the electrode cell with a new portion of fresh water.

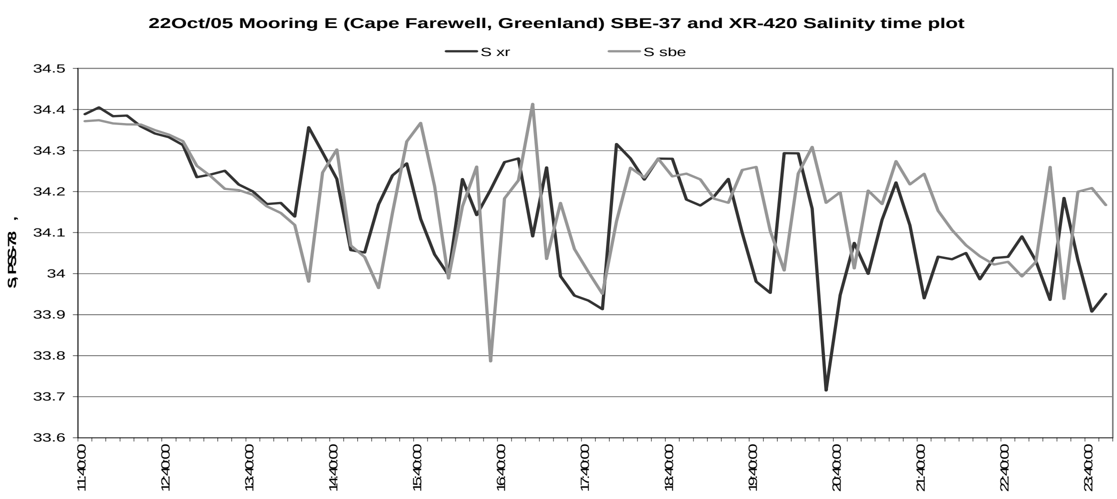

Fig. 7. Time domain plot for freshwater intrusions

Again, the best way to compare the cell flushing performance and overall ability of the CTD systems to perform accurate salinity measurements should be based on the comparison of TS relationship. Correlation between TS parameters in water masses analysis itself can have different values, but comparison of TS-diagrams of the same water masses for the same period of time reflects the comparative performance of the CTD systems. Fig. 8 shows the data of Fig 7 in a form of TS-diagrams. As seen, narrow band of distribution of the dots along the hypothetical TS-curve for the XR-420 ($R^2xr=0.78$) correlated much better then wide spread dots of the SBE-37 data ($R^2sbe=0.22$)

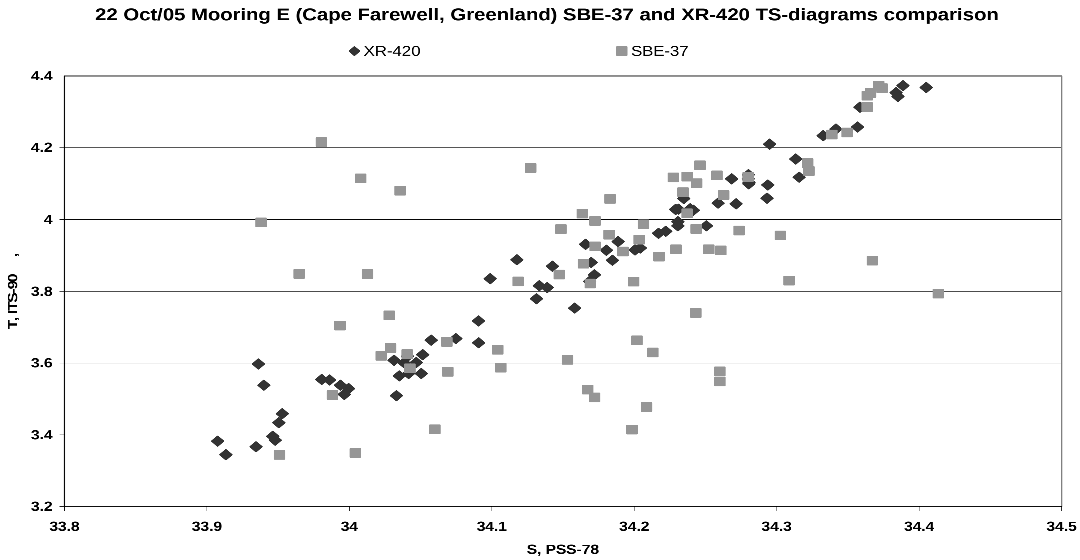

Fig. 8. T-S plot for freshwater intrusions

IV. CONCLUSIONS

1. The conductivity channel with Delrin/ceramic inductive cell as developed by RBR satisfies UNESCO IOC requirements. Durability of the mechanical properties of the inductive cell together with good metrological characteristics of the conductivity channel makes it possible to provide oceanographers with a reliable accurate CTD system for oceanographic observatories.

2. A two-point calibration procedure performed with Micro-salinometer MS-310 using conductivity ratio principle and set at T=15°C, makes RBR conductivity channel calibration independent from the PSS-78 converted conductivity. Metrological traceability of the conductivity measurements relate only to the measurement uncertainty of the determination of the value C(35,15,0). Evaluation of the stability of the RBR conductivity channel at these 2 points allows an estimate of typical drift to be less then 0.01mS/cm per year.

3. Conductivity to temperature correction algorithm works well as compensation of the error of calibrated at S35T15 point conductivity channel in the dynamic temperature range. Typical conductivity to temperature non-compensated error is 0.001mSm/cm per °C, and after temperature correction, uncompensated residuals lie within uncertainties of the method of the conductivity determination and typically do not exceed ±0.005mS/cm.

4. The mechanical design of the cell allows surrounding seawater to flush freely through the cell without the need for pumping of the sample. This is a big advantage in the conditions of the limited power deployments. Comparison of the flushing ability of the RBR inductive cell with the SBE-37 in the laboratory controlled conditions and on the mooring deployment in dynamic environment demonstrates a significant advantage of the RBR CTD system to measure dynamic changes in salinity of water masses without pumping.

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